1.0 Introduction

Our changing climate is considered one of the globe's most significant environmental, social and economic threats. In Canada, changes observed in the climate over the past number of decades have influenced an increase in economic losses from extreme weather events, premature weathering of infrastructure, stresses on water supplies, worsening air quality and related health and economic impacts, affecting the quality of life Canadians and the economy. It has been projected that Ontario may in the future experience changes in the frequency and/or severity of extreme weather as well as changes to average climate over several decades or more as a result of our changing climate. These changes are expected to continue to affect natural, social and built infrastructure, potentially having significant socio-economic consequences.

The effects of climate change presents a two-fold challenge: mitigation that is limiting further climate change by reducing the production of greenhouse gases; and adaptation which is about preparing for the altered temperature and precipitation regimes that global warming will bring.

The Ministry of Environment, Conservation and Parks' (MOECP) expectations for considering climate change in the preparation, execution and documentation of environmental assessment studies and processes is outlined in their guidance document "Consideration of Climate Change in Environmental Assessment in Ontario" published on December 14, 2017. It requires consideration of:

- the impacts of a project on climate change
- the impacts of climate change on a project
- various means of identifying and minimizing negative impacts during project implementation

Consideration of climate change during the environmental assessment process results in a project that has:

- taken into account alternative methods to reduce its greenhouse gas emissions; and,
- been planned in a manner that takes into account future changes in climate and the impacts a changing climate could have on the project.

This brief addresses this MOECP expectation to address climate change as it relates to the project

1.1 Work Scope

The focus of this climate change review is on the development of climate change influenced rainfall scenarios that can be used to support modelling and design of drainage features associated with the subject roadway at the detailed design stage. These rainfall estimates have been developed to align with relevant modelling completed to date for the project and, as such, the focus events have been identified as the 25 year return period event for 6-hour and 12-hour durations. The future timeframes for this analyses have been identified as 2050 and 2080.

2.0 Climate Change Overview

Most studies that incorporate climate change rely on model-generated projections. These projections are most often computed with the use of global climate models (GCMs), which are dynamical system-based models that represent complex interactions between physical processes in the atmosphere, ocean, cryosphere and land surface. These are currently the most advanced tools to estimate how the climate system may respond to the natural and human driven stresses (e.g., increasing in greenhouse gas emissions, population, and other behaviours).

There are various climate groups that conduct climate change modelling research and share their projections to the Coupled Model Inter-comparison Project Phase 5 (CMIP5). CMIP5 is the official body of science used by the Intergovernmental Panel on Climate Change (IPCC), which is a United Nations body founded with the purpose of evaluating climate change science. There are currently twenty (20) different climate modelling groups that lead the evolution of climate models, resulting in a large repository of models available for various applications.

It is important to note that because each GCM provides a slightly different conceptualization of the earth-atmosphere system, the IPCC recommends using an ensemble approach. An ensemble is a grouping of climate projections. Together, the models in an ensemble provide a better characterization of the future and its uncertainty than a single model used in isolation.

2.1 Greenhouse Gas Emissions Scenarios

It is unknown what future greenhouse gas (GHG) emissions will be. Therefore, the IPCC developed four Representative Concentration Pathways (RCP) as part of a new initiative for the Fifth Assessment Reports (Taylor et al. 2012). These RCP scenarios move away from the prescriptive GHG emissions based on assumptions of socioeconomic scenarios (e.g., population growth, mitigation policy, and other prescriptive assumptions) and focus on representing the forcing which may be realized through a much broader set of socioeconomic scenarios while also incorporate carbon emission controls, which the previous iteration of scenarios (e.g., double CO_2, and SRES scenarios) were criticized for not including in a more integrated manner. These RCPs were created with Integrated Assessment Models (IAM) which include climate, economic, land use, demographic, and energy-usage effects. The outputs of these IAMs, which estimate GHG concentrations, were then converted to an emission trajectory using carbon cycle models. The RCP scenarios 2.6, 4.5, 6.0 and 8.5 reflect various levels of climate change mitigation efforts (RCP 2.6, resulting in an increase of 2.6 W/m^2 in radiative forcing to the global climate system) and business-as-usual GHG emissions continuing (RCP 8.5, an increase of 8.5 W/m^2).

It is suggested for this project to assess projections for RCP 4.5 (a moderate emissions scenario that would require substantial reductions from current emission levels) and RCP 8.5 (business-as-usual). RCP 6.0 is not suggested for inclusion as it has been found to be very similar to RCP 4.5, which is deemed sufficient to represent the "medium" GHG scenario. Table 2-1 provides a description of each RCP scenario while Figure 2-1 illustrates the projected global warming associated with the four scenarios.

Table 2-1 RCP Scenario Descriptions

Scenario	Description
RCP 2.6	Lowest projected GHG concentrations, resulting from dramatic climate change mitigation measures implemented globally. It represents an increase of 2.6 W/m^2 in radiative forcing to the climate system.
RCP 4.5	Moderate projected GHG concentrations, resulting from substantial climate change mitigation measures. It represents an increase of 4.5 W/m^2 in radiative forcing to the climate system.
RCP 6.0	Moderate projected GHG concentrations, resulting from some climate change mitigation measures. It represents an increase of 6.0 W/m^2 in radiative forcing to the climate system.
RCP 8.5	Highest projected GHG concentrations, resulting from business-as-usual emissions. It represents an increase of 8.5 W/m^2 in radiative forcing to the climate system.

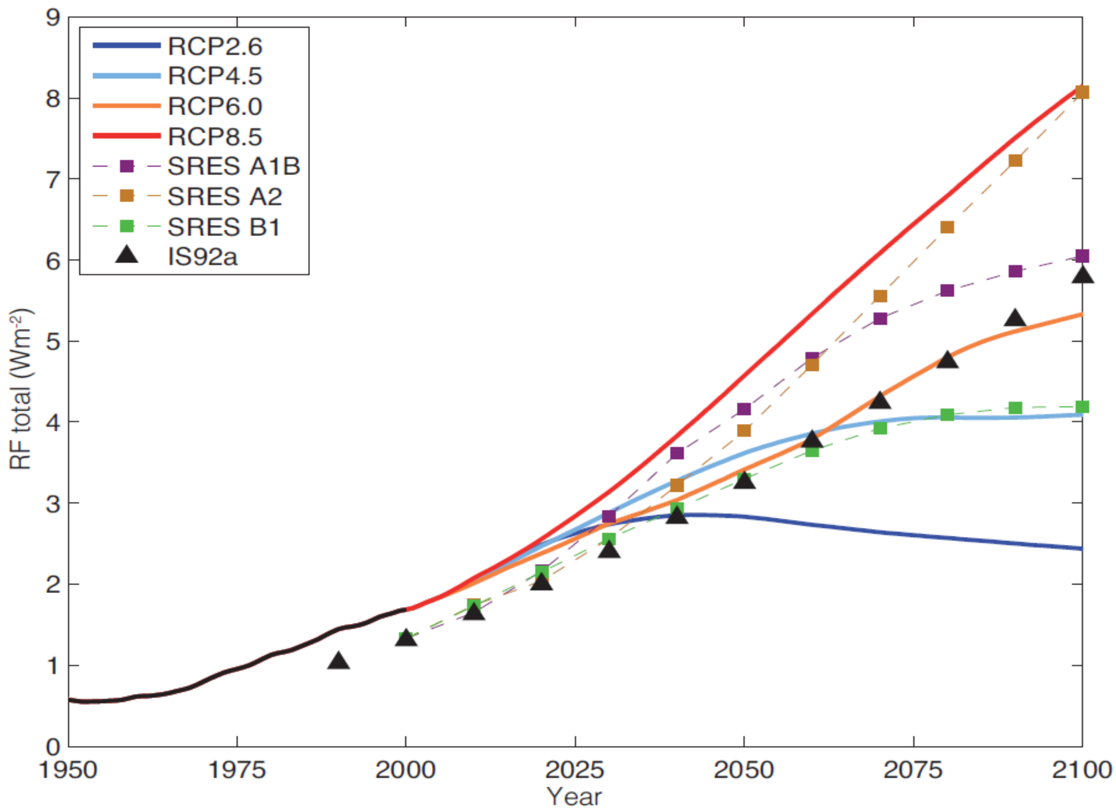

Figure 2-1 RCPs Used for Climate Modeling and Research

(Notes: Historical and projected total anthropogenic radiative forcing (W/m^2) relative to preindustrial (about 1765) between 1950 and 2100. Previous IPCC assessments (SAR IS92a, TAR/ AR4 SRES A1B, A2 and B1) are compared with RCP scenarios.

(Source: Cubasch et al (2013); Figure 1.15)

3.0 Rainfall Scenarios Data Sources

The future rainfall scenarios proposed for evaluation through this assignment have been compiled through various source, namely:

- Town the Caledon
- Environment and Climate Change Canada
- University of Western Ontario Intensity-Duration-Frequency (IDF) CC Tool
- Ontario Climate Change Data Portal
- Ministry of Transportation Ontario Trending Tool

Additional descriptions for each of these data sources and the resultant projected rainfall is provided in the following report sections.

3.1 Town of Caledon

The Town of Caledon provides definitions for design rainfall in its *Development Standards, Policies & Guidelines*. The Town's IDF curves were originally derived from the rainfall data taken from the Guelph Ontario Agricultural College (O.A.C.). This station (ID 6143083) ceased operations in 1973. Using the rainfall definitions provided in the Town's Manual, the following rainfall scenarios are computed:

- 25 year, 6 hour duration event has a total depth of 74.9 mm
- 25 year, 12 hour duration event has a total depth of 80.0 mm

It is also noted that the Town's guidelines do not presently provide direction with regard to integrating climate change into engineering design.

3.2 Environment and Climate Change Canada (ECCC)

IDF data, version 2.30 dated December 12, 2014, was downloaded from ECCC. This version, the most recent, was a major revision of the IDF information across Canada based on new observational data up to 2013. As noted in Section 3.1, the Guelph OAC station stopped recording rainfall data in 1973. The only alternate station in proximity to the Guelph OAC station for which an IDF relationship is available within the ECCC IDF dataset (v2.30) is the Guelph Turfgrass CS station (ID 6143090) which has a data record from 1954 to 2003. The following rainfall metrics are identified from this IDF data:

- 25 year, 6 hour duration event has a total depth of 62.3 mm
- 25 year, 12 hour duration event has a total depth of 72.1 mm

3.3 University of Western Ontario IDF CC Tool

The University of Western Ontario developed a "*Computerized Tool for the Development of Intensity-Duration-Frequency Curves under a Changing Climate*" (available at http://www.idf-cc-uwo.ca/). This computerized web-based IDF tool integrates a user interface with a Geographic Information System (GIS). By creating or selecting a station the user is able to carry out statistical analysis on historical data, as well as generate and verify possible future change based on a methodology using a combination of global climate model outputs and locally observed weather data. Some specific comments regarding the tool are outlined below:

- There have been three (3) versions of the tool to the time of writing of this report. From Version 1 to Version 2 was when the greatest change was made – change from the Gumbel distribution to the GEV distribution for extreme value analysis. Comparison of estimates made using the Gumbel versus the GEV generally demonstrates higher values are associated with the GEV approach. The GEV distribution used to fit IDF data is deemed to be more statistically accurate and there have been recent studies confirming this conclusion (summarized in Millington et. al, 2011).
- The change from Version 2 to Version 3 included restriction of the time base for projection to a minimum length of 50 years. This as a result of the move to the GEV distribution as it is very sensitive to the length of data series, so the longer the dataset, the better the results statistically.
- Version 3 (December 2018) of the tool has also introduced a new dataset of IDF curves for ungauged locations in Canada. With the new module, users can obtain IDF curves for any location in the country, including regions where no station observations are available.
- The tool still provides the opportunity to select the Gumbel distribution for review of historic data as Environmental Canada still utilizes this method for historical IDFs. It is noted that Environment Canada has no plans to change their approach to IDFs in the foreseeable future.
- The tool recommends an ensemble approach (the tool presently embodies data from twenty-four [24] GCMs and nine [9] downscaled GCMs). However, the tool also allows the user to review the differences in results between models. If there is a vast difference between the values, the user can apply what is deemed to be most appropriate for the type of study. For example, when looking at flood risk, one might want use a more conservative estimate.
- The tool provides projections for the RCP 2.6, 4.5 and 8.5 scenarios.

Version 3.5 of the tool was released in May 2019 and includes the following features:

- Updated dataset of IDF curves from the ECCC with precipitation data up to 2017
- New stations introduced by ECCC
- Changes in the names and/or code of stations introduced by ECC

A review of the historic data for the Guelph Turfgrass CS station available from the IDFCC Tool indicates the following:

- 25 year, 6 hour duration event has a total depth of 63.4 mm based on a GEV statistical distribution
- 25 year, 12 hour duration event has a total depth of 72.3 mm based on a GEV statistical distribution
- 25 year, 6 hour duration event has a total depth of 61.4 mm based on a Gumbel statistical distribution
- 25 year, 12 hour duration event has a total depth of 69.9 mm based on a Gumbel statistical distribution

The ungauged data option was also used for a location representing the McLaughlin Road / Spine Road project. The IDFCC Tool indicates the historical data for the selected location (Latitude: 43.73092 ° and Longitude: -79.84473 ° - see Figure 3-1) as:

- 25 year, 6 hour duration event has a total depth of 79.1 mm based on a GEV statistical distribution
- 25 year, 12 hour duration event has a total depth of 89.6 mm based on a GEV statistical distribution

Projected IDF relationships have been developed, using the IDFCC Tool, for the Guelph Turfgrass CS station using an ensemble bias-corrected approach and computed for the two (2) of the three (3) available RCPs (ref. Section 2).

The 2050 and 2080 timeframes selected for assessment represent the five decade periods of 2015-2065 and 2045 to 2095 respectively. These time periods were selected for alignment with the end years of the pre-defined time periods used by the Ontario Climate Change Data Portal (OCCDP). It was considered that including more the from the past would likely have less impact to the IDF comparison between these two tools than including more future data would.

Locations representing the approximate project site in the Town of Caledon and the Guelph Turfgrass CS gauging station were selected for estimation of projected IDF data. The results are outlined in Table 3-1. Please note that the IDFCC Tool only provides future projections using the GEV distribution.

Table 3-1 Summary of IDFCC Tool Projected Rainfall Estimates

Location	RCP	Timeframe	25 year Rainfall Events	
			6 hour duration	12 hour duration
Guelph Turfgrass CS	4.5	2050	79.6	91.1
		2080	95.0	108.8
	8.5	2050	85.8	98.2
		2080	95.4	109.3
McLaughlin Road / Spine Road Study Area (represented by location at Latitude 43.73092 ° and Longitude -79.84473 °)	4.5	2050	107.2	121.4
		2080	145.7	165.0
	8.5	2050	114.9	130.2
		2080	143.6	162.7

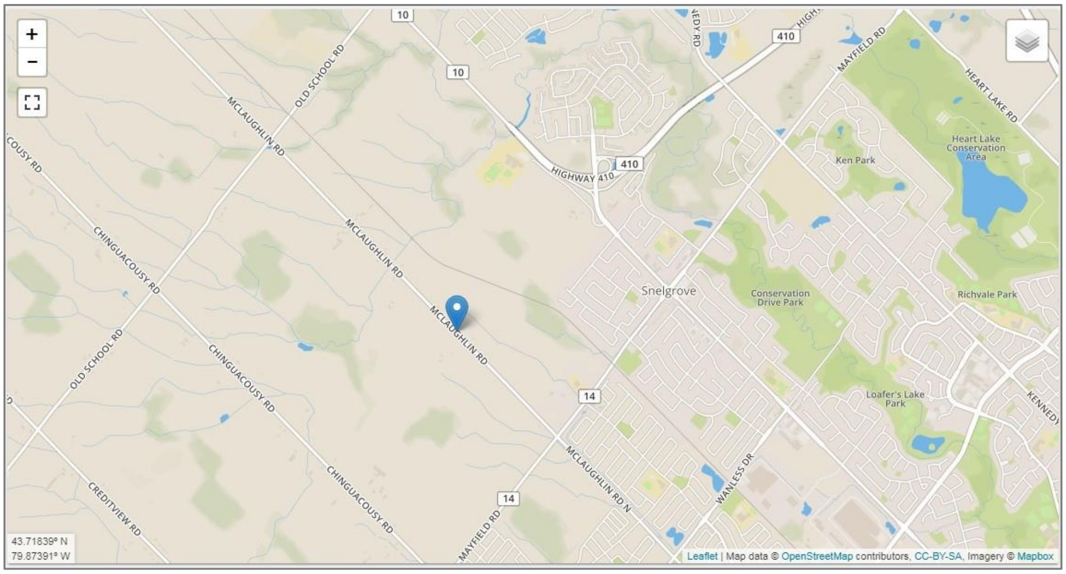

Figure 3-1 IDFCC Tool - Location used to represent the McLaughlin Road / Spine Road Study Corridor

3.4 Ontario Climate Change Data Portal (OCCDP)

The Ontario Climate Change Data Portal[1] has incorporated the high-resolution (25 km x 25 km) climate projections developed by the Institute for Energy, Environment and Sustainable Communities (IEESC) at the University of Regina using the PRECIS model (under A1B emissions scenario) and the RegCM model (under RCP 8.5 emissions scenario). Presently, projected IDF data is now available based on climate projections under the RCP 4.5 and 8.5 scenarios. However, the associated data tables the tool is supposed to provide is not functioning properly at present. Only the IDF graphical representation is downloadable, however the resolution of the graphical image is insufficient to provide an accurate estimate of the estimated rainfall intensity. As such, this assessment reverted to the A1B emissions scenario IDF estimates.

Using this tool, IDF relationships have been estimated for 2050 and 2080 as represented by the tri-decade periods 2035 to 2065 and 2065 to 2095, respectively (ref. Section 2) for the grid cell representing the project location. The grid location selected for projected IDF data are illustrated in Figure 3-2.

IDF data has been abstracted associated with the A1B emissions scenario 90th percentile, as follows:

- 2050 - 25 year, 6 hour duration event has a total depth of 106.0 mm
- 2050 - 25 year, 12 hour duration event has a total depth of 129.0 mm
- 2080 - 25 year, 6 hour duration event has a total depth of 124.4 mm
- 2080 - 25 year, 12 hour duration event has a total depth of 151.1 mm

[1] Available via URL http://ontarioccdp.ca/

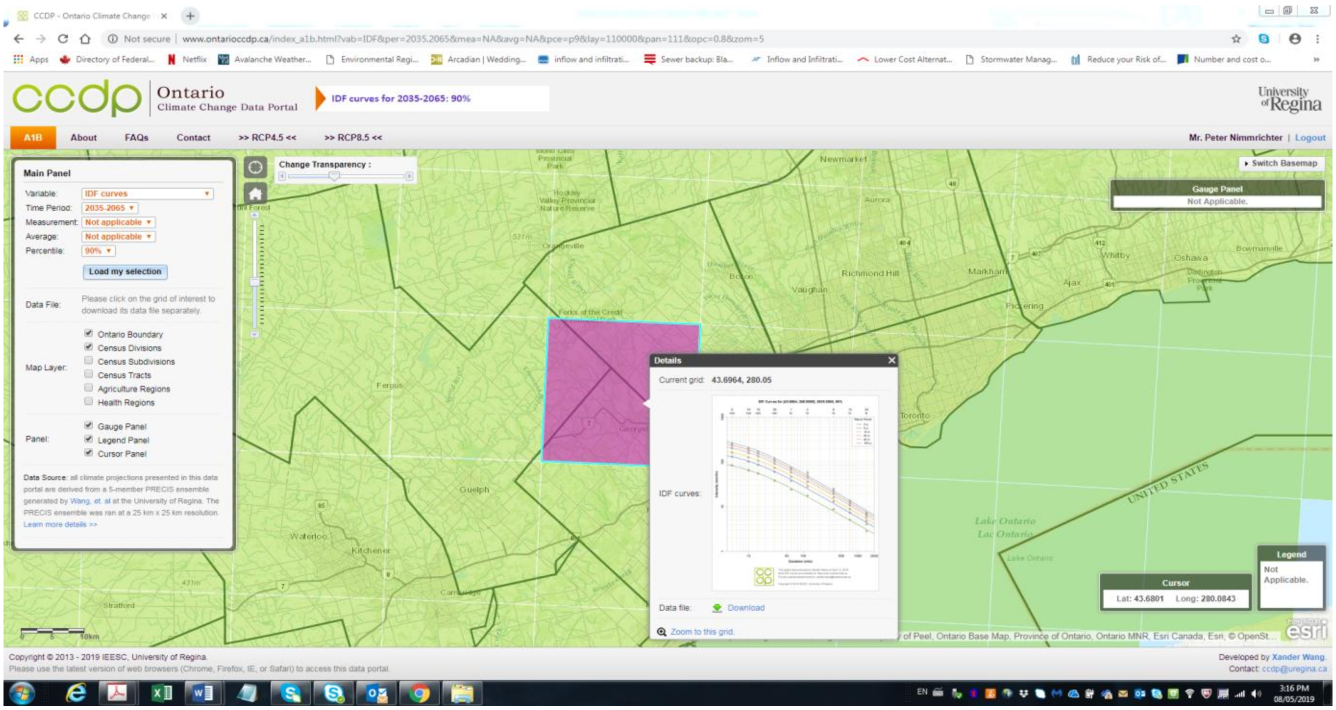

Figure 3-2 OCCDP Tool - Location of Grid Cell used to represent the McLaughlin Road / Spine Road Study Corridor

3.5 Ministry of Transportation Ontario (MTO) Trending Tool

The Ontario Ministry of Transportation has implemented a number of recent updates to its IDF curves to ensure they are as current as possible and regularly incorporate additional and recent rainfall data. MTO has also developed an IDF modelling tool[2] that allows generation of a unique rainfall intensity curve for any point or area in the province. The most recent update to this tool also includes a predictive modelling component to enable generation of a future IDF curve accounting for the predictive impacts of climate change.

Using this tool, IDF relationships have been estimated for 2050 and 2080 (ref. Section 4) for the same location representing the project location as used with the OCCDP. The location selected for projected IDF data are illustrated in Figure 3-3.

IDF data estimated using this tool for the noted location is outlined as follows:

- 2050 - 25 year, 6 hour duration event has a total depth of 70.8 mm
- 2050 - 25 year, 12 hour duration event has a total depth of 87.6 mm
- 2080 - 25 year, 6 hour duration event has a total depth of 72.6 mm
- 2080 - 25 year, 12 hour duration event has a total depth of 90.0 mm

[2] Available via URL: http://www.mto.gov.on.ca/IDF_Curves/

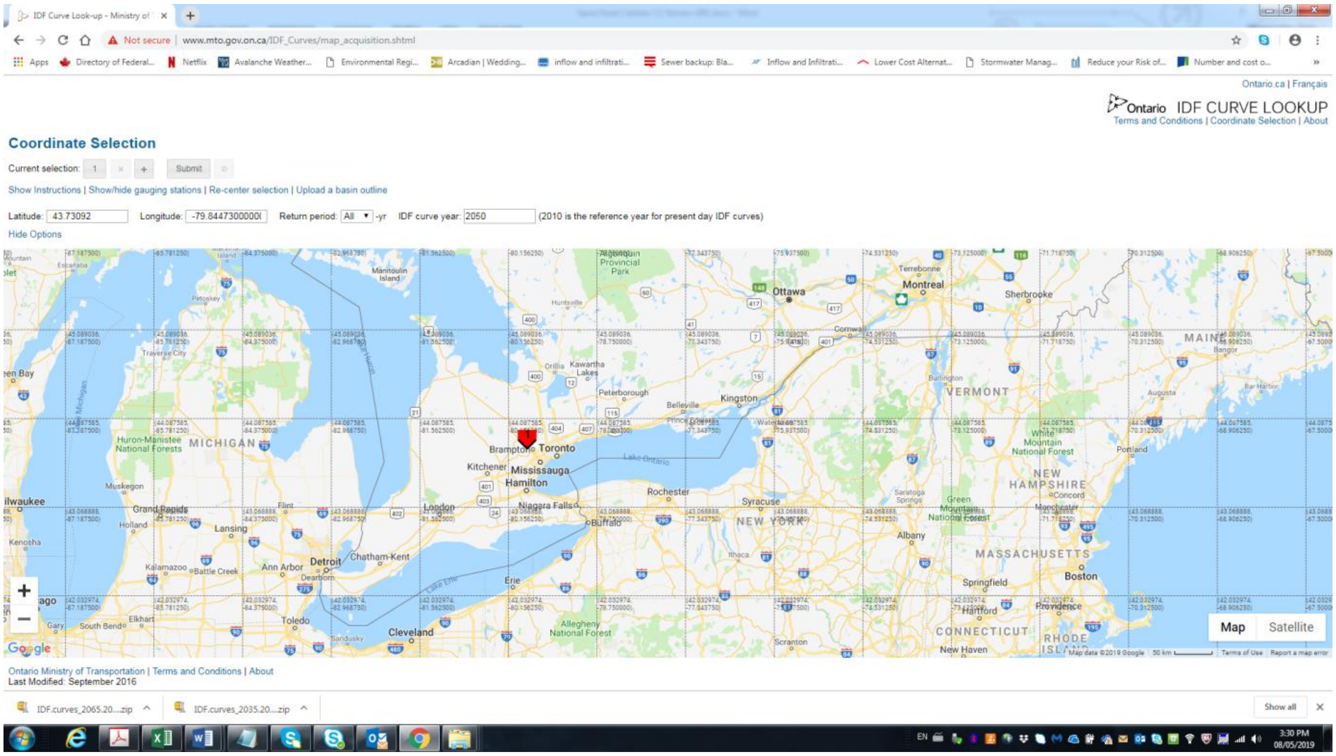

Figure 3-3 MTO Trending Tool - Location used to represent the McLaughlin Road / Spine Road Study Corridor

4.0 Rainfall Scenarios Analysis

Each of the tools used in this assessment embodies its own methods of analysis, display and output of data. As such, a direct comparison of the IDF scenarios generated by the various tools is not possible as the input parameters upon which the scenarios have been generated do not overlap exactly. For instance, OCCDP provides data for grid cells over Ontario and estimates IDFs using 30 year averages (e.g. aligned with climate normals as defined by the World Meteorological Organization), while the IDFCC Tool provides data on a spatial point basis and uses 50 year periods (as available in v3+) as a minimum to estimate IDFs. Therefore, the comparison of the scenarios ensemble developed from the various data sources (both historical based IDF, as well as those that incorporate outputs from climate modelling) has been approached simply.

4.1 Comparisons

Table 4-1 provides a summary of the various rainfall estimates generated for this rainfall scenario review. In addition to rainfall estimates, as described in the preceding sections, two (2) additional scenarios have been included in Table 4-1, namely +15% and +20% increases to the Town of Caledon IDF standard. This method of assessing impacts of climate change on municipal infrastructure has been adopted by numerous municipalities in Ontario. As noted in the Table, the estimates ranges, overall, from 62.3 mm to 148.5 mm. This is a very typical result and highlights the difficulty in integrating climate change influenced rainfall estimates into engineering design.

Table 4-1 Summary of Projected Rainfall Estimates

Tool	Location	25 Year Return Period Rainfall Estimates (mm)					
		Today		2050		2080	
		6 hour	12 hour	6 hour	12 hour	6 hour	12 hour
Town of Caledon Standards	Municipality	74.9	80.0				
ECCC	Guelph Turfgrass CS	62.3 (Gumbel)	72.1 (Gumbel)				
IDFCC Tool	Guelph Turfgrass CS	63.4 (GEV)	72.3 (GEV)				
		RCP 4.5 (GEV)		79.6	91.1	95.0	108.8
		RCP 8.5 (GEV)		85.8	98.2	95.4	109.3
	Project Location	79.1 (GEV)	89.6 (GEV)				
		RCP 4.5 (GEV)		107.2	121.4	114.9	130.2
		RCP 8.5 (GEV)		145.7	165.0	143.6	162.7
OCCDP	Project Location	Gumbel		106.0	129.0	124.4	151.1
MTO Trending Tool	Project Location	Gumbel		69.6	86.4	72.6	90.0
Town of Caledon Standards +15%	Municipality	Gumbel		86.1 (6 hour) / 92.0 (12 hour)			
Town of Caledon Standards +20%	Municipality	Gumbel		89.9 (6 hour) / 96.0 (12 hour)			

4.2 Discussion of Results

The purpose of this assignment has been to develop several scenarios/estimates of climate change influenced "future" rainfall in support of the study corridor for the McLaughlin Road / Spine Road Study Corridor Environmental Assessment and recommendations for future modelling for the detailed design of drainage sizing associated with water crossings of the roadway.

The analysis has focused on the 25 year return period 6-hour and 12-hour duration events, and incorporated the 2050s and 2080s future time periods for the GHG emission scenarios RCP 4.5 and RCP 8.5, as well as the scenario SRES A1B. Furthermore, 15% and 20% increases to historical IDF estimates were included for comparison purposes. Following the IPCC recommendations, an ensemble approach was adopted for those tools where outputs from GCM models were sources of data. Five main sources of data were used to obtain new rainfall IDF relationships these included: IDFCC, OCCDP, MTO, and previously known IDF relationships from other sources (Town of Caledon and ECCC).

This resulted in numerous scenarios (ref. Table 4-1). Challenges exist when approaching an inter-comparison of outputs from tools that update IDF relationships to include climate change with various methods. This is particularly complex due to the lack of agreement of results (ref. Table 4-1) and of what methodologies are best for this purpose, what specific time periods define the 2050s and 2080s, and what length of record (e.g., 30 years, 50 years) is necessary to be included in the analysis of climate projections to provide the most accurate future IDF relationships, and what future emission scenario will become a reality. Therefore, the discussion and conclusions of this assignment are presented around a few general questions that are of both interest and utility to the project, namely:

1. Should the project focus on the present Town of Caledon rainfall standard based on the Guelph OAC station, which ceased operations in 1973, or use one of the available tools to estimate rainfall in the vicinity of the project within the boundaries of the Town.

   The results demonstrate that rainfall estimates are generally higher for the McLaughlin Road / Spine Road study specific location in comparison with estimates for the Guelph Turfgrass CS station location. If conservatism in design is an objective of the culvert assessment then using the study specific location for rainfall estimation would align with that objective. However, decision to use one location over the other as a basis for rainfall estimation lies with risk tolerance of the client and the balance of costs and benefits associated with culvert designs associated with the various rainfall estimates.

2. Which future basis scenario (RCP or SRES) should the project base its future rainfall guidance on? If RCP, which representation should be adopted … 4.5 or 8.5?

   The selection of an emission scenario in climate change analysis incorporates the significant uncertainty of which emission scenario will become reality. Impact analysis literature suggests that scenario RCP 8.5 should be a default to examine, as it is currently the most realistic scenario based on present emissions and feedbacks from existing GHGs in the atmosphere from past emissions. RCP 4.5 may be incorporated in future analysis as a scenario representing the successful achievement of present global GHG mitigation targets. While past SRES scenarios are not considered to be "outdated" or "wrong", RCP scenarios represent an evolution of SRES scenarios and therefore should take priority when projects are unable to incorporate a broader approach. In the context of this analysis, it is recommended to adopt the rainfall estimates associated with the RCP 8.5 scenario.

3. Are both future time periods (i.e. 2050s vs 2080s) relevant?

It is a significant challenge to select one future time period to consider in infrastructure design using a data approach alone. Furthermore, the various tools available incorporate definitions of time periods that are not always in alignment. In this assignment the comparison of identical time periods was restricted by the options available within the tools (e.g., selecting 30 year averages, vs 50 year averages). It is recommended that the selection of what time period is used for design (2050s vs 2080s) for this project should be dependent on elements such as the expected lifespan of the infrastructure, cost-benefit analysis and/or triple bottom line analysis, resilience return on investment, life-cycle costs, and criticality of the infrastructure, etc.

4. Should the Town maintain its standard statistical representation of rainfall based on a Gumbel distribution or move to the GEV distribution?

   Comparison of Gumbel based rainfall estimates, presented in the assessment report, versus the GEV based estimates generally demonstrates higher estimates are associated with the GEV approach. The GEV distribution used to fit IDF data is deemed to be more statistically accurate and there have been recent studies confirming this conclusion (Millington et. al, 2011; Nguyen and Nguyen, 2016, Switzman et. al, 2017).

   Notwithstanding, ECCC has indicated that the organization has no expectation, at this time, to change the Gumbel approach upon which its published rainfall information is based.

   A comprehensive comparison of the impact of updating the existing Caledon IDF relationship using GEV is not part of the scope for this assignment, and would require the analysis of the raw rainfall data used to develop the existing Caledon design IDF. However, previous station comparisons for the "best" fit distribution function (Switzman et. al, 2017) using eleven (11) fit criteria demonstrated that the GEV distribution function was the "best" fit.

5.0 Recommendations

The following recommendations stem from the foregoing assessment of climate change influenced rainfall:

[1] It is recommended that the project maintain reliance on the Gumbel based estimates for assessment and design, given the direction adopted by ECCC and the differences between the Gumbel and GEV based estimates.

[2] It is recommended that the project give consideration to using rainfall estimates based on a GEV approach for design stress testing purposes.

[3] It is recommended that the client be consulted to determine the appropriate rainfall scenario to use for detailed design of drainage works associated with the roadway.

It is anticipated that all of these recommendations would be actioned during detailed design.

6.0 References

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