Prepared for:

The City of Guelph

Stormwater Management Master Plan

Appendix J: Rainfall and IDF Curve Analysis

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1 Introduction

The intensity-duration-frequency (IDF) curves currently used by the City of Guelph were created in the 1970s based on 16 years of rainfall data from the Guelph Arboretum rain gauge between 1954 and 1970. Rainfall analyses were conducted for the 2007 Stormwater Management Study and Environmental Assessment for Ward One and the 2012 Stormwater Management Master Plan. While the Ward One study recommended updating the City's IDF curves every five years, neither study indicated that changes to the existing IDF curves were warranted. However, it has been eight years since the last rainfall analysis was conducted, and the effects from climate change are ongoing.

2 Purpose

The purpose of this technical memorandum is to summarize the methodology and results of an analysis of historical rainfall trends and projected impacts of climate change on IDF curves, and to provide recommendations for future use of rainfall data.

3 Objectives

The objectives of this technical memorandum are as follows:

- Analyze historical rainfall records to determine whether trends can be observed in short and long storm durations (10 min to 24 hour, 2 and 5 day, monthly, and annual);
- If indicated by rainfall trends, create new IDF curves;
- Using climate change projections, determine the impact of climate change on IDF curves in 2050, 2100 and 2200;
- Recommend how to incorporate climate change adaptations in stormwater management and drainage infrastructure; and
- Evaluate the current rain gauge network and recommend whether new gauges should be installed.

4 Background

It is important for managers of municipal infrastructure to understand the response of stormwater conveyance and treatment networks to extreme rainfall events. This allows hydrologists and stormwater engineers to establish a level of service associated with normal operating ranges for stormwater systems as well as precipitation thresholds associated with significant impacts such as:

- Sewer surcharging;
- Local urban flooding;
- By-pass of treatment devices;
- Spills from private drainage networks and sub-catchments; and
- Overtopping of roadways, bridges and pathways.

Long-term rainfall monitoring allows for updates to IDF curves used by stormwater practitioners to consider risk when designing stormwater infrastructure. The uncertainty regarding the frequency and severity of rainfall events resulting from climate change presents a risk to much of Ontario's stormwater infrastructure. Municipal engineers are typically concerned with short duration events that cause flooding very quickly in urban settings with high impervious cover and short times of concentration. These short-term events (typically 2 hours or less) are often the product of thunderstorms that may be

associated with convective heating or fast-moving storm fronts. These storm fronts may be highly localized and can go unrecorded if precipitation monitoring stations are spaced too widely apart. Knowing the magnitude of precipitation events that damage to public infrastructure and/or private property is important for reducing risk and liability associated with the expected level of stormwater service.

4.1 Responsibility to Consider Climate Change

The extent to which climate change will impact precipitation patterns in a given location contains inherent uncertainties. These uncertainties arise in the difficulty of predicting the rate of change in greenhouse gas emissions; downscaling global climate models to a local level; and modeling how these emissions will predict precipitation patterns. It is nonetheless important to use the best available information to predict how climate change will impact extreme precipitation events, and apply this information to local design standards.

To minimize their risk, it is recommended that municipalities formalize a process for updating climate change data and ensure it is applied within the municipality by municipal staff and contractors. Additionally, "active, valid policy decisions" should be made and documented, even if the decision is to maintain existing policies once the risks and costs have been analyzed. An important distinction is made between a policy decision and an operational decision. A policy decision is necessary, and should be based on social, economic and political factors. To further understand the City's potential obligations in regards to considering the effects of climate change on stormwater management systems and municipal infrastructure, staff can refer to the report "Stormwater Management in Ontario: Legal Issues in a Changing Climate" (Zizzo et al., 2014).

5 Precipitation Analysis

5.1 Data Sources

A rainfall trend analysis was conducted to determine what changes have occurred with respect to rainfall depths, durations and frequencies since the last time this analysis was undertaken. Multiple data sources were used to conduct the rainfall analysis, as no rain gauge has a complete long-term record. Both raw rain gauge data and rain gauge summaries were used (**Appendix A**). Environment Canada's summaries were used for the following stations:

- Guelph Turfgrass Station: Environment Canada's annual maxima for 5, 10, 15, and 30 minutes, and 1, 2, 6, 12, and 24 hours. These data were available from 1954 to 2017, but were missing the following:
    - 5-minute and 10-minute maxima for 1960;
    - 12-hour and 24-hour maxima for 1989; and
    - All durations for 1974, 1975, 1992-1996, and 2005-2006.
- Guelph Smallfield Farm Station: Environment Canada's annual maxima for 5 and 10 minutes for 1960.
- Waterloo Wellington A Station: Environment Canada's annual maxima for 5, 10, 15, and 30 minutes, and 1, 2, 6, 12, and 24 hours. These values supplemented the missing years from the Guelph Turfgrass station, including 1974-1975, 1989, 1992-1996, and 2005-2006.

Raw rain gauge data were obtained from the following sources:

- City owned or operated rain gauges:

    - F.M. Woods Water Treatment Plant: 5-minute interval from 2014-2020
    - Arkell Well 15: 5-minute interval from 2012-2020
    - Clair Rd Emergency Services Centre: 5-minute interval from 2016-2020
    - Sir Isaac Brock Public School: 1-minute interval from 2017-2020
    - City Hall: time recorded for every 0.25 mm tip from 2017-2020
    - Helmar Well: 5-minute interval from 2019-2020
    - West End Recreation Centre: 5-minute interval from 2019-2020
- Daily precipitation reports from Environment Canada for the following stations:
    - Guelph OAC: Daily results available from 1954-1973
    - Guelph Arboretum: Daily results available from 1976-1994
    - Waterloo Wellington A: Daily results used to supplement missing years from Guelph stations, including 1974-1975 and 1995-1996
    - Region of Waterloo Int'l Airport: Daily results used to supplement missing months from Guelph stations, including sporadically from 2004-2009
    - Kitchener/Waterloo: Daily results used to supplement missing years or months from Guelph stations, including sporadically from 2010-2011
- Hourly precipitation reports from the Guelph Turfgrass Institute:
    - Full data sets available from 1997-2004
    - Partial data sets available from 2004-2011

The Guelph Lake rain gauge, operated by the Grand River Conservation Authority, also had hourly precipitation data from 1999-2019. Means and standard deviations from the Guelph Lake gauge were compared with those from the Turfgrass Institute and the Waterloo rain gauges for years when all three gauges produced data. It was found that the results from the Waterloo rain gauges were more similar to the Turfgrass results than those from Guelph Lake. Therefore, the Waterloo results were used in place of the Guelph Lake results when no results were available from gauges within the city.

5.2 Seasonal Data Availability

Most rain gauges did not distinguish between snow and rainfall, therefore precipitation during all twelve months of the year was analyzed. To improve the quality of the analysis, separating snow and rainfall during all months is recommended. Although results from 1954 to 1996 separated snow and rainfall, none of the more recent results did. Since the effects of climate change will be more significant in recent years, identifying how much precipitation falls as rain during the winter months is important.

Figure 5.1 illustrates the annual precipitation, distinguishing between April to November precipitation and winter precipitation in January through March and December. No results were available for December 1969 or January 2003, so the winter total may be artificially low for these years. Data used for **Figure 5.1** are available in **Appendix A**, which also identifies which rain gauges were used for each year.

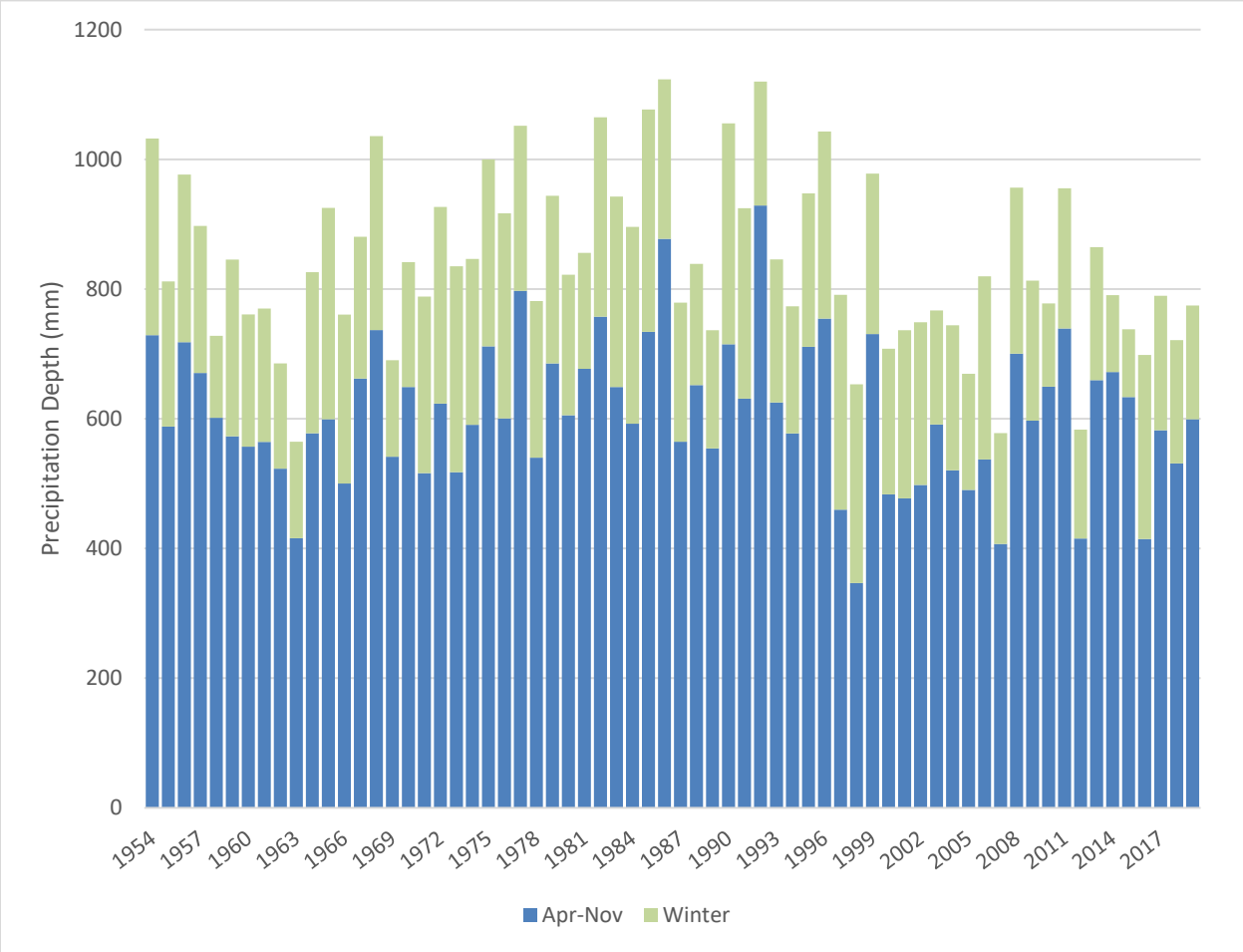


Figure 5.1: Annual Precipitation

5.3 Precipitation Spatial Distribution

Since 2012, the City of Guelph has been increasing the number of rain gauges throughout the city to better capture the spatial variation of precipitation. Monthly precipitation totals from each available gauge are reported in **Appendix B**, but do not distinguish between rain and snow. All rain gauges, except for the one at Sir Isaac Brock Public School are heated. Results from the Brock gauge were therefore not used, as they were not comparable to the other City gauges.

Results from the Clair Road rain gauge are frequently substantially higher than the results from other gauges, at times by up to 50 percent. **Table 5.1** shows the annual average of the other three rain gauges operational during the same time period as the Clair Road rain gauge, and compares the percent difference between the recorded precipitation at Clair Road compared to the other three rain gauges. As can be seen, the Clair Road rain gauge recorded substantially higher precipitation in all four years. This is unlikely to be due to geographical rainfall patterns given the gauge's proximity to other City rain gauges. As no information was provided regarding equipment type, calibration, maintenance procedures, QA/QC protocols for collection, and data transfer, the Clair Road gauge was excluded from the analysis. Should the data be validated in the future, future analyses can include the results from this gauge.

Table 5.1: Clair Road Rain Gauge Assessment

	Annual Precipitation (mm)			
	2016	**2017**	**2018**	**2019**
City Hall	-	737.5	608.5	699.75
Arkell Well 15	676	821.75	831.5	839.25
FM Woods	721	809.25	723.5	765.75
Annual Average	699	790	721	768
Clair Rd	910.2	1204.2	1002.8	978.6
% difference (Clair Rd vs Annual Average)	30.3%	52.5%	39.1%	27.4%

5.4 Rainfall Trend Analysis

A trend analysis was conducted on all years with available rainfall data to determine whether any statistically significant trends are occurring. The Mann-Kendall Trend Test was used, as it is a non-parametric test that can analyze a data set for increasing or decreasing trends. As is standard statistical practice, a p-value of 0.05 was used to determine whether a trend was significant. The R statistical package was used for all statistical analyses reported in **Section 5.4**. The R script and output can be found in **Appendix C.** For all Mann-Kendall analyses, the null hypothesis was that there was no monotonic trend in the analyzed data; the alternative hypothesis was that a monotonic trend was present in the data.

5.4.1 Trends in 5-Minute to 24-Hour Rain Events

Intervals from 5-minute to 24-hour, except for 4-hour, were obtained from Environment Canada summary reports as described in **Section 5.1**. Hourly data were available from the Guelph Turfgrass Institute, so the 4-hour annual maxima was calculated from 1997 to 2003 from this station. The City gauge data recorded data every 30 seconds to 5 minutes, so these results were used for estimating all maxima from 2012 to 2020. From 2012 to 2017, the maximum of the City rain gauge and the Environment Canada Turfgrass Station was used.

While Environment Canada provided annual maxima for all events except the 4-hour from 1954 to 2017, the annual maxima were calculated for all 4-hour events and for all results obtained from the City rain gauges. Since these gauges didn't distinguish rain and snow, any annual maxima from winter months (December through March) were verified against air temperatures to confirm they resulted from rain. **Table 5.2** presents these results. **Figure 5.2** and **Figure 5.3** present linear trends of these data. Because the year 2020 was not yet complete at the time of analysis, there was the potential for higher maxima to occur later in the year. If the 2020 year-to-date maximum for a particular duration was lower than the average maxima from previous years, it was excluded from the analysis. Therefore, only the 12-hour and 24-hour maxima were used for 2020.

Table 5.2: Mann-Kendall Significance Results (5-min to 24-hour)

Duration	Years Included	Trend	p-value	Significance*
5 Minute	1954-2019	Increasing	0.21267	Not significant
10 Minute	1954-2019	Increasing	0.22804	Not significant
15 Minute	1954-2019	Increasing	0.16251	Not significant
30 Minute	1954-2018	Increasing	0.053646	Not significant
1 Hour	1954-2019	Increasing	0.018634	Significant (p<0.05)
2 Hour	1954-2019	Increasing	0.12752	Not significant
4 Hour	1997-2003, 2012-2019	Decreasing	0.76653	Not significant
6 Hour	1954-2019	Increasing	0.90316	Not significant
12 Hour	1954-2020	Decreasing	0.98193	Not significant
24 Hour	1954-2020	Decreasing	0.30279	Not significant

* Statistically significant results are indicated by a p-value below 0.05, and demonstrate that the result is unlikely to be random or due to chance.

Increasing trends were observed for most short-duration events, including a significant increase in the 1-hour event, indicating that this increase is unlikely to be due to chance. Non-significant trends may be attributed to chance due to the inherent variability in rainfall.

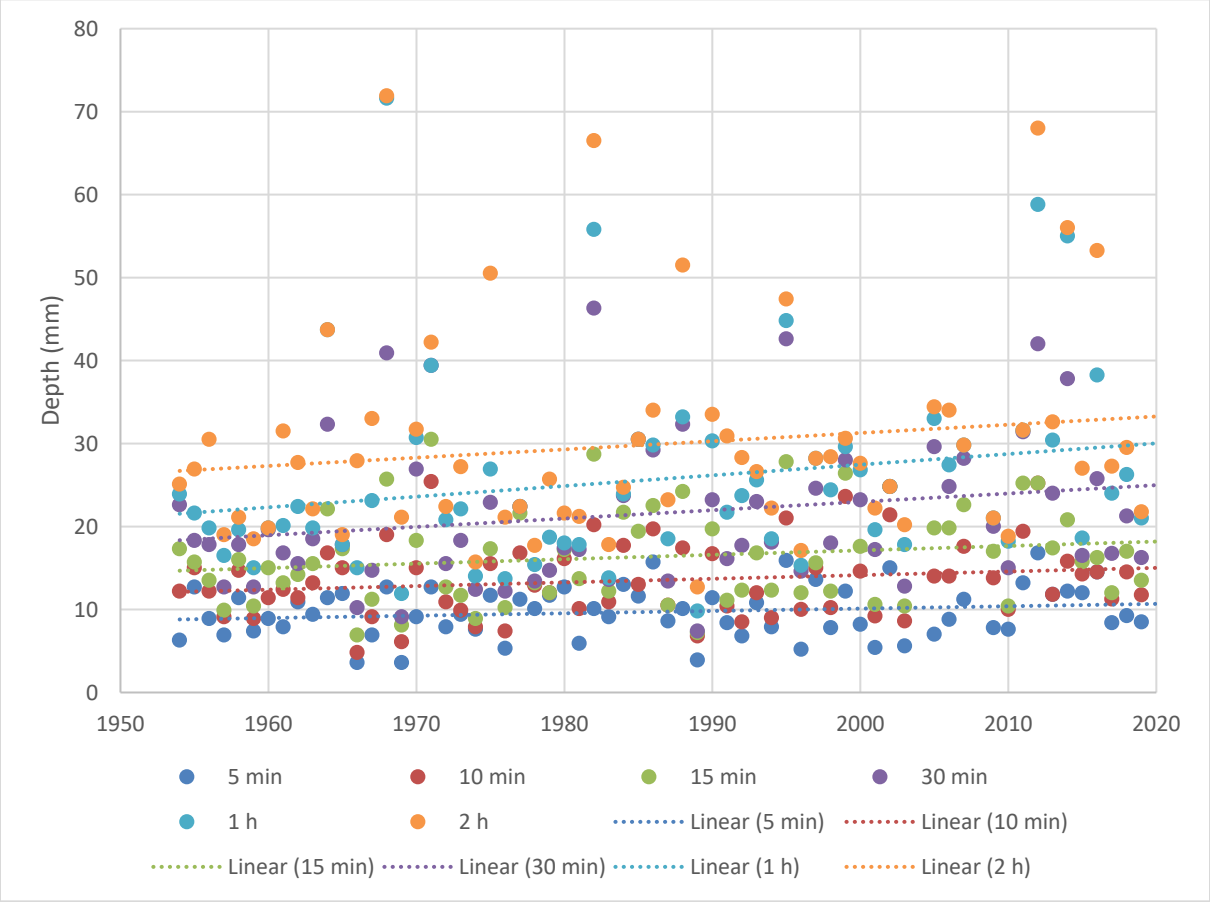


Figure 5.2: Rainfall Trends (5-min to 2-hour) from 1954-2019

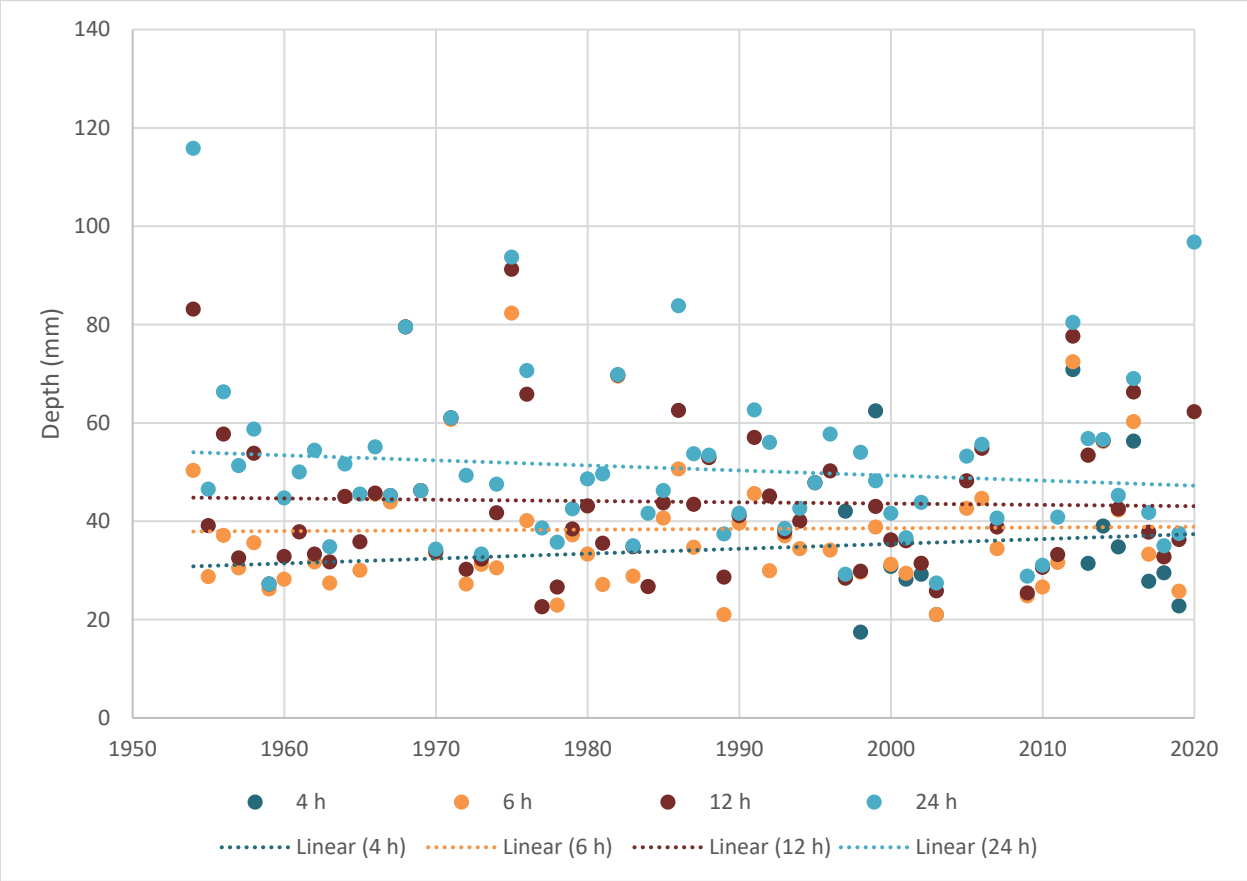


Figure 5.3: Rainfall Trends (4-hour to 24-hour) from 1954-2019/2020

5.4.2 Trends in Multi-Day Events

The 2-day and 5-day rainfall maxima were calculated for each year by conducting a rolling sum of rainfall from April through November. Winter months were removed from this analysis, because a mix of rain and snow was common in these longer duration events. These results are all presented in **Table 5.3** and **Figure 5.4**. Decreasing trends were observed for both durations, but were not significant. Non-significant trends may be attributed to chance due to the inherent variability in rainfall.

Table 5.3: Mann-Kendall Significance Results (2-day to 5-day)

Duration	Years Included	Trend	p-value	Significance*
2 Day	1954-2019	Decreasing	0.090363	Not significant
5 Day	1954-2019	Decreasing	0.29813	Not significant

* Statistically significant results are indicated by a p-value below 0.05, and demonstrate that the result is unlikely to be random or due to chance.

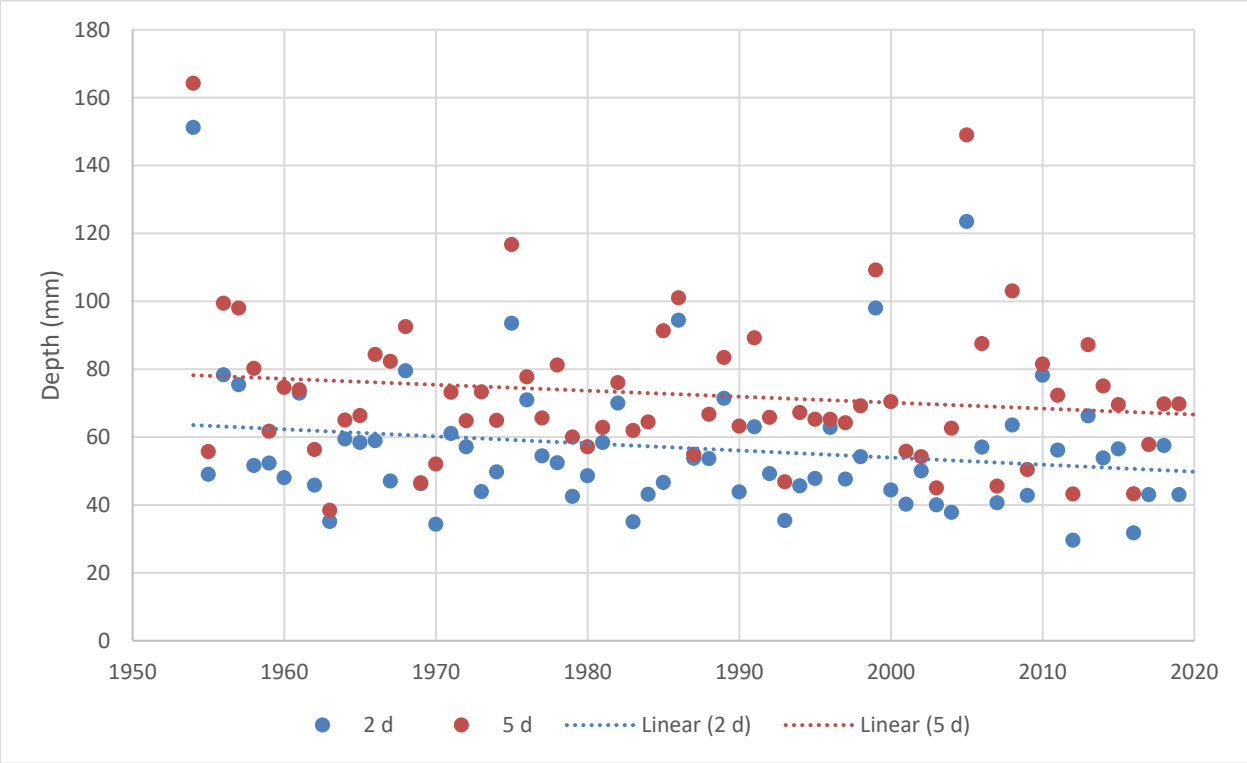


Figure 5.4: Rainfall Trends (2-day and 5-day) from 1954-2019

5.4.3 Hurricane Hazel

Hurricane Hazel hit southern Ontario in October 1954. This was a large, slow-moving storm and is now considered the Regional storm for the City of Guelph. The data record used for the above analyses included 1954. The 6-hour through 5-day events were analyzed again after removing 1954 to determine the extent to which the large amount of rainfall from Hurricane Hazel is impacting the trends observed for these durations (**Table 5.4** and **Figure 5.5**). By removing 1954, the trend for the 12-hour storm went from decreasing to increasing, while the p-values for the increasing trends of the 6-hour event dropped, indicating a higher likelihood. The p-value for the 24-hour, 2-day and 5-day events increased, indicating a lower likelihood of the decreasing trend.

Table 5.4: Mann-Kendall Significance Results (6-hour to 5-day, excluding 1954)

Duration	Years Included	Trend	p-value	Significance
6 Hour	1955-2020	Increasing	0.66626	Not significant
12 Hour	1955-2020	Increasing	0.72638	Not significant
24 Hour	1955-2020	Decreasing	0.49416	Not significant
2 Day	1955-2020	Decreasing	0.17243	Not significant
5 Day	1955-2020	Decreasing	0.4862	Not significant

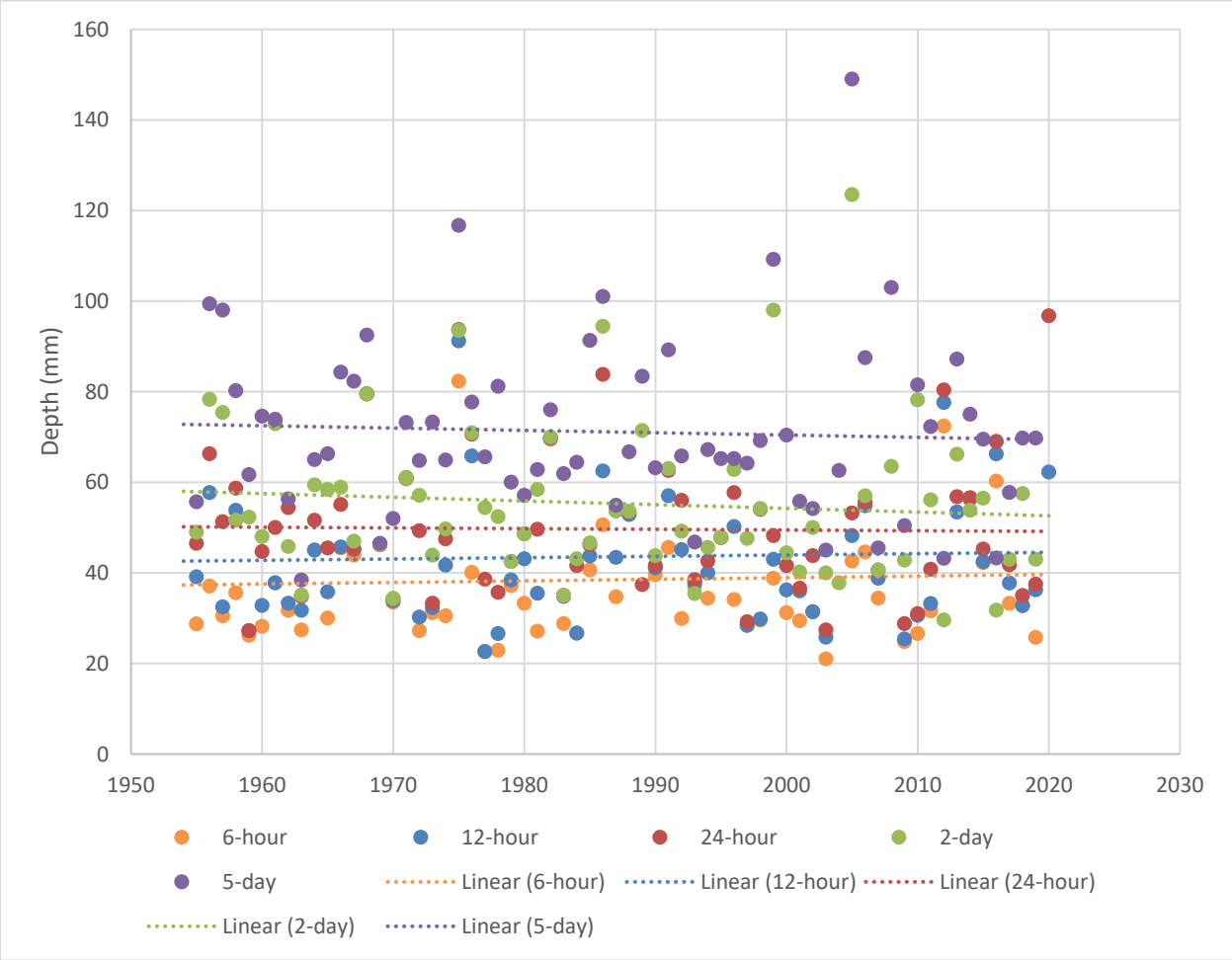


Figure 5.5: Rainfall Trends (6-hour to 5-day) from 1955-2019/2020

5.4.4 Monthly Precipitation Trends

The precipitation in each month was totalled and analyzed using the Mann-Kendall test (**Table 5.5**). Monthly precipitation decreased during most months, with the exception of May to July and October, although none of these trends were significant. These trends are presented in **Figure 5.6** and **Figure 5.7**.

Table 5.5: Mann-Kendall Significance Results (Monthly)

Month	Years Included	Trend	p-value	Significance
January	1954-2020	Decreasing	0.48554	Not significant
February	1954-2020	Decreasing	0.66899	Not significant
March	1954-2020	Decreasing	0.17265	Not significant
April	1954-2020	Decreasing	0.40767	Not significant
May	1954-2020	Increasing	0.46174	Not significant
June	1954-2020	Increasing	0.78671	Not significant
July	1954-2019	Increasing	0.98234	Not significant
August	1954-2019	Decreasing	0.096868	Not significant
September	1954-2019	Decreasing	0.97351	Not significant
October	1954-2019	Increasing	0.97792	Not significant
November	1954-2019	Decreasing	0.22552	Not significant
December	1954-2019	Decreasing	0.080218	Not significant

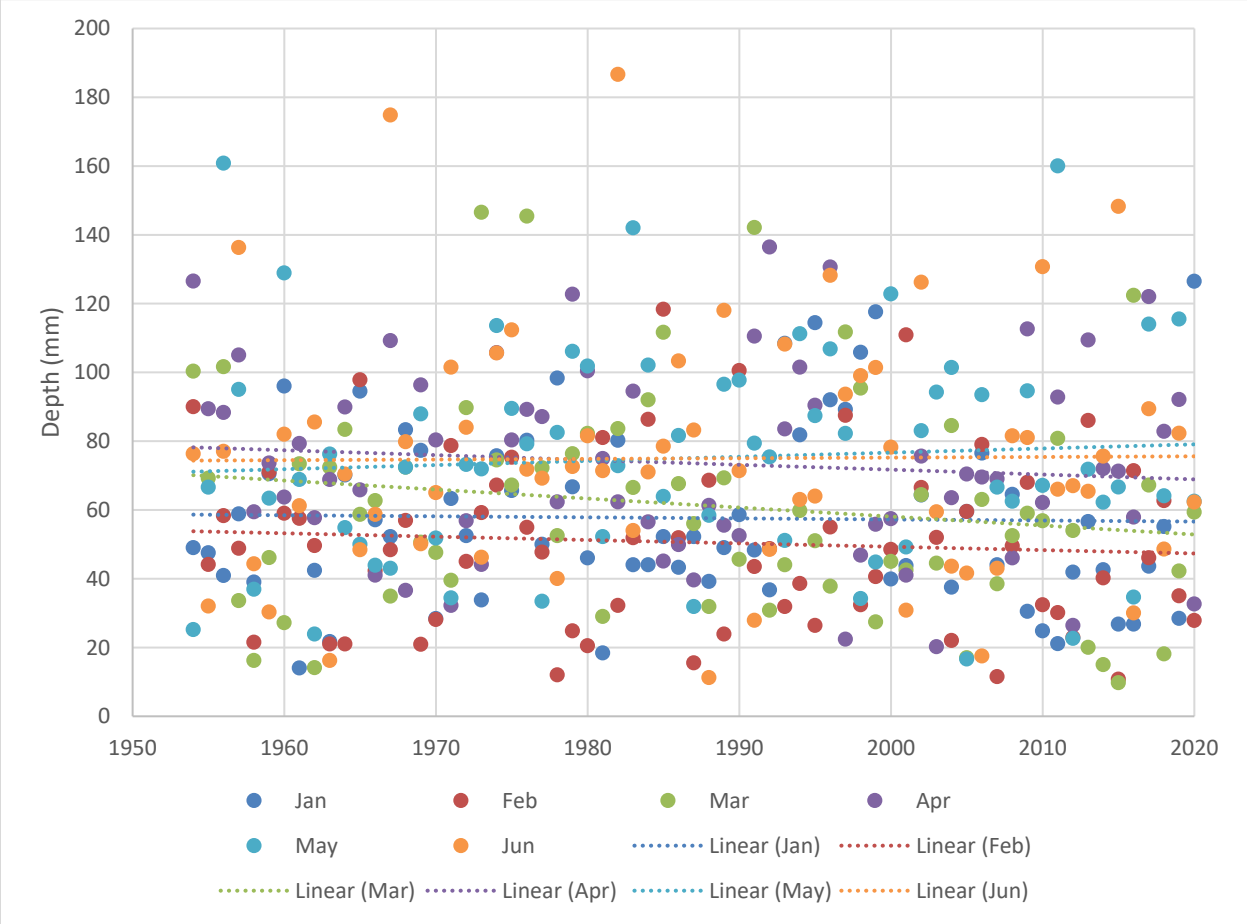


Figure 5.6: Monthly Precipitation Trends (January–June)

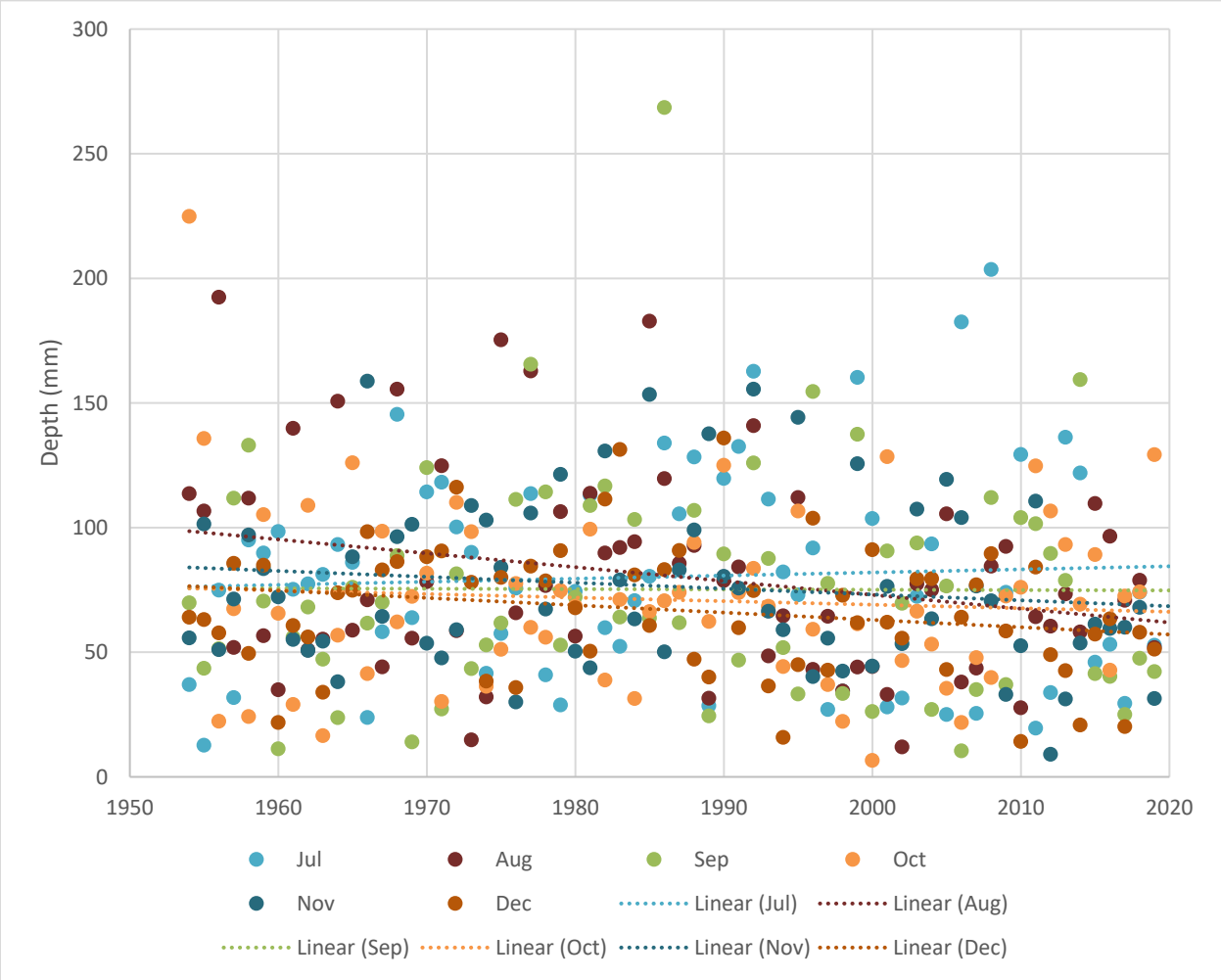


Figure 5.7: Monthly Precipitation Trends (July–December)

5.4.5 Annual Precipitation Trends

The annual precipitation, whether for the entire year or just for April through November was analyzed using the Mann-Kendall test (**Table 5.6**). A decreasing trend in annual precipitation and in rainfall from April to November was noted, although no trend was significant ($p<0.05$). These trends are also presented in **Figure 5.8**.

Table 5.6: Mann-Kendall Significance Results (Annual)

Months	Years Included	Trend	p-value	Significance
April – November	1954-2019	Decreasing	0.39715	Not significant
January - December	1954-2019	Decreasing	0.1014	Not significant
April – November	1955-2019	Decreasing	0.54843	Not significant
January - December	1955-2019	Decreasing	0.162	Not significant

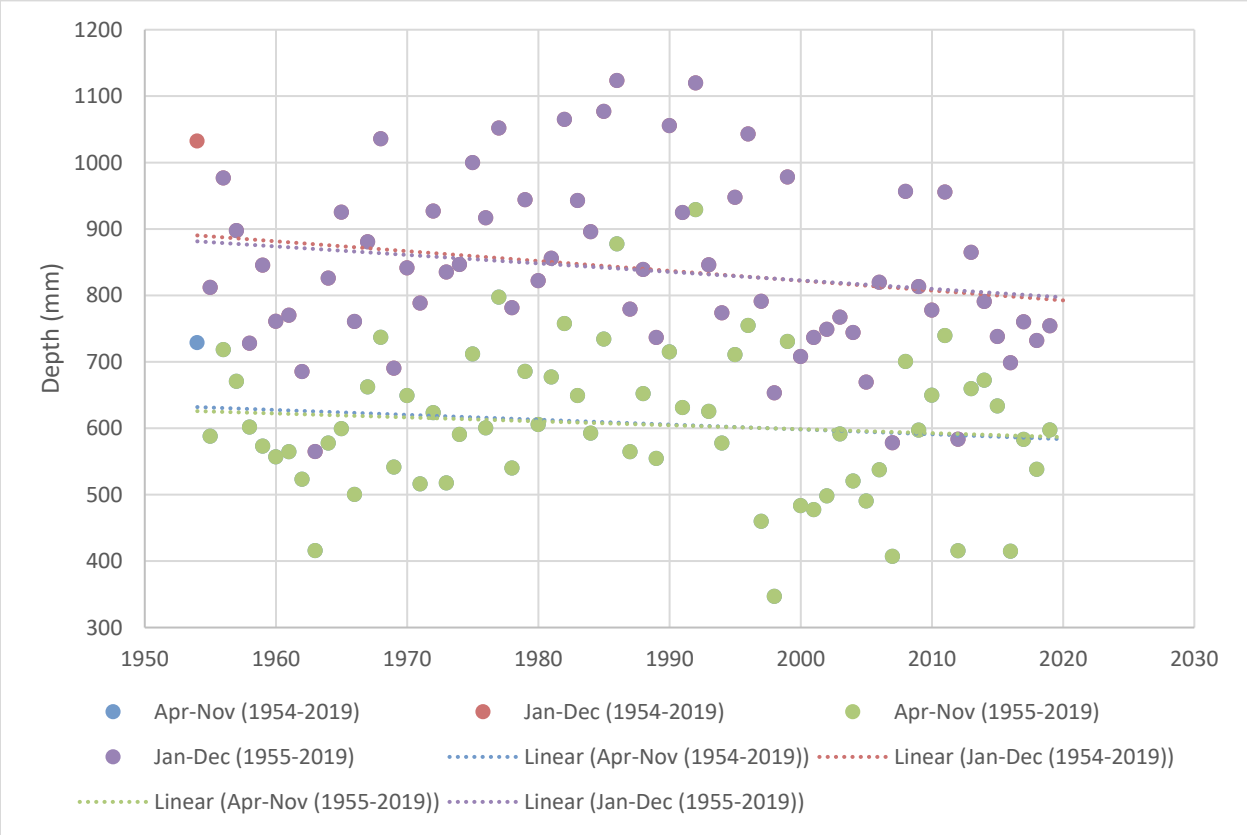


Figure 5.8: Annual Precipitation Trends

6 IDF Curve Updates

Based on the results from the statistical analysis conducted in **Section 5**, it is not necessary to update the City's IDF curves due to changes in historical rainfall patterns. Although there is an increasing trend for many storm durations, these trends are not significant, except for the 1-hour event, indicating that it is not possible to differentiate the trends from the effects of chance.

7 Climate Change Effects Forecasting

Several tools have been developed by climate scientists and statisticians to project future IDF relationships for rain events in Ontario. Three (3) of these tools are discussed below:

1) The **Ontario Climate Change Data Portal (Ontario CCDP)** was developed through the University of Regina with funding from the Ontario Ministry of the Environment and Climate Change (now Ministry of Environment, Conservation and Parks - MECP). This tool was launched to ensure technical or non-technical end-users (e.g. municipalities, private sector) have easy and intuitive access to the latest climate data over the Province of Ontario. Climate projections for several parameters are made on a 25 km grid resolution based on regional climate modelling using PRECIS model and the RegCM model under three (3) emissions scenarios. The model uses two Representative Concentration Pathways (RCP) representing future greenhouse gas concentrations, including the RCP 4.5 and RCP 8.5 scenarios as published by the International Panel on Climate Change (IPCC) 5th Assessment Report.

2) The **IDF_CC Tool 4.0** was developed through the University of Western Ontario and the Institute for Catastrophic Loss Reduction. This tool was designed as a simple and generic decision support system to generate local IDF curve information that accounts for the possible impacts of climate change. It applies a user-friendly GIS interface and provides rain accumulation depths for a variety of return periods (1:2, 1:5, 1:10, 1:25, 1:50 and 1:100 years) and durations (5, 10, 15 and 30 minutes and 1, 2, 6, 12 and 24 hours), and allows users to generate IDF curve information based on historical data, as well as future climate conditions that can inform infrastructure decisions. The IDF_CC tool stores data associated with 700 Environment and Climate Change Canada operated rain stations from across Canada. The IDF_CC tool allows users to select multiple future greenhouse gas concentration scenarios and apply results from a selection of 24 Global Circulation Models (GCMs) and 9 downscaled GCMs that simulate various climate conditions to local rainfall data.

3) The **MTO IDF Curves Finder** was developed by the Ontario Ministry of Transportation (MTO) to provide a convenient method to interpolate IDF curve parameters between Meteorological Services Canada stations for MTO projects. The tool projects data forward using a linear trend line. It should be noted that this methodology is not based in climate projections but rather historical observations and as such, results vary considerably from the two models introduced above which rely on downscaled global climate models.

While the Ontario CCDP and the IDF_CC tools both use global climate models to estimate future IDF curves, they differ in how they do so. The Ontario CCDP tool relies on one climate model (HadGEM2-ES) whereas the IDF_CC tool uses 24 raw models, including HadGEM2-ES, and reports the median result. Additionally, the method of downscaling differs between the two tools. The IDF_CC tool uses statistically-downscaled projections, whereas the Ontario CCDP tool uses dynamically-downscaled projections.

Statistical downscaling uses a mathematical relationship between the model output and historical climate data, using this relationship to downscale future climate projections to a local scale (Schardong et al., 2018). Limitations of statistical downscaling include the length of historical data records required to develop the mathematical relationship, as well as the assumption that historical relationships will still apply to future climate scenarios (MetOffice, 2020).

Dynamic downscaling uses regional models to simulate physical processes at a regional scale, acting at a higher resolution than the global climate models (MetOffice, 2020; Schardong et al., 2018). Ontario CCDP uses PRECIS, which is a Regional Climate Model that downscales Global Climate Models such as HadGEM2-ES to specific regions with a resolution from 25 to 50 km (MetOffice, 2020). Although dynamic downscaling represents climate extremes better than statistical downscaling, its limitations include its high complexity and computational requirements, as well as the biases arising from the inherent incompleteness of the regional physical system model (MetOffice, 2020).

Of the three tools, only the IDF_CC tool provides statistical analyses, including box plots for the projected IDF curves. Each box plot shows the minimum, first quartile, median, third quartile, and maximum result. These box plots are presented in **Appendix D** for each analysis discussed below.

7.1 Existing Conditions

The existing conditions IDF curve is based on the IDF parameters presented in **Table 7.1** which results in the rainfall depths presented in **Table 7.2** and intensities presented in **Table 7.3**. The City's Development Engineering Manual specifies the following design storms:

- The minor system is designed using the 5-year design storm with a 10-minute duration for parks and single detached residential areas, and a 5-minute duration for all other land uses;
- The major system is designed to convey the 100-year storm and Hurricane Hazel overland flow; and
- In the absence of site-specific criteria, post-development peak flows shall be controlled to pre-development peak flows for the 2-year through 100-year storm events.

Table 7.1: Existing IDF Parameters

Parameter	2-Year	5-Year	10-Year	25-Year	50-year	100-Year
a	743	1593	2221	3158	3886	4688
b	6	11	12	15	16	17
c	0.7989	0.8789	0.908	0.9355	0.9495	0.9624

Table 7.2: Existing IDF Rainfall Depths (mm)

Duration	2-Year	5-Year	10-Year	25-Year	50-year	100-Year
5 min	9.1	***11.6****	14.1	16	18	19.9
10 min	13.5	***18.3****	22.4	25.9	29.4	32.8
15 min	16.3	22.7	27.8	32.8	37.3	41.7
30 min	21.2	30.5	37.3	44.9	51.2	57.6
1 hr	26.1	37.6	45.7	55.6	63.6	71.7
2 hr	31.2	43.9	52.7	64.2	73.2	82.3
6 hr	39.9	52.7	61.8	74.1	83.7	93.3
12 hr	46.2	58.1	66.8	78.9	88.4	97.8
24 hr†	53.3	63.6	71.7	83.3	92.5	101.6

** indicates the design storm for the minor system*
† indicates the design storms for the major system

Table 7.3: Existing IDF Rainfall Intensities (mm/hr)

Duration	2-Year	5-Year	10-Year	25-Year	50-year	100-Year
5 min	109.2	**139.2***	169.2	192.0	216.0	238.8
10 min	81.0	**109.8***	134.4	155.4	176.4	196.8
15 min	65.2	90.8	111.2	131.2	149.2	166.8
30 min	42.4	61.0	74.6	89.8	102.4	115.2
1 hr	26.1	37.6	45.7	55.6	63.6	71.7
2 hr	15.6	22.0	26.4	32.1	36.6	41.2
6 hr	6.7	8.8	10.3	12.4	14.0	15.6
12 hr	3.9	4.8	5.6	6.6	7.4	8.2
24 hr†	2.2	2.7	3.0	3.5	3.9	4.2

** indicates the design storm for the minor system*
† indicates the design storms for the major system

7.2 Forecast to 2050

All three tools were used to predict the impacts of climate change on IDF curves. The Ontario CCDP tool has four specific time ranges for which projections are generated. The 2040-2069 range contains the year 2050, so was selected for analysis. Although any 30-year time period from 2006-2100 can be selected for analysis by the IDF_CC tool, 2040-2069 was selected to align with the time range used by the Ontario CCDP. The MTO IDF tool requires one year to be selected, so 2050 was used.
The most conservative results from each model and the existing IDF curve are presented in **Table 7.4**, and the percent increase from existing conditions is presented in **Table 7.5**. **Figure 7.1** shows the comparison with the existing IDF curve. Full projection results from 2-year to 100-year and 5-min to 24-hour are presented in **Appendix E.**

Table 7.4: Rainfall Depth (mm) from Climate Change IDF Curve to 2050

Duration	2-Year	5-Year	10-Year	25-Year	50-year	100-Year
5 min	11.2	***14.7****	17.1	20	22.1	24.3
10 min	14.9	***19.5****	22.4	25.9	29.4	32.8
15 min	17.8	23.5	27.8	32.8	37.3	41.7
30 min	21.8	30.5	37.3	44.9	51.2	58.9
1 hr	26.1	37.6	45.7	55.6	63.7	78.5
2 hr	31.2	43.9	52.7	64.2	73.2	83.1
6 hr	42.6	55.2	66.8	81.8	92.9	103.9
12 hr	52.8	68.4	79.8	95.6	107.5	119.3
24 hr†	64.8	84.0	98.9	117.6	131.5	145.4

IDF_CC RCP 8.5	CCDP RCP 8.5	MTO IDF	Existing IDF

** indicates the design storm for the minor system*
† indicates the design storms for the major system

Table 7.5: Percent Increase from Existing Conditions to 2050

Duration	2-Year	5-Year	10-Year	25-Year	50-year	100-Year
5 min	23.08	***26.72****	21.28	25.00	22.78	22.11
10 min	10.37	***6.56****	0	0	0	0
15 min	9.20	3.52	0	0	0	0
30 min	2.83	0	0	0	0	2.26
1 hr	0	0	0	0	0.16	9.48
2 hr	0	0	0	0	0	0.97
6 hr	6.77	4.74	8.09	10.39	10.99	11.36
12 hr	14.29	17.73	19.46	21.17	21.61	21.98
24 hr†	21.58	32.08	37.94	41.18	42.16	43.11

** indicates the design storm for the minor system*
† indicates the design storms for the major system

Prediction results were not consistent between the different models, and is an indication of the uncertainty associated with the varying assumptions and available data used for each model. The following are comparative observations based on the values in **Table 7.4**:

- The existing IDF parameters and IDF_CC RCP 8.5 produced the highest depths for the short to mid-range durations;
- The MTO IDF tool generated the greatest depths for short duration and high frequency events; and
- The CCDP RCP 8.5 generated the greatest depths for longer duration and lower frequency events.

The maximum percent increase was 43.11 percent for the 100-year 24-hour event.

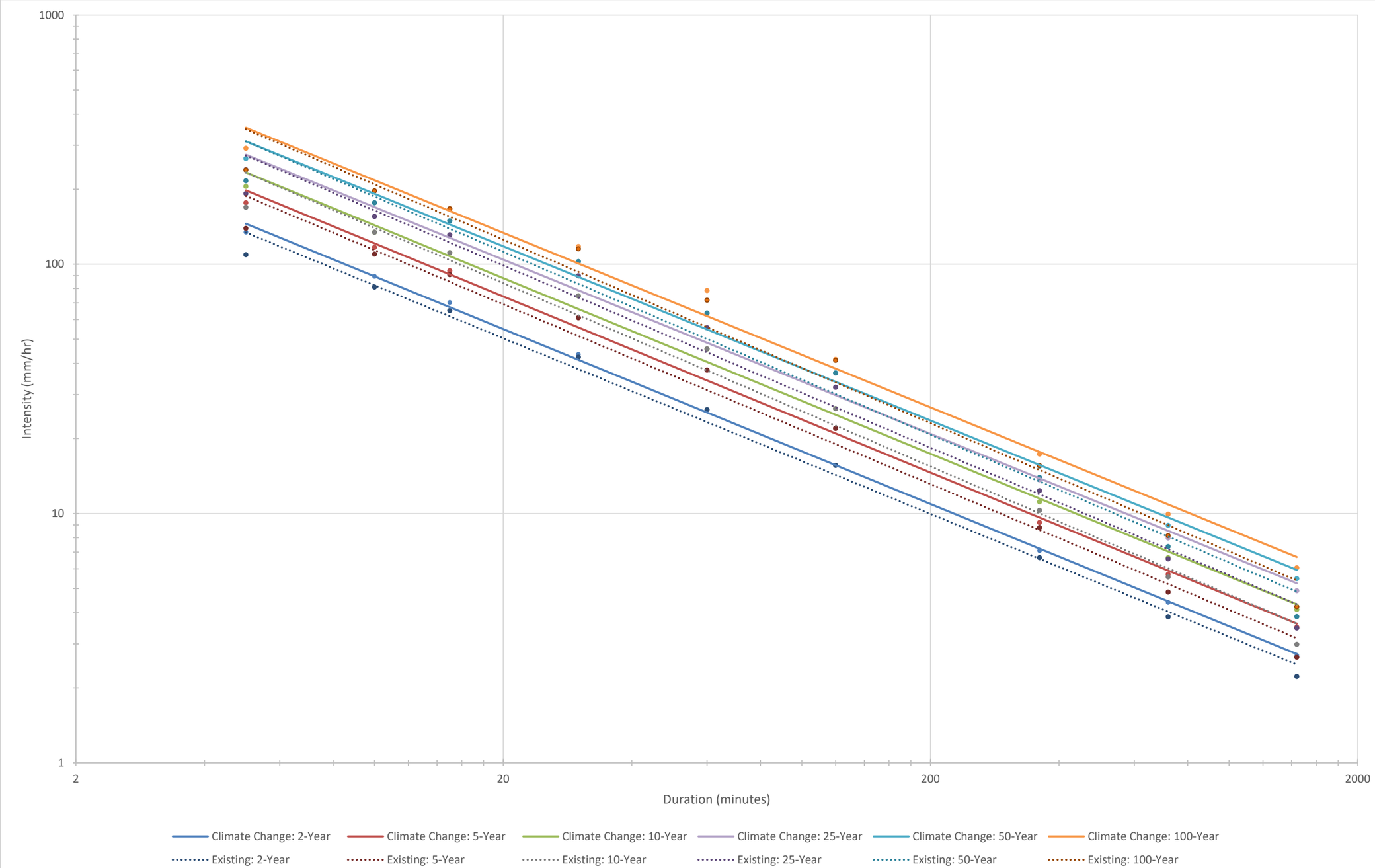


Figure 7.1: Comparison of Existing IDF Curve and 2050 Climate-Adjusted IDF Curve

7.3 Forecast to 2100

To conduct a forecast to 2100, the 2070-2099 time period was selected for the Ontario CCDP tool and the IDF_CC tool. The year 2100 was selected for the MTO IDF tool. The most conservative results from each model and the existing IDF curve are presented in **Table 7.6**, with the percent increase from existing conditions presented in **Table 7.7**.

Table 7.6: IDF Projection Results – 2100

Duration	2-Year	5-Year	10-Year	25-Year	50-year	100-Year
5 min	11.6	***15.1****	17.5	20.4	22.5	24.7
10 min	15.87	***21.18****	24.91	28.87	31.78	34.14
15 min	18.73	25.57	30.63	36.26	40.74	44.24
30 min	23.24	32.7	39.9	49.77	57.41	64.93
1 hr	26.54	37.6	45.91	59.68	71.92	84.03
2 hr	32	48.12	61.72	78.92	91.68	104.34
6 hr	45.6	71.34	90	113.58	131.04	148.44
12 hr	57.6	87.12	107.76	134.04	153.36	172.68
24 hr†	74.88	108.48	130.56	158.4	179.04	199.68

IDF_CC RCP 8.5	CCDP RCP 8.5	MTO IDF	Existing IDF

* *indicates the design storm for the minor system*
† *indicates the design storms for the major system*

Table 7.7: Percent Increase from Existing Conditions to 2100

Duration	2-Year	5-Year	10-Year	25-Year	50-year	100-Year
5 min	27.47	***30.17****	24.11	27.50	25.00	24.12
10 min	17.56	***15.74****	11.21	11.47	8.10	4.09
15 min	14.91	12.64	10.18	10.55	9.22	6.09
30 min	9.62	7.21	6.97	10.85	12.13	12.73
1 hr	1.69	0	0.46	7.34	13.08	17.20
2 hr	2.56	9.61	17.12	22.93	25.25	26.78
6 hr	14.29	35.37	45.63	53.28	56.56	59.10
12 hr	24.68	49.95	61.32	69.89	73.48	76.56
24 hr†	40.49	70.57	82.09	90.16	93.56	96.54

* *indicates the design storm for the minor system*
† *indicates the design storms for the major system*

The percent differences are greater than for the 2050 projection, with the maximum at 96.54 percent for the 100-year 24-hour event.

There is greater uncertainty inherent in making predictions over a longer time span with many unknowns over the next 80 years. When comparing the results between the different models, the IDF_CC tool consistently predicted lower rainfall depths than the Ontario CCDP tool. To determine whether this is due to the ensemble of models, the IDF_CC tool was run for just the HadGEM2-ES model, but it was found to still estimate a much lower projected rainfall depth than the Ontario CCDP tool (eg.

97.39 mm vs 124.02 mm for 100-year 6-hour RCP 4.5). This difference is therefore likely attributed to the downscaling method, where the dynamic downscaling used by the Ontario CCDP results in a greater rain intensity and depth than the statistical downscaling used by the IDF_CC.

7.4 Forecast to 2200

Neither the Ontario CCDP or the IDF_CC tool allows for projections to 2200. Since the MTO IDF tool uses linear interpolation, it was the only tool that projected that far into the future. Since there are so many uncertainties regarding future greenhouse gas emissions and climate change mitigation activities, projections to 2200 are highly uncertain. In addition, due to non-stationarity caused by climate change, linear interpolation from historical trends is not a recommended approach as historical trends do not necessarily apply to a future impacted by climate change. **Table 7.8** presents the most conservative results from the MTO model and the existing IDF curve results, while **Table 7.9** presents the percent increase from existing conditions to 2200. However, due to the modelling methodology, many of the depths presented in **Table 7.8** are lower than those presented in **Table 7.6** for the year 2100.

Table 7.8: IDF Projection Results – 2200

Duration	2-year	5-year	10-year	25-year	50-year	100-year
5 min	12.4	***15.9****	18.3	21.1	23.3	25.5
10 min	15.6	***19.9****	22.8	26.3	29.4	32.8
15 min	17.9	22.7	27.8	32.8	37.3	41.7
30 min	22.5	30.5	37.3	44.9	51.2	57.6
1 hr	28.4	37.6	45.7	55.6	63.6	71.7
2 hr	36	45	52.7	64.2	73.2	82.3
6 hr	52.8	65.4	73.8	84	92.4	99.6
12 hr	67.2	82.8	93.6	106.8	116.4	126
24 hr†	86.4	105.6	117.6	134.4	146.4	158.4

MTO IDF	Existing IDF

** indicates the design storm for the minor system*
† indicates the design storms for the major system

Table 7.9: Percent Increase from Existing Conditions to 2200

Duration	2-year	5-year	10-year	25-year	50-year	100-year
5 min	36.26	***37.07****	29.79	31.88	29.44	28.14
10 min	15.56	***8.74****	1.79	1.54	0	0
15 min	9.82	0	0	0	0	0
30 min	6.13	0	0	0	0	0
1 hr	8.81	0	0	0	0	0
2 hr	15.38	2.51	0	0	0	0
6 hr	32.33	24.10	19.42	13.36	10.39	6.75
12 hr	45.45	42.51	40.12	35.36	31.67	28.83
24 hr†	62.10	66.04	64.02	61.34	58.27	55.91

** indicates the design storm for the minor system*
† indicates the design storms for the major system

7.5 Worst-Case Climate-Adjusted IDF Curve to 2050

Based on the modelling results, it is anticipated that by 2050, climate change will increase rainfall depths for most storm events (**Table 7.4**). From these projections, a series of worst-case IDF curves can be calculated using the following equation:

$$Intensity\ (mm/hr) = At^B$$

where *t* is the storm duration (minutes) and A and B are parameters from **Table 7.10**. All R^2 values are greater than 0.99, indicating a good fit between the data points and the line of best fit. The projected curves are presented in **Figure 7.2**.

Table 7.10: Recommended IDF Parameters – Worst-Case Scenario

	A	B	R^2
2-year	449.77	-0.702	0.9956
5-year	616.92	-0.707	0.9928
10-year	725.9	-0.705	0.9905
25-year	847.01	-0.699	0.9892
50-year	958.24	-0.699	0.9856
100-year	1089.2	-0.7	0.9796

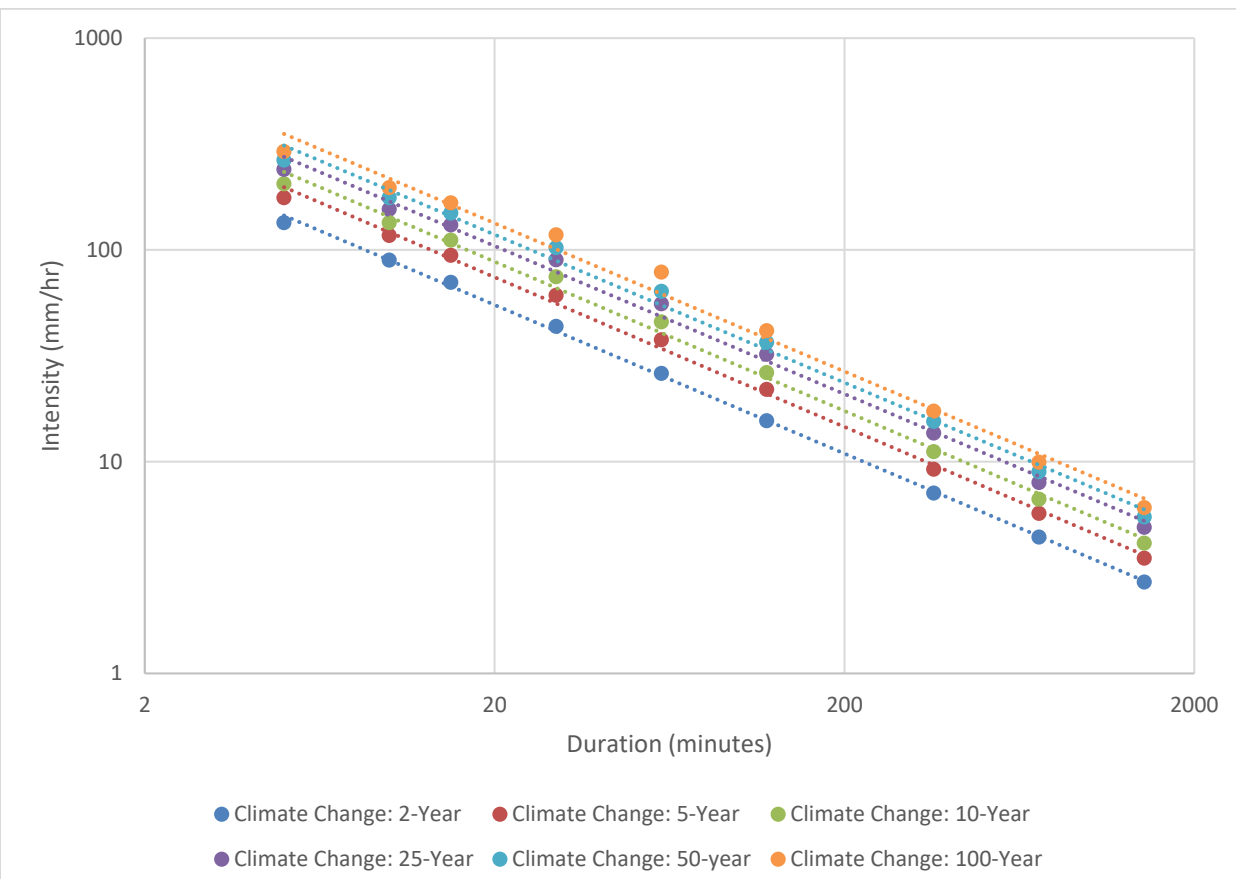


Figure 7.2: Worst-Case Scenario Climate-Adjusted IDF Curve to 2050

7.6 Mid-Range Climate-Adjusted IDF Curve to 2050

Section 7.5 outlined a worst-case climate-adjusted IDF curve. However, actions being taken by countries around the world to decrease greenhouse gas emissions would reduce the impact of climate change on extreme rainfall events. A mid-range climate-adjusted IDF curve was also developed using the IDF_CC RCP 4.5 scenario. The RCP 4.5 scenario assumes global emissions are stable and then begin to decline by 2050, and is therefore a middle-of-the-road scenario.

The IDF_CC RCP 4.5 scenario was chosen over the Ontario CCDP RCP 4.5 scenario as it used 24 raw climate models, while Ontario CCDP relies on only one model (HadGEM2-ES). Using the median of 24 climate models reduces reliance on one model and the assumptions used by this model. **Table 7.11** presents the rainfall depths estimated by the IDF_CC RCP 4.5 scenario.

Table 7.11: Mid-Range Climate-Adjusted IDF Curve Rainfall Depths (mm)

Duration	2-year	5-year	10-year	25-year	50-year	100-year
5 min	10.5	**13.3***	14.7	16.0	16.9	17.5
10 min	14.4	**18.9***	21.5	24.5	26.9	28.7
15 min	17.0	22.8	26.4	31.2	34.4	37.3
30 min	21.1	29.2	35.0	42.8	48.4	53.9
1 hr	24.1	32.9	40.0	51.1	59.2	69.4
2 hr	28.5	37.5	44.6	55.7	63.6	73.9
6 hr	37.9	48.9	57.0	68.6	76.6	86.0
12 hr	42.7	55.9	65.4	78.6	87.8	97.0
24 hr†	50.1	64.7	74.8	88.4	97.7	106.7

** indicates the design storm for the minor system*
† indicates the design storms for the major system

The RCP 4.5 IDF curve generated by the aggregated models in the IDF_CC tool generally predicts lower precipitation than the existing IDF curve for most events, although it does predict higher precipitation for the events used for designing the City's major and minor flows. A comparison of the RCP 4.5 rainfall depths with the existing IDF rainfall depths for the City's design storms indicates:

- 14.7 percent increase for the 5-minute 5-year event (minor system);
- 3.1 percent increase for the 10-minute 5-year event (minor system); and
- Range from 5.9 percent decrease to 6.1% percent increase for the 24-hour storm events (major system).

From this projection, a series of IDF curves can be calculated using the following equation:

$$Intensity\ (mm/hr) = At^B$$

where *t* is the storm duration (minutes) and A and B are parameters from **Table 7.12**. All R^2 values are greater than 0.99, indicating a good fit between the data points and the line of best fit. The projected curves are presented in **Figure 7.3**.

Table 7.12: Recommended IDF Parameters – Mid-Range Scenario

	A	B	R^2

2-year	475.61	-0.738	0.9883
5-year	632.75	-0.741	0.9794
10-year	721.92	-0.736	0.9706
25-year	822.74	-0.725	0.9513
50-year	893.80	-0.719	0.9365
100-year	953.29	-0.711	0.9199

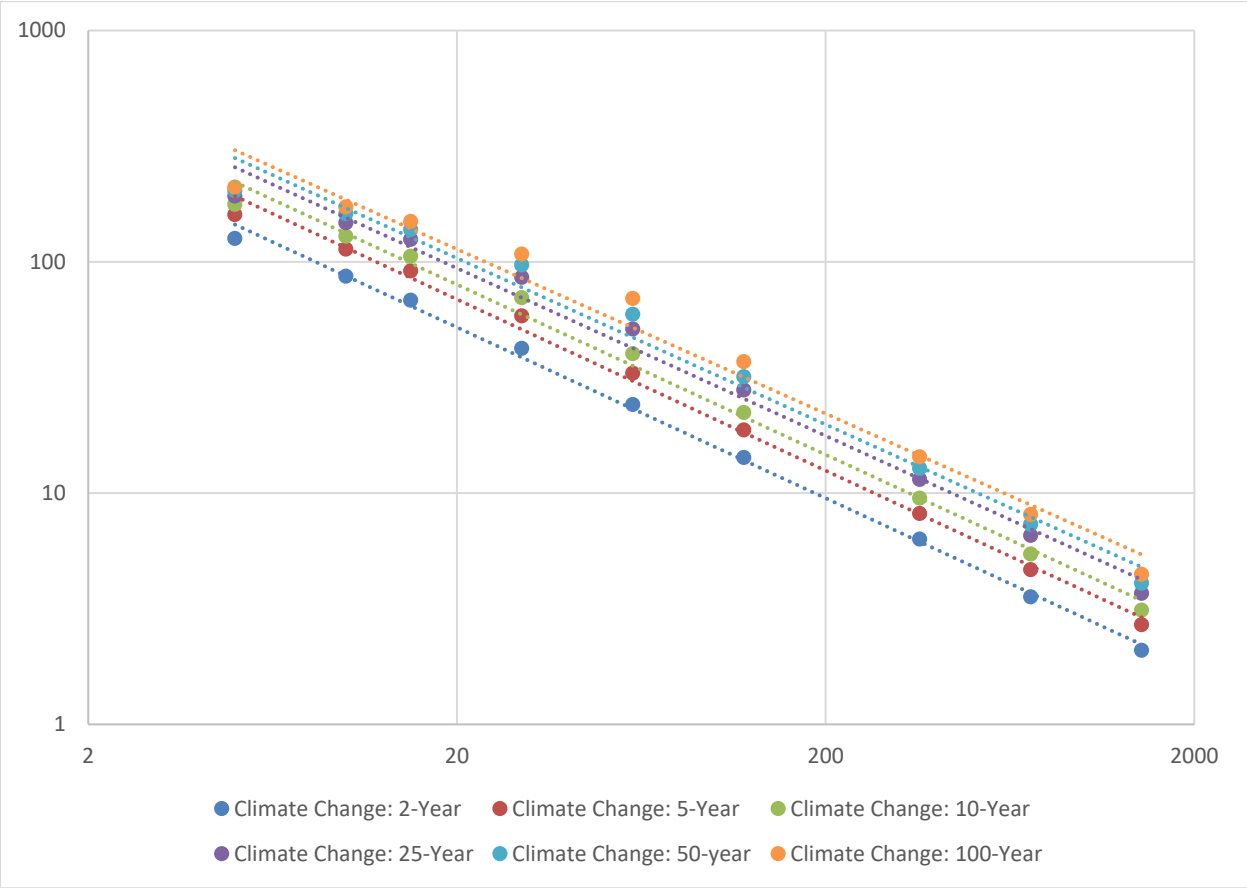


Figure 7.3: Mid-Range Scenario Climate-Adjusted IDF Curve to 2050

7.7 Application of Climate-Adjusted IDF Curve

It is recommended that the effects of climate change be taken into account by using the IDF projection results to 2050 as a sensitivity analysis during the design of stormwater infrastructure.

The City will decide, upon completion of the City-wide PCSWMM model, which IDF curve to consider for future use, at which point the SWM Criteria will be updated accordingly. The three curves under consideration include:

- The existing IDF curve: Historical data do not indicate a need to update the existing IDF curve, which is still conservative.

- RCP 4.5 IDF curve (IDF_CC): This curve, as presented in **Table 7.11** and **Table 7.12**, represents a mid-range scenario.
- Worst-case IDF curve: This curve, as presented in **Table 7.4** and **Table 7.10**, represents the worst-case scenario, and is the most conservative curve presented.

Since greenhouse gas emissions and mitigation measures over the next several years can have a significant impact on the severity of climate change, it is recommended that IDF projections should be updated on a 5-year basis as global climate models are updated.

Since present long-term projections to 2100 depend on many assumptions that may change over the next 80 years, it is not recommended to use these long-term projections during the design process, but rather to continue updating projections as described above.

8 Rainfall Data Use

As discussed previously, climate change is likely to impact precipitation patterns, which should therefore be considered in the delivery of capital projects and asset management. Applying the 2050 climate change projections to the design of stormwater infrastructure is one way of applying this.

8.1.1 Cost and Risk Effects

Increased capital costs are expected due to the projected increase in rainfall depth as larger storm sewer pipes and stormwater ponds may be required. However, some resiliency is expected due to the standardization of pipe sizes which result in the installation of pipes with a larger flow capacity than would be necessary under existing conditions. In addition, the construction of low impact development (LID) facilities for water quality purposes may also provide climate change resilience by controlling the first 0-30mm of a rain event depending on the design criteria.

Sewer-related claims against the City could arise if the City has not effectively demonstrated sound policy decisions regarding the effects of climate change on stormwater management. Other municipalities in Ontario have already experienced claims, including the following described by Moudrak and Feltmate (2019):

- City of Stratford – 2002 rainfall resulted in flooding and sewage in basements. With claims of “negligence in design, construction, operation, and maintenance” the City settled for $7.7 million in addition to $1.3 million spent for emergency relief (total $9 million). In response, the City now designs to the 250-year storm.
- City of Mississauga – Ongoing, systemic flooding occurred in the Lisgar area, and residents filed a $200 million claim against the upper and lower tier municipalities, the province, and the conservation authority in 2012. Although the claim was withdrawn before a trial, this case illustrates that large, one-time floods aren’t the only flood type to lead to lawsuits.
- City of Thunder Bay – A $300 million claim against the City from floods in 2012, where allegations of “negligence in repair, inspection, and maintenance of the water pollution control plant, as well as lack of diligent operation and supervision at the time of the flood”. The City claims that if residents had complied with the downspout disconnection bylaw, the plant failure would not have occurred. This case has not yet been resolved.

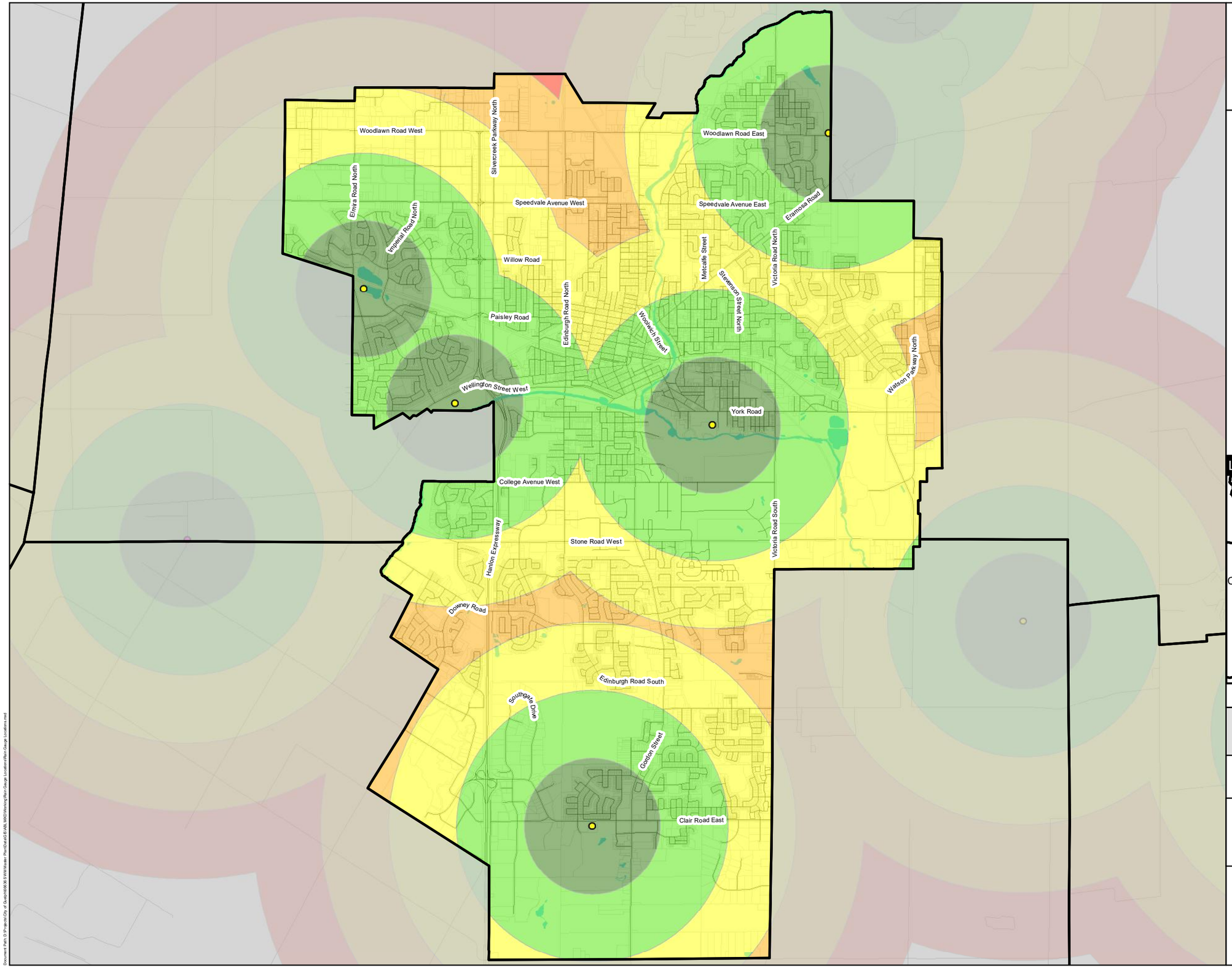
As part of Task 4 of the Stormwater Master Plan, Major/Minor System Hydrologic and Hydraulic Analysis, the storm sewer network will be modelled under existing conditions and a projected climate

change scenario to 2050. The results from this model will be used to assess increased capital costs from upsizing sewers, installing LID facilities, and enlarging SWM facilities. These results will also be used to analyze the risk of sewer-related claims against the City.

As the effects of climate change continue to evolve over time, the risk factors will change, which is why a regular analysis of historical rainfall and future climate projections is important. This will allow the City to regularly review the most up-to-date climate projections and respond to changes in rainfall patterns in a timely manner. When the design standards need to be updated, it is recommended to choose a conservative projection for several years in the future to keep design standards from becoming out of date on a regular basis.

9 Rainfall Gauge Network Evaluation

The City currently has two rain gauges reporting to FlowWorks, one at the West End Community Centre and one at the Helmar Well. The City operates four additional rain gauges elsewhere in the city, including at FM Woods, WWTP, Arkell Well 15, and the Clair Rd. Emergency Services Building, but these gauges are not connected to FlowWorks. The rain gauges at City Hall and Sir Isaac Brock Public School will be decommissioned in 2020, and were therefore not included in the current rainfall gauge network evaluation. Additionally, the GRCA operates two rain gauges near Guelph, including one at Guelph Lake and one where Wellington Road 32 crosses the Speed River. These gauges are shown in **Figure 9.1**.



CITY OF Guelph
Making a Difference

Legend

- Municipal Boundary
- Property
- Rivers
- Road Centreline

Existing Rain Gauge Operator:

- CITY OF GUELPH
- GRCA

Rain Gauge Proximity (km):

- 5
- 4
- 3
- 2
- 1

LOCATOR MAP

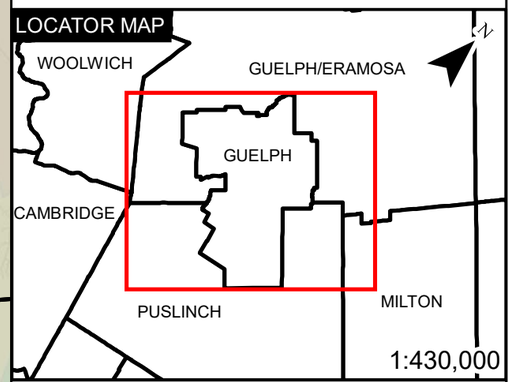


Figure 9.1

Existing Rain Gauge Locations

Date: 2020-05-27
Projection: NAD83_UTM_Zone_17N
Data Source: City of Guelph, GRCA
Created by: J.R.

0 0.5 1 2
Kilometres

Aquafor Beech Limited

This existing network of rain gauges provides good coverage to the City, with most of the city within 4 km of a rain gauge. To improve the rain gauge coverage, an additional two rain gauges are recommended to provide coverage at a 3 km radius for most of the city (**Figure 9.2**). The two recommended locations include the rooftops of the Scottsdale Branch of the Guelph Public Library and the Exhibition Park Arena.

9.1 Siting a Precipitation Gauge

The Meteorological Service of Canada has published siting standards for meteorological observing sites (MSC, 2001), including precipitation stations. The standards state that the site should be located:

1. on open, level ground with a primary area at least 15m x 15m covered with short grass or at least on natural ground with a secondary turf covered area of at least 30m x 30m, surrounded as by a single rail, cable, or chain link fence, and a protected area of 90m x 90m centered on the primary area.
2. such that sensors shall be at a distance from vertical obstructions of four times the height of the obstruction for precipitation gauges.
3. in an area which provides ease of access for the observer and for maintenance of instruments and the installation of electrical ducts.

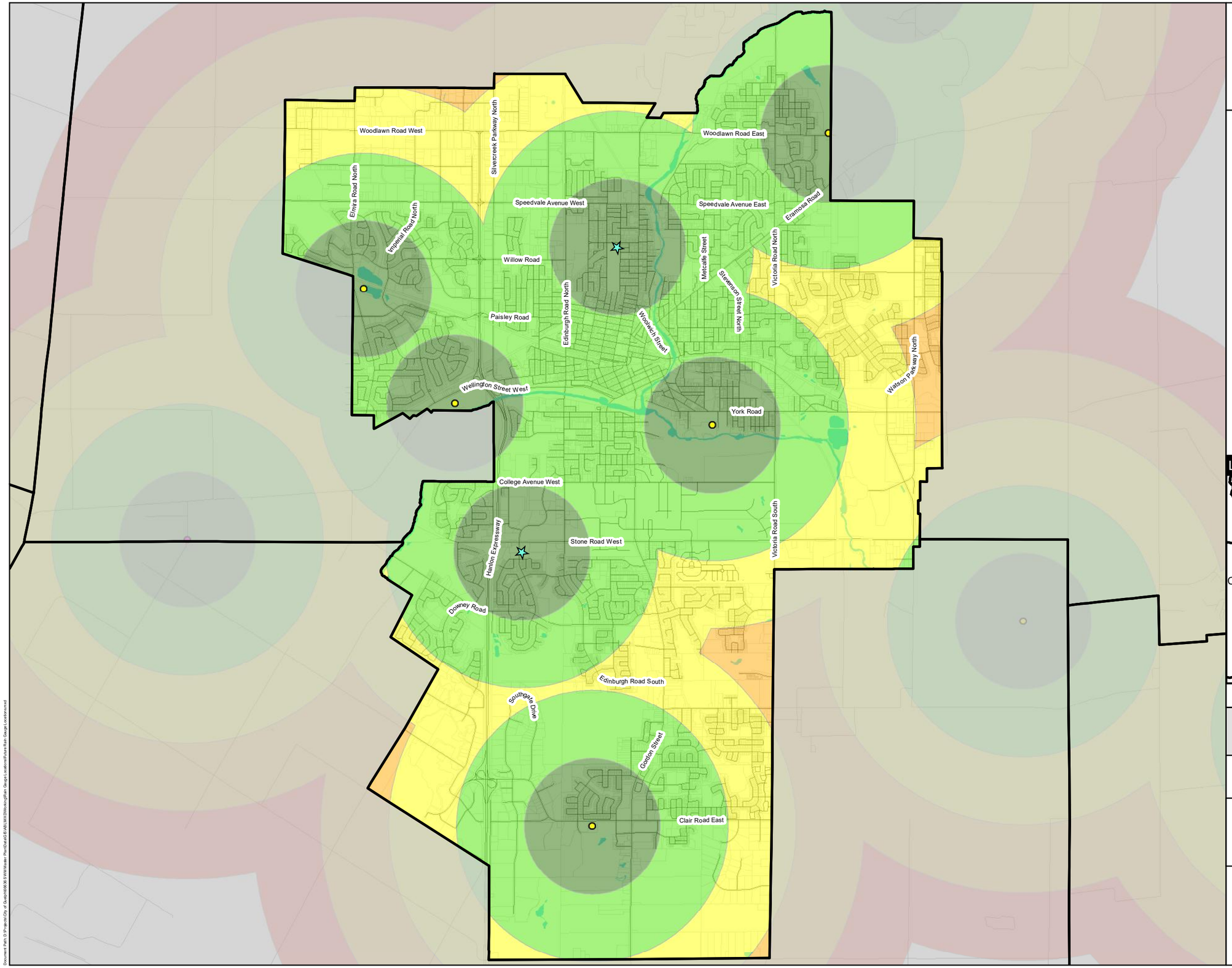
The standards state that locations for sites that should be avoided include:

1. the top of hills.
2. in hollows, at the bottom of narrow valleys, and near hills or ridges, or cliffs.
3. near isolated ponds or streams.
4. near roads where snow from snow clearance operations, or dust, can affect the site.
5. where there is excessive human or animal traffic.
6. where excessive drifting snow accumulates.
7. near vehicle parking areas.
8. where heat is exhausted by vehicles or buildings

Although technical guidance generally suggests that siting precipitation and temperature sensors on rooftops should be avoided due to wind turbulence and rooftop temperature bias, rooftop installations are common in urban setting as a result of limited availability of accessible open space. Rooftops also have the advantage of being close to an electrical source to power heaters and telemetry (note: solar is another option), and are generally safe from accidental damage or vandalism by site users including the public.

9.2 Equipment Recommendations

There are several types of precipitation gauges, with the two most common being tipping bucket gauges and weighing bucket gauges. A tipping bucket precipitation gauge is recommended due to the low capital cost and minimal maintenance requirements apart from calibration. A tipping bucket precipitation gauge consists of a funnel that collects and channels the onto a tipping device. After a pre-set amount of precipitation falls, the lever tips, dumping the collected water and sending an electrical signal. These devices should be equipped with telemetry and incorporated into the City's data delivery and data management system.



Legend

- Municipal Boundary
- Property
- Rivers
- Road Centreline
- Potential Future Rain Gauge Location

Existing Rain Gauge Operator:

- CITY OF GUELPH
- GRCA

Rain Gauge Proximity (km):

- 5
- 4
- 3
- 2
- 1

LOCATOR MAP

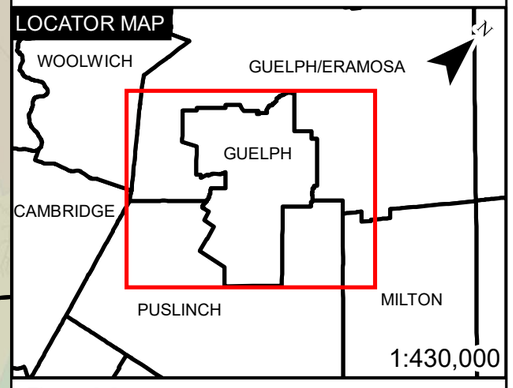


Figure 9.2

Potential Future Rain Gauge Locations

Date: 2020-05-27
Projection: NAD83_UTM_Zone_17N
Data Source: City of Guelph, GRCA
Created by: J.R.

0 0.5 1 2
Kilometres

10 Conclusions and Recommendations

Key conclusions from the rainfall trend analysis include:

- Only one statistically significant trend was found through the precipitation trend analyses, namely the increase in the depth in the 1-hour storm, although the depth for most short-duration storm events has been increasing with time;
- Monthly precipitation generally decreased from 1954 to 2019/2020 although these trends were not significant. Monthly precipitation increased non-significantly in May to July and October;
- Hurricane Hazel resulted in substantially higher rainfall maxima in 1954 for long-duration rain events. Excluding this year from the analysis changed the trend of the 12-hour storm from decreasing to increasing.

Based on these results, it is not recommended to update the City's IDF curves based on historical trends. However, the climate change forecasting tools indicate that the effects of climate change could alter precipitation patterns in Guelph, so it is recommended to consider the projected 2050 IDF curves during the analysis of stormwater management infrastructure (new infrastructure and retrofits). While the existing IDF parameters for the city estimated a greater rainfall depth for some storm durations and frequencies, this was not consistent. 2050 IDF curves will be tested in the model as per **Section 7.7**.

Historical rainfall trends and future IDF projections should be reviewed every 5 years as global climate models are updated. This will allow frequent review of the existing design parameters and enable the City to update these parameters as needed. When the design standards need to be updated, it is recommended to choose a conservative projection for several years in the future to keep design standards from becoming out of date on a regular basis.

The existing rain gauge network in the city should be updated to include additional rain gauges at the Scottsdale Branch of the Guelph Public Library and the Exhibition Park Arena to adequately represent localized storms that move through the area. Since some of the City's rain gauges are heated, it is recommended to distinguish between winter snow and rain so that future analyses can determine whether there are significant increases in rainfall versus snow during the winter.

11 References

Bruce J. P., Egener, M., and Noble, D. 2006. *Adapting to Climate Change: A Risk-based Guide for Ontario Municipalities*. Available from: http://ww.coastalchange.ca/download_files/external_reports/Bruce_(2006)_AdaptingtoClimateChange_ARisk-basedGuideforONMunicipalities.pdf.

Environment and Climate Change Canada. 2019. *Changes in Precipitation*. Available from: https://www.canada.ca/en/environment-climate-change/services/climate-change/canadian-centre-climate-services/basics/trends-projections/changes-precipitation.html

MetOffice. 2020. *An Introduction to the PRECIS System.* Retrieved from: https://www.metoffice.gov.uk/research/applied/international/precis/introduction.

Moudrak, N. and Feltmate, B. 2019. *Weathering the Storm: Developing a Canadian Standard for Flood-Resilient Existing Communities*. Intact Centre on Climate Adaptation.

MSC. 2001. *Siting Standards for Meteorological Observing Sites.*

Schardong, A., Gaur, A., Simonovic, S.P., and Sandink, D. 2018. *Computerized Tool for the Development of Intensity-Duration-Frequency Curves Under a Changing Climate: Technical Manual.* University of Western Ontario Department of Civil and Environmental Engineering and Institute for Catastrophic Loss Reduction.

Zizzo, L.L., Allan, T., and Kocherga, A. 2014. *Stormwater Management in Ontario: Legal Issues in a Changing Climate*.

Appendix A – Precipitation Data

Table A.1: Monthly and Annual Precipitation (mm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Apr-Nov
1954	49	90	100.3	126.5	25.2	76.3	37	113.6	69.8	224.8	55.7	64	1032.2	728.9
1955	47.5	44.1	69.2	89.4	66.6	32	12.7	106.6	43.5	135.7	101.4	63.1	811.8	587.9
1956	40.9	58.3	101.6	88.3	160.8	77	74.9	192.4	51.4	22.3	51	57.7	976.6	718.1
1957	58.8	48.8	33.6	105	95	136.3	31.8	51.9	111.8	67.4	71.3	85.6	897.3	670.5
1958	39	21.5	16.2	59.4	36.9	44.3	95	111.8	133	24.2	97	49.5	727.8	601.6
1959	70.5	71	46.1	73.6	63.4	30.3	89.8	56.6	70.5	105.2	83.5	84.9	845.4	572.9
1960	96	59	27.2	63.7	128.9	82	98.4	34.9	11.2	65.6	72.2	21.8	760.9	556.9
1961	14	57.5	73.4	79.3	68.8	61.2	75.2	139.8	56	29	55.1	60.7	770	564.4
1962	42.4	49.6	14.1	57.7	23.9	85.5	77.4	50.9	68.1	108.9	50.7	56.1	685.3	523.1
1963	21.7	21	72.4	68.8	76.2	16.2	81.2	55.2	47.2	16.5	54.4	33.9	564.7	415.7
1964	70.1	21	83.4	89.9	54.8	70.4	93.2	150.7	23.7	56.8	38.1	73.8	825.9	577.6
1965	94.5	97.8	58.7	65.8	50	48.4	86	58.8	76	126	88.3	74.8	925.1	599.3
1966	57.1	42.3	62.7	41	43.9	58.7	23.8	71	61.6	41.4	158.7	98.3	760.5	500.1
1967	52.2	48.4	34.9	109.2	43	174.8	58.2	44.1	70	98.5	64.3	83	880.6	662.1
1968	83.3	56.9	72.4	36.6	72.4	79.8	145.4	155.5	88.7	62.1	96.3	86.3	1035.7	736.8
1969	77.3	20.9	50.6	96.3	87.9	50.1	63.8	55.6	14	72.4	101.3		690.2*	541.4
1970	28.4	28.1	47.6	80.3	51.8	65	114.3	78.3	124	81.7	53.6	88.3	841.4	649
1971	63.3	78.7	39.5	32.2	34.4	101.5	118.2	124.8	27.2	30.2	47.7	90.6	788.3	516.2
1972	52.5	45	89.7	56.8	73.2	84	100.2	58.6	81.4	110.1	59	116.2	926.7	623.3
1973	33.8	59.2	146.5	44.1	71.9	46.2	90	14.8	43.4	98.3	108.8	78	835	517.5
1974	75.7	67.2	74.5	105.7	113.6	105.6	41.5	32	52.9	36.3	103	38.4	846.4	590.6
1975	65.6	75.3	67.2	80.3	89.5	112.3	57.5	175.3	61.7	51.1	84	80	999.8	711.7
1976	80.2	54.9	145.4	89.2	79.2	71.8	75.7	65.8	111.3	77.5	30	35.8	916.8	600.5
1977	50	47.7	72.2	87.1	33.4	69.2	113.6	162.8	165.5	59.9	105.8	84.5	1051.7	797.3
1978	98.3	12	52.5	62.3	82.5	40	40.9	76.7	114.3	56	67.3	78.6	781.4	540
1979	66.7	24.8	76.3	122.7	106.1	72.6	28.8	106.4	52.8	74.7	121.3	90.7	943.9	685.4
1980	46	20.5	82.2	100.4	101.8	81.5	74.4	56.4	72.1	68.5	50.4	67.8	822	605.5

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Apr-Nov
1981	18.4	81	29	74.9	52.2	71.4	113	113.7	108.8	99.3	43.7	50.4	855.8	677
1982	80.2	32.2	83.6	62.3	72.8	186.6	59.8	89.8	116.7	38.8	130.7	111.4	1064.9	757.5
1983	44	51.9	66.5	94.5	142	54	52.3	92	64.1	71.1	79	131.3	942.7	649
1984	44	86.3	92	56.5	102.1	71	70.7	94.3	103.2	31.4	63.3	81	895.8	592.5
1985	52.2	118.3	111.6	45.1	63.9	78.5	80.4	182.8	63.7	66.3	153.4	60.7	1076.9	734.1
1986	43.3	51.9	67.6	49.9	81.6	103.3	133.9	119.6	268.5	70.6	50.1	83.1	1123.4	877.5
1987	52.2	15.5	56	39.6	31.9	83.2	105.5	85.6	61.8	74	83	90.8	779.1	564.6
1988	39.2	68.6	31.9	61.3	58.4	11.2	128.3	92.8	106.9	94	99	47.2	838.8	651.9
1989	49	23.9	69.3	55.5	96.5	118	28.5	31.5	24.4	62.3	137.6	40	736.5	554.3
1990	58.6	100.5	45.6	52.5	97.7	71.4	119.7	78.7	89.4	125	80.4	135.9	1055.4	714.8
1991	48.3	43.5	142.1	110.5	79.4	27.9	132.5	84.2	46.8	73.9	75.7	59.8	924.6	630.9
1992	36.7	48.7	30.8	136.4	75.4	48.5	162.7	140.9	125.9	83.6	155.5	74.7	1119.8	928.9
1993	108.4	31.9	44	83.5	51.1	108.2	111.4	48.5	87.6	68.4	66.4	36.4	845.8	625.1
1994	81.8	38.6	59.8	101.5	111.2	63	82.2	64.6	51.8	44.2	59	15.8	773.5	577.5
1995	114.4	26.4	51	90.4	87.4	64	73	112	33.2	106.6	144.2	45	947.6	710.8
1996	92	55	37.8	130.6	106.8	128.2	91.8	43.1	154.6	59.2	40.2	103.7	1043	754.5
1997	89.2	87.5	111.7	22.4	82.2	93.6	27	64.4	77.6	37	55.6	42.8	791	459.8
1998	105.8	32.4	95.4	46.8	34.2	99	34.4	34.4	33.4	22.2	42.4	72.8	653.2	346.8
1999	117.6	40.6	27.4	55.8	44.8	101.4	160.2	44	137.4	61.4	125.6	61.8	978	730.6
2000	39.9	48.5	45	57.4	122.8	78.2	103.6	44.2	26.2	6.6	44.4	91.1	707.9	483.4
2001	43.8	110.9	42.5	41	49.2	30.8	28	33	90.6	128.4	76.4	62	736.6	477.4
2002	64.3	66.5	64.4	75.6	83	126.2	31.6	12	69.6	46.6	53.4	55.6	748.8	498
2003		52	44.5	20.2	94.2	59.4	72.4	77.4	93.8	66.4	107.4	79.4	767.1*	591.2
2004	37.5	22	84.5	63.5	101.4	43.6	93.4	75	27	53.2	63.4	79.5	744	520.5
2005	59.5	59.5	17	70.4	16.6	41.6	25	105.5	76.5	35.5	119.3	43	669.4	490.4
2006	76.5	79	63	69.5	93.5	17.5	182.5	38	10.4	21.8	104	64	819.7	537.2
2007	44	11.5	38.5	69	66.6	43	25.4	43.6	35	47.8	76.5	77	577.9	406.9
2008	64.5	49.5	52.5	46	62.5	81.5	203.5	84.5	112	39.8	70.6	89.5	956.4	700.4
2009	30.5	68	59	112.6	94.6	81	74	92.4	37	72.5	33	58.5	813.1	597.1

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Apr-Nov
2010	24.8	32.4	56.8	62.1	67.1	130.7	129.3	27.7	104	76	52.6	14.2	777.7	649.5
2011	21.1	30.1	80.8	92.8	160	66	19.5	64.2	101.5	124.7	110.6	84.1	955.4	739.3
2012	41.9	22.9	54.0	26.4	22.6	67.0	33.8	60.4	89.6	106.6	9.0	49.0	583.2	415.4
2013	56.6	86.0	20.0	109.4	71.8	65.4	136.2	73.4	78.8	93.2	31.2	42.6	864.6	659.4
2014	42.6	40.2	15.0	72.0	62.2	75.6	121.9	58.1	159.4	69.3	53.6	20.8	790.6	672.1
2015	26.8	10.8	9.8	71.3	66.6	148.3	46.0	109.6	41.4	89.1	61.3	57.3	738.0	633.5
2016	26.8	71.4	122.4	57.9	34.6	30.0	53.1	96.5	40.3	42.8	59.5	63.4	698.5	414.6
2017	52.5	61.4	71.5	114.5	113.1	90.2	29.4	72.4	29.3	72.9	60.5	21.8	789.5	582.3
2018	55.0	61.2	22.0	84.0	66.6	63.3	74.3	72.2	45.0	67.8	58.2	51.8	721.2	531.2
2019	26.3	42.7	55.3	85.0	105.8	81.7	55.1	55.6	48.7	137.0	30.4	51.2	774.5	599.2
2020	126.5	27.9	59.4	32.6	62.5	62.3								

* missing one month of data

OAC
Waterloo/Wellington A / Region of Waterloo Int'l Airport / Kitchener/Waterloo
Guelph Arboretum
Turfgrass Institute
City of Guelph Gauges

Table A.2: Annual Maxima (mm)

Year	5 min	10 min	15 min	30 min	1 h	2 h	6 h	12 h	24 h
1954	6.3	12.2	17.3	22.6	23.9	25.1	50.3	83.1	115.8
1955	12.7	15	15.7	18.3	21.6	26.9	28.7	39.1	46.5
1956	8.9	12.2	13.5	17.8	19.8	30.5	37.1	57.7	66.3
1957	6.9	9.1	9.9	12.7	16.5	19	30.5	32.5	51.3
1958	11.4	14.7	16	17.8	19.6	21.1	35.6	53.8	58.7
1959	7.4	8.9	10.4	12.7	15	18.5	26.2	27.2	27.2
1960	8.9	11.4	15	19.6	19.8	19.8	28.2	32.8	44.7
1961	7.9	12.4	13.2	16.8	20.1	31.5	37.8	37.8	50
1962	10.9	11.4	14.2	15.5	22.4	27.7	31.7	33.3	54.4
1963	9.4	13.2	15.5	18.5	19.8	22.1	27.4	31.7	34.8
1964	11.4	16.8	22.1	32.3	43.7	43.7	45	45	51.6
1965	11.9	15	17.3	17.8	17.8	19	30	35.8	45.5
1966	3.6	4.8	6.9	10.2	15	27.9	45.5	45.7	55.1
1967	6.9	9.1	11.2	14.7	23.1	33	43.9	45.2	45.2
1968	12.7	19	25.7	40.9	71.6	71.9	79.5	79.5	79.5
1969	3.6	6.1	8.1	9.1	11.9	21.1	46.2	46.2	46.2
1970	9.1	15	18.3	26.9	30.7	31.7	33.5	33.8	34.3
1971	12.7	25.4	30.5	39.4	39.4	42.2	60.7	61	61
1972	7.9	10.9	12.7	15.5	20.8	22.4	27.2	30.2	49.3
1973	9.4	9.9	11.7	18.3	22.1	27.2	31.2	32.3	33.3
1974	7.6	7.9	8.9	12.4	14	15.7	30.5	41.7	47.5
1975	11.7	15.5	17.3	22.9	26.9	50.5	82.3	91.2	93.7
1976	5.3	7.4	10.2	12.2	13.7	21.1	40.1	65.8	70.6
1977	11.2	16.8	21.6	22.4	22.4	22.4	22.6	22.6	38.6
1978	10.1	12.9	13.2	13.4	15.4	17.7	22.9	26.6	35.7
1979	11.7	12	12	14.7	18.7	25.7	37.2	38.4	42.5
1980	12.7	16.1	17.2	17.4	18	21.6	33.3	43.1	48.6
1981	5.9	10.1	13.7	17.2	17.8	21.2	27.1	35.5	49.6
1982	10.1	20.2	28.7	46.3	55.8	66.5	69.5	69.7	69.8
1983	9.1	10.9	12.2	13.6	13.8	17.8	28.8	34.8	35
1984	13	17.7	21.7	23.7	23.9	24.7	26.7	26.7	41.6
1985	11.6	13	19.4	30.5	30.5	30.5	40.6	43.7	46.2
1986	15.7	19.7	22.5	29.2	29.8	34	50.6	62.5	83.8
1987	8.6	10.5	10.5	13.4	18.5	23.2	34.7	43.4	53.7
1988	10.1	17.4	24.2	32.3	33.2	51.5	52.9	52.9	53.4
1989	3.9	6.8	7.2	7.4	9.8	12.7	21.0	28.6	37.4
1990	11.4	16.7	19.7	23.2	30.3	33.5	39.6	41.1	41.6
1991	8.4	10.4	11.1	16.1	21.7	30.9	45.6	57	62.6
1992	6.8	8.5	12.3	17.7	23.7	28.3	29.9	45.1	56

Year	5 min	10 min	15 min	30 min	1 h	2 h	6 h	12 h	24 h
1993	10.8	12	16.8	23	25.6	26.6	37	37.8	38.5
1994	7.9	9	12.3	18.1	18.5	22.2	34.4	40	42.6
1995	15.9	21	27.8	42.6	44.8	47.4	47.8	47.8	47.8
1996	5.2	10	12	14.6	15.3	17.1	34.1	50.2	57.7
1997	13.6	15	15.6	24.6	28.2	28.2	28.4	28.4	29.2
1998	7.8	10.2	12.2	18	24.4	28.4	29.6	29.8	54
1999	12.2	23.6	26.4	28	29.6	30.6	38.8	43	48.2
2000	8.2	14.6	17.6	23.2	26.8	27.6	31.2	36.2	41.6
2001	5.4	9.2	10.6	17.2	19.6	22.2	29.4	36	36.6
2002	15	21.4	24.8	24.8	24.8	24.8	31.4	31.4	43.8
2003	5.6	8.6	10.4	12.8	17.8	20.2	21	25.8	27.4
2004	-	-	-	-	-	-	-	-	-
2005	7	14	19.8	29.6	33	34.4	42.6	48.2	53.2
2006	8.8	14	19.8	24.8	27.4	34	44.6	54.8	55.6
2007	11.2	17.6	22.6	28.2	29.8	29.8	34.4	38.8	40.6
2008	-	-	-	-	-	-	-	-	-
2009	7.8	13.8	17	20	21	21	24.8	25.4	28.8
2010	7.6	10	10.4	15	18.2	18.8	26.6	30.6	31
2011	13.2	19.4	25.2	31.4	31.6	31.6	31.6	33.2	40.8
2012	16.8	25.2	25.2	42.0	58.8	68.0	72.4	77.6	80.4
2013	11.8	11.8	17.4	24.0	30.4	32.6	53.4	53.4	56.8
2014	12.2	15.8	20.8	37.8	55.0	56.0	56.2	56.4	56.6
2015	12	14.25	15.75	16.5	18.6	27	42.25	42.5	45.25
2016	14.5	14.5	16.25	25.75	38.25	53.25	60.25	66.25	69
2017	8.4	11.25	12	16.75	24	27.25	33.25	37.75	41.75
2018	9.25	14.5	17	21.25	26.25	29.5	32.75	32.75	35
2019	8.5	11.75	13.5	16.25	21	21.75	25.75	36.25	37.5
2020								62.25	96.75

Guelph Turfgrass
Guelph Smallfield Farm
Waterloo/Wellington A
City of Guelph Gauges

Table A.3: Additional Annual Maxima (mm)

	4 h*	2 d	5 d	Data Source
1954		151.2	164.2	OAC
1955		49	55.7	OAC
1956		78.3	99.4	OAC
1957		75.4	98	OAC
1958		51.6	80.2	OAC
1959		52.3	61.7	OAC
1960		48	74.6	OAC
1961		72.9	73.9	OAC
1962		45.8	56.3	OAC
1963		35.1	38.4	OAC
1964		59.4	65	OAC
1965		58.4	66.3	OAC
1966		58.9	84.3	OAC
1967		47	82.3	OAC
1968		79.5	92.5	OAC
1969		46.2	46.5	OAC
1970		34.3	52	OAC
1971		61	73.2	OAC
1972		57.1	64.8	OAC
1973		43.9	73.3	OAC
1974		49.7	64.9	Waterloo
1975		93.5	116.7	Waterloo
1976		70.9	77.7	Arboretum
1977		54.4	65.6	Arboretum
1978		52.4	81.2	Arboretum
1979		42.5	60	Arboretum
1980		48.6	57.1	Arboretum
1981		58.4	62.8	Arboretum
1982		70	76	Arboretum
1983		35	61.9	Arboretum
1984		43.1	64.4	Arboretum
1985		46.6	91.3	Arboretum
1986		94.4	101	Arboretum
1987		53.7	54.9	Arboretum
1988		53.6	66.7	Arboretum
1989		71.4	83.4	Arboretum
1990		43.8	63.2	Arboretum
1991		63	89.2	Arboretum
1992		49.2	65.8	Arboretum

	4 h*	2 d	5 d	Data Source
1993		35.4	46.8	Arboretum
1994		45.6	67.2	Arboretum
1995		47.8	65.2	Waterloo
1996		62.8	65.2	Waterloo
1997	42	47.6	64.2	Turfgrass
1998	17.4	54.2	69.2	Turfgrass
1999	62.4	98	109.2	Turfgrass
2000	30.8	44.4	70.4	Turfgrass
2001	28.2	40.2	55.8	Turfgrass
2002	29.2	50	54.2	Turfgrass
2003	21	40	45	Turfgrass
2004		37.8	62.6	GTI all but April, September (Waterloo)
2005		123.5	149	GTI Apr-June, Waterloo July-Nov
2006		57	87.5	Waterloo Apr-Aug, GTI Sept-Nov
2007		40.6	45.5	GTI April - October 11; Waterloo Oct 12 - November 30
2008		63.5	103	Waterloo Apr-Sept, GTI Oct-Nov
2009		42.8	50.4	GTI Apr-Sept, Waterloo Oct-Nov
2010		78.2	81.5	Waterloo Sept-Aug, GTI Sept-Nov
2011		56.1	72.3	GTI April, Waterloo May-Nov
2012	70.8	29.6	43.2	City of Guelph Gauges
2013	31.4	66.2	87.2	City of Guelph Gauges
2014	39.0	53.8	75.0	City of Guelph Gauges
2015	34.75	56.5	69.5	City of Guelph Gauges
2016	56.25	31.75	43.25	City of Guelph Gauges
2017	27.75	43	57.75	City of Guelph Gauges
2018	29.5	57.5	69.75	City of Guelph Gauges
2019	22.75	43	69.75	City of Guelph Gauges
2020	32.5	-	-	City of Guelph Gauges

* 4-hour rainfall calculated over January–December. 2-day and 5-day rainfall calculated from April–November

Appendix B – Monthly Precipitation from City Rain Gauges

Table B.1: Monthly Precipitation from City Rain Gauges

Year	Month	City Hall	Sir Isaac Brock*	Clair Rd	Helmar Well	West End	Arkell Well 15	FM Woods
	Mar						54.00	
	Apr						26.40	
	May						22.60	
	Jun						67.00	
	Jul						33.80	
	Aug						60.40	
	Sep						89.60	
	Oct						106.60	
	Nov						9.00	
	Dec						49.00	
2012	**Total**						**-**	
	Jan						56.60	
	Feb						86.00	
	Mar						20.00	
	Apr						109.40	
	May						71.80	
	Jun						65.40	
2013	Jul						136.20	
	Aug						73.40	
	Sep						78.80	
	Oct						93.20	
	Nov						31.20	
	Dec						42.60	
	Total						**864.60**	
	Jan						42.60	
	Feb						40.20	
	Mar						15.00	
	Apr						72.00	
	May						62.20	
	Jun						61.00	90.25
2014	Jul						113.00	130.75
	Aug						50.25	66
	Sep						157.00	161.75
	Oct						72.25	66.25
	Nov						57.50	49.75
	Dec						20.75	20.75
	Total						**763.75**	**-**
2015	Jan						27.50	26
	Feb						16.50	5

Year	Month	City Hall	Sir Isaac Brock*	Clair Rd	Helmar Well	West End	Arkell Well 15	FM Woods
	Mar						10.75	8.75
	Apr						70.50	72
	May						65.50	67.75
	Jun						133.00	163.5
	Jul						50.00	42
	Aug						106.25	113
	Sep						45.50	37.25
	Oct						85.50	92.75
	Nov						63.00	59.5
	Dec						57.25	57.25
	Total						**731.25**	**744.75**
2016	Jan			46.6			27.75	25.75
	Feb			67.4			41.25	101.5
	Mar			124.6			126.75	118
	Apr			69.2			61.75	54
	May			104.4			31.75	37.5
	Jun			31.6			26.75	33.25
	Jul			62			46.50	59.75
	Aug			137.6			102.50	90.5
	Sep			56.8			44.25	36.25
	Oct			50.4			42.00	43.5
	Nov			63.6			62.50	56.5
	Dec			96			62.25	64.5
	Total			**910.2**			**676.00**	**721**
2017	Jan	18.5	17	126.8			71.00	68
	Feb	58.25	0	106.8			64.00	62
	Mar	68.5	54.25	191.6			71.50	74.5
	Apr	105	144.5	145.6			115.50	123
	May	120.75	116.75	157.2			112.50	106
	Jun	95.5	87	87.4			96.75	78.25
	Jul	24.75	29.5	43.4			36.75	26.75
	Aug	76.25	66	52.2			67.50	73.5
	Sep	24.5	12	29.4			24.75	38.75
	Oct	69.5	71.25	89			73.25	76
	Nov	55.25	58.5	113.4			63.00	63.25
	Dec	20.75	15.25	61.4			25.25	19.25
	Total	**737.5**	**672**	**1204.2**			**821.75**	**809.25**
2018	Jan	61	55.5	93			57.50	46.5
	Feb	67.5	67.25	75.2			61.25	54.75
	Mar	23.25	6.5	37			22.75	20

Year	Month	City Hall	Sir Isaac Brock*	Clair Rd	Helmar Well	West End	Arkell Well 15	FM Woods
	Apr	42.5	79.25	131			110.50	99
	May	60.25	56.5	150.4			72.50	67
	Jun	58.5	4.5	74.8			63.75	67.5
	Jul	60	73.25	48.6			99.75	63
	Aug	69.25	99	99.4			84.00	63.25
	Sep	46.25	55.25	50			47.50	41.25
	Oct	39.25	93.5	111.2			86.25	77.75
	Nov	30.75	97.5	114.8			71.00	72.75
	Dec	50	76.5	17.4			54.75	50.75
	Total	**608.5**	**764.5**	**1002.8**			**831.50**	**723.5**
2019	Jan	24.75	35	36.2			31.25	22.75
	Feb	46.75	12	147.6			42.50	38.75
	Mar	57.75	3	73.4			56.50	51.5
	Apr	86.5	113.25	112			86.50	82
	May	94.5	144.75	133.6			112.75	110
	Jun	66.25	84	84.6			97.75	81
	Jul	39	45.75	37.8			77.00	49.25
	Aug	50.25	40.5	53.2			63.25	53.25
	Sep	37.75	22.75	54.8			56.50	51.75
	Oct	124.5	106	153.4			133.75	152.75
	Nov	28.5	36.25	40.4	31.5	30.25	33.75	28
	Dec	43.25	28.75	51.6	65.5	54.75	47.75	44.75
	Total	**699.75**	**672**	**978.6**	**-**	**-**	**839.25**	**765.75**
2020	Jan	103.25	124.75	113.6	163.75	131.25	122.50	111.5
	Feb	28.5	22.75	23.4	39.75	28.5	24.75	17.75
	Mar	53.5	66.25	91.8	70	71.75	49.25	52.25
	Apr			14†	40.75	38.5	31.75	19.5
	May				69	65.5	53.00	
	Jun				72.5†	67†	62.25	

* Rain gauge unheated.

† Data not recorded for the entire month.

Appendix C – R Script and Output

R Script

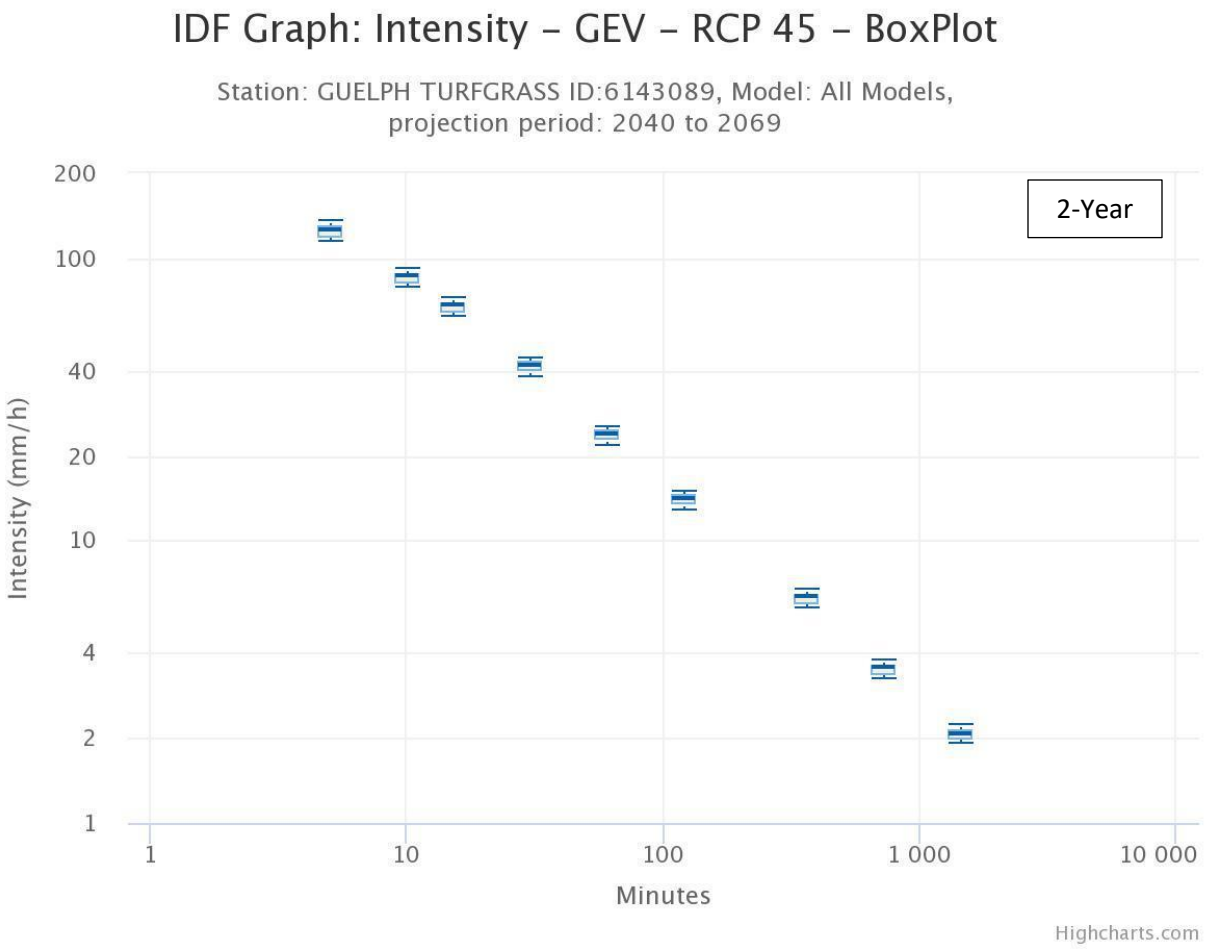
```
library(Kendall)
library(reshape2)

#MONTHLY ANALYSIS
monthly_rain <- read.csv("MonthAnnualRainfall3.csv", header = TRUE)

MannKendall(monthly_rain$Jan)
MannKendall(monthly_rain$Feb)
MannKendall(monthly_rain$Mar)
MannKendall(monthly_rain$Apr)
MannKendall(monthly_rain$May)
MannKendall(monthly_rain$Jun)
MannKendall(monthly_rain$Jul)
MannKendall(monthly_rain$Aug)
MannKendall(monthly_rain$Sep)
MannKendall(monthly_rain$Oct)
MannKendall(monthly_rain$Nov)
MannKendall(monthly_rain$Dec)

#ANNUAL ANALYSIS
MannKendall(monthly_rain$Apr.Nov)
MannKendall(monthly_rain$Jan.Dec)
MannKendall(monthly_rain$Apr.Nov.1954)
MannKendall(monthly_rain$Jan.Dec.1954)

#DURATIONS
rain_duration <- read.csv("RainfallDurations3.csv", header = TRUE)

MannKendall(rain_duration$X5.min)
MannKendall(rain_duration$X10.min)
MannKendall(rain_duration$X15.min)
MannKendall(rain_duration$X30.min)
MannKendall(rain_duration$X1.h)
MannKendall(rain_duration$X2.h)
MannKendall(rain_duration$X4.h)
MannKendall(rain_duration$X6.h)
MannKendall(rain_duration$X12.h)
MannKendall(rain_duration$X24.h)
MannKendall(rain_duration$X2.d)
MannKendall(rain_duration$X5.d)

#LONG DURATIONS WITHOUT 1954 (HURRICANE HAZEL)
MannKendall(rain_duration$X6.h.1954)
MannKendall(rain_duration$X12.h.1954)
MannKendall(rain_duration$X24.h.1954)
MannKendall(rain_duration$X2.d.1954)
MannKendall(rain_duration$X5.d.1954)
```

R Output

```
> library(Kendall)
> library(reshape2)
>
> #MONTHLY ANALYSIS
> monthly_rain <- read.csv("MonthAnnualRainfall3.csv", header = TRUE)
>
> MannKendall(monthly_rain$Jan)
tau = -0.0593, 2-sided pvalue =0.48554
> MannKendall(monthly_rain$Feb)
tau = -0.0362, 2-sided pvalue =0.66899
> MannKendall(monthly_rain$Mar)
tau = -0.114, 2-sided pvalue =0.17265
> MannKendall(monthly_rain$Apr)
tau = -0.0697, 2-sided pvalue =0.40767
> MannKendall(monthly_rain$May)
tau = 0.062, 2-sided pvalue =0.46174
> MannKendall(monthly_rain$Jun)
tau = 0.0231, 2-sided pvalue =0.78671
> MannKendall(monthly_rain$Jul)
tau = 0.00233, 2-sided pvalue =0.98234
> MannKendall(monthly_rain$Aug)
tau = -0.14, 2-sided pvalue =0.096868
> MannKendall(monthly_rain$Sep)
tau = -0.00326, 2-sided pvalue =0.97351
> MannKendall(monthly_rain$Oct)
tau = 0.0028, 2-sided pvalue =0.97792
> MannKendall(monthly_rain$Nov)
tau = -0.103, 2-sided pvalue =0.22552
> MannKendall(monthly_rain$Dec)
tau = -0.149, 2-sided pvalue =0.080218
>
>
> #ANNUAL ANALYSIS
>
> MannKendall(monthly_rain$Apr.Nov)
tau = -0.0718, 2-sided pvalue =0.39715
> MannKendall(monthly_rain$Jan.Dec)
tau = -0.138, 2-sided pvalue =0.1014
> MannKendall(monthly_rain$Apr.Nov.1954)
tau = -0.0515, 2-sided pvalue =0.54843
> MannKendall(monthly_rain$Jan.Dec.1954)
tau = -0.119, 2-sided pvalue =0.162
>
>
> #DURATIONS
> rain_duration <- read.csv("RainfallDurations3.csv", header = TRUE)
>
>
> MannKendall(rain_duration$X5.min)
tau = 0.108, 2-sided pvalue =0.21267
> MannKendall(rain_duration$X10.min)
tau = 0.104, 2-sided pvalue =0.22804
> MannKendall(rain_duration$X15.min)
tau = 0.121, 2-sided pvalue =0.16251
> MannKendall(rain_duration$X30.min)
tau = 0.166, 2-sided pvalue =0.053646
> MannKendall(rain_duration$X1.h)
tau = 0.203, 2-sided pvalue =0.018634
> MannKendall(rain_duration$X2.h)
tau = 0.131, 2-sided pvalue =0.12752
> MannKendall(rain_duration$X4.h)
tau = -0.0667, 2-sided pvalue =0.76653
> MannKendall(rain_duration$X6.h)
```

```
tau = 0.0109, 2-sided pvalue =0.90316
> MannKendall(rain_duration$X12.h)
tau = -0.0024, 2-sided pvalue =0.98193
> MannKendall(rain_duration$X24.h)
tau = -0.0881, 2-sided pvalue =0.30279
> MannKendall(rain_duration$X2.d)
tau = -0.143, 2-sided pvalue =0.090363
> MannKendall(rain_duration$X5.d)
tau = -0.0882, 2-sided pvalue =0.29813
>
> #LONG DURATIONS WITHOUT 1954 (HURRICANE HAZEL)
> MannKendall(rain_duration$X6.h.1954)
tau = 0.0381, 2-sided pvalue =0.66626
> MannKendall(rain_duration$X12.h.1954)
tau = 0.0307, 2-sided pvalue =0.72638
> MannKendall(rain_duration$X24.h.1954)
tau = -0.0591, 2-sided pvalue =0.49416
> MannKendall(rain_duration$X2.d.1954)
tau = -0.116, 2-sided pvalue =0.17243
> MannKendall(rain_duration$X5.d.1954)
tau = -0.0596, 2-sided pvalue =0.4862
```

Appendix D – Box Plots from IDF_CC Projections


IDF Graph: Intensity - GEV - RCP 45 - BoxPlot
Station: GUELPH TURFGRASS ID:6143089, Model: All Models,
projection period: 2040 to 2069
2-Year
Intensity (mm/h)
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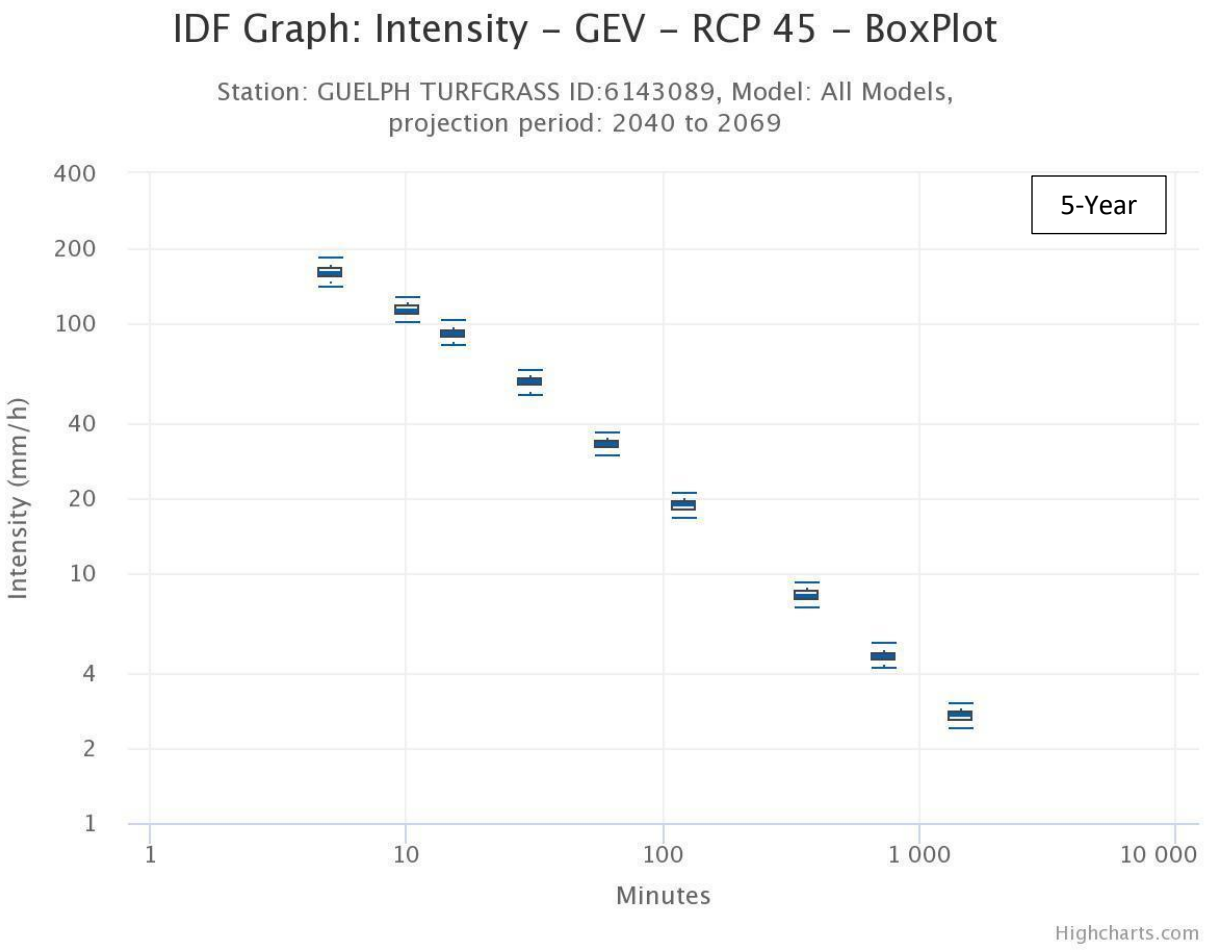
40
20
10
4
2
1
1
10
100
1 000
10 000
Minutes
Highcharts.com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Station: GUELPH TURFGRASS ID:6143089, Model: All Models,
projection period: 2040 to 2069
5-Year
Intensity (mm/h)
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100
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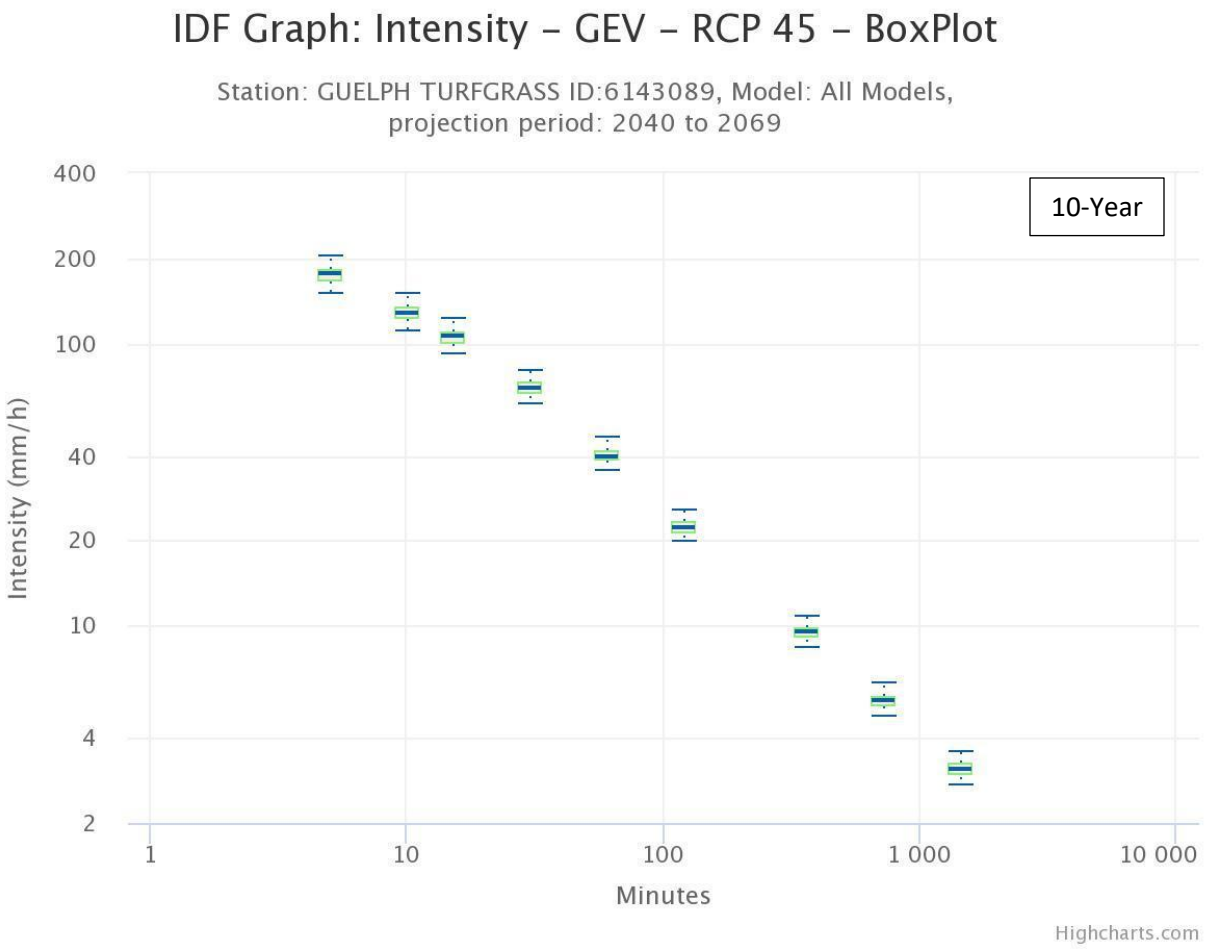
10 000
Minutes
Highcharts.com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projection period: 2040 to 2069
10-Year
Intensity (mm/h)
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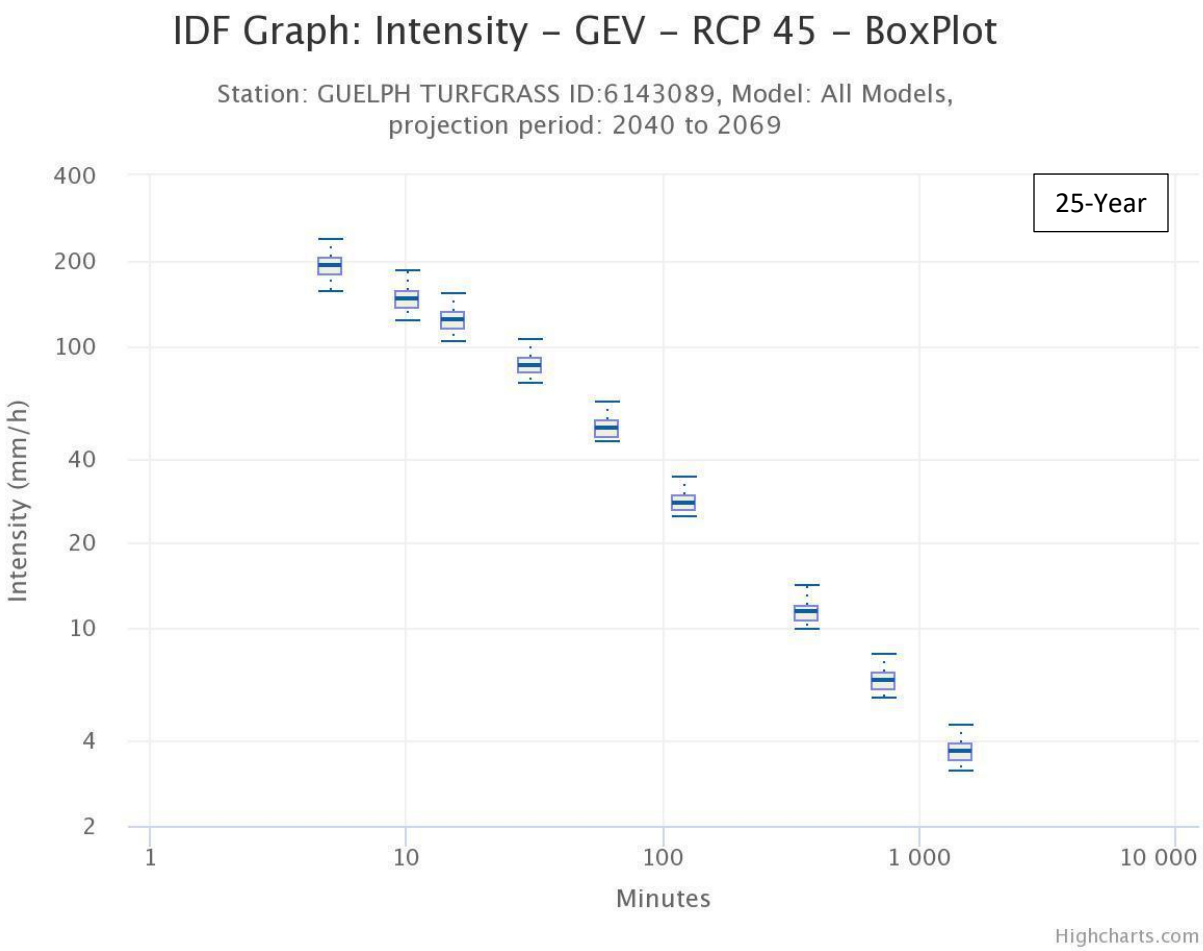
Minutes
Highcharts.com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25-Year
Intensity (mm/h)
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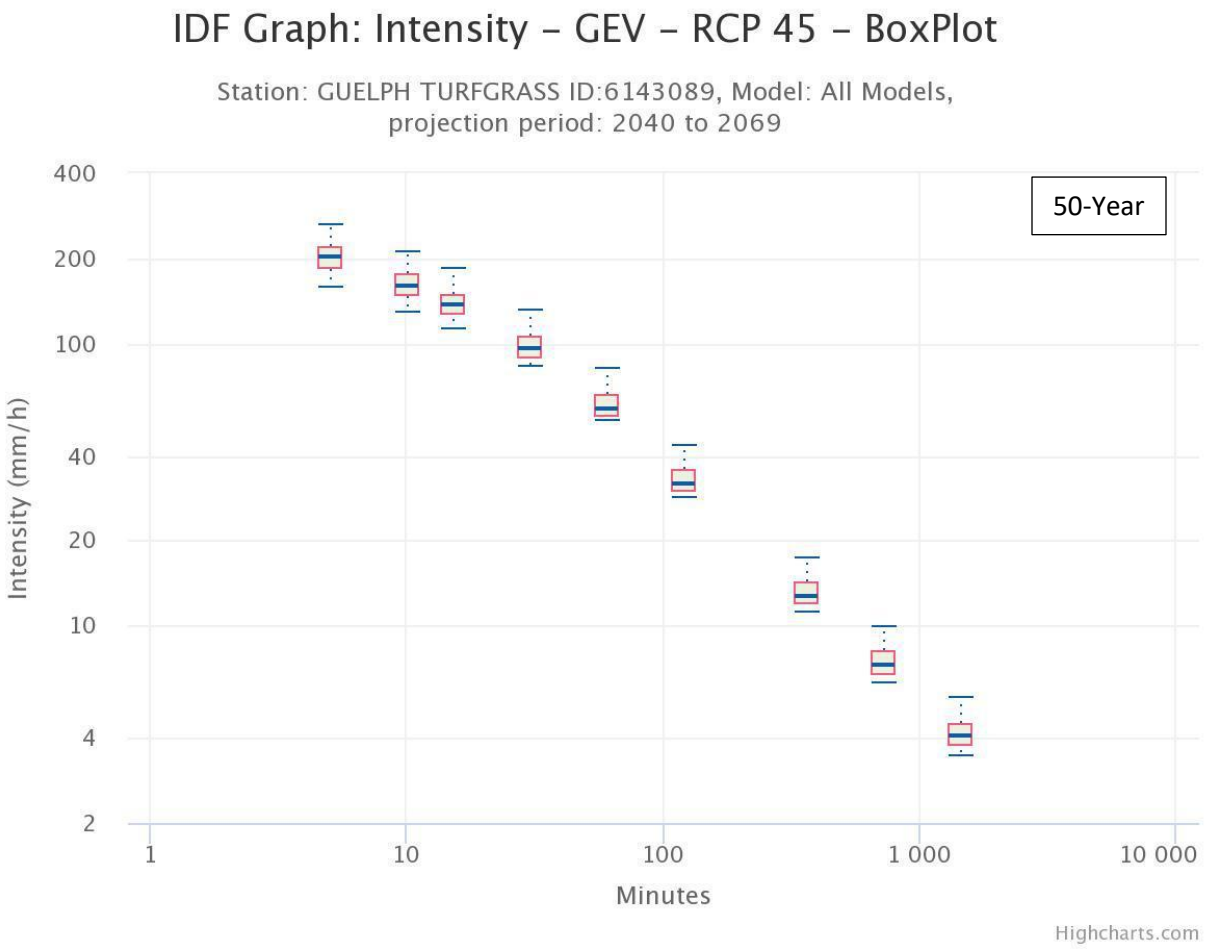
Minutes
Highcharts.com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projection period: 2040 to 2069
50-Year
Intensity (mm/h)
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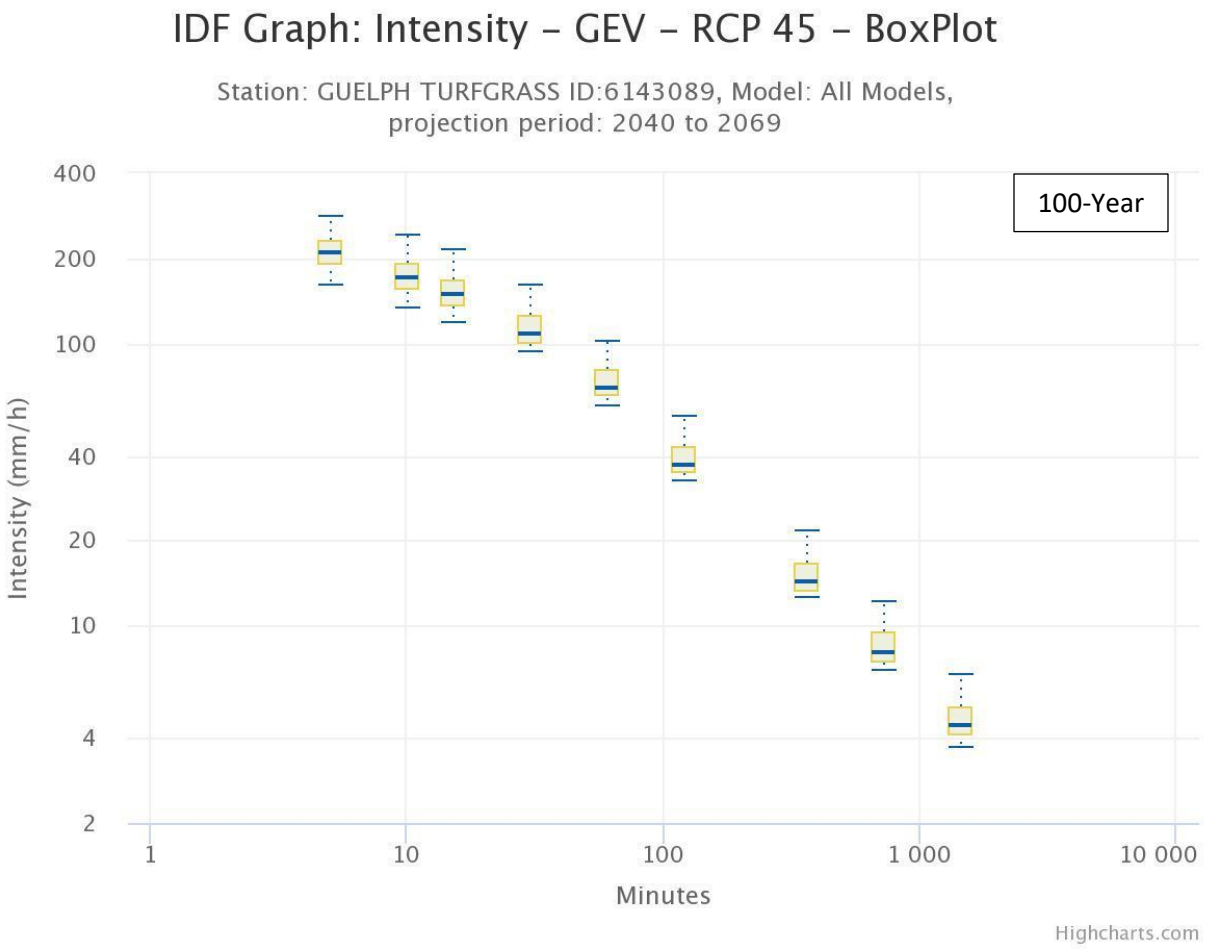
Minutes
Highcharts.com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100-Year
Intensity (mm/h)
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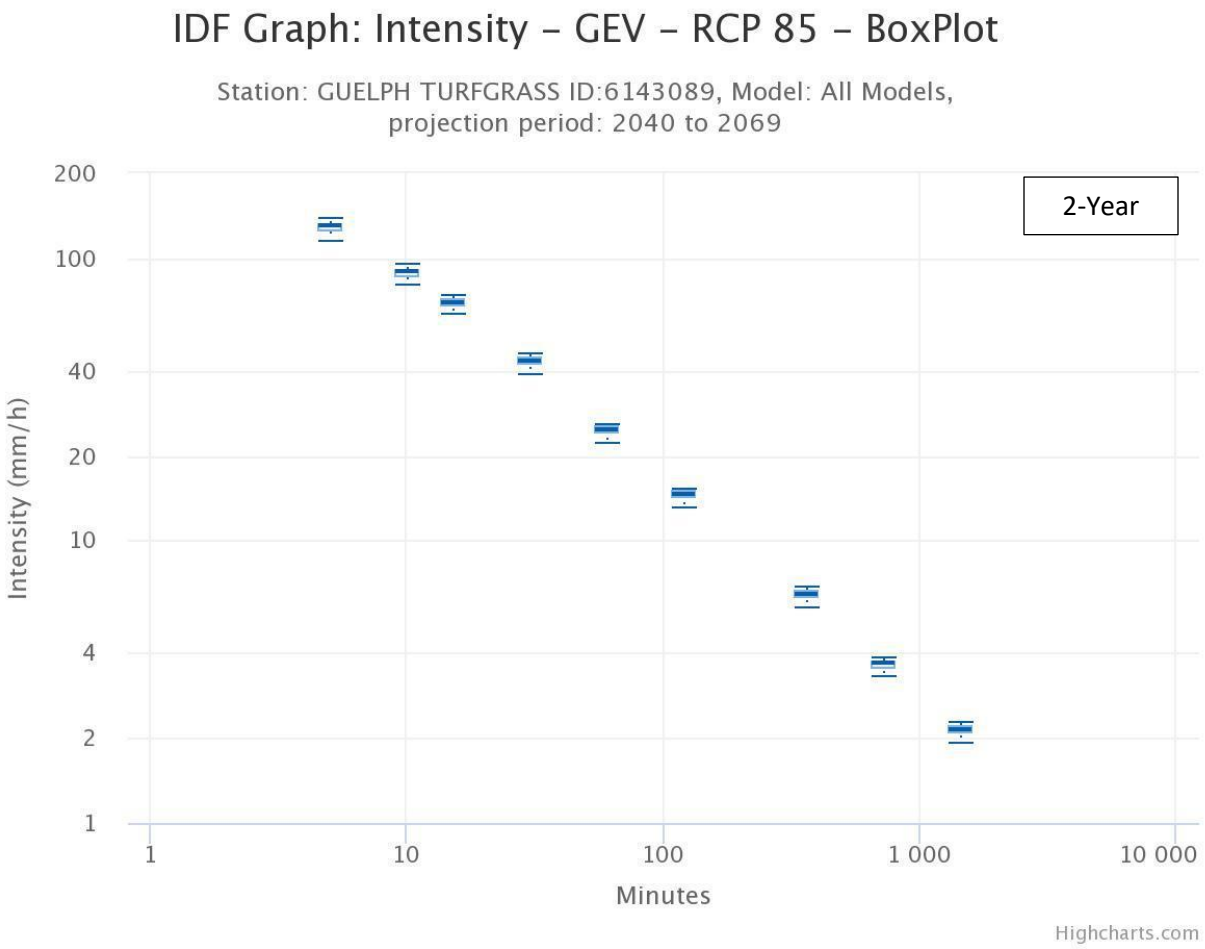
Minutes
Highcharts.com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2-Year
Intensity (mm/h)
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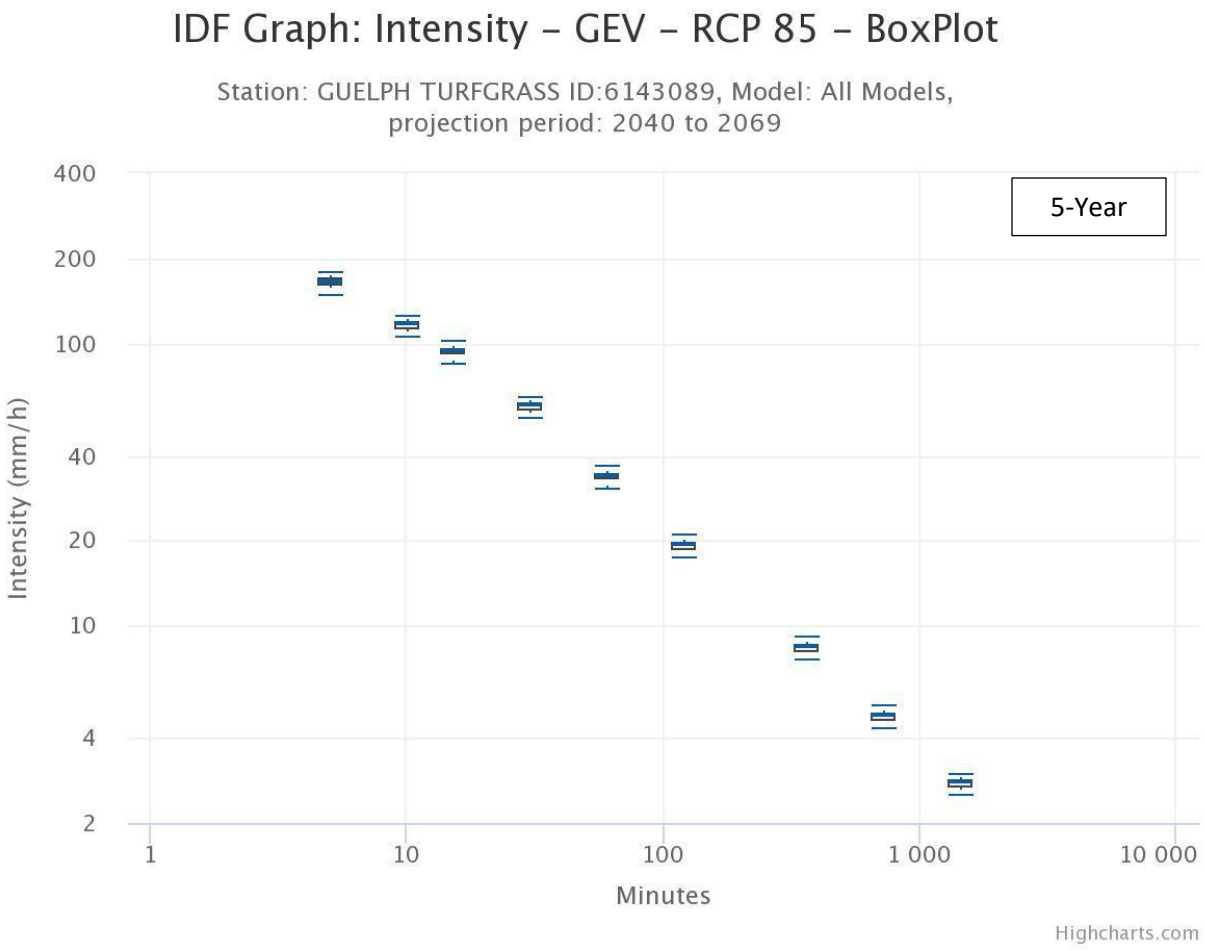
Minutes
Highcharts.com


IDF Graph: Intensity - GEV - RCP 85 - BoxPlot
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5-Year
Intensity (mm/h)
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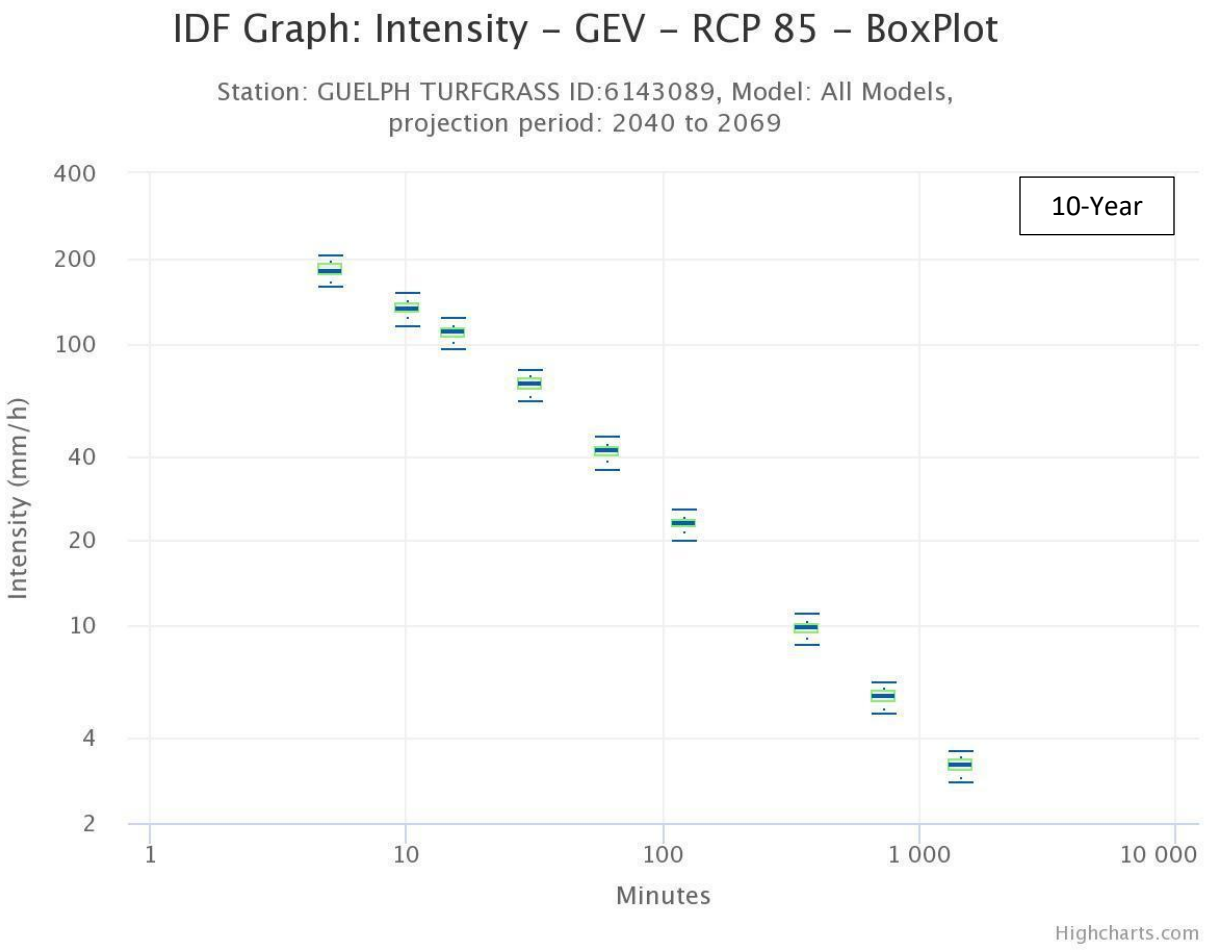
Minutes
Highcharts.com


IDF Graph: Intensity - GEV - RCP 85 - BoxPlot
Station: GUELPH TURFGRASS ID:6143089, Model: All Models,
projection period: 2040 to 2069
10-Year
Intensity (mm/h)
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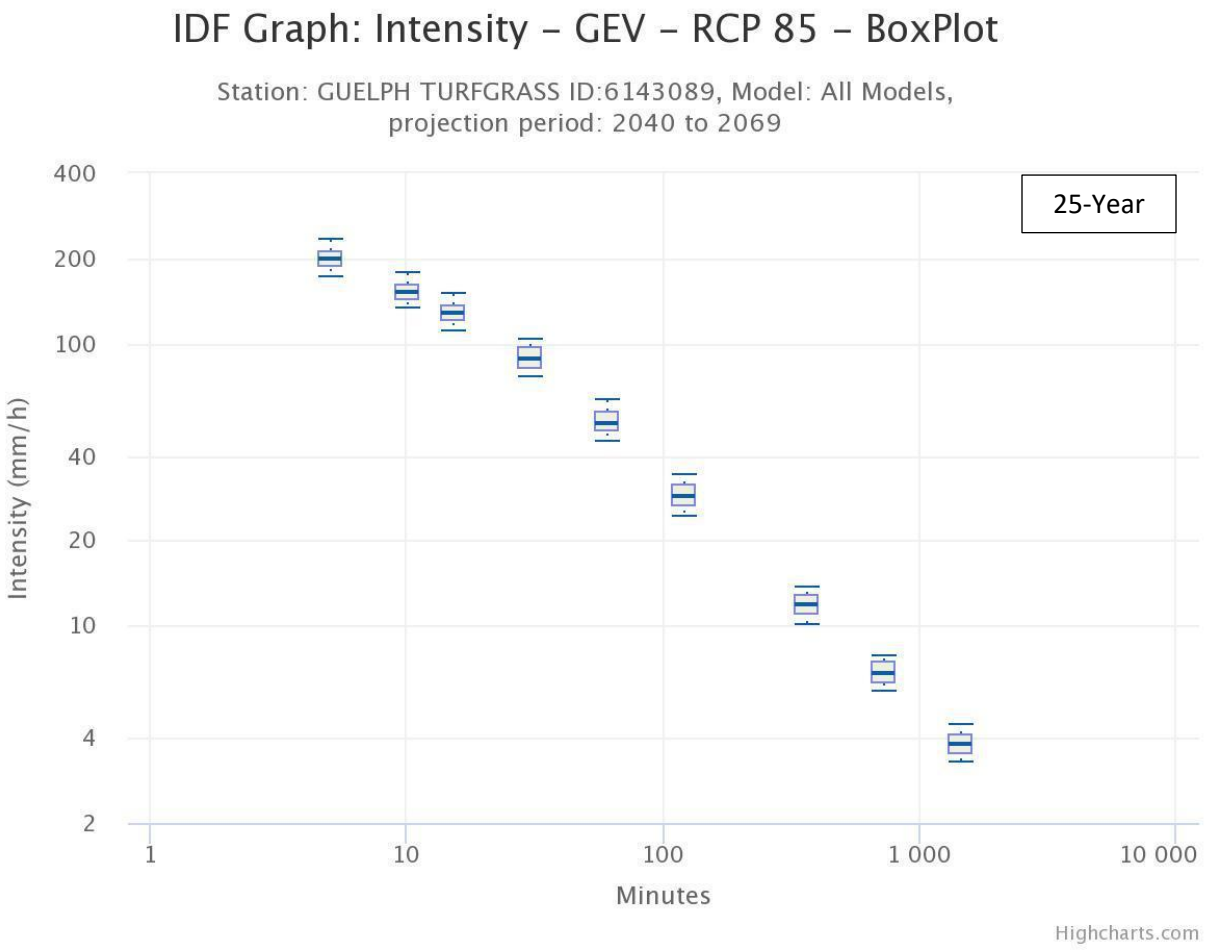
Highcharts.com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25-Year
Intensity (mm/h)
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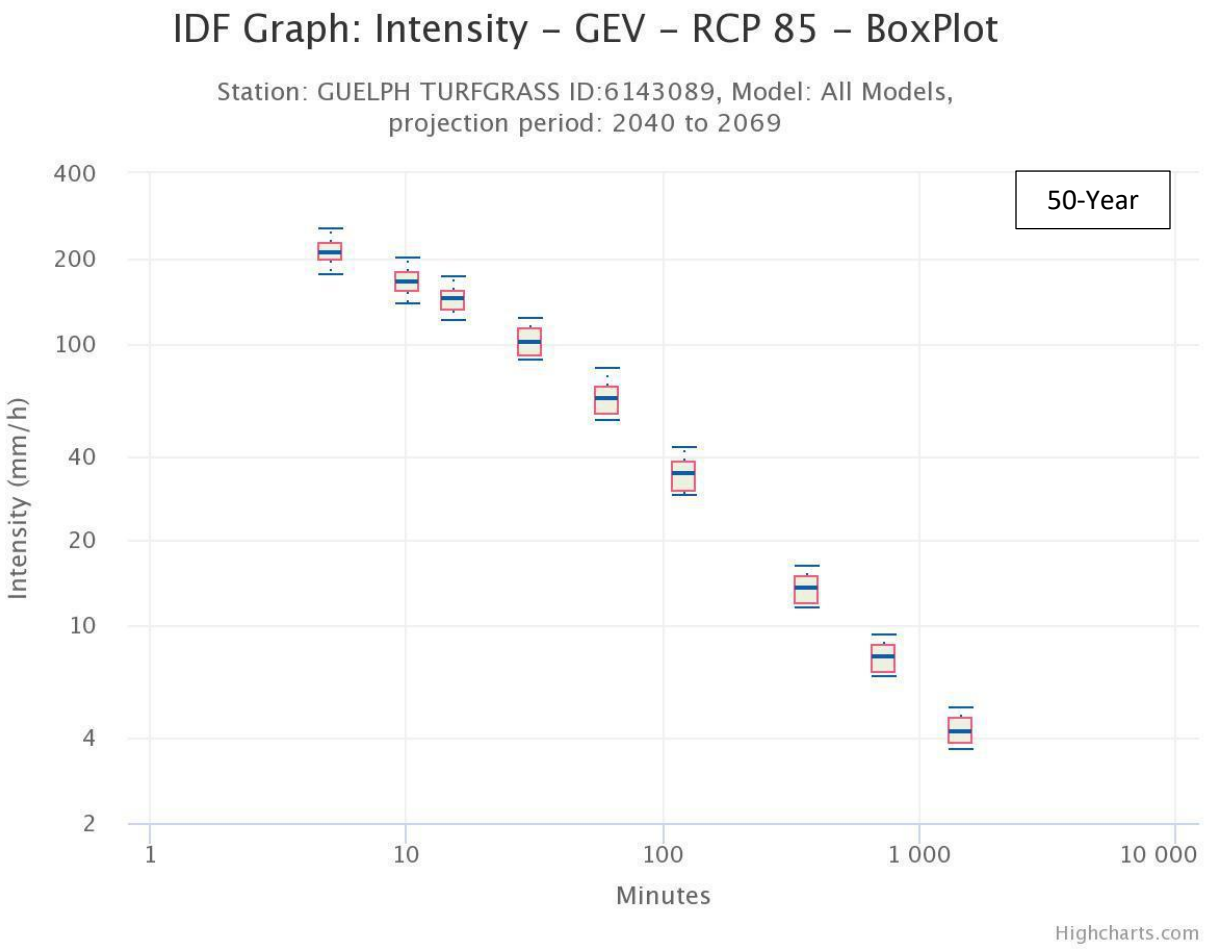
Minutes
Highcharts.com


IDF Graph: Intensity - GEV - RCP 85 - BoxPlot
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50-Year
Intensity (mm/h)
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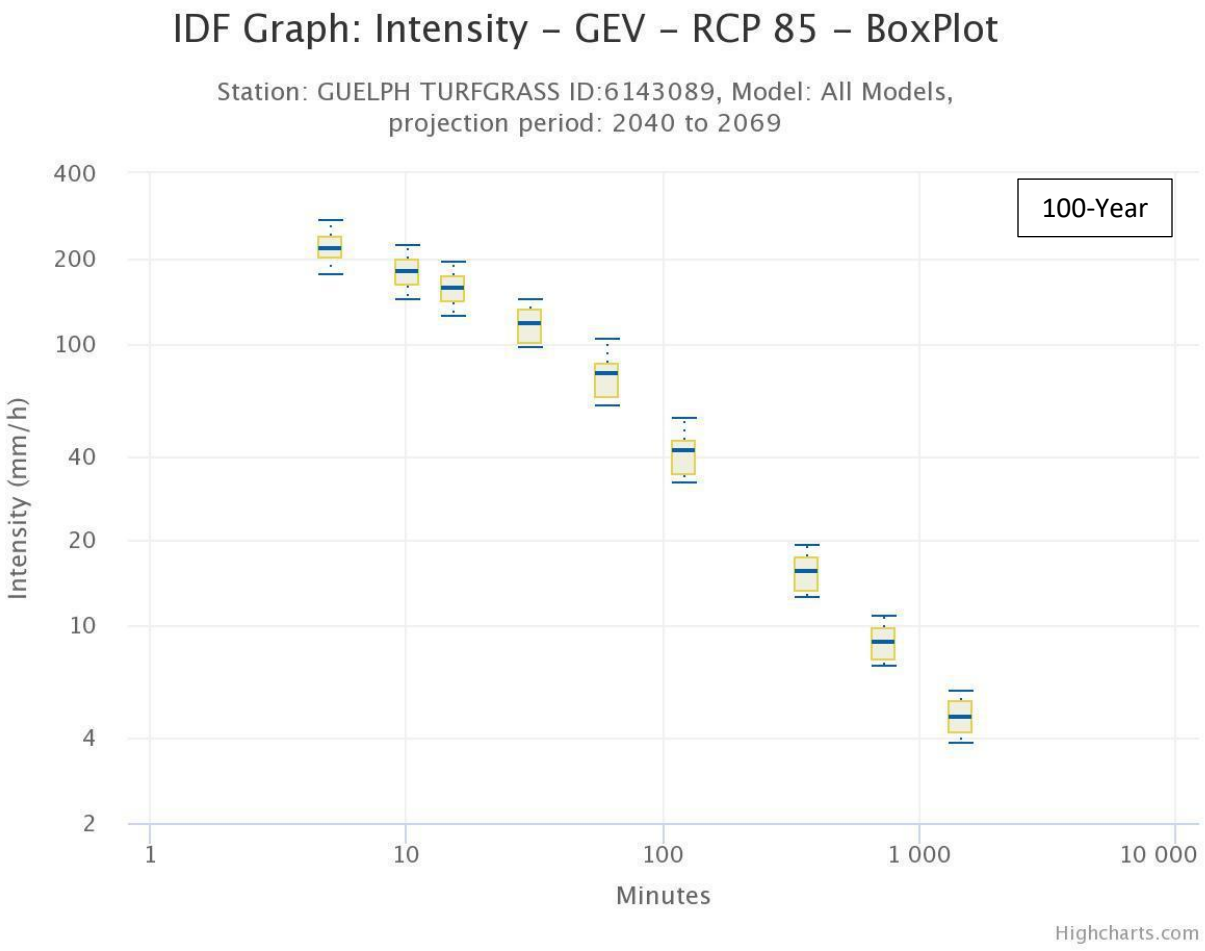
Minutes
Highcharts.com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100-Year
Intensity (mm/h)
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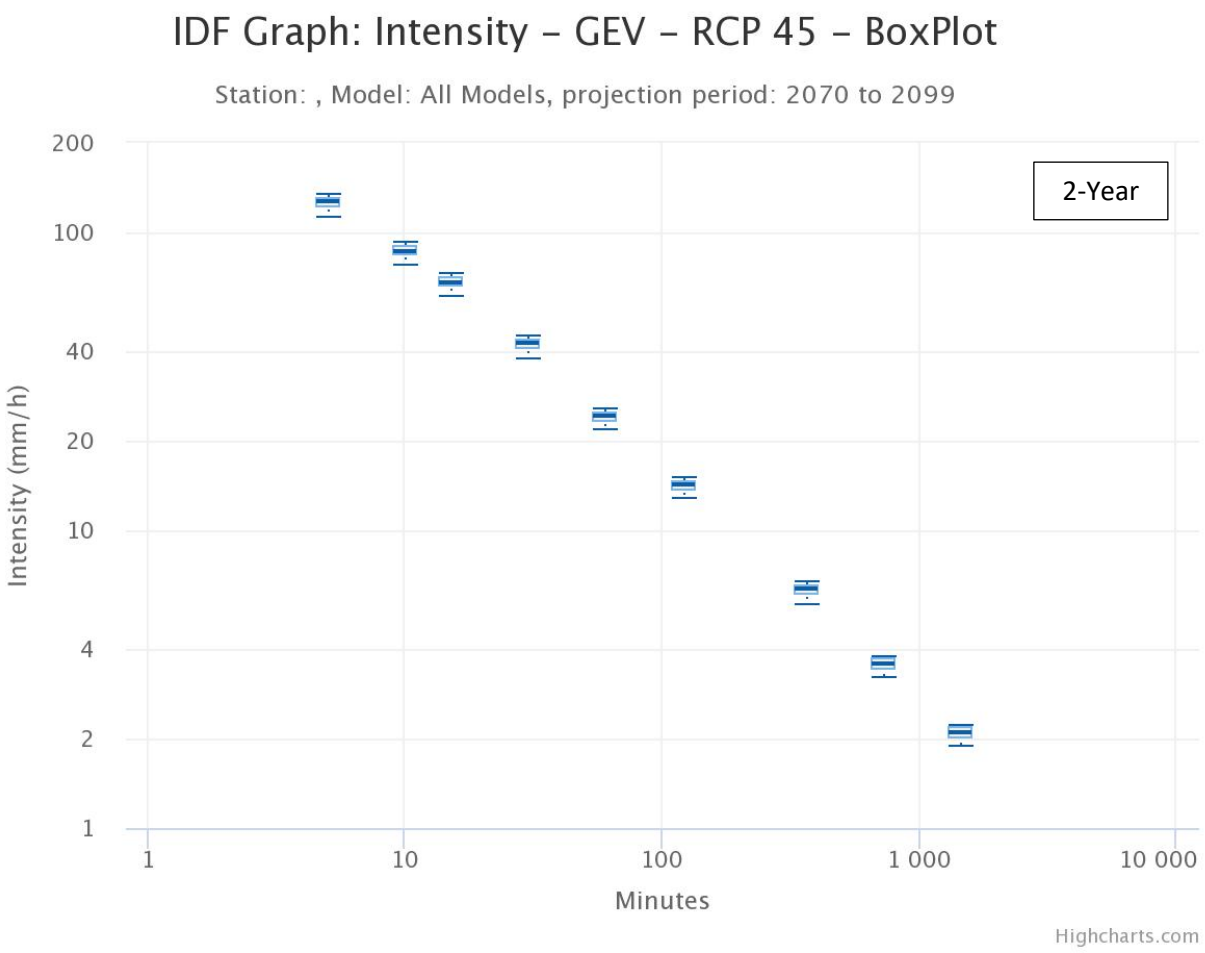
Highcharts.com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2-Year
Intensity (mm/h)
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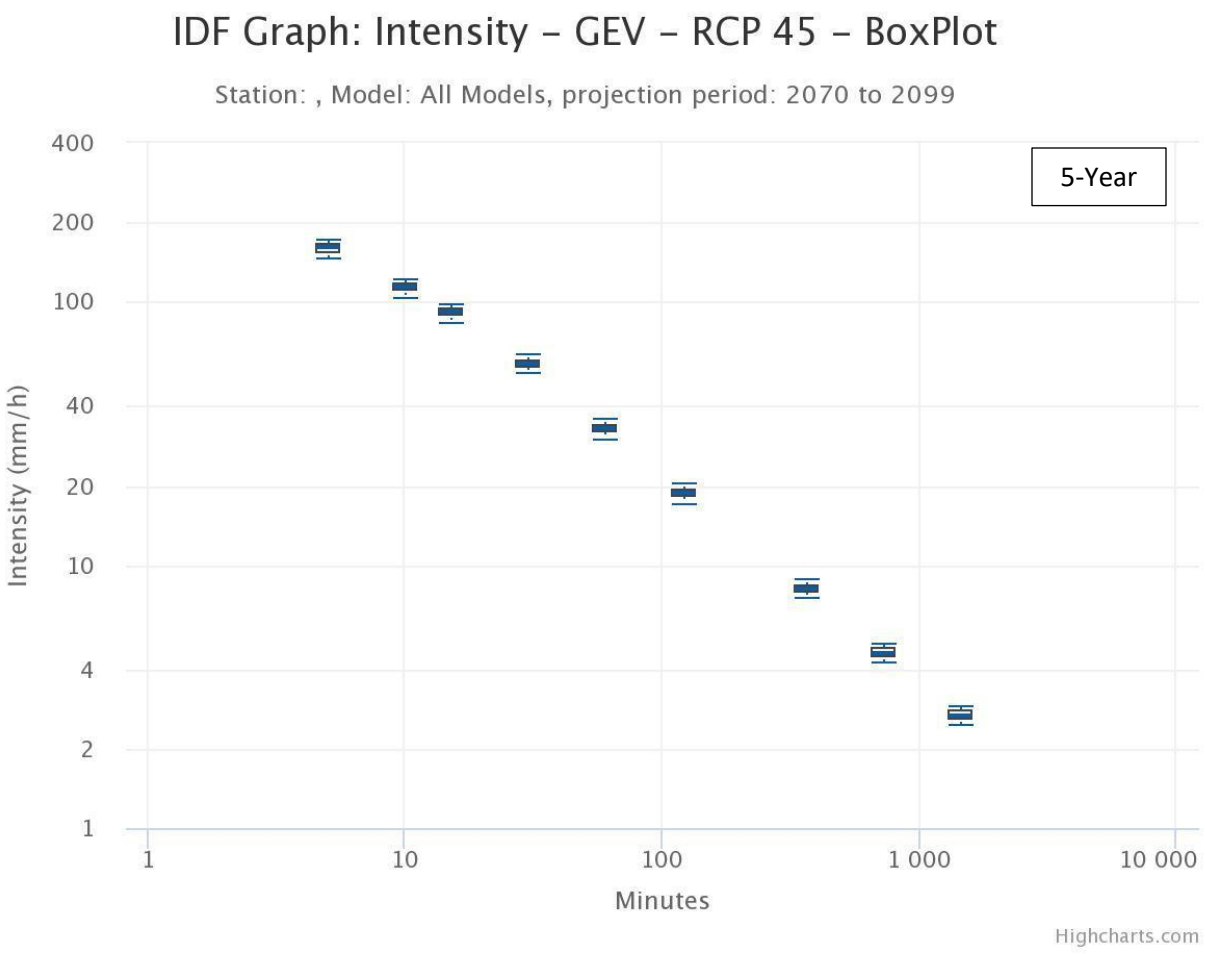
Minutes
Highcharts.com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5-Year
Intensity (mm/h)
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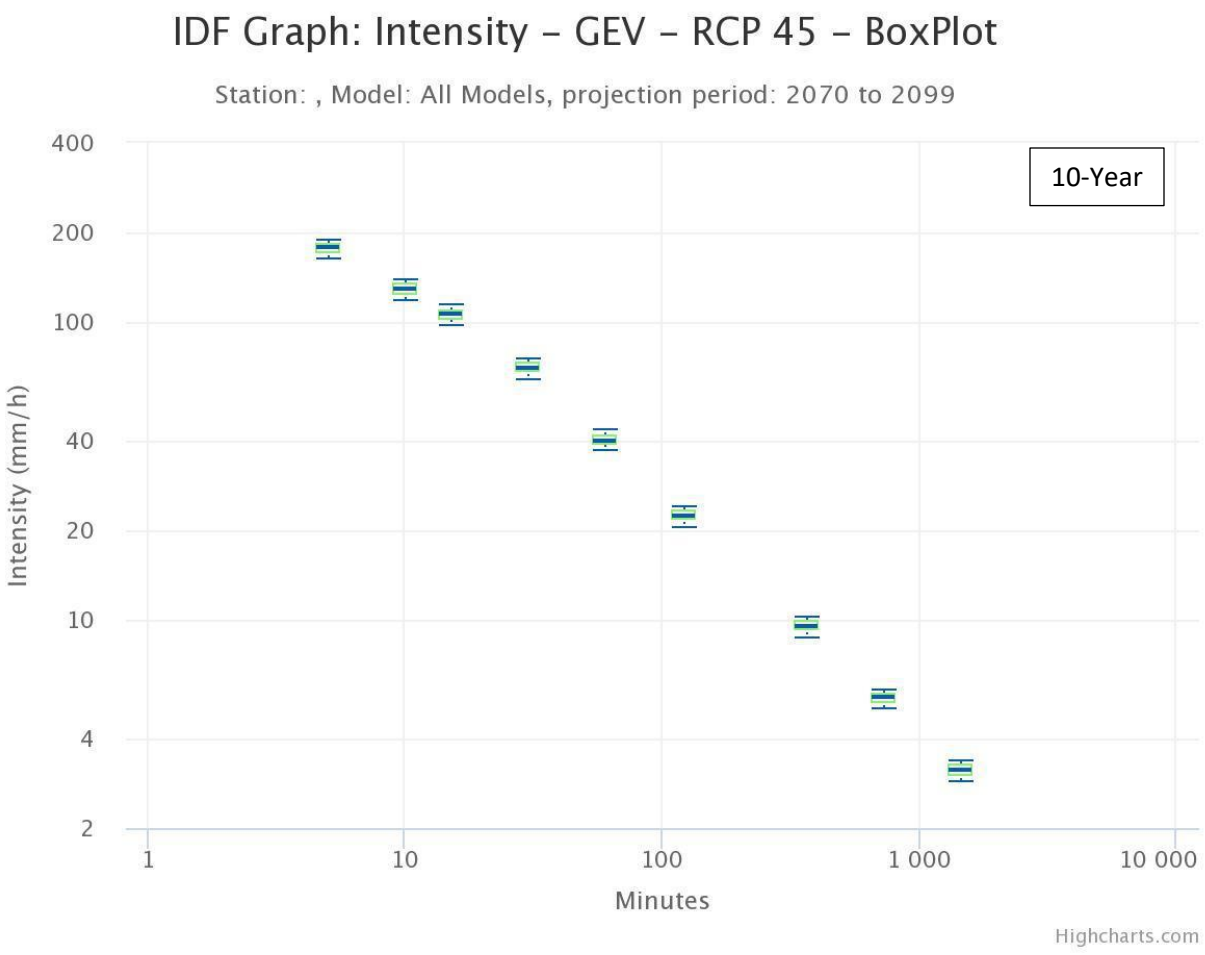
Minutes
Highcharts.com


IDF Graph: Intensity - GEV - RCP 45 - BoxPlot
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10-Year
Intensity (mm/h)
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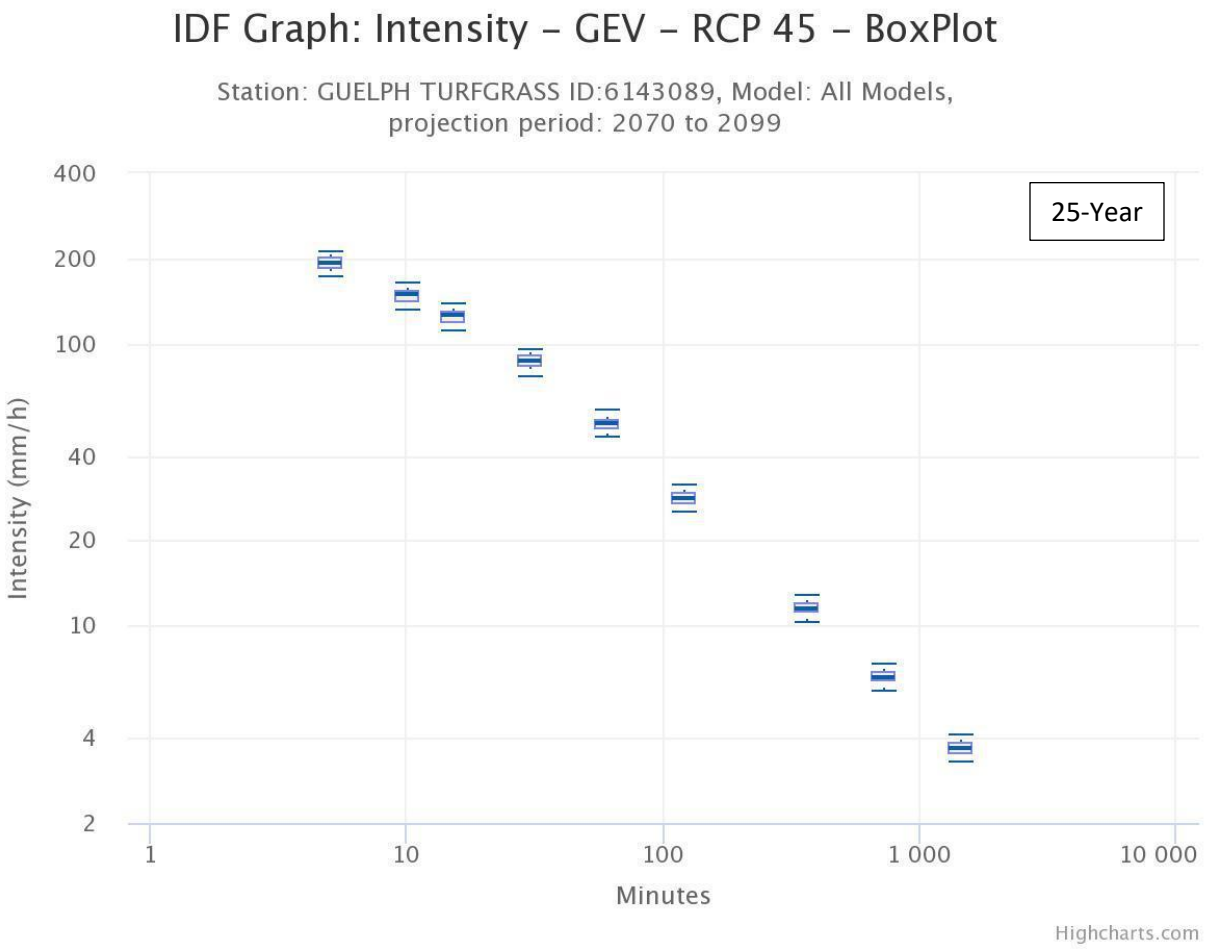
Minutes
Highcharts.com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projection period: 2070 to 2099
25-Year
Intensity (mm/h)
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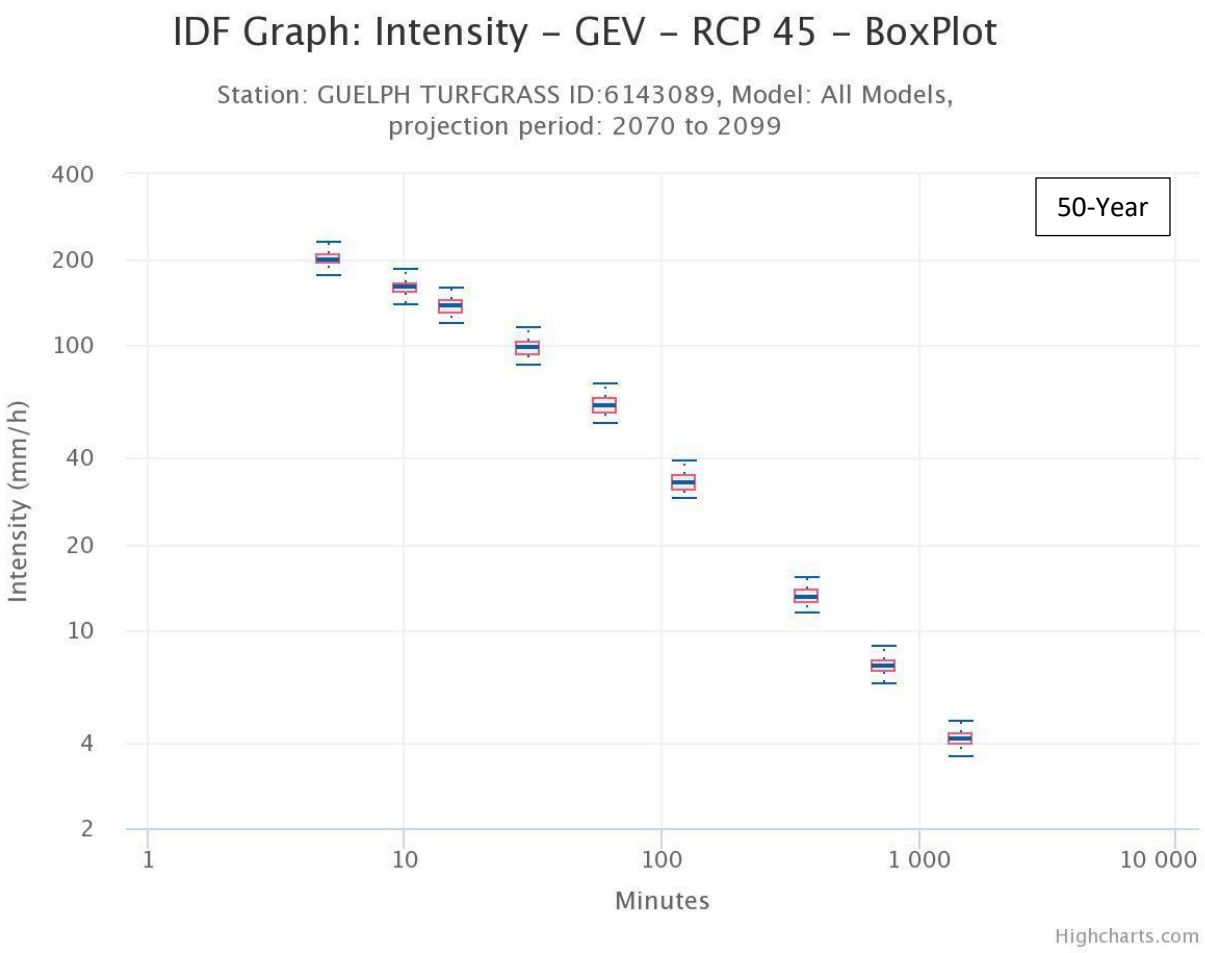
Minutes
Highcharts.com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projection period: 2070 to 2099
50-Year
Intensity (mm/h)
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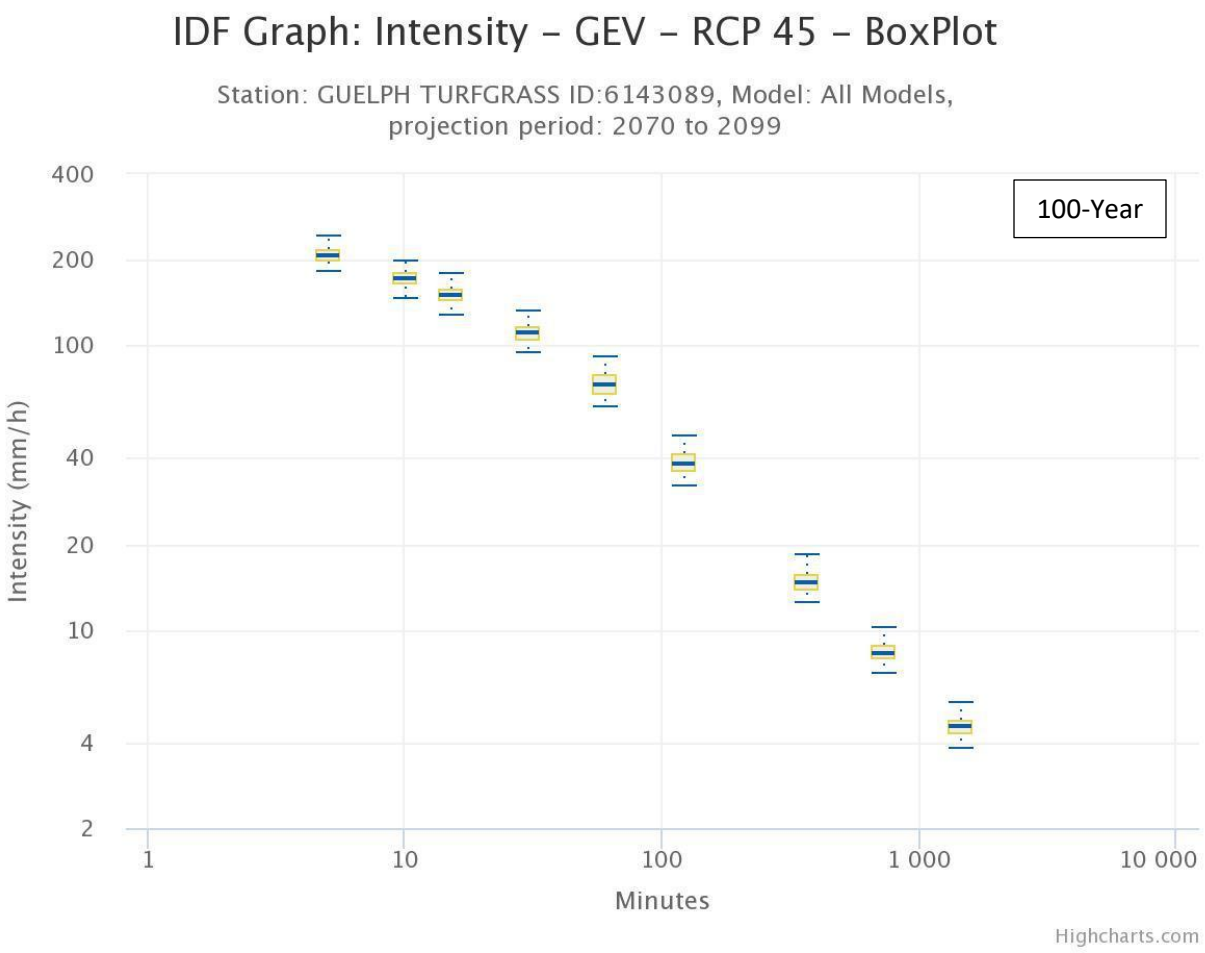
Minutes
Highcharts.com


IDF Graph: Intensity - GEV - RCP 45 - BoxPlot
Station: GUELPH TURFGRASS ID:6143089, Model: All Models,
projection period: 2070 to 2099
100-Year
Intensity (mm/h)
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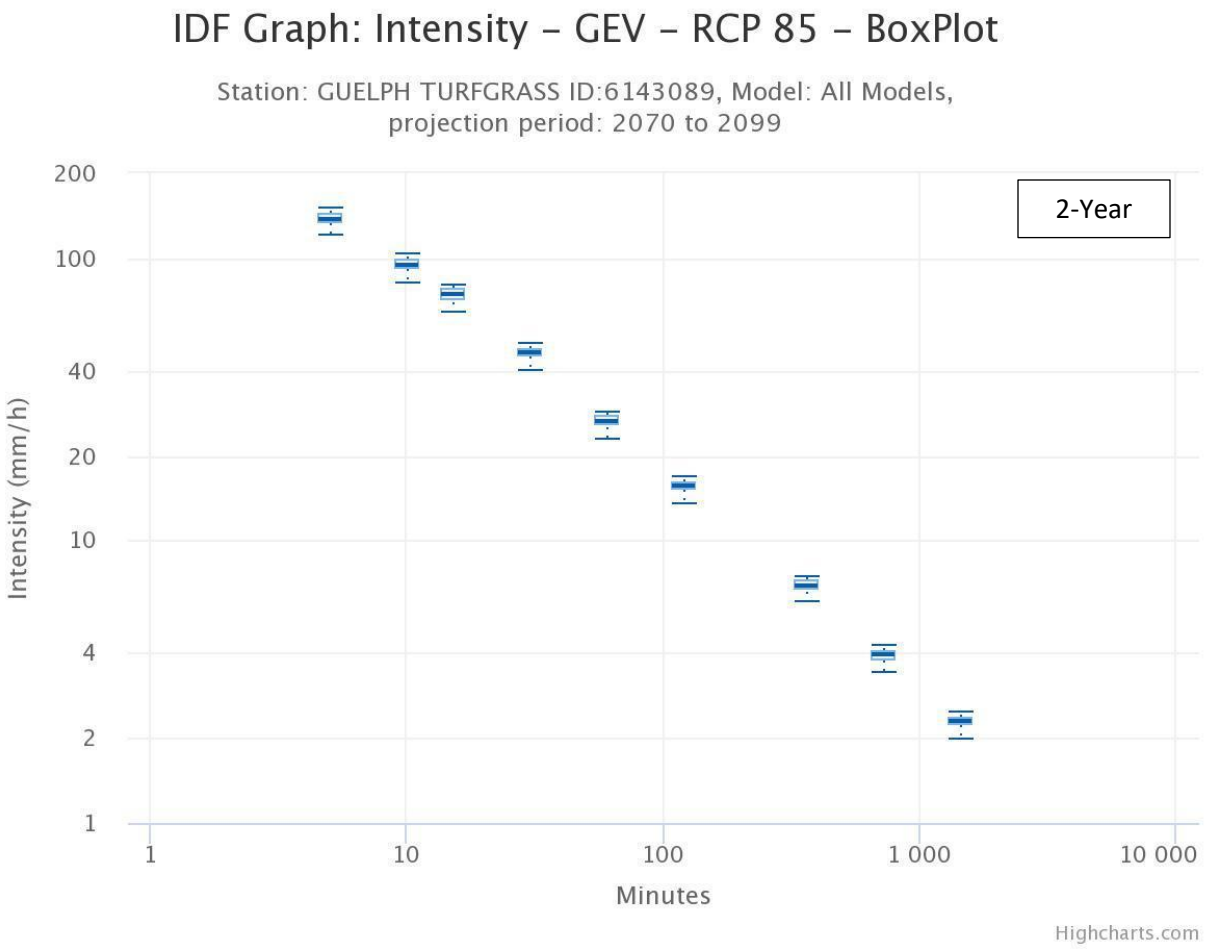
Minutes
Highcharts.com


IDF Graph: Intensity - GEV - RCP 85 - BoxPlot
Station: GUELPH TURFGRASS ID:6143089, Model: All Models,
projection period: 2070 to 2099
2-Year
Intensity (mm/h)
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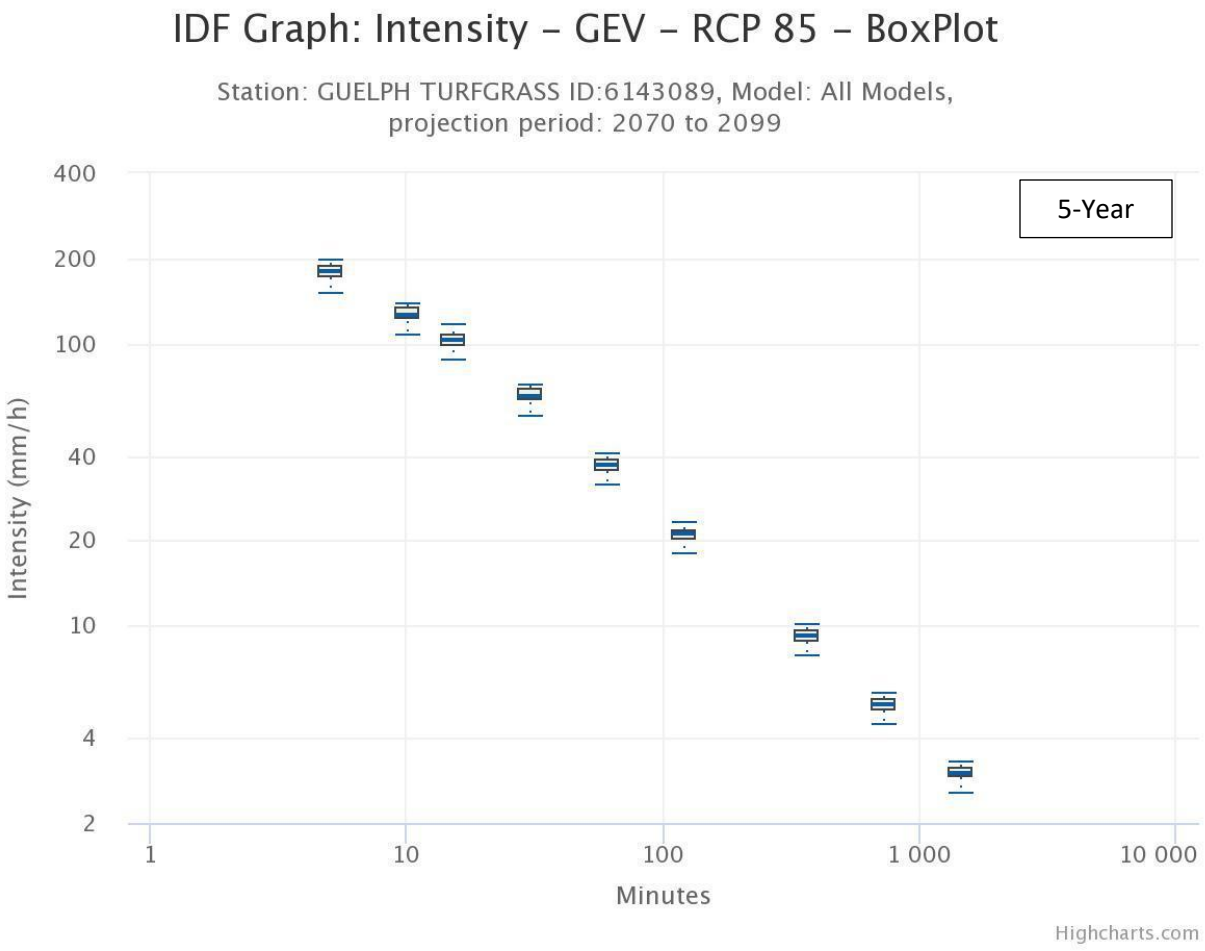
Minutes
Highcharts.com


IDF Graph: Intensity - GEV - RCP 85 - BoxPlot
Station: GUELPH TURFGRASS ID:6143089, Model: All Models,
projection period: 2070 to 2099
5-Year
Intensity (mm/h)
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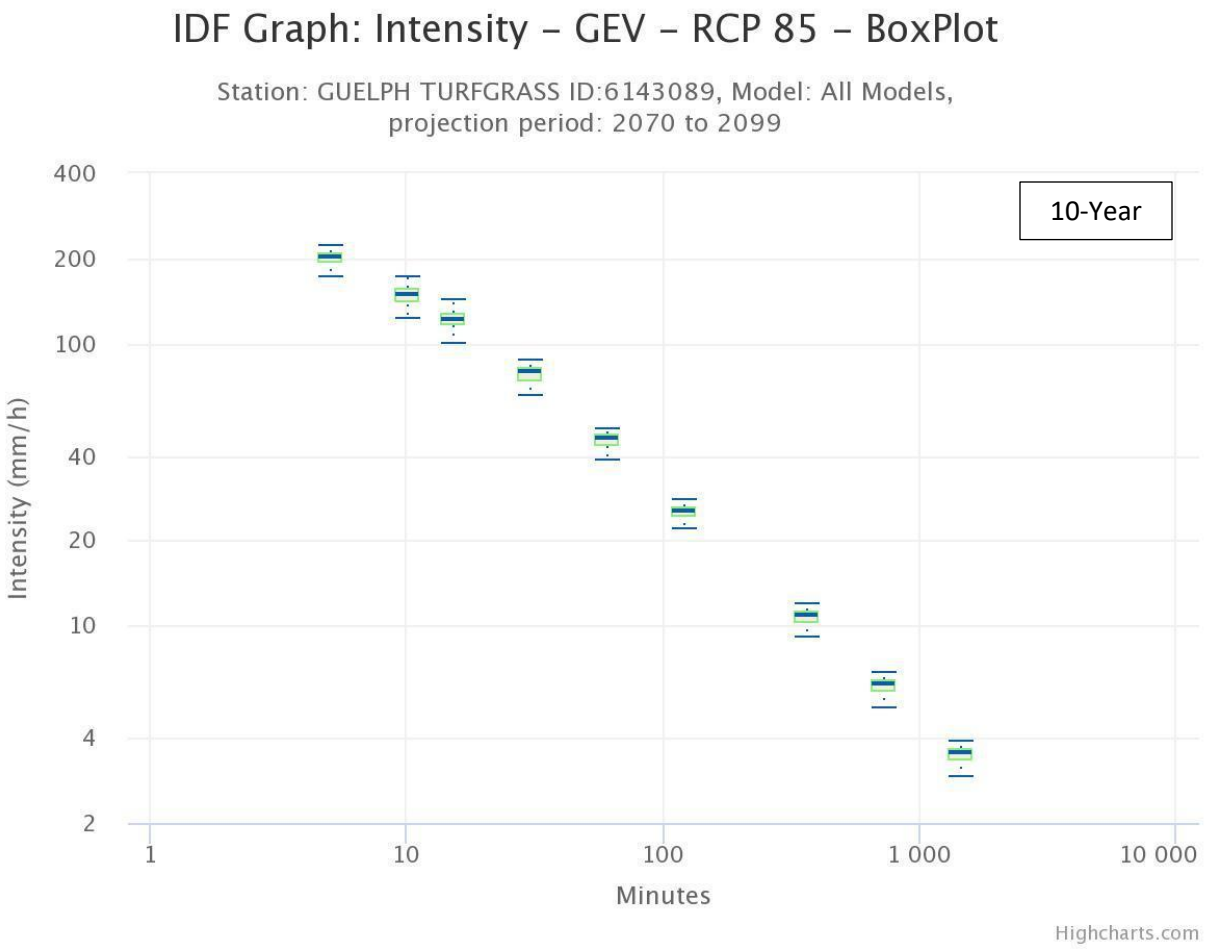
100
1 000
10 000
Minutes
Highcharts.com


IDF Graph: Intensity - GEV - RCP 85 - BoxPlot
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10-Year
Intensity (mm/h)
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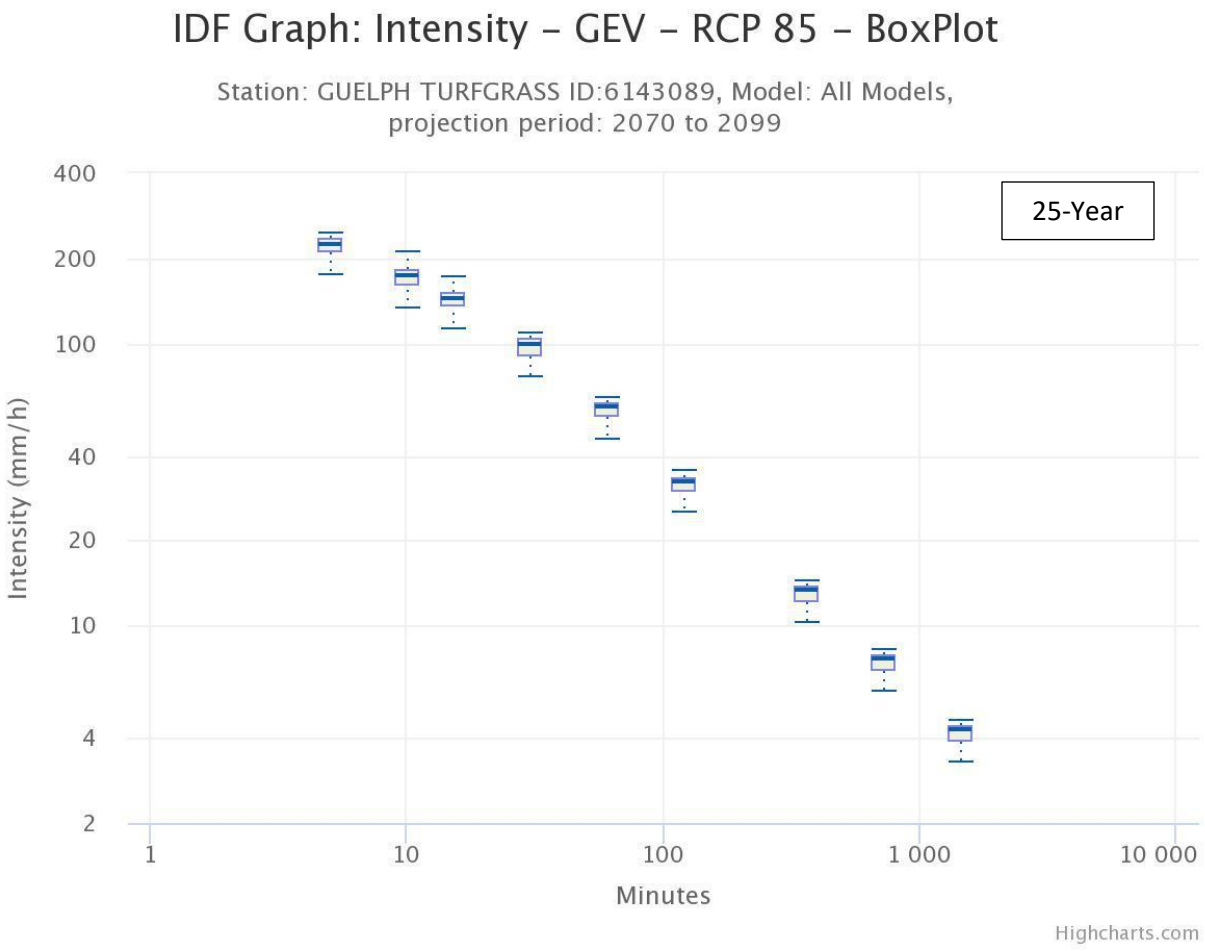
Minutes
Highcharts.com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projection period: 2070 to 2099
25-Year
Intensity (mm/h)
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100
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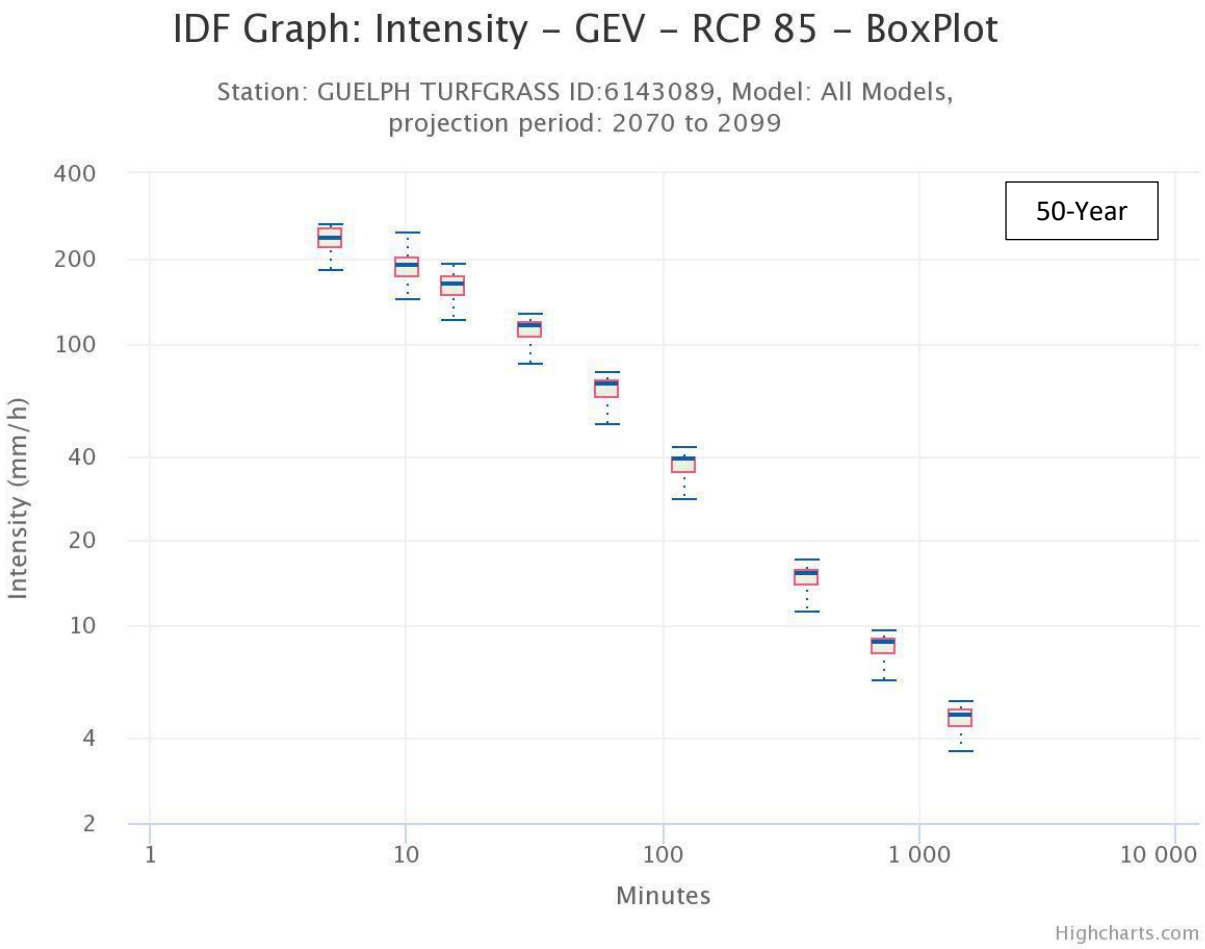
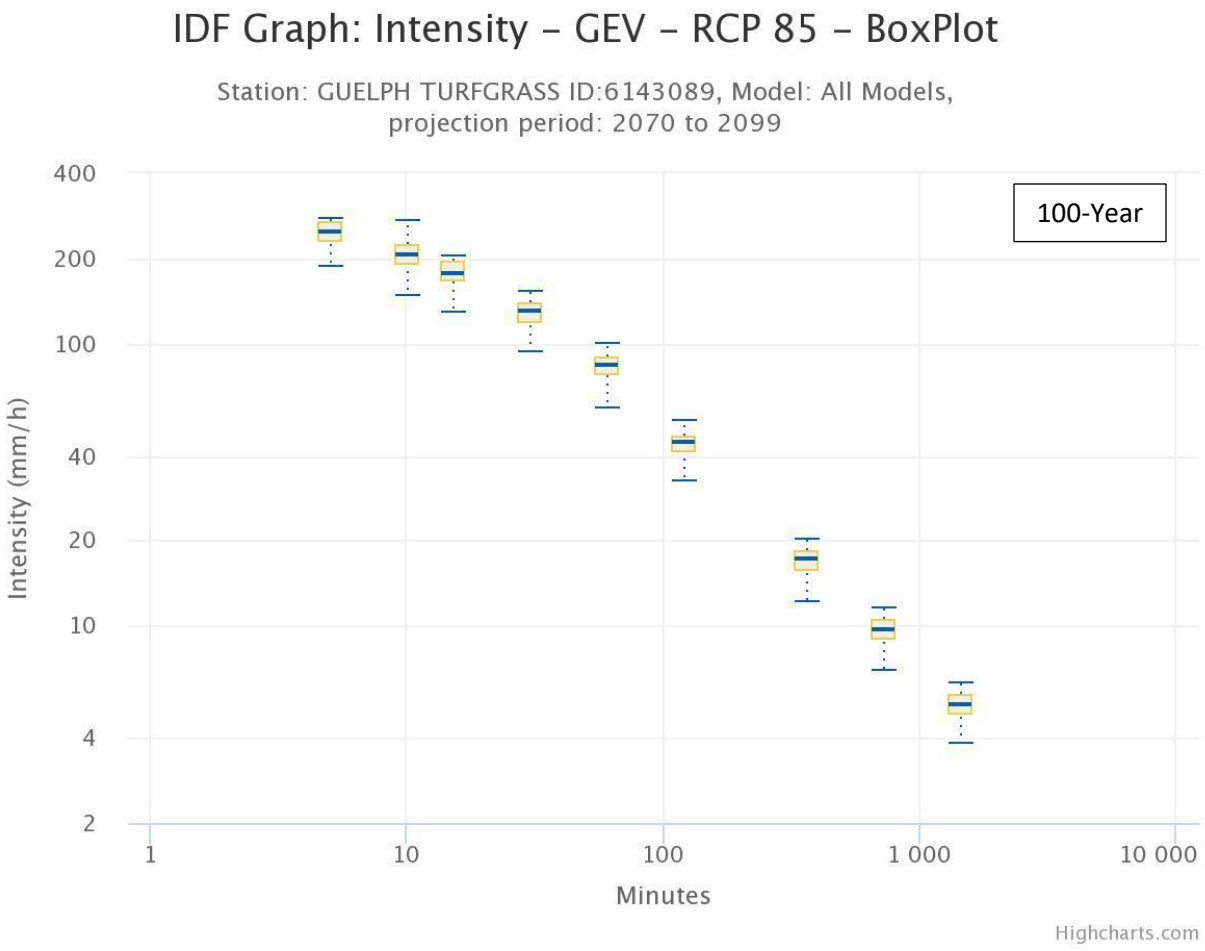
10 000
Minutes
Highcharts.com


IDF Graph: Intensity - GEV - RCP 85 - BoxPlot
Station: GUELPH TURFGRASS ID:6143089, Model: All Models,
projection period: 2070 to 2099
50-Year
Intensity (mm/h)
400
200
100
40
20
10
4
2
1
10
100
1 000
10 000
Minutes
Highcharts.com


IDF Graph: Intensity - GEV - RCP 85 - BoxPlot
Station: GUELPH TURFGRASS ID:6143089, Model: All Models,
projection period: 2070 to 2099
100-Year
Intensity (mm/h)
400
200
100
40
20
10
4
2
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Minutes
Highcharts.com

Appendix E – Climate Change Projections

Projections to 2050 – RCP 2.6

Rainfall Depth (mm): IDF_CC – RCP2.6 2040-2069						
	2-year	**5-year**	**10-year**	**25-year**	**50-year**	**100-year**
5-min	10.24	13	14.42	16.07	17.01	17.73
10-min	14.09	18.37	21.16	24.63	27.04	29.17
15-min	16.61	22.2	26.09	31.09	34.5	38.28
30-min	20.57	28.2	34.23	42.82	48.59	55.65
1-hr	23.55	31.89	39.84	51.13	60.86	70.94
2-hr	27.77	36.2	44.41	55.76	65.12	75.32
6-hr	36.93	47.18	56.04	68.35	77.57	87.86
12-hr	41.6	53.9	63.96	78.56	88.42	100.25
24-hr	48.9	62.35	73.06	88.24	97.8	110.31

Projections to 2050 – RCP 4.5

Rainfall Depth (mm): CCDP - RCP4.5 2040-2069						
	2-year	**5-year**	**10-year**	**25-year**	**50-year**	**100-year**
5-min	3.48	5.86	7.43	9.41	10.89	12.35
10-min	5.41	9.09	11.53	14.61	16.89	19.16
15-min	6.85	11.51	14.60	18.50	21.40	24.27
30-min	9.49	15.96	20.24	25.65	29.66	33.64
1-hr	12.01	20.20	25.62	32.46	37.54	42.58
2-hr	19.18	29.12	35.70	44.02	50.18	56.30
6-hr	32.28	43.80	51.42	61.02	68.16	75.24
12-hr	41.40	54.36	62.88	73.56	81.60	89.52
24-hr	54.48	66.72	74.88	85.20	92.64	100.32

Rainfall Depth (mm): IDF_CC - RCP4.5 2040-2069						
	2-year	**5-year**	**10-year**	**25-year**	**50-year**	**100-year**
5-min	10.5	13.31	14.73	16.02	16.89	17.52
10-min	14.43	18.87	21.47	24.54	26.86	28.72
15-min	17.02	22.81	26.39	31.2	34.44	37.28
30-min	21.09	29.15	34.96	42.81	48.36	53.88
1-hr	24.13	32.93	40.02	51.12	59.2	69.36
2-hr	28.49	37.46	44.55	55.72	63.6	73.91
6-hr	37.88	48.93	56.99	68.62	76.64	85.98
12-hr	42.67	55.91	65.4	78.62	87.79	96.96
24-hr	50.14	64.67	74.76	88.35	97.74	106.74

Projections to 2050 – RCP 8.5

Rainfall Depth (mm): CCDP - RCP8.5 2040-2069						
	2-year	**5-year**	**10-year**	**25-year**	**50-year**	**100-year**
5-min	4.33	7.77	10.05	12.94	15.07	17.20
10-min	6.71	12.06	15.60	20.07	23.39	26.69
15-min	8.50	15.28	19.76	25.43	29.63	33.80
30-min	11.79	21.17	27.39	35.24	41.07	46.85
1-hr	14.92	26.80	34.67	44.61	51.98	59.30
2-hr	23.12	38.62	48.86	61.82	71.42	80.96
6-hr	37.14	55.02	66.84	81.84	92.94	103.92
12-hr	48.12	67.08	79.80	95.64	107.52	119.28
24-hr	61.44	84.00	98.88	117.60	131.52	145.44

Rainfall Depth (mm): IDF_CC - RCP8.5 2040-2069						
	2-year	**5-year**	**10-year**	**25-year**	**50-year**	**100-year**
5-min	10.84	13.76	15.1	16.55	17.44	17.99
10-min	14.9	19.47	22.2	25.5	27.8	30.06
15-min	17.57	23.54	27.37	32.26	35.82	39.04
30-min	21.75	30.15	36.14	44.33	50.74	58.87
1-hr	24.94	34.25	41.57	52.5	63.73	78.46
2-hr	29.42	38.94	46.17	57.24	68.83	83.06
6-hr	39.11	50.7	58.74	71.03	81.7	94.06
12-hr	44.03	57.88	67.41	81.48	92.6	105.97
24-hr	51.76	66.91	76.93	91.81	101.88	114.78

Projections to 2050 – Linear Trend

Rainfall Depth (mm): MTO IDF Linear Projection 2050						
	2-year	**5-year**	**10-year**	**25-year**	**50-year**	**100-year**
5-min	11.2	14.7	17.1	20	22.1	24.3
10-min	13.9	18.2	21.1	24.7	27.3	30
15-min	15.8	20.6	23.9	27.9	30.9	33.9
30-min	19.6	25.6	29.5	34.5	38.2	41.9
1-hr	24.2	31.6	36.5	42.6	47.2	51.7
2-hr	30	39.2	45.2	52.8	58.4	64
6-hr	42.6	55.2	63.6	73.8	81.6	89.4
12-hr	52.8	68.4	79.2	91.2	100.8	110.4
24-hr	64.8	84	98.4	112.8	124.8	136.8

Projections to 2100 – RCP 2.6

Rainfall Depth (mm): IDF_CC – RCP2.6 2070-2099						
	2-year	**5-year**	**10-year**	**25-year**	**50-year**	**100-year**
5-min	10.18	13.06	14.4	15.78	16.58	17.18
10-min	13.97	18.44	21.13	24.09	26.03	27.96
15-min	16.46	22.28	26.03	30.53	33.57	36.5
30-min	20.35	28.47	34.4	42.22	48.24	54.69
1-hr	23.16	32.16	39.3	51.05	61.2	72.28
2-hr	27.38	36.5	43.74	55.6	65.69	77.04
6-hr	36.55	47.69	55.86	67.86	77.49	87.78
12-hr	41.17	54.52	64.32	77.56	87.87	98.79
24-hr	48.43	63.06	73.49	87.16	96.59	106.76

Projections to 2100 – RCP 4.5

Rainfall Depth (mm): CCDP - RCP4.5 2070-2099						
	2-year	**5-year**	**10-year**	**25-year**	**50-year**	**100-year**
5-min	4.55	8.37	10.90	14.09	16.46	18.81
10-min	7.07	12.99	16.91	21.86	25.54	29.19
15-min	8.95	16.45	21.42	27.69	32.35	36.97
30-min	12.41	22.80	29.69	38.38	44.84	51.24
1-hr	15.70	28.86	37.57	48.58	56.75	64.86
2-hr	24.12	41.40	52.82	67.28	78.00	88.64
6-hr	36.72	60.12	75.60	95.16	109.62	124.02
12-hr	44.28	65.88	80.16	98.28	111.72	125.04
24-hr	57.36	83.04	99.84	121.20	137.04	152.88

Rainfall Depth (mm): IDF_CC - RCP4.5 2070-2099						
	2-year	**5-year**	**10-year**	**25-year**	**50-year**	**100-year**
5-min	10.54	13.35	14.83	16.14	16.81	17.33
10-min	14.53	18.86	21.66	24.89	26.76	28.48
15-min	17.13	22.76	26.65	31.47	34.33	37.50
30-min	21.21	29.09	35.06	43.16	49.28	55.10
1-hr	24.34	32.87	40.31	51.73	61.08	72.52
2-hr	28.72	37.36	44.93	56.48	65.68	76.79
6-hr	38.16	48.80	57.37	69.42	78.55	88.12
12-hr	42.96	55.77	65.75	79.34	89.74	99.84
24-hr	50.49	64.50	75.12	89.18	99.64	109.28

Projections to 2100 – RCP 8.5

Rainfall Depth (mm): CCDP – RCP8.5 2070-2099						
	2-year	**5-year**	**10-year**	**25-year**	**50-year**	**100-year**
5-min	5.34	9.22	11.79	15.04	17.45	19.84
10-min	8.29	14.31	18.30	23.34	27.07	30.78
15-min	10.50	18.13	23.18	29.56	34.29	38.99
30-min	14.56	25.13	32.13	40.97	47.53	54.04
1-hr	18.42	31.81	40.66	51.86	60.16	68.41
2-hr	27.56	48.12	61.72	78.92	91.68	104.34
6-hr	43.14	71.34	90.00	113.58	131.04	148.44
12-hr	55.80	87.12	107.76	134.04	153.36	172.68
24-hr	74.88	108.48	130.56	158.40	179.04	199.68

Rainfall Depth (mm): IDF_CC – RCP8.5 2070-2099						
	2-year	**5-year**	**10-year**	**25-year**	**50-year**	**100-year**
5-min	11.56	15.01	16.91	18.80	19.79	20.63
10-min	15.87	21.18	24.91	28.87	31.78	34.14
15-min	18.73	25.57	30.63	36.26	40.74	44.24
30-min	23.24	32.70	39.90	49.77	57.41	64.93
1-hr	26.54	37.02	45.91	59.68	71.92	84.03
2-hr	31.31	42.11	51.10	65.11	77.57	89.60
6-hr	41.88	54.90	65.07	79.71	91.65	103.08
12-hr	47.17	62.69	74.66	91.34	104.41	116.73
24-hr	55.49	72.47	85.27	102.55	115.51	126.92

Projections to 2100 – Linear Trend

Rainfall Depth (mm): MTO IDF Linear Projection 2100						
	2-year	**5-year**	**10-year**	**25-year**	**50-year**	**100-year**
5-min	11.6	15.1	17.5	20.4	22.5	24.7
10-min	14.5	18.8	21.7	25.2	27.9	30.5
15-min	16.5	21.4	24.6	28.6	31.6	34.6
30-min	20.5	26.6	30.5	35.5	39.2	42.9
1-hr	25.6	33	37.9	44	48.6	53.1
2-hr	32	41.2	47.2	54.6	60.4	66
6-hr	45.6	58.8	67.2	77.4	85.2	93
12-hr	57.6	73.2	84	96	106.8	115.2
24-hr	72	91.2	105.6	120	132	144

Projections to 2200 – Linear Trend

Rainfall Depth (mm): MTO IDF Linear Projection 2200						
	2-year	**5-year**	**10-year**	**25-year**	**50-year**	**100-year**
5-min	12.4	15.9	18.3	21.1	23.3	25.5
10-min	15.6	19.9	22.8	26.3	29	31.7
15-min	17.9	22.7	25.9	30	33	36
30-min	22.5	28.5	32.5	37.4	41.1	44.8
1-hr	28.4	35.8	40.7	46.8	51.4	55.9
2-hr	36	45	51.2	58.6	64.4	69.8
6-hr	52.8	65.4	73.8	84	92.4	99.6
12-hr	67.2	82.8	93.6	106.8	116.4	126
24-hr	86.4	105.6	117.6	134.4	146.4	158.4