Durham Community Climate Adaptation Plan

- **Flood Vulnerable Road and Crossing Hydraulic Capacity Assessment**

Prepared by Toronto Region Conservation Authority

2021

Flood Vulnerable Road and Culvert Hydraulic Capacity Assessment

Prepared for Durham Region

Written by **Ying Qiao, P.Eng.**
Senior Engineer

Reviewed by **Rehana Rajabali, P.Eng.**
Associate Director

CONTRIBUTORS

Name	Job Title	Role
Ying Qiao, P.Eng.	Senior Engineer	Primary Author
Rehana Rajabali, P.Eng.	Associate Director	Reviewer, Co-author
Glenn Milner	Climate Change Specialist	Co-author
Shelley Hazen	Climate Change Specialist	Co-author
Yuestas David	Senior Project Manager	Co-author
Sara Sadr, P.Eng.	Project Manager	Co-author

DATE: Thursday, March 3, 2022

605 Rossland Road East,

Whitby, L1N 6A3

Attention: Mani Rajendran, MSc. Eng., P.Eng.

       Project Manager, Works Department – Transportation Design

       The Regional Municipality of Durham

Dear Mr. Rajendran:

Subject: Durham Climate Change Adaptation - Flood Vulnerable Road and Culvert Hydraulic Capacity Assessment

We are pleased to submit our **Final** report that summarizes the methodology and results of the flood vulnerable road and culvert capacity screening analysis within the Durham Region and TRCA's jurisdiction.

The final report has been prepared in accordance with the tasks identified in the TRCA Project Proposal and addresses all comments and questions from the Region that arose during the course of the study.

We trust the submission of this document meets your requirements. We wish to thank the Region staff for your invaluable assistance in acquiring the necessary information required to complete the study.

Should you have any comments or questions, please do not hesitate to reach out to us; we look forward to your response.

Yours sincerely,

Ying Qiao, M.Sc. P.Eng.,

Senior Engineer, Flood Risk Management,

Engineering Service, Development and Engineering Services Division

TRCA

ACKNOWLEDGEMENTS

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1   INTRODUCTION

The Region of Durham's Community Climate Adaptation Plan (DCCAP) outlines a strategy to build resiliency while adapting to our changing climate. The plan includes sector-based objectives aimed at increasing resilience, including reducing riverine flooding (from the Flooding Sector objectives) and improving the resilience of road systems to extreme rain storms as well as protecting from washout at stream crossings (from the Roads Sector objectives). To enable the identification of priority roads and culverts for enhanced resilience measures, the DCCAP Roads working group, as well as the flooding working group, identified the need to assess the vulnerability of roads to flooding under current and future climate scenarios, as well as screen crossings (culverts and bridges) for their ability to meet intended design standards. The Region of Durham approached the Toronto and Region Conservation Authority (TRCA) to undertake a project that would assist the Region in identifying:

1.   Crossings that merit further attention as candidates for upsizing, based on hydraulic performance under current and future climate scenarios, to inform future asset management plans with an aim of increasing resilience;

2.   Roads that are vulnerable to flooding under different riverine flood scenarios (for both current and future climates) to inform future disaster route planning; and

3.   A method of assessing the criticality of roads, in order to assist in prioritizing which ones merit investment to increase resilience to riverine flooding (considering both current and future climate conditions).

As the stewards of riverine flooding information, including hydraulic modelling, Conservation Authorities are natural partners in this endeavour. As each Conservation Authority is the custodian of flood model data in its own jurisdiction, TRCA developed a proposal that would undertake the requisite analysis within TRCA's jurisdiction and provide a methodology that could be replicated by other Conservation Authorities. Thus, the study area for this project is the riverine regulatory flood plain within TRCA's jurisdiction, within Durham Region. This includes flood plain areas within the Town of Ajax, the majority of the City of Pickering, and the south portion of the Township of Uxbridge. The study area includes the Carruthers Creek watershed, Frenchman's Bay watershed, and the majority of the Petticoat and Duffins Creek watersheds (Figure 1-1). The Rouge watershed is not included in this study as its riverine regulatory floodplain boundaries within TRCA's jurisdiction does not intersect any roads. Note also that this study focuses on riverine flooding, as opposed to urban flooding which occurs when rainfall overwhelms the local storm drainage infrastructure that is managed by the municipality. Note also that this study does not assess waterfront flooding caused by high lake levels, which is a distinct process which is influenced differently by a changing climate.

One of the objectives of this project is to assess road vulnerability and crossing capacity under a plausible 'future climate' scenario. As determined together with the Region, this was represented by assessing conditions for the 'future return period' corresponding to each of the modelled flood extents. At the Region's invitation, Savanta (a GEI Company) was retained to develop the future climate scenario as well as to provide input into the factors influencing a road's criticality score. The provided climate change return period shifts was used to assess road and crossing capacity as part of TRCA's tasks. For details about the methodology behind the climate change return period shifts, please refer to Savanta's technical memo, as summarized in Section 4

The intent of this project has been to use TRCA's most current available flood plain mapping and modelling files, so no new models or model updates were created for the purpose of this project. As outlined by TRCA, mapping/modelling work in Petticoat Creek and Frenchman's Bay watersheds were not recently updated, however the modelling and mapping for both Duffins Creek and Carruthers Creek watersheds were recently updated in 2019 and 2020, respectively.

Further to the three objectives noted above, this study has generated three types of geodatabases:

1. A crossing geodatabase that is used to compare the hydraulic performance of crossings to Ministry of Transportation (MTO) criteria for current and future climate scenarios;

2. A flood vulnerable 'road segment' geodatabase that characterizes the degree of disruption to traffic caused by flooding (by assigning closure durations to flood depths, and combining that information with Average Annual Daily Traffic information and Annual Exceedance Probabilities). For the purpose of this study, a road segment is described as each instance of where the regulatory flood plain overlays the road.

3. A Risk Ranking geodatabase that considers the relative importance road segments based on various criticality factors independent of the flood hazard

This report summarizes the methodology on data preparation and data extraction for both road segments and crossings under various annual exceedance probabilities (AEP), as well as the methodologies for defining road closure threshold, calculating Annual Average Disruption (AAD), defining risk and criticality for each road segment, and assessing whether crossings meet their design level of service.
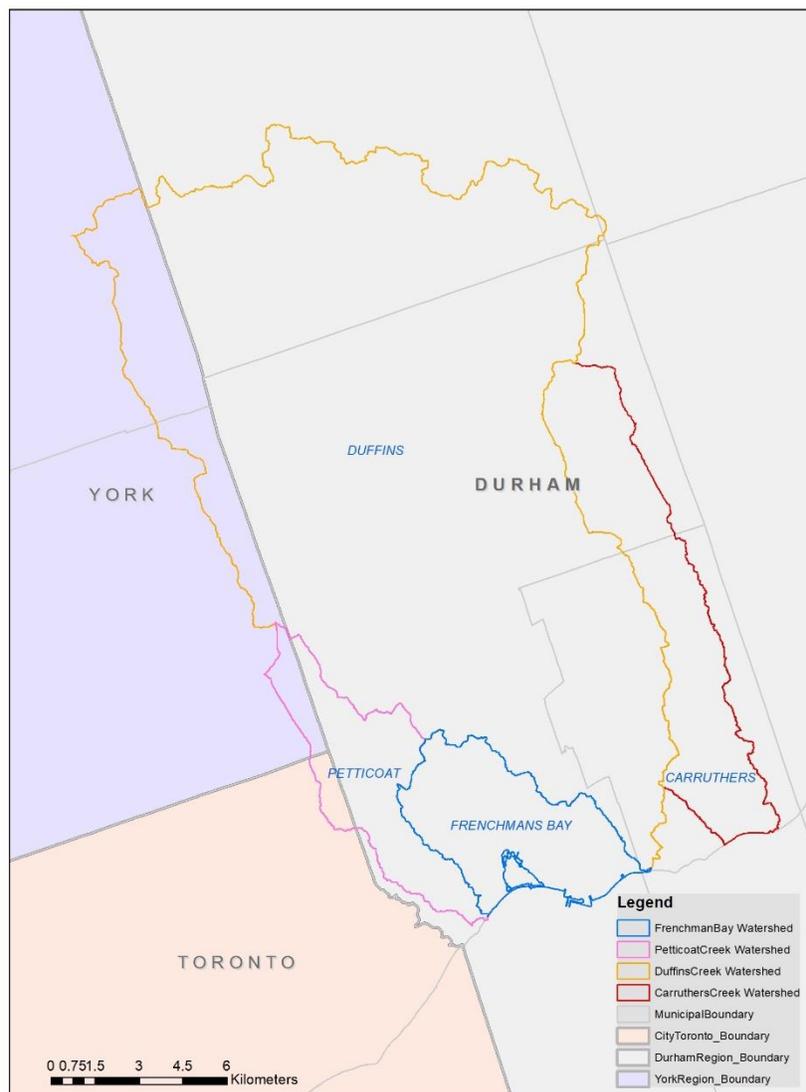
FIGURE 1-1 TRCA WATERSHEDS WITHIN DURHAM REGION

1.1 Overview of TRCA Watersheds within Durham Region

There are four TRCA watersheds that are within, or mostly within, the Durham Region boundary as shown in Figure 1-1; key characteristics of each watershed are summarized below:

1) Frenchman's Bay

Frenchman's Bay watershed is about 2,700 hectares of land within the City of Pickering. The watershed includes 4 sub-watersheds that drains into Frenchman's Bay, then eventually into Lake Ontario. These are: Amberlea Creek, Dunbarton Creek, Krosno Creek, and Pine Creek. The Frenchman's Bay watershed has undergone significant development in the past 50-60 years, and most of the land within the watershed is developed. The land use is dominated by low and medium density residential, as well as industrial/commercial/institutional land uses.

2) Petticoat Creek

Petticoat Creek watershed is about 2,417 hectares in area, mostly within the City of Pickering with a very small portion of the watershed located in Markham and in the City of Toronto. It is surrounded by the Rouge River, Duffins Creek and Frenchman's Bay watersheds. The watershed consists of the Main Branch, and the East and West tributaries, which join with Main Branch at Finch Ave then drain southward into Lake Ontario. The land use within the watershed can be divided between rural (agricultural) land uses north of Finch Avenue and urban (mainly low and medium density residential and a small portion of industrial/commercial) land uses south of Finch Avenue.

3) Carruthers Creek

Carruthers Creek watershed has an approximate drainage area of 3,971 hectares within the City of Pickering and the Town of Ajax. The watershed consists of the Main Branch, and East and West tributaries, which join with the Main Branch approximately 300 metres upstream of Taunton Road East. The creek then drains through Carruthers Marsh into Lake Ontario. The land within the watershed can be generally divided between rural (agricultural/golf course) land uses north of Taunton Rd E, and mix of urban (mainly low and medium density residential) land uses and open space to the south.

4) Duffins Creek

Duffins Creek watershed is the biggest watershed among these four watersheds, and it spans an approximate drainage area of 28,216 hectares. Most of the watershed lies within the City of Pickering, with some portions of the watershed extending into the City of Markham and Town of Whitchurch-Stouffville to the west, and into the Township of Uxbridge to the north. The watercourse network includes the Lower Duffins, and Main Duffins, East Duffins, West Duffins, and Miller Creek. The East Duffins and West Duffins join with Main Duffins Creek at approximately 600m downstream of Brock Road, and then Main Duffins and Miller Creek join with Lower Duffins Creek at approximately 1km downstream of Highway 401, with the Lower Duffins eventually draining through Duffins Marsh into Lake Ontario.

While Duffins Creek watershed has experienced urban growth in recent years, only 10% of the lands are urban, and 19% are urbanizing. 71% of the watershed still has a predominantly rural landscape. Rural areas dominate the north of the watershed while the southern portions are urban or urbanizing.

1.2 Scope of Work

This study focused on riverine crossings and roads within TRCA's jurisdiction in Durham Region only and does not consider flood vulnerability of roads under urban (non-riverine) flooding scenarios. As a screening-level analysis, the methodology was developed assuming only the availability of TRCA's most current model files for each watershed; no new hydraulic analysis was undertaken as part of this study. The key tasks comprising this study are outlined below:

- Background review

- Data extraction for crossings and inundated road segments

- Geodatabase compilation for crossings and road segments

- Annual Average Disruption calculation

- Risk and Priority assessment based on frequency of flooding and criticality (importance of roadway)

- Future climate change output incorporation

- Preparation of final report summarizing all technical work

- Preparation of final deliverables, including executive summary report

2 BACKGROUND

As mentioned in Scope of Work, the methodology was based on the use of the most recent existing available hydraulic models, as well as road network data provided by the Region of Durham.

2.1 TRCA Existing Hydraulic Models

Details on the hydraulic models that were utilized for each watershed are provided below.

2.1.1 Frenchman's Bay

The Frenchman's Bay models include four HEC-RAS models for each sub-watershed, which were developed by different consulting firms in various years between 2002 and 2008 based on underlying hydrology studies that were completed between 2002 and 2007 (Table 2-1). These HEC-RAS models were not geo-referenced and all used old topographic data that could not be found in the TRCA GIS archive. In total, 39 crossings were modelled in the Frenchman's Bay models. While the regulatory floodline had been mapped, spatial outputs (grids of flood depth) or flood extent mapping were not available for the 2- year to 100-year return period events.

TABLE 2-1 SUMMARY OF YEARS OF COMPLETION OF HEC-RAS AND HYDROLOGY – FRENCHMAN'S BAY

Sub-watershed	Year of completion (Hydrology)	Year of completion (Hydraulic)
Amberlea Creek	March 2005	July 2005
Dunbarton Creek	January 2007	January 2008
Krosno Creek	March 2002	March 2002
Pine Creek	January 2007	March 2007

2.1.2   Petticoat Creek

The Petticoat Creek watershed hydrology study was completed in October 2006 and the hydraulics were modelled with one HEC-RAS model that was completed in November 2006. . The Petticoat HEC-RAS model was geo-referenced and used a mix of sources of topographic data, such as field measurements, a total station GPS survey, and digital topographic data, although these topographic data sets were not incorporated in the TRCA archive. In total, 34 crossings were simulated in the Petticoat Creek model. While the regulatory floodline had been mapped, spatial outputs (grids of flood depth) or flood extent mapping were not available for the 2-year to to100- year return period events.

2.1.3   Carruthers Creek

The Carruthers Creek HEC-RAS model was recently completed in January 2020. The majority of the watershed was modelled using a one-dimensional (1D) HEC-RAS model, with the exception of the Lower Carruthers area, which was modelled using a two-dimensional (2D) model to delineate the flood extent and characterize flood risk for the spill at Seabreeze Road. The underlying hydrology study was done in October 2011. The recently updated HEC-RAS model used 2015 LiDAR data and the most recent available crossing information. In total, 48 crossings were simulated in the Carruthers model and floodlines and depth grid outputs are available for 2-year to 100-year year events as well as the Regional storm.

2.1.4   Duffins Creek

The Duffins Creek HEC-RAS model was recently completed in October 2020The majority of the watershed was modelled using a 1D HEC-RAS model, except for the Pickering/Ajax Special Policy Area (SPA) (from Valley Farm Rd to Highway 401), which was modelled using a 2D model to better define flood extent and characterize the flood risk within the SPA. The Hydrology study was completed in February 2013. The recently updated HEC-RAS model used 2015 LiDAR data, supplemented with 2019 LiDAR at new grading change areas, and the most recent available crossing information. In total, 218 crossings were modeled in the Duffins model. In terms of mapping output, there are floodlines and depth grid outputs available for 2-year to100-year events as well as the Regional storm.

Watershed	Subwatershed	Completion Date		Crossings Simulated
		Hydrology Model	Hydraulic Model	
Frenchman's Bay				39
	Amberlea Creek	Mar-05	Jul-05	
	Dunbarton Creek	Jan-07	Jan-08	
	Krosno Creek	Mar-02	Mar-02	
	Pine Creek	Jan-07	Mar-07	
Petticoat Creek		Oct-06	Nov-06	34
Carruthers Creek		Oct-11	Jan-20	48
Duffins Creek		Feb-13	Oct-20	218

2.2   Durham Region Available Data

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The Region provided the regional road network and Average Annual Daily Traffic (AADT) data for regional roads in a GIS shapefile format.

2.2.1 Road Network

This dataset contains centre-line data for the road network within the Durham Region (Figure 2-1). Information is updated from registered drawings, and attribute information is updated based on municipal notifications.

The road network data was cropped into segments at every point of overlap within the regulatory floodplain extents to generate the road segment geodatabase. This dataset contains several important attributes which are used in both the crossing capacity and road segment geo-databases; key attributes are summarized below:

1) ID: A six-digit number that defines a unique ID for each road segment, which is used as the primary key to link to geo-database tables;

2) FULL_NAME: contains road name and road suffix;

3) FUNCTION: contains the functional classification of the road, which includes the freeway, a_arterial, b_arterial, c_arterial, collector, local and ramp types;

4) POL_CLASS: contains a hierarchy of the road system in order of 1 to 5, with 1 being a higher order road;

5) JURISDICT: contains road ownership/authority, i.e.: provincial, regional, municipal, private; and

6) MUNICIPAL: identifies the name of the municipality where the road is located.
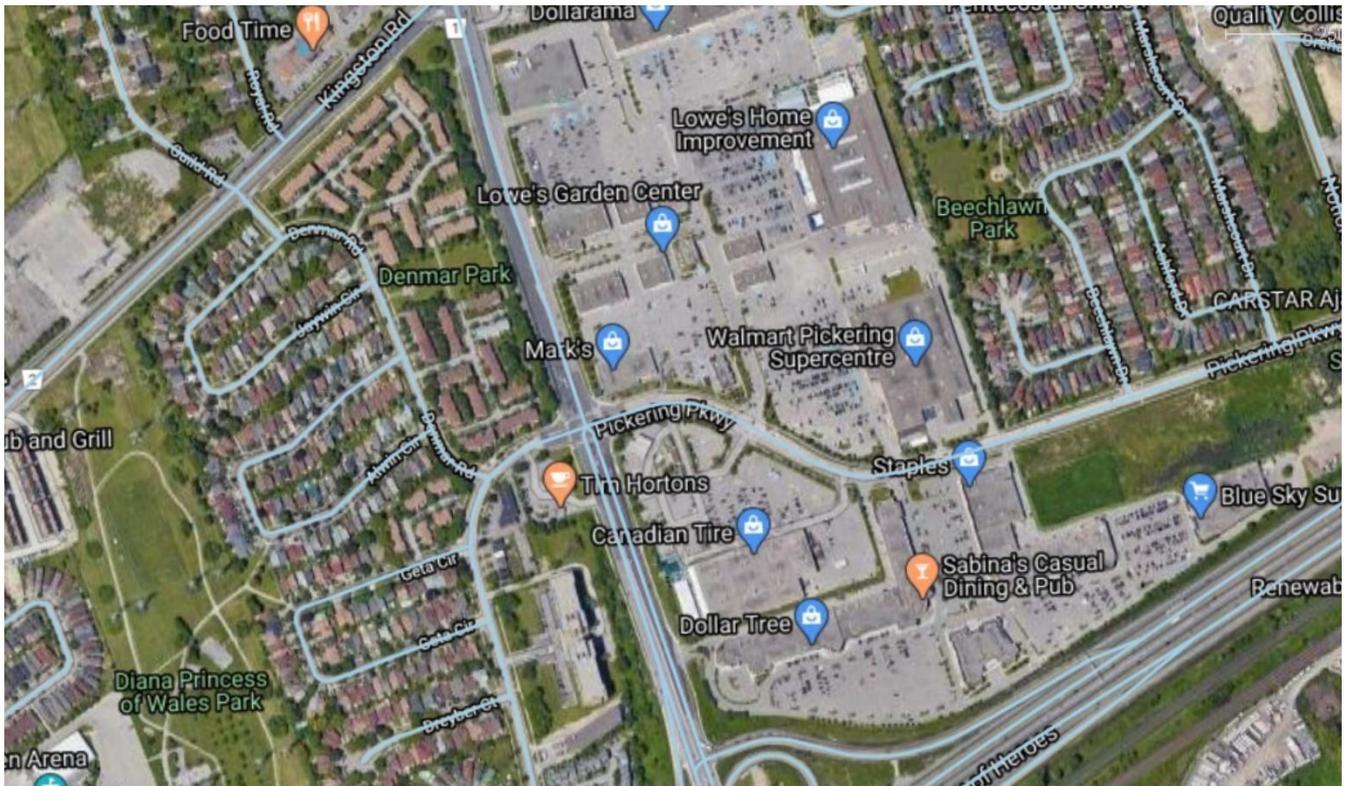
FIGURE 2-1 EXAMPLE OF ROAD CENTER-LINE DATASET

2.2.2 Available Average Annual Daily Traffic (AADT) Data

Average Annual Daily Traffic (AADT) information is utilized in both the road segment geodatabase and the criticality geodatabase. AADT is an averaged measure of the volume of a traffic on a given roadway or road segment, often taken as the total volume of traffic over the course of a year, divided by 365. In many cases, the total annual volume is not available but AADT is estimated by adjusting other traffic counts, as outlined in the sections below. For the purpose of this study, AADT is used in the Average Annualized Disruption (AAD) calculation as the AADT is first multiplied by the flood closure duration for each return period event to provide an estimate of the disrupted trips caused by that given flood event. As this study represents a desktop, screening-level analysis, the disruption as calculated by this method is not meant to represent an actual modelled disruption to traffic flow. Rather, this approach is meant to highlight that the closure (due to flooding) of a highly travelled road would be more impactful than that of a less-travelled road. The AADT values were also used in the criticality database to assign a sub-factor score of 1 to 5 to each road segment to illustrate the importance (from a useage perspective) of each road segment. Because AADT values were not necessarily available for every road segment, a 'best available data' approach was utilized, as outlined below, to populate this field for the road segment and criticality databases.

2.2.2.1 Durham Region AADT Data

Durham Region AADT data contains AADT values for most regional roads for 2017 through 2019. Some roads did not have values for all three years. The most recent available AADT value was used when assigning AADT to the road segment database. For example, if a road segment had all three years of data available, then the 2019 data is used; if a road segment only had 2017 and 2018 data, then 2018 data is used; otherwise 2017 data is used. Church Street did not have any AADT values for these three years as the Automatic Traffic Recorder (ATR) was deactivated in 2016. AADT values on Church St road segments in Ajax near Highway 401 are derived based on Ajax's ATR counts.

2.2.2.2 Town of Ajax AADT Data

The Town of Ajax provided Automatic Traffic Recorder (ATR) counts and Turning Movement Counts (TMC) for years 2017 through 2019 for select road segments. ATR counts cover a full 24-hr period while TMC data only cover certain parts of the day. Given this, the following approach is used to derive AADT data for roads within Ajax:

- For roads where ATR data is available, then AADT is taken directly from ATR data first;
- For roads where TMC data is available, but ATR data is not available, AADT is estimated from TMC peak hour data, I.e. the two-way PM peak hour volume on the relevant leg of the intersection from 4pm to 5pm times 10 as suggested by Region of Durham.

- For local roads within Ajax without ATR and TMC data, AADTs are taken from ATR data for Mill Street, since the road type is the same, the ATR data covers the full-day period, and the urban environment is similar.

AADT values derived from ATR or TMC counts have not been adjusted with factors such as a day-of-week factor or seasonal factor etc., as this would be out of the scope of this project.

2.2.2.3 City of Pickering AADT Data

The City of Pickering provided an AADT Range as specific AADT values are not available (see Figure 2-2). To be conservative, the upper limit of the AADT range is used for this study, e.g. for Sideline 20, the provided AADT range was 0-49, resulting in an assigned AADT value of 49.

FID	Shape *	ID	FUNCTION_	FULL_NAME	POL_CL	RdEnvironm	SpeedLimit	AADTRange	Road_Width
92	Polyline M	100099	local	Sideline 20	5	Rural	50	0-49	4
38	Polyline M	100169	local	Heska Road	5	Semi-Urban	40	200-499	6.7
111	Polyline M	100183	local	Westney Road	5	Rural	50	50-199	6.7
87	Polyline M	100480	local	Seventh Concession Road	5	Rural	50	200-499	6
60	Polyline M	100845	local	Bronwen Lane	5	Urban	40	200-499	7.5
39	Polyline M	100852	local	Uxbridge Pickering Townline Road	5	Semi-Urban	60	500-999	6.7
113	Polyline M	100872	local	Sideline 34	5	Rural	50	0-49	4
71	Polyline M	100976	b arterial	Fifth Concession Road	4	Rural	50	500-999	6
119	Polyline M	101555	local	Sideline 8	5	Rural	50	0-49	5.5
2	Polyline M	101624	local	Sideline 4	5	Rural	50	50-199	5.7
11	Polyline M	101637	local	Sideline 12	5	Rural	50	50-199	6

FIGURE 2-2 ATTRIBUTES OF AADT DATA FROM CITY OF PICKERING

2.2.2.4   AADT for Highways and Highway Ramps

Within the study area, a few highway and highway ramp segments are inundated by some storm events (typically only the Regional event). These road segments include Highway 401, Highway 7, Highway 407, and Highway 401 Ramps. The sources of AADT values for these road segments are described in detail as follows:

Provincial Highway 401/7 2016 AADT

The Ontario Ministry of Transportation (MTO) published AADT data on most highway segments managed by MTO for 2016 (website: https://www.library.mto.gov.on.ca/SydneyPLUS/TechPubs/Portal/tp/tvOnDemand.aspx?lang=en-US).

FIGURE 2-3 SCREENSHOT OF MTO PUBLISHED HWY 401/HWY 7 AADT VALUES AT LOCATIONS WITHIN DURHAM REGION

TABLE 2-2 HIGHWAY 401 2020 AADT BASED ON MTO 2016 AADT WITH ANNUAL GROWTH RATE OF 1.5%

Highway	Location From	Location To	2016 AADT	2020 AADT
401	HWY12 IC-410-Brock ST-WHITBY	SALEM RD IC 404	166,900	177,142
401	SALEM RD IC 404	WESTNEY RD IC 401	202,800	215,245
401	WESTNEY RD IC 401	BROCK RD IC-399-REG RD 1-PICKERING	210,000	222,886
401	BROCK RD IC-399-REG RD 1-PICKERING	LIVERPOOL RD IC-397-REG RD 29-PICKERING	223,000	236,684
401	LIVERPOOL RD IC-397-REG RD 29-PICKERING	WHITE RD IC-394-REG RD 38-PICKERING	230,000	244,114
401	WHITE RD IC-394-REG RD 38-PICKERING	401-HWY 2 KINGSTON RD IC 392	226,000	239,868
401	S JCT HWY 12 (BROOKLIN)	DURHAM RD 1-BROCK RD	21,900	23,244
401	DURHAM RD 1-BROCK RD	0.985 KM W OF YORK RD 30	8,550	9,075

 shows an excerpt of MTO's published AADT table, in which the AADT values for highlighted highway segments were used for this study.

Since the MTO published AADT values were for 2016, a growth factor was applied to reflect 2020 traffic patterns. As per Region'sstaff suggestion, an annual growth rate of 1.5% was applied to Highway 401 values. This annual growth rate is based on a 10-year traffic history. The final AADTs for Highway 401 for year of 2020 were calculated using following formula:

$$MTO\ 2016\ AADT * (1 + 1.5\%)^n \text{ where n = 4 (i.e. 2017, 2018, 2019 and 2020)}$$

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Highway	Location Description From	Location Description To	Dist. (KM)	2016 AADT
401	BENNETT RD IC-435-NEWCASTLE	LIBERTY ST IC 432-REG RD 14-BOWMANVILLE	2.5	82,400
401	LIBERTY ST IC 432-REG RD 14-BOWMANVILLE	WAVERLEY RD IC-431-NEWCASTLE	1.2	85,600
401	WAVERLEY RD IC-431-NEWCASTLE	HOLT RD IC-428-NEWCASTLE	2.9	89,600
401	HOLT RD IC-428-NEWCASTLE	COURTICE RD IC-425-REG RD 34-NEWCASTLE	3.2	98,000
401	COURTICE RD IC-425-REG RD 34-NEWCASTLE	BLOOR ST/HARMONY RD IC-419-REG RD 33	5.5	98,500
401	BLOOR ST/HARMONY RD IC-419-REG RD 33	RITSON RD IC-418-REG RD 16-OSHAWA	1.4	124,200
401	RITSON RD IC-418-REG RD 16-OSHAWA	SIMCOE ST IC-417-REG RD 2-OSHAWA	0.8	128,700
401	SIMCOE ST IC-417-REG RD 2-OSHAWA	STEVENSON RD IC-415-OSHAWA	1.6	134,200
401	STEVENSON RD IC-415-OSHAWA	THICKSON RD IC-412-REG RD 26-WHITBY	2.4	129,100
401	THICKSON RD IC-412-REG RD 26-WHITBY	HWY 12 IC-410-BROCK ST-WHITBY	2.5	151,200
401	HWY 12 IC-410-BROCK ST-WHITBY	SALEM RD IC 404	6.2	166,900
401	SALEM RD IC 404	WESTNEY RD IC 401	2.2	202,800
401	WESTNEY RD IC 401	BROCK RD IC-399-REG RD 1-PICKERING	2.6	210,000
401	BROCK RD IC-399-REG RD 1-PICKERING	LIVERPOOL RD IC-397-REG RD 29-PICKERING	1.7	223,000
401	LIVERPOOL RD IC-397-REG RD 29-PICKERING	WHITES RD IC-394-REG RD 38-PICKERING	2.5	230,000
401	WHITES RD IC-394-REG RD 38-PICKERING	401-HWY 2 KINGSTON RD IC 392	3.7	226,000

Highway	Location Description From	Location Description To	Dist. (KM)	2016 AADT
7	PEACE AV(N) OLD MILL RD(S)	KAWARTHA LAKES RD 36(N) GOLDEN MILE RD(S)	7.0	8,850
7	KAWARTHA LAKES RD 36(N) GOLDEN MILE RD(S)	HWY 35 E JCT(S) KAWARTHA LAKES RD 15(N)-LINDSAY ST. S.(N)	1.5	14,000
7	HWY 35 E JCT(S) KAWARTHA LAKES RD 15(N)-LINDSAY ST. S.(N)	KAWARTHA LK RD4-LIT BRITAIN (S) ANGELINE ST(N	1.3	14,000
7	KAWARTHA LK RD4-LIT BRITAIN (S) ANGELINE ST(N	W JCT HWY 35(N) DEW DROP INN RD(S)	4.0	7,400
7	W JCT HWY 35(N) DEW DROP INN RD(S)	ELGIN ST(N)	8.6	9,100
7	ELGIN ST(N)	FINGERBOARD RD(S) KAWARTHA LK RD 46(N)	6.2	6,750
7	FINGERBOARD RD(S) KAWARTHA LK RD 46(N)	DUR RD2-SIMC ST(S)-KAWARTHA LK RD2-SIMC ST(N)	3.0	3,800
7	DUR RD2-SIMC ST(S)-KAWARTHA LK RD2-SIMC ST(N)	N JCT HWY 12	7.0	4,000
7	N JCT HWY 12	RIVER ST. (W)	2.8	9,100
7	RIVER ST. (W)	ALBERT ST(W)	1.1	6,400
7	ALBERT ST(W)	DURHAM RD 6(E)14TH LINE (W)	7.9	7,250
7	DURHAM RD 6(E)14TH LINE (W)	HWY 47	5.7	7,400
7	HWY 47	DURHAM RD 8 / REACH ROAD	4.2	7,550
7	DURHAM RD 8 / REACH ROAD	HWY 7A(E)DURHAM RD 21(W)MANCHESTER	2.8	8,300
7	HWY 7A(E)DURHAM RD 21(W)MANCHESTER	DURHAM RD 26(E)THICKSON RD	10.0	13,000
7	DURHAM RD 26(E)THICKSON RD	S JCT HWY 12(BROOKLIN)	4.0	12,200
7	S JCT HWY 12(BROOKLIN)	DURHAM RD 1-BROCK RD	12.6	21,900
7	DURHAM RD 1-BROCK RD	0.985 KM W OF YORK RD 30	7.8	8,550

FIGURE 2-3 SCREENSHOT OF MTO PUBLISHED HWY 401/HWY 7 AADT VALUES AT LOCATIONS WITHIN DURHAM REGION

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Provincial Highway 407 AADT

The Highway 407 ETR website only publishes overall average daily trips for the years of 2012 to date; (Table 2-3), there are no published average daily values at a specific location. The average daily trips from 2012 to 2019 were **332,244**. TRCA staff believe this average value would over-estimate AADT on Highway 407 segments within Durham Region as

areas within Durham Region along Highway 407 are mostly rural areas with much less population comparedcomparing to areas along Highway 407 within York Region. TRCA provided this average daily trip count to the Region and expressed the concern that this value does not reflect traffic conditions on Highway 407 segments within Durham Region.

The Region agreed that the average daily trips reported by 407 ETR are too high to be representative for Highway 407 in Durham, as these numbers are comparable to some of the higher volume sections of Highway 401 in Toronto and would not be possible given the current 407 configurations in Durham Region. Instead, theThe Region obtainedprovided MTO spring 2018 ATR counts on Highway 407 that showed the Average Daily Traffic to be about 26,000 between Brock Road and Lake Ridge Road (east of Brock Road).

All inundated Hwy 407 segments within the study area are west of Brock Road. In the Region's travel demand forecasting model, the Region compared 407 ETR volume west of Brock Road vs. Highway 407 volume east of Brock Road from the Region's travel demand forecasting model, and the ratio is about 1.5. This ratio was applied to the estimated AADT for Highway 407 east of Brock Road (i.e. 26,000), resulting in an estimated AADT for the 407 ETR west of Brock Roadof about 39,000. Since the calculation is based on the 2018 ATR counts, the Region suggested applying same annual growth rate that was used for Highway 401 (i.e. 1.5%) to get 2020 AADT values (i.e. 40,179), which is calculated using following formula:

$$MTO\ 2018\ AADT * (1 + 1.5\%)^n \text{ where n = 2 (i.e. 2019 and 2020)}$$

$$\text{i.e. } 39000, * (1 + 1.5\%)^2 = 40,179$$

TABLE 2-3 HWY 407 USAGE STATISTICS – AVERAGE DAILY TRIPS

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
2012	279,700	284,101	292,682	299,319	331,808	343,679	320,297	332,407	326,364	336,796	341,023	275,500	313,640
2013	284,168	281,856	281,121	310,001	332,537	333,548	332,618	331,367	333,986	341,569	329,464	282,288	314,544
2014	288,940	291,276	289,648	315,078	339,632	349,688	340,035	331,506	352,132	353,263	331,038	301,202	323,620
2015	284,806	295,683	306,094	329,092	341,010	368,101	354,514	340,615	359,005	352,080	346,669	307,455	332,094
2016	283,462	298,250	301,774	335,355	352,337	383,430	351,819	366,303	375,788	356,898	366,376	310,924	340,226
2017	290,706	306,572	320,843	327,483	359,765	386,599	353,624	370,244	368,504	368,027	368,829	311,366	344,380
2018	304,499	313,144	314,536	330,481	373,086	385,576	362,369	370,927	359,576	373,501	371,766	302,204	346,805
2019	297,444	297,828	312,973	336,692	360,195	372,373	371,024	367,847	363,132	375,351	355,892	300,936	342,641

Highway 401 Ramp AADT Data

In the study area, there are three Highway 401 ramp segments that intersect with regulatory floodlines, and their AADT values are listed in Table 2-4 as estimated by Durham Region:

TABLE 2-4 HIGHWAY 401 RAMP AADT

Ramp Location	AADT
Hwy 401 Eastbound at Westney Rd	19,000
Hwy 401 Westbound at Westney Rd	11,000
Hwy 401 West collector at Kingston Rd	9,000

3   METHODOLOGY

The following sections outline the steps taken to build the road segment and crossing geodatabases, to extract the hydraulic model information and populate the relevant attributes, to compare the hydraulic performance of the culverts to MTO criteria, and to step through the process of moving from flood depth to event-based disruption caused by the flood event, to Average Annualized Disruption.

3.1   Flow Charts of Construction of Geodatabase

As described earlier, geodatabases were constructed for the flood vulnerable road segments and for the crossings. Flowcharts were created to develop and to illustrate the workflow of building each of these two geodatabases, as outlined in Figure 3-1 and Figure 3-2. Each flowchart briefly describes the steps and tools used to extract and process the data. The major software tools used for this study are: HEC-RAS (including RAS Mapper), GeoHEC RAS for model results preparation and extraction, Excel spreadsheets, and ESRI ArcGIS for data pre- and post-processing.

The sections following the flowcharts describe the steps of the process for constructing the crossings and road segment geodatabases in more detail.
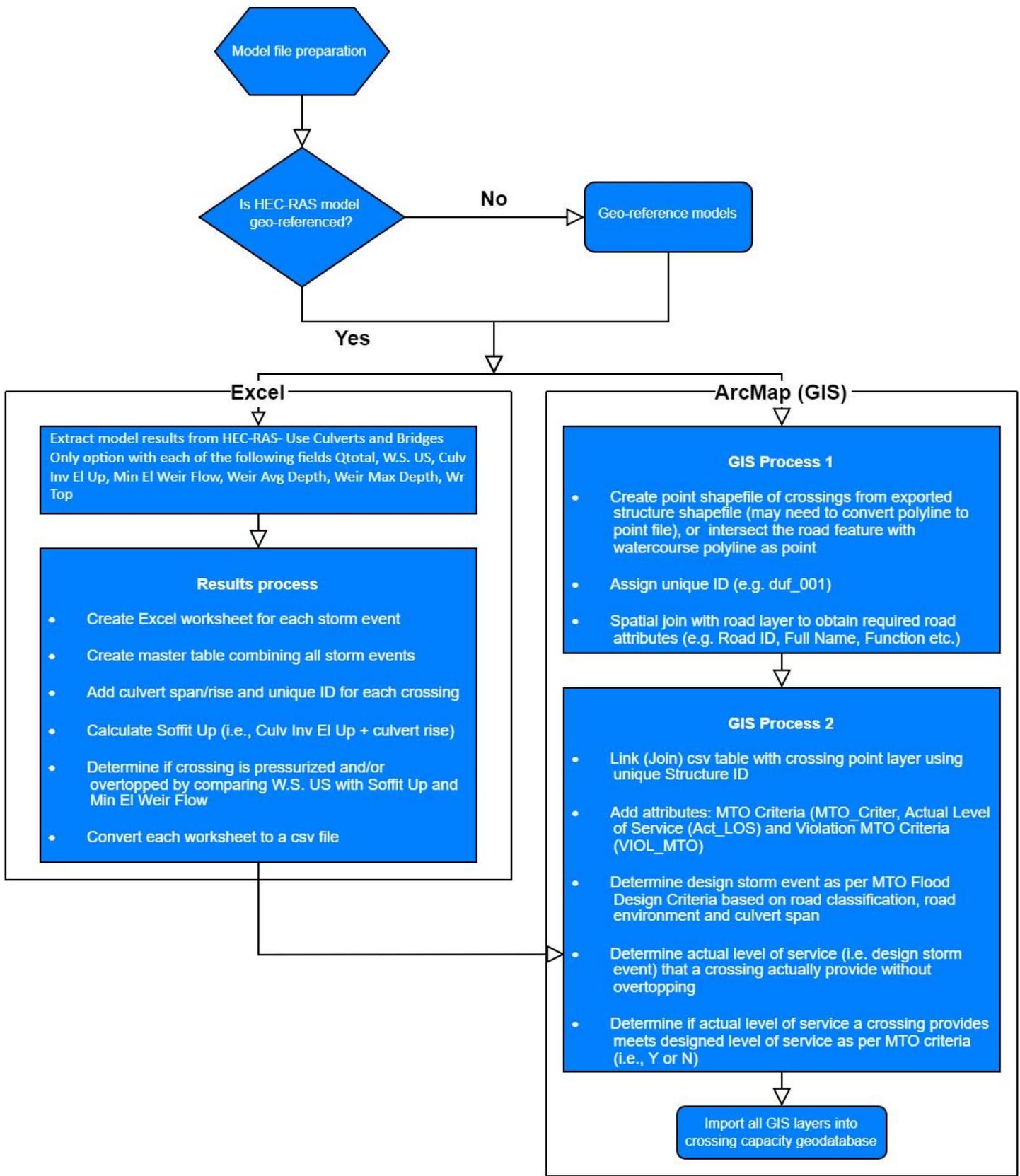
FIGURE 3-1 FLOW CHART- WORKFLOW FOR CREATING THE CROSSINGS DATABASE
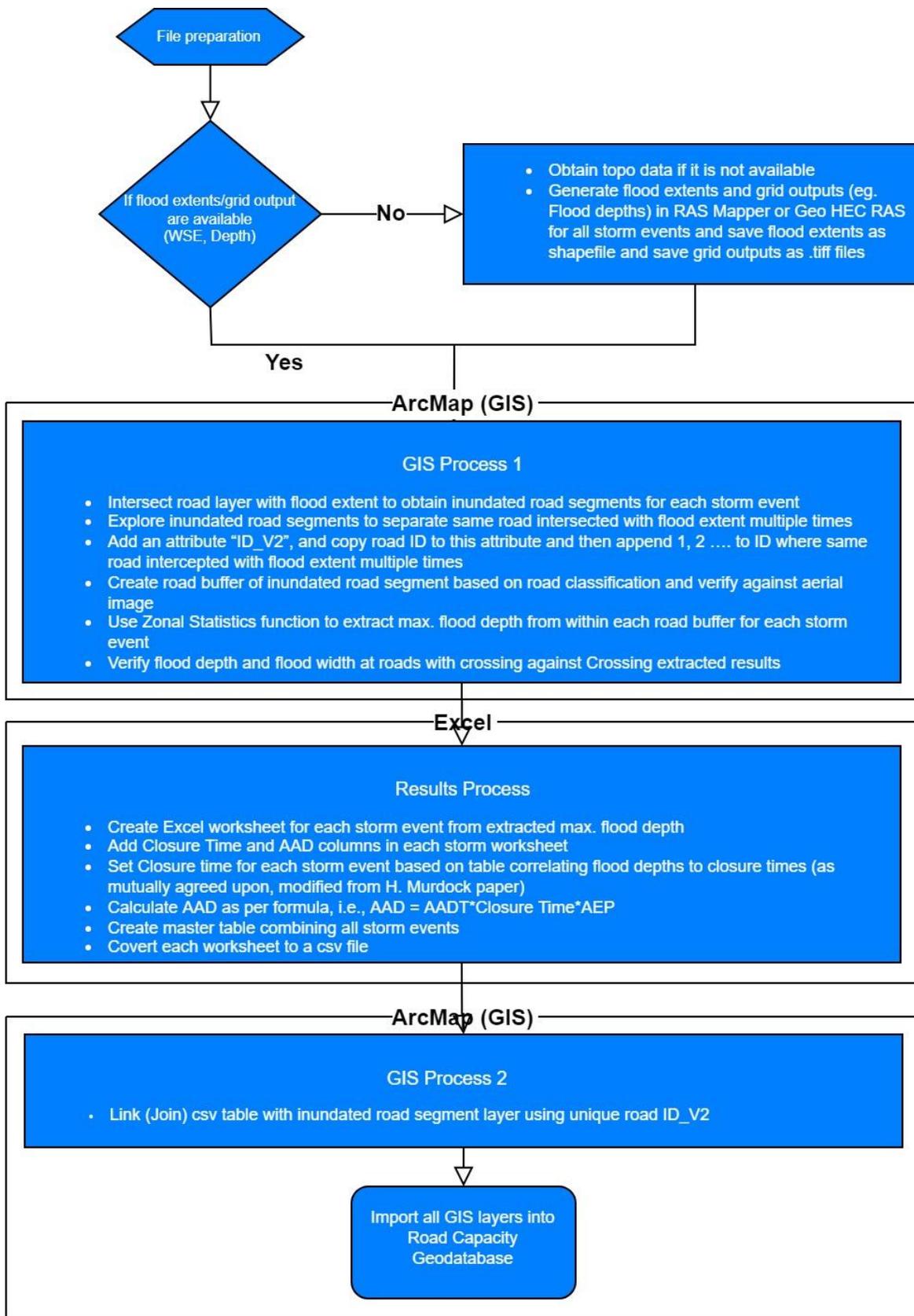
FIGURE 3-2 FLOW CHART - WORKFLOW FOR CREATING THE ROAD CAPACITY GEODATABASE

3.2 File Preparation for Data Extraction

As mentioned in Section 2.1, some of the hydraulic models were recently updated with current information, i.e., the Carruthers Creek and Duffins Creek models. These models are geo-referenced, so for these two watersheds, models and GIS outputs could be used directly, eliminating the need to do file preparation for data extraction. The Petticoat Creek and Frenchman's Bay hydraulic models, by contrast, were done 10-15 years ago, and topographic data used to build these models is not available for this study. The Petticoat Creek model was geo-referenced, but the Frenchman's Bay models (one for each of the subwatersheds: Amberlea, Dunbarton, Krosno, and Pine Creek) were not geo-referenced. Because the original topographic base data was not available for these models, the most recent 1-m LiDAR data (2015) was used for generating the grid outputs, such as the Water Surface Elevation (WSE) and depth of flow from the tabular HEC-RAS model results.

Because the Frenchman's Bay hydraulic models were not geo-referenced, in order to generate gridded outputs of WSE and flow depth, either the models themselves, or the results files, needed to be geo-referenced. Although several attempts were made and effort expended to geo-reference the models, it was finally determined that they were too old and lacked sufficient data for geo-referencing. Instead, staff developed a new approach to generate geo-referenced grid outputs detailed as follows:

1. Because the final flood plain mapsheets are geo-referenced, the cross-sections were extracted from the Auto-CAD file formats of the mapsheets, and converted into a polyline shapefile with the cross-section river station labels corresponding to the existing HEC-RAS river stations.
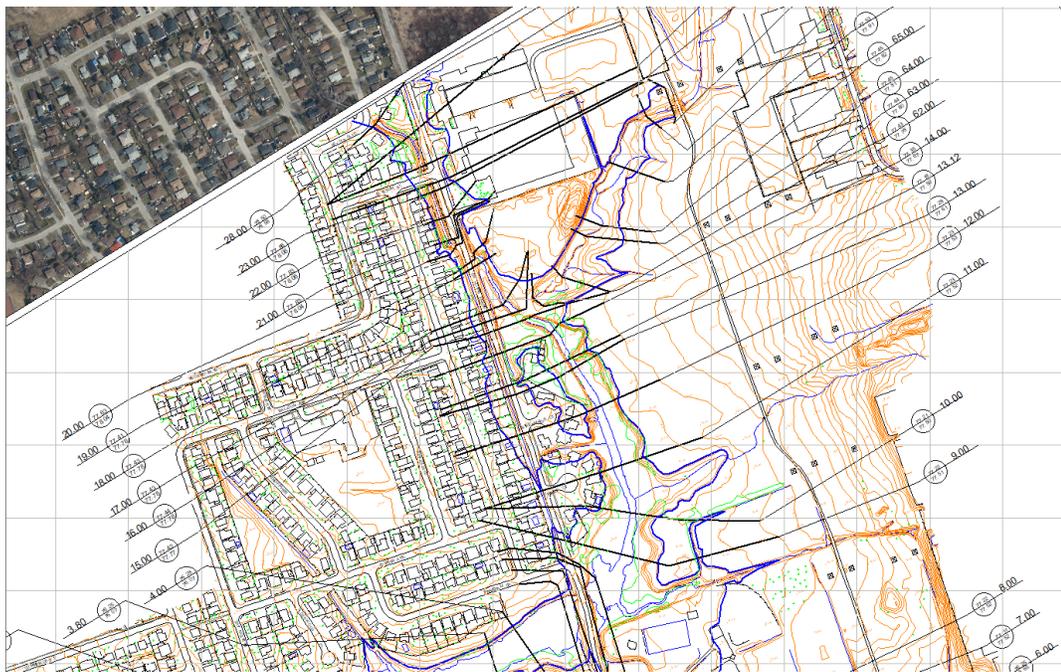
FIGURE 3-3 EXAMPLE OF FRENCHMAN'S BAY MAP SHEETS

2. The computed WSEs were assigned for all storm events from existing HEC-RAS models to each cross-section obtained from Step 1.
3. With the Geo HECRAS Generate Terrain function, a WSE surface was generated for each storm based on a linear interpolation approach using WSE values on each cross-section; or the cross-sections were converted in ArcGIS to a point shapefile with an attribute of WSE, and then one of the interpolation methods (IDW or Natural Neighbor) under Spatial Analyst was used to generate a WSE surface.

4. In ArcGIS, the flood depth surface was calculated for each of the storms by subtracting the WSE surface obtained from Step 2 from the 2015 LiDAR, and then setting cells with values =< 0 to Null.
5. The final flood depth surface was converted to a flood extent polygon for each of the storms.
6. The flood extent polygon was cleaned up to remove off-line ponded areas and holes, and then the flood depth was clipped clip flood depth using the regulatory flood extent polygon in ArcGIS.

For Petticoat Creek, since the hydraulic model is geo-referenced, the inundation extents could be calculated directly in either traditional HEC-RAS or Geo HEC-RAS; the steps are summarized below using traditional HEC-RAS:

1. WSEs for all storm events were computed in HEC-RAS

2. In RAS Mapper, a new terrain model was generated from 1-m 2015 LiDAR

3. All relevant outputs were computed for all storm events including Inundation Boundary, Water Surface Elevation, Velocity and Depth Raster based on Terrain as shown in Figure 3-4.
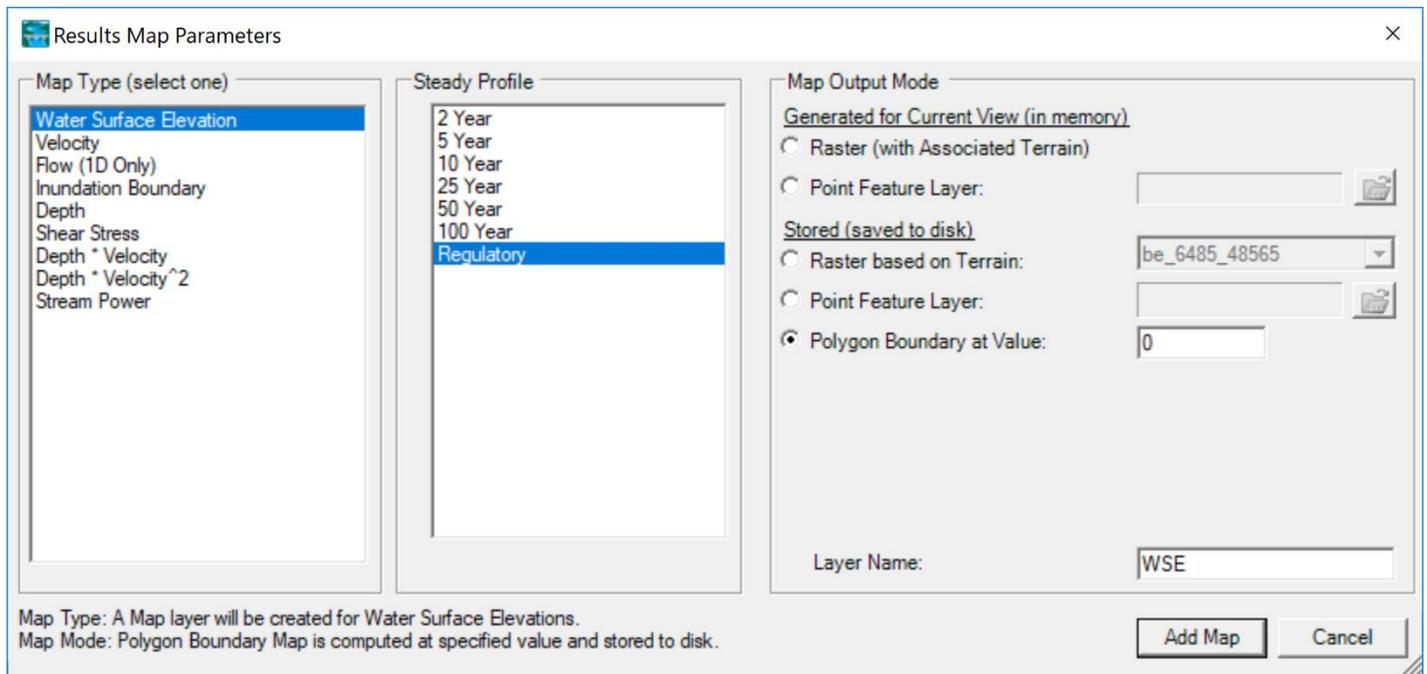
FIGURE 3-4 RESULTS MAP PARAMETERS PAGE IN RAS MAPPER.

4. The flood extent polygon was cleaned up and raster outputs to remove off-line ponded areas and holes.

3.3 Data Extraction and Processing

For this study, data extraction was required for watercourse crossings which are modeled in the existing TRCA HEC-RAS models, and also for roads that are inundated by all storm events (i.e. Regional, 2- year to 100-year events). The following sections detail the approach that TRCA took to extract and process the model results to be utilized in the crossing and road segment geodatabases.

3.3.1 Crossings Data Extraction and Processing

3.3.1.1 Crossings Data Extraction

HEC-RAS generates several detailed outputs at each modelled crossing for all storm events, with the available fields depending on the type of crossing (i.e. bridge or culvert). Table 3-1 lists the detailed output fields relevant to the study, and Figure 3-5 and Figure 3-6 show examples of typical HEC-RAS outputs for a culvert and bridge, respectively.

TABLE 3-1 LIST OF HEC-RAS OUTPUT FIELDS RELEVANT TO THE STUDY

Output Fields	Description	Note
Q Total	Total flow in a cross-section	Total flow in a cross-section immediately upstream of a crossing. It is not used for crossing capacity analysis but displayed to show peak flowrate for each storm event at each modelled crossing in a sub-table for the corresponding event.
W.S.US	Upstream water surface elevation upstream of bridge, culvert or weir	It is used for crossing capacity analysis, and it is also included in a sub-table for the corresponding event.
Min El Weir Flow	Elevation where weir flow begins	It is used for crossing capacity analysis.
Weir Avg Depth	Average depth over the weir	Average depth of flow over the road deck when road deck is overtopped. Empty in the HEC RAS output table means road deck is not overtopped. It is not used for crossing capacity analysis as Weir Max Depth is used for the analysis, but it is included in a sub-table for corresponding event.
Weir Max Depth	Max depth over the weir	Max. depth of flow over the road deck when road deck is overtopped. Empty in the HEC RAS output table means road deck is not overtopped. It is used for crossing capacity analysis and included in the final master database as Max. depth of flow flooded by corresponding storm events. And it is also included in a sub-table for the corresponding event.
Wr Top Width	Total width of water over the weir	Total width of water over the road deck when road deck is overtopped. Empty in the HEC RAS output table means road deck is not overtopped. It is used for crossing capacity analysis and included in the final master database as Road segment length flooded by the corresponding storm events.
Cul Vel US	Velocity in culvert at defined upstream	Velocity in entrance of culvert It is not used for crossing capacity analysis but included in a sub-table for the corresponding event as per request from Durham Region.
BR Open Vel	Average velocity inside the bridge opening	It is not used for crossing capacity analysis but included in a sub-table for the corresponding event as per request from Durham Region.

FIGURE 3-5 EXAMPLE OF TYPICAL HEC-RAS OUTPUT FOR A CULVERT

FIGURE 3-6 EXAMPLE OF TYPICAL HEC-RAS OUTPUT FOR A BRIDGE

3.3.1.2   Crossings Data Processing

Post-processing of extracted results is carried out in an Excel spreadsheet, with a worksheet created for each storm with identical information.

Flood Vulnerable Road and Culvert Hydraulic Capacity Assessment

Table 3-2 shows an example worksheet for the regional storm in the Carruthers Creek watershed.

TABLE 3-2 EXAMPLE OF WORKSHEET USED FOR ANALYSIS

Stru_ ID	River	Reach	River Sta.	Profile	Q Total	W.S. (US)	Min Elv. Weir Flow	Cul. Invert El. (US*)	Cul. Rise	Cul. Span	Soffit El. (US)	Press-urized ?	Overt OT*?	Weir Avg. Depth	Weir Max Depth	Weir Top Width	Cul.Culv. Vel. (US*)
					(m³/s)	(m)	(m)	(m)	(m)	(m)	(m)	Y/N	Y/N	(m)	(m)	(m)	(m/s)
CAR_03	West Carruthers	Reach 2	2812 Culv. #2	Regional	10.21	168.95	168.85	167.2	1.75	3.5	168.95	Y	Y	0.08	0.14	51.67	2.96
CAR_06	West Carruthers	Reach 1	6078 Culv. #1	Regional	24.53	149.18	150.12	147.45	1.43	4	148.88	Y	N	0	0	0	2.47
CAR_18	West Carruthers	Reach 1	3550 Culv. #1	Regional	31.06	139.32	139.19	136.28	1.55	4.86	137.83	Y	Y	0.1	0.16	111.18	3.36

*US = upstream; OT = Overtopped

In the above example worksheet, a few items were added in addition to HEC-RAS extracted results, and these items are explained as follows:

- Cul. Inv El. US: invert elevation of the entrance of a crossing

- Cul. Rise: opening height of a crossing

- Cul. Span: opening width of a crossing, and it is used as one of conditions to assign MTO flood criteria along with road function and road environment.

- Soffit El. US: upstream soffit elevation - the top of opening elevation (i.e., invert of culvert entrance + culvert rise)

- Pressurized ? (Y/N): when water level upstream of a crossing is equal to or higher than top of opening elevation, a crossing is under pressure (i.e., Y); otherwise, it is set to N.

- Overt OT (Overt overtopped): when water level upstream of a crossing is higher than minimum deck elevation, a crossing is overtopped (i.e., Y); otherwise, it is set to N (under this condition values in Weir Avg. depth/Weir Max. depth/Wr Top Width should be 0).

Flood Vulnerable Road and Culvert Hydraulic Capacity Assessment

Once data is processed in Excel for all modelled crossings, it is joined with a crossing point shapefile based on a unique TRCA structure ID field, and then the crossing point shapefile is spatially joined with the road layer to associate each crossing with a road feature. As outlined in the scope of work for this study, railway crossings and any pedestrian/driveway crossings that are not part of the GIS road layer were not included in the analysis.

FOLLOWING THE DATA PROCESSING DESCRIBED ABOVE, THE GEODATABASE REPORTS IF A CROSSING IS OVERTOPPED OR NOT FOR A GIVEN STORM EVENT, AND WHICH OF THE MODELLED STORM EVENTS THE CROSSING BEGINS TO OVERTOP FOR. THE GEODATABASE CAN ALSO BE USED TO DETERMINE IF A GIVEN CROSSING PROVIDES THE CORRESPONDING LEVEL OF SERVICE AS PER THE MTO DESIGN FLOOD CRITERIA (HTTP://WWW.MTO.GOV.ON.CA/ENGLISH/PUBLICATIONS/PDFS/DRAINAGE/MINISTRY-DIRECTIVE-B100.PDF) AS SHOWN IN

Table 3-3. The MTO Design Flood Criteria for Bridges and Culverts are based on two criteria, i.e., road classification and crossing span, and the road classification also includes road environment, i.e., Rural or Urban. Durham Region provided further road classification guidance to tie the Durham Region Road Functional Class to the categories in the MTO Design Flood Criteria (see Table 3-4).

In GIS, the following three attributes were added in the crossing geo-database for each watershed:

MTO_CRITER: LEVEL OF SERVICE A CROSSING IS SUPPOSED TO PROVIDE AS PER MTO DESIGN FLOOD CRITERIA (

- Table 3-3) based on Road Classification, Road Environment and Total Span.

- Act_LOS: Actual level of service a crossing provides, i.e., max. design storm at which a crossing is not overtopped.

- VIOL_MTO: A Yes/No field that indicates if the actual level of service of a crossing meets the MTO criteria. If Y, then the Act_LOS is smaller than MTO_Criter. If N, then the Act_LOS is equal to or larger than MTO_Criter.

TABLE 3-3 MTO DESIGN FLOOD CRITERIA, HIGHWAY DRAINAGE DESIGN STANDARDS, JANUARY 2008

Design Flow Return Period for Bridges and Culverts – Standard Road Classifications			
Functional Road Classification	Return Period of Design Flows (Years) [1,2,3]		Check Flow for Scour
	Total Span less than or equal to 6.0 m	Total Span greater than 6.0 m	
Freeway, Urban Arterial	50	100	130% of 100 year
Rural Arterial, Collector Road	25	50	115% of 100 year
Local Road	10	25	100% of 100 year

[1]The listed design flows apply to roads under the jurisdiction of the Ministry of Transportation.

[2]The Fish Passage Design Flow for culverts is defined in Standard WC-12 Fish Passage Requirement Through Culverts

[3]Sometimes referred to as Normal Design Flow

TABLE 3-4 DURHAM REGION SUGGESTED ROAD CLASSIFICATION USED FOR DESIGN FLOOD CRITERIA

MTO Road Classification	Durham Road Functional Class
Freeway, Urban Arterial	Regional Urban Arterials (all types) shall be assessed for this road classification. Region does not have any freeways.
Rural Arterial, Collector Road	Regional Rural Arterials (all types) shall be assessed for this road classification
Local Road	Local Roads fall under the jurisdiction of Local Area Municipalities

For assigning values for the MTO criteria (MTO_Criter), Actual level of services (Act_LOS) and violation of MTO criteria (VIOL_MTO) fields, TRCA developed Visual Basic (VB) scripts within the ArcGIS Field Calculator. The VB scripts are provided in Appendix E. VB script for assigning values to MTO_Criter, Act_LOS, and VIOL_MTO fields. For comparing actual level of service (Act_LOS) with MTO criteria (MTO_Criter) within the VB script, return periods in both MTO_Criter and Act_LOS were converted to a number (i.e., MTO_NUM and LOS_NUM) as shown in

Table 3-5. Note that arbitrary values were assigned for the Regional and <2 year storms. Thereafter, the 'Y – Not meet MTO criteria' or 'N – Meet MTO criteria' values were assigned using the VB script.

TABLE 3-5 RETURN PERIODS CONVERSION TO NUMBERS

Return Periods	Number
Regional	1,000*
100 year	100
50 year	50
25 year	25
10 year	10
5 year	5
2 year	2
< 2 year	1

*Hurricane Hazel, as an actual historic storm of record, does not have a return period associated with it. The 1,000 year value was assigned in keeping with the assumptions used in TRCA's 2018 Flood Risk Assessment and Ranking study.

Flood Vulnerable Road and Culvert Hydraulic Capacity Assessment

Table 3-6 summarizes the number of crossings that meet or do not meet the MTO criteria. Figure 3-7 through Figure 3-10 illustrate the crossings in each watershed that do meet the MTO criteria in green and those that do not meet MTO criteria in red, for the existing climate condition.

Section 6 illustrates the performance of the crossings against MTO criteria for existing as well as future climate change conditions.

TABLE 3-6 SUMMARY OF NUMBER OF CROSSINGS MEETING OR NOT MEETING MTO CRITERIA – CURRENT CLIMATE SCENARIO

Watersheds	Total Number of Crossings	Number of Crossings that Meet MTO Criteria	Number of Crossings that Do Not Meet MTO Criteria
Frenchman's Bay	33	22	11
Petticoat Creek	25	23	2
Duffins Creek	149	139	10
Carruthers Creek	34	33	1
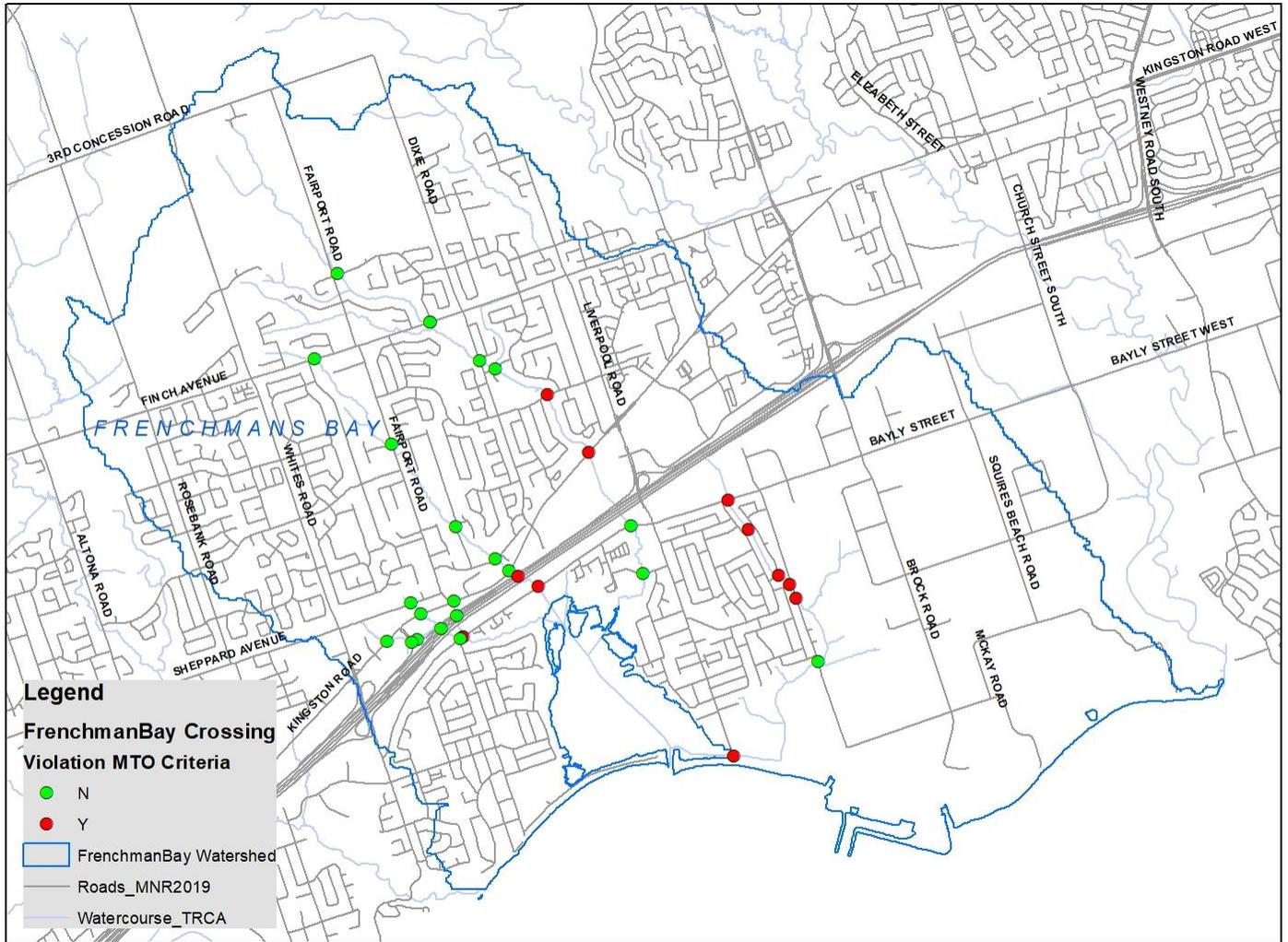
FIGURE 3-7 CROSSINGS IN FRENCHMAN'S BAY WATERSHED FOR EXISTING CLIMATE CONDITION

(N – NOT IN VIOLATION OF MTO CRITERIA, Y –IN VIOLATION OF MTO CRITERIA)
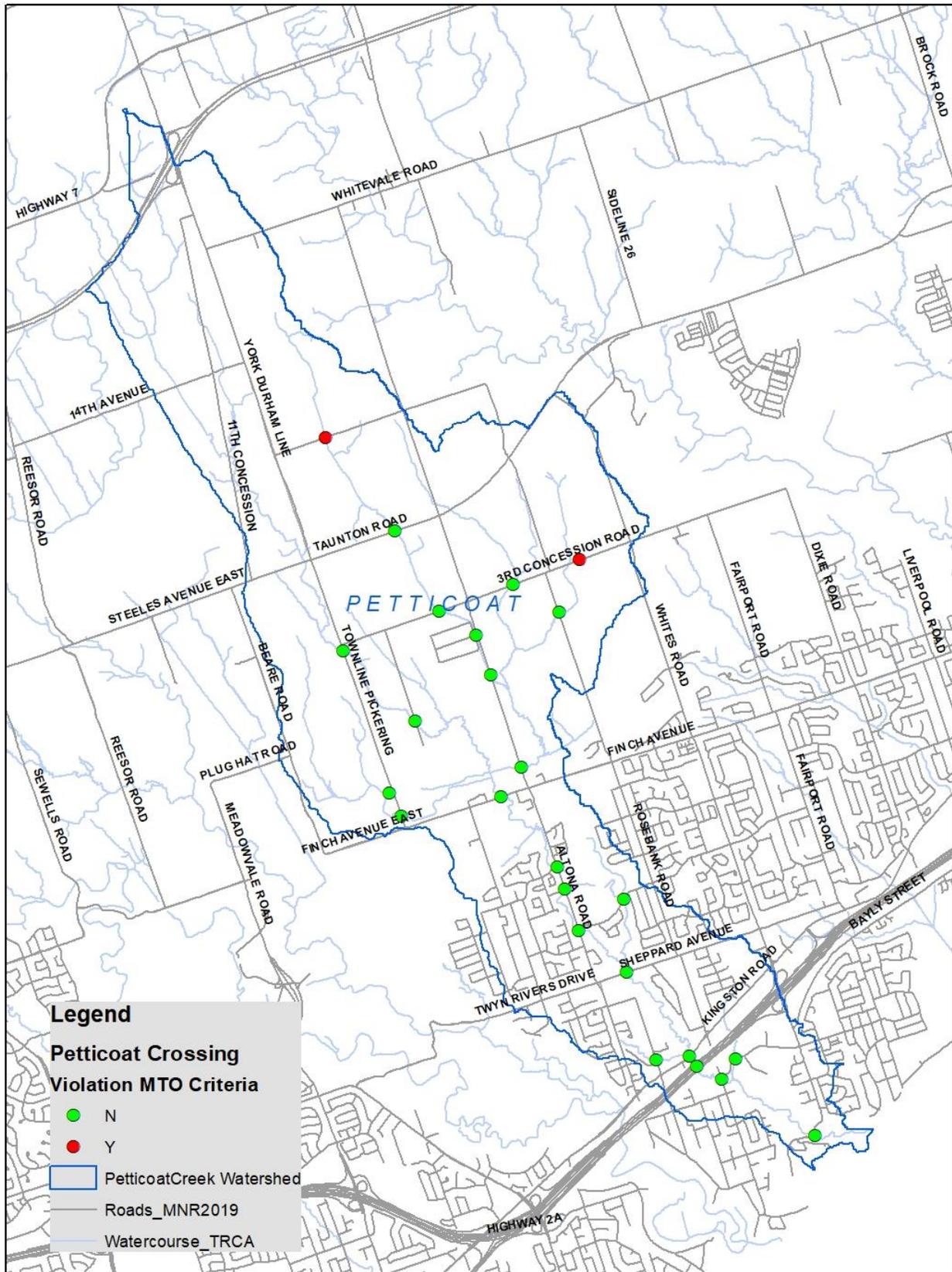
FIGURE 3-8 CROSSINGS IN PETTICOAT CREEK WATERSHED FOR EXISTING CLIMATE CONDITION

(N – NOT IN VIOLATION OF MTO CRITERIA, Y – IN VIOLATION OF MTO CRITERIA)
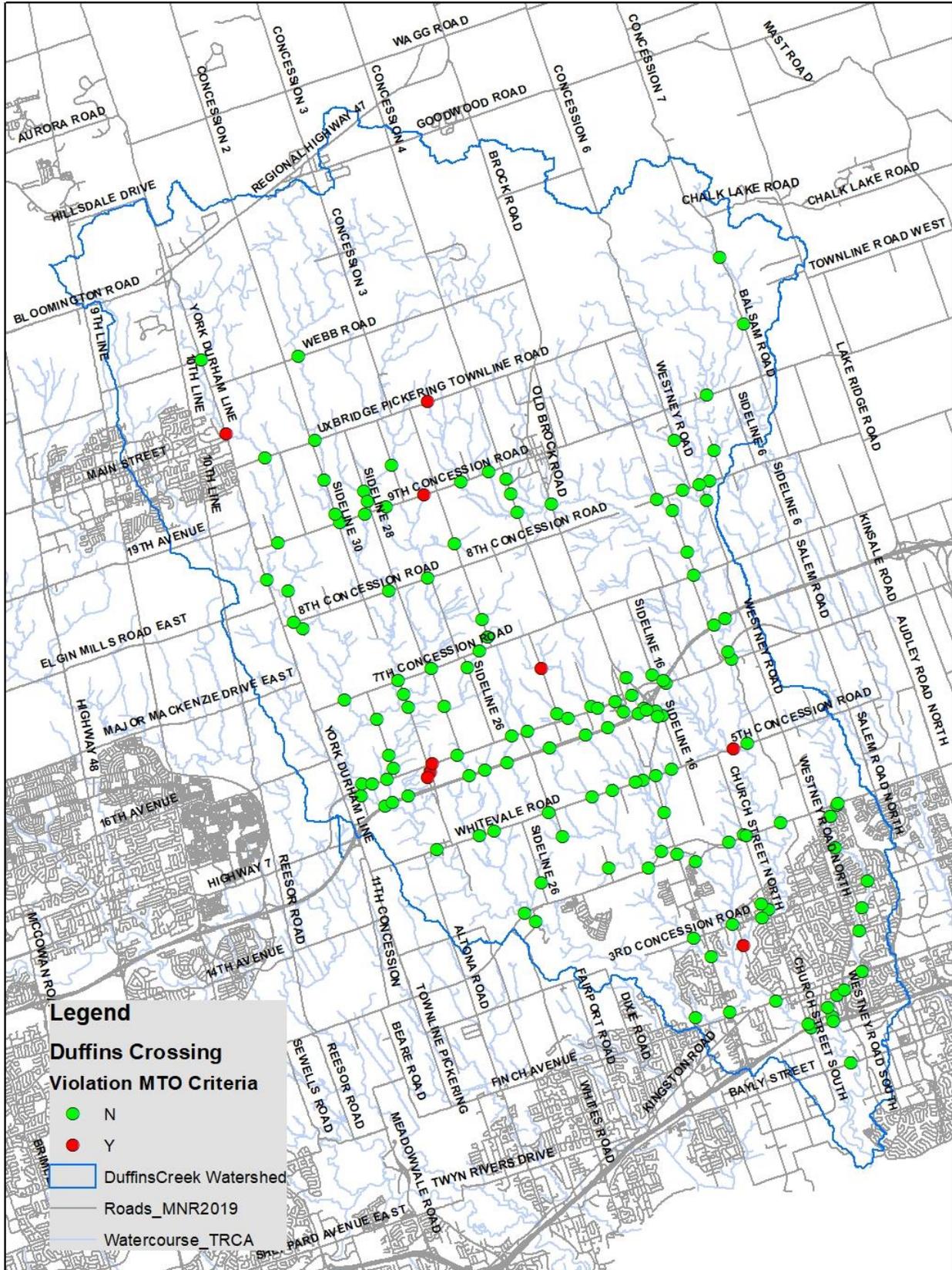
FIGURE 3-9 CROSSINGS IN DUFFINS CREEK WATERSHED FOR EXISTING CLIMATE CONDITION

(N – NOT IN VIOLATION OF MTO CRITERIA, Y – IN VIOLATION OF MTO CRITERIA)
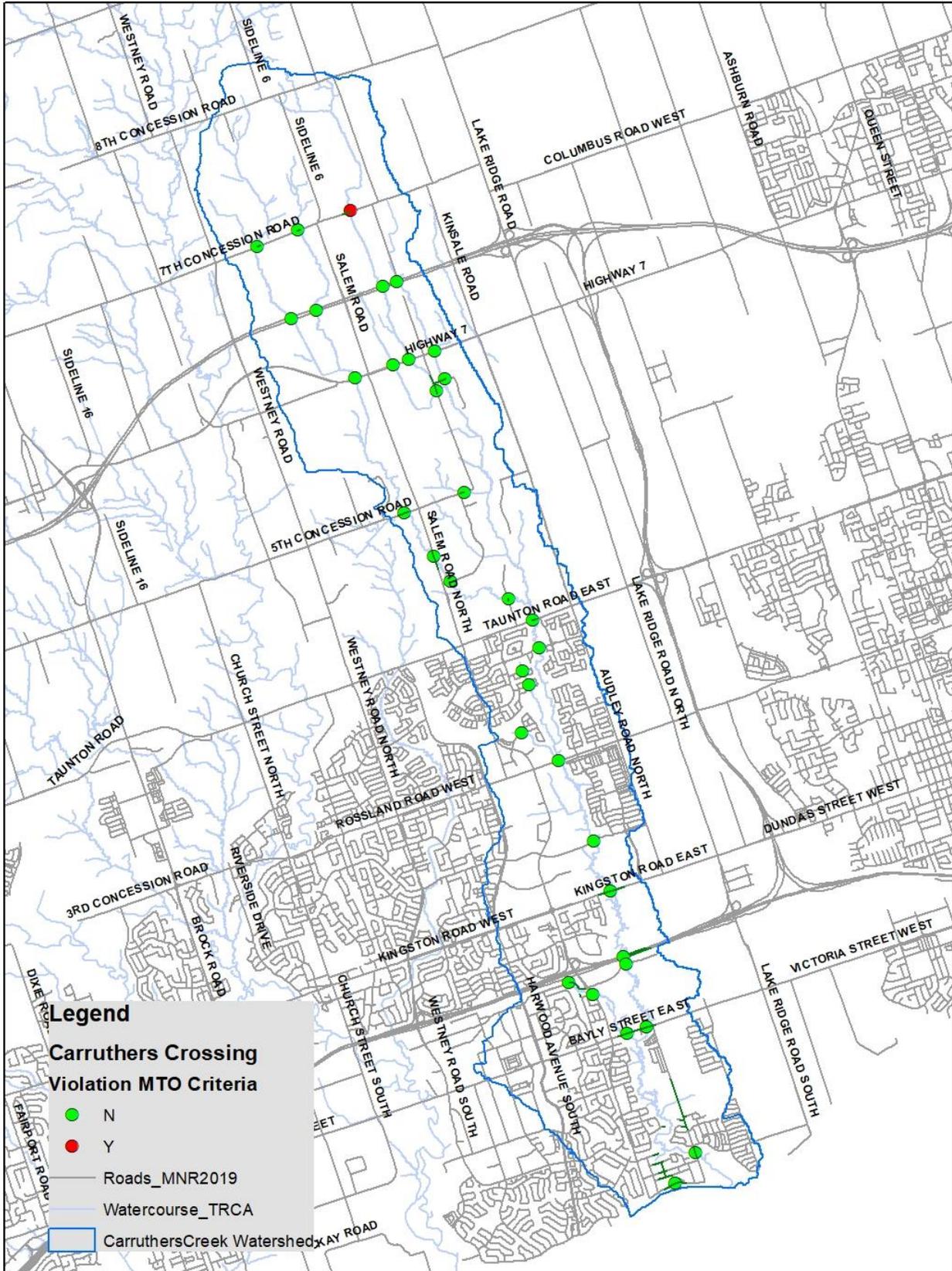
FIGURE 3-10 CROSSINGS IN CARRUTHERS CREEK WATERSHED FOR EXISTING CLIMATE CONDITION

(N – NOT IN VIOLATION OF MTO CRITERIA, Y – IN VIOLATION OF MTO CRITERIA)

3.3.2 Road Segment Data Extraction and Processing

3.3.2.1 Road Segment Data Extraction

As mentioned in Section 3.1, the HEC-RAS model can generate inundation polygons as well as grid outputs (e.g. Water Depth) based on the computed WSEs and underlying terrain. The road segment data extraction process generates the polyline segment that is inundated by each storm event, and the maximum flood depth on the inundated road segment. To get this information, the following steps are carried out in ArcGIS:

1. Intersect the Road Centreline layer (Durham Road Network layer) with TRCA's final flood extent polygon to get inundated road segments, then break out the road segments along the same road that intersect with the flood extent polygon using the Explode function in ArcGIS.

    Figure 3-11 shows an example where different portions of a road intersect with the regulatory flood plain at several locations (shown in red). In this example, four portions of Sideline 30 intersect with the flood plain. Typically, ArcGIS would treat all 4 segments as one polyline feature (i.e. a single record). This would only allow one max. flood depth to be assigned and would assume the total length of these 4 segments to be the inundated road segment, even though each segment may have different flood depths and different lengths of inundation. To allow for each of the segments to be recognized as separate features with their own respective data, the 'Explode' function is used in GIS, which separates all of the component parts into single-part features, copying the feature attributes from the multipart feature to each of the new features. Figure 3-12 shows the attributes of the different portions of road that intersect with the regulatory flood plain after using the 'Explode' function. As depicted in the attribute table in Figure 3-12, each segment is assigned its own corresponding flood depth and inundation length. A new field called ID_V2 is added to differentiate each road segment having the same Road ID and numbering.
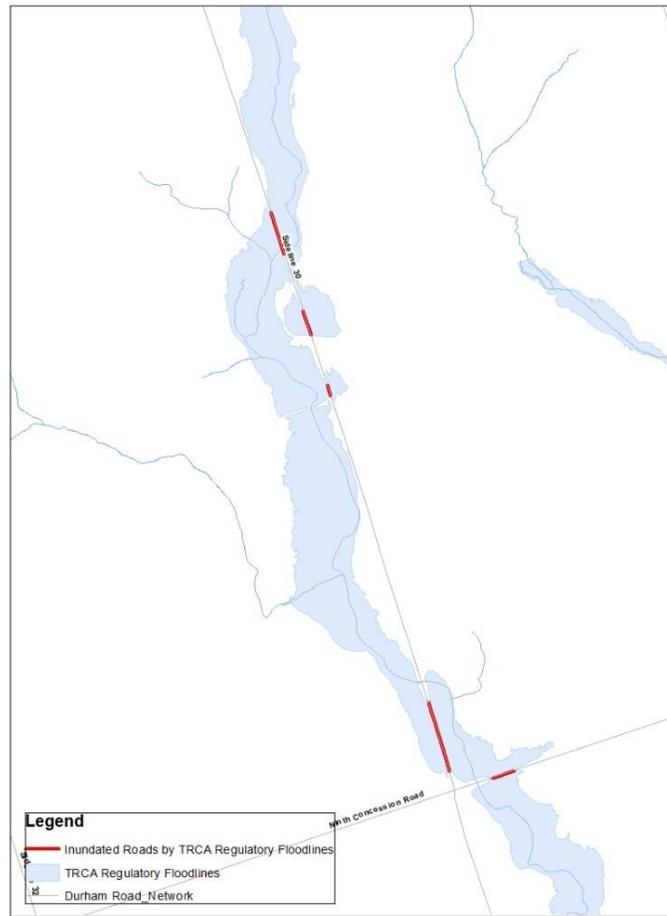
FIGURE 3-11 EXAMPLE OF DIFFERENT PORTIONS OF ROAD INTERSECTING WITH REGULATORY FLOODLINES

Inundated Roads by TRCA Regulatory Floodlines

FUNCTION_	Watershed	ID_V2	JURISDICT	FULL_NAME	Leng_Reg	Dept_Reg
local	Duffins Creek	113795.1	municipal	Sideline 30	82.396275	0.88
local	Duffins Creek	113795.2	municipal	Sideline 30	47.884401	0.37
local	Duffins Creek	113795.3	municipal	Sideline 30	21.574261	0.22
local	Duffins Creek	113795.4	municipal	Sideline 30	135.567134	0.96

FIGURE 3-12 INDIVIDUAL FEATURE ATTRIBUTE FOR DIFFERENT PORTIONS OF ROAD INTERSECTING WITH REGULATORY FLOODLINES

2. Create the road buffer based on the width of the road from curb to curb (or edge to edge of paved surface) and then use the Zonal Statistic function to extract the max. flood depth (from the overlaid hydraulic model results) for each road segment in ArcGIS (see Figure 3-13).

Figure 3-13 shows a screen capture of the Zonal Statistics as a Table page in ArcGIS. For each inundated road segment, a unique Zone field is required. Here, ID_V2 is used as it has the separated road segments from the same single road ID as outlined in the previous step. The Zonal Statistics function extracts statistical values (Min/Max/Mean depth in this case) to a table for each zone (i.e. each road buffer). This step is repeated for each

storm event (2-year-100-year and Regional storm), and then all tables from all events are joined to the master table based on the unique ID_V2 field.
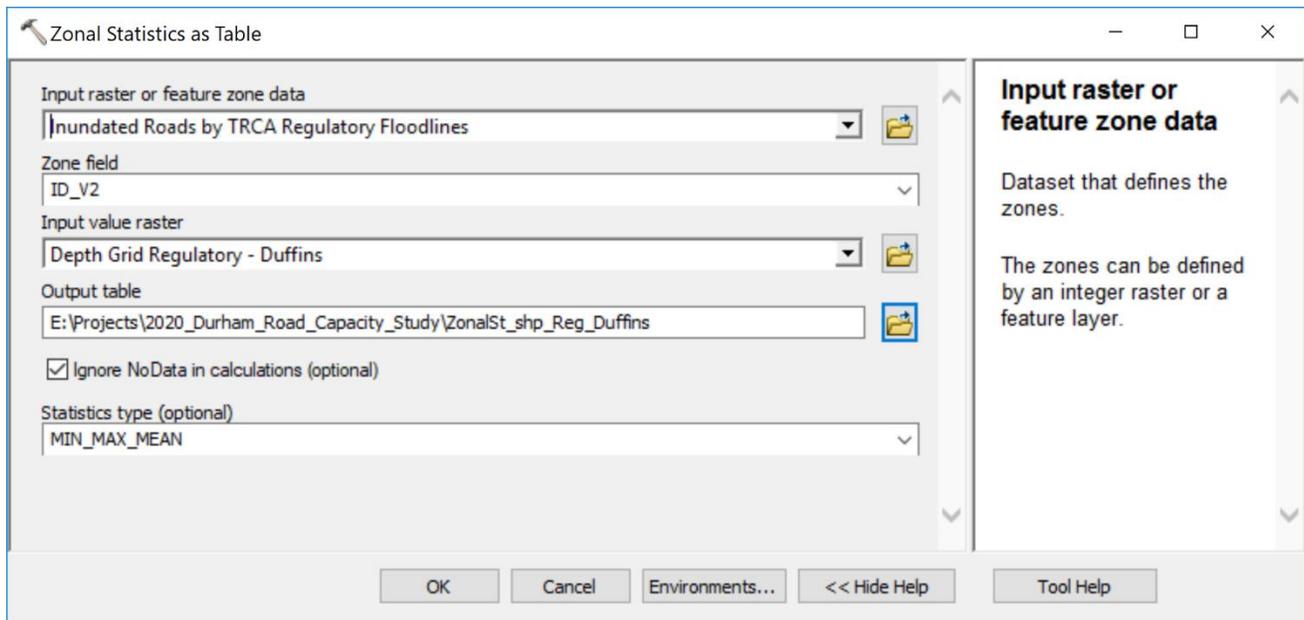
FIGURE 3-13 ZONAL STATISTICS FUNCTION IN ARCGIS FOR EXTRACTING FLOOD DEPTH ON INUNDATED ROAD SEGMENTS

Buffers are required because the maximum flood depth along the road may not necessarily occur along the centreline of the road, and they allow for intersecting the flood depth grids with the applicable road surface for each road segment in order to find the maximum flood depth. Figure 3-14 shows an example of the inundated road segment buffer in a rural environment. This section of Highway 7 runs through a rural area and includes ditches on either side of the road. In this case, the width of road buffer is from edge to edge of paved surface where traffic would occur. If the buffer were overestimated and captured the drainage ditches on either side, the maximum flood depth would erroneously include the depth of water in the ditches, which would not be reflective of the depth of flooding on the paved surfaces.

Figure 3-15 shows an example of the inundated road segment buffer in an urban environment. In an urban environment, a typical road would have curbs on either side of the road, with a mild sloping of the surface towards the curbs for drainage purposes. In this case, the width of the road buffer is from curb to curb including the paved road surface.

FIGURE 3-14 EXAMPLE #1 OF INUNDATED ROAD BUFFER IN DUFFINS CREEK WATERSHED (RURAL ENVIRONMENT)

FIGURE 3-15 EXAMPLE #2 OF INUNDATED ROAD BUFFER IN DUFFINS CREEK WATERSHED (URBAN ENVIRONMENT)

3.4   Average Annualized Disruption Estimation

Where many types of flood risk assessments utilize average annualized damages to assess the impacts of flooding to structures, there can often be impacts to the road network that do not trigger structural damages. Clean up and repair costs can occur with flooding, but understanding the *disruption* caused by flooding is a more useful metric when assessing from a network impact perspective. Annualized Disruption (AD) is the measurement of disruption to traffic caused by a given storm event (e.g. the 100-year design storm), multiplied by its likelihood of occurrence in a given year (1/100, in this case). The disruption is characterized as diverted traffic due to the closure and is measured as the product of the road segment's AADT multiplied by the Duration of Closure time in days. Average Annualized Disruption (AAD) is the sum of annual disruptions of all storm events. There are several steps towards determining the Average Annualized Disruption, as outlined below.

Depth Threshold for Road Closure

Among the practical examples for characterizing the impact of road closures that have been applied to case studies in the Greater Toronto Area is the methodology developed by Heather J. Murdock for *Resilience of critical infrastructure to flooding: quantifying the resilience of critical infrastructure to flooding in Toronto, Canada* (Murdock, 2017). The methodology was derived from in-person workshops and first-hand accounts from critical infrastructure operators and determined both the minimum closure threshold (the tolerance above which the road should be considered closed), as well as the closure duration. Table 3-7 shows the depth closure thresholds used in Murdock, 2017.

TABLE 3-7 REFERENCE OF THRESHOLDS AND CLOSURE TIME (MURDOCK, 2017, P.65)

Critical Infrastructure Element	Water Depth Closure Threshold (m)	Cause of Closure/Failure
Highway (Don Valley Parkway)	0.15	Cars can't pass safely
Secondary Road (Bayview)	0.15	Cars can't pass safely
Commuter Rail (Go Train)	0.1	Trains cant' pass safely
Power (1)(non-redundant)	0.5	Water damage to equipment
Power (2) (redundant)	0.5	Water damage to equipment
Power (2) (redundant)	3	Water damage to equipment

TRCA presented the above thresholds to Durham Region, who consulted internally on the proposed closure thresholds. Through project meetings, it was agreed by all parties that that common closure threshold criteria be used, and kept at a conservative 0.15m of flooding, which was carried into the subsequent Average Annual Disruption calculations. This is in keeping with public safety commentary, such as from the Insurance Bureau of Canada, to avoid driving through flooded roads, as 15cm (6 inches) is the threshold that can cause engine stalling. It is understood that in practice, the actual closure of the road will depend also on the discretion of the attending transportation officer, however this study is meant to assess the flood risk based on modelled scenarios, thus the constant threshold was utilized. Table 3-8 shows the final thresholds for closure based on function of the road used in this study.

TABLE 3-8 FINAL THRESHOLDS FOR CLOSURE BASED ON FUNCTION OF ROAD USED IN THE STUDY

Function of Road	Flood Depth Closure Threshold (m)	Cause of Closure
Highways	0.15	Cars cannot pass safely
Secondary/Regional Roads	0.15	Cars cannot pass safely
Local Roads	0.15	Cars cannot pass safely

Duration of Road Closure

As indicated above, it is understood that in practice the onset of road closure and the duration of any such closure, would depend on the discretion of the attending respective emergency management or municipal staff. Because steady-state modelling is utilized in the production of flood plain mapping in the study area, a duration of flooding is not available from the model outputs. Thus, an estimated closure duration must be used, which can vary for the depth of flooding. The length of closure increases with the depth of flooding not just because higher flood depths also correspond to longer durations of the water surface elevation being above the road elevation, but also because severe flooding may necessitate inspections or clean-up before re-opening. In the absence of other reputable sources, TRCA provided the recommended flood depth-closure time relations for the different road types based on the researched values in Murdock, 2017. These are shown in Table 3-8.

TABLE 3-9 DURATION OF CLOSURE TIME VS. FLOOD DEPTH FOR DIFFERENT FUNCTION OF ROADS

Flood Depth	Highway	Secondary/Regional Roads	Local Roads
(m)	Closure Time (day)	Closure Time (day)	Closure Time (day)
0	0	0	0
0.15	0.1	0.1	0.1
0.3	0.25	0.25	0.25
0.5	0.5	0.5	0.5
>=1	1	1	1

Average Annualized Disruption Calculation

Once the closure duration has been calculated for each flood event, it is beneficial to do an Average Annualized Disruption (AAD) calculation which assigns the probability of seeing each storm event to the disruption caused by that event. Annualizing the disruption allows for a comparison between roads that have a lot of flooding in a very unlikely storm with roads that have a little bit of flooding but very often. Annualizing the disruption basically takes the area

under the curve of a likelihood vs disruption chart, which is similar to the expected annual damage (EAD) graph traditionally used for flood damage analysis as shown in Figure 3-16.
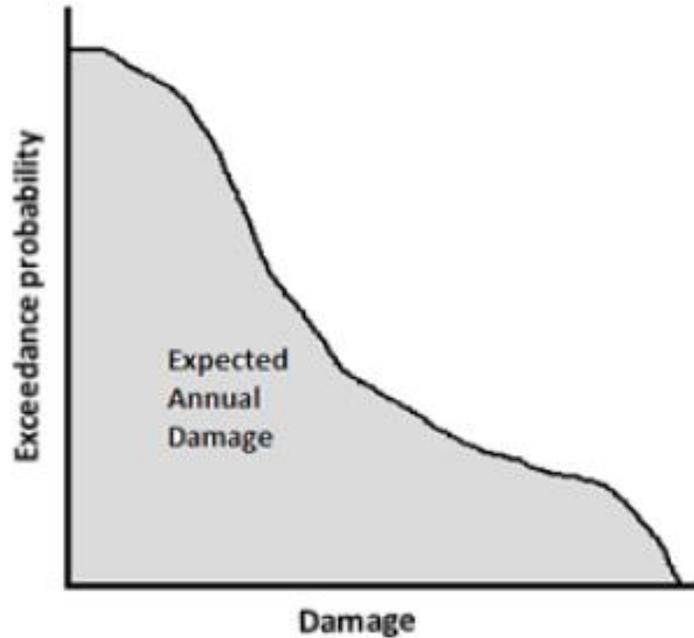
FIGURE 3-16 EXPECTED ANNUAL DAMAGE; ADAPTED FROM (USACE, 1989)

In this study EAD is replaced by AAD; the damage would instead be disruption for particular return periods, and the area under the curve would be AAD. If we apply this curve to disruption the equation would be:

$$AAD = \int_{0}^{1} P \times D(P) \, dP$$

Where D(P) is the disruption as a function of probability which is calculated as Closure Time (day) * AADT, and P is the annual flood probability. This is integrated over the range of probabilities and therefore the area under the curve.

The above equation can be rewritten to a more intuitive equation as shown below:

AAD = ∑ (closure time (i) *AEP(i)) *AADT,

where i = 0.1%, 0.3%, 1%, 2%........50%

Disruption = Closure time (i) * AADT

AEP = Annual Exceedance Probability (shown in Table 3-10)

TABLE 3-10 ANNUAL EXCEEDANCE PROBABILITY

AEP (i)	Return Period
0.1%	1,000

AEP (i)	Return Period
0.3%	350
1%	100
2%	50
4%	25
10%	10
20%	5
50%	2

Note that here the use of 1/1,000 for the AEP for the Regional Storm (Hurricane Hazel) is an arbitrary decision and does not represent the return period for Hurricane Hazel (there is no return period, it is a historical storm of record). The use of 1/1,000 is, however, consistent with what is used by TRCA for other flood risk studies, such as the 2019 Flood Risk Assessment and Ranking study.

The AEPs or Return Period (they are the inverse of each other) in the above table refers to the likelihood of the simulated events as per the current climate scenario. The outcome from the future climate analysis by Savanta is an updated (shifted) set of the return periods from the above table, thus the AAD for the Future Climate Scenario is re-calculated based on the shifted Return Period (which in turn changes the AEP).

4   CLIMATE CHANGE

NOTE – the following sections have been provided directly by Savanta. TRCA is incorporating their report into this summary report for ease of use.

4.1   Introductory Remarks

The purpose of this section is to document key elements of the scoping, methodology, and results of Durham's flood vulnerable road and culvert capacity assessment as it pertains to shifting future return periods to account for climate change. The following are key messages that the authors recommend each reader consider carefully:

1. Methodology and results contained in this report have been developed specifically for Durham Region's roads and culvert capacity assessment.
2. Results display an ensemble average shift in return period ("one number"). However, the authors recommend caution in using one number with additional considerations. To complement this, a range is included in results to indicate the uncertainty in future climate projections.
3. Confidence ratings have also been applied to the results. However, the authors caution that "moderate" confidence is not an indication for the results to be broadly applied to inform regional infrastructure upgrades and re-sizing without further investigation or engineering analysis.
4. The authors recommend that the results in this report not be simply adopted for other infrastructure planning projects without a fulsome discussion regarding risk tolerance, cost-benefit trade-offs, and regional council

appetite for such investments. Projected shifts in some return periods can be significant and carry large implications at the municipal level. If interest exists in applying the results contained herein, please contact the authors for guidance on things to keep in mind.

5. For reference, the results developed as part of this report are consistent with several studies and datasets that exist, including the Canada in a Changing Climate Report (Bush and Lemmen, 2019). For example, nationally it is characterized that a 50-year, 24-hour storm is projected to become closer to a 20-year event by the 2050s and closer to a 10-year event by the end of the century. These studies and datasets are identified throughout this document and are discussed in additional detail.

6. Please note that the business-as-usual ("worst-case") scenario of Representative Concentration Pathway, RCP8, RCP 8.5, was used to characterize these results. This is consistent with a precautionary approach at estimating risk. One could envision a different set of shifted future return periods for a lower emissions scenario such as RCP 4.5.

4.2   Scope of work and Context

The intensity, duration and frequency of extreme precipitation events is linked with how the climate is changing. Climate modelling efforts by the international community demonstrate that as global air temperatures warm, the availability of moisture increases, thereby potentially increasing the amount and intensity of precipitation during extreme weather events. How often extreme rainfall events occur is still an active area of research globally, but numerous academics, municipalities and decision makers are developing approaches to update tools used in infrastructure design to consider future conditions, such as intensity, duration and frequency (IDF) curves.

While it is out of scope to update IDF curves for the Region as part of this scope of work, Savanta and the Climate Risk Institute (CRI) have been tasked with providing an approach of "shifting" return periods based on future climate scenarios. This task can be guided through the following research question: "What is the expected new return period based on a given historical event (e.g., 2-year) amount of rainfall?" In other words, this task focuses on "shifting" the annual exceedance probability (AEP) considering climate change, not determining the future amount of extreme rainfall (i.e., in millimetres). AEP refers to the probability of a given event occurring in any given year, expressed as a percentage (e.g., a 1% chance to occur in any one year is a 1% AEP, or a 100-year event).

The project team undertook a literature review to identify potential methodologies, analyses, and approaches towards updating return periods in light of future climate change. These included, broadly:

1. Temperature scaling;
2. Applying a "climate-model derived" safety factor;
3. Transposing a design storm from another jurisdiction or altering its application to approximate future conditions; and
4. Using a statistical analysis to update annual exceedance probabilities (e.g., extreme value, or a sensitivity analysis).

Following discussions among TRCA and Durham Region staff, Savanta and CRI confirmed to undertake the fourth method identified above - namely a statistical procedure and sensitivity analysis that leveraged future precipitation and storm-related information available across Ontario. More specifically, the project team conducted an analysis to compare future IDF-related information and interpret the extent to which return periods may be shifting in TRCA watersheds within Durham Region. Step-by-step methodological details are provided in Section 4.3. Two IDF tools were evaluated for use as part of this scope of work:

1) The University of Western Ontario's IDF_CC Tool 4.0; and
2) The Ministry of Transportation (MTO)/University of Waterloo's IDF Curve Lookup Tool.

In addition to the tools above, future IDF uncertainty characterization was adapted from Coulibaly et al. 2016, and the latest climatological guidance from CSA Group (2019) and Bush and Lemmen (2019).

4.2.1 Time Horizons

Adjusted storm return periods have been provided for two future time horizons, the "2050s" and "2080s". These horizons are considered "climate normals", and represent the average value of a meteorological element over 30 years:

- The 2050s: represents the average for the years 2041-2070; and
- The 2080s: represents that average for the years 2071-2100.

4.2.2 Representative Concentration Pathway Selection

The project team looked at plausible futures under a "business as usual" Representative Concentration Pathway (RCP) 8.5 emission scenario. The RCP 8.5 pathway is a high emissions scenario that represents baseline action being undertaken to reduce greenhouse gas emissions at a global scale. It is the recommended pathway by most institutions for climate change adaptation planning, since it takes a precautionary approach when estimating risk. This RCP has been selected based on data availability and widespread historical precedent across local governments in Ontario. Other scenarios are either less likely to occur based on the latest climate observations conducted globally (i.e., RCP 4.5 and RCP 2.6) or do not yet contain a sufficient number of climate model runs to ensure a robust estimate in future projected return periods (e.g., RCP 6.0, which has fewer climate scenarios available than RCP8.5).

4.2.3 Data Uncertainty, Limitations and Confidence Rating

The extent to which results are uncertain was then characterized as part of this analysis. Uncertainty can arise from numerous sources, including but not limited to:

- Historical data availability and the statistical assumptions made in developing intensity-duration-frequency (IDF) curves;
- The selection of an emissions scenario and its implicit assumptions of future warming (i.e., RCP8., RCP 8.5);
- Climate models used and whether a sufficient ensemble approach is used to determine the spread in projections and a multi-model ensemble average;
- The downscaling method employed as part of the climate modelling; and
- The specific locations used where data were available for historical and future extreme precipitation.

This report does not describe each of the above in detail; however, a subset of these is characterized below in Sections 4.2.4, 4.2.5 and 4.2.6.

4.2.4 Intensity-Duration-Frequency Statistics

Rainfall intensity-duration-frequency (IDF) statistics are used in many water management applications, including drainage design, stormwater and watershed planning, flooding and erosion risk management, and infrastructure operations. While these tools have become commonplace in Ontario for engineering applications, industry experts and recent literature (e.g., Coulibaly et al., 2016) identify that there is inherent uncertainty that must be accounted for and be acknowledged. IDF curves rely on sub-daily observational datasets; however, several factors lead to uncertainty in their derivation, even historically. These include: 1) the availability of monitoring data within a given geography; 2) sufficient length of record and sub-daily data for statistical analyses; 3) the selection of a particular statistical distribution used in fitting datasets such as the Gumbel distribution; and 4) assumptions made throughout the analysis. For example, two assumptions typically made in IDF derivation include that data obtained from one climate station may

be realistically representative of a broader geography and that climate conditions are stationary over time (which is a principle expected to be no longer valid due to climate change).

Incorporating future climate conditions adds a layer of significant uncertainty when deriving projected IDF curves because of how climate modelling processes are undertaken (see Section 4.2.5) and how extreme precipitation projections are statistically analyzed to inform future extreme values. Numerous climate models tend to contain bias in model outputs when they are derived at the sub-daily or very localized scale. Thus, the approach used in this project did not involve analyzing raw hourly model output. Rather, future IDF curves were obtained based on future daily projections, extracting yearly maximum precipitation values, and the fitting of the General Extreme Value distribution (GEV) for statistical inference. Section 4.4 of this report describes all future climate datasets examined as part of this project and the methodology in further detail.

4.2.5 Climate Modelling and Downscaling

Climate modelling is inherently uncertain, as anthropogenic changes in future climate forcing cannot be predicted with 100% accuracy. Over the past few decades, there has been a gradual increase in confidence of climate model projections as higher quality observations of the changing climate and improvements in the model equations/parameterizations, and their spatial and temporal detail becoming available.

The approach used to downscale climate model outputs also informs the level of uncertainty. Downscaling is the process of generating climate information from a global climate model with coarse spatial scales to finer spatial scales. Two types of approaches, statistical downscaling and dynamical downscaling, have been established to achieve detailed regional and local atmospheric data. Both approaches are best analyzed using an ensemble (multi-model) approach to display the range in future conditions and capture potential individual model bias. Statistical downscaling is based on a statistical process that compares large-scale climate variables from global climate models to smaller scale regional or local climate and relies on historical relationships among climate variables. Dynamical downscaling is based on a spatial-scale numerical atmospheric model, commonly referred to as a Regional Climate Model, and incorporates GCM data to provide initial conditions and boundary conditions. The climate model data used in this project employed the use of an ensemble approach based on bias-corrected model data, which was statistically downscaled due to the availability of future IDF information and project scope constraints. However, RCM outputs could add value by being used to derive future IDF curves in Durham Region and capturing lake-based influences on precipitation (e.g., for a future study). A summary of the key advantages and disadvantages of both statistical and dynamical downscaling are provided in Table 4-1 (Hostetler et al., 2011).

As you move further into the future, the "spread" between climate models and model runs increases, thereby indicating a greater degree of uncertainty. For example, a 24-hour, 2-year event may have less uncertainty than a 1-hour, 100-year event when being resolved via climate models. It should be noted that for the purposes of this analysis, detailing differing levels of uncertainty between individual return periods for the same design storm is considered out of scope (e.g., how the confidence rating may differ for a 2-year event vs. a 100-year event based on a 1-hour AES design storm). This is due to the level of granularity in available future climate change-storm related sources of information that are at the crux of Savanta and CRI's analysis, and without undertaking primary frequency and probability analysis for each storm under each future scenario, this would not be possible.

TABLE 4-1 KEY ADVANTAGES AND DISADVANTAGES OF DOWNSCALING TECHNIQUES

Statistical	Dynamical
+ fast (relatively)	+ true simulation of high resolution forcing and climate
+ high resolution (e.g., 4 km or less)	+ large, internally consistent set of atmospheric and surface variables
+ multiple GCMs for ensembles and different emissions scenarios	- time consuming
- limited ability to correct for displaced features such as mountain ranges	- limited number of GCMs
- may not conserve mass and heat	- added model biases

4.2.6 Location Uncertainty within Analysis

Finally, it is also important to describe uncertainty associated with the locations used in this analysis. Historical rainfall depths and design storms (see Section 4.4) provided by TRCA are based on observational records at a downtown Toronto location (University of Toronto, St. George Campus). This station was selected based upon the length and completeness of the historical record. However, future IDF information is based on a spatially averaged location to the northeast selected to capture the TRCA watersheds in Durham Region (with coordinates of 43.937500°N, 79.062500 °W). There may be discrepancies in future IDF statistics as a result in this difference; however, a brief cross-comparison between future related climate outputs indicate these differences should not exceed 10 to 15% (on average). Ultimately, uncertainty ratings described in Section 4.2.7 have taken this discrepancy into account, and one should notice that no future return period result in any future time horizon has been assigned a rating of "high confidence", or robust.

4.2.7 Confidence Ratings

The project team assigned a qualitative confidence rating to each design storm and time horizon, factoring in the uncertainties described above (Sections 4.2.3 to 4.2.6). For instance, this included:

- Climate model biases and their inherent uncertainty.
- The future data source used and how robust it is considered to be, including their methodology in deriving future IDF information; and
- The number of data sources available and included in the analysis (e.g., the future 24-hour design storm has been tested and analyzed in greater detail than the 1-hour design storm).

After reviewing these considerations for each design storm and future time horizon, the project team used expert judgment to assign one of three ranking criteria:

1) High – Robust (Green);
2) Medium – Some Limitations (Yellow); and
3) Low: Use with Caution (Red).

High: Robust	Medium: Some Limitations	Low: Use with Caution

4.3 Approach and Methodology

The following provides a step-by-step approach used to undertake the analysis and estimate future return periods for each design storm provided by TRCA:

1. Obtain all future storm-related information previously completed across Durham Region, and Southern Ontario as well as the localized climate projections (daily, hourly) produced for Durham Region;
2. Inventory all future storm information that has already been assessed, including a) the time horizon(s) selected, b) the climate models used in the assessment, c) the return periods available, and d) for which design storm(s);
3. Identify gaps, where they exist, and document an approach for filling these gaps (e.g., the 4-hour Chicago design storm may not be as readily available as the AES storm when incorporating future climate conditions in Ontario);
4. Undertake sensitivity analysis and develop an estimated range in future return periods for each design storm, including:
   a. Obtaining the IDF statistics developed for a spatially averaged area over TRCA's watersheds in Durham Region (estimated at the following location: 43.937500°N, 79.062500°W);
   b. Identifying anticipated changes in storm conditions by comparing the extent to which historical design storm return periods (annual exceedance probabilities) may shift in relation to projected IDF curve information (or whether they fall within the range of climate model spread); and
   c. Estimating the range (where it exists) in return periods for the 2050s and 2080s.
5. Apply confidence ratings based on the analyses above; and
6. Document rationales as part of this report and within the results.

4.4 Data and Information

Table 4-2 presents a summary of the data obtained, considered and/or used to complete the analysis.

TABLE 4-2 SUMMARY OF DATA USED OR CONSIDERED IN ANALYSIS

Source	Description
Canada in a Changing Climate Report (Bush and Lemmen, 2019)	A 24-hour AES Design Storm under RCP 8.5 for Canada as a whole. The results show: • A historic 10-year return period (AEP = 10%) decreasing to a 5-year event (AEP = 20%) in 2050 and a 3.7-year event in 2080s (AEP = 27%). • A historic 50-year return period (AEP = 2%) decreasing to a 20-year event (AEP = 5%) in 2050 and a 12-year event in 2080s (AEP = 8%). The report does not include a detailed methodology for how these results were derived and are very general as it is for intended to represent a trend across Canada.
The Ministry of Transportation (MTO)/University of	Rainfall depth was obtained for 2-, 5- 10-, 25-, 50- and 100-year events for a location representing a spatial average across the watersheds (Coordinates: 43.937500°N,79.062500°W).

Source	Description
Waterloo's IDF Curve Lookup Tool	The "2050s" projection are an average of the 2041 and 2070 results. The "2080s" are an average of the 2071 and 2100 results.
(Soulis et al., 2016)	The method of analysis used by the University of Waterloo is referred to as the Square Grid Technique because it uses UTM grid squares as elementary sub-catchments. The premise is that local climate is strongly influenced by local and regional topography and a Digital Elevation Model (DEM) was used to derive physiographic characteristics that become independent variables in a regression analysis with station statistics. The time trend analysis was done using observations from 1960 to 2014. A linear trend was observed and extrapolated from this period to 2060.
The University of Western Ontario's IDF_CC Tool 4.0	Rainfall depth (mm) and intensity (mm/hr) were obtained for 2-, 5- 10-, 25-, 50- and 100-year events for a location representing a spatial average across the watersheds (Coordinates: 43.937500°N,79.062500°W).
(Simonovic et al., 2018)	The tool allows for date ranges to be inputted directly and were obtained for 2041-2070 and 2070-2100.
	Global Climate Models (GCMs) are complemented with nine bias corrected models developed by the Pacific Climate Impacts Consortium (PCIC) for Environment Canada (PCIC, 2013) and are downscaled to gridded climate data for Canada. This tool uses an equidistant quantile matching (EQM) method to update the IDF curves under changing climate conditions by temporally downscaling precipitation data to explicitly capture the changes in the GCM data between the baseline period and the future period. This methodological approach is illustrated in Figure 1.
	The minimum, Q1, median, Q3 and maximum modelled results were ultimately evaluated for each dataset to develop a range for results, and this is described further in Sections 3 and 4 of this report.

Design Storms used in Durham Region watersheds
 	
(Toronto and Region Conservation Authority, 2020)
	The following historical design storms were provided directly by TRCA:
	
	1. Frenchman's Bay:
	   a. Pine Creek and Dunbarton Creek: 1-hr AES design storm;
	   b. Krosno Creek: 4-hr Chicago design storm;
	   c. Amberlea Creek: 6-hr AES design storm;
	2. Petticoat Creek: 12-hr AES design storm;
	3. Duffins Creek: 12-hr AES design storm; and
	4. Carruther's Creek: 24-hr AES design storm.

The results of the Canada in a Changing Climate Report and the MTO/University of Waterloo's IDF tool were reviewed to develop an understanding of the following:

- The extent to which future projected annual exceedance probabilities have been developed;
- The level of detailed methodology available in literature and authoritative sources;
- The extent to which future return periods may be changing in Southern Ontario; and

- Potential alternative techniques to consider in the analysis.

Ultimately, information obtained from the Western University IDF-CC Tool were selected for two reasons: 1) the datasets enabled further sensitivity analysis based on their download capabilities and localized nature to the TRCA watersheds, and 2) data were developed using a methodology which incorporated an ensemble of bias corrected climate models and through extreme value statistical analyses (see Figure 4-1). Additional publications and literature related to Western University's methodology is also readily available such as a user manual and technical manuals for additional understanding (Schardong et al., 2018).
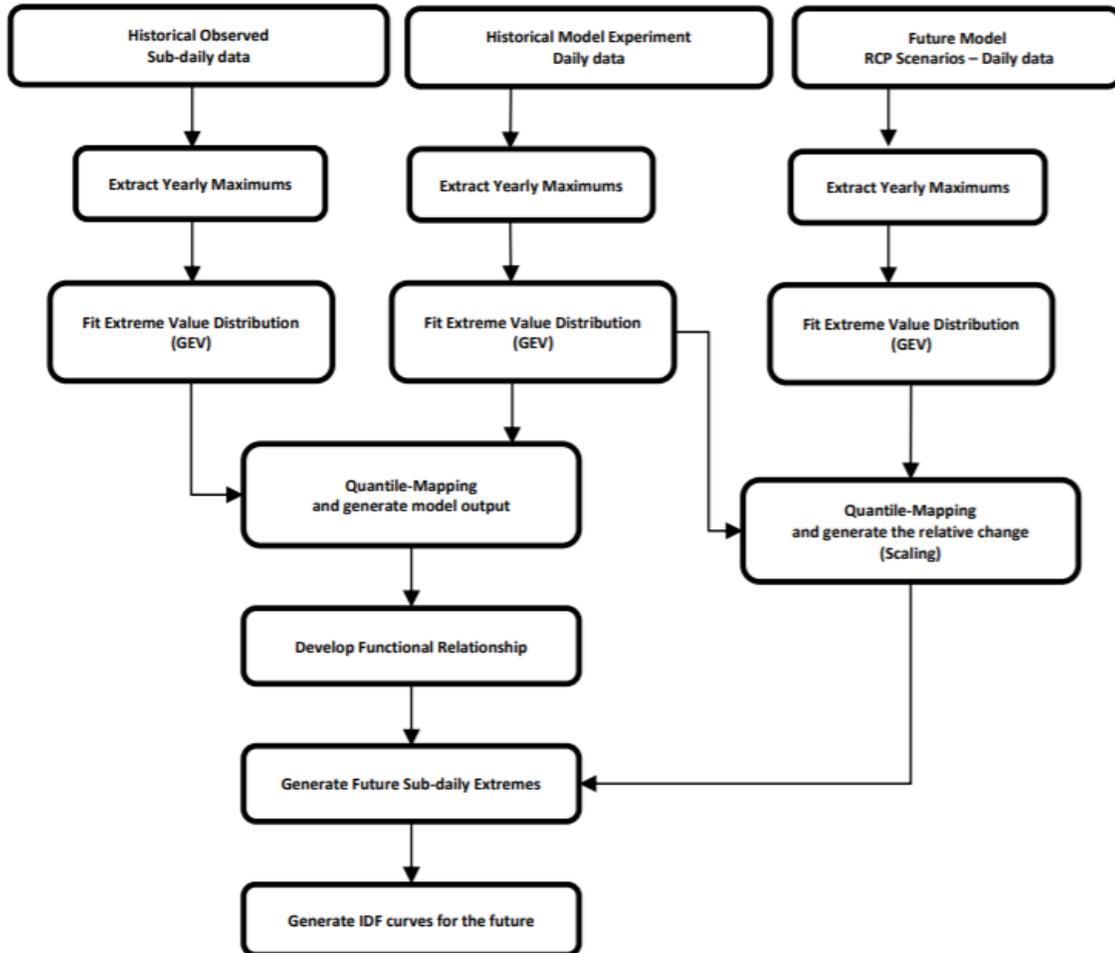
FIGURE 4-1 WESTERN UNIVERSITY'S EQUIDISTANCE QUANTILE-MATCHING (EQM) APPROACH THAT WAS USED FOR GENERATING FUTURE IDF CURVES UNDER CLIMATE CHANGE (SCHARDONG ET AL., 2018). DATA USED TO UPDATE RETURN PERIODS FOR TRCA WATERSHEDS WITHIN DURHAM REGION WERE EXTRACTED FROM FUTURE IDF CURVES BASED UPON THIS APPROACH.

4.5   Results

IDF Curves were generated using the Western University portal results for RCP 8.5 for the 2050s and 2080s. Figure 4-2 shows a comparison of the historical, 2050s and 2080s 2-Year event IDF curve, demonstrating the projected increase in rainfall intensity due to climate change. Future IDF curves plotted in the figure for the 2050s and 2080s display a multi-model ensemble median condition (e.g., the 50th percentile of all model projections).
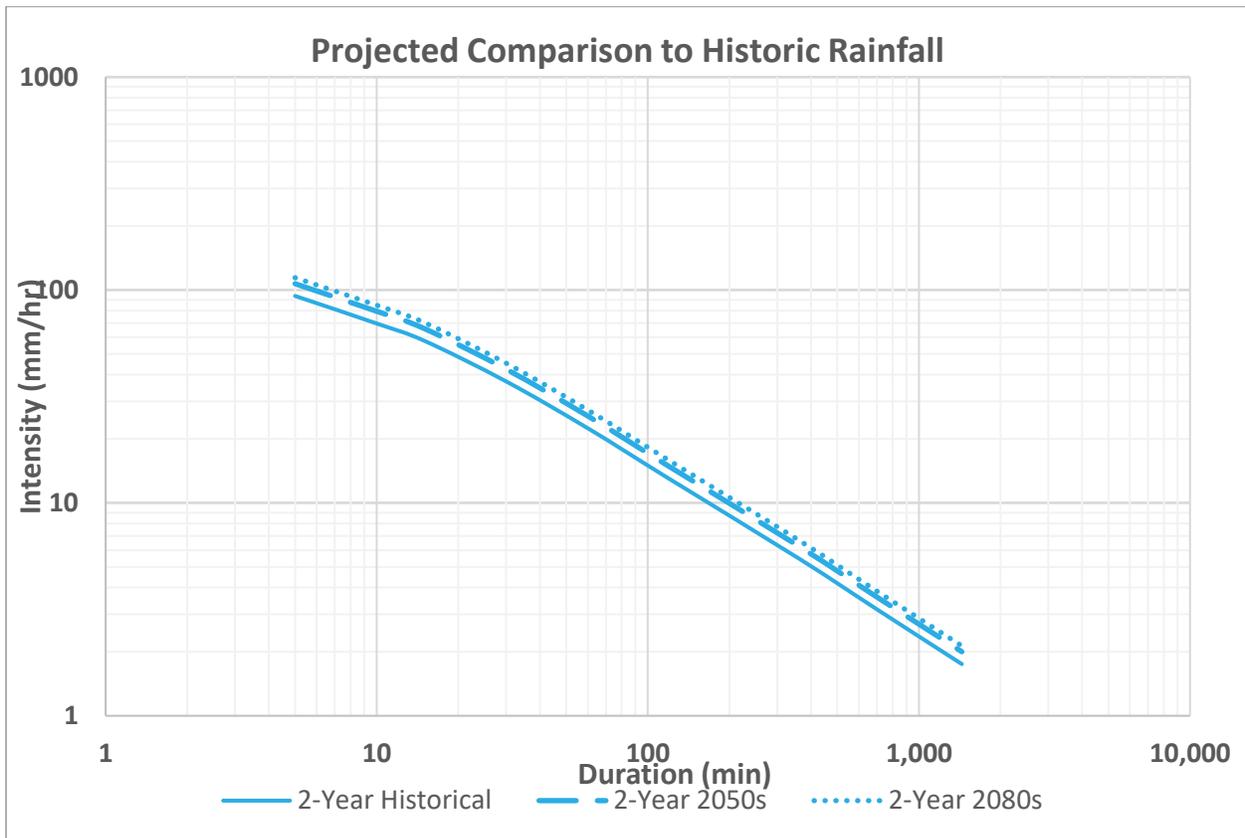
FIGURE 4-2: HISTORICAL AND PROJECTED 2-YEAR IDF CURVES, WITH THE 2050S AND 2080S DISPLAYING THE MULTI-MODEL ENSEMBLE MEDIAN VALUES IN PROJECTED DATA

In order to obtain a "shift" in the annual exceedance probability (AEP), the relevant TRCA design storms outlined in Table 4-2 were plotted along with the projected rainfall intensities obtained from the IDF Tool as demonstrated in Figure 4-3. The future return period was then selected based on the graphed results. For example, the 24-hour AES Design storm for Carruthers Creek falls between the 5-year and 10-year line and was assigned a new value of 6 years (AEP = 17%), with a range of 4.5-10 years based on modelled minimum and maximum values. This process was repeated for the mid-century and end of century for each design storm event. **Appendix A1** includes additional figures demonstrating the results for visual interpretation.
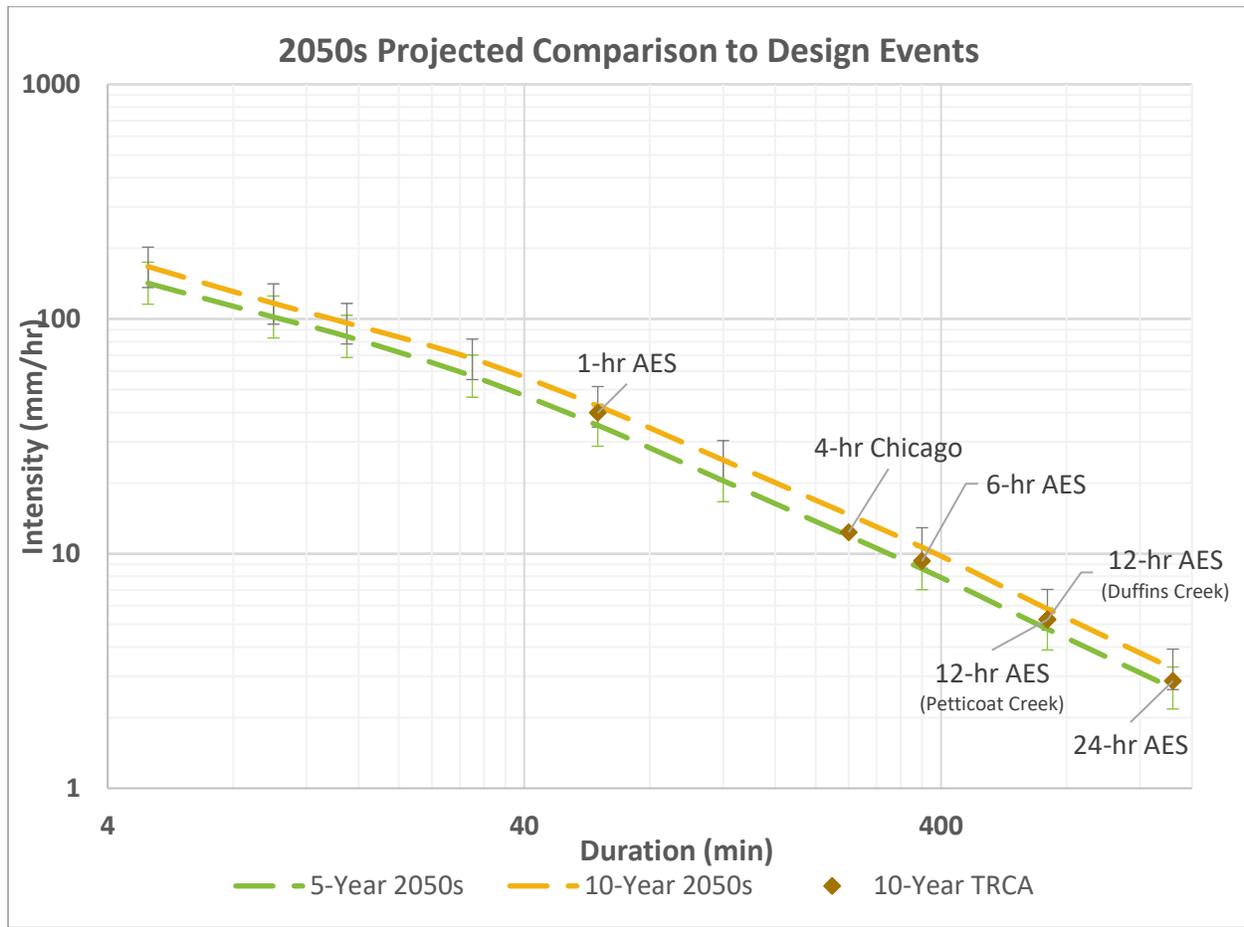
FIGURE 4-3: THE ORANGE AND GREEN LINES SHOW THE PROJECTED 5-YEAR AND 10-YEAR IDF CURVE GENERATED USING THE IDF DATA INCLUDING THE MINIMUM AND MAXIMUM MODELLED VALUES. THE GREY POINTS INDICATE THE 10-YEAR EVENT FOR THE TRCA LOCATIONS.

It is critical to consider the range, or spread, between the ensemble of projected intensities in addition to only the median value. Figure 4-3 indicates the ensemble values as vertical lines, ranging from the minimum projected intensity to the maximum projected intensity. In addition to the minima and maxima values, the 25th and 75th percentile values were also evaluated for additional information, though these are not shown in Figure 4-3.

An ensemble, or multi-model, approach to projecting climate has the advantage of capturing a larger range of possible scenarios and representing those projections using a statistical distribution. Statistical distributions are useful because they allow the user to interpret trends probabilistically and assess the uncertainty associated with climate modelling. The use of multi-model ensembles has the advantage of accounting for possible biases associated with individual model runs and can therefore provide the user with the most robust analysis of overall trends in climate (Auld et al., 2016).

To clearly demonstrate the potential uncertainty in future annual exceedance probabilities, the project team has indicated a multi-model ensemble median return period and AEP value, alongside the range in projected return periods based upon the minimum and maximum percentile conditions in the 2050s and 2080s. We urge that caution be used when interpreting these values should only one number be used, as uncertainty remains challenging to characterize and therefore high.

4.6   Deliverables

Six tables have been produced in Excel and are summarized in Table 4-3: Projected Return Period and Annual Exceedance Probabilities. **Appendix A2** within this report also summarizes the same data. Each table represents the projected "shifted return period", range and confidence for each watershed/design storm previously selected by TRCA.

TABLE 4-3: PROJECTED RETURN PERIOD AND ANNUAL EXCEEDANCE PROBABILITIES

1-hr AES Design Storm
Frenchman's Bay - Pine and Dunbarton Creeks (Jan 2007 report)

Historical			Mid-Century (2041-2070)				End of Century (2071-2100)			
Return Period (yr)	AEP	Rainfall Amount	Return Period (yr)	Range	AEP	Confidence	Return Period (yr)	Range	AEP	Confidence
2	50%	24.39	1.8	<2-2	56%	Moderate	1.5	<2-2	67%	Low
5	20%	33.58	4.5	3 - 5	22%		3.5	2.2-5	29%	
10	10%	39.78	8.0	4.5-10	13%		5.0	4-10	20%	
25	4%	47.48	20.0	8-25	5%		15.0	5-25	7%	
50	2%	53.27	35.0	15-50	3%		27.0	12-50	4%	
100	1%	58.97	60.0	20-100	2%		52.0	15-100	2%	

4-hr Chicago Design Storm
Frenchman's Bay - Krosno Creek (March 2002)

Historical			Mid-Century (2041-2070)				End of Century (2071-2100)			
Return Period (yr)	AEP	Rainfall Amount	Return Period (yr)	Range	AEP	Confidence	Return Period (yr)	Range	AEP	Confidence
2	50%	31.38	1.5	<2-2	67%	Low	1.7	<2-2	58.8%	Low
5	20%	42.15	3.5	2.5-5	29%		3.0	2-5	33.3%	
10	10%	49.25	6.0	5-10	17%		5.0	4-10	20.0%	
25	4%	58.26	12.0	10-25	8%		11.0	7.5-25	9.1%	
50	2%	64.84	20	15-50	5%		18.0	10-50	5.6%	
100	1%	71.42	28.0	20-100	4%		25.0	10-100	4.0%	

6-hr AES Design Storm
Frenchman's Bay - Amberlea Creek (March 2005 report)

Historical			Mid-Century (2041-2070)				End of Century (2071-2100)			
Return Period (yr)	AEP	Rainfall Amount	Return Period (yr)	Range	AEP	Confidence	Return Period (yr)	Range	AEP	Confidence
2	50%	36.00	1.8	<2-2	56%	Moderate	1.5	<2-2	66.7%	Low
5	20%	47.81	4.0	3-5	25%		3.5	2-5	28.6%	
10	10%	55.69	6.5	5-10	15%		5.5	4-10	18.2%	
25	4%	65.59	12.5	6-25	8%		9.0	5-25	11.1%	
50	2%	73.00	20.0	10-50	5%		15.0	7.5-50	7%	
100	1%	80.31	27.0	18-100	4%		23.0	10-100	4%	

12-hr AES Design Storm
Petticoat Creek (October 2006)

Historical			Mid-Century (2041-2070)				End of Century (2071-2100)			
Return Period	AEP	Rainfall Amount	Return Period (yr)	Range	AEP	Confidence	Return Period (yr)	Range	AEP	Confidence
2	50%	42.00	2.0	<2-2	50%	Moderate	1.8	<2-2	57.1%	Moderate
5	20%	54.38	4.8	3-5	21%		4.0	2-5	25.0%	
10	10%	62.71	7.5	5-10	13%		6.0	4.5-10	16.7%	
25	4%	73.10	12.5	6-25	8%		10.0	5-25	10.0%	
50	2%	80.82	20.0	10-50	5%		18.0	8-50	5.6%	
100	1%	88.54	30.0	15-100	3%		26.0	10-100	3.8%	

12-hr AES Design Storm
Duffins Creek (February 2013)

Historical			Mid-Century (2041-2070)				End of Century (2071-2100)			
Return Period (yr)	AEP	Rainfall Amount	Return Period (yr)	Range	AEP	Confidence	Return Period (yr)	Range	AEP	Confidence
2	50%	43.20	2.0	<2-2	50%	Moderate	1.8	<2-2	57%	Moderate
5	20%	55.50	4.8	3-5	21%		4.0	2-5	25%	
10	10%	62.90	7.5	5-10	13%		6.0	4.5-10	17%	
25	4%	72.80	12.5	6-25	8%		10.0	5-25	10%	
50	2%	80.10	20.0	10-50	5%		18.0	8-50	6%	
100	1%	87.50	30.0	15-100	3%		26.0	10-100	4%	

24-hr AES Design Storm
Carruther's Creek (October 2011)

Historical			Mid-Century (2041-2070)				End of Century (2071-2100)			
Return Period (yr)	AEP	Rainfall Amount	Return Period (yr)	Range	AEP	Confidence	Return Period (yr)	Range	AEP	Confidence
2	50%	47.08	2.0	<2-2	50%	Moderate	1.8	<2-2	55.6%	Moderate
5	20%	60.08	4.5	3-5	22%		3.5	2-5	28.6%	
10	10%	68.76	6.0	4.5-10	17%		5.5	3.5-10	18.2%	
25	4%	79.70	12.5	6-25	8%		9.5	5-25	10.5%	
50	2%	87.80	20.0	10-50	5%		15.0	10-50	6.7%	
100	1%	95.92	30.0	10-100	3%		24.0	10-100	4.2%	

Rationale

To obtain a "shift" in the annual exceedance probability (AEP), each design storm was plotted along with the projected rainfall intensities developed by Western University's IDF tool (https://www.idf-cc-uwo.ca/). The future return period was then interpolated based on the graphed results. The ranges indicated above identify the minimum and maximum projected return period, and the AEP valus indicate the multi-model ensemble average. More detailed methodology, assumptions and limitations are provided in the Technical Memo, dated Dec. 1, 2020. The following summarize several points regargin uncertainty:

1. The 4-hr storm has been interpolated between the 1-hr and 6-hr and is therefore less accurate.

2. Longer duration events (i.e. 24 hour) are somewhat more accurate than shorter duration events (i.e. 1-hr) as projected climate modelling is less granular than historical data.

3. There are larger margins of error for larger storm events (100-year) than smaller events, but confidence ratings provided above are assigned at the design storm level, not for each return period of storm (e.g., 2-yr vs. 100-yr) based on methodological limitations.

4. Further time horizons (end of century) have a larger "spread" between climate models, thereby indicating a greater degree of uncertainty.

4.7   Recommendations

Assessing and reducing climate risks, as well as undertaking comprehensive adaptation efforts is an iterative process. Infrastructure planners, designers, engineers, and all other municipal staff in this space should expect the need to revisit research, these results, how they are interpreted, and their implications on a regular basis (e.g., every five years) to ensure they can be updated as new science and implicating choices are being made.

The following are recommendations and considerations made as an output of this report and analysis:

1. Always ensure that a fulsome discussion regarding Durham Region's risk tolerance, associated cost-benefit trade-offs, and the level of regional appetite for upgrading infrastructure exists prior to adapting results contained in this report. Projected shifts in some return periods can be significant and carry large implications at the municipal level.

2. It is recommended to avoid using *only* the single multi-model ensemble average ("one number") result in the 2050s- and 2080s-time horizons for future return periods of storms. Rather, consider the range in projected return periods and annual exceedance probabilities as part of future investigations.

3. Generally, as these future return periods are applied to public works and implementation of infrastructure-related projects, additional consideration and/or engineering analysis is warranted to ensure that the results are appropriate for site-specific contexts. It is important to recall that climate scenarios can change, and that there is no one scenario that municipalities can design for. Therefore, enable flexibility wherever possible and examine the range in these results as part of engineering analyses and design criteria.

5   CRITICALITY AND PRIORITIES

Section 5.1 has been contributed by Savanta under separate cover, however it has been copied here for ease of use. Please refer to Appendix D for the full report.

A risk scoring matrix is an approach used to assign a level of risk present within a defined area based on various factors. In the context of Durham's flood vulnerable roads and culvert capacity assessment, while the Average Annualized Disruption can consider both the likelihood and the impact of flooding to a given road, for a full consideration of risk there is a need to consider and incorporate how *critical* that particular road is, alongside the likelihood and impact of current and future flooding. The following sections summarize the scoring approach used to characterize the criticality of a given road segment based on a suite of indicators.

To interpret relative differences in what makes a road critical, a suite of indicators was identified in consultation with Durham Region and TRCA staff. At a high level, these include:

1. Functional classification of roads
2. Average annual daily traffic
3. Designated Transit Routes
4. Goods movement routes
5. Degree of redundancy
6. Evacuation and disaster recovery - proximity to nuclear hazards
7. Proximity to sensitive receptors

8. Social equity and justice

Each of the above indicators was refined through further definition as they relate to Durham's roads, rationalizing why it is related to criticality and assigned a score, based on a scale from 1 to 5. A score of 5 represents the most critical (most important) and a score of 1 represents the least critical (least important). Once data is analyzed and scored for each indicator across Durham roads, an additive analysis is completed to obtain an overall criticality score. The larger the combined score along a road, the more critical a given road segment is. The project team decided that the criticality of roads based on these risk factors should be an additive process with no (i.e., equal) weighting. Assigning all factors equal weighting avoids making assumptions regarding impact thresholds that are not readily available, and thus an equal weighting approach is often considered more defensible.

It should be noted that the information contained herein only establishes proposed logic for further analysis of each indicator. All thresholds/scoring are based on available authoritative reports or guidelines from organizations, or through agreement with Durham Region staff. Actual analysis was conducted by TRCA in ArcGIS and Excel. As each indicator is mapped and assigned scores, it is important to reflect on the suitability of each scoring system to ensure it captures roads and routes known to be important across Durham Region. This process may be iterative in future editions of this type of analysis for indicators where thresholds are not well studied (e.g., social equity).

Additional detail for each indicator is summarized in Table 5-1, including a rationale, and a proposed scoring approach.

TABLE 5-1 SUMMARY OF DURHAM ROAD CRITICALITY CRITERIA AND PROPOSED SCORING

Indicator	Definition used for Durham Region	Data Source	Scoring Approach *From 1 (least critical) to* *5 (most critical)*
Factor_1 Functional classification of roads	Though the functional classification of roads is most quantitatively measured by its AADT, other factors qualitatively describe it as well. The US Federal Highway Administration notes that the functional classification of roads is not specific, indicating many "borderline" roadway classifications that exist. Other quantitative measures include lane width, shoulder width, divided/undivided status, access control and access points. Durham roads are classified based on the variations in design standards, flow characteristics, traffic volumes, traffic control, access control, vehicle type and abutting land use. Durham's Regional Official Plan (ROP) defines roads based on functional types of higher order roads having greater	Municipal road network layers	**1:** Local Roads **2:** Collector Roads **3:** Type C Arterial roads **4**: Type B Arterial roads and Rural Type A Arterial roads **5:** Urban Type A Arterial roads and freeways

Indicator	Definition used for Durham Region	Data Source	Scoring Approach *From 1 (least critical) to* *5 (most critical)*
	vehicle movement and fewer access points in terms of local intersections and driveways than lower order streets.		
Factor_2 Average annual daily traffic (AADT)	Annual average daily traffic (AADT) is the average daily vehicle traffic over a year on a road section. Traffic volume is a key factor is establishing road classification. The higher the traffic volume, the larger the risk to public safety and/or impact to the transportation system, should a disruption occur. Roads with higher traffic volumes may serve more prominently as arteries or important routes within or out of areas across Durham Region. Notably, scoring less than 3,000 has been included to accommodate local municipal roads.	Various sources as described in section 2.2.2	**1**: Less than 1,000 AADT **2**: 1,000 – 2,999 AADT **3**: 3,000 – 8,000 AADT **4**: 8,001 to 20,000 AADT **5**: Greater than 20,000 AADT
Factor_3 Designated Transit Priority Network	Transit routes play an important supportive role in the overall transportation system. Roads identified as a designated transit routes are considered more critical, as disruption to those routes can impact level of service and disrupt travel for more people. A Designated Transit Priority Network has been identified by the Region in the ROP.	Durham Region Official Plan Designated Priority Transit Network map	**1**: Not identified as part of Transit Priority Network **3**: Identified as High Frequency Transit Network or Other Transit Connection **5**: Identified as a Rapid Transit Spine
Factor_4 Goods movement routes	Providing efficient, continuous, and connected goods movement is integral to the Region's economic competitiveness and growth, including the growth of traditional and emerging agricultural industries in	Goods movement roads identified in the Durham Region Official Plan	**1**: Not identified as a goods movement route in ROP. **5**: Identified as a goods movement route in ROP.

Indicator	Definition used for Durham Region	Data Source	Scoring Approach *From 1 (least critical) to* *5 (most critical)*
	rural communities. The Regional Official Plan (ROP) designates a Strategic Goods Movement Network (SGMN) for existing haul routes and major generators of truck traffic. Goods movements roads have been identified by the Region in the ROP.		
Factor_5 Degree of redundancy	Priority to improve the resilience of Durham's roads should also be based on the availability of alternative routes in the network. Redundancy of roadways is the availability of alternative routes that can be used during emergency road closures. Redundant routes can also assist in reducing traffic congestion and provide alternate routes when roads are under construction, and they allow road networks to maintain a "level of service" in times of need. A screenline analysis was used to determine the level of redundancy for a given road. Roads in a zone with a greater number of roads crossing a the screenlines bounding that zone screenline would have a lower criticality. For details on screenline locations and zones, please see Appendix C.	Region of Durham Transportation Department	**1**: 16+ roads crossing a relevant screenline **3**: 7 to 15 roads crossing a relevant screenline **5**: Up to 6 roads crossing a relevant screenline
Factor_6 Evacuation and disaster recovery - proximity to nuclear hazards	Given the importance of nuclear facilities within Durham Region and their potential for environmental hazard, it is proposed that emergency evacuation be quantified by the proximity of nuclear power generating facilities to roads. Durham Region has two nuclear facilities; however, only one, Pickering Nuclear Generating Station, is within scope of this project, as it is located within TRCA watershed		**1:** Greater than 50km away from a nuclear facility *(No zone)* **3:** Between 10 to 50km away from a nuclear facility *(Secondary Zone)*

Indicator	Definition used for Durham Region	Data Source	Scoring Approach *From 1 (least critical) to* *5 (most critical)*
	boundaries. The scoring scale for criticality is proposed based on Durham's Emergency Management Office and Durham Nuclear Emergency Response Plan (2017) definitions of primary and secondary zones. The primary zone is the area around the nuclear station out to a radius of 10km, which includes the Contiguous Zone. The secondary zone is the area around a nuclear station out to a radius of 50km within which it is necessary to plan for ingestion control measures based on the monitoring of the food chain for contamination.		**5:** Less than 10km away from a nuclear facility *(Primary Zone)*
Factor_7 Proximity to sensitive receptors	Sensitive receptors are defined as key locations including schools, daycare facilities, nursing and retirement homes, and emergency services stations. Sensitive receptors provide critical and/or essential services to the Region's residents and those requiring access in the event of extreme weather. Given the diversity of receptors across Durham Region, a simplified scoring method is proposed based on an approximate distance (or "buffer") surrounding each designated sensitive receptor. Roads within 500m of a given sensitive receptor are considered more critical due to the need for access in the event of extreme weather. Roads that are within 500m of more than one sensitive receptor are scored based on the higher ranking receptor.	Durham Region Open Data portal (https://opendata.durham.ca/ search?tags=Durham%20Community %20Services)	**Roads within 500m of…** **1:** Any road outside of 500m of defined key locations **2:** Schools or daycares/ Community centers or places of worship **3:** Nursing or retirement homes **4:** Fire halls or police stations **5:** Hospitals

Indicator	Definition used for Durham Region	Data Source	Scoring Approach *From 1 (least critical) to* *5 (most critical)*
Factor_8 Social equity and justice	Flooding and climate change impacts are not spatially uniform, and impacts can exacerbate existing social inequalities. Operationalizing social equity into municipal planning and climate resilient design provides an opportunity to build a climate-resilient city that is also socially just. A variety of different indicators can be used to show disparities in social equity within vulnerable groups, which can be displayed by neighbourhood. Data on the measures of social equity are measured by an average of information available from Durham's Health Neighbourhood data. These measures include a) low-income rate, b) indigenous population, c) recent immigrants to the region, d) unemployment, e) visible minorities, f) seniors living alone, g) mental health. TRCA developed an integrated social equity factor score based on each of these contributing metrics. Given that universal impact thresholds do not exist, a scoring approach is recommended based on percentiles. Percentile-driven approaches are commonly applied in risk assessments where a lack of impact or failure thresholds exist and are meant to represent the relative gradient in a particular indicator's condition across a geography. For example, a neighbourhood where health data is in the bottom 30th percentile is considered "equity seeking" given that	Durham Region Open Data Portal https://opendata.durham.ca/ search?tags=Durham%20Health	**1**: Roads located in neighbourhoods where equity is >70th percentile (highest 30%) of equity data (e.g., highest incomes, lowest unemployment, fewest visible minorities, etc.) **3**: Roads located in neighbourhoods where equity is between the 30th and 70th percentile **5**: Roads located in neighbourhoods where equity is <30th percentile (e.g., lowest incomes, highest unemployment, highest visible minorities, etc.)

Indicator	Definition used for Durham Region	Data Source	Scoring Approach *From 1 (least critical) to* *5 (most critical)*
	70% of all other neighbourhoods in Durham have fewer inequalities. The authors propose that the integrated health dataset that the Region developed be overlaid with all roads and scoring assigned based on the estimated equity scoring in each neighbourhood.		

5.1   Methodology to assign criticality scores

This section summarizes the steps taken to assign a ranking score for each factor based on the scoring approach shown in Table 5-1. Note that the criticality analysis is only done for roads which are inundated by Regulatory floodlines.

5.1.1   Factor 1 - Functional classification of roads

The provided Durham Road Network layer contains an attribute called "FUNCTION_" which classifies roads into 7 classes, i.e., local, a arterial, b arterial, c arterial, collector, ramp and freeway (see Figure 5-1). Road environment (i.e., RdEnv) was also used to define Rural or Urban, which is used to differentiate Rural Arterial A and Urban Arterial A in scoring # 4 and #5. Figure 5-1 displays the functional classification of the roads within the study area.

For assigning scoring, TRCA developed a Visual Basic (VB) script within ArcGIS Field Calculator to assign scoring numbers. The VB script is provided in Appendix E. VB Script for Assigning Functional Classification Values to Roads.
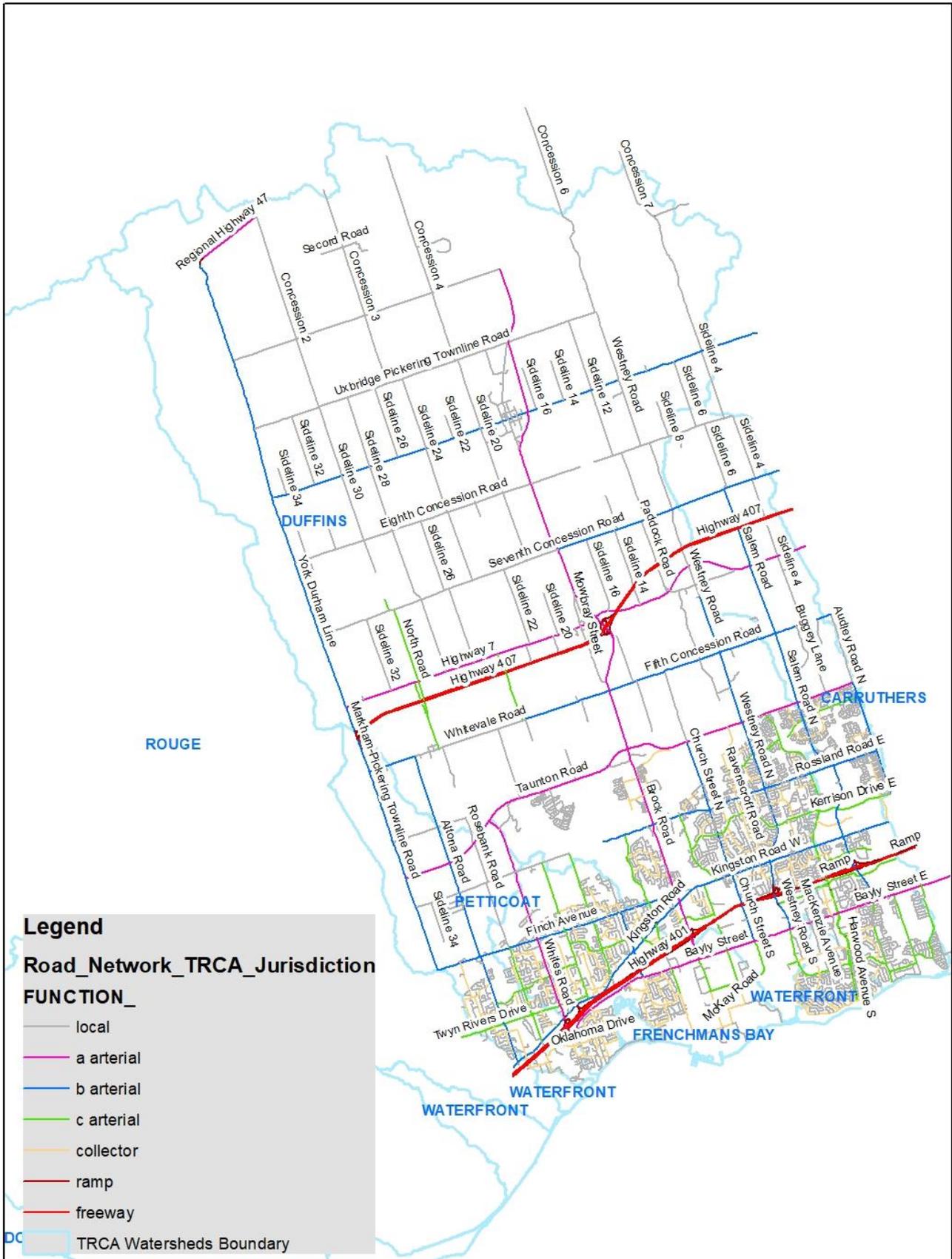
FIGURE 5-1 DURHAM REGION ROAD NETWORK WITHIN TRCA JURISDICTION

5.1.2   Factor 2 - Average annual daily traffic (AADT)

The Average Annual Daily Traffic (AADT) is the average daily traffic (calculated to eliminate day of week or time-of-year variations). Traffic volume is a key factor is establishing road criticality; the higher the traffic volume, the larger the risk to public safety should an impact or disruption occur. As mentioned in Section 2.2.2, AADT values were collected from three sources: Durham Region Open Data, City of Pickering and Town of Ajax data sets.

For assigning the criticality score for AADT, TRCA developed a VB script within the ArcGIS Field Calculator to assign scoring numbers. The VB script is provided in Appendix E.

5.1.3   Factor 3 - Designated Transit Priority Network (non-highway)

Durham Region provided a map of the Transit Priority Network in a pdf format, as illustrated in Figure 5-2 (an extract from Schedule 'C' – Map 'C3' – Official Plan of the Regional Municipality of Durham). A higher resolution map is available in Appendix B. This map highlights roads within TRCA's jurisdiction that are identified as:

- Rapid Transit Spine (Scoring of 5): Kingston Road (Regional Highway 2)

- High Frequency Transit Network and Other Transit Connection (Scoring of 3):

    - Taunton Road (Regional Road 4)

    - Brock Road (Regional Road 1)

    - Westney Road (Regional Road 31)

    - Bayly Street (Regional Road 22)

Roads that are not defined as part of Transit Priority Network receive a score of 1. For assigning scoring, TRCA developed a VB script within the ArcGIS Field Calculator to assign scoring numbers. The VB script is provided in Appendix E.
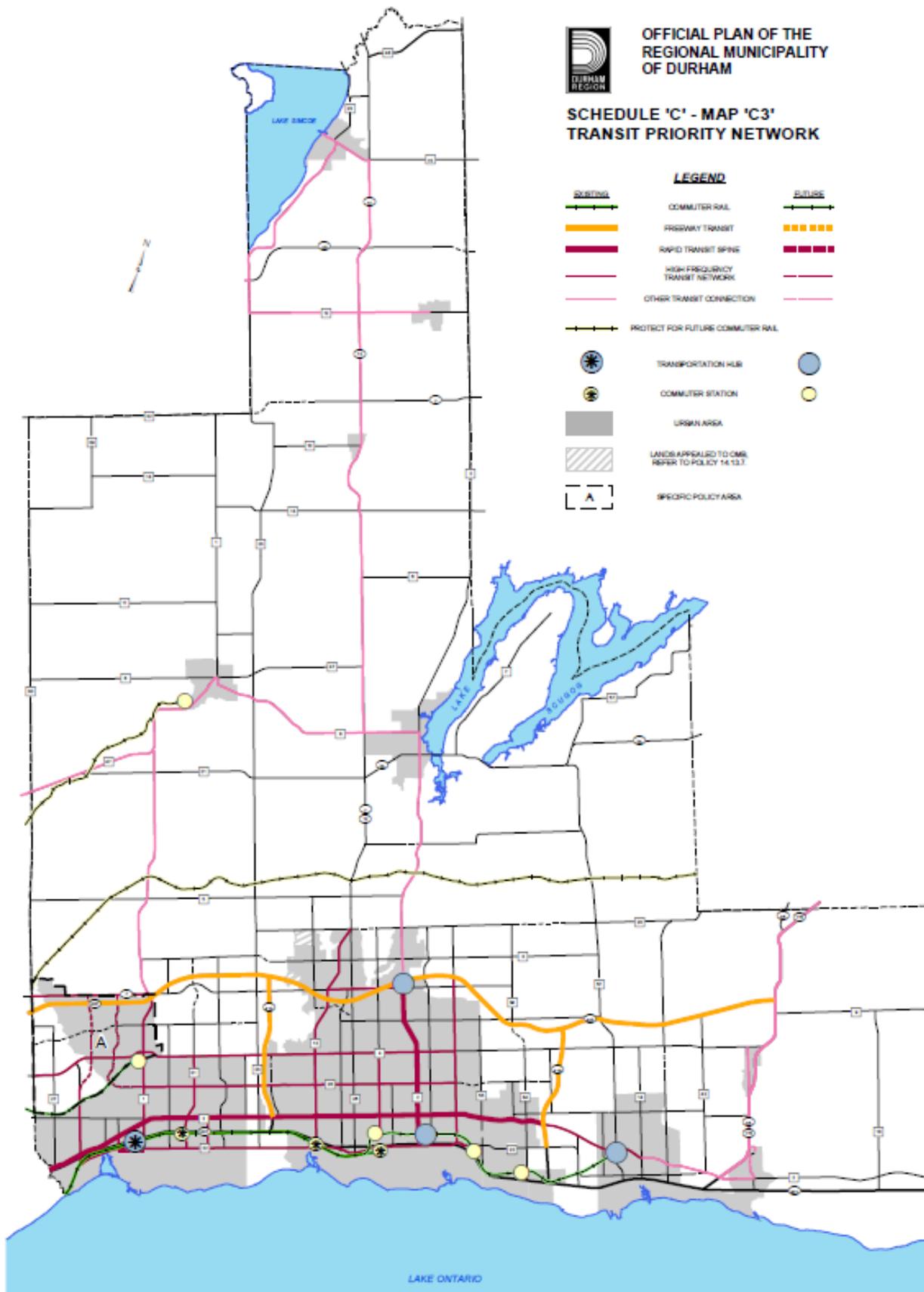
FIGURE 5-2 SCHEDULE 'C' – MAP 'C3' TRANSIT PRIORITY NETWORK

5.1.4 Factor 4 - Goods movement routes

The Regional Official Plan (ROP) designates a Strategic Goods Movement Network (SGMN) for existing haul routes and major generators of truck traffic as shown in Figure 5-3. The following roads within TRCA's jurisdiction are identified as part of the SGMN:

- Provincial Highway (Score of 5): Highway 401, Highway 407 and Highway 7

- Regional Road (Score of 5): Tauton Road (Regional Road 4), Brock Road (Regional Road 1) and Bayly Street (Regional Road 22)

Roads that are not defined as part of the SGMN receive a score of 1. For assigning scoring, TRCA developed a VB script within ArcGIS Field Calculator to assign scoring numbers. The VB script is provided in Appendix E.
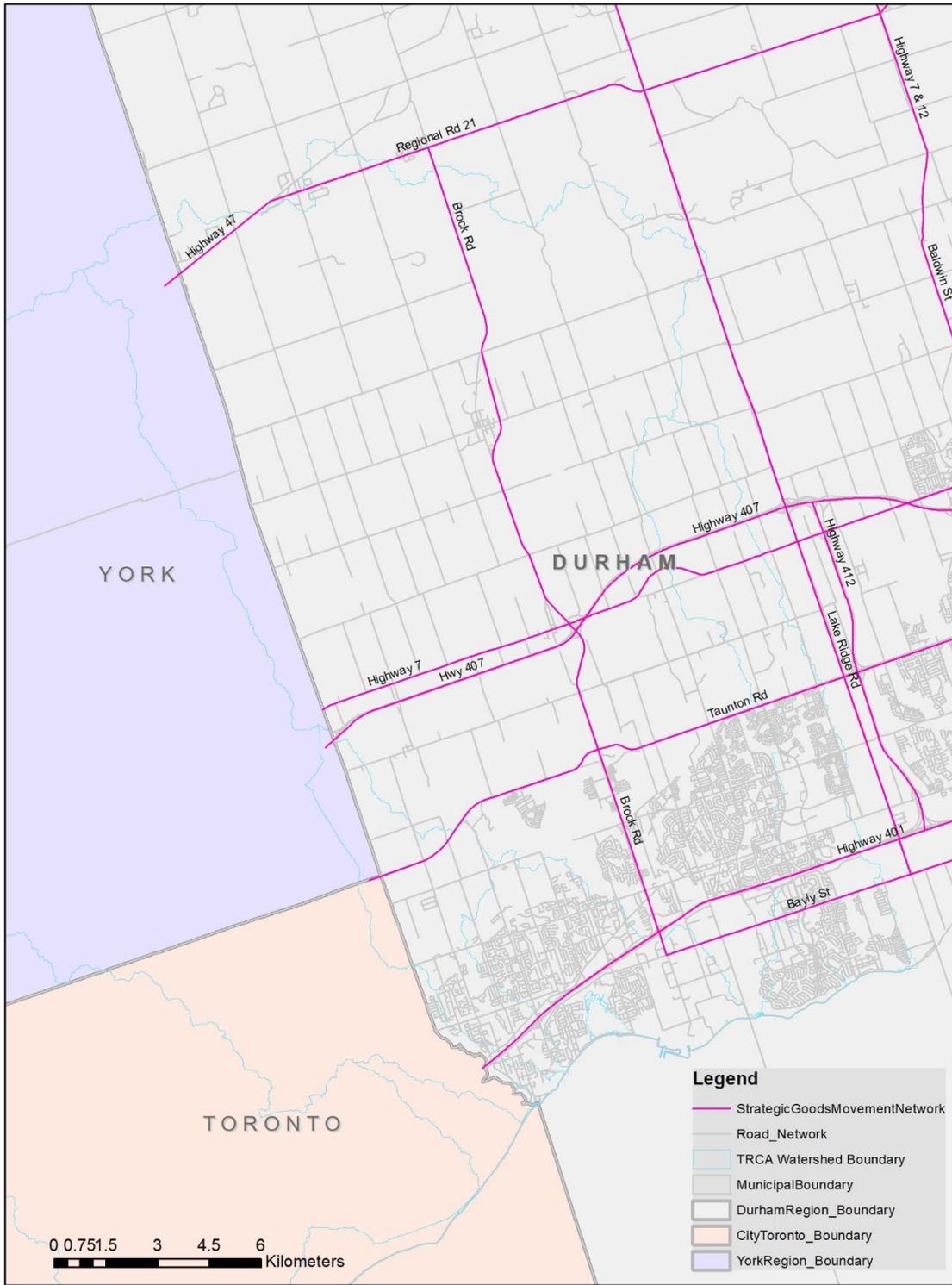
FIGURE 5-3 DURHAM REGION STRATEGIC GOODS MOVEMENT NETWORK

5.1.5   Factor 5 - Degree of redundancy

Redundancy of routes can assist in reducing traffic congestion and provide alternate routes when roads are flooded, under construction, or otherwise unavailable, and allows road networks to maintain a given "level of service" in times of need. At the suggestion of Durham Region staff, a screenline analysis is used to rank redundancy, with the road network divided into zones, where each zone is provided a scoring based on the number of roads crossing the screenlines that bound that zone. Roads within a zone with a greater number of roads crossing a screenline will result in a lower criticality (because there are more routes available in/out of that zone).

Screenline locations and zones were identified by Durham Region as shown in Figure 5-6 - Proposed Screenline Locations and Zones, while the scoring for the identified 22 zones within TRCA jurisdiction is shown in Table 5-3.

The following examples illustrate a section of the study area with the screenline zone numbers noted in orange (Figure 5-4). There are four Zones within this area: Zone 1, Zone 2, Zone 10 and Zone 11, as bounded by the screenlines shown in red.
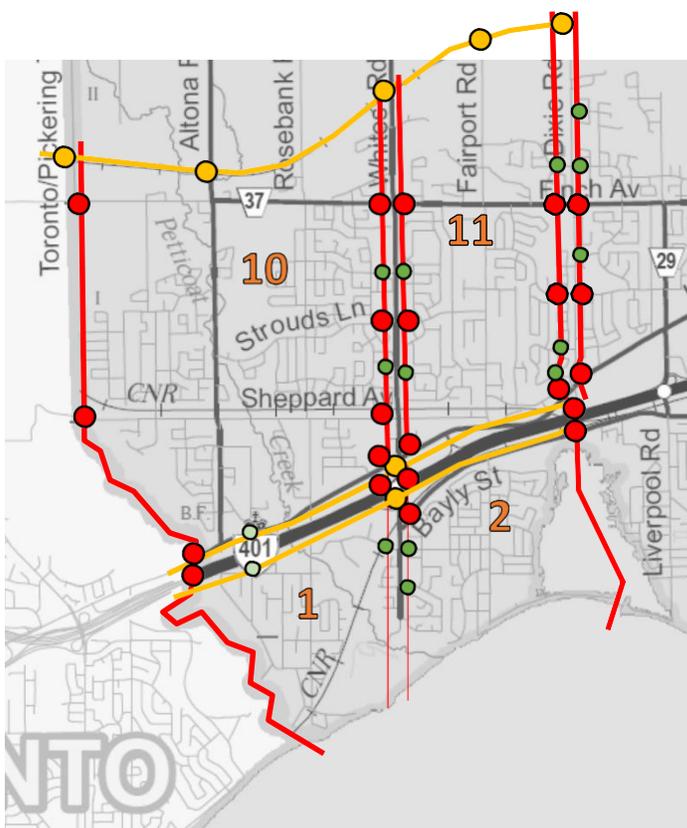
FIGURE 5-4 EXAMPLE OF SCREENLINES AND ZONES

Screenlines are imaginary lines that help measure the degree of connectivity on the road network, broken down into various zones. The screenlines form logical boundaries for north-south or east-west traffic flows to and from zones, following municipal boundaries, major roads, railway, and watercourse features.

Zone 1 has two freeway crossings (Highway 401 at the west and east screenlines for the zone) but does not have any arterials as crossings on any screenline. It has two Collector roads crossing the zone: Rougemount Drive across the screenline on the south side of Highway 401 and Granite Court across the screenline on the west side of Whites Road. In total, Zone 1 has five screenline crossings (representing ways in or out of the zone).

Zone 2 has two Freeway crossings (Highway 401 at west and east screenlines for the zone). It has three Arterial roads crossing the zone: Whites Road across the screenline on the south side of Highway 401, Bayly Street across the screenline on the east side of Whites Road, and Bayly Street across the screenline at Frenchman's Bay. It has two collector roads crossing the screenline east of Whites Road. In total, Zone 2 has seven screenline crossings.

Zone 10 has two Freeway crossings (Highway 401 at west and east screenlines for the zone). It has 11 Arterial roads crossing the zone: three on the CPR Belleville screenline, one on the screenline north of Highway 401, three on the Toronto-Durham Boundary screenline, and four on the screenline west of Whites Road. It has three Collector road crossings: two on the screenline west of Whites Road and one on the screenline north of Highway 401. In total, Zone 10 has 16 screenline crossings.

In order to assess the criticality of roads in terms of the Degree of Redundancy criterion, the proposed scoring was applied to each zone, and all roads within a given zone were given the same zone score for their Degree of Redundancy criterion. The score was assigned as follows to each zone (and in turn, to each road within that zone):

1: 16+ roads crossing a relevant screenline

3: 7 to 15 roads crossing a relevant screenline

5: Up to 6 roads crossing a relevant screenline

All existing Freeway, Arterial and Collector road crossings, are given the same weight for the scoring (each road = 1 crossing).

Returning to the example above, roads within Zone 1 are given a score of 5 (lowest connectivity/redundancy) and roads in Zone 2 are given a score of 3 (medium connectivity/redundancy).

For assigning the Degree of Redundancy score for a road that forms a boundary between two or more zones, the score for that road was based on the zone with the lower scoring for Degree of Redundancy as it shares connectivity with both zones. For example, Whites Road forms the boundary between Zones 1 and 2, and is given a score of 3.

For north-south or east-west screenlines in an adjacent zone that end in the middle of a screenline for the subject zone, they are not counted as road crossings for that zone. For example, the Taunton Road crossings of the screenlines east and west of Church Street, and east and west of Salem Road, are used for Zones 13, 14 and 15 but not for Zone 34 (see Figure 5-5).

In order to apply the scoring to each road segment, TRCA created a GIS polygon layer based on the screenlines and zones defined in Figure 5-6 - Proposed Screenline Locations and Zones. Each polygon represents one zone with a unique Zone Number from 1 to 52, and the zone numbers were used to link Table 5-3 into this GIS layer. Table 5-2 shows the attribute table of the screenline zones, as transcribed from the table that Durham Region provided (Table 5-3). Figure 5-5 shows screenlines zones labeled with zone number and score.

The assigning of the score to each road segment based on the screenline zone layer was done in GIS using the Select by Location tool. The Target Layer would be the Road layer, and Source Layer would be the zone layer with same scoring. Selected features were then assigned the corresponding score for Factor 5 (Degree of Redundancy) using the Field Calculator. The selection of roads by zone starts from zones with lower scoring (i.e., 1) and then moves to zones with higher scoring (i.e., 3 and then 5),; this allows roads that represents the boundaries of zones to receive the more conservative score.

TABLE 5-2 DEGREE OF REDUNDANCY – SCREENLINE ZONES ATTRIBUTE TABLE

cy_Screenlines_Zones_Score_F

Zone_Num	Municipali	West_LMT	North_LMT	East_LMT	South_LMT	HWY_Ex	Arter_EX	Collec_EX	SubTot_EX	Arter_FU	Collec_FU	SubTot_FU	Total_FU	Scoring_FU	Scoring_EX
1	Pickering	Toronto-Durham Boundary	Highway 401	Whites Road	Lake Ontario	2	1	2	5	0	0	0	5	5	5
2	Pickering	Whites Road	Highway 401	Frenchman's Bay	Lake Ontario	2	3	2	7	0	0	0	7	3	3
3	Pickering	Frenchman's Bay	Highway 401	Brock Road	Lake Ontario	2	4	2	8	0	0	0	8	3	3
4	Pickering/Ajax	Brock Road	Highway 401	Duffins Creek	Lake Ontario	2	5	1	8	0	0	0	8	3	3
5	Ajax	Duffins Creek	Highway 401	Pickering Beach Road	Lake Ontario	2	7	1	10	0	0	0	10	3	3
6	Ajax	Pickering Beach Road	Highway 401	Lake Ridge Road	Lake Ontario	2	6	0	8	0	0	0	8	3	3
10	Pickering	Toronto-Durham Boundary	CPR Belleville Line	Whites Road	Highway 401	2	11	3	16	0	0	0	16	1	1
11	Pickering	Whites Road	CPR Belleville Line	Dixie Road	Highway 401	2	10	5	17	0	0	0	17	1	1
12	Pickering	Dixie Road	CPR Belleville Line	Brock Road	Highway 401	2	11	7	20	1	0	1	21	1	1
13	Pickering/Ajax	Brock Road	Taunton Road	Church Street	Highway 401	2	12	4	18	1	1	2	20	1	1
14	Ajax	Church Street	Taunton Road	Salem Road	Highway 401	2	18	5	25	0	0	0	25	1	1
15	Ajax	Salem Road	Taunton Road	Lake Ridge Road	Highway 401	2	14	3	19	0	0	0	19	1	1
20	Pickering	Toronto-Durham Boundary	Taunton Road	West Duffins Creek	CPR Belleville Line	0	11	0	11	1	0	1	12	3	3
21	Pickering	West Duffins Creek	Taunton Road	Brock Road	CPR Belleville Line	0	7	0	7	4	0	4	11	3	3
31	Pickering	Toronto-Durham Boundary	407 ETR	West Duffins Creek	Taunton Road	2	6	0	8	0	0	0	8	3	3
32	Pickering	West Duffins Creek	407 ETR	Whites Road	Taunton Road	2	2	1	5	2	1	3	8	3	5
33	Pickering	Whites Road	407 ETR	Brock Road	Taunton Road	2	8	1	11	4	4	8	19	1	3
34	Pickering/Ajax	Brock Road	407 ETR	Lake Ridge Road	Taunton Road	2	13	0	15	0	0	0	15	3	3
41	Pickering	Toronto-Durham Boundary	Uxbridge-Pickering Townline Road	Brock Road	407 ETR	2	7	0	9	0	0	0	9	3	3
42	Pickering	Brock Road	Uxbridge-Pickering Townline Road	Lake Ridge Road	407 ETR	2	9	0	11	0	0	0	11	3	3
51	Uxbridge	Toronto-Durham Boundary	Regional Hwy. 47/Goodwood Road	Brock Road	Uxbridge-Pickering Townline Road	0	6	0	6	0	0	0	6	5	5
52	Uxbridge	Brock Road	Goodwood Road	Lake Ridge Road	Uxbridge-Pickering Townline Road	0	6	0	6	0	0	0	6	5	5
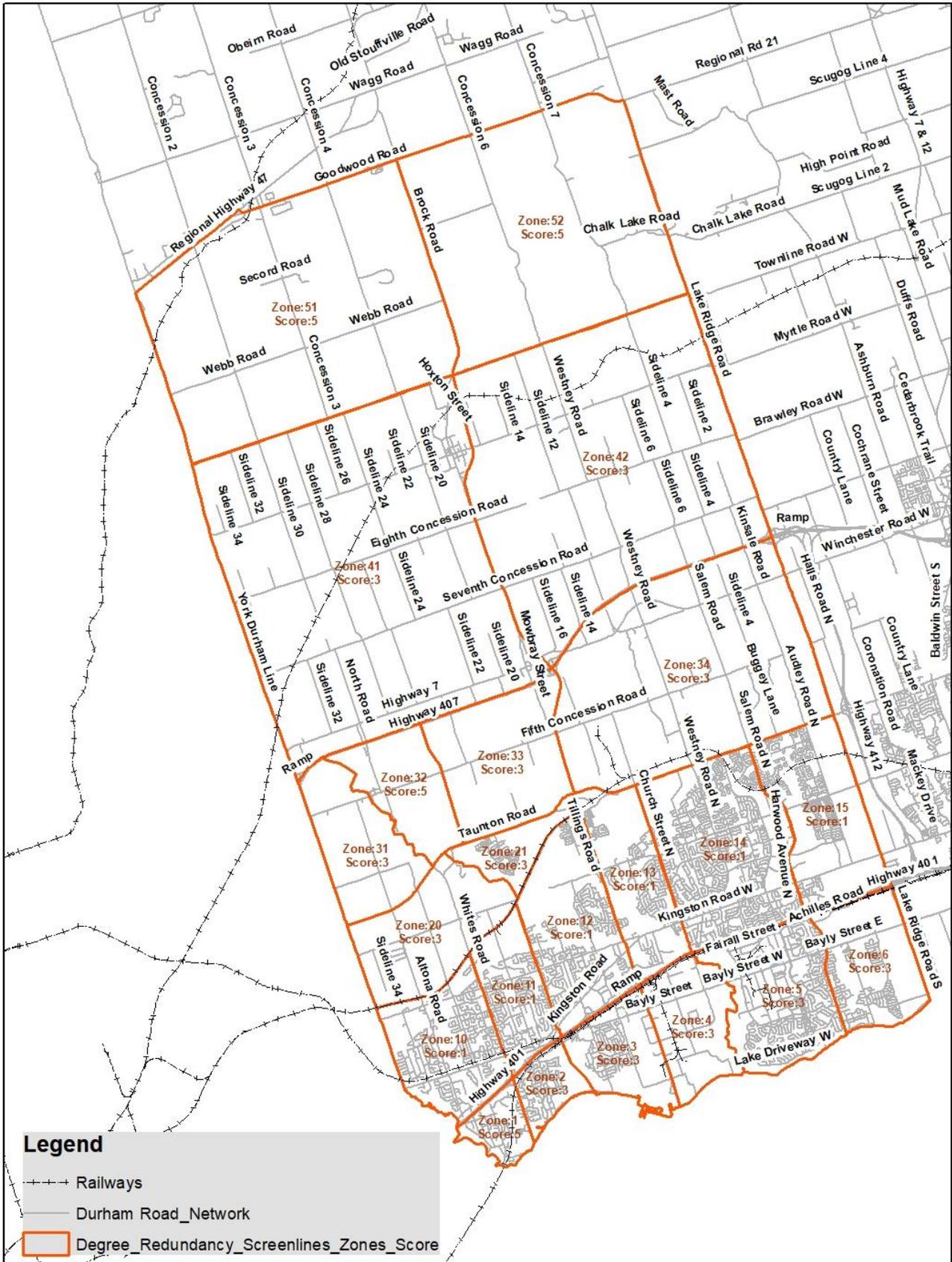
FIGURE 5-5 DEGREE OF REDUNDANCY SCREENLINE ZONES WITH DEFINED SCORES

TABLE 5-3 DEGREE OF REDUNDANCY CRITERION: NUMBER OF SCREENLINE CROSSINGS BY ZONE AND SCORING

Zone #	Municipality	Zone Extents				Screenline Crossings for Existing Roads by Road Type				Screenline Crossings for Future Roads by Road Type (2031)			Total	Scoring	Scoring for Existing Roads Only
		West Limit	North Limit	East Limit	South Limit	Freeway	Arterial	Collector	Sub-Total	Arterial	Collector	Sub-Total			
1	Pickering	Toronto-Durham Boundary	Highway 401	Whites Road	Lake Ontario	2	1	2	5			0	5	5	5
2	Pickering	Whites Road	Highway 401	Frenchman's Bay	Lake Ontario	2	3	2	7			0	7	3	3
3	Pickering	Frenchman's Bay	Highway 401	Brock Road	Lake Ontario	2	4	2	8			0	8	3	3
4	Pickering/Ajax	Brock Road	Highway 401	Duffins Creek	Lake Ontario	2	5	1	8			0	8	3	3
5	Ajax	Duffins Creek	Highway 401	Pickering Beach Road	Lake Ontario	2	7	1	10			0	10	3	3
6	Ajax	Pickering Beach Road	Highway 401	Lake Ridge Road	Lake Ontario	2	6		8			0	8	3	3
10	Pickering	Toronto-Durham Boundary	CPR Belleville Line	Whites Road	Highway 401	2	11	3	16			0	16	1	1
11	Pickering	Whites Road	CPR Belleville Line	Dixie Road	Highway 401	2	10	5	17			0	17	1	1
12	Pickering	Dixie Road	CPR Belleville Line	Brock Road	Highway 401	2	11	7	20	1		1	21	1	1
13	Pickering/Ajax	Brock Road	Taunton Road	Church Street	Highway 401	2	12	4	18	1	1	2	20	1	1
14	Ajax	Church Street	Taunton Road	Salem Road	Highway 401	2	18	5	25			0	25	1	1
15	Ajax	Salem Road	Taunton Road	Lake Ridge Road	Highway 401	2	14	3	19			0	19	1	1
20	Pickering	Toronto-Durham Boundary	Taunton Road	West Duffins Creek	CPR Belleville Line		11		11	1		1	12	3	3

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Zone #	Municipality	Zone Extents				Screenline Crossings for Existing Roads by Road Type				Screenline Crossings for Future Roads by Road Type (2031)			Total	Scoring	Scoring for Existing Roads Only
		West Limit	North Limit	East Limit	South Limit	Freeway	Arterial	Collector	Sub-Total	Arterial	Collector	Sub-Total			
21	Pickering	West Duffins Creek	Taunton Road	Brock Road	CPR Belleville Line		7		7	4		4	11	3	3
31	Pickering	Toronto-Durham Boundary	407 ETR	West Duffins Creek	Taunton Road	2	6		8			0	8	3	3
32	Pickering	West Duffins Creek	407 ETR	Whites Road	Taunton Road	2	2	1	5	2	1	3	8	3	5
33	Pickering	Whites Road	407 ETR	Brock Road	Taunton Road	2	8	1	11	4	4	8	19	1	3
34	Pickering/Ajax	Brock Road	407 ETR	Lake Ridge Road	Taunton Road	2	13		15			0	15	3	3
41	Pickering	Toronto-Durham Boundary	Uxbridge-Pickering Townline Road	Brock Road	407 ETR	2	7		9			0	9	3	3
42	Pickering	Brock Road	Uxbridge-Pickering Townline Road	Lake Ridge Road	407 ETR	2	9		11			0	11	3	3
51	Uxbridge	Toronto-Durham Boundary	Regional Hwy. 47/Goodwood Road	Brock Road	Uxbridge-Pickering Townline Road		6		6			0	6	5	5
52	Uxbridge	Brock Road	Goodwood Road	Lake Ridge Road	Uxbridge-Pickering Townline Road		6		6			0	6	5	5
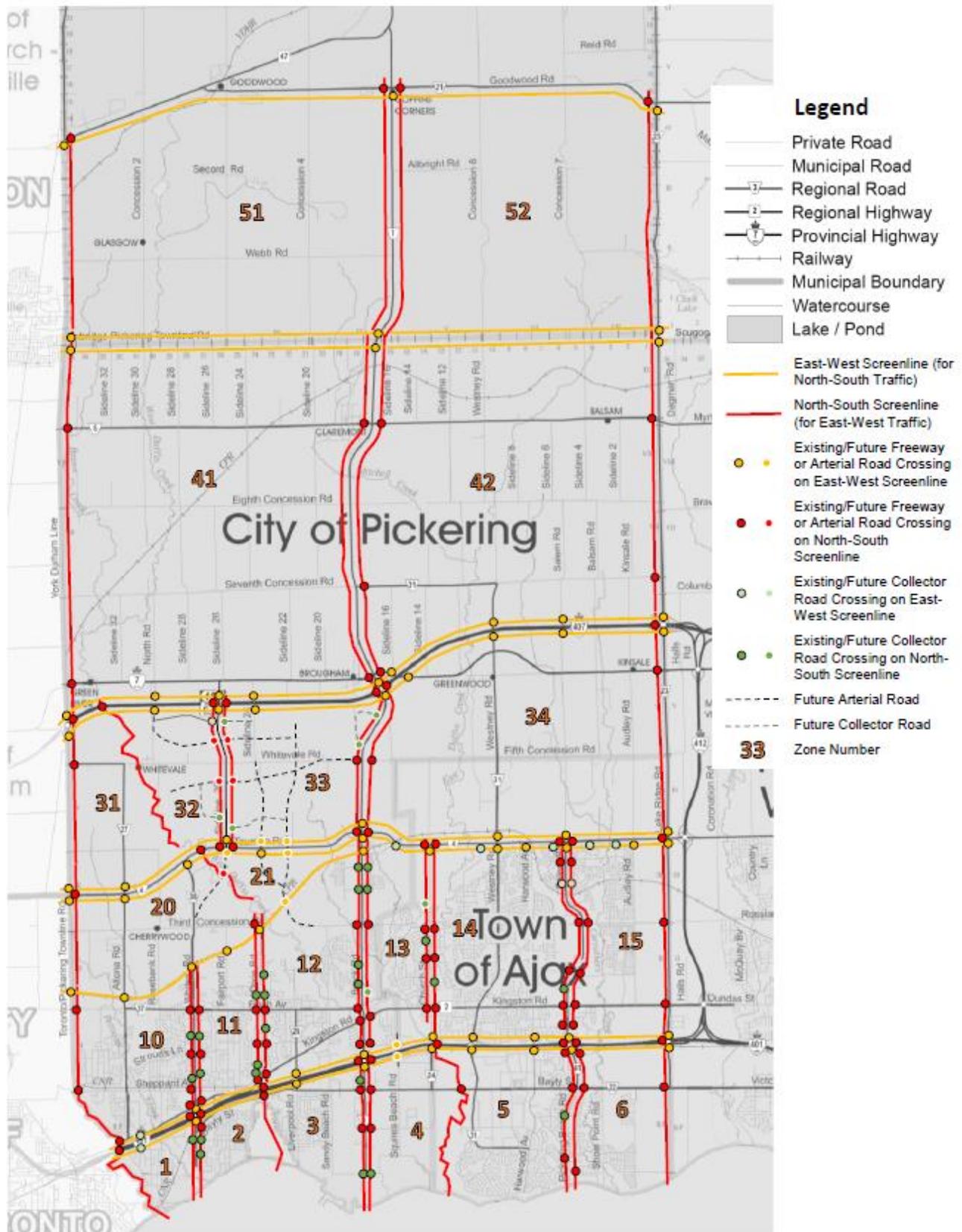
FIGURE 5-6 - PROPOSED SCREENLINE LOCATIONS AND ZONES

5.1.6   Factor 6 - Evacuation and disaster recovery - proximity to nuclear hazards

Given the importance of the nuclear facilities within Durham Region and their potential for environmental hazard, the proximity of each road segment to nuclear hazards was considered the key driver for Factor 6 in terms of criticality: evacuation and disaster recovery importance. Durham Region has two nuclear facilities; however, only one, Pickering Nuclear Generating Station, is within the study area of this project, as it is located within TRCA watershed boundaries.

The scoring scale is proposed based on the Durham Emergency Management Office and Durham Nuclear Emergency Response Plan (2017) definitions of primary and secondary zones. The primary zone is the area around the nuclear station out to a radius of 10km, which includes the Contiguous Zone/Detailed Planning Zone. The secondary zone is the area around a nuclear station out to a radius of 50km within which it is necessary to plan for ingestion control measures based on the monitoring of the food chain for contamination. The scoring is defined as:

- No zone (Score of 1): Greater than 50km away from Pickering nuclear facility
- Secondary Zone (Score of 3): Between 10 to 50km away from Pickering nuclear facility
- Primary Zone (Score of 5): Less than 10km away from Pickering nuclear facility

For assigning scores to roads, TRCA generated a 10km buffer zone and a 50 km buffer zone in GIS from the Pickering Nuclear Plant (see Figure 5-7), and progressively selected roads to assign the scores, moving from zones with higher scores (i.e., 5) and then moves to zones with lower scores (i.e., 3 and then 1). All roads in the study area within TRCA's jurisdiction are in the primary zone or secondary zone, which means only a score of 5 or 3 was assigned.

Selection in GIS can be done using the Select by Location function, with the Target Layer being the Road layer, and the Source Layer being the zone layer (i.e., 10km and 50km zones). For selected features, the corresponding score for Factor 6 was assigned using the Field Calculator.
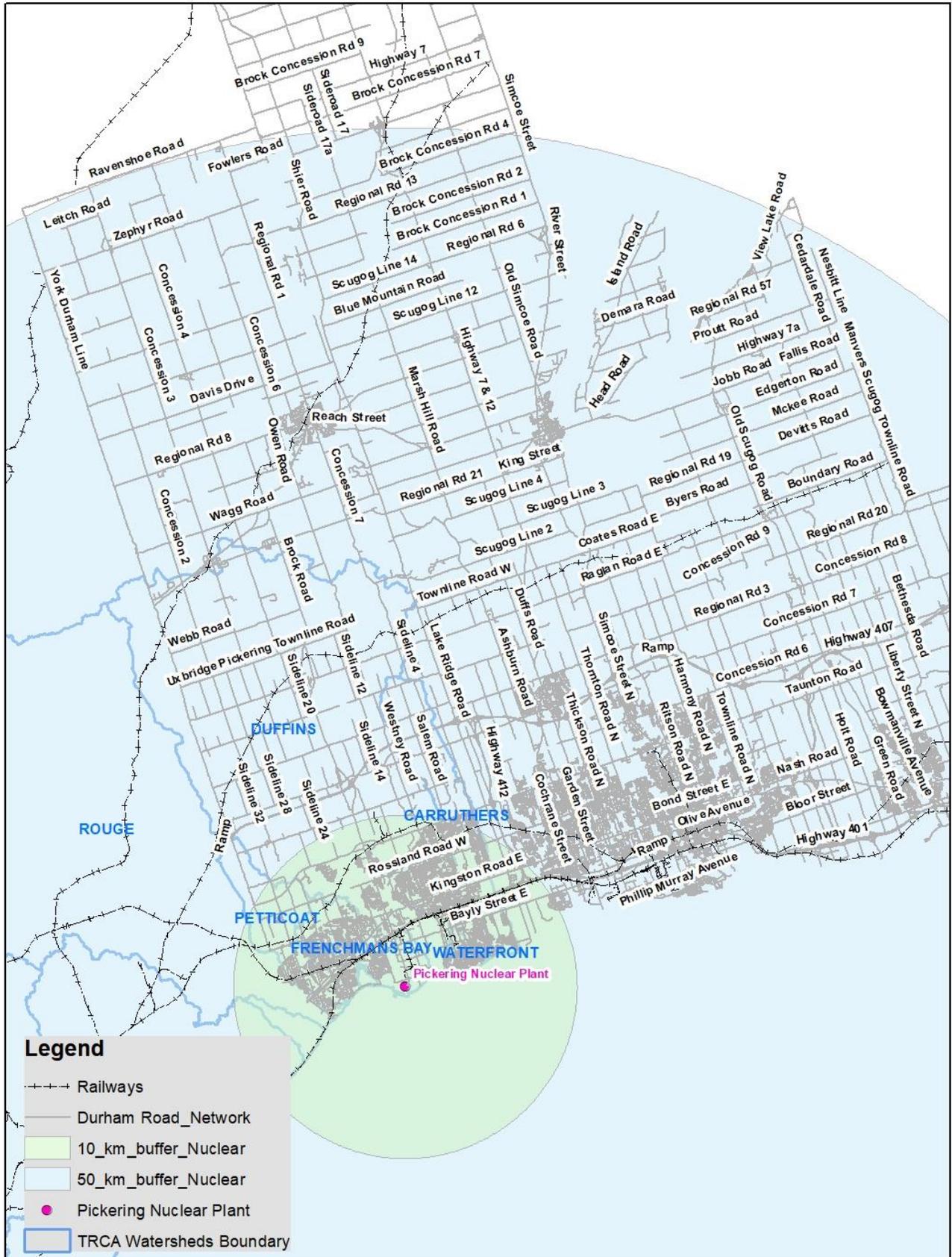
FIGURE 5-7 10KM AND 50KM BUFFER ZONES AROUND PICKERING NUCLEAR PLANT STATION

5.1.7   Factor 7 - Proximity to sensitive receptors

Sensitive receptors are defined as key locations including schools, daycare facilities, nursing and retirement homes, and emergency services (fire halls, police stations). Sensitive receptors are assumed to provide critical and/or essential services to the Region's residents, which may still need to be accessed in the event of extreme weather. Given the diversity of receptors across Durham Region, a simplified scoring method is proposed based on an approximate distance (or "buffer") surrounding each type of designated sensitive receptor. Roads within 500m of a given sensitive receptor are considered more critical given the priority of accessing these areas in the event of extreme weather. The scoring is definedas follows:

- 1: Any road segment not within 500 m of defined key locations
- 2: Road segments within 500 m of schools or daycares/ Community centers or places of worship
- 3: Road segments within 500 m of nursing or retirement homes

- 4: Road segments within 500 m of fire halls or police stations5: Road segments within 500 m of hospitals

If a road is within 500 m of two or more key locations, higher scoring is applied, for example, if a road is within 500m of both Firehall and Community Center, then in this case scoring of 4 is assigned. For scoring the roads, TRCA generated a 500m buffer zone layer for each receptor type location in GIS (see Figure 5-8 to Figure 5-11), and the selection of roads by zone starts from zones with higher scores (i.e., 5 for the 500 m surrounding a hospital), then moves to zones with lower scores (i.e., 4 through 1). Any roads outside of the 500 m buffer zones of all defined key locations would receive a score of 1.
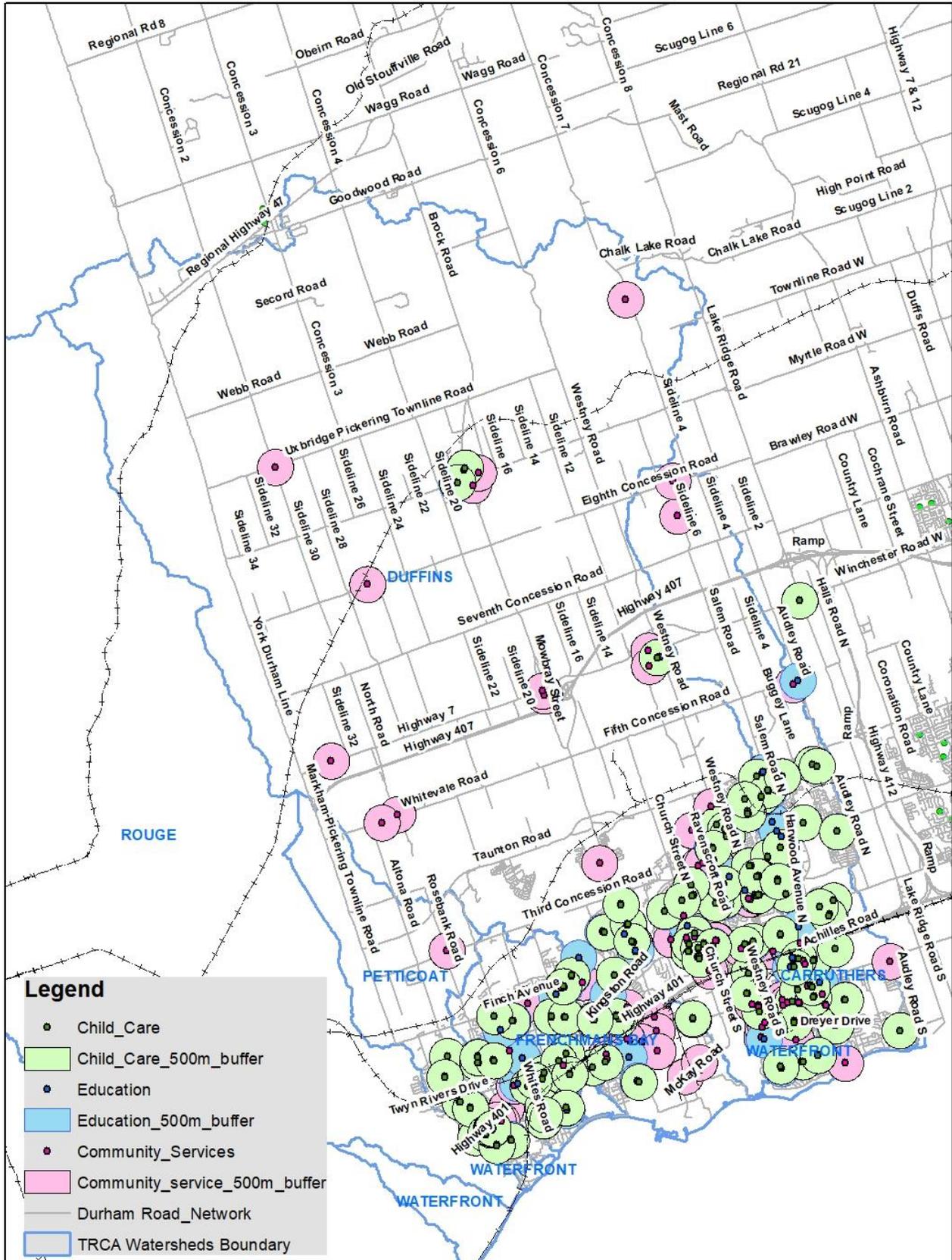
FIGURE 5-8 LOCATION OF SCHOOLS AND CHILD CARE AND EDUCATION AND COMMUNITY CENTERS WITH THEIR 500M BUFFERS
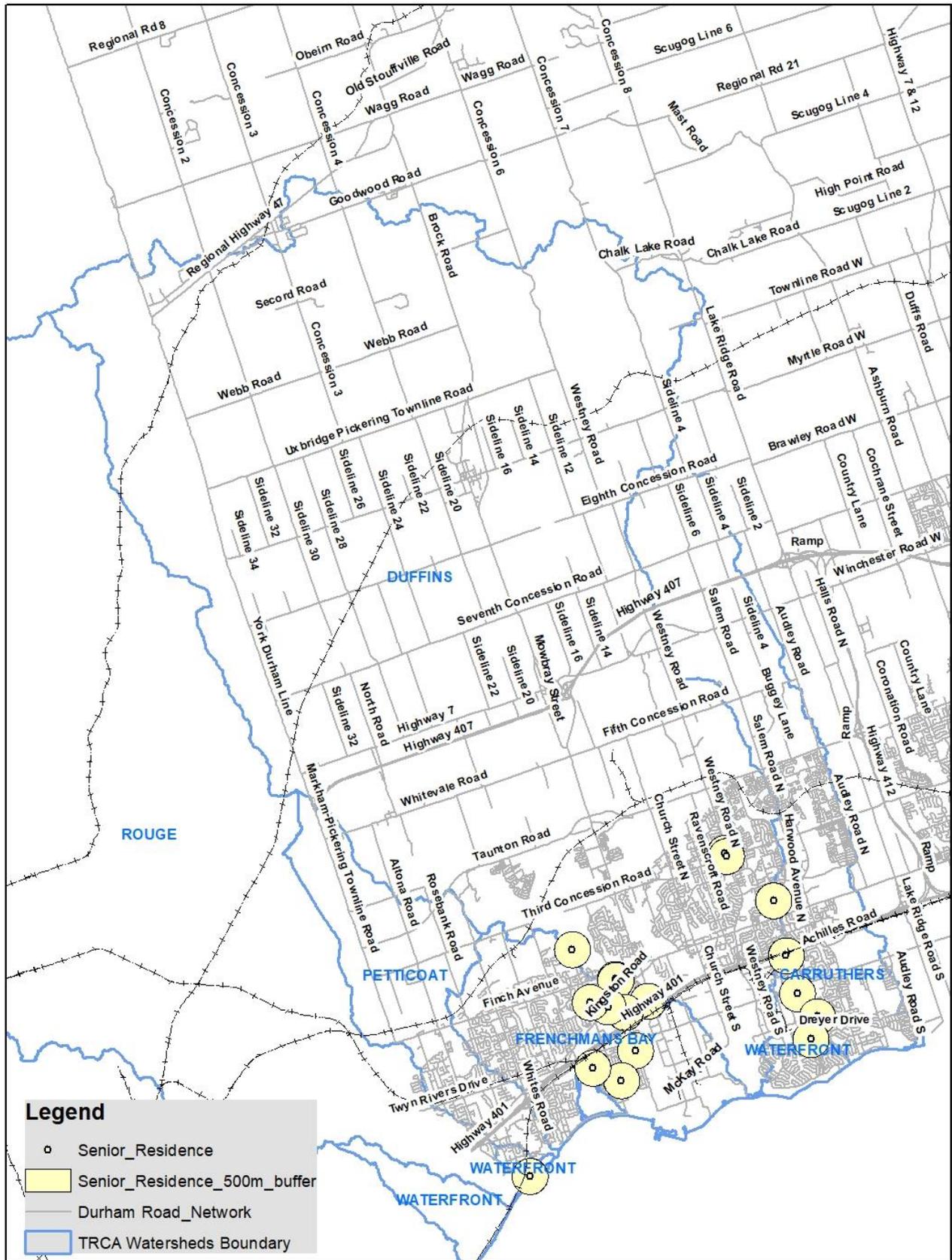
FIGURE 5-9 LOCATION OF SENIOR RESIDENCE WITH THEIR 500M BUFFER
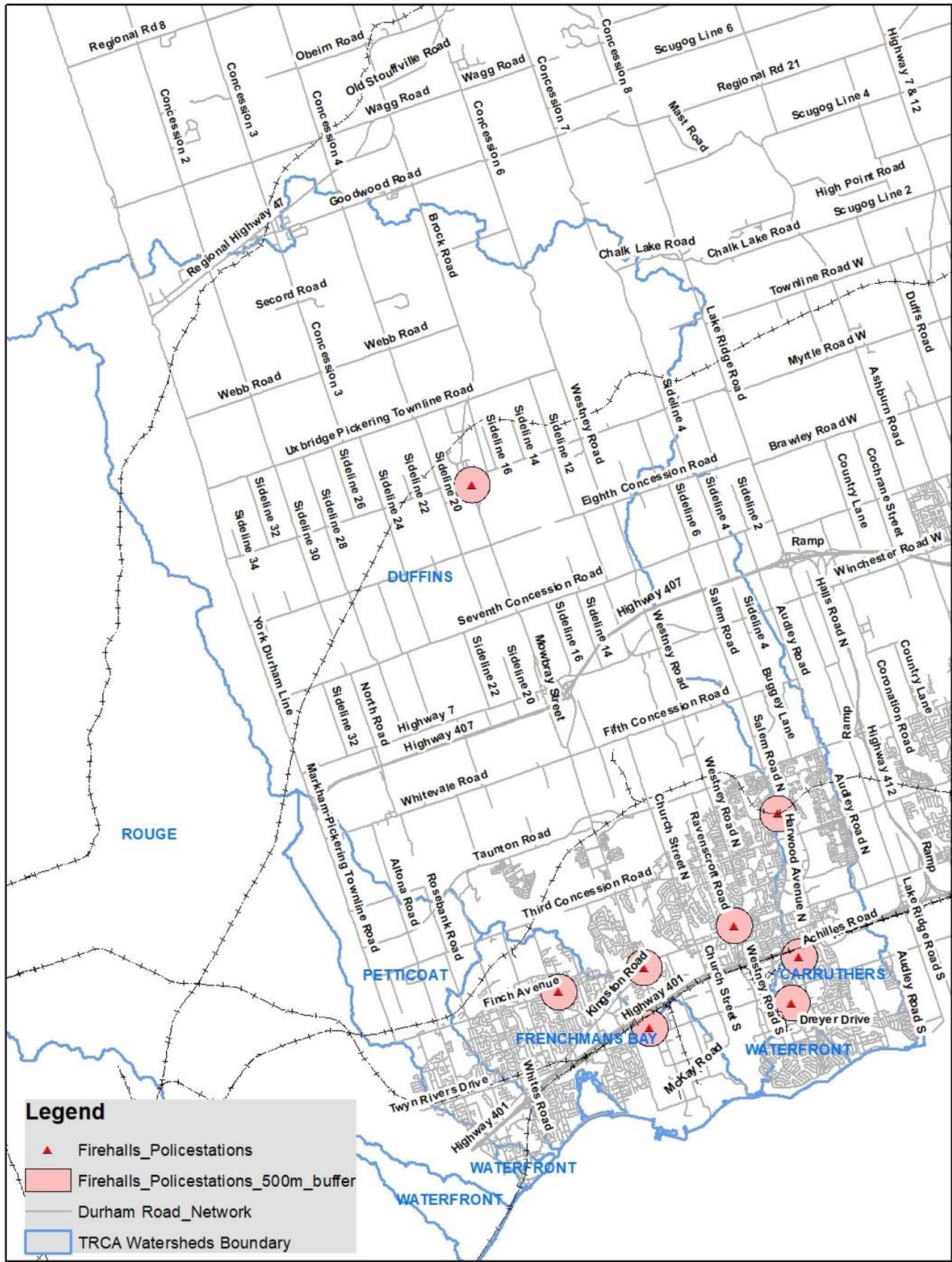
FIGURE 5-10 LOCATION OF FIREHALLS AND POLICE STATIONS WITH THEIR 500M BUFFER
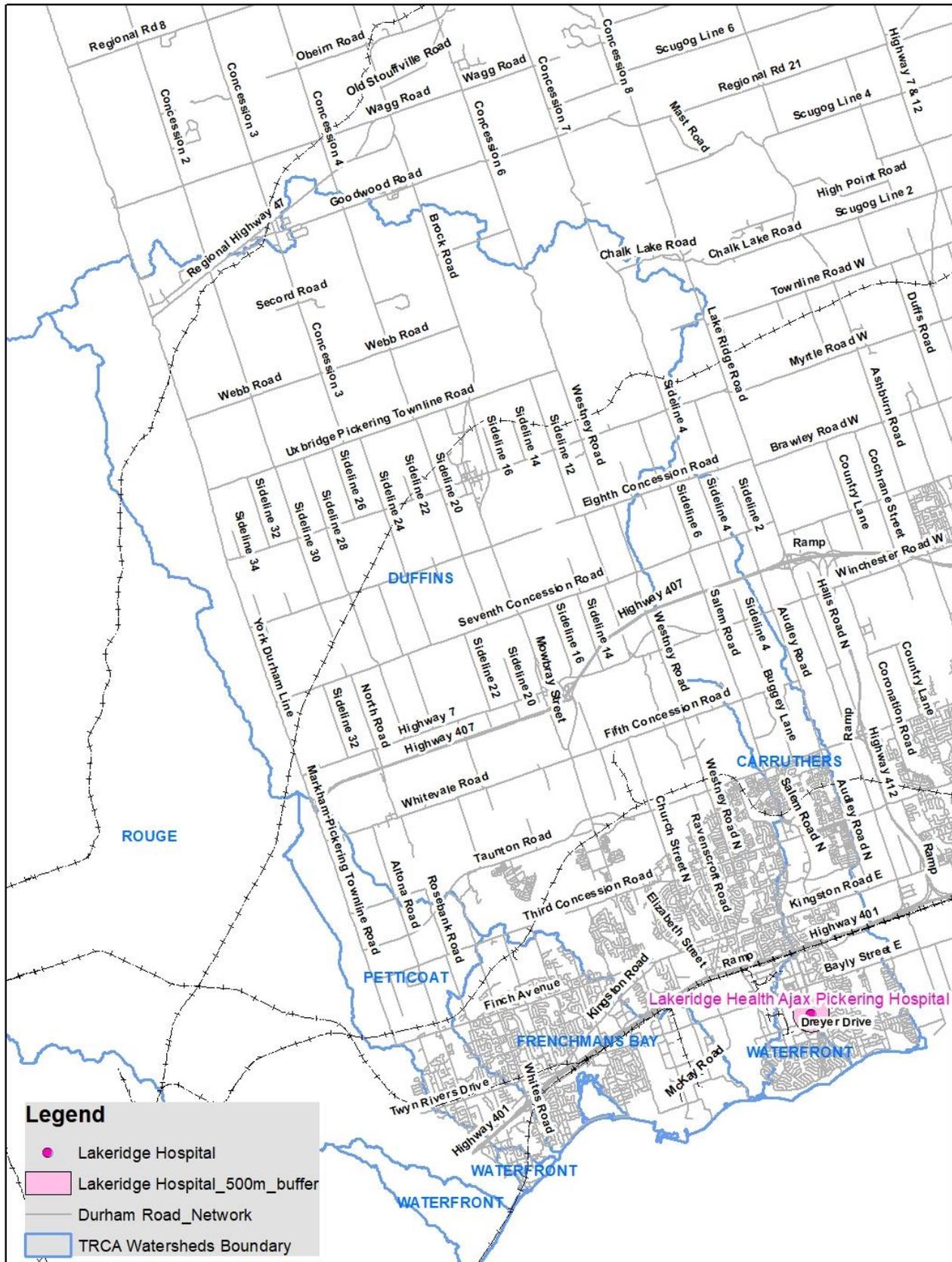
FIGURE 5-11 LOCATION OF LAKERIDGE HEALTH AJAX PICKERING HOSPITAL WITH ITS 500M BUFFER

5.1.8   Factor 8 - Social equity and justice

As outlined in Appendix D , flooding and climate change impacts are not spatially uniform, and impacts can exacerbate existing inequalities. Operationalizing social equity into municipal planning and climate resilient design provides an opportunity to build a climate-resilient city that is also socially just. A variety of different indicators can be used to show disparities in social equity within vulnerable groups, which can be displayed by neighbourhood. Data on the measures of social equity are measured by an average of information available from Durham's health neighbourhood data.

Among the health neighbourhood data sets that were selected by Savanta and confirmed by the Region of Durham to relate to response capacity were: a) low-income rate, b) indigenous population, c) recent immigrants to the region, d) unemployment, e) visible minorities, f) seniors living alone and g) mental health.

For these types of indicators, universal impact thresholds do not exist (i.e. there is no 'percentage of low-income rate' threshold for a given neighbourhood that necessarily makes that area less resilient). Therefore, a scoring approach is recommended based on percentiles. Percentile-driven approaches are commonly applied in risk assessments where a lack of impact or failure thresholds exist, and are meant to represent the relative gradient in a particular indicator's condition across a geography. For example, a neighbourhood where health data is in the bottom 30th percentile is considered "equity seeking" given that 70% of all other neighbourhoods in Durham have fewer inequalities. The scoring approach is shown as follows:

- 1: Roads located in neighbourhoods where equity is >70th percentile (highest 30%) of equity data (e.g., highest incomes, lowest unemployment, fewest visible minorities, etc.).
- 3: Roads located in neighbourhoods where equity is between the 30th and 70th percentile.
- 5: Roads located in neighbourhoods where equity is <30th percentile (e.g., lowest incomes, highest unemployment, highest visible minorities, etc.).

Durham Region provided Health Neighbourhood layers (i.e., Demographics Indicators and Early Child Development Indicators), which divided Durham Region into 50 neighbourhoods. These two layers were retrieved from the Durham Region Open Data portal (https://opendata.durham.ca/search?tags=Durham%).

Since there was no integrated health dataset combining the above indicators developed by Durham Region, TRCA came up with an approach based on percentiles to derive an integrated health dataset based on the above indicators a) through g) as follows:

- Calculate the 30th and 70th percentiles for each *individual* indicator for each neighbourhood.

- Assign score of 1, 3, 5 for each individual indicator for each neighbourhood.

- Calculate integrated score using the statistical median of all 7 indicators.

Derivation of the integrated score was carried out in an Excel spreadsheet. The PERCENTILE function in Excel was used to calculate the 30th and 70th percentiles for each indicator, and then a score (1, 3, or 5) was assigned to each neighbourhood for each individual indicator as per the scoring approach. Lastly, the MEDIAN function in Excel was used to calculate the median from the scores for each of the 7 indicators for each neighbourhood. Table 5-4 shows the integrated dataset with integrated scoring based on 30th and 70th percentiles.

Once the integrated score was calculated in Excel, it was linked to the integrated Score Social Equity Justice GIS layer based on the unique neighbourhood id field (NEIGH_ID). Figure 5-12 shows the attribute of Integrated Score Social Equity Justice GIS layer with scores for each indicator as well as integrated score of 7 indicators.

For assigning scoring to roads, TRCA generated three separate neighbourhood layers, and each neighbourhood layer contains the same integrated score. The selection of roads by neighbourhood starts from neighbourhoods with a higher

score (i.e., 5) and then moves to zones with lower scores (i.e., 3 to 1). When assessing a road that forms a boundary between two or more neighbourhoods, the zone with the higher score for Social Equity and Justice was selected as it shares a neighbourhood with more vulnerable groups. For example, Pickering Beach Road forms the boundary between A2 (has score of 5) and A3 (has score of 3) and is given a score of 5.

Integrated_Score_Social_Equity_Justice

NEIGH_ID	NAME	COMMON_NAM	MUNICIPAL_	MUNICIPALI	LOWINC_SCO	UNEMPL_SCO	RECIMM_SCO	VISMIN_SCO	SENIOR_SCO	ABORIG_SCO	MENTAL_SCO	INT_SCORE
1	Pickering 1	Frenchman's Bay	P1	Pickering	1	3	3	3	3	1	3	3
2	Pickering 2	West Rouge	P2	Pickering	3	3	5	5	1	1	5	3
3	Pickering 3	Amberlee	P3	Pickering	5	1	3	5	1	3	1	3
4	Pickering 4	Dunbarton	P4	Pickering	1	1	3	5	1	3	5	3
5	Pickering 5	Pickering City Centre	P5	Pickering	5	5	5	5	5	3	1	5
6	Pickering 6	Brock Ridge Pickering	P6	Pickering	5	3	5	5	1	1	5	5
7	Pickering 7	Pickering North	P7	Pickering	3	5	3	3	1	1	5	3
8	Ajax 1	Ajax Waterfront	A1	Ajax	1	3	3	3	3	3	5	3
9	Ajax 2	Downtown Ajax	A2	Ajax	5	5	5	3	5	3	1	5
10	Ajax 3	Carruthers	A3	Ajax	3	3	5	5	1	1	5	3
11	Ajax 4	Central Ajax	A4	Ajax	3	5	3	5	3	3	5	3
12	Ajax 5	Riverside-Hermitage	A5	Ajax	1	3	5	5	1	1	5	3
13	Ajax 6	Westney Heights	A6	Ajax	3	3	5	5	3	3	5	3
14	Ajax 7	Applecroft	A7	Ajax	5	5	5	5	1	3	5	5
15	Ajax 8	Ajax Northwest	A8	Ajax	3	3	5	5	1	1	3	3
16	Ajax 9	Ajax Northeast	A9	Ajax	3	3	5	5	1	1	5	3
17	Whitby 1	Whitby South	W1	Whitby	3	1	5	3	3	3	3	3
18	Whitby 2	Downtown Whitby	W2	Whitby	5	5	3	3	5	5	3	5
19	Whitby 3	Cochrane South	W3	Whitby	1	1	1	3	3	3	3	3

FIGURE 5-12 ATTRIBUTE TABLE – INTEGRATED SCORE SOCIAL EQUITY AND JUSTICE
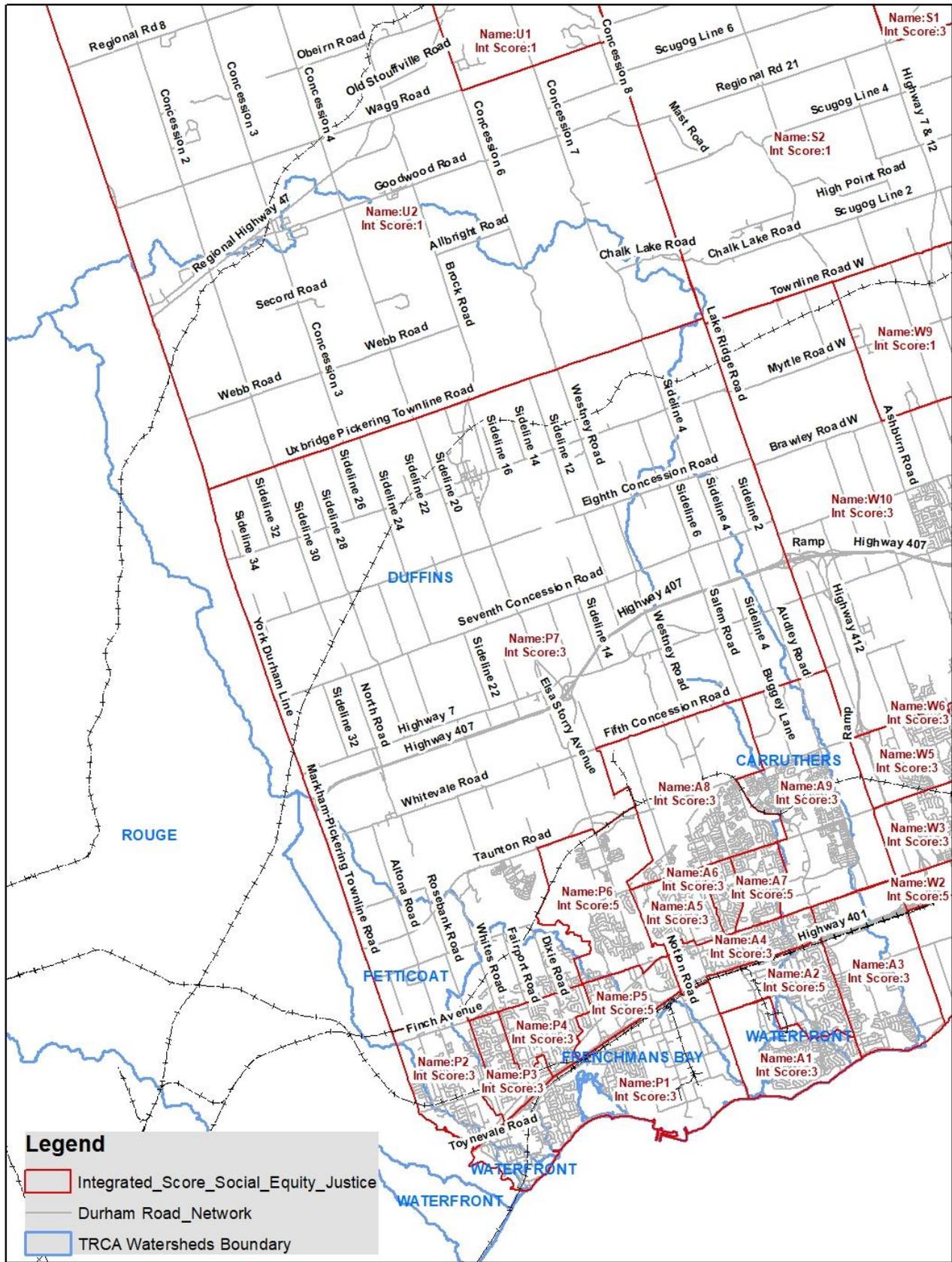
FIGURE 5-13 INTEGRATED SCORE OF SOCIAL EQUITY AND JUSTICE

TABLE 5-4 INTEGRATED HEALTH DATASET WITH DERIVED INTEGRATED SCORE

					Indicator 1		Indicator 2		Indicator 3		Indicator 4		Indicator 5		Indicator 6		Indicator 7		
NEIGH_ID	NAME	COMMON_NAM	MUNICIPAL_	MUNICIPALI	LOWINC_HSH	Score	UNEMPLOY	Score	RECENT_IMM	Score	VIS_MINOR	Score	SENIOR_ALO	Score	ABORIG_POP	Score	MENTAL HLTH	Score	Integrated Score_Median
1	Pickering 1	Frenchman's Bay	P1	Pickering	7.6	1	7.8	3	2.8	3	16.6	3	20.0	3	0.8	1	69.7	3	**3**
2	Pickering 2	West Rouge	P2	Pickering	8.9	3	8.8	3	6.6	5	42.6	5	9.3	1	0.9	1	76.6	5	**3**
3	Pickering 3	Amberlee	P3	Pickering	10.6	5	7.1	1	3.8	3	43.7	5	11.9	1	1.1	3	67.8	1	**3**
4	Pickering 4	Dunbarton	P4	Pickering	5.3	1	7.2	1	3.6	3	25.8	5	10.5	1	1.2	3	78.3	5	**3**
5	Pickering 5	Pickering City Centre	P5	Pickering	11.3	5	10.1	5	7.2	5	46.4	5	30.8	5	1.5	3	67.4	1	**5**
6	Pickering 6	Brock Ridge Pickering	P6	Pickering	11.2	5	8.5	3	7.9	5	58.9	5	8.1	1	0.6	1	83.0	5	**5**
7	Pickering 7	Pickering North	P7	Pickering	8.0	3	9.4	5	2.2	3	25.0	3	11.2	1	0.8	1	78.9	5	**3**
8	Ajax 1	Ajax Waterfront	A1	Ajax	5.0	1	8.4	3	1.8	3	11.8	3	20.8	3	1.4	3	78.1	5	**3**
9	Ajax 2	Downtown Ajax	A2	Ajax	15.6	5	9.6	5	5.3	5	24.1	3	33.1	5	1.3	3	57.8	1	**5**
10	Ajax 3	Carruthers	A3	Ajax	9.9	3	8.2	3	7.9	5	42.6	5	6.9	1	0.7	1	78.5	5	**3**
11	Ajax 4	Central Ajax	A4	Ajax	10.5	3	11.1	5	4.4	3	30.0	5	22.1	3	1.7	3	78.0	5	**3**
12	Ajax 5	Riverside-Hermitage	A5	Ajax	5.2	1	7.5	3	4.8	5	49.3	5	6.9	1	0.6	1	78.7	5	**3**
13	Ajax 6	Westney Heights	A6	Ajax	10.4	3	8.3	3	7.6	5	40.7	5	15.7	3	1.4	3	83.8	5	**3**
14	Ajax 7	Applecroft	A7	Ajax	12.2	5	10.3	5	7.3	5	55.6	5	10.3	1	1.4	3	84.7	5	**5**
15	Ajax 8	Ajax Northwest	A8	Ajax	8.8	3	7.6	3	10.9	5	68.8	5	6.8	1	0.5	1	73.9	3	**3**
16	Ajax 9	Ajax Northeast	A9	Ajax	7.7	3	8.1	3	15.1	5	71.7	5	3.2	1	0.4	1	75.9	5	**3**
17	Whitby 1	Whitby South	W1	Whitby	8.0	3	6.7	1	4.9	5	22.2	3	19.7	3	1.5	3	70.7	3	**3**
18	Whitby 2	Downtown Whitby	W2	Whitby	15.6	5	11.2	5	3.3	3	11.7	3	33.9	5	2.1	5	74.1	3	**5**
19	Whitby 3	Cochrane South	W3	Whitby	6.9	1	7.2	1	1.2	1	9.1	3	14.9	3	1.3	3	71.5	3	**3**
20	Whitby 4	Manning	W4	Whitby	7.7	3	7.5	3	1.9	3	12.9	3	17.7	3	1.1	3	68.1	1	**3**
21	Whitby 5	Williamsburg	W5	Whitby	7.8	3	4.7	1	6.0	5	38.1	5	9.6	1	1.3	3	81.1	5	**3**
22	Whitby 6	Whitby Brock North	W6	Whitby	7.6	1	7.3	1	7.5	5	25.7	3	25.0	5	0.9	1	75.4	3	**3**
23	Whitby 7	Dryden-Anderson	W7	Whitby	6.8	1	7.5	3	3.6	3	25.8	5	16.9	3	0.5	1	70.0	3	**3**

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					Indicator 1		Indicator 2		Indicator 3		Indicator 4		Indicator 5		Indicator 6		Indicator 7		
NEIGH_ID	NAME	COMMON_NAM	MUNICIPAL_	MUNICIPALI	LOWINC_HSH	Score	UNEMPLOY	Score	RECENT_IMM	Score	VIS_MINOR	Score	SENIOR_ALO	Score	ABORIG_POP	Score	MENTAL HLTH	Score	Integrated Score_Median
24	Whitby 8	Dryden East	W8	Whitby	8.9	3	9.2	3	5.6	5	28.4	5	14.5	3	1.8	5	73.5	3	3
25	Whitby 9	Brooklin East	W9	Whitby	5.2	1	4.9	1	2.9	3	9.6	3	12.3	1	0.9	1	74.1	3	1
26	Whitby 10	Brooklin West	W10	Whitby	10.0	3	5.3	1	3.5	3	15.7	3	14.6	3	0.9	1	77.5	5	3
27	Oshawa 1	Lakeview	O1	Oshawa	26.5	5	14.0	5	0.9	1	7.4	3	25.0	5	2.3	5	65.4	1	5
28	Oshawa 2	Gibb West	O2	Oshawa	18.7	5	12.4	5	2.8	3	9.5	3	27.2	5	1.7	3	70.2	3	3
29	Oshawa 3	Downtown Oshawa	O3	Oshawa	28.1	5	15.5	5	1.1	1	7.3	1	54.0	5	3.4	5	67.5	1	5
30	Oshawa 4	Central Park	O4	Oshawa	11.6	5	11.6	5	1.8	3	5.3	1	27.5	5	2.8	5	67.2	1	5
31	Oshawa 5	Grandview South	O5	Oshawa	8.3	3	11.0	5	1.3	3	9.6	3	19.9	3	1.6	3	68.4	1	3
32	Oshawa 6	Stevenson North	O6	Oshawa	11.1	5	10.1	5	1.8	3	8.1	3	22.0	3	2.2	5	75.8	3	3
33	Oshawa 7	Hillsdale	O7	Oshawa	9.0	3	8.4	3	1.3	3	5.4	1	24.9	5	1.8	5	68.8	1	3
34	Oshawa 8	Beatrice South	O8	Oshawa	7.6	1	7.7	3	1.3	3	5.2	1	27.8	5	1.6	3	71.3	3	3
35	Oshawa 9	Grandview North	O9	Oshawa	4.2	1	7.2	1	3.5	3	11.4	3	11.3	1	1.4	3	69.8	3	3
36	Oshawa 10	Beatrice North	O10	Oshawa	19.8	5	13.9	5	4.3	3	12.6	3	33.3	5	1.7	3	68.2	1	3
37	Oshawa 11	Oshawa Northwest	O11	Oshawa	11.9	5	10.9	5	2.1	3	11.1	3	14.2	3	2.2	5	71.6	3	3
38	Oshawa 12	Oshawa Northeast	O12	Oshawa	8.7	3	7.7	3	4.7	5	19.9	3	11.6	1	1.1	3	80.5	5	3
39	Clarington 1	Courtice South	C1	Clarington	5.2	1	8.1	3	2.5	3	10.3	3	13.2	3	2.7	5	69.0	1	3
40	Clarington 2	Courtice North	C2	Clarington	7.8	3	7.0	1	0.9	1	5.9	1	17.5	3	1.4	3	68.9	1	1
41	Clarington 3	Bowmanville South	C3	Clarington	7.9	3	8.6	3	1.0	1	4.8	1	25.9	5	1.3	3	72.0	3	3
42	Clarington 4	Bowmanville Central	C4	Clarington	7.8	3	11.0	5	1.0	1	3.1	1	29.5	5	2.1	5	73.2	3	3
43	Clarington 5	Bowmanville North	C5	Clarington	11.7	5	7.0	1	1.4	3	7.1	1	17.7	3	2.2	5	74.0	3	3
44	Clarington 6	Darlington	C6	Clarington	6.8	1	8.2	3	0.4	1	2.1	1	18.1	3	2.2	5	71.4	3	3
45	Clarington 7	Clarke	C7	Clarington	7.9	3	6.7	1	1.0	1	4.0	1	18.5	3	2.1	5	74.7	3	3
46	Scugog 1	Port Perry	S1	Scugog	5.6	1	6.0	1	1.3	3	3.2	1	24.3	3	2.4	5	76.8	5	3
47	Scugog 2	Rural Scugog	S2	Scugog	6.7	1	9.4	5	0.4	1	1.8	1	14.1	3	1.4	3	65.2	1	1

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NEIGH_ID	NAME	COMMON_NAM	MUNICIPAL_	MUNICIPALI	Indicator 1 LOWINC_HSH	Score	Indicator 2 UNEMPLOY	Score	Indicator 3 RECENT_IMM	Score	Indicator 4 VIS_MINOR	Score	Indicator 5 SENIOR_ALO	Score	Indicator 6 ABORIG_POP	Score	Indicator 7 MENTAL HLTH	Score	Integrated Score_Median
48	Uxbridge 1	Urban Uxbridge	U1	Uxbridge	5.5	1	6.1	1	1.0	1	3.2	1	26.7	5	1.1	3	70.3	3	1
49	Uxbridge 2	Rural Uxbridge	U2	Uxbridge	7.7	3	5.4	1	1.0	1	4.8	1	11.4	1	1.2	3	0.0	1	1
50	Brock 1	Brock	B1	Brock	12.7	5	7.4	3	0.5	1	1.9	1	26.1	5	2.4	5	65.9	1	3
				30th Percentile	7.7		7.4		1.3		7.4		12.9		1.1		69.5		
				70th Percentile	10.5		9.4		4.5		25.7		24.5		1.7		75.8		

5.1.9   Criticality

The project team decided that the criticality of roads based on these risk factors should be an additive process with no (i.e., equal) weighting. Assigning all factors equal weighting avoids making assumptions regarding impact thresholds that are not readily available, and thus an equal weighting approach is often considered more defensible. The formula for Criticality is shown as follows:

Criticality = [Factor_1] + [Factor_2] + [Factor_3] + [Factor_4] + [Factor_5] + [Factor_6] + [Factor_7] + [Factor_8]

For the final criticality calculation, all eight individual Factors were combined to form a combined road ranking layer, and a ninth attribute for ranking called Critical_ was added. The final score for Critical_ can be calculated using Field Calculator in GIS using the above formula (see Figure 5-14). It was also determined with the Region that the criticality score would not be multiplied with the AAD as the approach to overlay the two layers was preferred.

A brief statistical analysis for the distribution of the final criticality score is presented in Figure 5-15, which shows the distribution of the combined criticality scores of the 291 inundated road segments, while Figure 5-16 shows the boxplot of the criticality score. It can be seen in these figures that the criticality score of most road segments (75% of road segments) is less than or equal to 21 (out of a maximum theoretical possible score of 40). The boxplot of criticality also indicates 50% of roads have a total criticality score between 16 and 21; if the total score were divided by 7 (the number of individual criticality factors) the average score would be 2.3. Recognizing that for individual indicators, a score of 3 was considered to mean moderately critical, 24.65% of road segments had a total criticality score less than 16 (i.e., less critical) while 25.35% of roads had a criticality score of over 21 (i.e., more critical).

Figure 5-17 shows the boxplot of criticality for each individual factor for each municipality (i.e., Pickering, Ajax and Uxbridge). Since the study area only covers a small portion of Uxbridge, the following discussion on the comparison only applies to Pickering and Ajax.

For Factor 1 and 2, since these factors are both related to the function of the road, the boxplots are very similar to each other, with the results for these factors being similar for both Pickering and Ajax, which means the distribution of roads based on the function is very similar in Pickering and Ajax. For Factors 3 and 4, since designated transit priority roads and strategic goods movement network routes are mostly overlapped, these two boxplots are very similar to each other; because only significant roads like freeways and significant Regional roads were included as part of these two networks, only those roads would have received a score of 5 for these factors. The majority of roads in the area would therefore have only had a score of 1 or 3, which lowers the median score for these two factors. For Factor 5 (Degree of Redundancy), both Pickering and Ajax have median scoring of 1, but Pickering has a bit higher mean scoring (over 2) than Ajax which is owing to areas north of Taunton Road where scores are equal to or larger than 3 because of the lower overall density of the road network there. For Factor 6 (Proximity to Nuclear Hazard), because the majority of Ajax falls within the 10km buffer zone, whereas Pickering has many roads north of Whitevale Road that are outside the 10km buffer, the median score for roads in Ajax for this factor is markedly higher than the median score for roads in Pickering in for this factor. For Factor 7 (Sensitive receptors), the boxplots are very similar for Pickering and Ajax, with 75% of roads have scores ranging between 1 and 2, but with Pickering having more roads within 500m of Senior Retirement Homes (score of 3). For Factor 8 (Social Equity and Justice), for both Pickering and Ajax scoring is concentrated in at 3, which means equity is balanced between the 30th and 70th percentiles when accounting for all the indicators, resulting in the Factor 8 criticality for the study area being mostly moderate.

Flood Vulnerable Road and Culvert Hydraulic Capacity Assessment

Road_Risk_ranking_combined

ID	FULL_NAME	FUNCTION_	MUNICIPAL	Factor_1	Factor_2	Factor_3	Factor_4	Factor_5	Factor_6	Factor_7	Factor_8	Critical_
100012	Highway 7	a arterial	Pickering	4	4	1	5	3	3	2	3	25
100099	Sideline 20	local	Pickering	1	1	1	1	3	3	1	3	14
100169	Heska Road	local	Pickering	1	1	1	1	3	5	1	3	16
100183	Westney Road	local	Pickering	1	1	1	1	3	3	1	3	14
100250	Highway 401	freeway	Pickering	5	5	1	5	1	5	2	3	27
100274	Highway 7	a arterial	Pickering	4	4	1	5	3	3	1	3	24
100354	Brock Road	a arterial	Pickering	5	5	3	5	1	5	4	5	33
100419	Rougemount Drive	collector	Pickering	2	2	1	1	1	5	2	3	17
100449	Westney Road N	b arterial	Ajax	4	5	3	1	1	5	4	5	28
100474	Christena Crescent	local	Ajax	1	1	1	1	1	5	2	3	15
100645	Altona Road	b arterial	Pickering	4	4	1	1	1	5	2	3	21
100845	Bronwen Lane	local	Pickering	1	1	1	1	3	5	3	3	18
100852	Uxbridge Pickering Townline	local	Uxbridge	1	1	1	1	5	3	2	3	17
100872	Sideline 34	local	Pickering	1	1	1	1	3	5	1	3	16
100904	Whitevale Road	b arterial	Pickering	4	1	1	1	3	3	1	3	17
100935	Taunton Road E	a arterial	Ajax	5	5	3	5	1	5	1	3	28
100935	Taunton Road E	a arterial	Ajax	5	5	3	5	1	5	1	3	28
100972	Betts Road	local	Ajax	1	1	1	1	1	5	2	3	15
100976	Fifth Concession Road	b arterial	Pickering	4	1	1	1	3	3	1	3	17

FIGURE 5-14 ATTRIBUTE TABLE OF COMBINED ROAD RISK RANKING
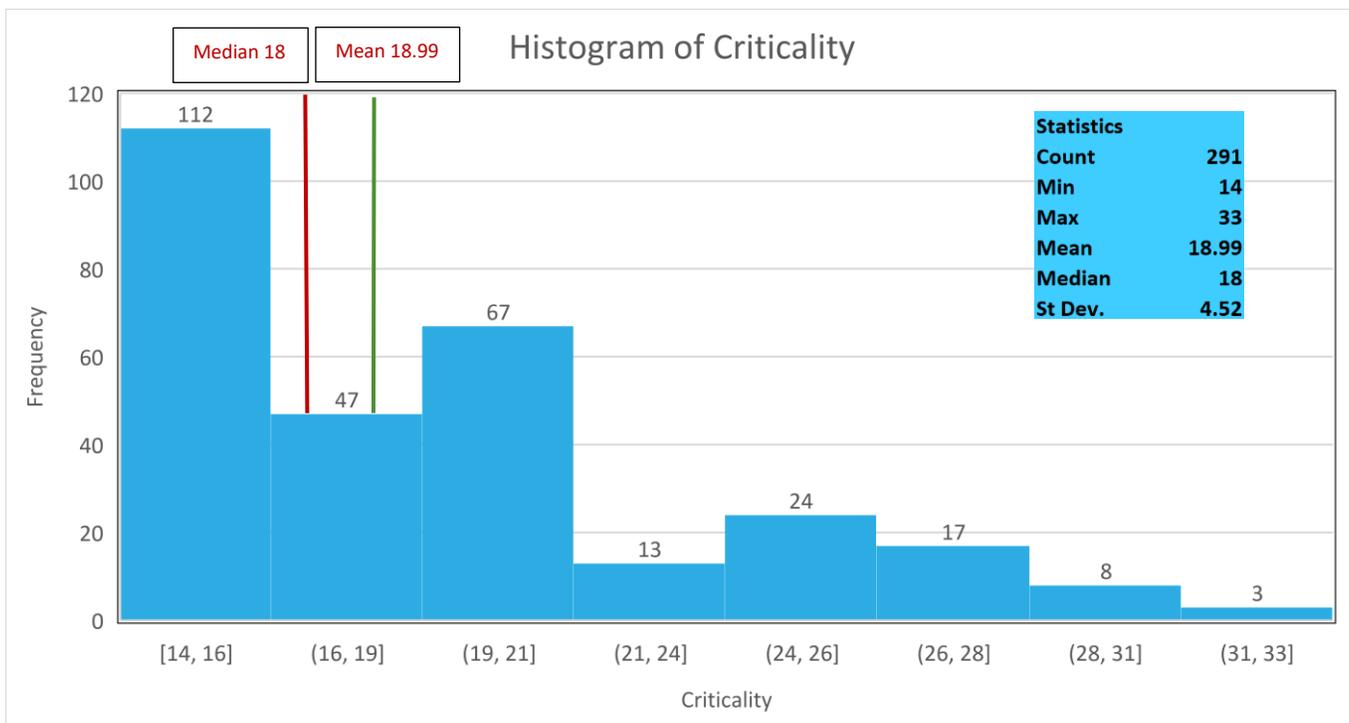

FIGURE 5-15 HISTOGRAM OF CRITICALITY SCORE OF INUNDATED ROADS
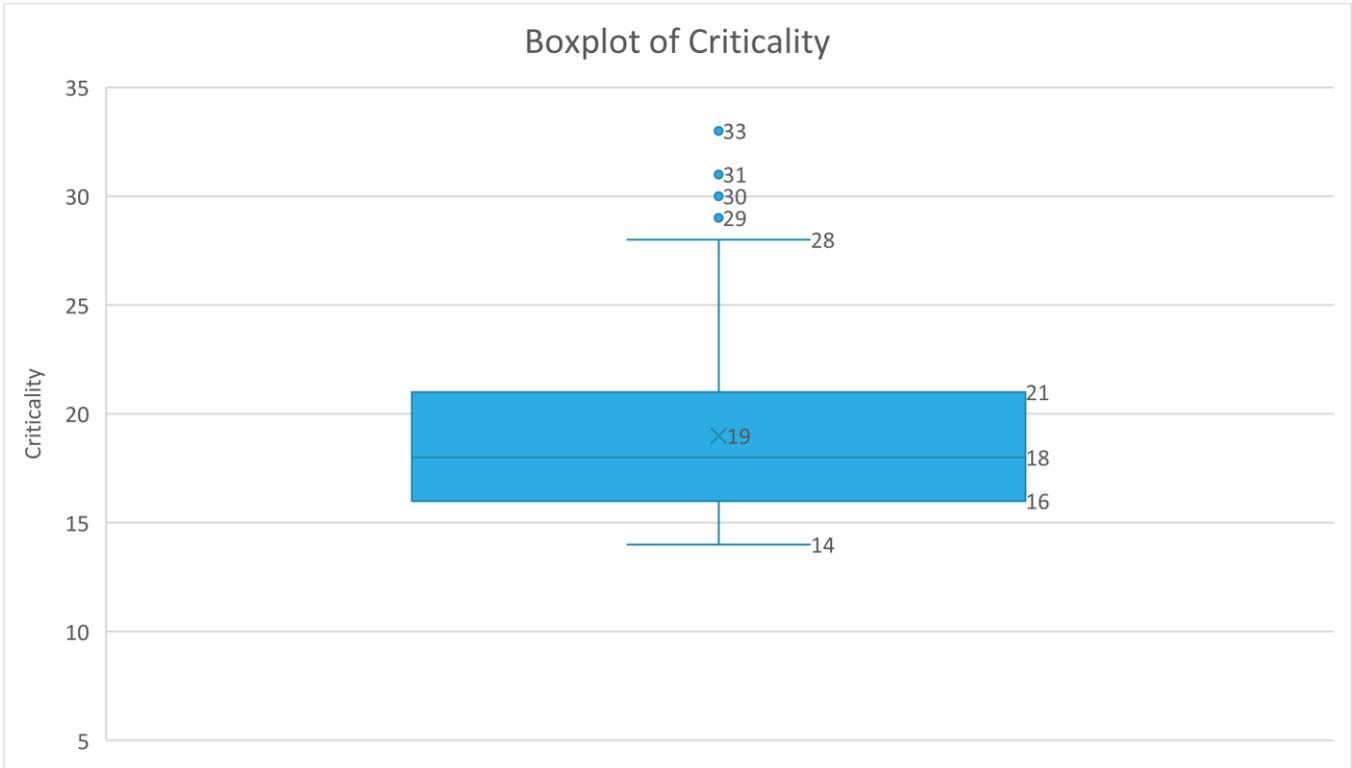
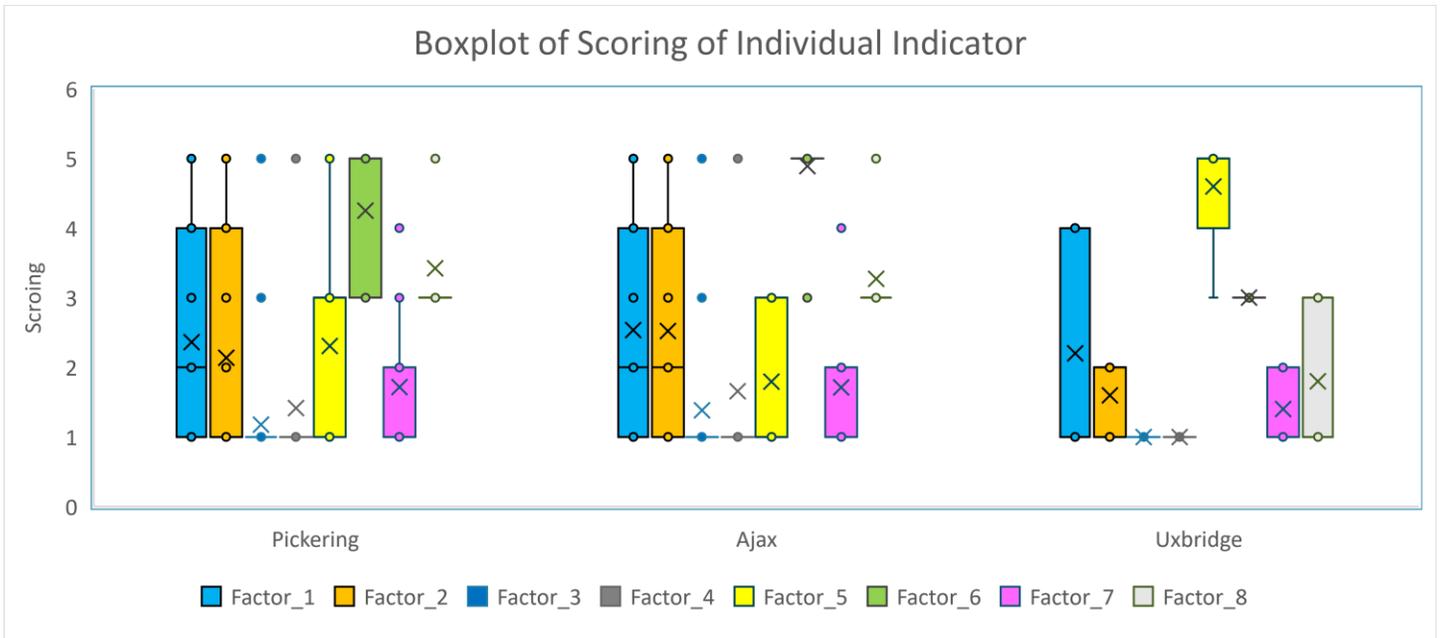**FIGURE 5-16 BOXPLOT OF CRITICALITY**

FIGURE 5-17 BOXPLOT OF CRITICALITY SCORES BY FACTOR FOR ROADS IN EACH MUNICIPALITY

6   BRIDGE AND CULVERT CAPACITY ASSESSMENT

The crossing capacity analysis produced two GIS layers (point shapefiles) for each watershed, one for the performance of the crossing under existing climate conditions, and another for the performance under future climate conditions. Two different future climate conditions were considered for each crossing: future mid-century (2050), and future end-of-century (2080). These scenarios consider the shifted return period of the simulated storms as derived from the analysis presented in Section 4. Each layer contains attributes as described in Table 6-1, and note that only the database for future climate contains attributes of Act_LOS_Ex, VIO_MTO_Ex, Act_LOS_FM, VIO_MTO_FM, and Act_LOS_FE, VIO_MTO_FE.

Table 6-2 summarizes the number of crossings that do not meet MTO criteria under existing, future-midcentury and future-end century conditions. As illustrated in the table, the return period shifts associated with climate change would significantly impact the level of service (in terms of hydraulic capacity) that a crossing could provide. In the climate change scenarios, extreme weather occurs more frequently, resulting in events that are considered rare in the current climate scenario (e.g. the100yr return period storm) occurring more frequently in the future (e.g. the 100yr storm would become the 50yr return period storm), thus more crossings would be overtopped in the future 50-year storm scenario.

In the Frenchman's Bay watershed, under existing climate conditions 11 out of 33 crossings (as represented in TRCA modelling) do not meet MTO criteria, comparing to 16 out of 33 under future climate conditions. In the Petticoat Creek watershed, under existing climate conditions only two out of 25 crossings do not meet MTO criteria, as compared to nine out 25 under the future climate scenarios. In Duffins Creek, under existing climate conditions, 10 out of 149 crossings do not meet MTO criteria, compared to 28 out of 149 under future climate conditions. In Carruthers Creek, under existing climate conditions only one out of 34 crossings does not meet MTO criteria, compared to 10 out 34 under future climate conditions.

Figure 6-1 to Figure 6-4 illustrate which crossings meet or do not meet MTO criteria, under both Existing and Future climate conditions. The legend for the annotation in the figures is as follows, with the Y/N fields indicating whether or not the crossing capacity violates the MTO criteria:

- Ex, FM, FE: Existing Climate Condition, Future Mid-Century Climate Condition, Future End-Century Climate Condition

- N, N, N: Meets MTO Criteria under Existing condition, Meets MTO Criteria under Future Mid-Century conditions, Meets MTO Criteria under Future End-Century conditions

- N, N, Y: Meets MTO Criteria under Existing conditions, Meets MTO Criteria under Future Mid-Century conditions, Does Not Meet MTO Criteria under Future End-Century conditions

- N, Y, Y: Meets MTO Criteria under Existing condition, Does Not Meet MTO Criteria under Future Mid-Century conditions, Does Not Meet MTO Criteria under Future End-Century conditions

- Y, Y, Y: Does Not Meet MTO Criteria under Existing conditions, Does Not Meet MTO Criteria under Future Mid-Century conditions, Does Not Meet MTO Criteria under Future End-Century conditions

TABLE 6-1 ATTRIBUTE TABLE FOR CROSSING CAPACITY DATABASE

Attribute	Type	Precision	Number of Characters	Description
ID	Long	10	2	Durham 6 digits road ID
Stru_ID	String	50	7	TRCA Structure ID defined as first three letter of watershed plus 2-3 digits, e.g., CAR_01 and duf_001
Watershed	String	50	9	TRCA watershed name
FUNCTION_	String	10	9	Road classifications
JURISDICT	String	10	9	Ownership of roads
FULL_NAME	String	32	9	Road name plus suffix of roads
RED_RD	String	25	6	Durham regional road plus number
POL_CLASS	Long	5	9	Road classifications
MUNICIPAL	String	10	9	Name of municipalities
RiverName	String	16	9	River Name assigned in TRCA hydraulic model
ReachName	String	16	9	Reach Name assigned in TRCA hydraulic model
River_Sta	Double		9	River Station assigned in TRCA hydraulic model
RdEnv	String	20	5	Environment where road is located, i.e., Urban, Rural or Semi-Urban; for this study, road is assigned either Urban or Rural for assessing level of service of road as per MTO criteria, so Semi-Urban has been reassigned either Urban or Rural based on whether road is close to Rural or closer to Urban
Stru_Span	Double		9	Total span of all openings at a crossing
MTO_Criter	String	50	10	MTO design flood criteria (Directive B-100) based on Road Environment, Total Span and Road Classification.
Leng_Reg	Double		8	Road segment length intersects with Regulatory flood extent
Dept_Reg	Double		8	Max. flood depth within road segment (road width) intersects with Regulatory flood extent
Leng_2yr	Double		8	Road segment length intersects with 2yr flood extent (Existing storm event)
Dept_2yr	Double		8	Max. flood depth within road segment (road width) intersects with 2yr flood extent (Exising storm event)
Leng_5yr	Double		8	Road segment length intersects with 5yr flood extent (Existing storm event)
Dept_5yr	Double		8	Max. flood depth within road segment (road width) intersects with 5yr flood extent (Exising storm event)
Leng_10yr	Double		9	Road segment length intersects with 10yr flood extent (Existing storm event)
Dept_10yr	Double		9	Max. flood depth within road segment (road width) intersects with 10yr flood extent (Exising storm event)
Leng_25yr	Double		9	Road segment length intersects with 25yr flood extent (Existing storm event)
Dept_25yr	Double		9	Max. flood depth within road segment (road width) intersects with 25yr flood extent (Exising storm event)
Leng_50yr	Double		9	Road segment length intersects with 50yr flood extent (Existing storm event)
Dept_50yr	Double		9	Max. flood depth within road segment (road width) intersects with 50yr flood extent (Exising storm event)
Leng_100yr	Double		10	Road segment length intersects with 100yr flood extent (Existing storm event)
Dept_100yr	Double		10	Max. flood depth within road segment (road width) intersects with 100yr flood extent (Exising storm event)
Act_LOS_Ex	String	25	10	Actual level of service a crossing provides, i.e. max. design storm at which a crossing is not overtopped (Existing storm event)
VIO_MTO_Ex	String	10	10	if actual level of service of a crossing does not meet MTO criteria, N - Act_LOS is smaller than MTO_Criter, i.e. not in violation of MTO criteria. And Y - Act_LOS is equal to or larger than MTO_Criter, i.e. in violation of MTO Criteria (Existing storm event)
Act_LOS_FM	String	25	10	Actual level of service a crossing provides, i.e. max. design storm at which a crossing is not overtopped (Future Climate - Mid Century)

Attribute	Type	Precision	Number of Characters	Description
VIO_MTO_FM	String	10	10	if actual level of service of a crossing does not meet MTO criteria, N - Act_LOS is smaller than MTO_Criter, i.e. not in violation of MTO criteria. And Y - Act_LOS is equal to or larger than MTO_Criter, i.e. in violation of MTO Criteria (Future Climate - Mid Century)
Act_LOS_FM	String	25	10	Actual level of service a crossing provides, i.e. max. design storm at which a crossing is not overtopped (Future Climate - End Century)
VIO_MTO_FM	String	10	10	if actual level of service of a crossing does not meet MTO criteria, N - Act_LOS is smaller than MTO_Criter, i.e. not in violation of MTO Criteria. And Y - Act_LOS is equal to or larger than MTO_Criter, i.e. in violation MTO Criteria (Future Climate - End Century)

TABLE 6-2 SUMMARY OF NUMBER OF CROSSING NOT MEETING MTO CRITERIA FOR EXISTING AND FUTURE CLIMATE

Watersheds	Total Number of Crossings	Number of Crossings Not Meeting MTO Criteria		
		Existing Climate	Future Climate Mid-Century	Future Climate End - Century
Frenchman's Bay	33	11	16	16
Petticoat Creek	25	2	9	9
Duffins Creek	149	10	28	28
Carruthers Creek	34	1	10	14

FIGURE 6-1 CROSSINGS IN FRENCHMAN'S BAY WATERSHED FOR EXISTING AND FUTURE CLIMATE CONDITION

(N – NOT IN VIOLATION OF MTO CRITERIA, Y –IN VIOLATION OF MTO CRITERIA)

FIGURE 6-2 CROSSINGS IN PETTICOAT CREEK WATERSHED FOR EXISTING AND FUTURE CLIMATE CONDITION

(N – NOT IN VIOLATION OF MTO CRITERIA, Y –IN VIOLATION OF MTO CRITERIA)

FIGURE 6-3 CROSSINGS IN DUFFINS CREEK WATERSHED FOR EXISTING AND FUTURE CLIMATE CONDITION

(N – NOT IN VIOLATION OF MTO CRITERIA, Y –IN VIOLATION OF MTO CRITERIA)
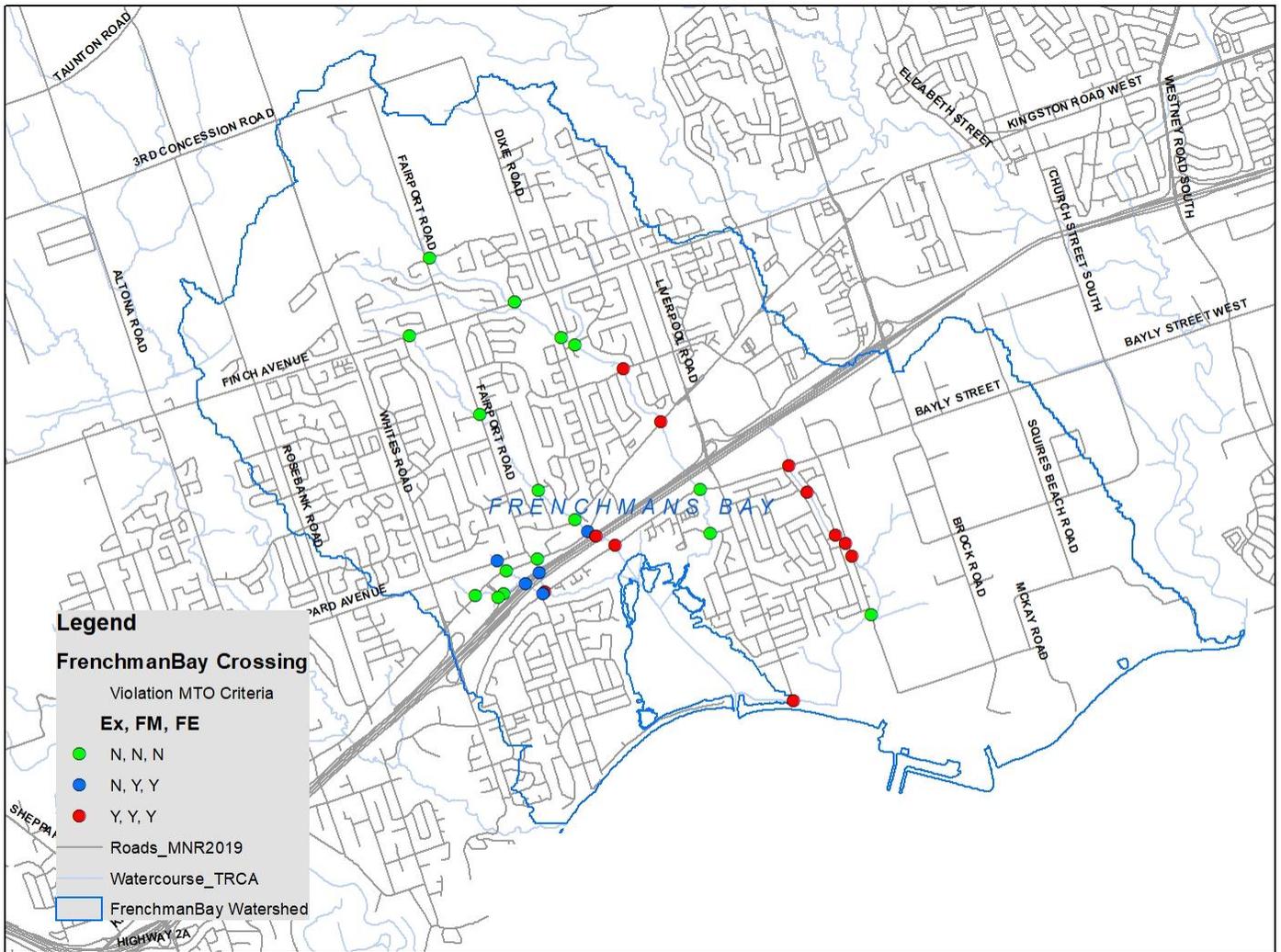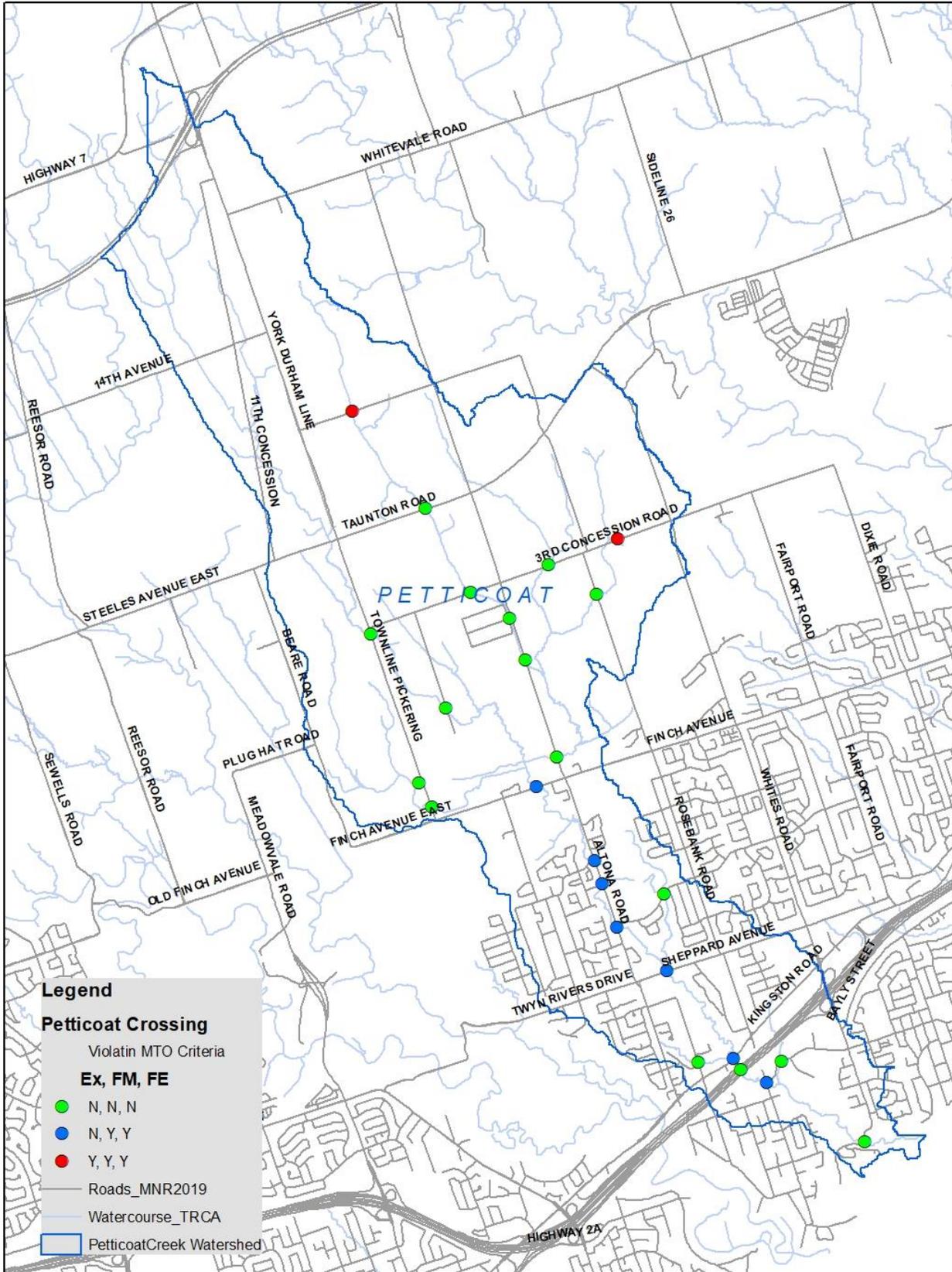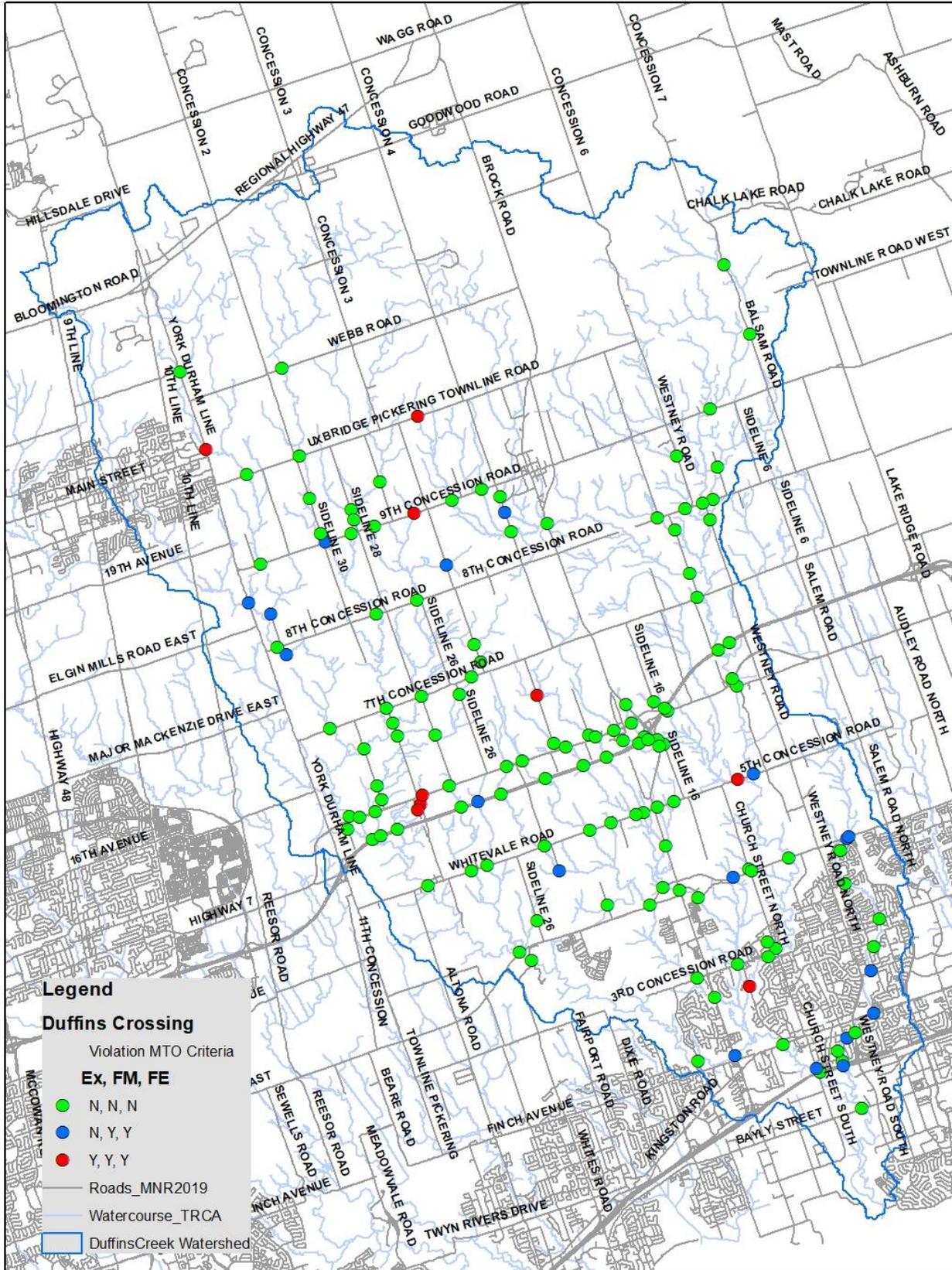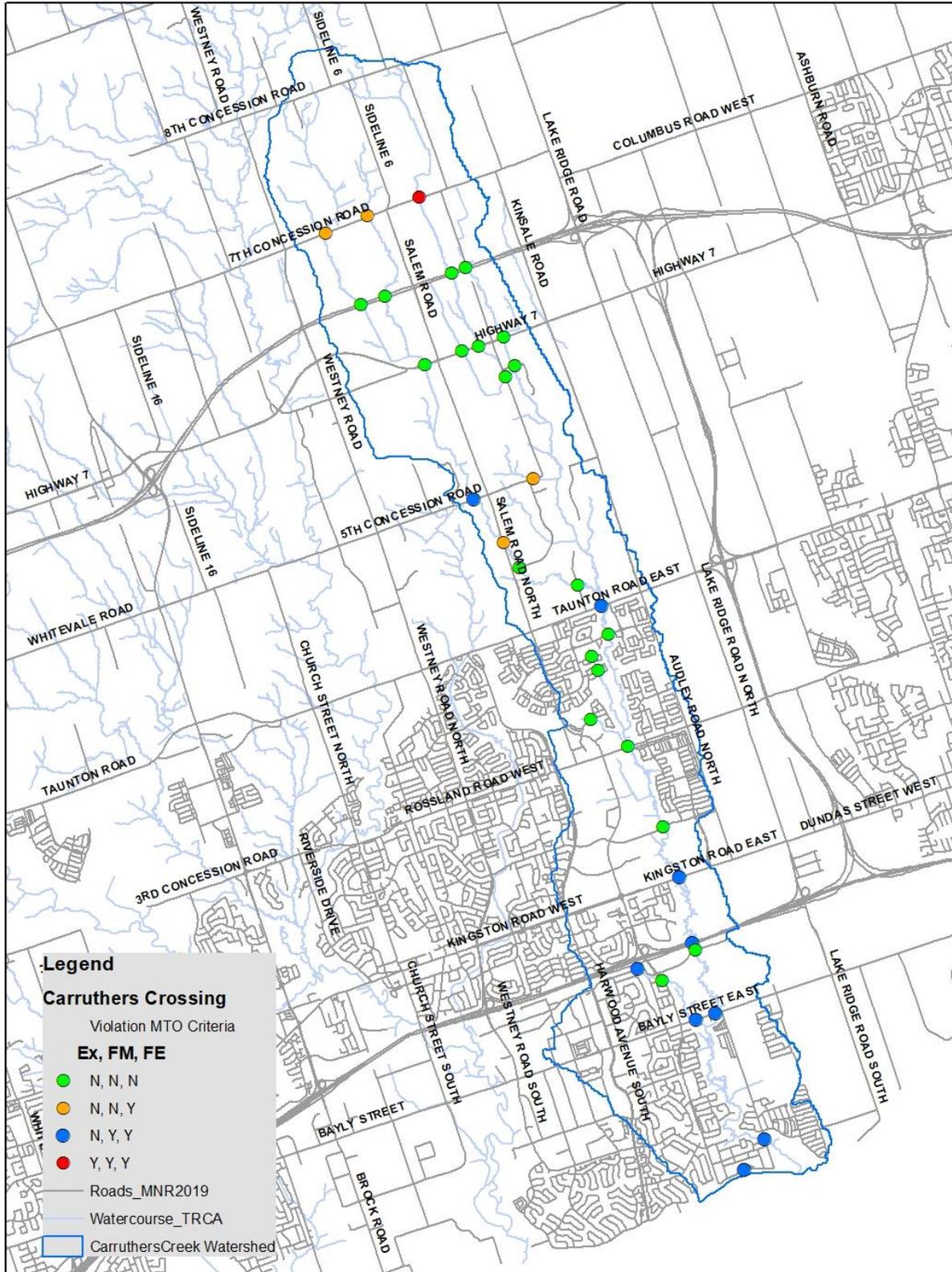
FIGURE 6-4 CROSSINGS IN CARRUTHERS CREEK WATERSHED FOR EXISTING AND FUTURE CLIMATE CONDITION

(N – NOT IN VIOLATION OF MTO CRITERIA, Y –IN VIOLATION OF MTO CRITERIA)

7 INUNDATED ROAD SEGMENT ASSESSMENT

The inundated road segment assessment (road database) is a separate database from the crossing capacity database and is built to assess the disruption and criticality of road segments that are impacted by riverine flooding, not just crossings. For each watershed there are two GIS layers (polyline shapefiles), one for the existing climate scenario and another for the future climate scenario. Each layer contains the attributes shown in Table 7-1; however only the database for future climate conditions contains the attributes of AAD_Ex (Average Annual Disruption – Existing Conditions), AAD_FM (Average Annual Disruption – Future Mid-Century Conditions), and AAD_FE (Average Annual Disruption – Future End-of-Century Conditions).

As described in Section 3.4, combining vulnerability information with flood depth information allows affected roads to be identified for each return period flood event. The information on traffic volume (i.e., AADT) provided by road segment is used to determine the average annual disruption (i.e., AAD). The steps are briefly summarized as follows:

- Affected roads: To determine whether a road would be disrupted due to flooding, the maximum flood depth for a given road segment was compared to the closure threshold, which was established as 0.15m as described in earlier sections. Roads with inundation of less than 0.15m would have an event-based disruption of 0 for that event.

- Disruption due to flooded roads: The disruption, which is the daily traffic x time of closure (with time of closure dependent of flood depth as previously described) is calculated for each return period event, and then the average annualized disruption is calculated by factoring in the likelihood of that event (i.e., Annual Exceedance Probability) with the event-based disruption.

Table 7-2 summarizes the number of inundated road segments categorized based on the function of the road within each watershed. Table 7-3 uses select roadways within Duffins Creek as an example to illustrate the disruption results based on the steps described above. It can be seen in this example that once freeways and regional roads are affected by flooding, the impact would be much higher than when only municipal arterials, collector, and local roads are flooded. This reflects both the likelihood and impact factors increasing, as freeways and regional roads carry very high volumes of traffic, and also freeways are usually designed such that they are only impacted by the most severe (less likely) of storms, such as Hurricane Hazel. Figure 7-2 to Figure 7-5 shows the location of inundated road segments as well as AAD categories for the existing climate conditions for each watershed.

Future Climate change is also incorporated in the disruption analysis, which is reflected in the revised values of AEP. With future climate change, less frequent return periods would occur more frequently (e.g., the 100yr storm under existing conditions would become the 30-year storm under future mid-century conditions, orthe 26yr storm under future end-century conditions). These increases in likelihood result in higher average annualized disruptions because the event-based disruption is multiplied by a higher probability factor. Table 7-4 shows a comparison of statistics of AADs among existing and future climate conditions for select roads, and Figure 7-1 shows the comparison of average AADs among existing and future climate conditions for each watershed. As expected, both figures illustrate an increase in AADs with the increased AEP due to future climate change. The increase in AADs is most significant in Frenchman's Bay, while the increase in AADs is least significant in Carruthers Creek.

The higher flood vulnerability in the Frenchman's Bay watershed may be due to the age of the underlying hydrology and hydraulic models used in these areas. Newer models utilize more detailed topographic data, as well as more up-to-date crossing information. Additionally, the part of Pickering that comprises the Frenchman's Bay watershed has a higher degree of historical development than the other watershed areas within TRCA's jurisdiction,, which in turn may imply a

higher proportion ofolder crossings (designed using older criteria or flow rates based on older data) and fewer stormwater management measures.

TABLE 7-1 ATTRIBUTE TABLE FOR ROAD CAPACITY DATABASE

Attribute	Type	Precision	Number of Characters	Description
ID	Long	10	2	Durham 6 digits road ID
ID_V2	String	25	5	Durham 6 digits road ID plus a sub number for same road intersects with same flood event
Watershed	String	20	9	TRCA watershed name
FUNCTION_	String	10	9	Road classifications
JURISDICT	String	10	9	Ownership of roads
FULL_NAME	String	32	9	Road name plus suffix of roads
RED_RD	String	19	6	Durham regional road plus number
POL_CLASS	Long	5	9	Road classifications
MUNICIPAL	String	10	9	Name of municipalities
Leng_Reg	Double		8	Road segment length intersects with Regulatory flood extent
Dept_Reg	Double		8	Max. flood depth within road segment (road width) intersects with Regulatory flood extent
Leng_2yr	Double		8	Road segment length intersects with 2yr flood extent
Dept_2yr	Double		8	Max. flood depth within road segment (road width) intersects with 2yr flood extent
Leng_5yr	Double		8	Road segment length intersects with 5yr flood extent
Dept_5yr	Double		8	Max. flood depth within road segment (road width) intersects with 5yr flood extent
Leng_10yr	Double		9	Road segment length intersects with 10yr flood extent
Dept_10yr	Double		9	Max. flood depth within road segment (road width) intersects with 10yr flood extent
Leng_25yr	Double		9	Road segment length intersects with 25yr flood extent
Dept_25yr	Double		9	Max. flood depth within road segment (road width) intersects with 25yr flood extent
Leng_50yr	Double		9	Road segment length intersects with 50yr flood extent
Dept_50yr	Double		9	Max. flood depth within road segment (road width) intersects with 50yr flood extent
Leng_100yr	Double		10	Road segment length intersects with 100yr flood extent
Dept_100yr	Double		10	Max. flood depth within road segment (road width) intersects with 100yr flood extent
RdEnv	String	20	5	Environment where road is located, i.e Urban, Rural or Semi-Urban; for this study, road is assigned either Urban or Rural for assessing level of service of road as per MTO criteria, so Semi-Urban has been reassigned either Urban or Rural based on whether road is close to Rural or closer to Urban
AADT	Long	10	4	Annual Average Daily Traffic volume; for Durham regional roads, AADT is taken from Regional AADT feature; for Highway 400 series/Highway 7, AADT is taken from MTO published AADT for year of 2016; for Highway 407, AADT is taken from 407 ETR published Usage Statistics; for local road, AADT is taken from the Pickering/Ajax provided data with high end of range to be conservative; for missing data, AADT is filled using known AADT values from similar type of roads in similar environment.
AAD_Ex	Double		6	Annualized Average Disruption, AAD is a sum of AADs of all storm events; AAD (event) = AEP*Closure Time*AADT where AEP is inverse of design storm (e.g. 1/100 = 1% for 100yr design storm) (Existing storm events)
AAD_FM	Double		6	Annualized Average Disruption, AAD is a sum of AADs of all storm events; AAD (event) = AEP*Closure Time*AADT where AEP is inverse of design storm (e.g. 1/100 = 1% for 100yr design storm) (Future Climate - End Century)
AAD_FE	Double		6	Annualized Average Disruption, AAD is a sum of AADs of all storm events; AAD (event) = AEP*Closure Time*AADT where AEP is inverse of design storm (e.g. 1/100 = 1% for 100yr design storm) (Future Climate - End Century)

TABLE 7-2 NUMBER OF INUNDATED ROAD SEGMENTS

Watersheds	Total Number of Crossings	Freeways/Ramps	Arterial Roads	Collectors	Local Roads
Frenchman's Bay	41	4	11	14	12
Petticoat Creek	45	3	17	5	20
Duffins Creek	166	10	57	12	87
Carruthers Creek	39	2	20	0	17

TABLE 7-3 SUMMARY OF MAX FLOOD DEPTH AND DISRUPTION DUE TO FLOODING ON SELECTED ROAD TYPE IN DUFFINS CREEK

Maximum Flood Depth/Closure Time on Selected Road Type in Duffins Creek (Grey = flood depth above threshold (i.e., 0.15m))

AEP	Return Period	Highway (HWY 401) ID: 114101	Regional Road (Finch Ave.) ID: 113792	Municipal Arterial (Church St.) ID: 116233	Local Road (Sideline 26) ID:115860
		(m)/(day)	(m)/(day)	(m)/(day)	(m)/(day)
0.1%	Hurricane Hazel	1.02/1	2.06/1	3.64/1	0.62/0.5
1%	100yr	0	0.22/0.1	0.20/0.1	0.42/0.25
2%	50yr	0	0.06	0.04	0.40/0.25
4%	25yr	0	0	0	0.38/0.25
10%	10yr	0	0	0	0.33/0.25
20%	5yr	0	0	0	0.30/0/0.25
50%	2yr	0	0	0	0.23/0.1

Event Based Disruption Due to Flooding in on Selected Road Types in Duffins Creek (AD = AADT*Closure time)

AEP	Return Period	Highway (HWY 401) ID: 114101	Regional Road (Finch Ave.) ID: 113792	Municipal Arterial (Church St.) ID: 116233	Local Road (Sideline 26) ID:115860
		(vehicle*days)	(vehicle*days)	(vehicle*days)	(vehicle*days)
0.1%	Hurricane Hazel	222886	11265	10050	250
1%	100yr	0	1127	1005	125
2%	50yr	0	0	0	125
4%	25yr	0	0	0	125
10%	10yr	0	0	0	125
20%	5yr	0	0	0	125
50%	2yr	0	0	0	50

Average Annualized Disruption Due to Flooding in on Selected Road Type in Duffins Creek (AAD = AADT*Closure time*AEP)

AEP	Return Period	Highway (HWY 401) ID: 114101	Regional Road (Finch Ave.)	Municipal Arterial (Church St.)	Local Road (Sideline 26)
		(vehicle*days)	(vehicle*days)	(vehicle*days)	(vehicle*days)
0.1%	Hurricane Hazel	223	11	10	0 (0.25)
1%	100yr	0	11	10	1
2%	50yr	0	0	0	3
4%	25yr	0	0	0	5
10%	10yr	0	0	0	12
20%	5yr	0	0	0	25
50%	2yr	0	0	0	25
AAD		**223**	**22**	**20**	**71**

TABLE 7-4 COMPARISON OF AADS AMONG EXISTING AND FUTURE CLIMATE CONDITIONS

Frenchman's Bay			
Statistics	Average Annual Disruption - Existing Conditions(AAD_Ex)	Average Annual Disruption - Future Mid-Century Conditions(AAD_FM)	Average Annual Disruption – Future End-of-Century Conditions (AAD_FE)
Min	0	0	0
Max	1891.88	3112.45	3722.74
Mean	99.13	167.89	199.15
St.Deviation	310.8	514.08	613.37
Petticoat Creek			
Min	0	0	0
Max	108.78	123.16	138.81
Mean	7.17	8.01	8.72
St.Deviation	17.02	19.38	21.86
Duffins Creek			
Min	0	0	0
Max	870.13	1000	1189.81
Mean	14.11	18.38	21.27
St.Deviation	73.51	95.55	114.97
Carruthers Creek			
Min	0	0	0
Max	166.9	166.9	166.9
Mean	10.3	10.72	10.96
St.Deviation	36.64	36.75	36.89

Comparison of Average AAD of Existing and Future Climate Conditions

	Frenchman's Bay	Petticoat Creek	Duffins Creek	Carruthers Creek
■ AAD_Ex	99	7	14	10
■ AAD_FM	168	8	18	11
■ AAD_FE	199	9	21	11
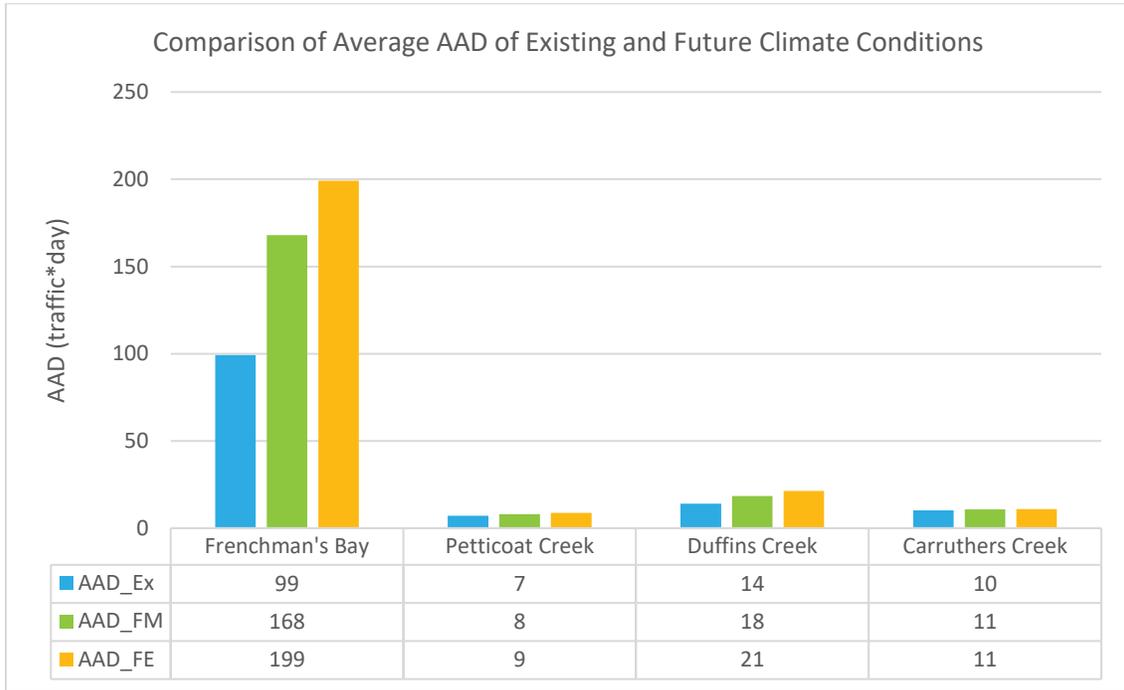
FIGURE 7-1 COMPARISON OF AVERAGE AAD OF EXISTING AND FUTURE CLIMATE CONDITIONS

Legend

FrenchmansBay Inundated Road Segments

AAD_Ex
- < 5
- 5 - 10
- 10 - 25
- 25 - 50
- 50 - 100
- 100 - 150
- 150 - 200
- 200 - 250
- 250 - 500
- 500 - 1000
- > 1000
- Roads_MNR2019
- TRCA Regulatory Floodlines
- FrenchmanBay Watershed
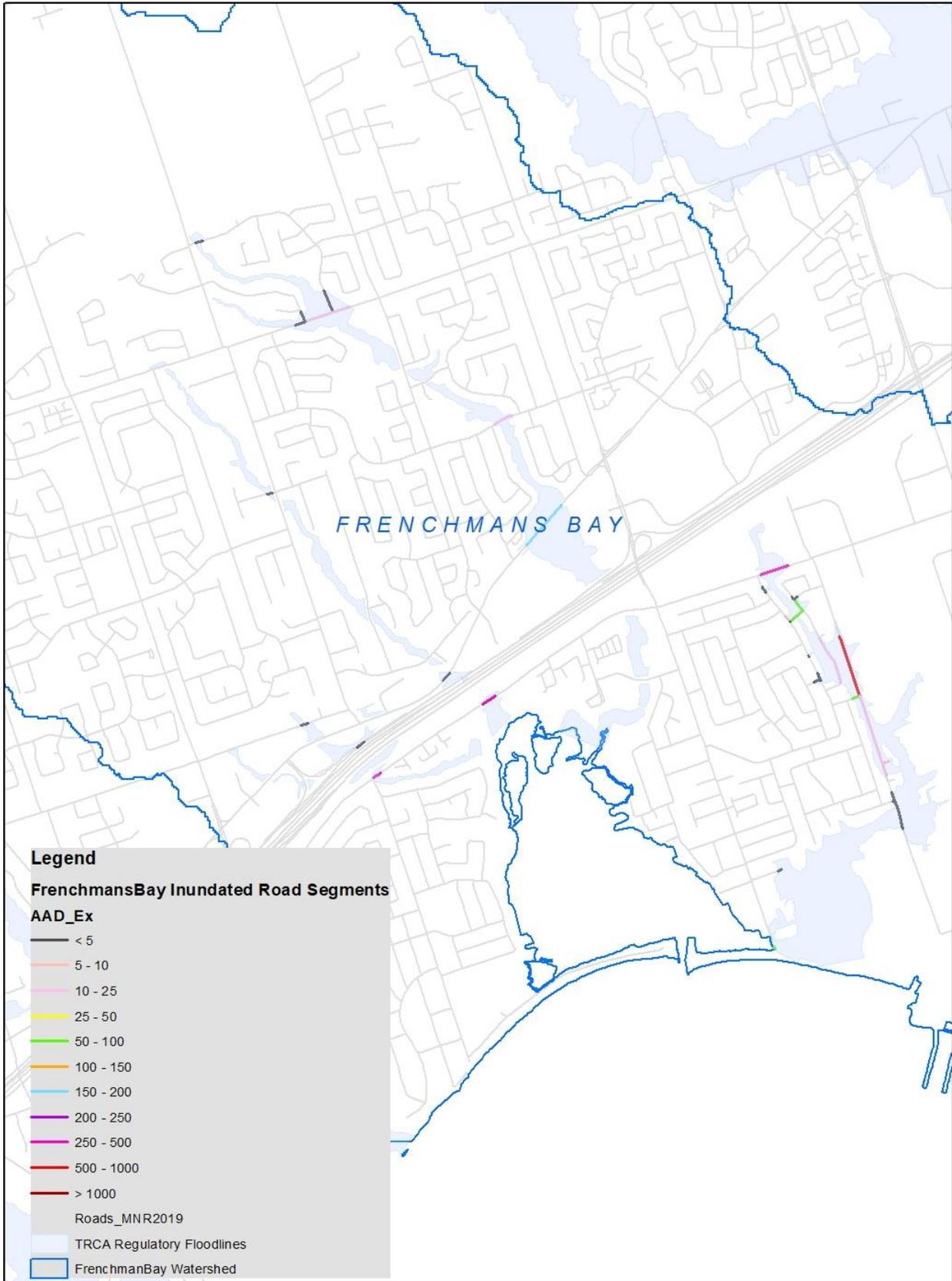
FIGURE 7-2 INUNDATED ROAD SEGMENTS IN FRENCHMAN'S BAY WITH AAD FOR EXISTING CLIMATE CONDITION
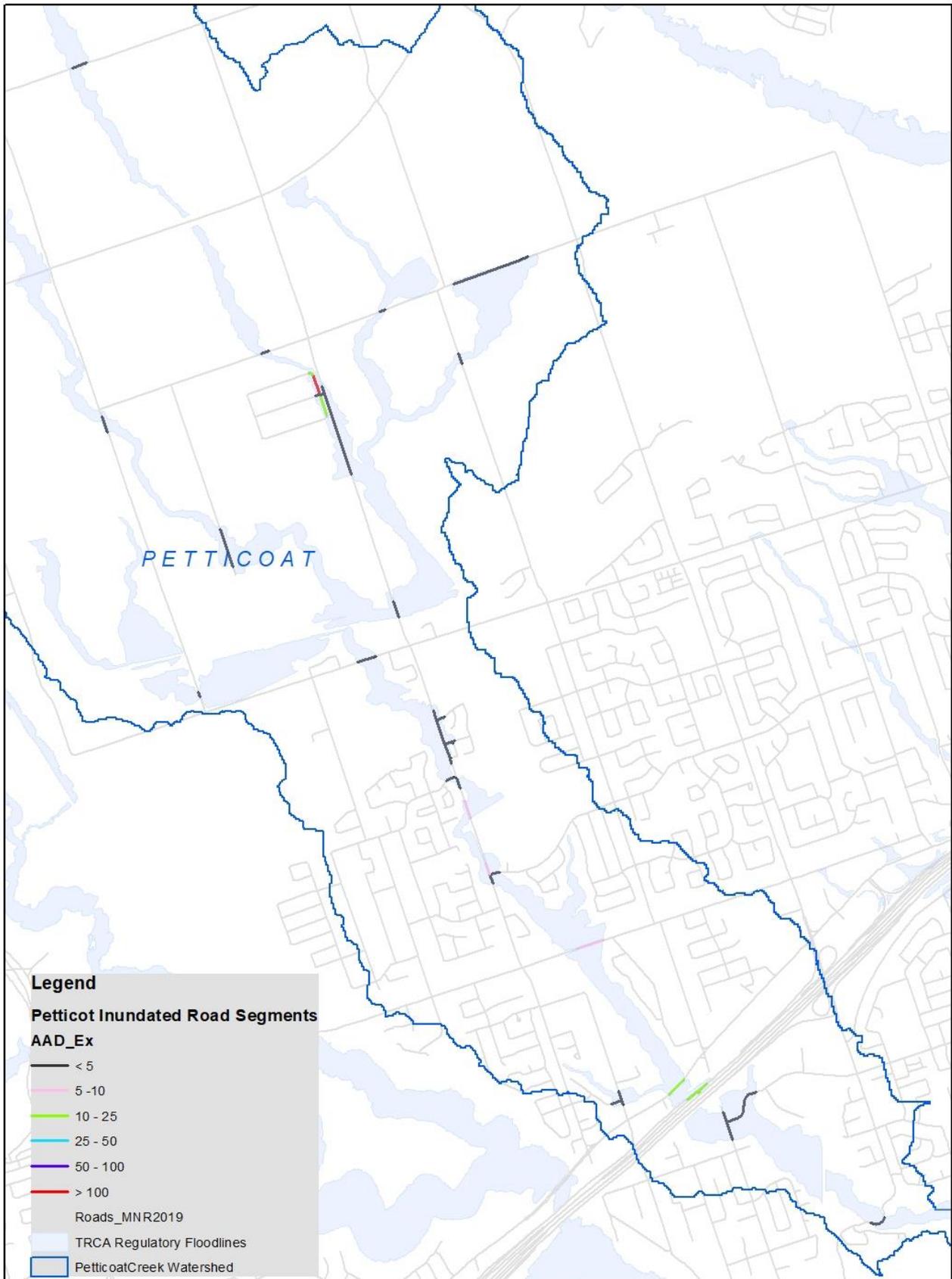
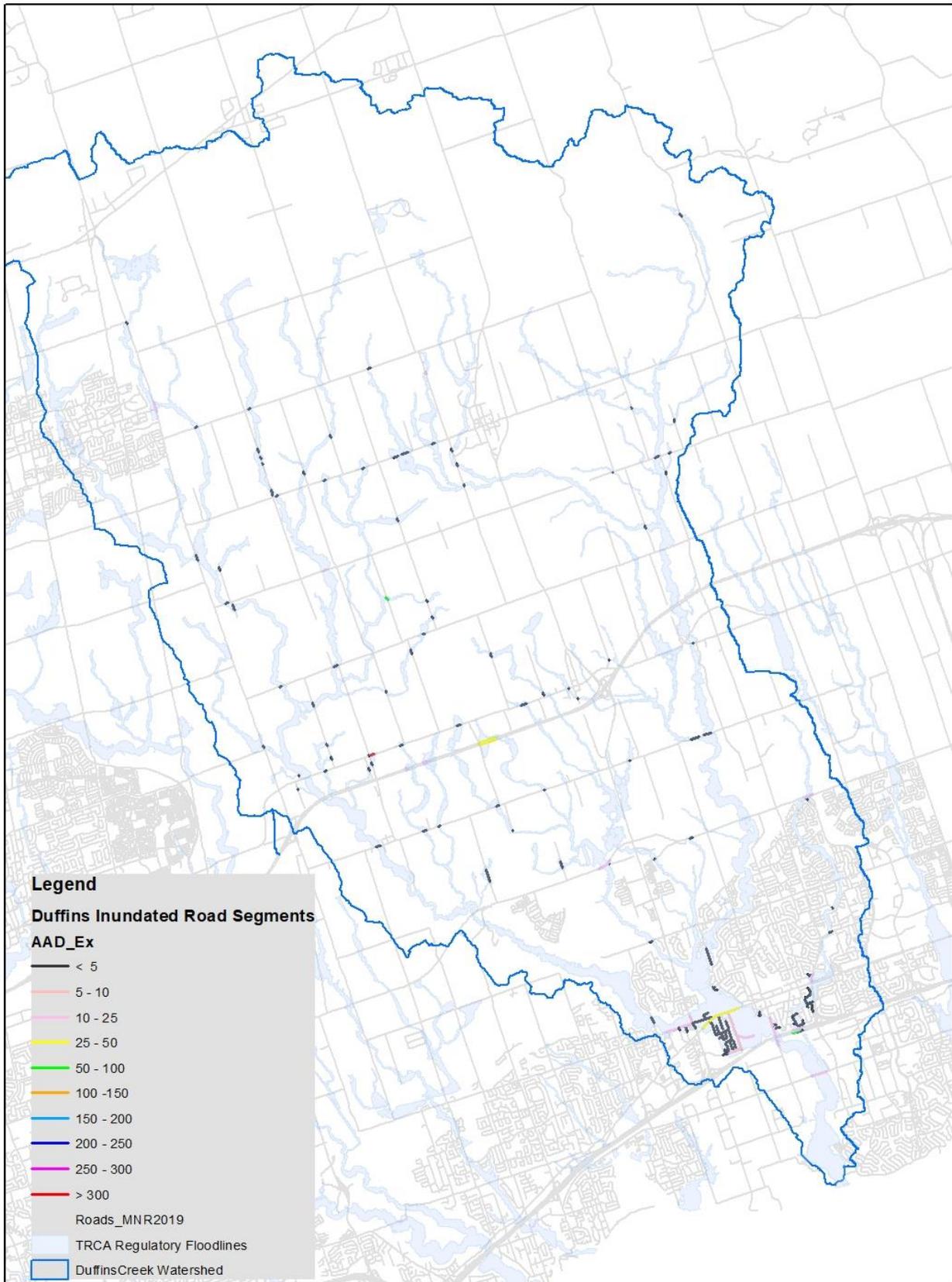**FIGURE 7-3 INUNDATED ROAD SEGMENTS IN PETTICOAT CREEK WITH AAD FOR EXISTING CLIMATE CONDITION**

FIGURE 7-4 INUNDATED ROAD SEGMENTS IN DUFFINS CREEK WITH AAD FOR EXISTING CLIMATE CONDITION
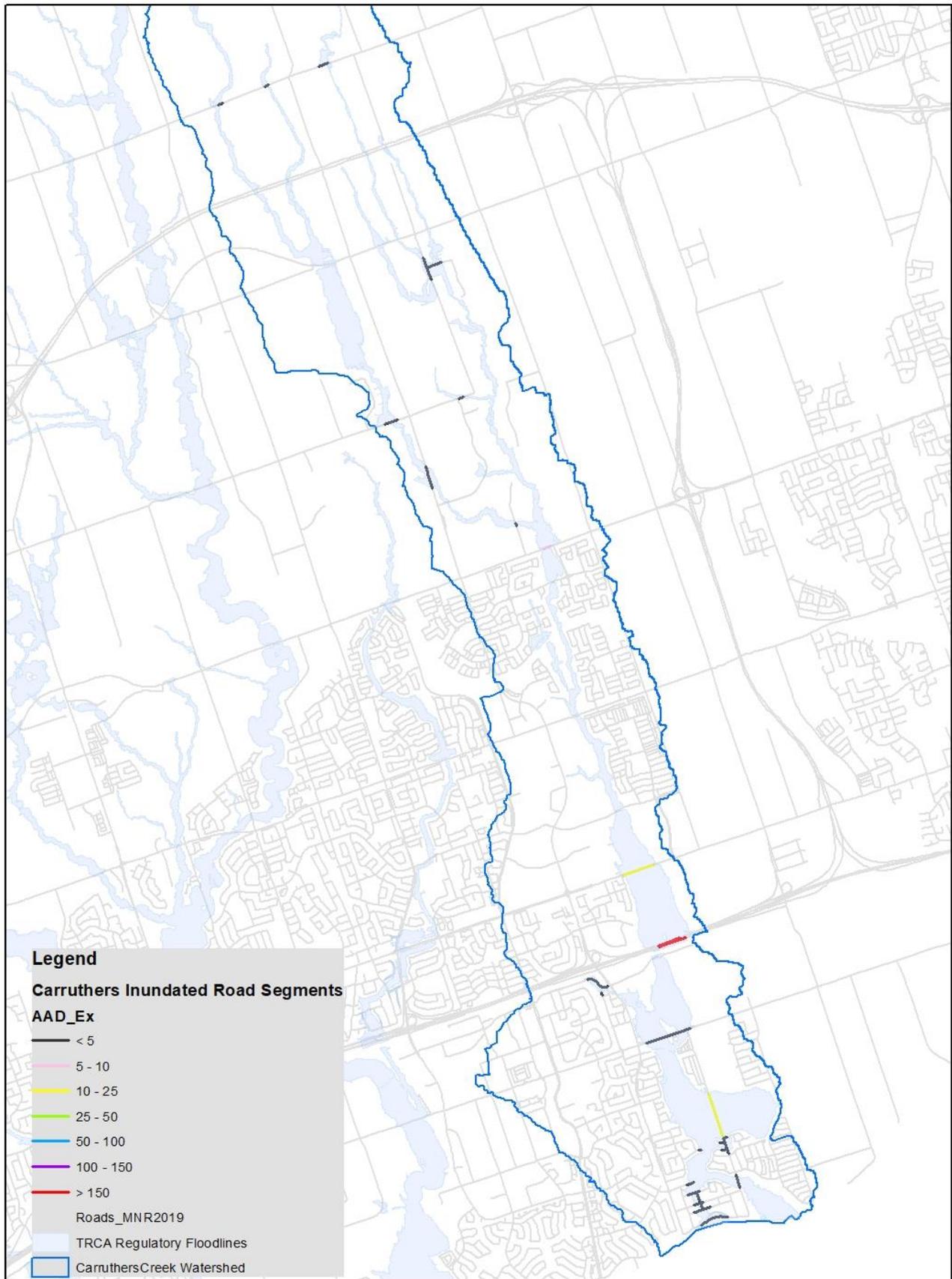
FIGURE 7-5 INUNDATED ROAD SEGMENTS IN CARRUTHERS CREEK WITH AAD FOR EXISTING CLIMATE CONDITION

8 SUMMARY

This project brought together flood impact information, road criticality information, and hydraulic model information to provide a desktop-based risk ranking of roads at risk of riverine flooding, as well as characterize the hydraulic performance of crossings (as reflected in TRCA's hydraulic models) in comparison to MTO Criteria. As part of this study, a study on how to incorporate future climate change was conducted by Savanta and the Climate Risk Institute (CRI) in which an approach of "shifting" return periods based on future climate scenarios was developed, i.e., "shifting" the annual exceedance probability (AEP) of already-modelled storms considering climate change. The results of this study, namely the projected "shifted return period" tables, were used to add a climate change scenario to the flood vulnerable roads and crossing databases.

Crossing information and results were extracted from TRCA's current hydraulic models for four watersheds within Durham Region. The extracted model information was further processed to identify which crossings were pressurized and/or overtopped, and the first return period at which they became pressurized or overtopped (meaning that they could not pass the associated storm event). This provided information on the actual level of service a crossing could provide. The Ontario Ministry of Transportation (MTO) provides Flood Design Criteria to assign the hydraulic level of service that a crossing is supposed to provide, depending on the road classification, road environment and crossing span. TRCA undertook a comparison between actual level of service provided by the crossing versus the MTO design level of service, which revealed that several crossings in each of the four watersheds did not provide the current level of service as per MTO design criteria. In addition, the crossing capacity assessment was also undertaken to incorporate future climate change conditions, i.e., shifted return periods, which identified more crossings that would not meet MTO criteria in the future, due to the anticipated shifting of return periods for the associated storm flows moving from being less frequent to more frequent.

The flood vulnerability of roads was also assessed by extracting the maximum flood depth for each modelled event over the road for each inundated road segment within the regulatory flood plain. Using consensus-based tables to assign a closure disruption to flood depth, and utilizing daily traffic information for each road segment, the event-based disruption and average annualized disruption (AAD) for the road segments was calculated. AAD is a function of closure time, annual average daily traffic and Annual Exceedance Probability (AEP). Future climate change scenarios were incorporated in the flood vulnerable road assessment, as reflected by revised AEP in calculations of AAD.

The criticality of road segments was also assessed, based on eight factors: 1) Functional classification of roads; 2) Average annual daily traffic; 3) Designated Transit Routes; 4) Goods movement routes; 5) Degree of redundancy; 6) Evacuation and disaster recovery - proximity to nuclear hazards; 7) Proximity to sensitive receptors and 8) Social equity and justice. Each of the above indicators was assigned a score, based on a scale from one to five, with an overall criticality score calculated as a sum of the scores for each of the eight factors for each inundated road segment. The larger the combined score along a road, the more critical a given road segment is. The criticality scores were then converted to a multiplier that was applied to the average annualized disruption, for a comprehensive flood risk score.

The deliverables from this study include:

1. A geodatabase of crossing capacity information for each watershed, including a crossing point shapefile, and a crossing table for each storm event for both existing and future climate conditions.
2. A geodatabase of road capacity information for each watershed, including the road segment polyline shapefile, the road table including disruption calculation for each storm event for both existing and future climate condition and the average annual disruption (AAD)

3. A geodatabase of criticality ranking for the road segments, including a road segment polyline shapefile for each factor, and one for the criticality score determined by the combined 8 factors.
4. An ArcGIS .mxd file which contains links to each above geodatabase and select map views.
5. A comprehensive report which details methodologies and results (this report), as well as a short executive summary report.

9   RECOMMENDATIONS

The Flood Vulnerable Road and Crossing Hydraulic Capacity Assessment represents a desktop-analysis based methodology that utilizes available information to screen for crossing upgrade candidates and the flood vulnerability of road segments. A significant component of the work involves pre- and post-processing of information into data formats that are suitable for geospatial analysis. It is important to recognize that the analysis will carry forward the data quality characteristics of the underlying model information. In this light, the following recommendations are provided:

1. Though not within the scope of this current project, the analysis should be updated for Frenchman's Bay and Petticoat Creek watersheds once the hydraulic modelling for those watersheds has been completed. Furthermore, in order to keep the risk assessment current, it should be done after comprehensive floodplain mapping is updated for each watershed.

2. Conservation Authorities wishing to undertake this analysis should make geospatial gridded outputs (including flood depth/elevation) part of the deliverables of flood plain mapping updates, in order to minimize the amount of data processing required as part of this project.

3. Durham Region or local municipalities can utilize this information to screen for potential crossing upgrade candidates but should verify the model structure information against field conditions to confirm performance prior to undertaking design-level analysis. This is particularly important for the Frenchman's Bay and Petticoat Creek crossings, as the Duffins and Carruthers models were more recently updated and utilized crossing information provided by municipal partners.

4. The crossing capacity, road segment, and criticality databases can, be layered in order to see capacity constraints, inundated roads, and criticality simultaneously.

5. There is opportunity for further analysis using the calculation fields in the geodatabase tables directly; for example, the duration of closure field could be utilized in transportation modelling to plan and evaluate disaster response routes.

6. The following summarizes the recommendations from Savanta with respect to the climate change analysis; for a fulsome description of the recommendations please refer to Section 4.

   a. Durham Region's risk tolerance, associated cost-benefit trade-offs, and appetite for upgrading infrastructure (in the face of uncertainty) should be considered prior to adapting results contained in the climate change section of the report. Projected shifts in some return periods can be significant and carry large implications at the municipal level.

b. For future studies, consider the range in projected return periods and annual exceedance probabilities as opposed using *only* the single multi-model ensemble average ("one number") result in the 2050s- and 2080s-time horizons for future return periods of storms.

c. Generally, as these future return periods are applied to public works and implementation of infrastructure-related projects, additional consideration and/or engineering analysis is warranted to ensure that the results are appropriate for site-specific contexts. It is important to recall that climate scenarios can change, and that there is no one scenario that municipalities can design for. Therefore, enable flexibility wherever possible and examine the range in these results as part of engineering analyses and design criteria.

7. As plans for infrastructure upgrades progress, please liaise with TRCA's Infrastructure Planning and Permits team for submission requirements.

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11 GLOSSARY

1-D hydraulic model: 1D hydraulic models solve the cross-sectional-averaged equations to predict water surface elevation and cross-sectional-averaged velocity in a watercourse. 1D hydraulic models are suitable for situations where flow direction is known, and flow is well confined.

2-D hydraulic model:2D hydraulic models discretize the computational domain into structured (uniform cells) or unstructured elements (flexible meshes), solve continuity and momentum equations for each element, and output depth of flow, water surface elevation and velocity at each element. 2D hydraulic models are suitable for situations where flow path of the water is not completely known such as spills, and detailed velocities for the hydraulics of flow (e.g., around a bridge pier) is important.

AEP: Annual Exceedance Probability (AEP) refers to the probability of a flood event occurring in any single year. The probability is expressed as a percentage. For example, a large flood that may be calculated to have a 1% chance to occur in any one year, is described as 1%AEP.

Boxplot: A statistical diagram to represent the range in a dataset using a 5 number summary (i.e, minimum, 25th percentile, 50th or median, 75th percentile, and the maximum). Outliers are plotted as points above and below the minimum and maximum points.

Depth of flow: depth of flow is the computed depth of water at a cross-section of a watercourse or depth of water over ground surface;

Future (climate change) return period shifts: Future climate change return period shifts indicate the expected new return period based on a given historical event amount of rainfall. In other words, how much can the annual exceedance probability (AEP) be expected to "shift" considering climate change projections. AEP refers to the probability of a given event occurring in any given year, expressed as a percentage (e.g., a 1% chance to occur in any one year is a 1% AEP, or a 100-year event).

HEC-RAS: HEC-RAS (Hydraulic Engineering Center's Riverine Analysis System) is a computer program that models the hydraulics of water flow through natural rivers and other channels, which is developed and maintained by U.S. Army Corps of Engineers – Hydrologic Engineering Center. Website: https://www.hec.usace.army.mil/software/hec-ras/;

Inundation polygon: inundation polygon represents the flood extent of a specific storm event which is calculated as computed WSE surface subtracted from terrain layer, and then converted to a polygon extent.

Grid outputs: grid output is a continuous surface with a uniform cell size covering the entire computational domain which is computed by a 2D model directly or is created using the interpolated surface from cross-sections in a 1D model. Grid output type could include water depth, WSE, velocity etc.

LiDAR: LiDAR stands for *Light Detection and Ranging* and is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth.

Return period: Return period, also known as a recurrence interval or repeat interval, is an average time or an estimated average time between events such as earthquakes, floods, landslides, or a river discharge flow to occur.

Regulatory flood line or flood plain: The regulatory flood line or flood plain is the approved standard used in a particular watershed to define the limit of the area that would be flooded under a particular storm event for regulatory purposes. This standard is defined by the Ontario Ministry of Natural Resources and Forestry. Within TRCA's jurisdiction, the regulatory flood plain is based on the more severe of the Regional Storm (Hurricane Hazel), or the 100-year storm; whichever is greater.

Representative Concentration Pathways (RCP): Greenhouse gas concentration trajectory based on volume of greenhouse gases to be emitted in the years to come under different socio-economic scenarios. The scenarios are labelled based on possible changes in radiation balance of the surface-troposphere system by external factors such as increased greenhouse gas concentrations in W/m^2.

SPA: Special Policy Areas (SPAs) are areas within flood plain boundaries of a watercourse where exceptions to the development restrictions of the natural hazards policy (3.1) in the Provincial Policy Statement (PPS), 2005, may be permitted in accordance with technical criteria established by the MNR.

Spill: A flood plain spill area exists where flood waters are not physically contained within the valley or stream corridor and exit into surrounding lands. As a consequence, the limit and depth of flooding are difficult to determine. Flood spill areas occur naturally or can occur as a result of downstream barriers to the passage of flood flows such as undersized bridges or culverts.

Urban Flooding: Also called pluvial flooding, this refers to the inundation of a built environment, caused by rainfall overwhelming the capacity of drainage systems, such as storm sewers and roads. It falls under the mandate of municipalities.

Watercourse crossings: structures (including roads with culverts/bridges) that cross natural watercourses such as rivers, ponds, creeks or other surface areas with running water.

WSE: Water surface elevation is the computed water level at a cross-section of a watercourse or water level over ground surface;

12 APPENDIX A1: CURRENT RETURN PERIOD DESIGN STORMS PLOTTED ON PROJECTED FUTURE IDF CURVES TO ESTIMATE SHIFT IN ANNUAL EXCEEDANCE PROBABILITIES (AEP).

The following section was prepared and provided to TRCA by GEI Consultants (Savanta Division) and CRI.

FIGURE A1 - 1: 2050S PROJECTED COMPARISON TO CURRENT 2-YEAR DESIGN EVENT

Flood Vulnerable Road and Culvert Hydraulic Capacity Assessment

FIGURE A1 - 2: 2080S PROJECTED COMPARISON TO CURRENT 2-YEAR DESIGN EVENT
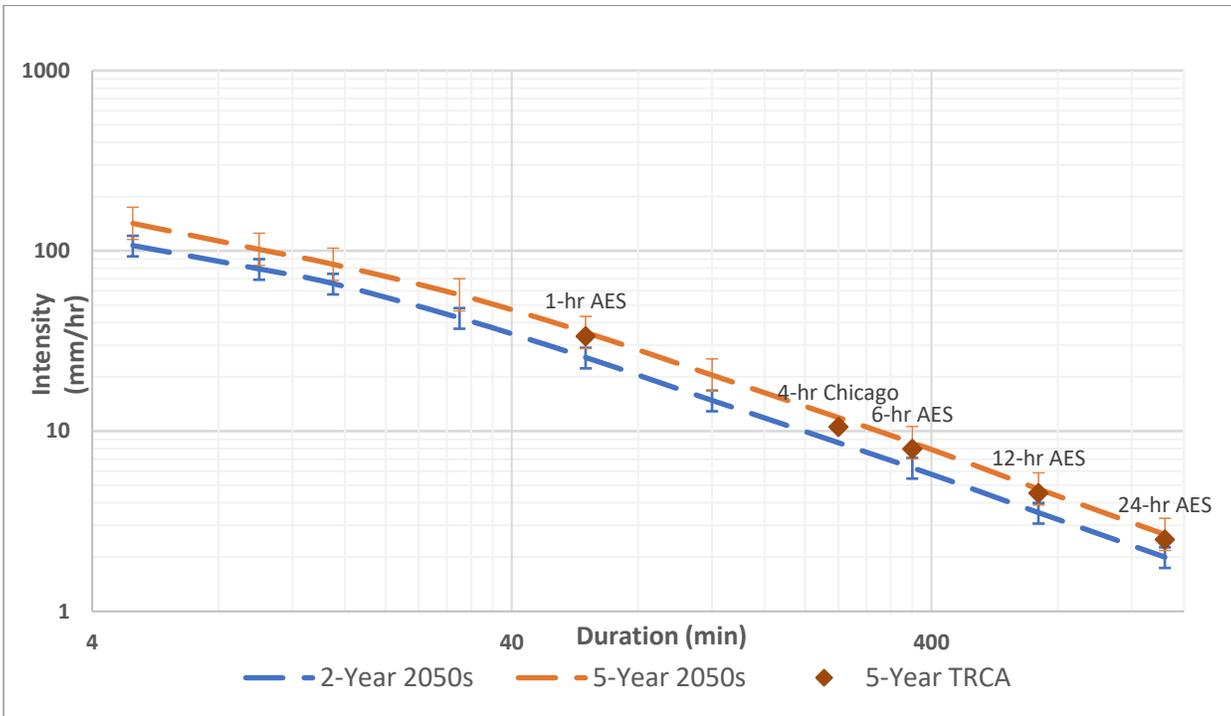
FIGURE A1 - 3: 2050S PROJECTED COMPARISON TO CURRENT 5-YEAR DESIGN EVENT

Flood Vulnerable Road and Culvert Hydraulic Capacity Assessment
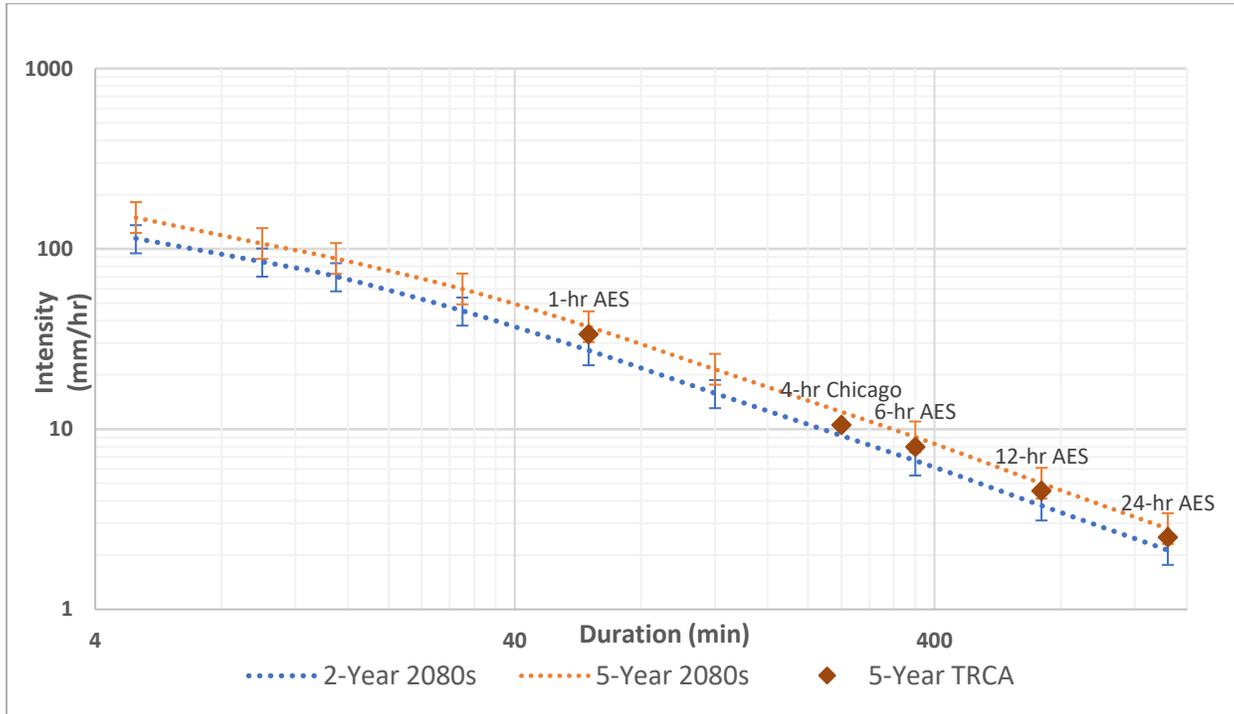
FIGURE A1 - 4: 2080S PROJECTED COMPARISON TO CURRENT 5-YEAR DESIGN EVENT
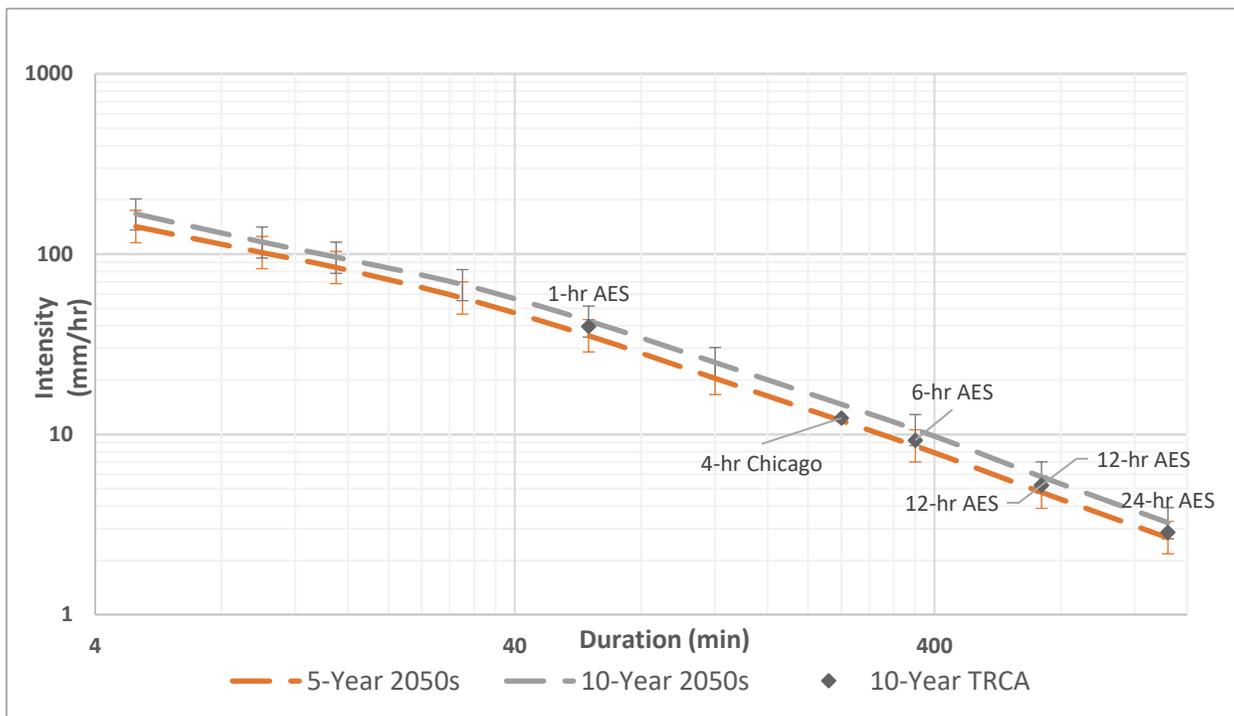
FIGURE A1 - 5: 2050S PROJECTED COMPARISON TO 10-YEAR DESIGN EVENT

Flood Vulnerable Road and Culvert Hydraulic Capacity Assessment
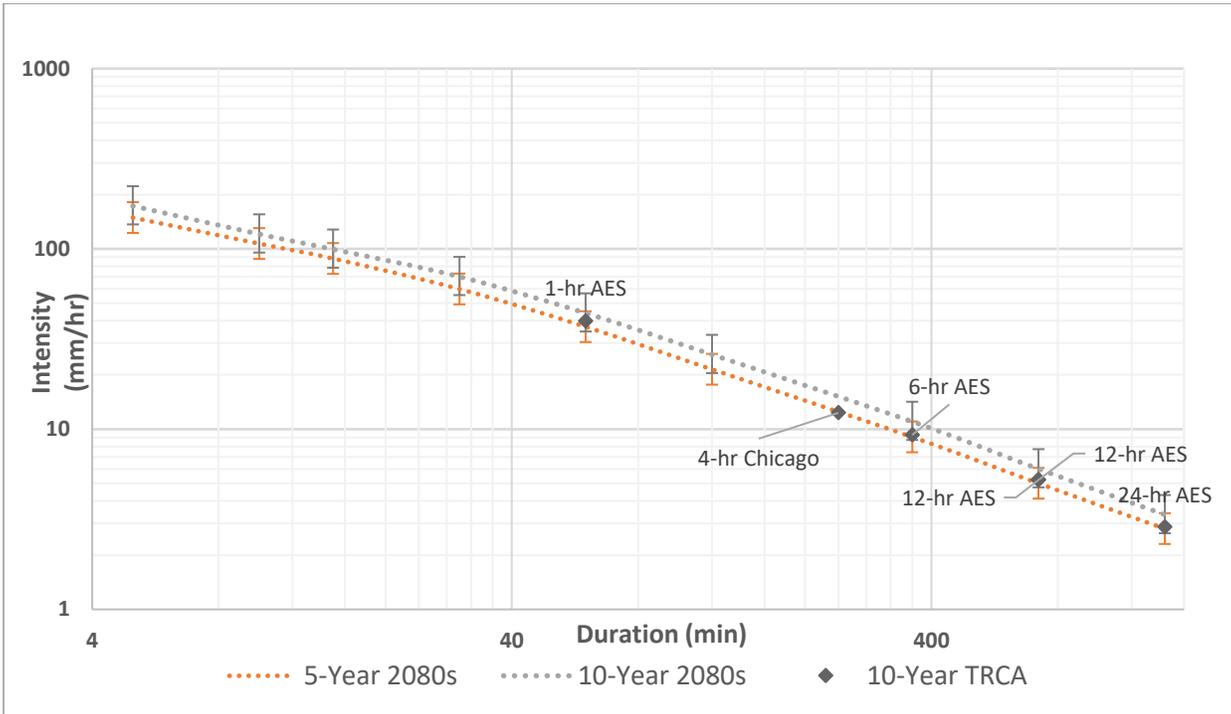
FIGURE A1 - 6: 2080S PROJECTED COMPARISON TO 10-YEAR DESIGN EVENT
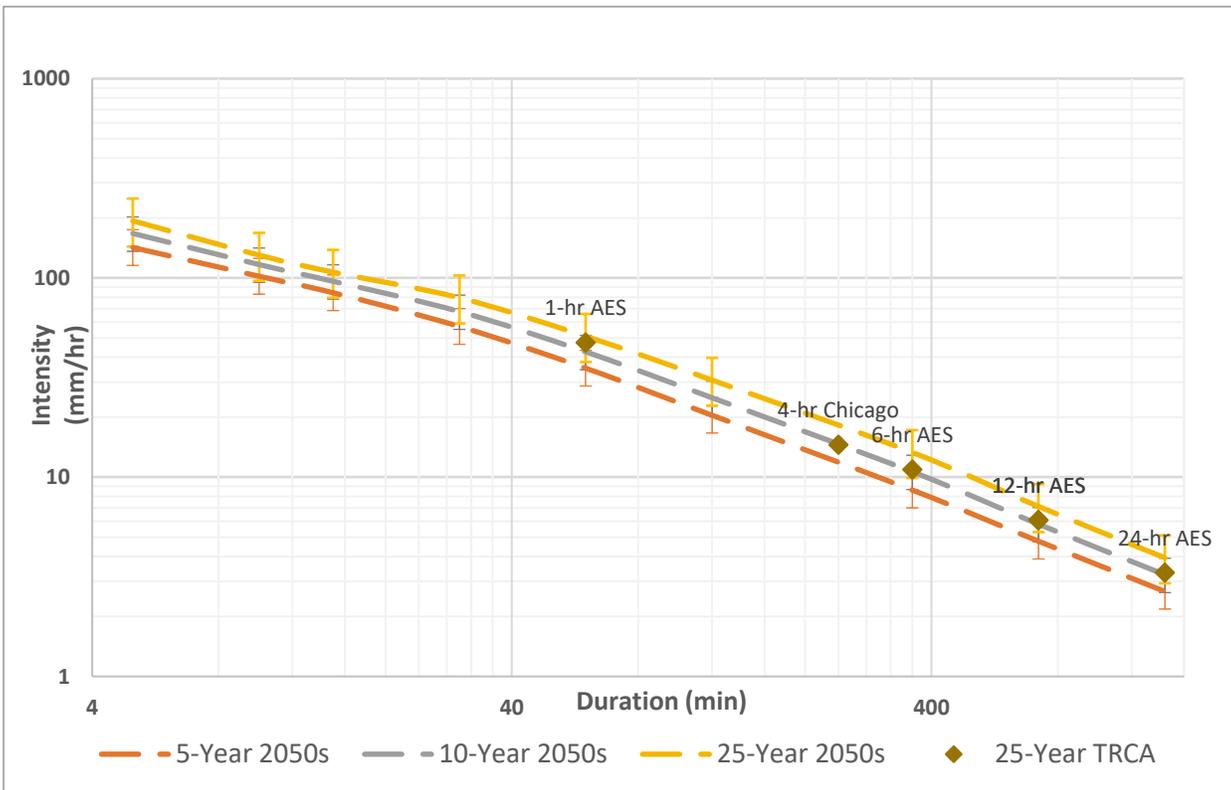
FIGURE A1 - 7: 2050S PROJECTED COMPARISON TO 25-YEAR DESIGN EVENT
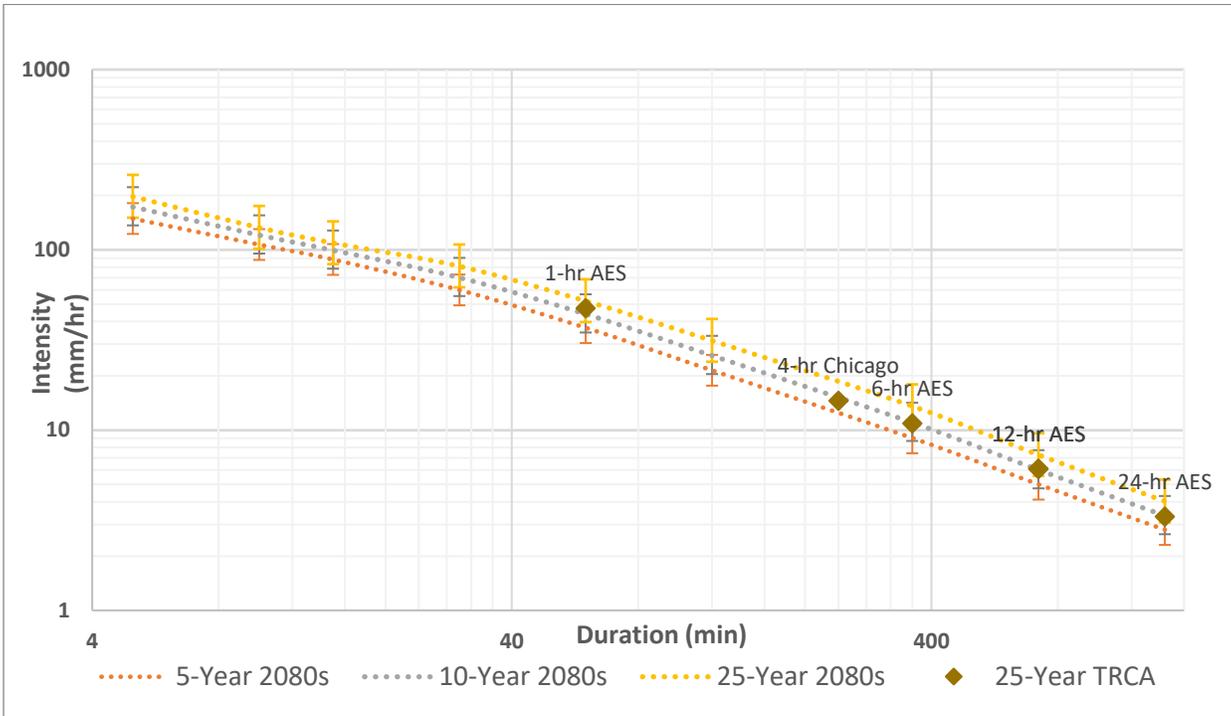
FIGURE A1 - 8: 2080S PROJECTED COMPARISON TO 25-YEAR DESIGN EVENT
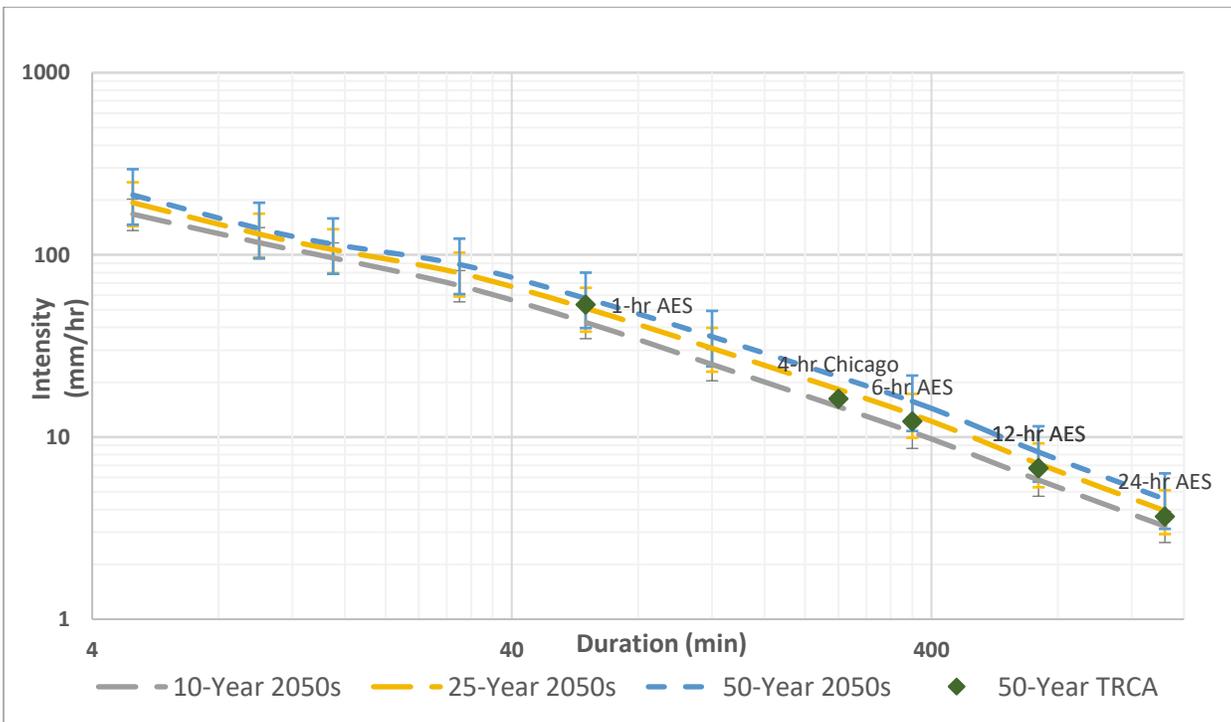
FIGURE A1 - 9: 2050S PROJECTED COMPARISON TO 50 YEAR DESIGN EVENT
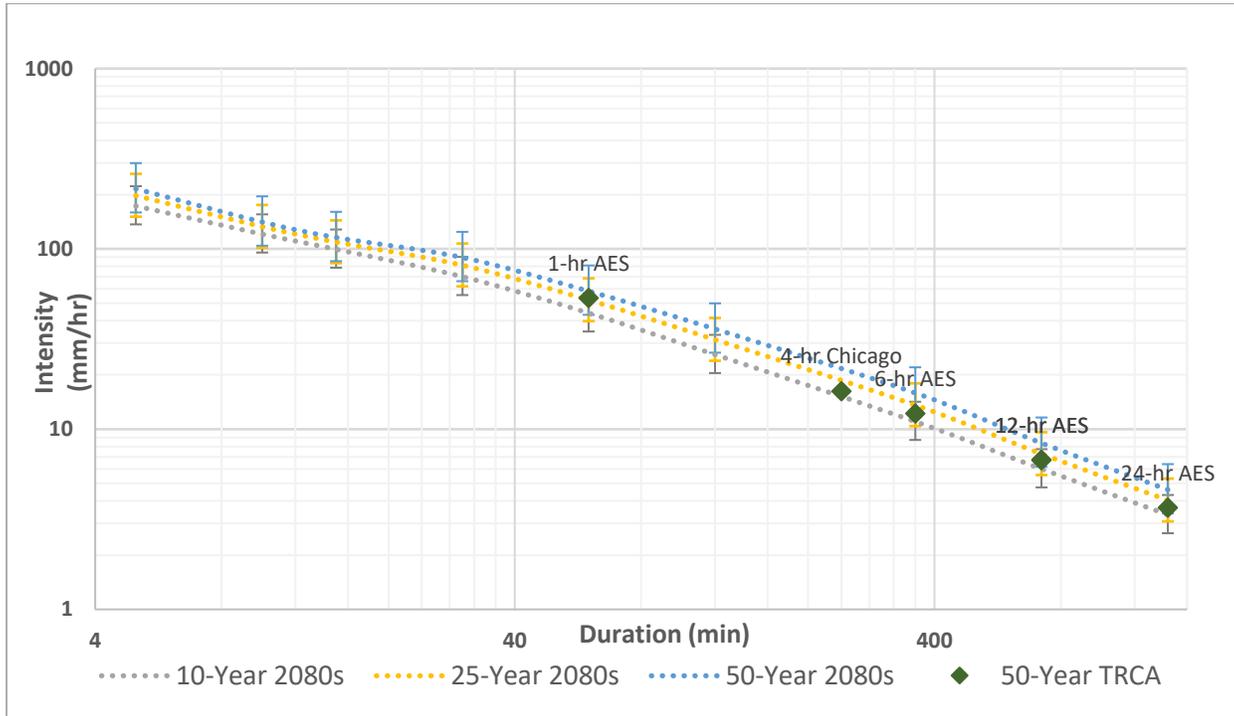
FIGURE A1 - 10: 2080S PROJECTED COMPARISON TO 50 YEAR DESIGN EVENT
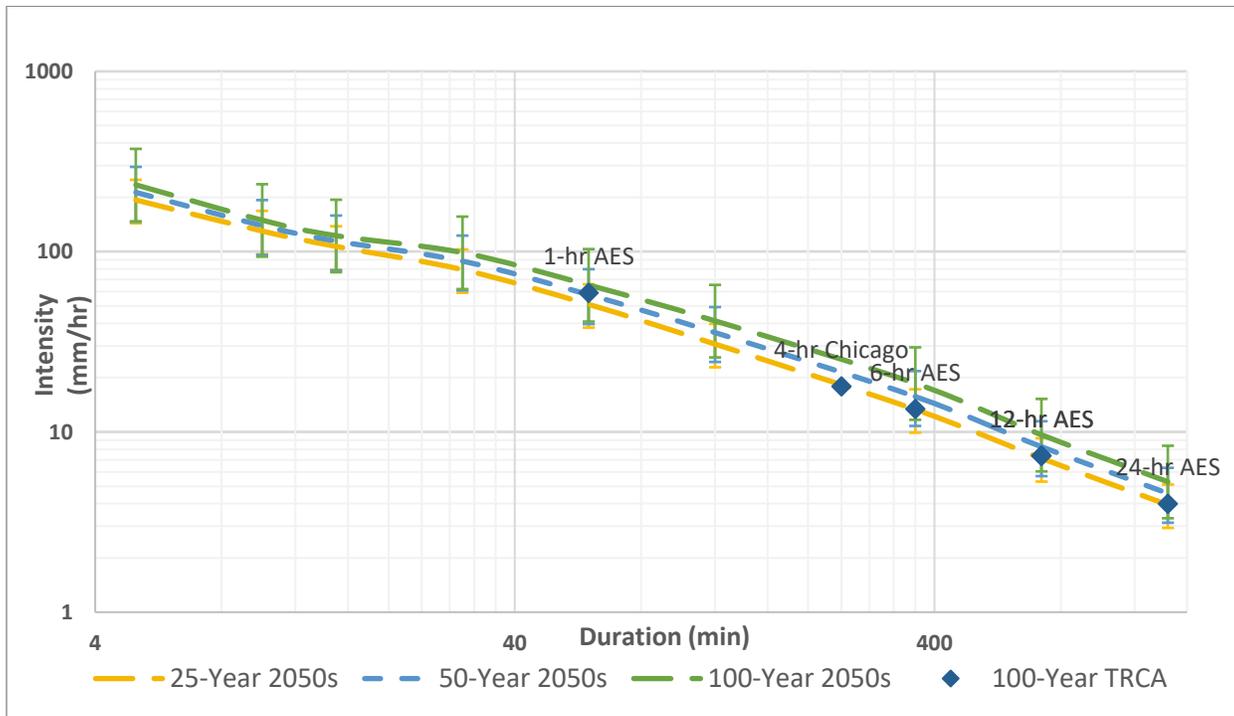
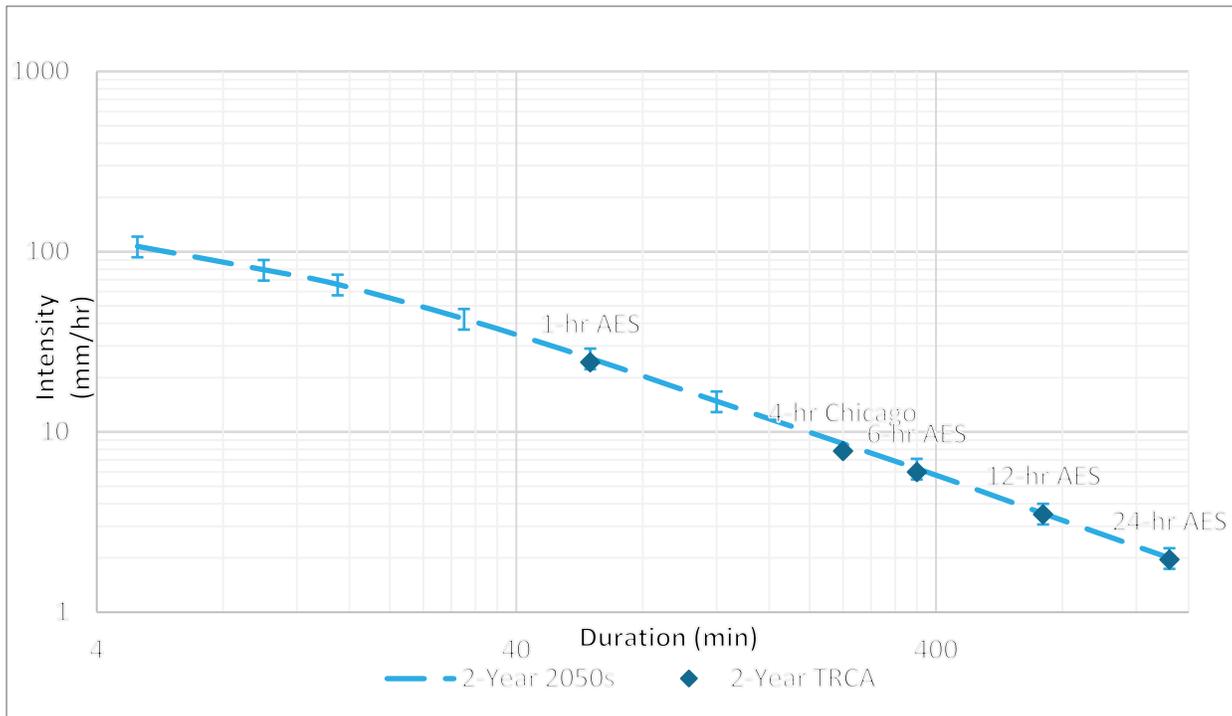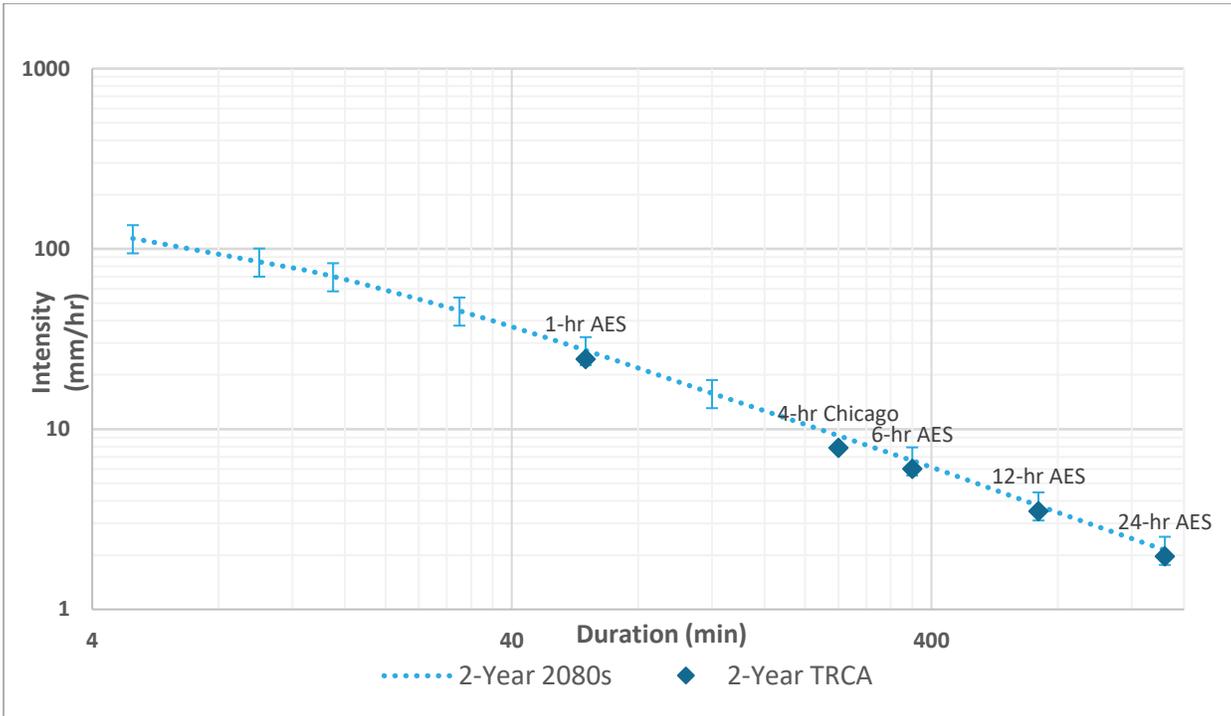**FIGURE A1 - 11: 2050S PROJECTED COMPARISON TO 100 YEAR DESIGN EVENT**
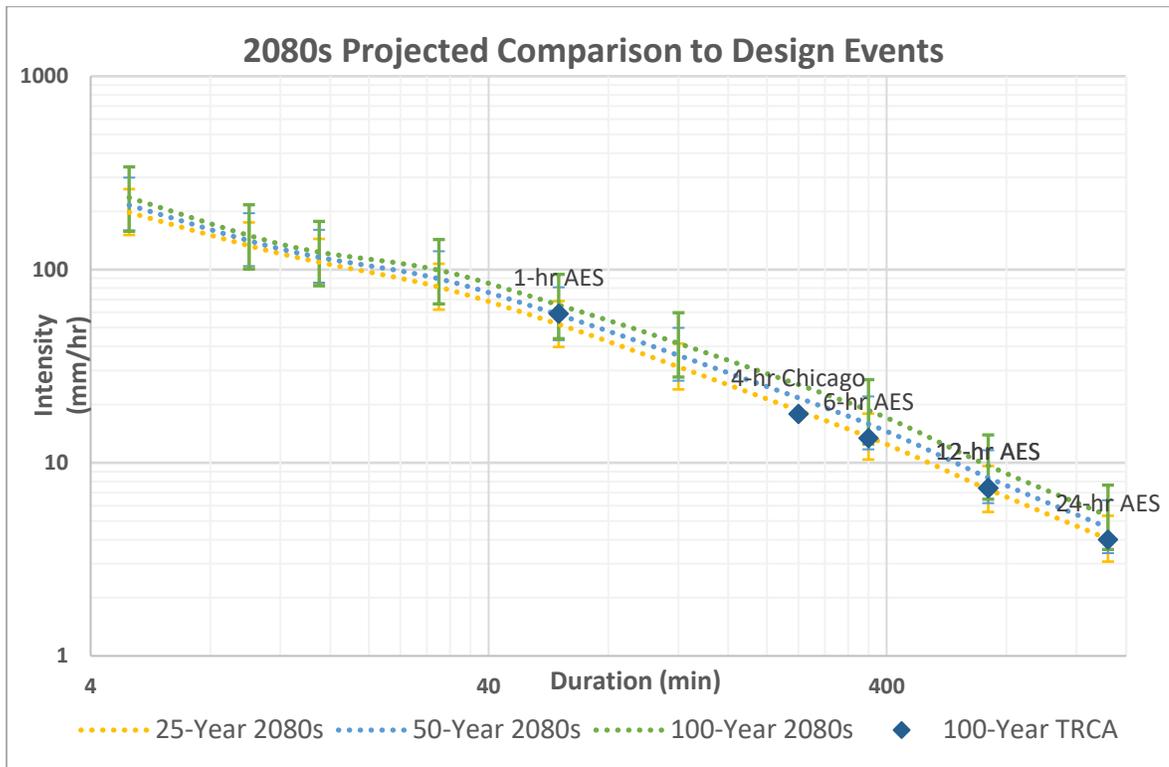
FIGURE A1 - 12: 2080S PROJECTED COMPARISON TO 100 YEAR DESIGN EVENT

Error bars are not displayed for the 4-hour Chicago event as the results were obtained using the interpolated equations fitted to the average IDF for future scenario RCP 8.5. The range was established using an average of the maximum and minimum values for a 2-hour and 6-hour storm event.
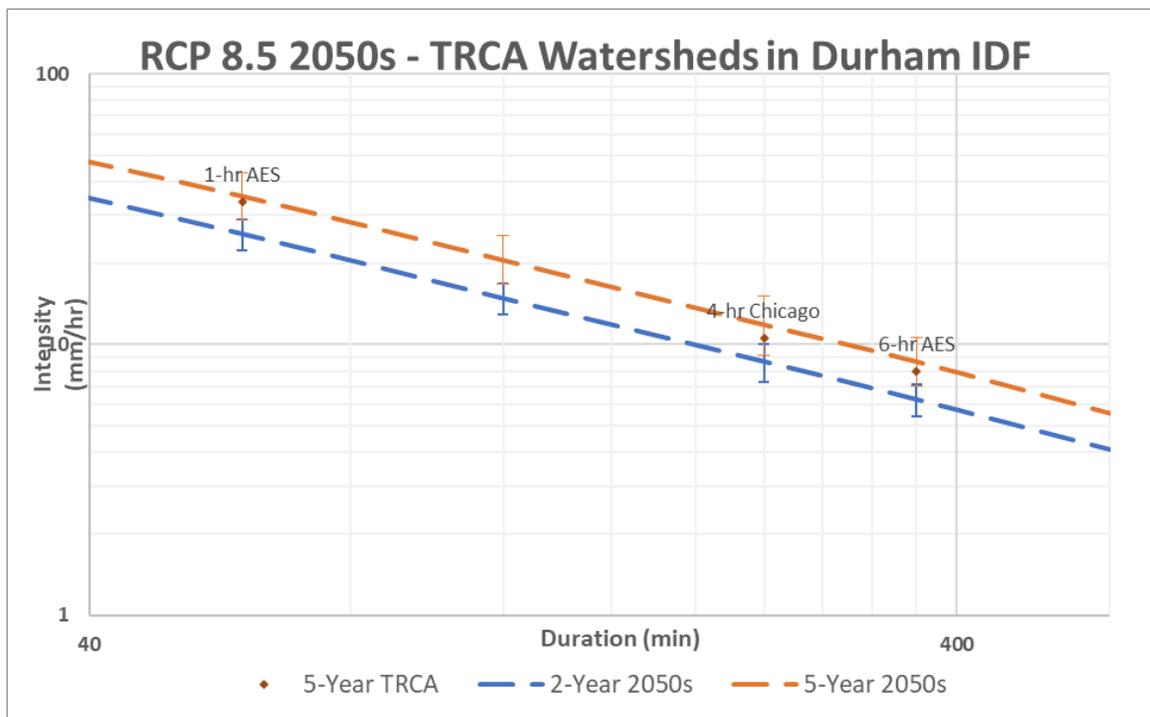
FIGURE A1 - 13: DEMONSTRATION OF ERROR AND RANGE ASSOCIATED WITH THE 4 HOUR CHICAGO EVENT AS MODELLED RESULTS WERE NOT AVAILABLE

Flood Vulnerable Road and Culvert Hydraulic Capacity Assessment

The two 12-hour storms (Petticoat Creek and Duffins Creek) do not appear in each graph above as the rainfall intensity values are close enough to not be visible. The differences are displayed below for example.
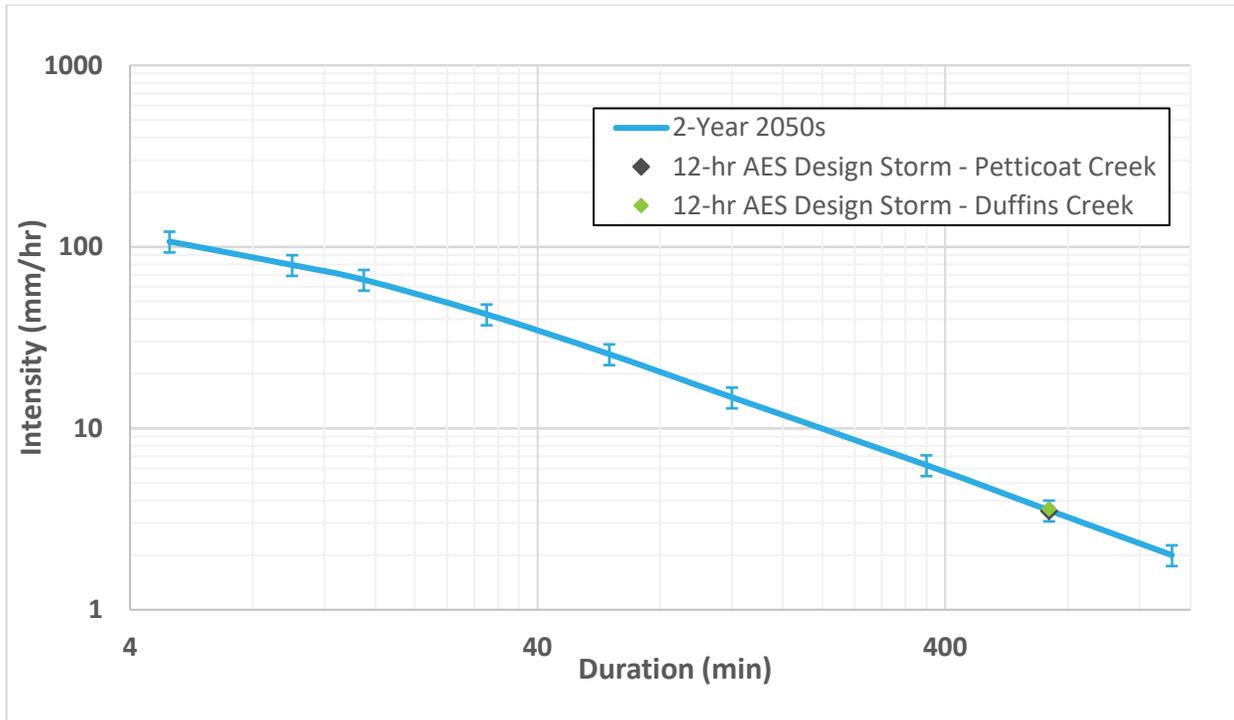
FIGURE A1 - 14: COMPARISON OF 12-HOUR EVENT PLOTTED AGAINST 2-YEAR 2050S PROJECTED VALUES

13 APPENDIX A2: TABLE 4-3: PROJECTED RETURN PERIOD AND ANNUAL EXCEEDANCE PROBABILITIES

The following appendix was prepared by GEI Consultants (Savanta Division) and CRI. The data summary tables display historical design storm information, the future (2050s and 2080s) "shifted return period" based on the multi-model ensemble average, projected range and confidence rating assigned for each design storm used by the Toronto and Region Conservation Authority. This

TABLE A2 - 1: 1-HR AES DESIGN STORM HISTORICAL RETURN PERIODS AND PROJECTED CHANGES IN THE 2050S AND 2080S.

1-hr AES Design Storm										
Frenchman's Bay - Pine and Dunbarton Creeks (Jan 2007 report)										
Historical			Mid-Century (2041-2070)				End of Century (2071-2100)			
Return Period (yr)	Annual Exceedance Probability	Rainfall Amount	Ensemble Average Return Period (yr)	Projected Range in Return Period	Ensemble Average Annual Exceedance Probability	Confidence	Ensemble Average Return Period (yr)	Projected Range in Return Period	Ensemble Average Annual Exceedance Probability	Confidence
2	50%	24.39	1.8	<2-2	56%	Moderate	1.5	<2-2	67%	Low
5	20%	33.58	4.5	3 - 5	22%		3.5	2.2-5	29%	
10	10%	39.78	8.0	4.5-10	13%		5.0	4-10	20%	
25	4%	47.48	20.0	8-25	5%		15.0	5-25	7%	
50	2%	53.27	35.0	15-50	3%		27.0	12-50	4%	
100	1%	58.97	60.0	20-100	2%		52.0	15-100	2%	

TABLE A2 - 2: 4-HR CHICAGO DESIGN STORM HISTORICAL RETURN PERIODS AND PROJECTED CHANGES IN THE 2050S AND 2080S.

4-hr Chicago Design Storm										
Frenchman's Bay - Krosno Creek (March 2002)										
Historical			Mid-Century (2041-2070)				End of Century (2071-2100)			
Return Period (yr)	Annual Exceedance Probability	Rainfall Amount	Ensemble Average Return Period (yr)	Projected Range in Return Period	Ensemble Average Annual Exceedance Probability	Confidence	Ensemble Average Return Period (yr)	Projected Range in Return Period	Ensemble Average Annual Exceedance Probability	Confidence
2	50%	31.38	1.5	<2-2	67%	Low	1.7	<2-2	58.8%	Low
5	20%	42.15	3.5	2.5-5	29%		3.0	2-5	33.3%	
10	10%	49.25	6.0	5-10	17%		5.0	4-10	20.0%	
25	4%	58.26	12.0	10-25	8%		11.0	7.5-25	9.1%	
50	2%	64.84	20	15-50	5%		18.0	10-50	5.6%	
100	1%	71.42	28.0	20-100	4%		25.0	10-100	4.0%	

TABLE A2 - 3: 6-HR AES DESIGN STORM HISTORICAL RETURN PERIODS AND PROEJCTED CHANGES IN THE 2050S AND 2080S.

6-hr AES Design Storm Frenchman's Bay - Amberlea Creek (March 2005 report)										
Historical			Mid-Century (2041-2070)				End of Century (2071-2100)			
Return Period (yr)	Annual Exceedance Probability	Rainfall Amount	Ensemble Average Return Period (yr)	Projected Range in Return Period	Ensemble Average Annual Exceedance Probability	Confidence	Ensemble Average Return Period (yr)	Projected Range in Return Period	Ensemble Average Annual Exceedance Probability	Confidence
2	50%	36.00	1.8	<2-2	56%	Moderate	1.5	<2-2	66.7%	Low
5	20%	47.81	4.0	3-5	25%		3.5	2-5	28.6%	
10	10%	55.69	6.5	5-10	15%		5.5	4-10	18.2%	
25	4%	65.59	12.5	6-25	8%		9.0	5-25	11.1%	
50	2%	73.00	20.0	10-50	5%		15.0	7.5-50	7%	
100	1%	80.31	27.0	18-100	4%		23.0	10-100	4%	

Flood Vulnerable Road and Culvert Hydraulic Capacity Assessment

TABLE A2 - 4: 12-HR AES DESIGN STORM (APPLIED TO PETTICOAT CREEK) HISTORICAL RETURN PERIODS AND PROJECTED CHANGES IN THE 2050S AND 2080S.

12-hr AES Design Storm Petticoat Creek (October 2006)											
Historical			Mid-Century (2041-2070)				End of Century (2071-2100)				
Return Period	Annual Exceedance Probability	Rainfall Amount	Ensemble Average Return Period (yr)	Projected Range in Return Period	Ensemble Average Annual Exceedance Probability	Confidence	Ensemble Average Return Period (yr)	Projected Range in Return Period	Ensemble Average Annual Exceedance Probability	Confidence
2	50%	42.00	2.0	<2-2	50%	Moderate	1.8	<2-2	57.1%	Moderate
5	20%	54.38	4.8	3-5	21%		4.0	2-5	25.0%	
10	10%	62.71	7.5	5-10	13%		6.0	4.5-10	16.7%	
25	4%	73.10	12.5	6-25	8%		10.0	5-25	10.0%	
50	2%	80.82	20.0	10-50	5%		18.0	8-50	5.6%	
100	1%	88.54	30.0	15-100	3%		26.0	10-100	3.8%	

TABLE A2 - 5: 12-HR AES DESIGN STORM (APPLIED TO DUFFINS CREEK) HISTORICAL RETURN PERIODS AND PROJECTED CHANGES IN THE 2050S AND 2080S.

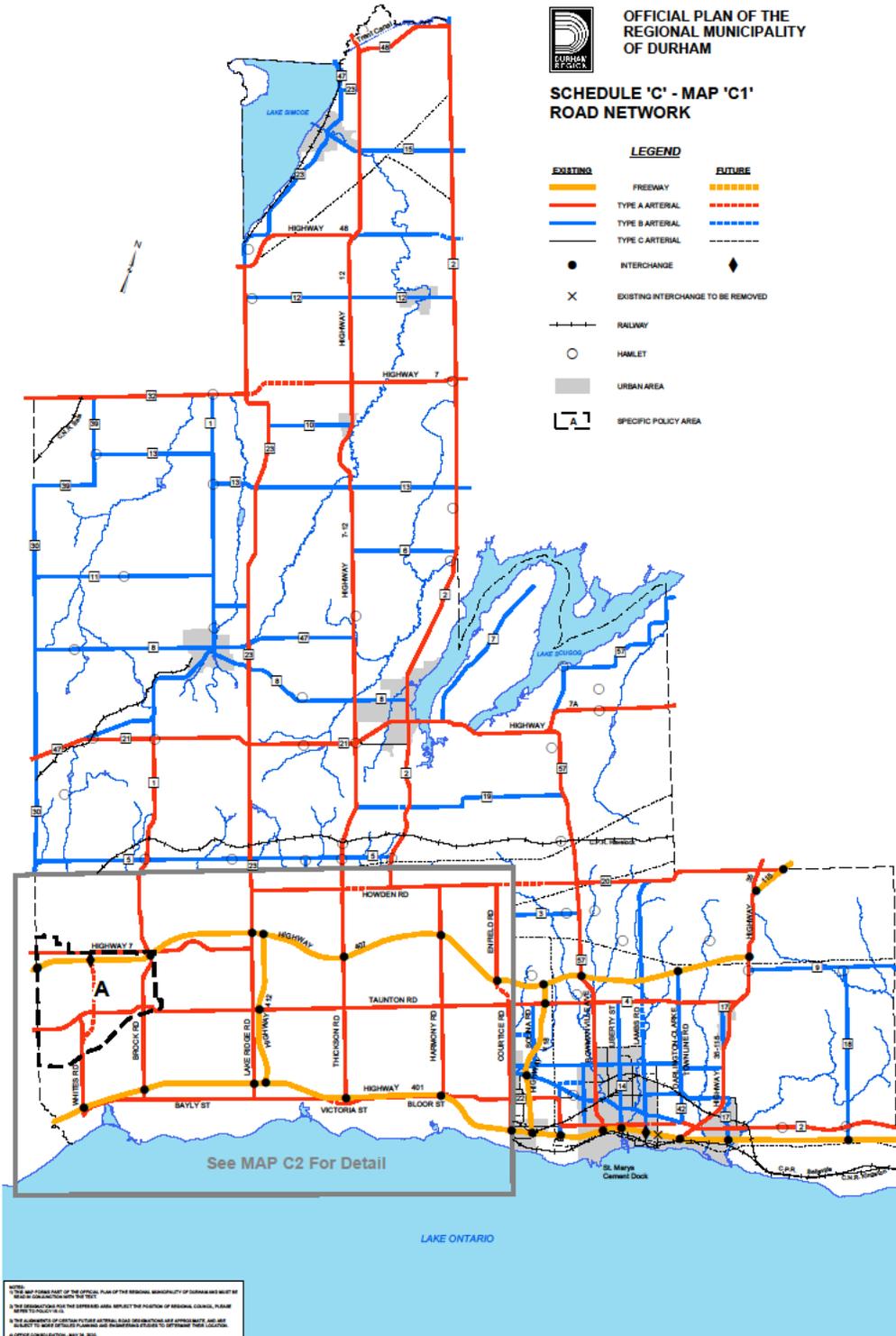| 12-hr AES Design Storm Duffins Creek (February 2013)											
Historical			Mid-Century (2041-2070)				End of Century (2071-2100)				
Return Period (yr)	Annual Exceedance Probability	Rainfall Amount	Ensemble Average Return Period (yr)	Projected Range in Return Period	Ensemble Average Annual Exceedance Probability	Confidence	Ensemble Average Return Period (yr)	Projected Range in Return Period	Ensemble Average Annual Exceedance Probability	Confidence
2	50%	43.20	2.0	<2-2	50%	Moderate	1.8	<2-2	57%	Moderate
5	20%	55.50	4.8	3-5	21%		4.0	2-5	25%	
10	10%	62.90	7.5	5-10	13%		6.0	4.5-10	17%	
25	4%	72.80	12.5	6-25	8%		10.0	5-25	10%	
50	2%	80.10	20.0	10-50	5%		18.0	8-50	6%	
100	1%	87.50	30.0	15-100	3%		26.0	10-100	4%	

TABLE A2 - 6: 24-HR AES DESIGN STORM HISTORICAL RETURN PERIODS AND PROJECTED CHANGES IN THE 2050S AND 2080S.

24-hr AES Design Storm Carruther's Creek (October 2011)											
Historical			Mid-Century (2041-2070)				End of Century (2071-2100)				
Return Period	Annual Exceedance Probability	Rainfall Amount	Ensemble Average Return Period (yr)	Projected Range in Return Period	Ensemble Average Annual Exceedance Probability	Confidence	Ensemble Average Return Period (yr)	Projected Range in Return Period	Ensemble Average Annual Exceedance Probability	Confidence
2	50%	47.08	2.0	<2-2	50%	Moderate	1.8	<2-2	55.6%	Moderate
5	20%	60.08	4.5	3-5	22%		3.5	2-5	28.6%	
10	10%	68.76	6.0	4.5-10	17%		5.5	3.5-10	18.2%	
25	4%	79.70	12.5	6-25	8%		9.5	5-25	10.5%	
50	2%	87.80	20.0	10-50	5%		15.0	10-50	6.7%	
100	1%	95.92	30.0	10-100	3%		24.0	10-100	4.2%	

14 APPENDIX B: SCHEDULE C MAPS – ROAD NETWORK (OFFICIAL PLAN OF THE REGIONAL MUNICIPALITY OF DURHAM'S OFFICIAL PLAN)

15 APPENDIX C: DEGREE OF REDUNDANCY CRITERION - PROPOSED SCREENLINE LOCATIONS AND ZONES BY REGIONAL MUNICIPALITY OF DURHAM

Degree of Redundancy Criterion:
Proposed Screenline Locations and Zones

Degree of Redundancy Criterion:
How Screenline Crossings Are Identified and Scored
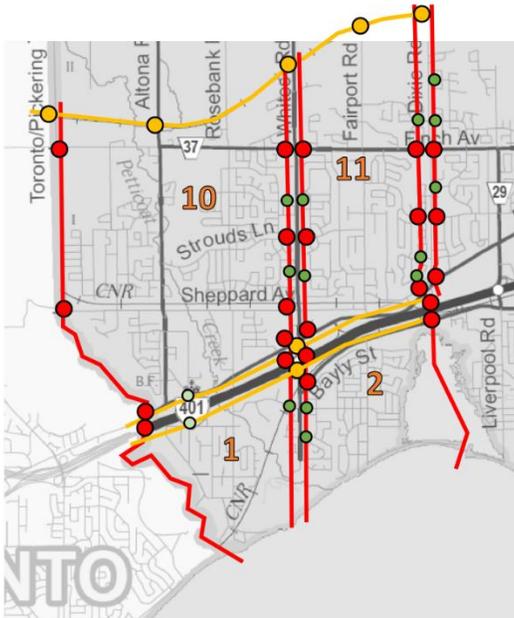
Notes:

Zone 1 is bounded by the Toronto-Durham Boundary (Rouge River); Highway 401; Whites Road; Lake Ontario.

Zone 2 is bounded by Whites Road; Highway 401; Frenchman's Bay and imaginary line connecting to Dixie Road; Lake Ontario.

Zone 10 is bounded by the Toronto-Durham Boundary (Rouge River) and Scarborough-Pickering Townline; CPR Belleville line; Whites Road; Highway 401.

Zone 11 is bounded by Whites Road, CPR Belleville Line, Dixie Road; Highway 401.

Example – Zones 1 and 2 (see excerpt of screenline map to the left)

For the Degree of Redundancy criterion, a screenline analysis is being proposed. The screenlines are imaginary lines that help measure the degree of connectivity on the road network, broken down into various zones. The screenlines form logical boundaries for north-south or east-west traffic flows to and from zones, following municipal boundaries, major roads, railway and watercourse features.

Zone 1 has 2 Freeway crossings (Highway 401 at the west and east screenlines for the zone) but does not have any arterials as crossings on any screenline. It has 2 Collector roads crossing the zone: Rougemount Drive across the screenline on the south side of Highway 401 and Granite Court across the screenline on the west side of Whites Road. In total, Zone 1 has 5 screenline crossings.

Zone 2 has 2 Freeway crossings (Highway 401 at west and east screenlines for the zone). It has 3 Arterial roads crossing the zone: Whites Road across the screenline on the south side of Highway 401, Bayly Street across the screenline on the east side of Whites Road, and Bayly Street across the screenline at Frenchman's Bay. It has 2 collector roads crossing the screenline east of Whites Road. In total, Zone 2 has 7 screenline crossings.

Zone 10 has 2 Freeway crossings (Highway 401 at west and east screenlines for the zone). It has 11 Arterial roads crossing the zone: 3 on the CPR Belleville screenline, 1 on the screenline north of Highway 401, 3 on the Toronto-Durham Boundary screenline and 4 on the screenline west of Whites Road. It has 3 Collector road crossings: 2 on the screenline west of Whites Road and one on the screenline north of Highway 401. In total, Zone 10 has 16 screenline crossings.

In order to assess Regional and other roads in terms of the Degree of Redundancy criterion, the proposed scoring for road sections in each zone can be applied as follows:

1: 16+ roads crossing a relevant screen line
3: 7 to 15 roads crossing a relevant screen line
5: Up to 6 roads crossing a relevant screen line

Therefore, roads within Zone 1 are given a score of 5 (lowest connectivity/redundancy) and roads in Zone 2 are given a score of 3 (medium connectivity/redundancy).

When assessing a road that forms a boundary between two or more zones, select the zone with the higher scoring for Degree of Redundancy as it shares connectivity with both zones. For example, Whites Road forms the boundary between Zones 1 and 2, and is given a score of 3.

All Freeway, Arterial and Collector road crossings, both existing and future, are given the same weight for the scoring (each road = 1 crossing).

For north-south or east-west screenlines in an adjacent zone that end in the middle of a screenline for the subject zone, they are not counted as road crossings for that zone. For example, the Taunton Road crossings of the screenlines east and west of Church Street, and east and west of Salem Road, are used for Zones 13, 14 and 15 but not for Zone 34.

16 APPENDIX D: CRITICALITY SCORE CRITERIA

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Durham Flood Vulnerable Roads and Culvert Capacity Assessment - Road Criticality Scoring Criteria

Project Context and Approach

Risk scoring is an approach used to assign a level of risk present within a defined area based on various factors. In the context of Durham's flood vulnerable roads and culvert capacity assessment, there is a need to consider and incorporate how *critical* a particular road is alongside whether it is at risk of current and future flooding. The following document summarizes the scoring approach used to characterize the criticality of a given road segment based on a suite of indicators.

To interpret relative differences in what makes a road critical, a suite of indicators was identified in consultation with Durham Region staff and the Toronto and Region Conservation Authority. At a high level, these include:

1. Functional classification of roads
2. Average annual daily traffic
3. Designated Transit Routes
4. Goods movement routes
5. Degree of redundancy
6. Evacuation and disaster recovery - proximity to nuclear hazards
7. Proximity to sensitive receptors
8. Social equity and justice

Each of the above indicators was refined through further definition as they relate to Durham's roads, rationalizing why it is related to criticality and assigned a score, based on a scale from 1 to 5. A score of 5 represents the most critical (most important) and a score of 1 represents the least critical (least important). Once data is analyzed and scored for each indicator across Durham roads, an additive analysis will be completed to obtain an overall criticality score. The larger the combined score along a road, the more at-risk a given road segment is. Following discussions among the project team, it was agreed that the criticality of roads based on these risk factors should be an additive process with no (or equal) weighting. Through assigning all factors equal weighting, it avoids making assumptions regarding impact thresholds that are not readily available and thus an equal weighting approach is often considered more defensible.

It should be noted that the information contained herein only establishes proposed logic for further analysis of each indicator. All thresholds/scoring are based on available authoritative reports or guidelines from organizations. Analyses are anticipated to be conducted by TRCA in GIS. As each indicator is mapped and assigned scores, it will be important to reflect on the suitability of each scoring system to ensure it captures roads and routes known to be important across Durham Region. This process may be iterative for indicators where thresholds are not well studied (e.g., social equity).

1

Additional detail for each indicator is summarized in the table below, including a rationale, and a proposed scoring approach.

2

Table 1. Summary of Durham Road Criticality Criteria and Proposed Scoring

Indicator	Definition used for Durham Region	Scoring Approach *From 1 (least critical) to 5 (most critical)*
Factor_1 Functional classification of roads	Though the functional classification of roads is most quantitatively measured by its AADT, other factors qualitatively describe it as well. The US Federal Highway Administration notes that the functional classification of roads is not specific, indicating many "borderline" roadway classifications that exist. Other quantitative include lane width, shoulder width, divided/undivided status, access control and access points. Durham roads are classified based on the variations in design standards, flow characteristics, traffic volumes, traffic control, access control, vehicle type and abutting land use. Durham's ROP defines roads based on basic function and functional types of higher order roads have great movement and access than lower order streets.	**1:** Local Roads **2:** Collector Roads **3:** Arterial Type C roads **4:** Rural Arterial Type A roads and Arterial Type B roads **5:** Urban Arterial type A roads and expressways
Factor_2 Average annual daily traffic (AADT)	Annual average daily traffic (AADT) is the total vehicle traffic in a year over a highway or road allowance. Traffic volume is a key factor is establishing road classification. The higher the traffic volume, the larger the risk to public safety should an impact or disruption occur. Likewise, roads with higher traffic volumes may serve more prominently as arteries or important routes within or out of areas across Durham Region. Notably, scoring less than 3000 has been included to accommodate local municipal roads, and all thresholds are established based on the ROP.	**1**: Less than 1000 AADT **2**: 1000 – 2999 AADT **3**: 3000 – 8,000 AADT **4**: 8,001 to 20,000 AADT **5**: Greater than 20,000 AADT
Factor_3 Designated Transit Priority Network	Transit routes play an important supportive role in the overall transportation system. Roads identified as a designated transit route are considered more critical, as disruption to those routes can impact level of service. A Designated Transit Priority Network have been identified by the Region in the ROP.	**1:** Not identified as part of Transit Priority Network. **3**: Identified as High Frequency Transit Network or Other Transit Connection. **5:** Identified as a Rapid Transit Spine.

3

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Indicator	Definition used for Durham Region	Scoring Approach *From 1 (least critical) to 5 (most critical)*
Factor_4 Goods movement routes	Providing efficient, continuous, and connected goods movement is integral to the Region's economic competitiveness and growth, including the growth of traditional and emerging agricultural industries in rural communities. The Regional Official Plan (ROP) designates a Strategic Goods Movement Network (SGMN) for existing haul routes, major generators of truck traffic and ROP road designations. Goods movements roads have been identified by the Region in the ROP.	**1:** Not identified as a goods movement route in ROP. **5:** Identified as a goods movement route in ROP.
Factor_5 Degree of redundancy	Priority to improve the resilience of Durham's roads should also be based on the availability of alternative routes in the network system. Redundancy of roadways is the availability of alternative routes in the road network that can provide an emergency-related redundancy function in time of need. Redundancy routes can also assist in reducing traffic congestion and provide alternate routes when roads are under construction and allows road networks to maintain "level of service" in times of need. Screening lines were provided as a pdf map and accompanied with an excel spreadsheet that specified the extent of each zone and its score. Roads within a zone would receive score defined for that zone.For roads at boundry of zones, lower score would be assigned to account for benefit of road connectivity.	**1:** 3+ roads crossing a relevant screen line **3:** 2 roads crossing a relevant screen line **5:** 1 road crossing a relevant screen line
Factor_6 Evacuation and disaster recovery - proximity to nuclear hazards	Given the importance of nuclear facilities within the Durham Region and its potential for environmental hazard, it is proposed that emergency evacuation be quantified by the proximity of nuclear power generating facilities to roads. Durham Region has two nuclear facilities, however, only 1 is deemed to be within scope of this project, as it is located within TRCA watershed boundaries, Pickering Nuclear Generating Station. The scoring scale is proposed based on Durham's Emergency Management Office and Durham Nuclear Emergency Response Plan (2017) definitions of primary and secondary zones. The primary zone is the area around the nuclear station out to a radius of 10km, which includes the Contiguous Zone. The secondary zone is the area around a nuclear station out to a radius of 50km within which it is necessary to plan for ingestion control measures based on the monitoring of the food chain for contamination.	**1:** Greater than 50km away from a nuclear facility *(No zone)* **3:** Between 10 to 50km away from a nuclear facility *(Secondary Zone)* **5:** Less than or equal to 10km away from a nuclear facility *(Primary Zone)*

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Indicator	Definition used for Durham Region	Scoring Approach *From 1 (least critical) to 5 (most critical)*
Factor_7 Proximity to sensitive receptors	Sensitive receptors are defined as key locations including schools, daycare facilities, nursing and retirement homes, and emergency services (fire halls, police stations). Sensitive receptors are considered providing critical and/or essential services to Region's residents and those requiring access in the event of extreme weather. Given the diversity of receptors across Durham Region, a simplified scoring method is proposed based on an approximate distance (or "buffer") surrounding each designated sensitive receptor. Roads within 500m of a given sensitive receptor are considered more critical due to access in the event of extreme weather.	**Roads within 500m of…** **1: A**ny road outside the 500 m radius of a sensitive receptor. **2:** Schools or daycares/ Community centres or places of worship **3:** Nursing or retirement homes **4:** Fire halls or police stations **5:** Hospitals
Factor_8 Social equity and justice	Flooding and climate change impacts are not spatially even and socially just. In many cases, impacts can exacerbate existing inequalities. Operationalizing social equity into municipal planning and climate resilient design provides an opportunity to build a climate-resilient city that is also socially just. A variety of different indicators can be used to show disparities in social equity within vulnerable groups, which can be displayed by neighbourhood. Data on the measures of social equity are measured by an average of information available from Durham's health neighbourhood data. These measures include a) low-income rate, b) indigenous population, c) recent immigrants to the region, d) unemployment, e) visible minorities, f) seniors living alone, g) mental health. It is anticipated that an integrated dataset developed by Durham Region has integrated several of these indicators prior to this project. This dataset will be accessed and leveraged, and the final indicators will be used to assign scores. Given that universal impact thresholds do not exist, a scoring approach is recommended based on percentiles. Percentile-driven approaches are commonly applied in risk assessments where a lack of impact or failure thresholds exist and are meant to represent the relative gradient in a particular indicator's condition across a geography. For example, a neighbourhood where health data is in the bottom 30th percentile is considered "equity seeking" given that 70% of all other neighbourhoods in Durham have fewer inequalities. The authors propose that the integrated health dataset that the Region developed be overlaid with all roads and scoring assigned based on the estimated equity scoring in each neighbourhood.	**1:** Roads located in neighbourhoods where equity is >70th percentile (highest 30%) of equity data (e.g., highest incomes, lowest unemployment, fewest visible minorities, etc.). **3:** Roads located in neighbourhoods where equity is between the 30th and 70th percentile. **5:** Roads located in neighbourhoods where equity is <30th percentile (e.g., lowest incomes, highest unemployment, highest visible minorities, etc.).

5

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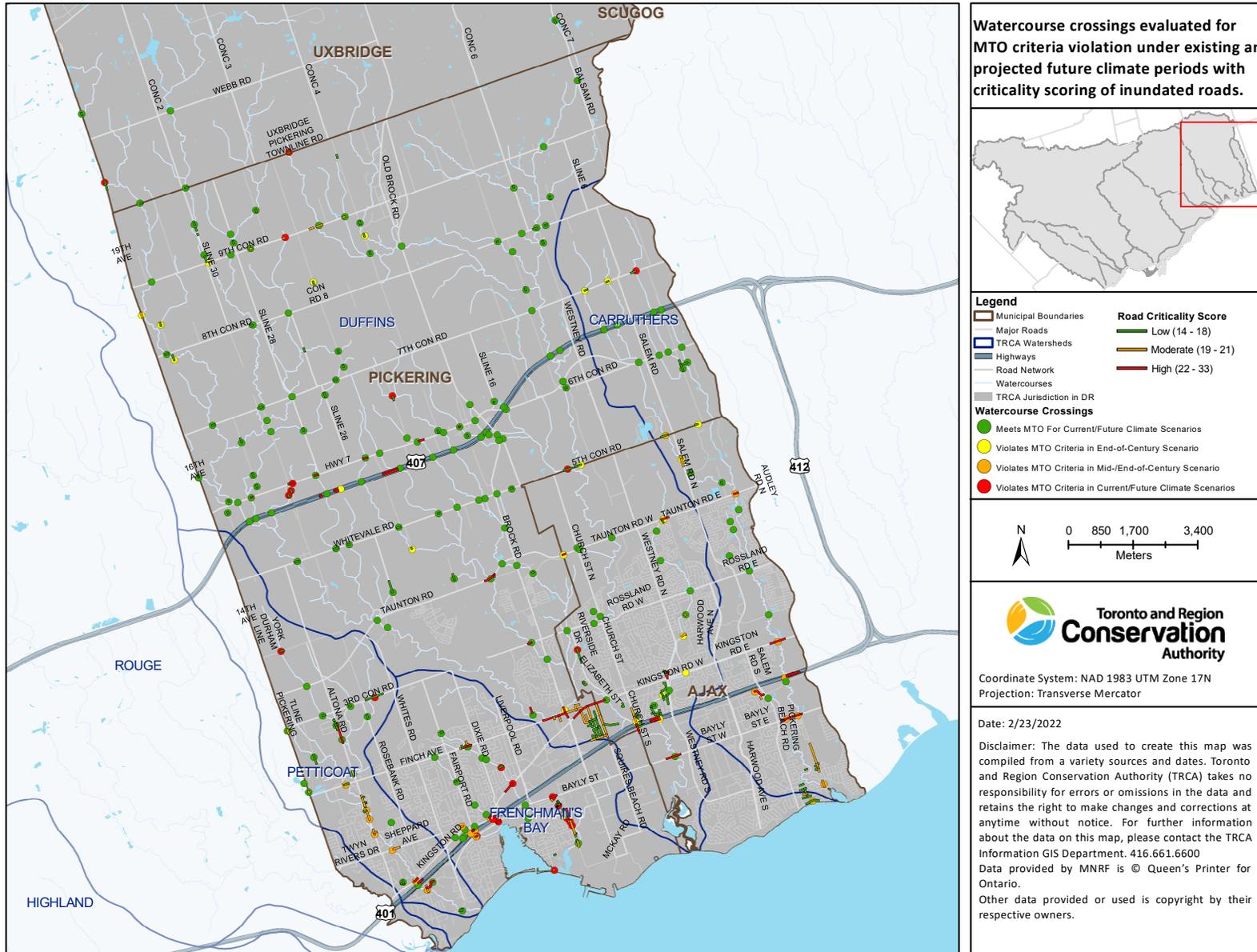| Indicator	Definition used for Durham Region	Scoring Approach *From 1 (least critical) to 5 (most critical)*

6

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17 APPENDIX E: OVERLAY MAP OF WATERCOURSE CROSSINGS EVALUATED FOR MTO CRITERIA VIOLATION AND CRITICALITY SCORING OF INUNDATED ROADS

Watercourse crossings evaluated for MTO criteria violation under existing and projected future climate periods with criticality scoring of inundated roads.

Legend

Municipal Boundaries
Major Roads
TRCA Watersheds
Highways
Road Network
Watercourses
TRCA Jurisdiction in DR

Road Criticality Score
Low (14 - 18)
Moderate (19 - 21)
High (22 - 33)

Watercourse Crossings
Meets MTO For Current/Future Climate Scenarios
Violates MTO Criteria in End-of-Century Scenario
Violates MTO Criteria in Mid-/End-of-Century Scenario
Violates MTO Criteria in Current/Future Climate Scenarios

0   850 1,700   3,400
Meters

Toronto and Region Conservation Authority

Coordinate System: NAD 1983 UTM Zone 17N
Projection: Transverse Mercator

Date: 2/23/2022

Disclaimer: The data used to create this map was compiled from a variety sources and dates. Toronto and Region Conservation Authority (TRCA) takes no responsibility for errors or omissions in the data and retains the right to make changes and corrections at anytime without notice. For further information about the data on this map, please contact the TRCA Information GIS Department. 416.661.6600
Data provided by MNRF is © Queen's Printer for Ontario.
Other data provided or used is copyright by their respective owners.

18 APPENDIX F: VISUAL BASIC SCRIPTS USED FOR GEOPROCESSING IN ARCGIS

18.1 VB Script for Assigning Values to MTO_Criter

Dim y

if [FUNCTION_] = "freeway" and [Stru_Span] =< 6 then

    y = "50 year"

elseif [FUNCTION_] = "freeway" and [Stru_Span] > 6 then

    y ="100 year"

elseif [FUNCTION_] = "collector" and [Stru_Span]=< 6 then

    y = "25 year"

elseif [FUNCTION_] = "collector" and [Stru_Span]> 6 then

    y = "50 year"

elseif [FUNCTION_] ="local" and [Stru_Span] =< 6 then

    y = "10 year"

elseif [FUNCTION_] ="local" and [Stru_Span] > 6 then

    y = "25 year"

elseif [FUNCTION_] = "a arterial" and [RdEnv] = "Urban" and [Stru_Span] =< 6 then

    y = "50 year"

elseif [FUNCTION_] = "a arterial" and [RdEnv] = "Urban" and [Stru_Span] > 6 then

    y ="100 year"

elseif [FUNCTION_] = "a arterial" and [RdEnv] = "Rural" and [Stru_Span] =< 6 then

    y = "25 year"

elseif [FUNCTION_] = "a arterial" and [RdEnv] = "Rural" and [Stru_Span] > 6 then

    y ="50 year"

elseif [FUNCTION_] = "b arterial" and [RdEnv] = "Urban" and [Stru_Span] =< 6 then

    y = "50 year"

elseif [FUNCTION_] = "b arterial" and [RdEnv] = "Urban" and [Stru_Span] > 6 then

    y ="100 year"

elseif [FUNCTION_] = "b arterial" and [RdEnv] = "Rural" and [Stru_Span] =< 6 then

    y = "25 year"

elseif [FUNCTION_] = "b arterial" and [RdEnv] = "Rural" and [Stru_Span] > 6 then

    y ="50 year"

```
elseif [FUNCTION_] = "c arterial" and [RdEnv] = "Urban" and [Stru_Span] =< 6 then

    y = "50 year"

elseif [FUNCTION_] = "c arterial" and [RdEnv] = "Urban" and [Stru_Span] > 6 then

    y ="100 year"

elseif [FUNCTION_] = "c arterial" and [RdEnv] = "Rural" and [Stru_Span] =< 6 then

    y = "25 year"

elseif [FUNCTION_] = "c arterial" and [RdEnv] = "Rural" and [Stru_Span] > 6 then

    y ="50 year"

end if
```

18.2 VB Script for Assigning Values to Act_LOS field

```
Dim Y

If [Depth_Reg] = 0 then

    y="Regional"

elseif [Depth_Reg]>0 and [Depth_100y]=0 then

    y="100 year"

elseif [Depth_Reg]>0 and [Depth_100y]>0 and [Depth_50yr] = 0 then

    y="50 year"

elseif [Depth_Reg]>0 and [Depth_100y]>0 and [Depth_50yr]>0 and [Depth_25yr] =0 then

    y="25 year"

elseif [Depth_Reg]>0 and [Depth_100y]>0 and [Depth_50yr]>0 and [Depth_25yr] >0 and [Depth_10yr] = 0 then

    y="10 year"

elseif [Depth_Reg]>0 and [Depth_100y]>0 and [Depth_50yr]>0 and [Depth_25yr] >0 and [Depth_10yr]>0 and [Depth_5yr] =0 then

    y="5 year"

elseif [Depth_Reg]>0 and [Depth_100y]>0 and [Depth_50yr]>0 and [Depth_25yr] >0 and [Depth_10yr]>0 and [Depth_5yr]>0 and
[Depth_2yr] =0 then

    y="2 year"

elseif [Depth_Reg]>0 and [Depth_100y]>0 and [Depth_50yr]>0 and [Depth_25yr] >0 and [Depth_10yr]>0 and [Depth_5yr]>0 and
[Depth_2yr]>0 then

    y="< 2 year"

end if
```

18.3 VB Script for Assigning Values to VIOL_MTO Field

```
    Dim y

    if [MTO_NUM] > [LOS_NUM] then

        y = "Y"

    else

        y ="N"

    end if
```

18.4 VB Script for Assigning Functional Classification Values to Roads

```
dim y

if [FUNCTION_] = "a arterial" and [RdEnv]="Urban" then

y = "5"

Elseif [FUNCTION_] = "a arterial" and [RdEnv]="Rural" then

y = "4"

Elseif [FUNCTION_] = "b arterial" then

y = "4"

elseif [FUNCTION_] = "c arterial" then

y = "3"

elseif [FUNCTION_] = "collector" then

y = "2"

elseif [FUNCTION_] = "ramp" then

y = "5"

elseif [FUNCTION_] = "freeway" then

y = "5"

elseif [FUNCTION_] = "local" then

y = "1"

end if
```

18.5 VB Script for Assigning Criticality Score to Roads Based on AADT

```
dim y

if [AADT] < "1000" then

y = "1"

Elseif [AADT] >="1000" and [AADT] <"3000" then
```

y = "2"

Elseif [AADT] >="3000" and [AADT] =<"8000" then

y = "3"

Elseif [AADT] >="8001" and [AADT] =<"20000" then

y = "4"

Elseif [AADT] >"20000" then

y = "1"

end if

18.6 VB Script for Assigning Criticality Score to Roads Based on Their Inclusion in the Transit Priority Network.

dim y

if [RED_RD] = "Regional Highway 2" then

y = "5"

Elseif [RED_RD] = "Regional Road 4" then

y = "3"

Elseif [RED_RD] = "Regional Road 1" then

y = "3"

elseif [RED_RD] = "Regional Road 31" then

y = "3"

elseif [RED_RD] = "Regional Road 22" then

y = "3"

else

y = "1"

end if

18.7 VB Script for Assigning Criticality Score to Roads Based on Their Inclusion in the Goods Movement Routes

dim yif [FULL_NAME] = "Highway 401" then

y = "5"

Elseif [FULL_NAME] = "Highway 407" then

y = "5"

Elseif [FULL_NAME] = "Highway 7" then

y = "5"

Elseif [RED_RD] = "Regional Road 4" then

y = "5"
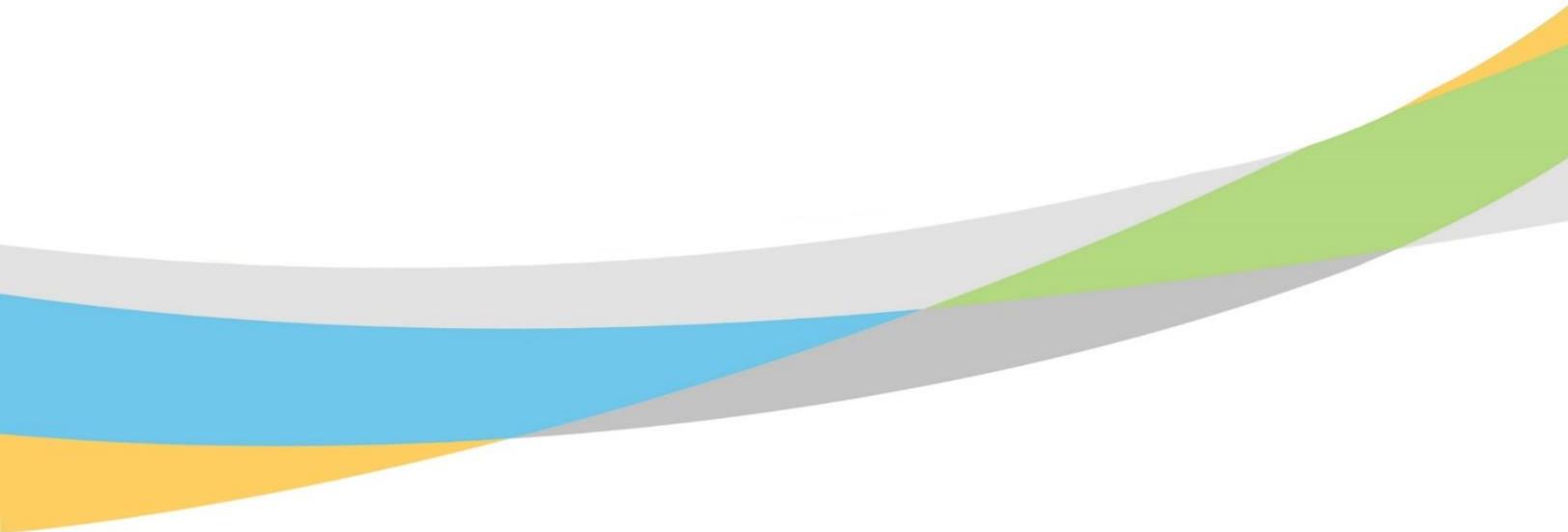
Elseif [RED_RD] = "Regional Road 1" then

y = "5"

elseif [RED_RD] = "Regional Road 22"and [MUNICIPAL] = "Ajax" then

y = "5"

else

y = "1"

end if

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