Climate Change and Resilience White Paper

Vaughan Transportation Plan

City of Vaughan

August 10, 2021

1 Introduction

Cities, communities, businesses and individuals are facing new and intensifying challenges from extreme weather events, increasing air temperatures, and changes in precipitation intensities and flooding as a result of climate change. The City of Vaughan (herein referred to as the "City") has chosen to be proactive in response to these changes and have transformed their thinking, begun to look at their transportation systems differently, and have engaged HDR to provide decision support for their resilient actions as part of the Vaughan Transportation Plan. In accordance with the Intergovernmental Panel on Climate Change (IPCC (AR5), 2014), Environment and Climate Change Canada (ECCC) defines resilience as the capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation. The goal of this study is to provide for the decision support necessary to create dynamic, adaptive systems that protect human health, economic security and environmental well-being.

This report is written to specifically address and quantify risk associated with the impacts of climate change to the City's transportation infrastructure. While many of the current policies and initiatives are concerned with climate change mitigation (reduction of greenhouse gases), this report concentrates on the potential implementation of adaptive measures as part of the City's Climate Change Adaptation and Resilience Framework (2020). Additionally, it addresses the assessment of climate vulnerability as stated in the York Region Climate Change Action Plan (2020). Similar to the definition of resilience supported by the IPCC, ECCC defines adaptation as the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects.

This step-by-step analysis utilizes historic climate trends to set the baseline for understanding projected future climate trends so that the current transportation system vulnerabilities can be correlated to those that are anticipated to change at future time scales due to climate change. Once the climate data was collected, analyzed and understood, these data were used to identify the infrastructure vulnerability to these changes as part of a vulnerability assessment. This assessment of infrastructure vulnerability should be combined with considerations for the consequences of infrastructure failure and system criticality to develop a quantification of risk.

2 Policy Context

Regional and Municipal policies and initiatives related to climate change and resilience is discussed in this section.

2.1 York Region Policies and Initiatives

York Region Climate Change Action Plan (2020)

The York Region Climate Change Action Plan (CCAP) responds to the need for urgent action to reduce carbon emissions and catastrophic climate change impacts[1]. The Region reinforces its commitment to initiatives at higher levels of government and recognizes the impact that climate change has already had and will continue to have. The Region's CCAP:

- Outlines the projected impacts of climate change on the Region;
- Describes and prioritizes actions in three priority areas: resilient communities and infrastructure, low carbon living and supporting an equitable transition;
- Identifies the Region's role in implementing these actions; and
- Provides a framework for government, businesses and communities to work together.

The CCAP evaluates different projected impacts and looks to bring together mitigation and adaptation to act now to avoid higher costs later. The plan, which was released in Q1 2020, is entering the implementation stage (which includes monitoring and reporting) and will be reviewed after five years for course correction, as needed. The following subsections describe resiliency actions for each priority action area[2]. For each action, the role of York Region, potential partners and action timeframe is identified.

RESILIENT COMMUNITIES AND INFRASTRUCTURE

Eight actions under the resilient communities and infrastructure priority action area were identified:

1. Track, report and identify actions required to adapt to the migration of invasive species;
2. Integrate climate change considerations in to existing and new municipal planning and development tools (e.g. climate change by-laws, development guidelines);
3. Conduct a vulnerability assessment on natural systems and integrate adaptive actions into watershed planning;
4. Assess the role natural systems play in mitigating and adapting to climate change; and
5. Enhanced building energy and water performance in new and existing buildings through performance targets and benchmarking within the community.
6. Adopt emission reduction targets and guidelines for low-carbon infrastructure construction practices;
7. Undertake climate change vulnerability and risk assessments on all regional infrastructure, systems and assets using a common methodology; and

[1] The Regional Municipality of York. (March 2020). *York Region Draft Climate Change Action Plan*. Ontario, Canada. York Region.
[2] Action item number corresponds to action within the York Region CCAP

8. Prioritize infrastructure and asset repairs in climate vulnerable areas using the asset management framework.

LOW CARBON LIVING

Five actions under the low carbon living priority action area were identified:

1. Establish community-wide greenhouse gas emission reduction targets;
2. Increase use of more sustainable modes of transportation, such as walking, cycling and transit, and community adoption of electric and low emissions vehicles;
3. Promote a sustainable and resilient food system;
4. Support waste prevention and circular economy practices in York Region; and
5. Identify resources and opportunities that show program alignment to support a circular economy approach through regional and local climate mitigation projects.

SUPPORTING AN EQUITABLE TRANSITION

Ten actions under the supporting an equitable transition priority action area were identified:

1. Include the most severe and likely climate-related risks in Enterprise Risk Management practice;
2. Integrate future climate information and adaptation planning into York Region's Emergency Preparedness Plans and Business Continuity Plans;
3. Co-ordinate strategies York Region and its partners can undertake to increase community resilience and emergency preparedness;
4. Update existing procurement policies to specify climate-related performance targets;
5. Leverage existing programs to support the transition to a low-carbon economy;
6. Work with vulnerable economic sectors and businesses to increase resiliency to climate change impacts;
7. Complete the York Region Climate Change and Health Vulnerability Assessment and share the findings with internal and external stakeholders;
8. Update policies and plans to ensure safety during extreme weather events (inclement weather policy);
9. Apply an equity lens to prioritizing and supporting climate mitigation and adaptation actions; and
10. Continue to build relationships with Indigenous communities around resilience.

Following actions specific to priority action areas are three direct implementation actions:

1. Develop performance indicators to track climate change indicators, greenhouse gas reduction, adaptive action and implementation of this plan;
2. Develop communication and education strategies on the impacts of climate change and strategies for reducing greenhouse gas emissions and increasing resiliency;
3. Develop or acquire the data and information needed to integrate climate change considerations into all decision-making (e.g. best available).

The list of above actions is aimed to achieve outcomes of becoming a net-zero Region by 2050 and increasing the resilience and capacity of the region.

2.2 City of Vaughan Policies

In June 2019, the Mayor of Vaughan and Members of Council declared a climate emergency in the City, joining a list of 21 Canadian municipalities that are deepening their commitment to climate action. The following subsections describe documents that support and define climate action in the City.

Green Directions Vaughan (2019)

Green Directions Vaughan, last updated in 2019, is the City's community sustainability and environmental master plan[3]. It is a guide to a more sustainable future by addressing environmental, cultural, social and economic values, and influences the City's operational and regulatory activities. It is also an Integrated Community Sustainability Plan and is recognized as a platform to request federal funding.

The City uses several themes to identify and describe the outcomes of sustainability actions, one of which is Climate Resiliency, assigned to sustainability actions "that address climate mitigation (reducing greenhouse gas emissions) and/or climate adaptation (better protecting against climate change impacts)". As a major theme across sustainable goals, some objectives defined within the plan that are relevant include:

- Objective 1.1 – To reduce greenhouse gas emissions and move towards carbon neutrality for the City's facilities and infrastructure;
  - Specifically, actions 1.1.1, 1.1.2, 1.1.3, 1.1.4, 1.1.5.
- Objective 1.2 – To promote the reduction of community greenhouse gas emissions in the City of Vaughan;
  - Specifically, actions 1.2.1, 1.2.2, 1.2.3 and 1.2.4.
- Objective 2.1 – To ensure a climate resilient City and build capacity for local action on climate change; and
  - Specifically, actions 2.1.1, 2.1.2 and 2.1.3.
- Objective 2.3 – To create a city with sustainable built form that is compact, resilient and designed to promote citizen health.
  - Specifically, actions 2.3.3, and 2.3.4.

Vaughan Community Climate Action Plan (2014)

Vaughan's Community Climate Action Plan was developed through engagement of citizens and stakeholders between September 2013 and January 2014. The purpose of this plan is to provide the community with practical ways to reduce GHG emissions from community sources to mitigate the impact of climate change. The community GHG emission reduction goal established through this plan is 20% per person by 2026. This plan looks at reducing GHGs from three approaches: in the home, at work, and on the move.

Vaughan Official Plan Review (2020)

As part of the Official Plan Review's Climate Change Adaptation and Resilience Framework, a Climate Change Vulnerability and Risk Assessment is currently being undertaken. This

[3] City of Vaughan. (2019). *Green Directions Vaughan: 2019 Sustainability Plan*. Vaughan, ON. City of Vaughan.

assessment will involve reviewing past work, identifying and analyzing risks, evaluating risks and risk treatment. The following methodology will be applied:

1. **Contextual review.** Brief review of existing work.
2. **Stakeholder workshop.** Online workshop with stakeholders to brainstorm potential climate change impacts to the City in systems such as infrastructure, buildings, parks/trails, natural heritage, social assets and economic assets.
3. **Survey.** Integrating the workshop results into an online survey to create a ranked list of hazards to the city.
4. **Climate change risk assessment.** Identifying risks by sector and evaluating likelihood and potential impacts through analysis.
5. **Adaptation measures.** Identifying adaptation objectives based on timeframes, which could include revision of policies, changes to engineering standards, changes to zoning and implementation of social initiatives such as public education material.

3 Best Practices Review

As climate change and resilience have increased in importance, best practices have also shifted towards these trends. This section describes a review that was undertaken to define best practices in planning, design and maintenance of transportation infrastructure.

Infrastructure Canada, National Research Council (NRC) – Climate-Resilient Buildings and Core Public Infrastructure Initiative (2015)
Infrastructure Canada's Climate-Resilient Buildings and Core Public Infrastructure (CRBCPI) initiative looks to "develop decision support tools, including codes, guides and models for the design of resilient new buildings and Core Public Infrastructure (CPI)"[4]. It also aims to "support rehabilitation of existing buildings and CPI in key sectors to ensure that climate change and extreme weather events are addressed".

Specifically, the program aimed to support the Pan Canadian Framework on Clean Growth and Climate Change and the Green Infrastructure objectives of the Canadian government, drawing on the expertise of the NRC and of Environment and Climate Change Canada (ECCC) to use climate data to develop new codes and guides. The program was supported with $42.5 million in financial support from Infrastructure Canada.

As part of this project, CRBCPI partners have developed future-looking climate data (temperature, precipitation and wind data) that will be used by building and infrastructure codes and guides[5]. The data will be implemented in the 2025 Canadian Highway Bridge Design Code (CHBDC) and will be submitted for consideration for the 2025 edition of the National Building Code. In addition, some other achievements of this program over the past five years include:

- Over 50 changes proposed to the Canadian Electrical Code to increase reliability and resiliency of electricity in the context of climate change and extreme weather;
- Developed best practices for flood risk reduction in residential communities, national guidelines for urban storm drainage, standards for Construction of Bioretention Systems, and development of buildings with buoyant foundations for communities with high flooding risk;
- Currently developing standalone national guidelines for wildland urban interface fires;
- Rewrote several Canadian Standard Association (CSA) guidelines to address durability and roofing standards in buildings;
- Developed a new standard with the CSA on climate change adaptation for wastewater treatment plants;
- Developed technical guidance for adaptable housing for the First Nations Building Officers Association (FNBOA);
- Conducted research to enable climate change adaptation of transit systems by equipping subway tunnels and trains in Toronto with instrumentation to collect data,

[4] Armstrong, M. (June 2020). *NRC's Climate-Resilient Buildings and Core Public Infrastructure Initiative*. National Research Council of Canada.
[5] Infrastructure Canada. (October 2020). *Climate-Resilient Buildings and Core Public Infrastructure Initiative*. Infrastructure Canada.

making the Toronto Metro the most instrumented system in the world, being used to research and provide guidance on overheating in public transit;
- Developing guidance to improve climate resilience of existing roads and to guide cost-effective maintenance and rehabilitation decisions; and
- Released the 2019 Canadian Highway Bridge Design Code (CHBDC), which features provisions related to climate change, sustainability and resilience and fully historical data. In addition, guidelines for bridge durability are being improved based on the NRC's newly developed wind tunnel facility where the impact of climate change and extreme weather are being tested.

Infrastructure Canada – Climate Lens Assessment (2019)
Infrastructure Canada's Climate Lens Assessment (CLA) is a horizontal requirement that is applicable to three programs: Infrastructure Canada's Investing in Canada Infrastructure Program (ICIP), Disaster Mitigation and Adaptation Fund (DMAF) and Smart Cities Challenge[6]. The CLA involves two components: the GHG mitigation assessment (which measures anticipated GHG emissions from a project), and the climate change resilience assessment (which uses a risk management approach to mitigate climate change impacts). Project proponents undertake one or both types of assessments, depending on the program, funding stream, and the estimated total cost of the project.

The CLA provides insight into climate impacts of individual projects and is consistent with Canada's commitment to reduce GHG emissions by 30% below 2005 levels by 2030. The GHG emission mitigation assessment has guidelines for establishing baseline emissions then estimating the project's emissions afterwards. The climate change resilience assessment consists of developing a risk management framework, by identifying, analyzing, and treating project risks. It is a systematic method to evaluate projects' GHG emissions and climate change resiliency that aims to facilitate better decision making in current and future infrastructure projects.

Metrolinx – Climate Adaptation Strategy (2018)
The Metrolinx Climate Adaptation Strategy describes the agency's commitment and approach to operate climate resilient transportation services. The agency has already undertaken improvements to mitigate climate risk, including building embankments to reduce flooding, improving monitoring, and changed new rail installation to avoid warping. The strategy involves forty (40) key actions, with the following goals:

- Plan for transportation needs in different timeframes and recommend projects and services where climate resiliency measures are needed;
- Build new regional rapid transit throughout the GTHA that are more resilient and adaptive to climate change and extreme weather;
- Operate regional service in a manner that reduces vulnerability to extreme weather and climate change and increases resiliency and capacity; and

[6] Infrastructure Canada. (October 2019). *Climate Lens – General Guidance*. Infrastructure Canada.

- Connect the region by coordinating work to enable better solutions that what could be achieved individually.

The forty (40) key actions are focused on the above listed goals, but are also categorized by sub-goals, and list the department accountable for its execution, the current status of the action and the estimated completion date.

Greater Golden Horseshoe Transportation Plan – Draft Environment Profile (2018)
As part of the Ministry of Transportation for Ontario's Greater Golden Horseshoe (GGH) Transportation Plan, an assessment was undertaken of natural systems by developing an environmental profile[7]. The GGH contains the most productive farmland in Canada and involves cultural heritage as well. From the environmental profile that was developed, a need was identified to meet population and economic growth without compromising environmental objectives by minimizing impacts on natural systems. A need was also identified to plan for resilient infrastructure to mitigate growing climate uncertainty. Emerging technologies and active modes were also identified as methods to enhance mobility, improving community health and reducing GHGs.

City of Ottawa – Kanata LRT EA, Planning for Climate Resilience (2018)
The City of Ottawa's Kanata LRT EA was completed in 2018 and was approved by the Province of Ontario. The climate change assessment for this project focused on the LRT extension to the former City of Kanata (now part of Ottawa)[8]. The project involves many infrastructure elements that are vulnerable to climate change impacts including the vehicle, electrification systems, rail systems, passenger pick-up/drop-off facilities, lighting and landscaping.

The Province of Ontario expects project proponents to consider both climate change mitigation (GHGs) and climate change adaptation (resiliency). For this project, climate projects based on historical averages and horizons in the years 2050 and 2080 were used, and sensitivity for low and high global warming. A risk assessment was undertaken by evaluating hazards for each infrastructure component and climate factor interaction, then determining the probability of a negative event and its severity. A risk matrix was prepared that compared infrastructure components (track/guideway, retaining structures, catenary systems) against climate change factors (extreme heat, annual rain, freezing rain, extreme wind). Stakeholder workshops were undertaken for feedback. Comments were provided for each set of interactions with infrastructure, along potential maintenance and operations consideration.

After the EA, an additional climate change study at the preliminary design state and a formal risk study (according to PIEVC engineering standards) was recommended. This project was the first application of a provincial climate change guidance to the City of Ottawa transportation EA study. The process brought awareness to the importance of considering climate change early in

[7] Ministry of Transportation for Ontario. (January 2018). *Draft Environment Profile*. Ministry of Transportation for Ontario.
[8] Harkness, Andrew. (September 2020). *City of Ottawa Kanata Light Rail Transit EA: Planning for Climate Resilience*. Transportation Association of Canada, 2020 Conference.

project planning. Commitments were made to complete further study climate change in the remainder of the project process.

City of Toronto – Resilience Strategy

The City of Toronto published its first resilience strategy in June 2019, which sets out a vision, goals and actions to help Toronto survive, adapt and thrive in the face of challenges such as climate change and growing inequity[9]. The strategy was developed in consultation with over 8,000 Torontonians in collaboration with the Ontario College of Art and Design using a Strategic Foresight process. Some key goals identified through this strategy that pertain to climate change resiliency include:

- Toronto is more resilient to climate change, including the hazards of flooding and heat;
- Infrastructure and buildings are resilient to a changing climate and reduce greenhouse gas emissions; and
- Toronto has multiple reliable, affordable, and safe mobility options that reduce the amount of time it takes to get around.

Under each of these goals, several actions necessary to achieve them are listed. A specific priority action to the City of Toronto is flood resilience, specifically to centralize resources towards a city-wide flood planning and prioritization tool.

[9] City of Toronto. (June 2019). *Toronto Resilience Strategy*. City of Toronto.

4 Historic Climate Trends

Historic climate trends are critical to setting a relationship between observed changes in the climate and projected changes in the future climate. They represent the here and now of climate hazards and how those hazards have changed over time in the observed record. This section investigates current climate trends, as well as their extrapolations into the future so that those extrapolations can be compared with future climate scenarios for the following environmental parameters.

4.1 Air Temperature

Increasing air temperatures are anticipated to be an outcome of climate change on a global scale, throughout Canada, and specific to the City (Zhang, P et al., 2019). While these increasing air temperatures are expected to have a significant impact on the health and mobility of the users of the City transportation infrastructure, only the potential for air temperature extremes, primarily extreme heat, are likely to have an impact on system infrastructure.

The meteorological reporting station at Toronto Pearson Intl. Airport was used due to its proximity to the City and its long period of record. **Figure 1** identifies a trend showing overall increases in both average annual maximum temperatures and average annual minimum air temperatures, but, more importantly, shows a dramatic shift (inflection) in these graphs around the year 1980. This same pattern regularly shows up in the analysis of average annual air temperatures across North America and is particularly pronounced as it pertains to nighttime low temperature annual averages.

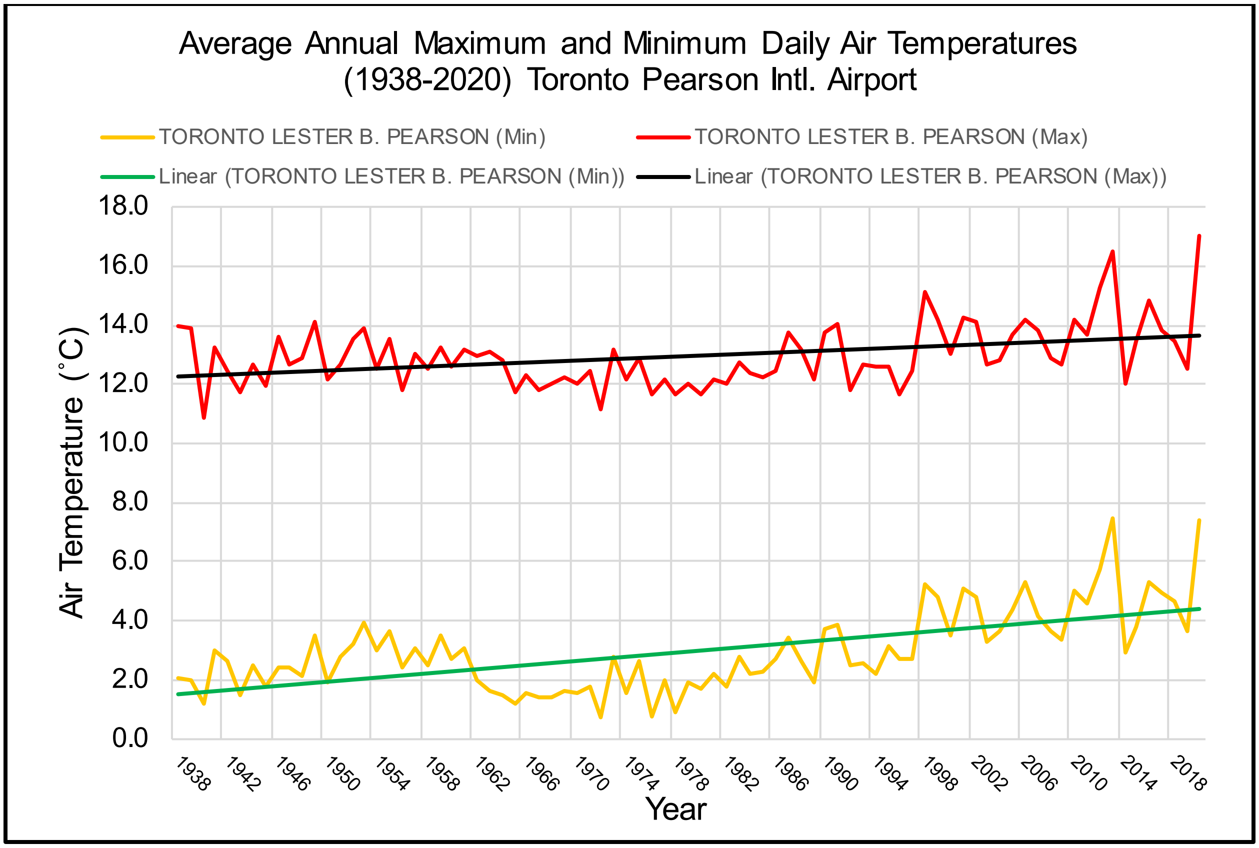

Figure 1. Average annual maximum and minimum Daily Air Temperatures at Toronto Pearson Intl. Airport (1938-2020). Trendlines in black and green. Source: NCDC

As will be discussed in relation to changes in the other environmental parameters in this study, decisions made in regard to climate resilience actions should consider observed climate trends as equally as they do projected climate trends. In order to better understand these decisions, it is necessary to provide a “What if?” scenario along the lines of, “What if the current (last 30-40 years) climate trends were to continue into the future?”.

Figure 2 shows the graphs of the current average annual maximum and minimum temperature trends (1980-2020) extrapolated out to the year 2100. This graph indicates that if the current trend continues through the year 2100, the average annual maximum air temperature will rise 4.2˚C and the average annual minimum air temperature will rise 7˚C.

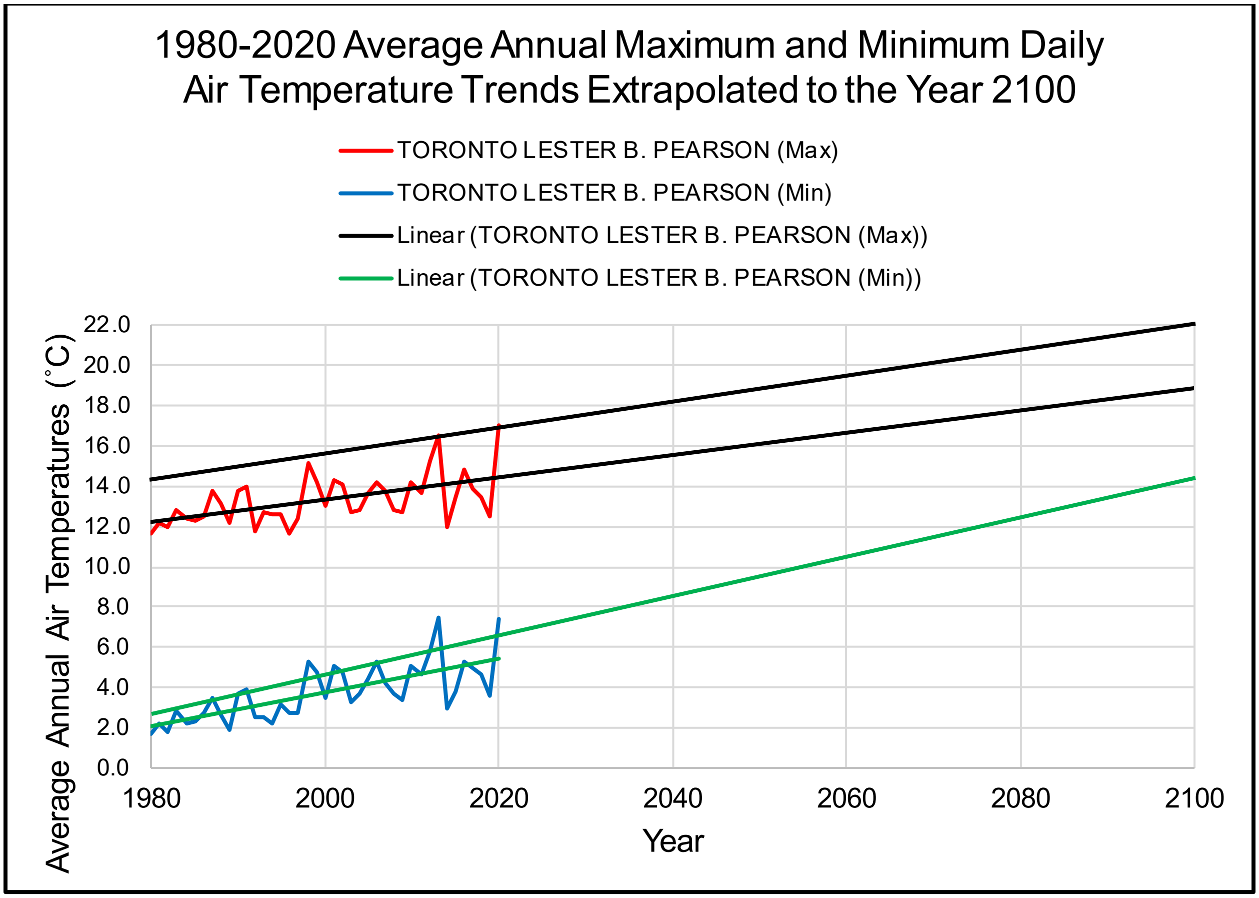

Figure 2. Average annual maximum and minimum daily air temperatures at Toronto Pearson Intl. Airport (1938-2020) extrapolated to the year 2100. Trendlines in black and green. Source: NCDC

Periods of extreme heat, or colloquially known as heat waves, are expected to be a consequence of climate change (Zhang, X. et al., 2019). **Figure 3** shows a graph of the historic climate trend in annual daily maximum air temperatures at Toronto Pearson Intl. Airport. The slowly decreasing trend in these values throughout the entire period of record is a phenomenon that is somewhat contrary to the anticipated increase in maximum temperatures but is also something that is occurring in many locations within North America. It is attributable to the atmospheric phenomenon wherein as the annual average temperatures increases so does the atmosphere's ability to hold moisture. Thus, maximum air temperatures are being capped by the increase in atmospheric moisture, which is producing cloud cover that keeps temperatures slightly lower. The relative humidity is higher, but the temperature is not as high as it could be under less humid conditions.

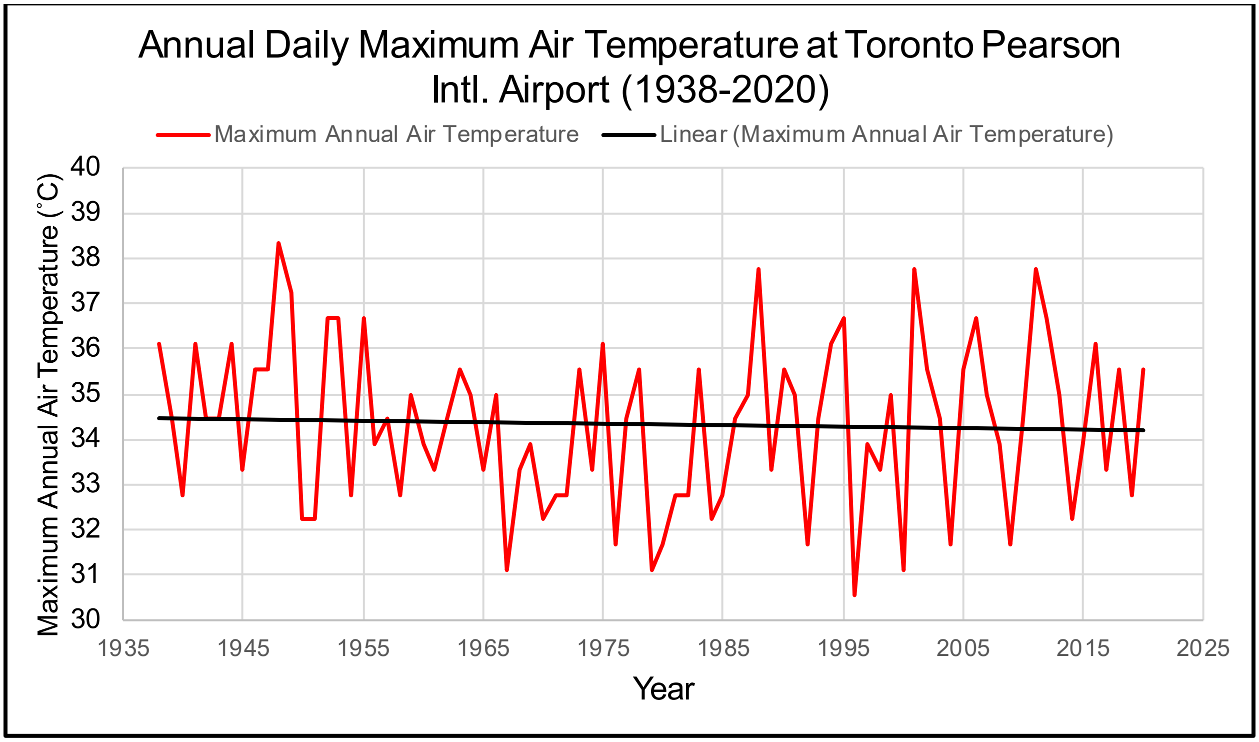

Figure 3. Annual daily maximum air temperature at Toronto Pearson Intl. Airport (1938-2020). Trendline in black. Source: NCDC

4.2 **Precipitation**

As noted in the previous section regarding changes in air temperatures, as the annual average air temperatures increase so does the atmosphere's ability to hold and release moisture. This is physically related to the Clausius-Clapeyron equation wherein as the temperature increases the atmosphere's ability to hold moisture increases approximately 6.3 percent per degree C. **Figure 4** shows the changes in annual maximum 24-hour precipitation at Toronto Pearson Intl. Airport (1938-2020). While the linear trend of these data does not show a significant trend up or down, there are significant swings in magnitude in the year-over-year variability of the data. During the years 1938-1984, the standard deviation was 12.43mm, but during the years 1985-2020 the standard deviation was 21.39mm. Thus, more recent climate trends are indicating that larger, more intense events are occurring in the region, but not necessarily every year.

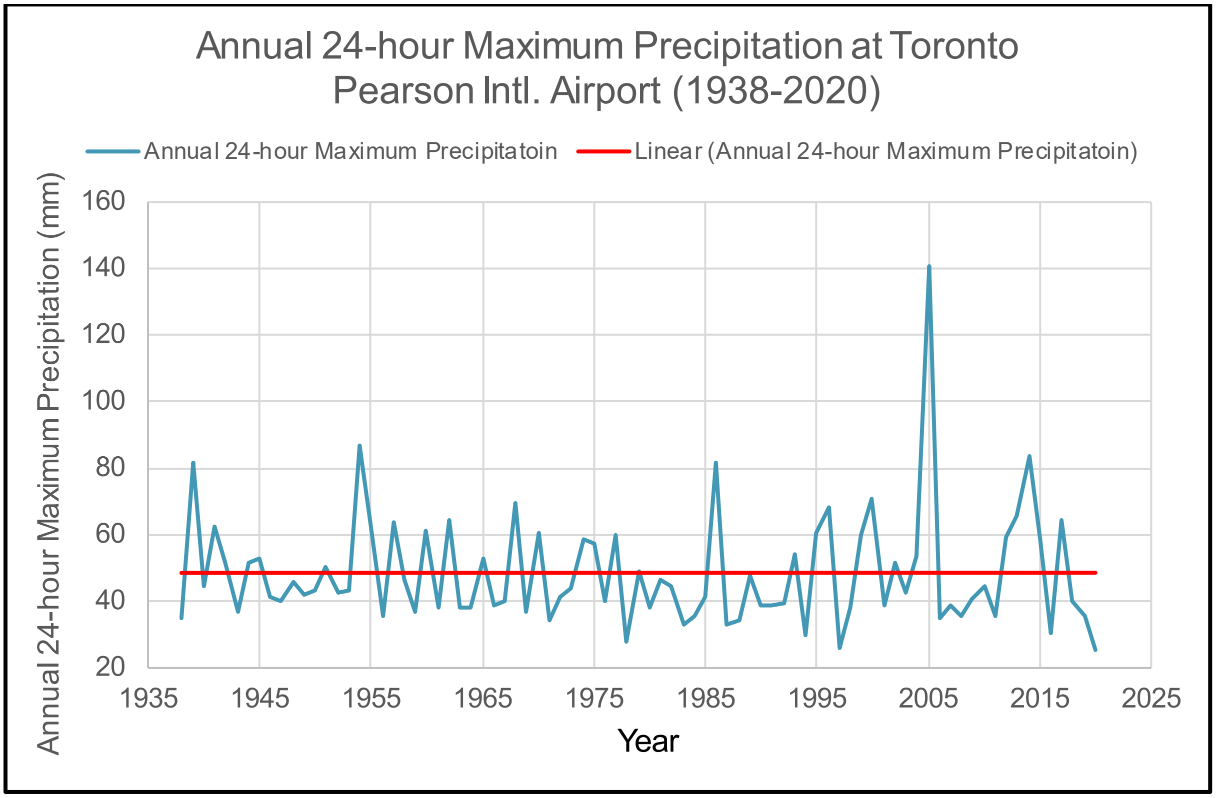

Figure 4. Annual 24-hour maximum precipitation at Toronto Pearson Intl. Airport (1938-2020). Trendline in red. Source: NCDC

The same principle of a warmer environment producing more precipitation is very apparent in the record for annual precipitation in the region as well. **Figure 5** clearly indicates that the total annual precipitation in the region is steadily increasing. This has many implications regarding the stability of infrastructure in saturated soils as well as to changes in runoff during extreme storm events. These topics will be covered during the discussion of potential impacts in the following sections.

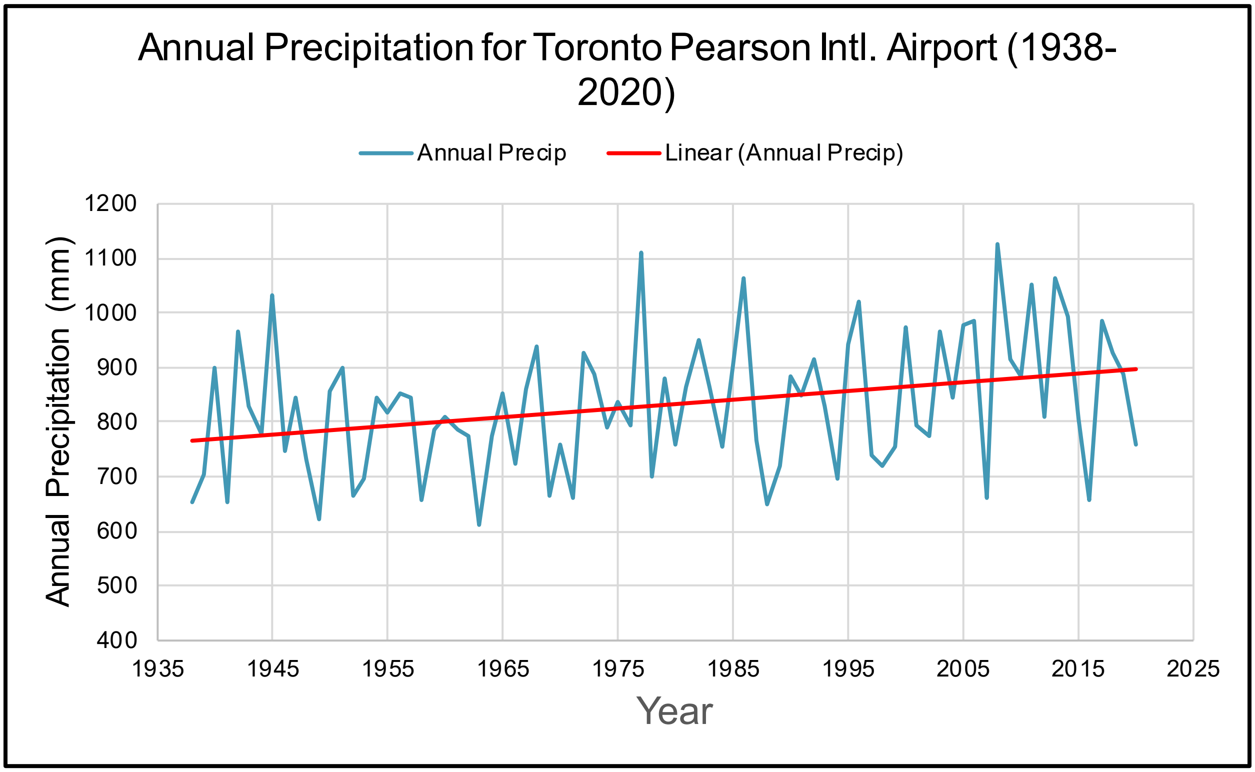

Figure 5. Annual precipitation at Toronto Pearson Intl. Airport (1938-2020). Trendline in red. Source: NCDC

5 Projected Climate Change

Climate change projections are manifestations of output from global climate models that utilize future climate scenarios (climate forcing) to quantify future changes in atmospheric parameters. Changes in air temperatures and precipitation, which may result in consequential changes in other hazards such as ice jams, flooding, and extreme storm events, are assessed through GHG mitigation or business-as-usual scenarios.

The emission of GHG from human activity is expected to be largely responsible for the magnitude of climate change through the end of this century. In order to capture an understanding of different climate change outcomes, this study utilized two future emissions scenarios or Representative Concentration Pathways (RCP) to provide a perspective on future change. RCP 4.5 represents a future wherein GHG emissions continue to increase until the year 2050 and then begin decrease through the year 2100. In this scenario it takes until the year 2070 before that decrease become impactful to the projections. RCP 8.5 represents a future where emissions continue to accelerate through the year 2100. RCP 4.5 is considered the middle-of-the-road case, while RCP 8.5 represents the highest level of future emissions.

The following sections provide projections of expected changes in atmospheric conditions and environmental hazards. Climate modeling and regional downscaling at future time scales were developed as part of the work performed for the Canada's Changing Climate Report (CCCR) (Bush, et al., 2019), which is consistent with the data used to produce the climate data report specific to the City of Vaughan (ECCC, 2021).

5.1 **Projected Air Temperature Change**

One of the most profound findings of CCCR is the fact that through analysis of the observed climate record, Canada is warming at a rate that is more than twice the global rate. This is primarily a consequence of phenomenon called "Arctic amplification", or the result of changes in a land area's, particularly the Canadian Arctic's, albedo. Basically, this equates to less snow and sea ice equals more radiative absorption, and, thus, more warming.

Future changes in air temperatures are expected to have a much greater impact on the human health and behavior (system demand) than on transportation system infrastructure, but the following climate projections and understanding of the potential impacts to the human condition are provided for consideration as part of the resiliency equation for the City. The downscaled climate data provided by the CCCR, specific to the City, were used to quantify expected changes in air temperature at future time scales.

Figure 6 shows the projected annual average maximum temperatures expected in the City for the years 2000-2100. As of the year 2000, the annual average maximum temperature was 12.6˚C. **Table 1** shows the anticipated annual average maximum air temperature projections for the year 2035, 2050, 2075, and 2100 based on RCP 4.5 and RCP 8.5 scenarios. **Figure 2**, the extrapolation of the current trend in annual average maximum air temperature, is in surprisingly good agreement with the RCP 8.5 projected trend.

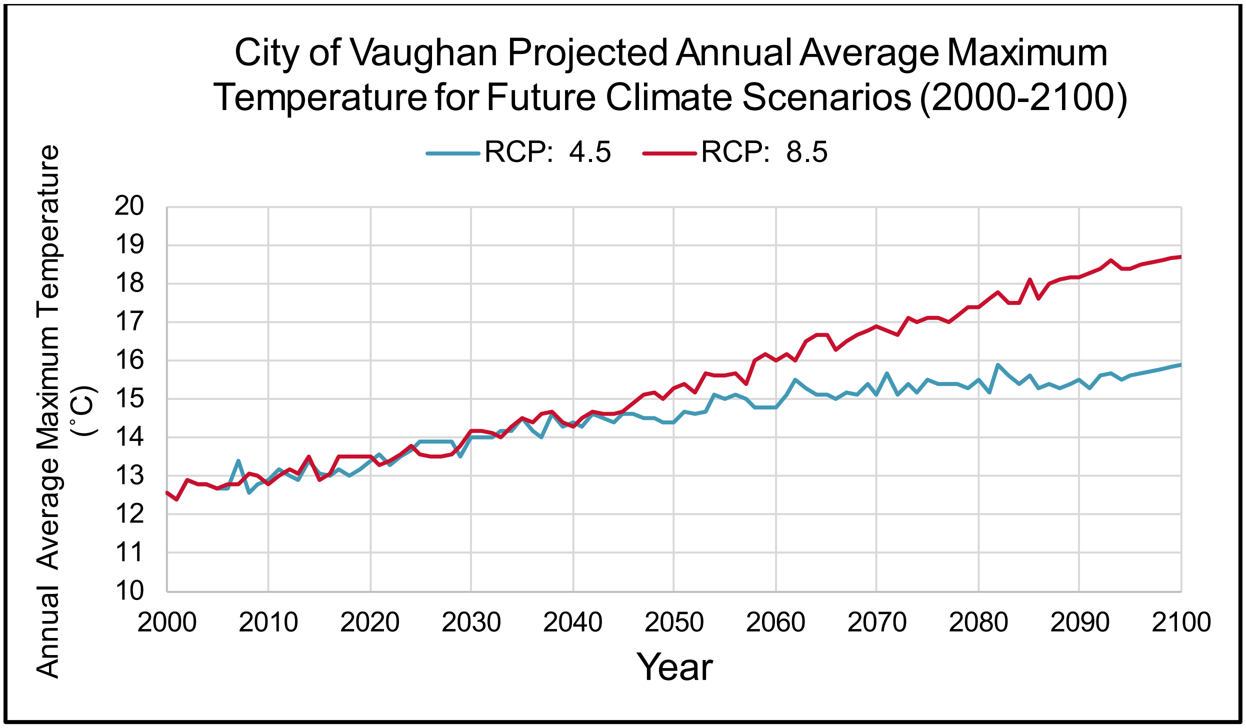

Figure 6. Projections of future annual average maximum air temperatures for the City to the year 2100. Source: CCCR

Table 1. Projected annual average maximum air temperatures for the City at future time scales.

Future Scenarios		
Year	RCP 4.5 (˚C)	RCP 8.5 (˚C)
2035	14.01	14.49
2050	14.50	15.47
2075	15.31	17.10
2100	16.12	18.73

Figure 7 shows the projected changes in annual average minimum air temperatures for the City under the two future climate scenarios. **Table 2** provides a quantification of these projections for future time scales. The projected changes in annual average air temperatures under the RCP 8.5 are actually less than those predicted in the extrapolation of the observed data for this parameter in **Figure 2**. As noted in the following section on future ice jam flooding in the region. These projected minimum air temperatures are expected to play a large role in an increasing frequency of ice breakup and/or ice jam potential on the region's rivers and streams during the mid-winter period.

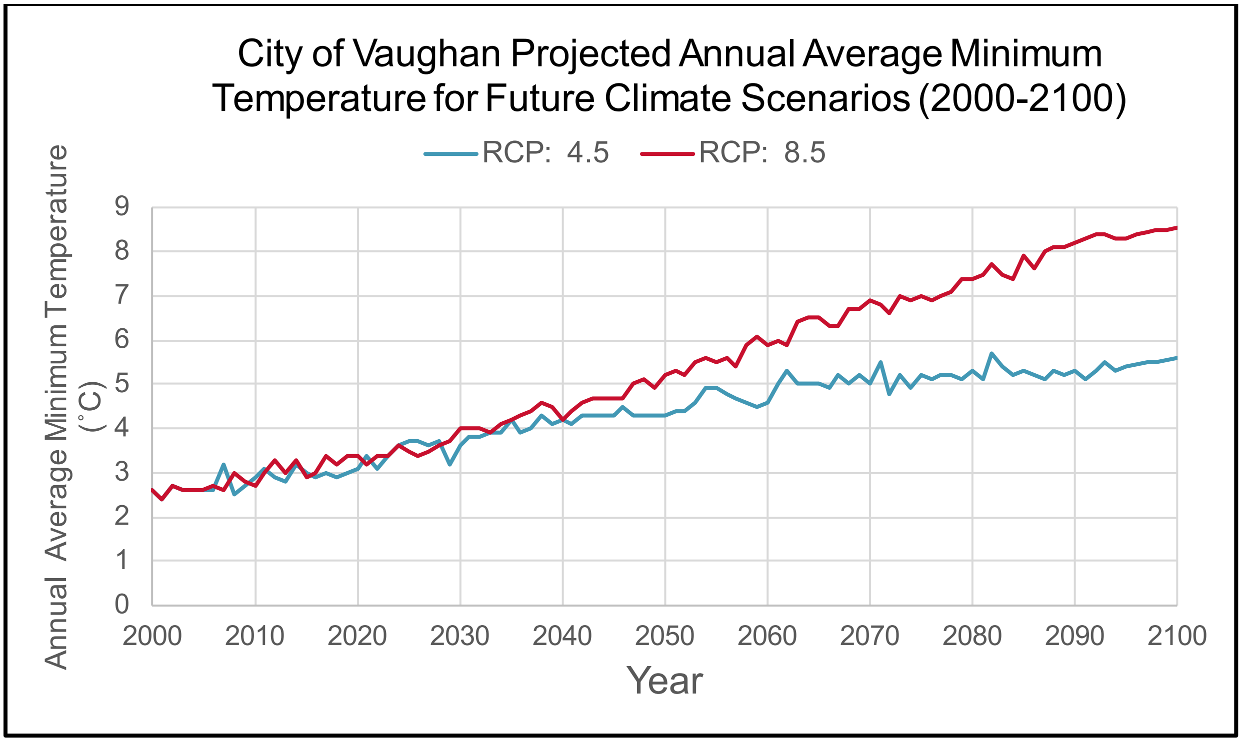

Figure 7. Projections of future annual average minimum air temperatures for the City to the year 2100. Source: CCCR

Table 2. Projected annual average minimum air temperatures for the City at future time scales.

Future Scenarios		
Year	RCP 4.5 (˚C)	RCP 8.5 (˚C)
2035	3.87	4.32
2050	4.35	5.31
2075	5.14	6.94
2100	5.93	8.58

As stated earlier in this section, air temperatures are expected to have a significant impact on human behavior as the residents of the City interact with the transportation system. This will be particularly true on very hot days equal to or greater than 30˚C. **Figure 8** shows the projected number of very hot days expected in conjunction with the two future climate scenarios used for this analysis. **Table 3** quantifies these number of days at future time scales.

While the increasing number of very hot days is only expected to have a nominal impact on infrastructure, primarily as a result of thermal expansion within components of the system, it may prove, along with changes in precipitation and other weather phenomenon, to become a major factor for changes in system demand. A recent study in Berlin, Germany (Nissen, K.M. et al., 2020) showed public transit ridership and road traffic decreasing 5 percent on very hot days (>28ºC), while ridership increased as much as 30% on very cold days (<-5 ºC) during a time when road traffic decreased. This report showed a decrease in ridership on buses and light rail during days with precipitation and an even greater decrease during times of heavy rain. The impact of precipitation on the number of drivers was difficult to quantify, but there is, quite obviously, a strong correlation between traffic accidents and precipitation.

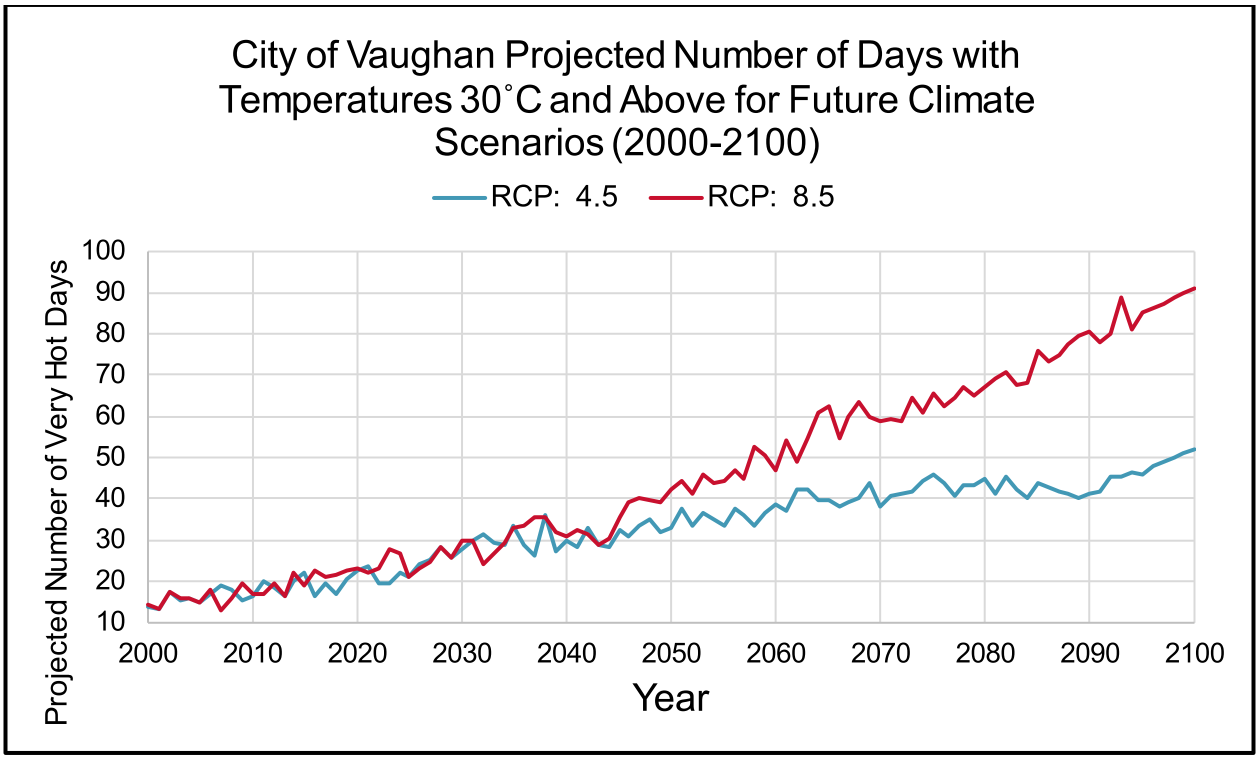

Figure 8. Projected number of very hot days (≥30˚C) for the City to the year 2100. Source: CCCR

Table 3. Projected number of days with air temperatures greater than or equal to 30°C for the City at future time scales.

Future Scenarios		
Year	RCP 4.5 (# days)	RCP 8.5 (# days)
2035	27.63	33.63
2050	32.83	45.21
2075	41.51	64.52
2100	50.18	83.83

While the increasing number of days of air temperatures greater than or equal to 30˚C are expected to have a greater impact on system users, the most extreme air temperatures could cause infrastructure problems or failure through thermal expansion (i.e. asphalt buckling). **Figure 9** shows the anticipated increase in maximum temperatures in the City under both future climate scenarios. **Table 4** quantifies these maximum temperatures at future time scales.

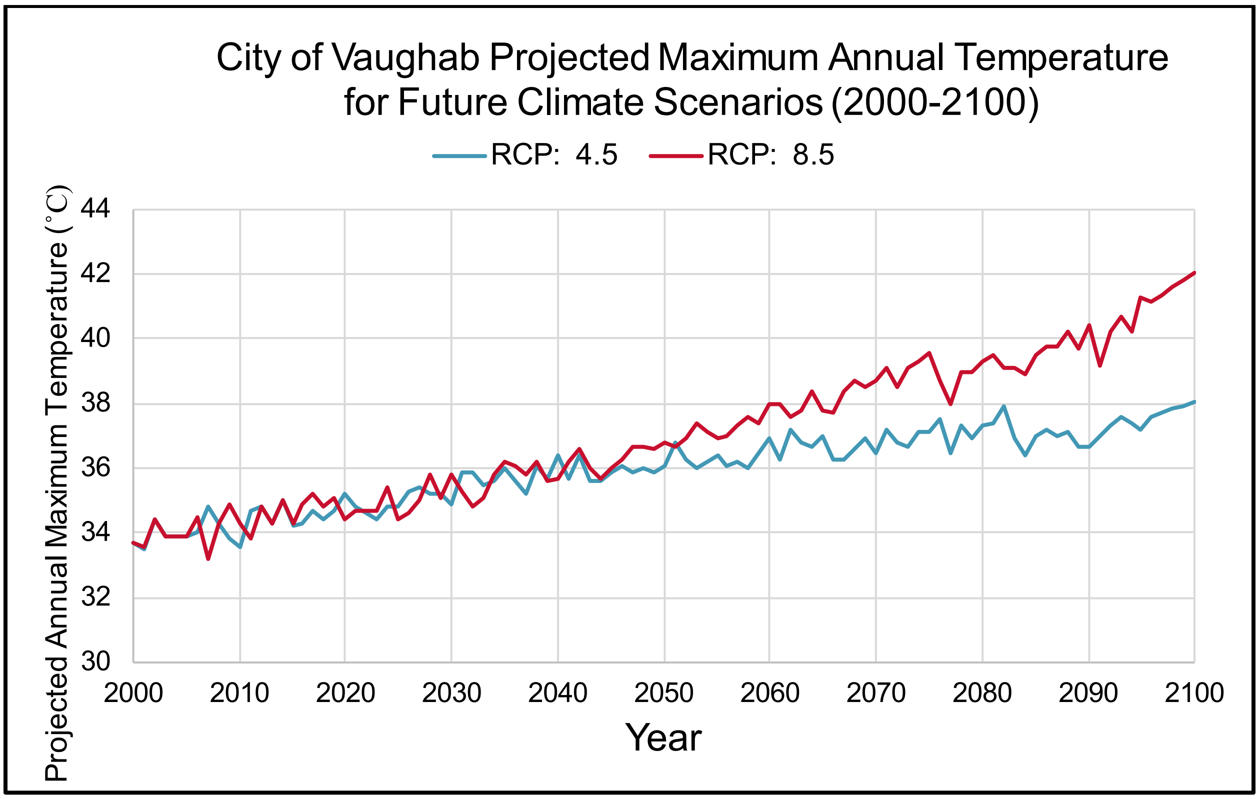

Figure 9. Projected maximum annual air temperature for the City to the year 2100. Source: CCCR

Table 4. Projected annual maximum air temperature for the City at future time scales.

Future Scenarios		
Year	RCP 4.5 (Max T °C)	RCP 8.5 (Max T °C)
2035	35.38	35.91
2050	35.95	37.04
2075	36.89	38.93
2100	37.84	40.81

One of the most important components of future air temperatures on the transportation infrastructure of the City relates to the freeze-thaw cycles within the region. Changes in the freeze-thaw cycles could destabilize the ground underneath transportation infrastructure and cause undue heaving, subsidence, or movement to roadbeds and foundations. A freeze-thaw cycle occurs when the daily maximum temperature is higher than 0°C and the daily minimum temperature is less than or equal to -1°C. The minimum temperature of -1°C is used as the threshold for freezing to raise the likelihood that water actually froze at the surface. Although the freeze-thaw cycle parameter is only partially correlated to the depth of frozen ground, it is a good proxy for it. **Figure 10** shows the number of days of freeze-thaw cycles for both future climate scenarios.

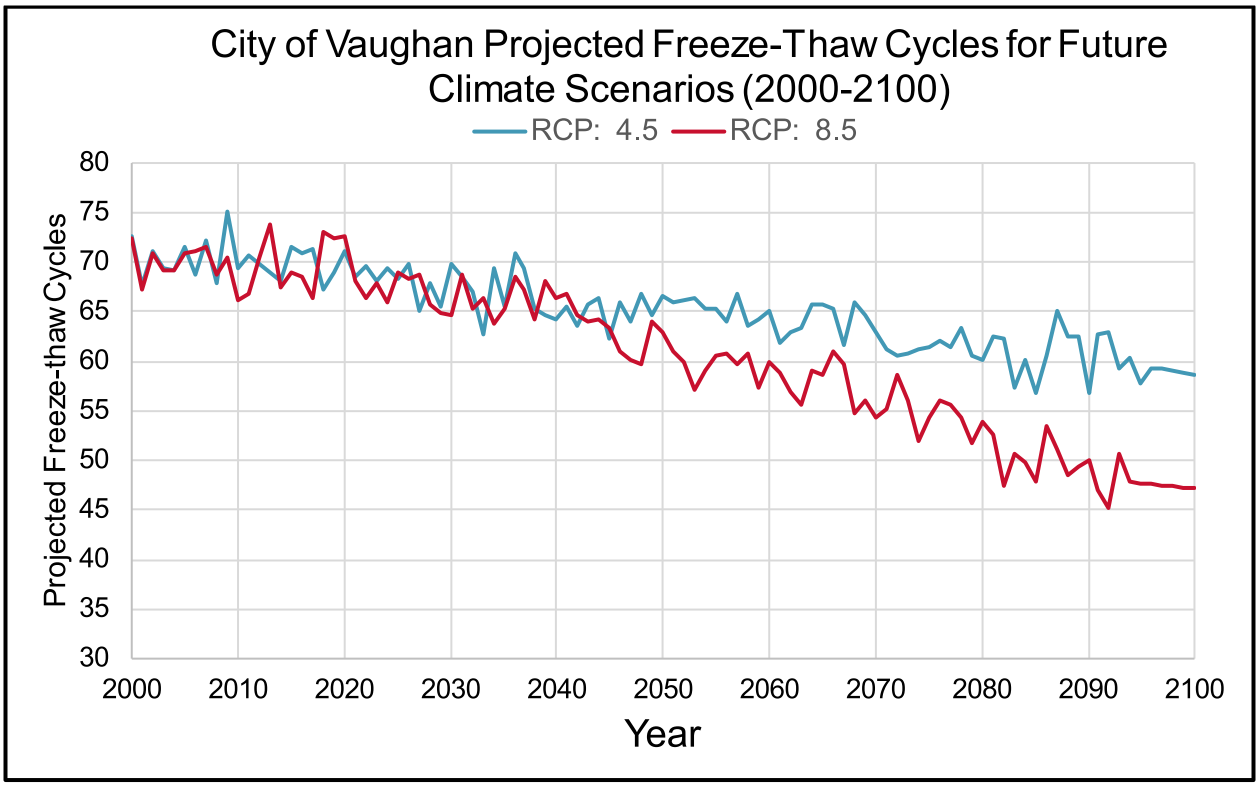

Figure 10. Projected freeze-thaw cycles for the City to the year 2100. Source: CCCR

Table 5. Projected freeze-thaw cycles for the City at future time scales.

Future Scenarios		
Year	RCP 4.5 (# days)	RCP 8.5 (# days)
2035	67.12	64.56
2050	65.31	60.74
2075	62.29	54.37
2100	59.27	48.00

5.2 **Projected changes in Precipitation**

There is a very well-founded physical equation called the Clausius-Clapeyron equation, which explains the relationship between air temperature and moisture within the atmosphere. Basically, as the air temperature increases so does the atmosphere's ability to hold and release moisture. Thus, it follows that as the atmosphere warms, annual precipitation, as well as, precipitation intensities, should increase. An approximation of this equation yields an increase in atmospheric moisture of 6.3 percent per 1˚C of mean temperature increase. **Figure 11** shows a projection of annual mean air temperatures for the City at future time scales according to the modeling of future climate scenarios. As was shown in the observed trend extrapolations for maximum and minimum temperatures in **Figure 2**, mean temperatures are expected to continue to increase as well. An accounting of the percent change in these projected mean air temperatures at future time scales from the current mean annual temperature would indicate that by the year 2035 atmospheric moisture would increase 4.63 percent, 7.66 percent by 2050, 12.72 percent by 2075 and 17.78 percent by 2100 under the RCP 4.5 scenario. Under the RCP 8.5 scenario, these percentages would increase to 7.53, 13.73, 24.07, and 34.40 percent, respectively.

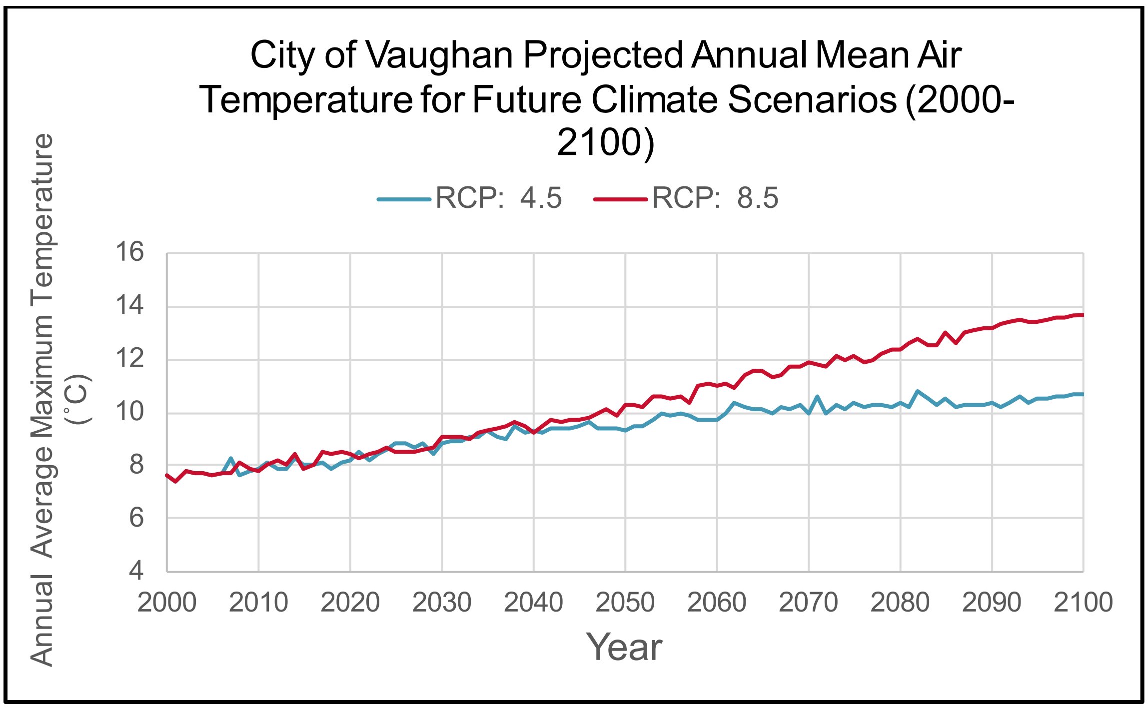

Figure 11. Projected changes in annual mean air temperature under future climate scenario to the year 2100. Source: CCCR

5.3 Projected Annual Precipitation

As noted in the previous section, the atmosphere's ability to hold and release moisture is expected to increase with increasing air temperatures. A projection of this increase on an annual basis can be seen in **Figure 12** for both RCP 4.5 and RCP 8.5. While these increases in annual precipitation in the region are significant, one of the more important factors that may result of this increase in annual precipitation is the increasing likelihood that the ground may be saturated before a significant precipitation event, which would result in a higher likelihood of flooding.

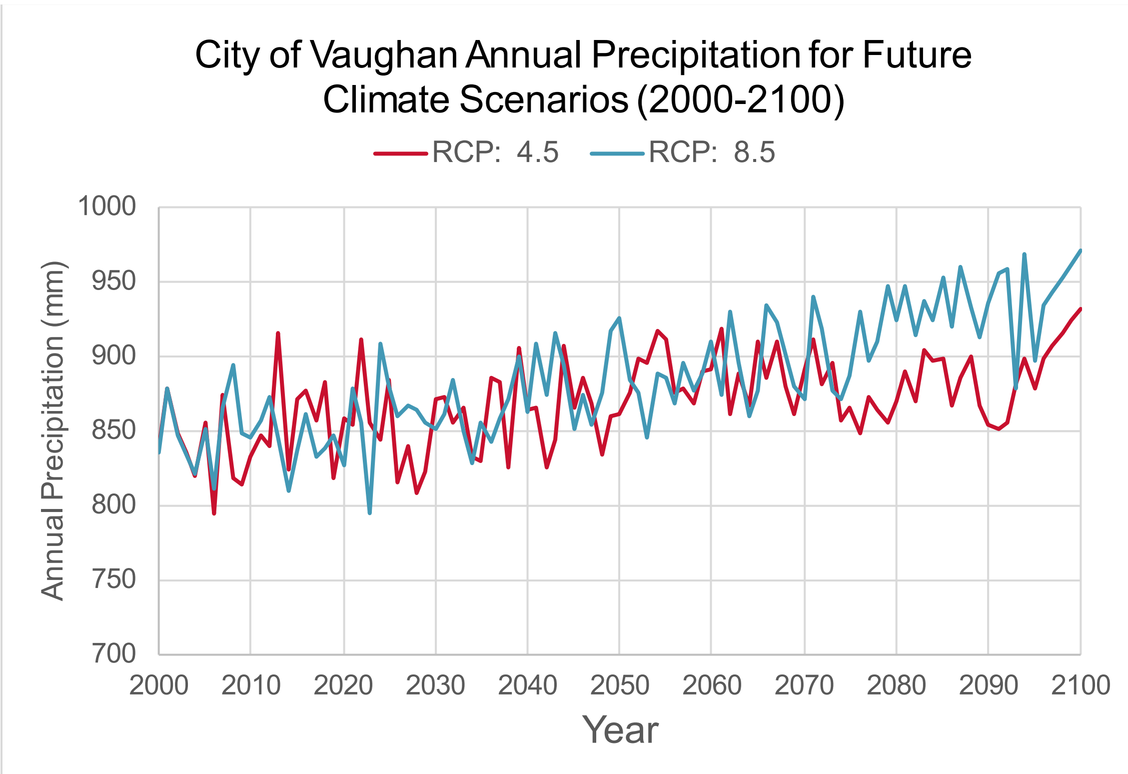

Figure 12. Projected changes in annual precipitation for the City to the year 2100. Source: CCCR

Table 6. Projected changes in annual precipitation for the City at future time scales.

Future Scenarios		
Year	RCP 4.5 (mm)	RCP 8.5 (mm)
2035	861.53	869.36
2050	869.46	883.27
2075	882.67	906.45
2100	895.88	929.63

5.4 Projected Precipitation Intensities

As was seen in the observed record for 24-hour maximum precipitation in **Figure 4**, there exists a significant variability between years with many days of heavy precipitation events and years without. **Figure 13** shows the projected annual number of days of heavy precipitation, which is quantified as days with greater than 20mm of precipitation. Although this 20mm benchmark may only emulate an event that could cause nuisance flooding, it also provides an understanding of the potential of extremely heavy precipitation events in excess of a 10-year return frequency or greater. Storms of this nature can produce significant flooding.

The projection of future heavy precipitation events is, decidedly, a consideration of future atmospheric warming. This can be clearly seen in **Figure 13** in the differences between the number of future heavy precipitation days a for RCP 4.5 and RCP 8.5 beyond the year 2070. According to the Intergovernmental Panel on Climate Change, RCP 4.5 indicates that although emissions begin to be curtailed in 2050, it takes all they way until 2070 before concentrations of GHG are reduced in the atmosphere. RCP 8.5 anticipates that emissions will continue to accelerate, thus, the number of heavy precipitation accelerates as well.

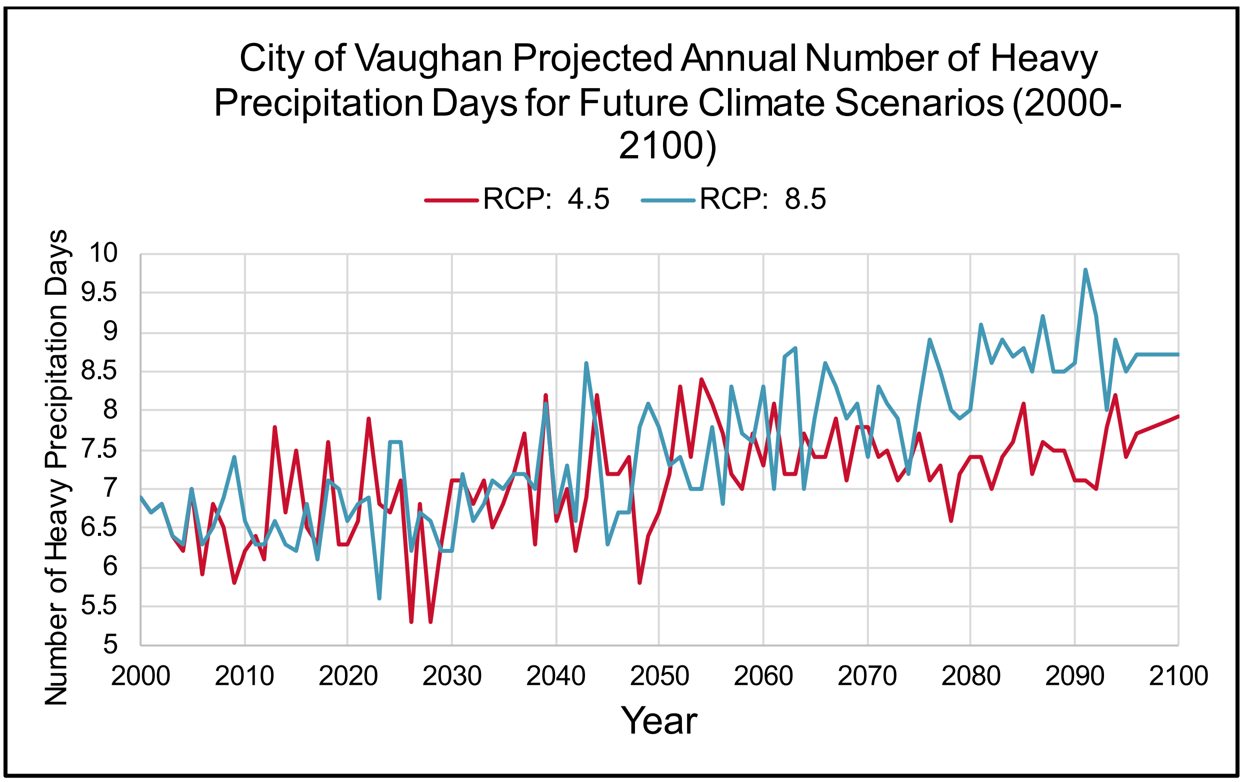

Figure 13. Projected changes in the annual number of heavy precipitation (>20mm) days for the City to the year 2100. Source: CCCR

Table 7. Projected changes in the annual number of days with heavy precipitation (20mm+) for the City at future time scales.

Future Scenarios		
Year	RCP 4.5 (days)	RCP 8.5 (days)
2035	6.92	7.07
2050	7.10	7.47
2075	7.42	8.13
2100	7.73	8.79

The increase in 24-hour (daily) precipitation intensities are important to understanding the potential change in flooding within the City, but the changes in multi-day storm event precipitation may, potentially, be even more important to an understanding of future flooding. **Figure 14** identifies the projected change in annual maximum 3-day precipitation as a result of the two different climate scenarios. **Table 8** provides a quantification of these projections at future time scales.

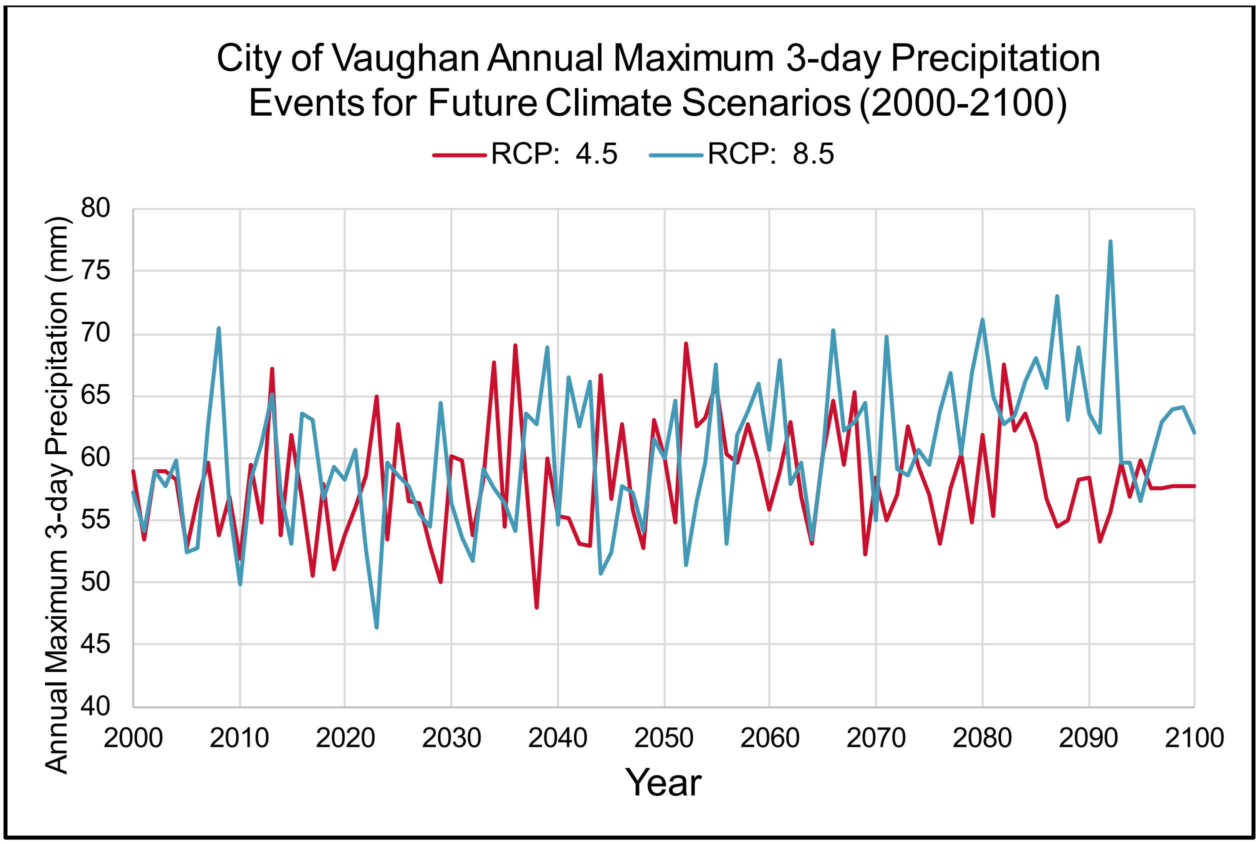

Figure 14. Projected change in annual maximum 3-day precipitation events for the City to the year 2100. Source: CCCR

Table 8. Projected changes in annual maximum 3-day precipitation events for the City at future time scales.

Future Scenarios		
Year	RCP 4.5 (mm)	RCP 8.5 (mm)
2035	57.87	59.30
2050	58.16	60.56
2075	58.65	62.66
2100	59.14	64.76

6 Projected Impacts from Climate Change

The previous sections provided an understanding of changes in air temperature and precipitation anticipated at future time scales for the City. The anticipated changes in both of these environmental parameters will result in impacts in and of themselves, but will also have ancillary impacts that will lead to changes in other hazards such as flooding, ice jam flooding, and extreme events such as tornadoes, severe thunderstorms, and flash flooding. Climate model output provides only the projection of future climate parameters such as temperature and precipitation, thus ancillary impacts from projected changes in those parameters require the application of hydro-meteorological principles to derive potential impacts. The following sections describe projections of future hazards as a result of the changes in air temperature and precipitation as anticipated by the climate projections previously noted.

6.1 Projected Ice Jam Flooding Potential

One of the descriptive ways climate scientists use to visualize future climate is to compare one region's current climate with how another region may be like it in the future. A study from Universite Laval (Anctil, 2012) made the analogy that southeastern Canada would be meteorologically similar to the U.S. states of New Jersey and Pennsylvania by the year 2050. Additionally, recent reporting by the U.S. Army Corp. of Engineers (Daly, 2020) research (Turcotte, et al., 2020) reveals that the observed number of ice jams in this northeast region of the U.S. follows a declining trend in recent decades.

Unlike the projection of future temperatures and precipitation, the understanding of the impact of climate change on future ice jam situations on streams and rivers requires a more dynamic, physical understanding of the changing environmental parameters that lead to ice jams and flooding. Ice jams are brought about by the occurrence of many interacting factors and are highly dependent on the timing of factors such as air temperature, precipitation, hydrologic setting, and, perhaps most importantly, location (morphological parameters). The frequency and intensity of these ice jams and resultant flooding are expected to be impacted by climate change.

As identified in the observed climate record in **Section 4** and in the climate projections identified in **Section 4**, air temperatures, particularly nighttime air temperatures, are expected to continue to increase over time across the region. These higher average wintertime air temperatures are expected to combine with the changing precipitation patterns as identified in Sections 1 and 2, and increases in weather variability (Bush, 2019) to change the timing, frequency and intensity of ice jams in the region. More variable weather conditions are expected to increase the frequency of a mid-winter breakups, but warmer spring temperatures and increased precipitation may reduce the intensity of spring breakups. As with the other hazards and environmental parameters that are part of this study, the timing, frequency and intensity of ice jam flooding is expected to transition at future time scales.

Generally, the risk associated with ice jams, expressed in terms of average annual damage communities in southern Quebec and Ontario, is expected to increase on average by 30 percent at future time scales (Turcotte et al., 2020). This is primarily expected to be due to the increase in the frequency of mid-winter breakup events during winters that will remain cold enough to produce a thick ice cover. Thus, transportation infrastructure that is currently vulnerable to ice jam flooding (i.e. Woodbridge core area) is expected to see an increase in the likelihood of those events, if not the intensity. Streets and intersections in this region that are particularly susceptible to current and future ice jam flooding will be identified in the graphics and GIS-locater spreadsheets in **Appendix A.** These streets and intersections should be considered the most vulnerable and at the greatest risk under future climate scenarios.

6.2 Projected Extreme Flooding Potential

The flood of record for the region was the result of a remnant hurricane, Hurricane Hazel, in October of 1954. Considerable research has been completed on the impacts of climate change on the frequency and intensity of Atlantic tropical cyclones at future time scales (Knutson, et al., 2015 and 2020). Recent storm records indicate that there have been increases in both tropical cyclone frequency and intensity, particularly in storm intensity with the number Category 4 and 5 storms rapidly on the rise. While Hurricane Hazel's path to the region surrounding the City was an aberration of a unique synoptic weather situation that would need to repeat itself for the city to experience a like event, if storms in the Atlantic are expected to increase in frequency and intensity, then the likelihood of that situation occurring increases as well.

This finding results in a qualification of future extreme flooding events rather than a quantification; however, considerations for future extreme floods have been made in the final risk analysis in the following section.

6.3 Projected Tornadoes, Severe Thunderstorms, and Lightning

Much like the potential for extreme flooding events, the projection of the likelihood of future severe storms events needs to be handled as a qualification rather than a quantification. Projected increases in air temperature and atmospheric moisture lend themselves to the understanding of the potential for future severe storms. The changes in these parameters form the foundation for changes in convective activity and the formation of tornadoes, severe thunderstorms and lightning.

In a recent article (Sills et al., 2020) in the Bulletin of the American Meteorological Society (BAMS), the Northern Tornadoes Project produced an extensive climatology of tornadic activity in Canada. **Figure 15** shows that during the years 2017-2019 the great majority of strong torandoes (>=EF1, enhanced Fujita scale) occurred in Ontario and Quebec, particularly in the southern areas of these two provinces. Thus, the City is already in a region of likely tornado activity as witnessed in the two EF2 tornadoes that hit the City on August 20, 2009.

As the atmosphere warms, the potential for an increase in the frequency and intensity of severe storms are expected to also increase. Climate change is like giving steroids to the atmosphere. It provides the vehicle for an increase in the differential between warm and cold air masses, which is at the root of most severe storm events. This increasing threat is expected to be spatially equal across the domain of the City, but the increase in the likelihood of severe weather has a potentially higher level of consequences for intersections where traffic is managed by signals and for transit stations with exposed areas.

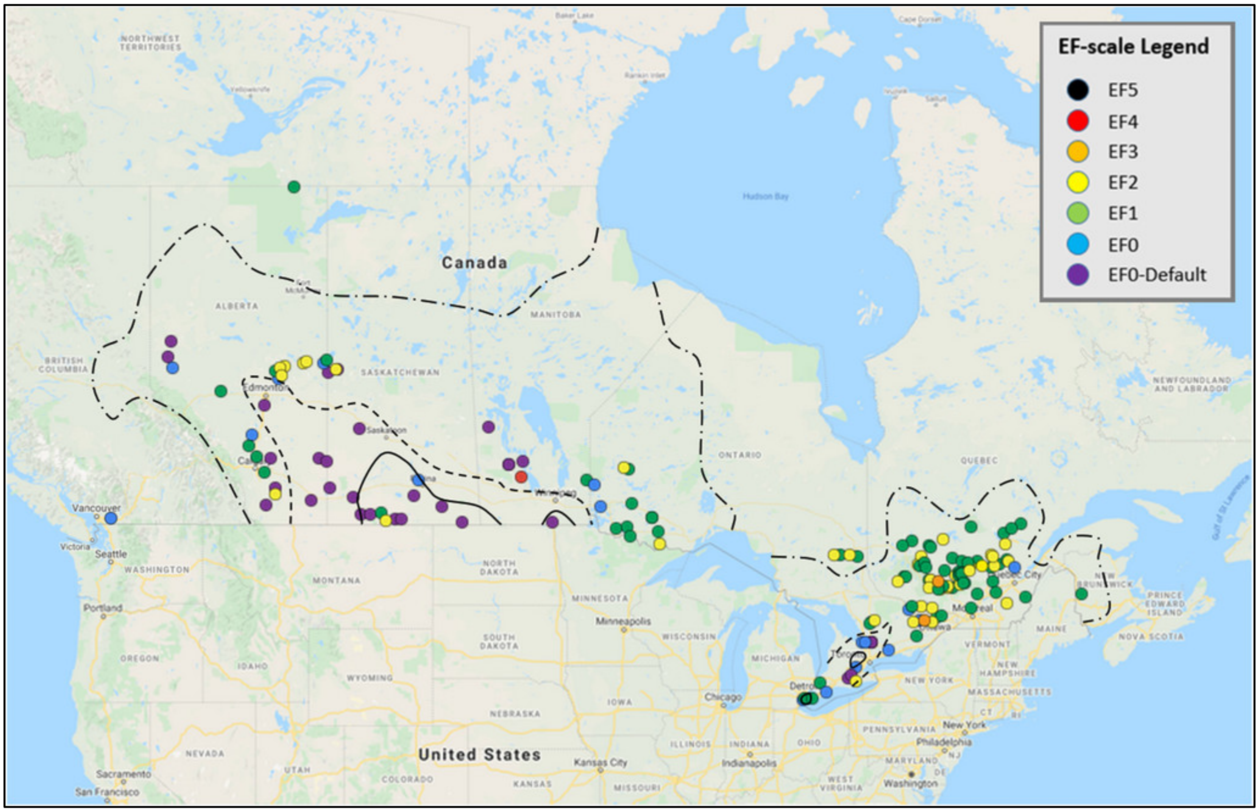

Figure 15. All 2017-2019 tornadoes reported in Canada.

7 Risks associated with Climate Change Impacts and System Vulnerabilities

The potential changes in climate described in the previous sections for parameters such as changes in air temperature and extreme storms are generally applicable to the entire city's transportation infrastructure with impacts being highly dependent on infrastructure condition rather than design; however, the environmental factors that will have a direct physical impact on infrastructure as a result of climate change are those associated with flooding, ice jam flooding, and changes in precipitation intensities that could result in flashing flooding or local inundation.

While hydrologic and hydraulic modeling of these future precipitation events would produce the most definitive quantification of the likely spatial extent of these future floods, this study utilized the percentage increase in future precipitation as a proxy for increases in flood extent for the region. Current floodplain maps produced by the Toronto Regional Conservation Authority (TRCA) were used as a basis for this analysis. These GIS maps, which provide a horizontal extent for floods of a certain recurrence interval, were multiplied by the precent increase expected in future precipitation and precipitation intensities, and remapped to show and identify locations where flooding inundation may impair roadways, intersections, and transit rail lines in the future.

Graphics showing varying levels of future inundation are provided in a hard copy format in **Appendix A** and in a GIS-ready spreadsheet format in electronic **Appendix B**. These data and supporting graphics will help enable the visualization of the location of impacted road sections, intersections, and the Barrie Corridor Go Rail line at future time scales. Levels of risk are specifically tied to levels of inundation. Thus, a street such as Clarence Street, for example, which is already at risk from flooding, is expected to become at a much greater risk of flooding at future time scales. As noted in Section 6.1, the Woodbridge area of the City is at the greatest risk from both current and future flooding.

8 Recommendations and Next Steps

This paper provides a quantification of future changes in climate parameters and hazards, and a qualitative examination of potential impacts and decision support for resilient actions. These findings are intended to lead to the next step a resiliency framework, which concerns the strategic planning, funding, and prioritization of these resilient actions. The recommendations in this document will become part of a broader discussion of resilient actions that will align stakeholders with the other components of this project at a later date. As a primer for that discussion, there are generally three options/actions, which are the more basic tenets of climate adaptation and resilience: 1) harden/redesign, 2) abandon, 3) adopt a more robust response and recovery program. Redesign provides the opportunity for a phased approach to climate resilience, abandonment is a cost-effective means to work around a problem rather than through it, and the respond and recover option, while being the least expensive in the near-term, could be the most costly in the long-term. These actions will be a part of broader discussion of climate adaptation as this project progresses.

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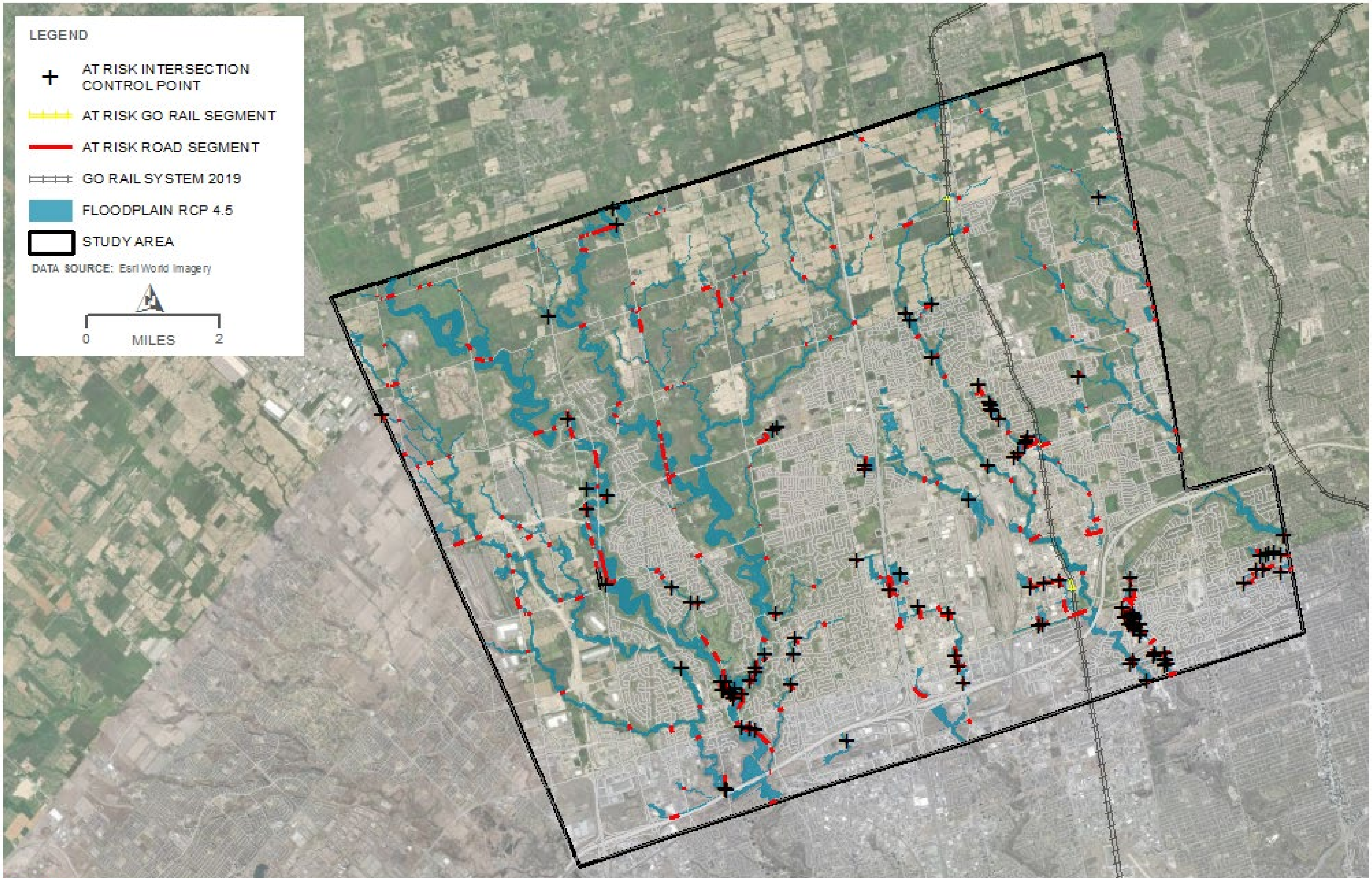
Appendix A

Maps of Changing Flood Inundation of City Transportation Infrastructure at Future Time Scales for RCP 4.5 and RCP 8.5 Climate Scenarios



CITY OF VAUGHAN

IMPACTED INFRASTRUCTURE
RCP 4.5, 3.2% INCREASE (2035)

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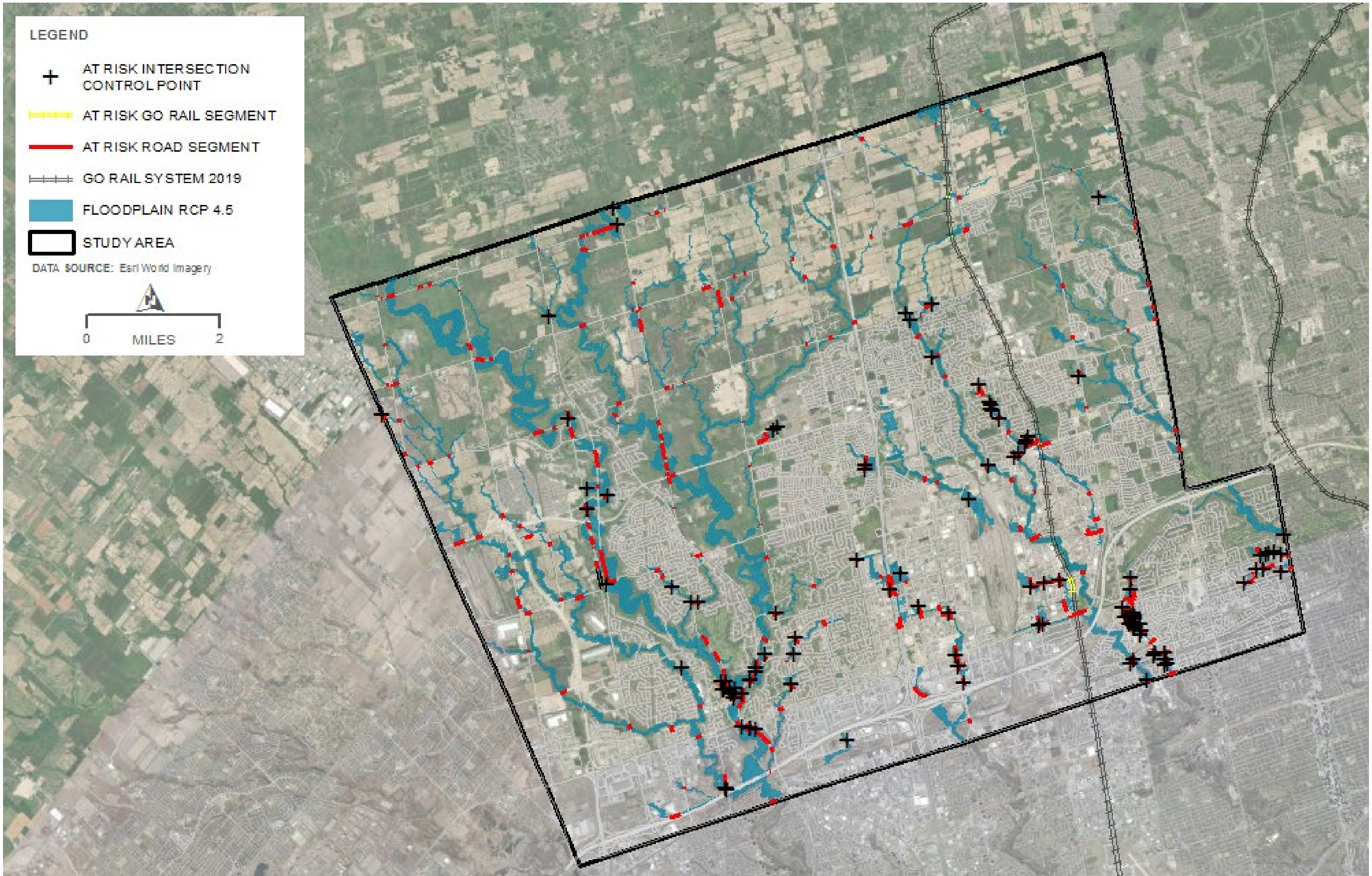
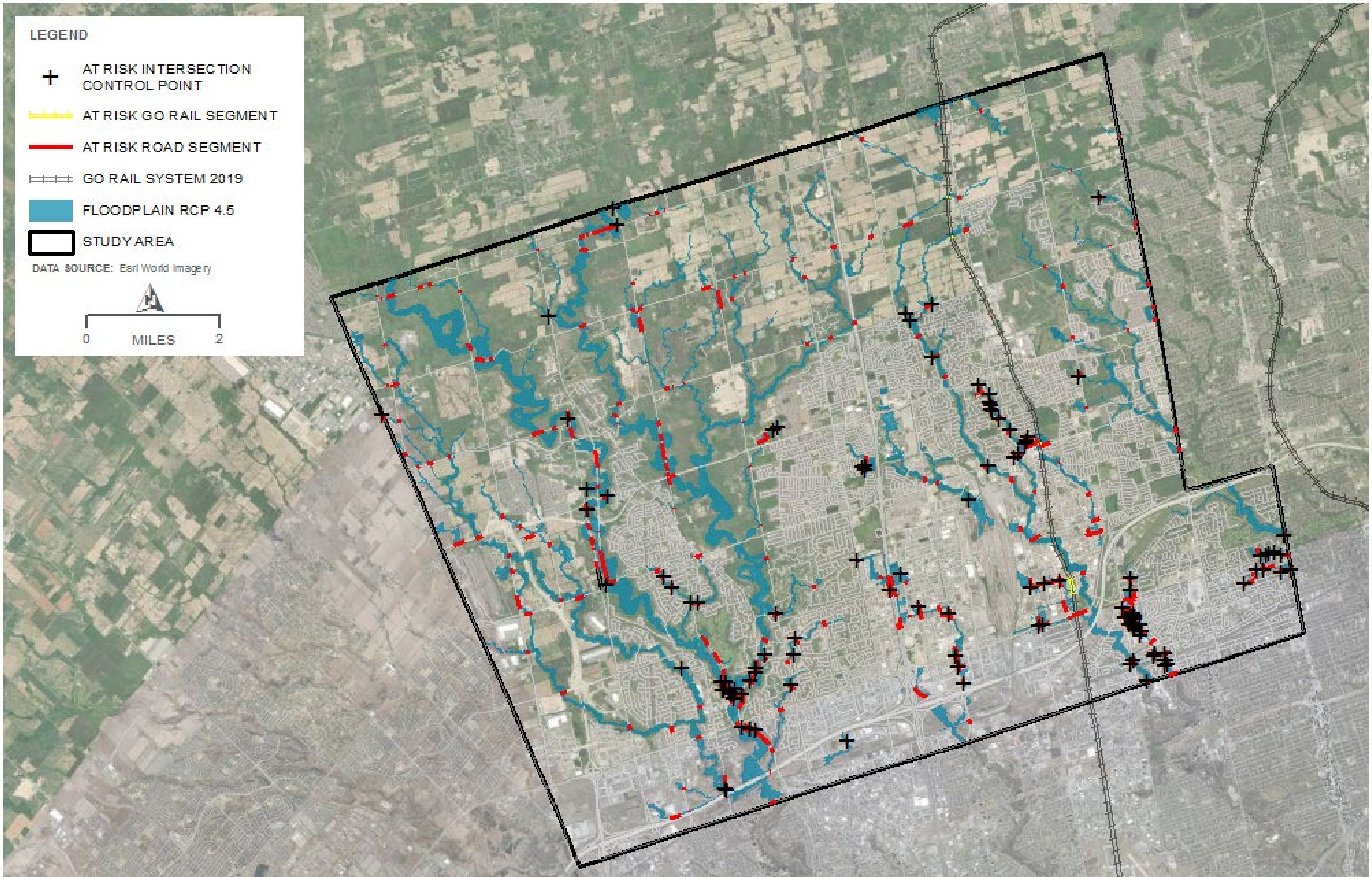


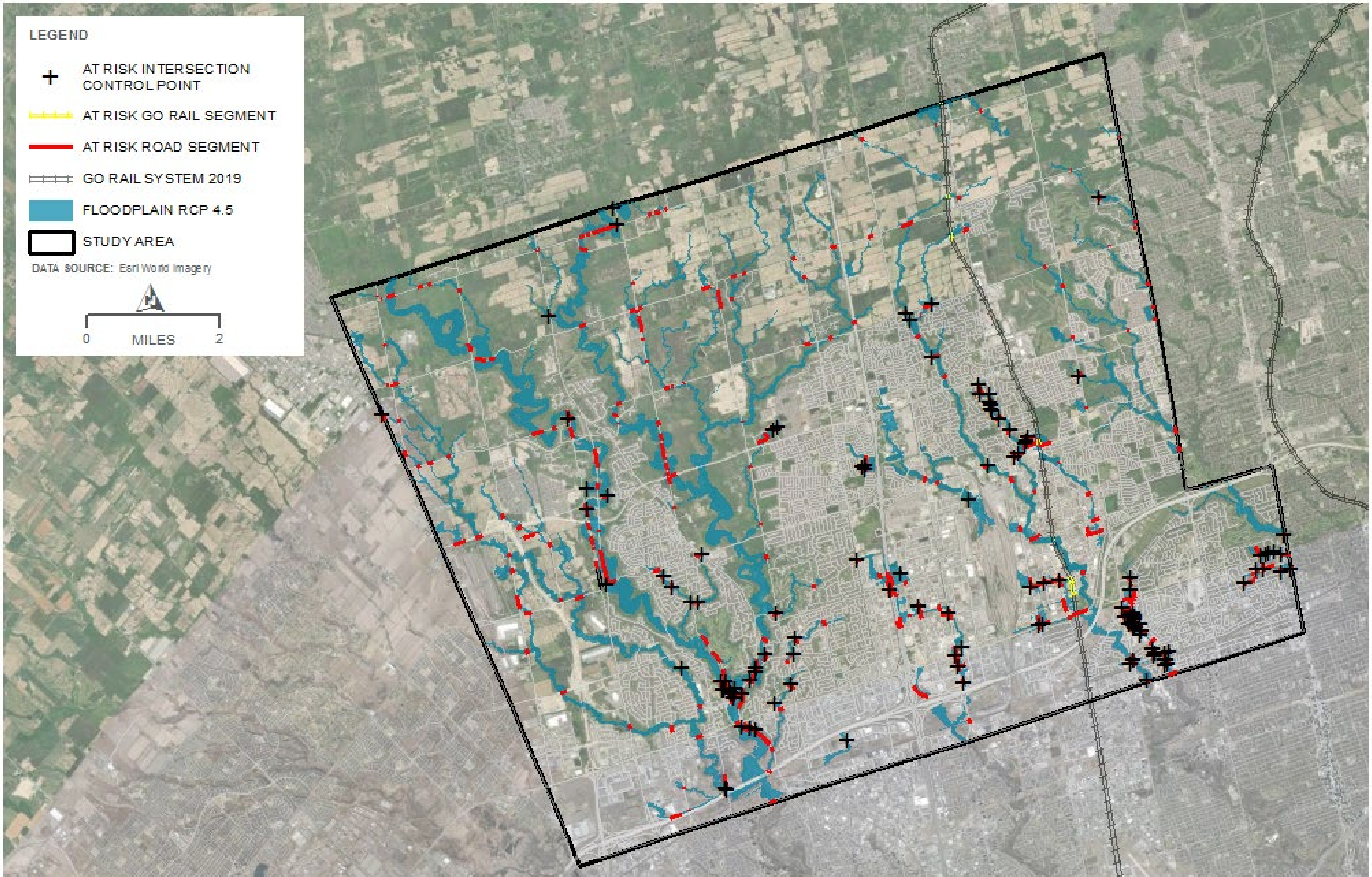
CITY OF VAUGHAN

IMPACTED INFRASTRUCTURE
RCP 4.5, 5.1% INCREASE (2050)



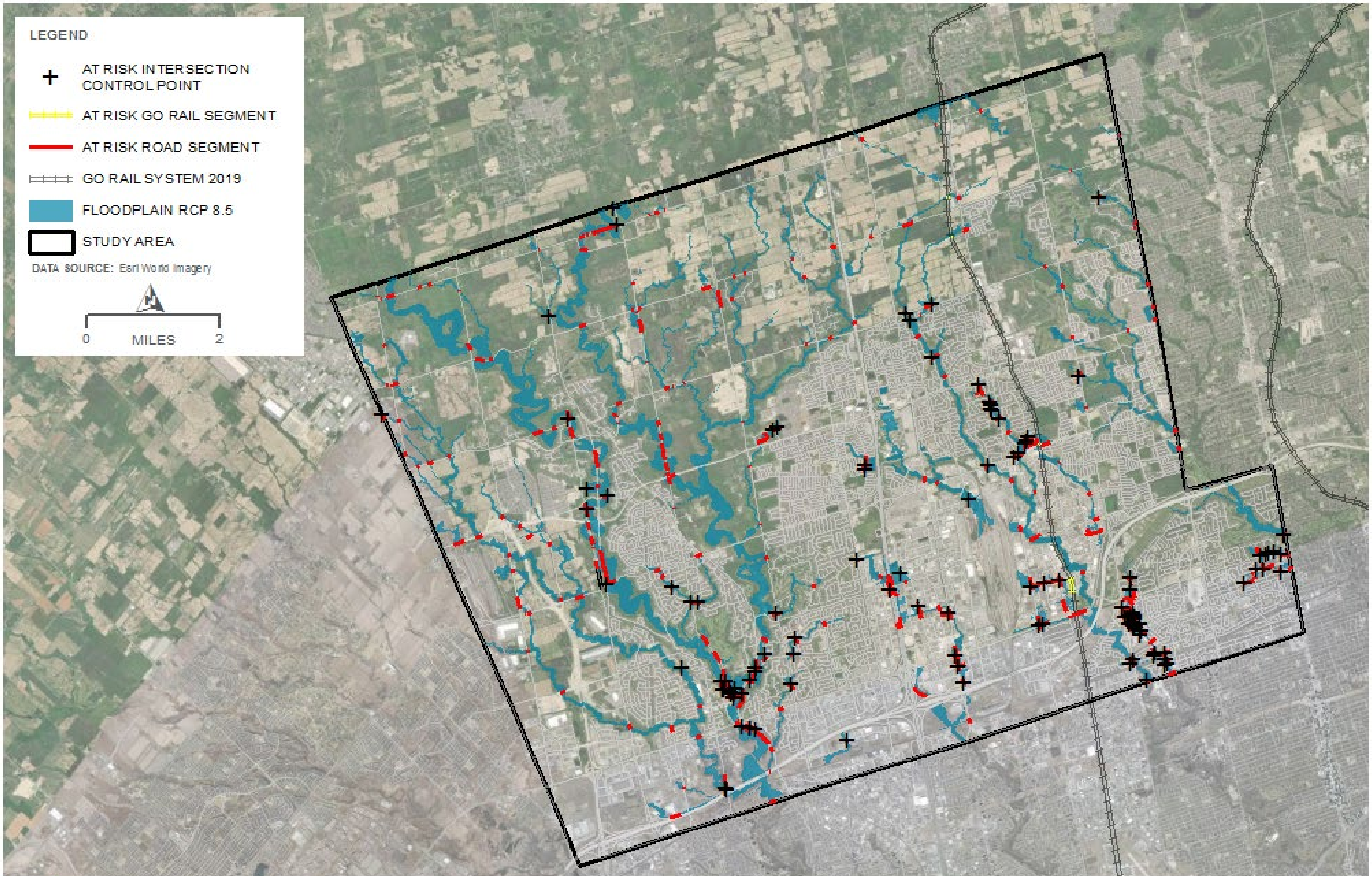
CITY OF VAUGHAN

IMPACTED INFRASTRUCTURE
RCP 4.5, 7.8% INCREASE (2075)



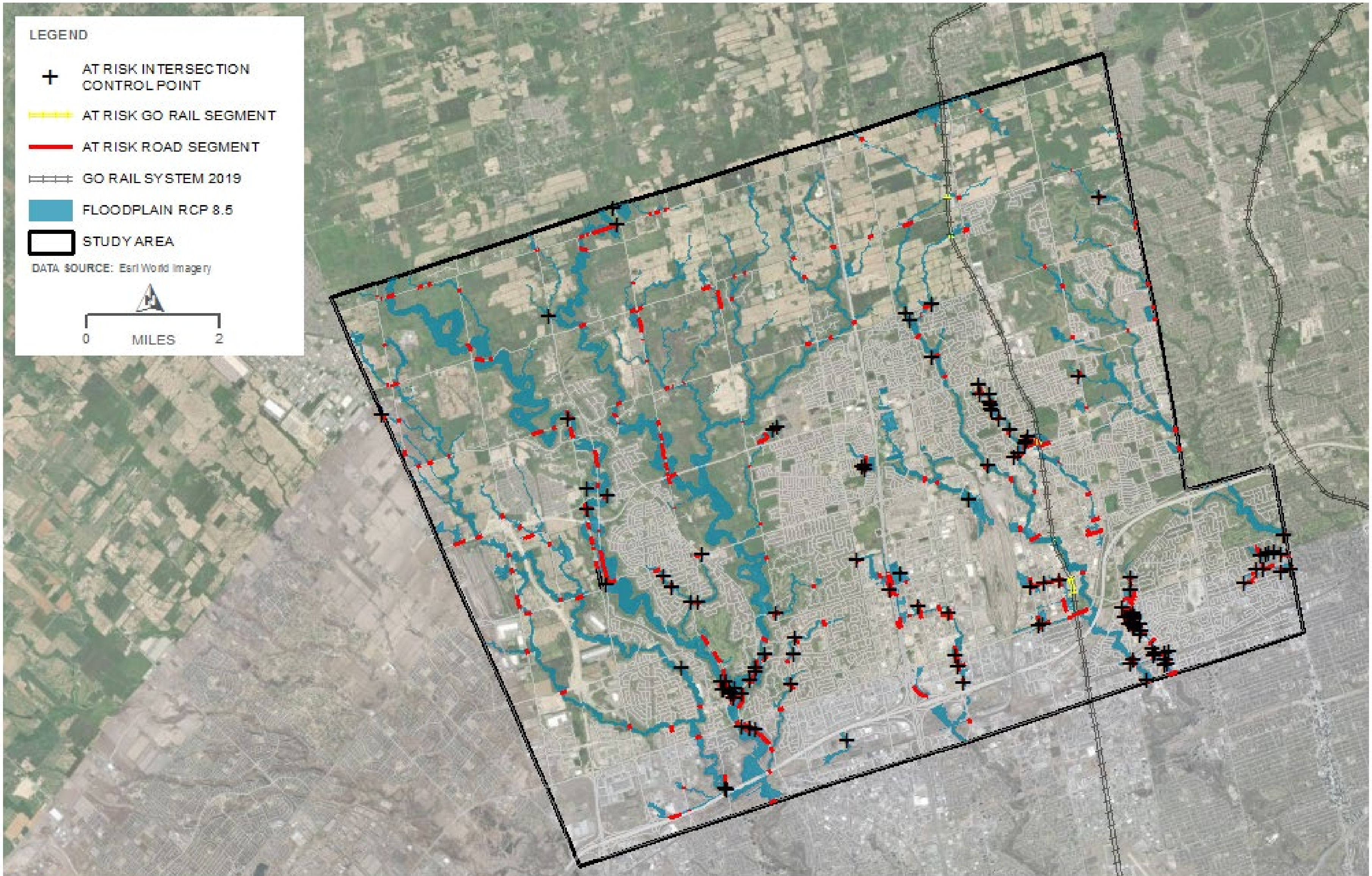
CITY OF VAUGHAN

IMPACTED INFRASTRUCTURE
RCP 4.5, 13.56% INCREASE (2100)



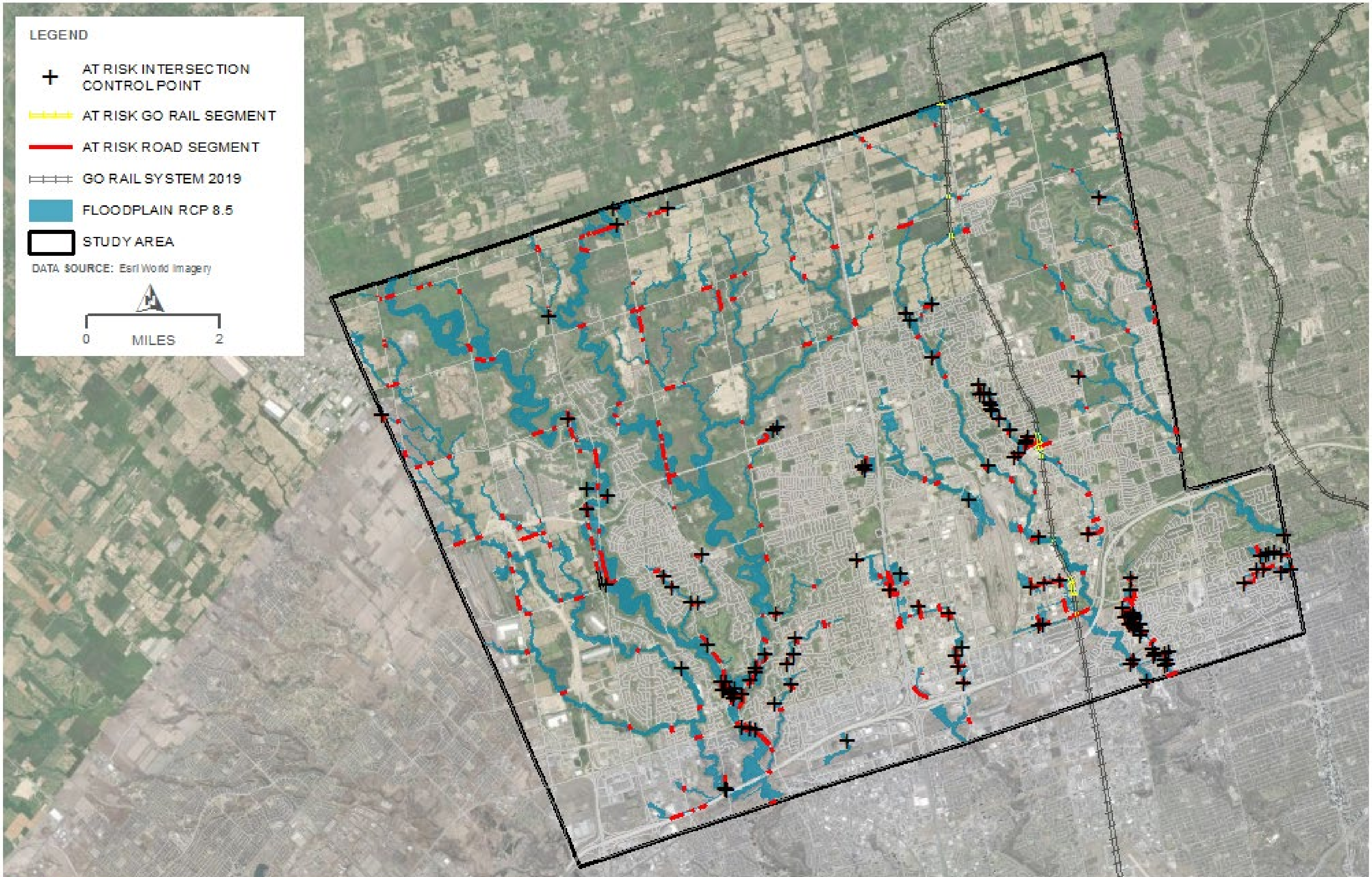
CITY OF VAUGHAN

IMPACTED INFRASTRUCTURE
RCP 8.5, 4.3% INCREASE (2035)



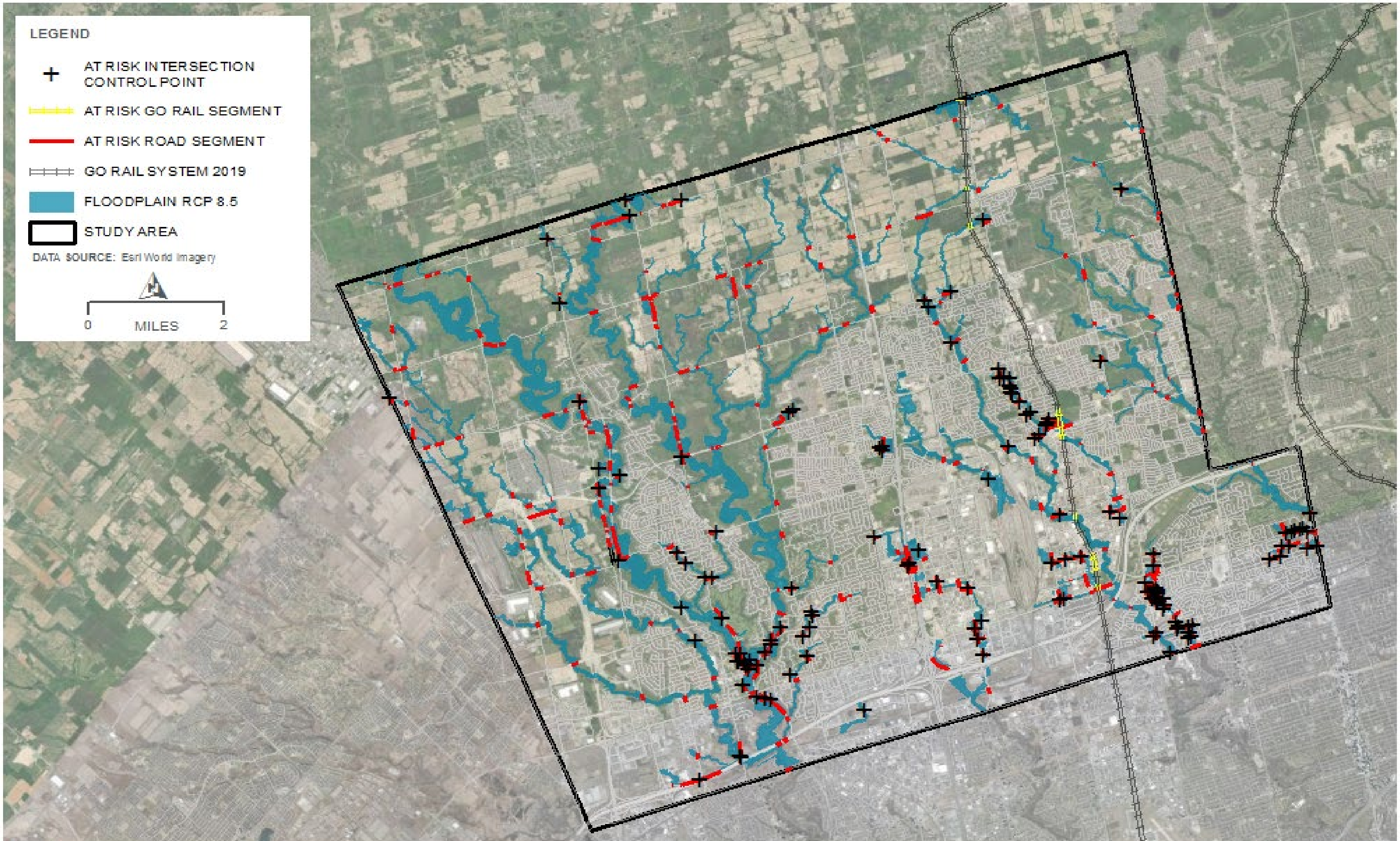
CITY OF VAUGHAN

IMPACTED INFRASTRUCTURE
RCP 8.5, 11.2% INCREASE (2050)



CITY OF VAUGHAN

IMPACTED INFRASTRUCTURE
RCP 8.5, 21.0% INCREASE (2075)



CITY OF VAUGHAN
IMPACTED INFRASTRUCTURE
RCP 8.5, 29.6% INCREASE (2100)

Electronic Appendix B

GIS-Locator Spreadsheets Identifying at Risk City Transportation Infrastructure at Future Time Scales for RCP 4.5 and RCP 8.5 Climate Scenarios