Matrix Solutions Inc.
A Montrose Environmental Company

GERMAN MILLS CREEK GEOMORPHIC SYSTEMS MASTER PLAN
CLIMATE CHANGE ASSESSMENT
APPENDIX D

Prepared for:
CITY OF TORONTO

Prepared by:
MATRIX SOLUTIONS INC., A MONTROSE ENVIRONMENTAL COMPANY

Version 1.0
December 2024
Mississauga, Ontario

Suite 3001, 6865 Century Ave.
Mississauga, ON, Canada L5N 7K2
T 905.877.9531 F 289.323.3785
www.matrix-solutions.com

APPENDIX D
Climate Change Assessment

Matrix Solutions Inc.
A Montrose Environmental Company

GERMAN MILLS CREEK GEOMORPHIC SYSTEMS MASTER PLAN
CLIMATE CHANGE ASSESSMENT

Prepared for:
CITY OF TORONTO

Prepared by:
MATRIX SOLUTIONS INC., A MONTROSE ENVIRONMENTAL COMPANY

Version 1.0
August 2023
Mississauga, Ontario

Suite 3001, 6865 Century Ave.
Mississauga, ON, Canada L5N 7K2
T 905.877.9531 F 289.323.3785
www.matrix-solutions.com

GERMAN MILLS CREEK GEOMORPHIC SYSTEMS MASTER PLAN

CLIMATE CHANGE ASSESSMENT

Prepared for City of Toronto, August 2023

August 30, 2024

Ziyang Zhang, M.Sc., P.Eng.
Water Resources Engineer

reviewed by
Roger Phillips, Ph.D., P.Geo., FGC
Senior Geomorphologist

CONTRIBUTORS

Name	Job Title	Role
Ziyang Zhang, M.Sc., P.Eng.	Water Resources Engineer	Author
Roger Phillips, Ph.D., P.Geo., FGC	Senior Geomorphologist	Reviewer
Shaina Blue, P.Eng.	Senior Water Resources Engineer	Project engineer
Steve Braun, P.Eng.	Senior Water Resources Engineer	Engineering technical review
Natasha Cyples, M.Sc., P.Geo.	Fluvial Geomorphologist	Fluvial geomorphologist

VERSION CONTROL

Version	Date	Issue Type	Filename	Description
V0.1	09-Mar-2023	Draft	32227-504 GM CCA R 2023-03-09 draft V0.1.docx	Issued to client for review
V1.0	30-Aug-2023	Final	32227-504 GM CCA R 2023-08-30 final V1.0.docx	Issued to client

TABLE OF CONTENTS

IN-TEXT FIGURES

IN-TEXT TABLES

APPENDICES

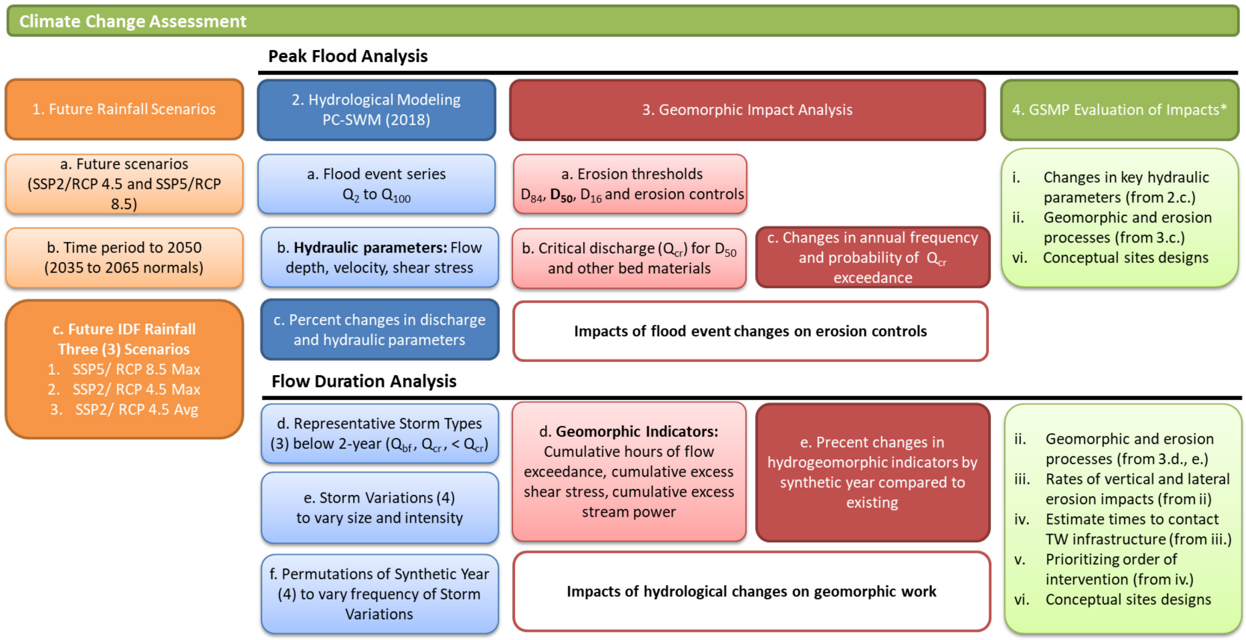
1 INTRODUCTION

Climate and environment are one of the four resilience challenges facing the City of Toronto (the City), as identified in the *Toronto Resilience Strategy* (City of Toronto 2019). Many of the 10 goals and 27 actions outlined in the resilience strategy focus on flood resilience. This focus on flood resilience is underpinned by the City's experience with five severe storms since 2000, which caused widespread impacts. Further, it is projected that climate change-influenced increases in the intensity of formative storms is only expected to exacerbate erosion and flood risks. Determining climate change influences on future rainfall and, thereby, runoff on the German Mills Creek system can be readily quantified using tools and outcomes developed in hydrologic and hydraulic modelling, water balance assessment of the seasonality of runoff, behavior of snowpack/melt, frequency and magnitude of storms, length and timing of dry periods, aquatic/riparian habitat, and public safety, etc. At present, neither the City, nor the Toronto and Region Conservation Authority (TRCA), provide any formal prescription for how future projected changes in rainfall due to climate change should be quantified or assessed.

As such, a climate change assessment approach was developed in consultation with City staff to meet the project objectives and included the following:

1. **Future Rainfall Scenarios**:	Three scenarios were shortlisted based on consideration of greenhouse gas and socioeconomic scenarios for the 2050s future time period (i.e., 2035 to 2065) for the evaluation of flood events. Total annual rainfall was analyzed, and one future climate was defined for total synthetic annual rainfall.
2. **Hydrological Modelling**:	An existing hydrologic model was used to simulate: • a climate-adjusted flood event series (Q_2, Q_5, Q_{10}, Q_{25}, Q_{50}, and Q_{100}) • annual synthetic hydrological year series ($<Q_2$) • hydrologic impacts of historic development
3. **Geomorphic Impact Analysis**:	Changes in annual frequency and probability of critical discharge exceedances were determined to evaluate expected flood event impacts to erosion controls and evaluate geomorphic indicators and impacts of hydrological changes in geomorphic work.
4. **Geomorphic System Master Plan (GSMP) Evaluation of Impacts**:	Impacts to key hydraulic parameters, geomorphic and erosion processes, and implications for design and management of erosion controls was considered in conceptual site designs.

A diagram of the climate change assessment components, tasks, and expected outcomes is provided in Figure 1.



Note:
*GSMP evaluation of impacts numbering i. to vi. is based on City comments, with Figure 1 predecessors noted in brackets.

FIGURE 1 Climate Change Assessment Approach

2 FUTURE RAINFALL SCENARIOS

2.1 Intensity Duration Frequency Data

In Ontario, there are a variety of publicly accessible tools for estimating projected rainfall as intensity-duration-frequency (IDF) data. Examples include:

- Environment and Climate Change Canada (ECCC)
- University of Western Ontario (Intensity-Duration-Frequency Curves under Climate Change [IDF_CC Tool])
- Ontario Climate Change Data Portal (OCCDP)
- Ontario Ministry of Transportation (MTO) Trending Tool
- simple offset of a base IDF relationship

Central to structured assessments of the impacts of climate change on rainfall is the use of an "ensemble" of estimates. This approach is advocated because each Global Climate Model (GCM) provides a slightly different conceptualization of the earth-atmosphere system, which has led the Intergovernmental Panel on Climate Change to recommend using an ensemble approach that groups climate projections. The estimates in an ensemble provide a better characterization of the future and its uncertainty than a single model used in isolation.

As precipitation is a key driver for the health of German Mills Creek, the first component of the climate change assessment involved compiling a long list of alternate future IDF rainfall estimates using the various available tools listed above and included various Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs). The suggested RCPs for this study are the current trend of RCP 8.5, which corresponds to a “non-climate policy” scenario and high-severity climate change impacts, and the optimistic case of RCP 4.5, reflecting implementation of global climate change mitigation measures (WSP 2022; Appendix A). The 2050s time horizon (i.e., 2035 to 2065) was selected for this study, as this generally coincides with the life span of the proposed design alternatives (e.g., 25 to 50 years). The long list of future IDF rainfall estimates was analyzed to establish a short list representing a range of values (e.g., average and maximum estimates) for the modelling component of the assessment.

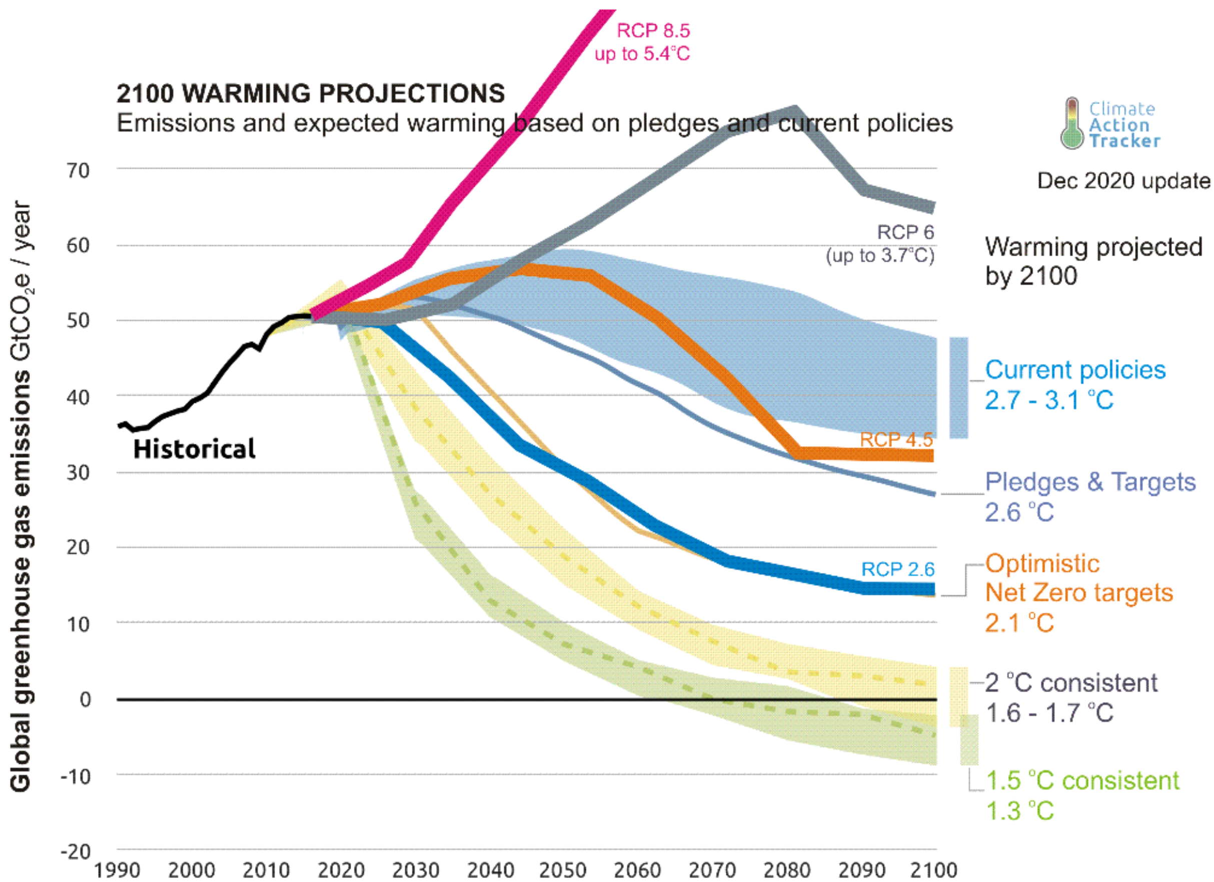


FIGURE 2 Representative Concentration Pathway Emission Scenarios Integrated with Mitigation Pledges and Policies (Source: Climate Action Tracker 2021)

The second component of this task was to define total annual rainfall amounts for existing and future climate scenarios. This total annual rainfall was used to develop a synthetic year of representative storm types that were subsequently manipulated and tested based on size, intensity, and frequency.

The full report on the development of future rainfall scenarios is included in Appendix A; a summary of the key recommendations and conclusions is included below:

- It is recommended to use **IDF_CC Tool v6** as the basis for future rainfall estimation in support of this evaluation.

- It is recommended that the rainfall estimates to be adopted for evaluation comprise an IDF relationship that is consistent with the **average** across all stations and the **maximum** IDF estimate to be used as a stress test.

- A future rainfall scenario was formulated by using a statistical average of 10 rainfall stations surrounding the German Mills Creek watershed. From the synthesis of data derived from these ten stations, the average future rainfall scenario and maximum (worst-case) future rainfall scenarios were determined (Table 3 in Appendix A). The **G Ross Lord Dam Station** and the **Toronto North York Station** in Table 1 were identified as the best representative stations for the average future rainfall scenario and maximum future rainfall scenario respectively, based on the statistical analysis of the 10 stations. These two stations were then **used in the geomorphological assessment (i.e., pertaining to future climate) of German Mills Creek**.

TABLE 1 Summary of University of Western Ontario (IDF_CC Tool v.6) Future Intensity-Duration-Frequency Rainfall Scenarios Used in this Study

Station ID	Station Name	Climate Model	Statistical Significance
HY027	G Ross Lord Dam	CMIP5 GCMs RCP 4.5	Average
615S001	Toronto North York	PCIC Bias Corrected CMIP6 SSP2-4.5	Maximum SSP2-4.5
615S001	Toronto North York	PCIC Bias Corrected CMIP6 SSP5-8.5	Maximum SSP5-8.5

Notes:
CMIP - Coupled Model Intercomparison Project
PCIC - Pacific Climate Impacts Consortium
RCP - Representative Concentration Pathway
SSP - Shared Socioeconomic Pathway

2.2 Annual Precipitation for Synthetic Annual Analysis

This study also included an assessment of the future annual hydrological impacts of climate change based on a synthetic year of typical rainfall events. To assess hydrological statistics of rainfall data for existing and future conditions, an assessment of average annual precipitation in the study area was completed for existing and future conditions and is documented in Appendix A. The total annual precipitation amounts informed the development of a synthetic year of representative storm types that can subsequently be manipulated and tested based on size, intensity, and frequency (Section 3.2). Annual precipitation was assumed to be entirely rainfall events for the purposes of this assessment, as snow and snowmelt impacts were outside of the scope of this study.

In summary, it was generally concluded that:

- The Toronto region is expected to experience a warmer and wetter climate, along with more variable weather patterns including higher intensity storms.
- The existing average annual total precipitation is 853 mm, obtained from the 1981 to 2020 climate normal data for Buttonville Airport.
- The upper estimate of the projected average annual total precipitation abstracted from ClimateData.ca for the 2031 to 2060 future climate period is 917 mm, which is a 7.5% overall increase from existing climate normals.
- There is no significant change to the number of dry days predicted and the Toronto area will still experience a similar number of rainfall events, on average, over a year.
- There is no significant difference in predicted annual precipitation between the RCP 4.5 and RCP 8.5 scenarios, and as such, one future climate scenario for annual precipitation was carried forward for hydraulic and geomorphic impact assessments.

The existing and future climate total annual precipitation used in this study are listed in Table 2.

TABLE 2 Summary of Total Annual Precipitation

	Existing Climate (1981-2020)	Future Climate (2031-2060)
Total Annual Precipitation (mm)	853	917

Notes:
Estimates from ClimateData.ca for Buttonville Airport climate station, summarized from Appendix A.

3 HYDROLOGIC AND HYDRAULIC MODELLING

The existing PCSWMM hydrology model from the *Don River Hydrology Update* (AECOM 2018) was used to simulate watershed response from select storm events at the outlet of German Mills Creek. The approach and hydrologic results for the peak flood analysis (flood events Q_2-Q_{100}) and the flow duration analysis (synthetic annual analysis for sub-Q_2) are outlined in Sections 3.1 and 3.2, respectively. The existing conditions model was not modified for this study other than adjusting the rainfall input, and the sensitivity analysis outlined in Section 3.3.

3.1 Peak Flood Analysis

In the *Don River Hydrology Update* (AECOM 2018), the 12-hour Atmospheric Environmental Service (AES) rainfall distribution was determined to be the most representative design storm distribution for the Don

River watershed. An areal reduction factor of 0.905 was applied to the rainfall for 2- through to 100-year return period peak flows at the outlet of German Mills Creek.

For an equivalent comparison between existing and future climate scenarios, the existing conditions was rerun using the Buttonville Airport climate station IDF data and generalized extreme value (GEV) statistical distribution, which is used in the IDF_CC Tool. Therefore, the existing climate scenario peak flows for German Mills Creek will not match the reported peak flows in the *Don River Hydrology Update* (AECOM 2018). The existing and future climate IDF data were used to generate 12-hour AES rainfall hyetographs (see Appendix B) for the 2- through 100-year return periods, with the 0.905 areal reduction factor, for the existing climate and the three future climate scenarios identified in Section 2.1.

The rainfall events were then simulated using the Don River PCSWMM hydrology model (AECOM 2018). The simulated rainfall depths and peak flows at the outlet of German Mills Creek under existing and future climate scenarios are presented in Table 3.

The percent change in rainfall depths are listed in Table 4 where the RCP 4.5 "average" future climate scenario predicts roughly a 10% increase rainfall, and the more extreme impacts from the SSP2-4.5 maximum and SSP5-8.5 maximum scenarios range from a 7% to 55% increase and a 13% to 64% increase in rainfall depths, respectively. Hydraulic impacts are discussed below.

TABLE 3 Rainfall Depth and Simulated Peak Flows for Existing and Climate-adjusted Scenarios

Return Period (year)	Existing (Buttonville Airport Station GEV Distribution)		RCP 4.5 (Average Based on CMIP5) Station HY027 at G Ross Lord Dam		SSP2-4.5 (Maximum Based on PCIC Bias Corrected CMIP6) Station 615S001 at Toronto North York)		SSP5-8.5 (Maximum based on PCIC Bias Corrected CMIP6) Station 615S001 at Toronto North York)	
	Rainfall Depth (mm)	Peak Flow (m^3/s)	Rainfall Depth (mm)	Peak Flow (m^3/s)	Rainfall Depth (mm)	Peak Flow (m^3/s)	Rainfall Depth (mm)	Peak Flow (m^3/s)
2	39	21	43	23	42	23	44	24
5	55	30	59	33	59	33	63	36
10	67	38	73	42	74	42	82	46
25	85	47	92	52	106	62	114	67
50	100	58	111	65	138	80	147	86
100	118	69	133	77	183	126	194	143

Notes:
CMIP - Coupled Model Intercomparison Project
GEV - generalized extreme value
PCIC - Pacific Climate Impacts Consortium
RCP - Representative Concentration Pathway
SSP - Shared Socioeconomic Pathway

TABLE 4 Percent Change in Rainfall Depth under Future Climates

Return Period (year)	Percent Change in Rainfall Depth under Future Conditions		
	RCP 4.5 (Average based on CMIP5) Station HY027 at G Ross Lord Dam	SSP2-4.5 (Maximum based on PCIC Bias Corrected CMIP6) Station 615S001 at Toronto North York	SSP5-8.5 (Maximum based on PCIC Bias Corrected CMIP6) Station 615S001 at Toronto North York
2	10%	8%	13%
5	7%	7%	15%
10	9%	10%	22%
25	8%	25%	34%
50	11%	38%	47%
100	13%	55%	64%
Average	**10%**	**24%**	**33%**
Maximum	**13%**	**55%**	**64%**

Notes:
CMIP - Coupled Model Intercomparison Project
GEV - generalized extreme value
PCIC - Pacific Climate Impacts Consortium
RCP - Representative Concentration Pathway
SSP - Shared Socioeconomic Pathway

Figure 3 illustrates the relationship between simulated peak flows and return period for existing and climate-adjusted scenarios. Table 5 presents the percent change in peak flows at the select return periods. The changes in peak flood events summarized in Section 3.1.2 will be discussed further in subsequent sections with respect to comparing climate change to historic land use impacts (Section 3.3) and with respect to geomorphic impacts (Section 3.4).

FIGURE 3 Climate-adjusted Peak Flows by Return Period for Existing and Climate-adjusted Scenarios

TABLE 5 Hydrologic Impacts of Peak Flow under Future Climates

Return Period (year)	Percent Change in Peak Flow under Future Conditions (%)		
	RCP 4.5 (Average based on CMIP5) Station HY027 at G Ross Lord Dam	SSP2-4.5 (Maximum based on PCIC Bias Corrected CMIP6) Station 615S001 at Toronto North York	SSP5-8.5 (Maximum based on PCIC Bias Corrected CMIP6) Station 615S001 at Toronto North York
2	11%	9%	16%
5	9%	9%	17%
10	10%	12%	21%
25	11%	31%	42%
50	13%	38%	49%
100	12%	82%	108%
Average	**11%**	**30%**	**42%**
Maximum	**13%**	**82%**	**108%**

Notes:
CMIP - Coupled Model Intercomparison Project
GEV - generalized extreme value
PCIC - Pacific Climate Impacts Consortium
RCP - Representative Concentration Pathway
SSP - Shared Socioeconomic Pathway

3.1.1 Peak Flood Hydraulic Changes

The peak flows obtained from the hydrology model were input in the one-dimensional (1D) hydraulic model (HEC-RAS) that was developed by Matrix Solutions Inc, a Montrose Environmental company (Matrix 2022, 2021), to quantify potential future changes to key hydraulic parameters including velocity, shear stress, and stream power. The hydraulic model was reviewed, and additional interpolated cross-sections were added in model geometry to refine the hydraulic computation results.

Climate change impacts to hydraulics were quantified based on the percent changes of each scenario relative to existing conditions within the study area. Tables 6, 7, and 8 present percent change results for velocity, shear stress, and stream power, respectively.

In general, more intensified greenhouse gas emission scenarios result in greater increases of peak flow, velocity, shear stress, and stream power. For peak flow results, the RCP 4.5 “average” scenario resulted in a consistent percent increase across all return periods. While for SSP2-4.5 and SSP5-8.5 “maximum” scenarios, the percent increase varied across return periods and larger storms have higher increases than smaller storms. For example, 100-year peak flows are estimated to increase by 82% under SSP2-4.5 “maximum” climate scenario and by 108% under SSP5-8.5 “maximum” climate scenario.

For flow velocity results, RCP 4.5 “average” climate scenario showed consistent increase (3%) for all return periods (except for 50-year which is 1%). For SSP2-4.5 and SSP5-8.5 “maximum” scenarios, flow velocity increases are generally small (≤10%) for 2-year through 50-year events. For 100-year event, SSP2-4.5 and SSP5-8.5 “maximum” scenarios showed greater increases of 30% and 40%, respectively.

TABLE 6 Hydraulic Impacts of Velocity under Future Climates, Velocity

Return Period (year)	Percent Change in Velocity under Future Conditions (%)		
	RCP 4.5 (Average based on CMIP5) Station HY027 at G Ross Lord Dam	SSP2-4.5 (Maximum based on PCIC Bias Corrected CMIP6) Station 615S001 at Toronto North York	SSP5-8.5 (Maximum based on PCIC Bias Corrected CMIP6) Station 615S001 at Toronto North York
2	3%	2%	4%
5	3%	3%	5%
10	3%	4%	6%
25	3%	5%	6%
50	1%	7%	10%
100	3%	30%	40%
Average	**3%**	**9%**	**12%**
Maximum	**3%**	**30%**	**40%**

Notes:
CMIP - Coupled Model Intercomparison Project
GEV - generalized extreme value
PCIC - Pacific Climate Impacts Consortium
RCP - Representative Concentration Pathway
SSP - Shared Socioeconomic Pathway

For impacts to shear stress and stream power, the climate-adjusted scenarios generally show a smaller percent increase (roughly <10%), with exceptions in the 50-year and 100-year “maximum” scenarios. The largest impacts in shear stress are predicted for the 100-year event, with 59% and 84% increases under SSP2-4.5 and SSP5-8.5 “maximum” climate scenarios, respectively). Similarly, the largest impacts in stream power are predicted for the 100-year event, with 106% and 157% increases under SSP2-4.5 and SSP5-8.5 "maximum" climate scenarios, respectively.

TABLE 7 Hydraulic Impacts of Shear Stress under Future Climates, Shear Stress

Return Period (year)	Percent Change in Shear Stress under Future Conditions (%)		
	RCP 4.5 (Average based on CMIP5) Station HY027 at G Ross Lord Dam	SSP2-4.5 (Maximum based on PCIC Bias Corrected CMIP6) Station 615S001 at Toronto North York	SSP5-8.5 (Maximum based on PCIC Bias Corrected CMIP6) Station 615S001 at Toronto North York
2	3%	3%	5%
5	3%	3%	6%
10	4%	5%	8%
25	3%	4%	5%
50	0%	9%	14%
100	6%	59%	84%
Average	**3%**	**14%**	**20%**
Maximum	**6%**	**59%**	**84%**

Notes:
CMIP - Coupled Model Intercomparison Project
GEV - generalized extreme value
PCIC - Pacific Climate Impacts Consortium
RCP - Representative Concentration Pathway
SSP - Shared Socioeconomic Pathway

TABLE 8 Hydraulic Impacts of Stream Power under Future Climates, Stream Power

Return Period (year)	Percent Change in Stream Power under Future Conditions (%)		
	RCP 4.5 (Average based on CMIP5) Station HY027 at G Ross Lord Dam	SSP2-4.5 (Maximum based on PCIC Bias Corrected CMIP6) Station 615S001 at Toronto North York	SSP5-8.5 (Maximum based on PCIC Bias Corrected CMIP6) Station 615S001 at Toronto North York
2	6%	5%	9%
5	6%	6%	11%
10	7%	9%	15%
25	6%	9%	11%
50	1%	16%	25%
100	9%	106%	157%
Average	**6%**	**25%**	**38%**
Maximum	**9%**	**106%**	**157%**

Notes:
CMIP - Coupled Model Intercomparison Project
GEV - generalized extreme value
PCIC - Pacific Climate Impacts Consortium
RCP - Representative Concentration Pathway
SSP - Shared Socioeconomic Pathway

3.1.2 Sensitivity Analysis Without Stormwater Management Ponds

An analysis was completed to assess the sensitivity of the hydraulic impacts to the storage and routing effects of modelled stormwater management (SWM) ponds. The existing 15 SWM ponds in the German Mills Creek subwatershed were removed from the model and the hydraulic results were re-evaluated. Only minor differences were observed, as such the results were not considered sensitive to the routing effects of the SWM ponds with respect to significantly changing the climate change assessment results and interpretation. The results of this sensitivity analysis are presented in Appendix C.

3.1.3 Peak Flood Analysis Summary

Overall, under a future climate scenario representing the average increase in forecasted IDF relationships for the study area for the 2050s, hydraulic parameters (flow, velocity, shear stress, and stream power) are estimated to generally have a moderate increase ranging from 0% to 13%, and an average of 6% increase at the outlet of German Mills Creek. Matrix also tested the higher severity climate change impacts, under the future climate scenarios representing the maximum changes in forecasted IDFs for the SSP2-4.5 (optimistic) and SSP5-8.5 (worst-case) climate policy scenarios. Under these “stress test” scenarios, the hydraulic parameters are estimated to increase proportionally to the size of the event; i.e., the more frequent events (2- to 10-year) showing more moderating increases (2% to 21%), the less frequent events (25- to 50-year) showing higher increases (5% to 49%) and very significant increases in the infrequent (100-year) event (30% to 157%).

Overall, considering the three future climate scenarios and all return periods, the range and average predicted percent increase in hydraulic parameters are summarized in Table 9. It is important to understand that no single future climate scenario is more or less accurate to predict climate change impacts. The use of average and maximum IDF forecasts provides insight as to the range in potential impacts. The impacts of hydrological changes in geomorphic work are assessed in Section 4.

TABLE 9 Summary of Percent Increase in Hydraulic Parameters under Future Climate Scenarios

Parameter	Overall Percent Change under all Future Climate Scenarios and Return Periods		
	Average	Minimum	Maximum
Peak Flow	28%	9%	108%
Flow Velocity	8%	1%	40%
Shear Stress	12%	0%	84%
Stream Power	23%	1%	157%

3.2 Flow Duration Analysis

Hydrological modelling included an assessment of the future annual hydrological impacts of climate change based on a synthetic year of representative storm events. The synthetic year of representative storm events was developed from a statistical analysis of the typical number of each event type per year based on historical IDF data. The cumulative outputs for the synthetic hydrological year were used to provide quasi-absolute values on an annual basis for changes in select hydrological parameters.

3.2.1 Overview of Approach

The following approach was developed to generate a synthetic representative year of hydrologic output:

- **Representative Storms (Section 3.2.2)**: three representative storm types producing flows less than the 2-year event ($<Q_2$) were defined with a range of representative rainfall volumes (23 mm, 14 mm, 7.4 mm) and durations (12-hour, 6-hour, 1-hour) that produce flows comparable to the bankfull discharge (Q_{bf}), critical discharge (Q_{cr} for D_{50}), and a flow less than critical discharge ($<Q_{cr}$ for D_{50}), respectively.

- **Existing Climate Synthetic Year (Section 3.2.3)**: based on the existing precipitation relationships, the annual precipitation was categorized into the three representative storm types and the annual frequency statistics were defined and then simulated to generate an existing synthetic annual flow exceedance curve.

- **Future Climate Scenarios (Section 3.2.4)**: the size, intensity, and frequency of the representative storm types were adjusted for four storm variations and simulated in the hydrological model. The storm variations were combined in four permutations of the synthetic year to evaluate climate change impacts on the annual flow exceedances and key hydrogeomorphic indicators, with further translation and interpretations to evaluate the geomorphic impacts, as outlined in Section 4.

3.2.2 Representative Storm Events

Matrix defined ranges in bankfull discharge (Q_{bf}), critical discharge (Q_{cr}) for D_{50}, and less than critical discharge ($<Q_{cr}$) based on previous field investigations and measurements, as listed in Table 10, for Reach 1 (outlet) of German Mills Creek (Matrix 2022; see Tables 3-22 and 3-24 in referenced report). Based on these ranges, a representative flow value was selected for the three thresholds to represent target flow rates: Q_{bf} (12 m³/s), Q_{cr} (7 m³/s), and $<Q_{cr}$ (3.5 m³/s), as listed in Table 10.

To determine the representative storm events that would generate Q_{bf}, Q_{cr}, and $<Q_{cr}$ under the existing climate, Matrix developed an IDF table for $<Q_2$ storms (Table 11) and analyzed possible storms that would generate Q_{bf}, Q_{cr}, and $<Q_{cr}$ discharges in the hydrology model. Storm parameters such as volume, duration, frequency, and simulated discharges for theoretical design storms and actual historical observed storms were analyzed to ensure that storm parameters display reasonable and realistic relationship amongst those selected. Table 10 summarizes the results of the selected representative storms for Q_{bf}, Q_{cr}, and $<Q_{cr}$ targets. These storms were selected because they:

- represent a good range in IDF characteristics (i.e., spread out on Table 11)
- are realistic events (i.e., correlate well with historical recorded rain events and peak flows)
- have logical relationships (i.e., [Q_{bf}] > [Q_{cr}] > [$<Q_{cr}$] in terms of volume, duration and return period)

TABLE 10 Representative Flow and Rainfall for Q_{bf}, Q_{cf}, and <Q_{cr} Representative Storm Events

Parameter		Bankfull Discharge Q_{bf}	Critical Discharge Q_{cr}	Less than Critical Discharge <Q_{cr}
Flow	Approximate Flow Range	9-15 m³/s	3-11 m³/s	>1 m³/s
	Representative Flow	12 m³/s	7 m³/s	3.5 m³/s
Rainfall	Volume	23 mm	14 mm	7.4 mm
	AES Storm Duration	12 hour	6 hour	1 hour
	Return Period (year)	1.05	1.001	1.0005

Notes:
AES - Atmospheric Environment Service

TABLE 11 Intensity-Duration-Frequency Table Based on Buttonville Airport Climate Station Rainfall Data with Generalized Extreme Value Distribution

Return Period (year)	Probability (%)	Rainfall Depth (mm) per Storm Duration								
		5 min	10 min	15 min	30 min	1 hour	2 hour	6 hour	12 hour	24 hour
100	1%	18	28	35	60	81	86	106	118	118
50	2%	17	25	32	50	66	71	89	100	102
25	4%	15	22	28	41	53	59	75	85	88
10	10%	13	19	24	32	40	44	58	67	72
5	20%	11	16	20	26	31	35	47	55	60
2	50%	9	12	15	18	21	24	33	39	45
1.4	71.43%	7	10	12	15	17	20	28	33	39
1.25	80.00%	7	9	11	13	15	18	25	29	36
1.11	90.09%	6	8	9	12	13	16	22	26	32
1.05	95.24%	5	7	8	11	12	14	20	23	29
1.02	98.04%	5	7	7	9	10	12	18	20	27
1.01	99.01%	4	6	6	9	9	11	17	19	25
1.005	99.50%	4	6	6	8	9	11	16	18	24
1.001	99.90%	4	5	4	7	8	9	14	15	22
1.0005	99.95%	3	4	4	7	7	9	13	15	21

Notes:
Shaded cells are the selected representative storm events.

3.2.3 Existing Climate Synthetic Year

To develop a synthetic year of rainfall events for the existing climate conditions, each representative storm event was assigned an appropriate annual frequency of occurrence. Therefore, a synthetic year of rainfall was made by multiplying each representative storm by their annual frequency of occurrence.

Matrix utilized the City's Rainfall Depth versus Percent of Total Average Annual Rainfall Depth relationship (Figure 4) from *Toronto Weather Flow Management Guidelines* (City of Toronto 2006, Figure 1a). This relationship is based on actual rainfall events from 1991, which was considered as the most representative of long-term average annual precipitation patterns, at 16 rain gauge stations across the City. In this figure, Matrix lumped daily rainfall into three bands to represent annual rainfall percentage for generating Q_{bf}, Q_{cr}, and <Q_{cr} thresholds, as follow:

- **0 to 4 mm: daily rainfall generating negligible geomorphic work:** Using the hydrology model, 4 mm of rainfall (1-hour AES) generated 1 m^3/s peak flow which was considered to cause negligible geomorphic work. As such, 4 mm was defined as the threshold of daily rainfall with geomorphic significance (representing 40% of annual average rainfall) and was not used when estimating the annual frequency of the three representative storm events.

- **4 to 10 mm: daily rainfall generating <Q_{cr}:** Daily rainfall amounts of 4 to 10 mm were defined as representing <Q_{cr} events, which represents 30% of average annual rainfall (Figure 4). Using the hydrology model, 4 to 10 mm of rainfall (1-hour AES) generated peak flows of 1 to 5 m^3/s at the outlet of German Mills Creek. This flow range is encompassing the representative discharge of 3.5 m^3/s for <Q_{cr} events. Therefore, **the rainfall from the 1-hour AES storm event was estimated to generate 30% of average annual rainfall, representing <Q_{cr} events**.

- **10 to 20 mm: daily rainfall generating Q_{cr}:** Daily rainfall amounts of 10 to 20 mm were defined as representing Q_{cr} events, which represents 20% of annual rainfall (Figure 4). Using the hydrology model, 10 to 20 mm rainfall (6-hour AES) generated peak flows of 4 to 12 m^3/s. This flow range is similar to the geomorphologically defined Q_{cr} range of 3 to 11 m^3/s, and therefore, **the rainfall from the 6-hour AES storm event was estimated to generate 20% of average annual rainfall, representing Q_{cr} events.**

- **20 to 40 mm - daily rainfall generating Q_{bf}:** Daily rainfall amounts of 20 to 40 mm were defined as representing Q_{bf} events, which represents 10% of annual rainfall (Figure 4). Using the hydrology model, 20 to 40 mm of rainfall (12-hour AES) generated peak flows of 10 to 23 m^3/s. This flow range provided reasonable representation of the geomorphologically defined Q_{bf} range of 9 to 15 m^3/s and is less than the 2-year 24-hour rainfall total (45 mm). Therefore, **rainfall from the 12-hour AES storm event was estimated to generate 10% of average annual rainfall, representing Q_{bf} events**.

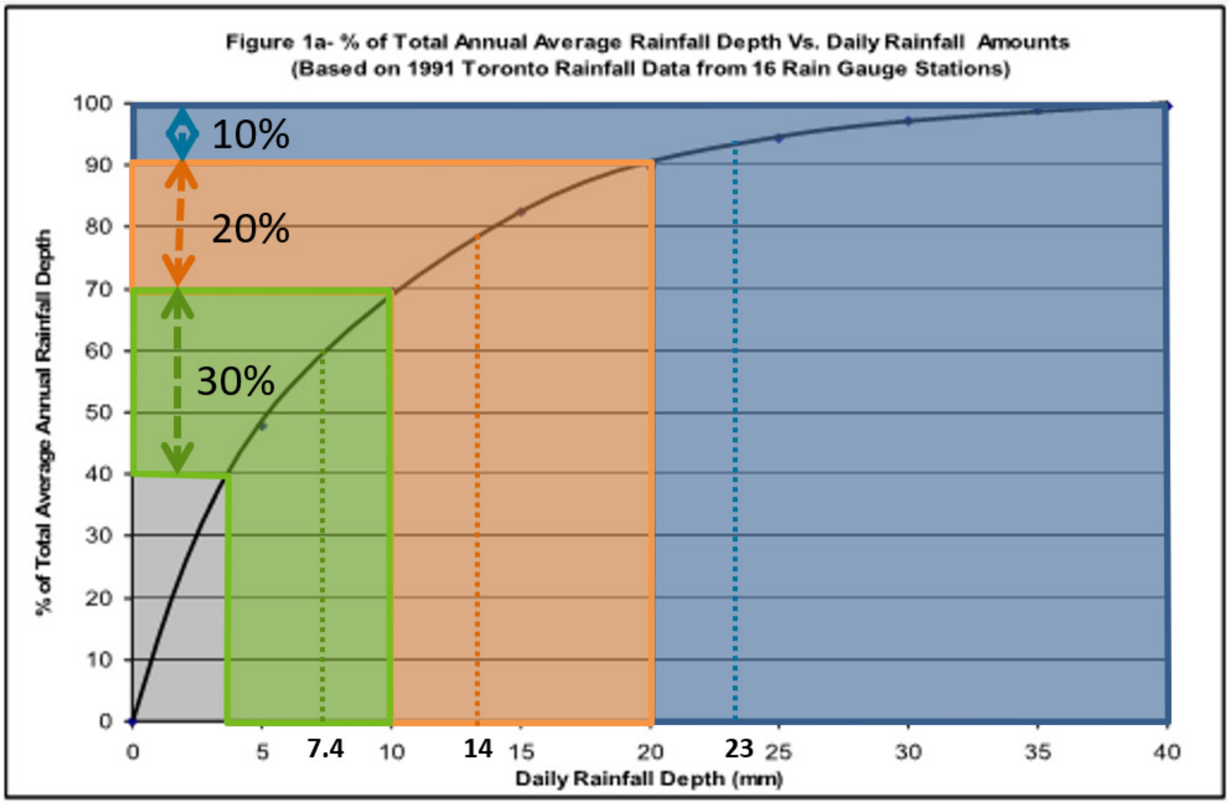


FIGURE 4 **Estimation of Daily Rainfall Groupings into Fractions of Average Annual Rainfall (adapted from Toronto Water 2006, Figure 1a)**

By multiplying the estimated percentages of annual average rainfall noted above (i.e., 10%, 20% and 30%), by the average annual precipitation for existing climate condition (853 mm Section 2.2), the approximate annual total rainfall that generates Q_{bf}, Q_{cr}, and <Q_{cr} events was calculated, for example:

$$Annual\ Total\ Rainfall\ for < Q_{cr} = 853\ mm\ \times 30\% = 256\ mm$$

Then the annual frequency of occurrence for Q_{bf}, Q_{cr}, and <Q_{cr} events can be estimated by dividing by the event volume, for example:

$$Annual\ Frequency\ of\ Occurrence\ for < Q_{cr} = \frac{Annual\ Total\ Rainfall\ for < Q_{cr}}{< Q_{cr}\ Rainfall\ Event\ Volume} = \frac{256\ mm}{7.4\ mm} = 35$$

Table 12 summarizes the calculated annual frequency of occurrence for Q_{bf}, Q_{cr}, and <Q_{cr} events and their associated rainfall depths to comprise a synthetic year of rainfall for the existing climate. Therefore, in the synthetic annual time series, bankfull discharge occurs 3 times/year, critical discharge occurs 13 times/year, and events less than critical discharge occur 35 times/year.

The total annual rainfall for geomorphic-significant events is 510 mm for existing conditions, which is roughly 60% of the total average precipitations of 853 mm, as the 0 to 4 mm events are considered to cause negligible geomorphic work and excluded.

TABLE 12 Synthetic Annual Rainfall Parameters for Existing Climate

Parameter	Bankfull Discharge Q_{bf}	Critical Discharge Q_{cr}	Less than Critical Discharge $<Q_{cr}$
Storm Event Rainfall Volume	23 mm	14 mm	7.4 mm
Annual Frequency of Occurrence	3	13	35
Annual Total Rainfall	69 mm	182 mm	259 mm
Percent of Total Average Annual Rainfall	8%	21%	30%

Notes:
Total average annual rainfall for geomorphic-significant events is 510 mm for existing conditions, which is 60% of 853 mm (Figure 4).

3.2.4 Existing Synthetic Flow Duration Curve

To generate the annual synthetic flow series for the existing climate, simulated flow hydrographs for the Q_{bf}, Q_{cr}, and $<Q_{cr}$ single storm events were multiplied by their associated annual frequency of occurrence (i.e., 3, 13, and 35, respectively). This annual synthetic flow series was then plotted as a flow exceedance graph (Figure 5). Using this curve, we can identify:

- The median (50% exceedance) flow is 0.35 m^3/s.
- The 10th percentile flow is 1.9 m^3/s.
- The 90th percentile flow is 0.12 m^3/s.

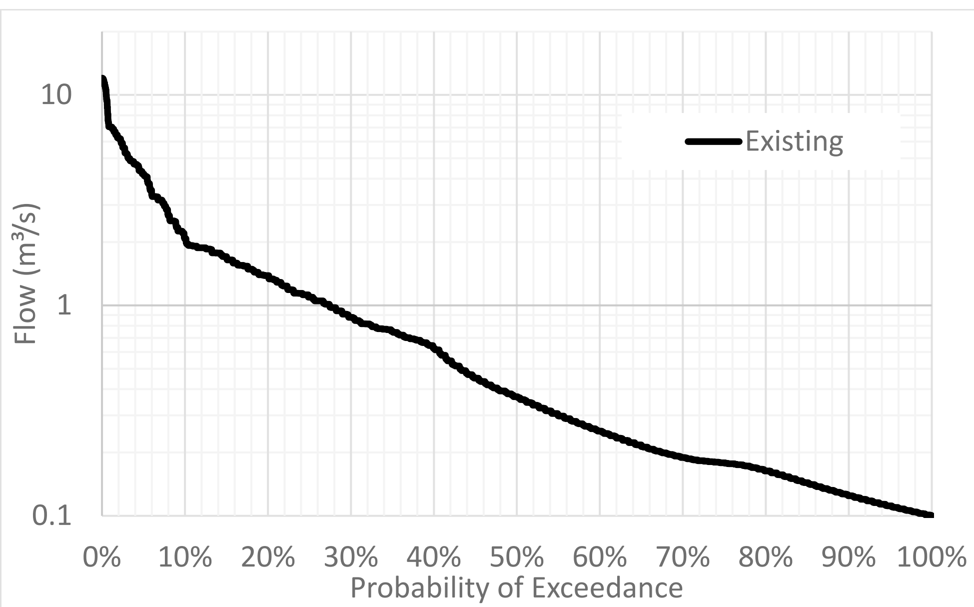


FIGURE 5 Annual Synthetic Flow Exceedance Curve for German Mills Creek under Existing Climate

3.2.5 Future Climate Adjusted Synthetic Year

To evaluate different possibilities of future climate conditions and their impacts on geomorphology, Matrix developed four different future climate scenarios and simulated the synthetic annual rainfall series using the hydrologic and hydraulic models to assess changes in geomorphic parameters.

Matrix made the following variations to the Q_{bf}, Q_{cr}, and $<Q_{cr}$ events total volume and maximum intensity based on the current understanding of potential climate change impacts:

- make each storm type bigger
- make each storm type more intense
- make each storm type bigger and more intense
- make each storm type much bigger and more intense

The storm variations for Q_{bf}, Q_{cr}, and $<Q_{cr}$ events were used to generate four permutations of the synthetic year of rainfall under climate-adjusted scenarios by assigning different rainfall volumes, maximum intensities, and annual frequency of occurrence. Table 13 provides a high-level summary of the four climate-adjusted scenarios. Table 14 presents the details of rainfall volume and frequency adjustments made to produce the climate-adjusted scenarios. Adjustments to rainfall intensity were made by altering the storm distributions for the 12-hour AES (Figure 6), 6-hour AES (Figure 7), and 1-hour AES (Figure 7) storm events. For scenarios 2 and 4, the more intense storm distributions include a shift in rainfall to generate a peakier, more intense storm pattern. For Scenario 3, the peak intensity was held for an extra time step of the storm. While these storm adjustments are completely theoretical, they represent potential changes to existing rainfall patterns that may be expected with a changing climate.

These rainfall adjustments were made to the future average annual total precipitation of 917 mm (Section 2.2, Table 2). Matrix considered the additional 64 mm precipitation as rain events greater than 4 mm and therefore each climate-adjusted scenario has an annual total rainfall roughly 64 mm higher than the existing climate. There are slight differences of a few millimetres between scenarios which is a limitation of the adjustments; however, the difference is insignificant in terms of the geomorphic impact assessment.

TABLE 13 Summary of Variations to Synthetic Year of Rainfall for Climate-Adjusted Scenarios

Climate-Adjusted Scenario	Rainfall Event Volume	Maximum Intensity	Annual Frequency of Occurrence
Scenario 1 Same number of bigger storms	Increase	Same	Same
Scenario 2 More storms of the same size	Same	Increase	Increase
Scenario 3 Same number of bigger, more intense storms	Increase	Increase	Same
Scenario 4 Fewer much bigger and much more intense storms	Large Increase	Large Increase	Decrease

TABLE 14 Synthetic Annual Rainfall Parameters for Climate-adjusted Scenarios

	Event Rainfall Volume					Annual Frequency of Occurrence				
	Existing Climate	Scenario 1 Same number of bigger storms	Scenario 2 More storms of the same size	Scenario 3 Same number of bigger, more intense storms	Scenario 4 Fewer much bigger and much more intense storms	Existing Climate	Scenario 1 Same number of bigger storms	Scenario 2 More storms of the same size	Scenario 3 Same number of bigger, more intense storms	Scenario 4 Fewer much bigger and much more intense storms
Q_{bf}	23 mm	26 mm (+13%)	23 mm	26 mm (+13%)	38 mm (+65%)	3	3	4	3	2
Q_{cr}	14 mm	16 mm (+14%)	14 mm	16 mm (+14%)	19 mm (+36%)	13	13	14	13	11
$<Q_{cr}$	7.4 mm	8.3 mm (+12%)	7.4 mm	8.3 mm (+12%)	9.5 mm (+15%)	35	35	39	35	31
Total	**510 mm**	**574 mm**	**577 mm**	**574 mm**	**575 mm**	**51**	**51**	**57**	**51**	**44**

Notes:
Q_{bf} - bankfull discharge
Q_{cr} - critical discharge
$<Q_{cr}$ - less than critical discharge
Total - total annual synthetic rainfall excludes the 0-4mm daily rainfall events - see Figure 4.

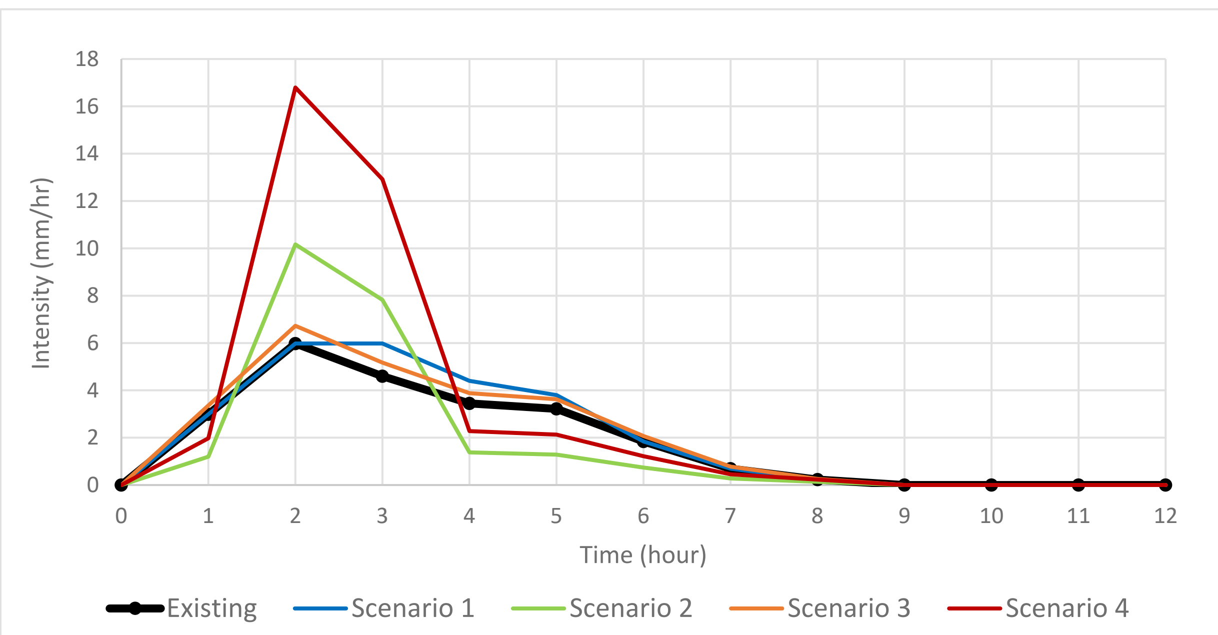


FIGURE 6 12-hour Atmospheric Environment Service Distributions for Existing and Climate-adjusted Scenarios

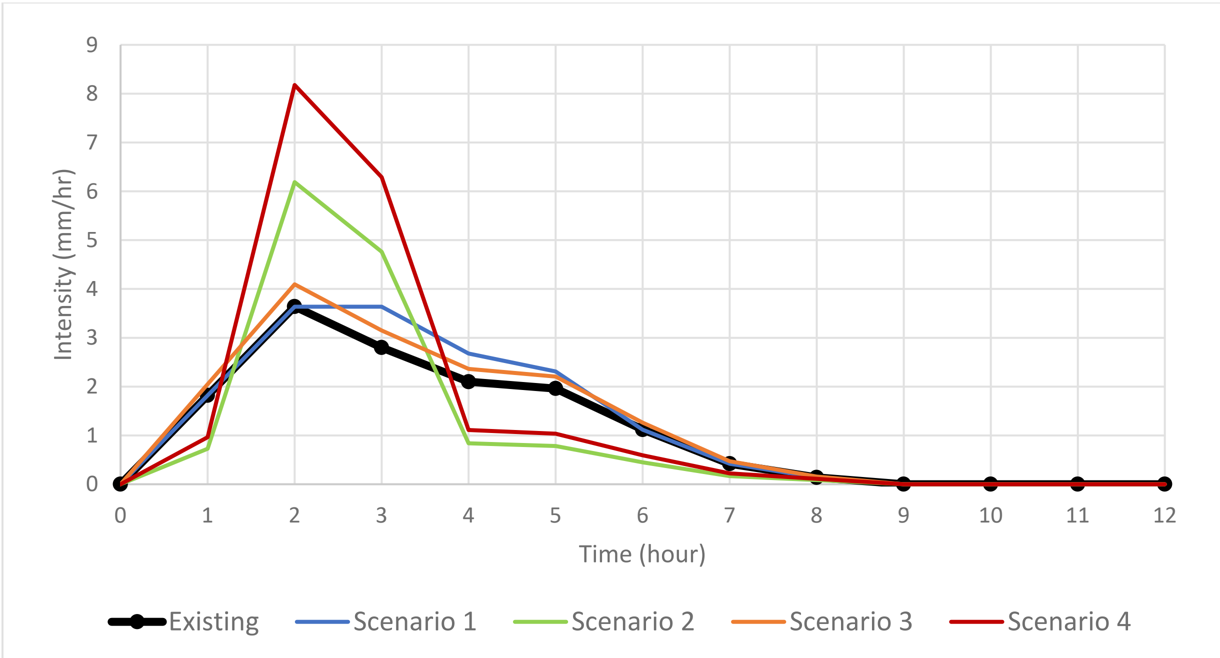


FIGURE 7 6-hour Atmospheric Environment Service Distributions for Existing and Climate-adjusted Scenarios

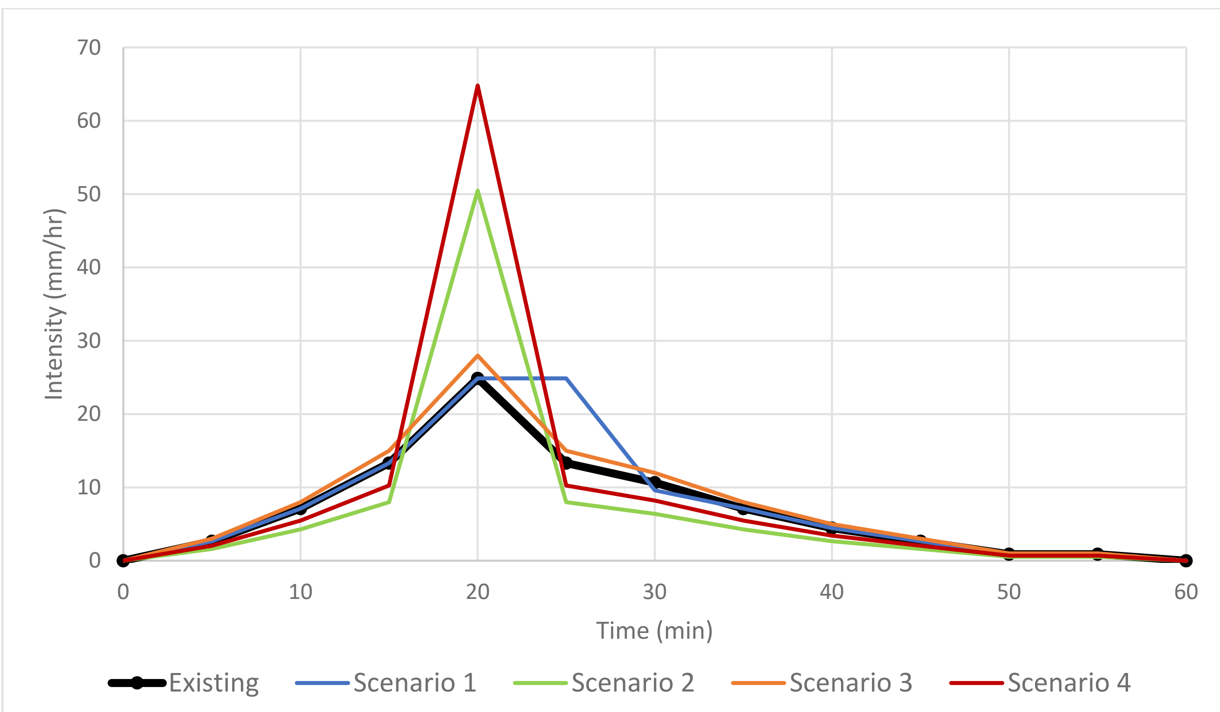


FIGURE 8 1-hour Atmospheric Environment Service Distributions for Existing and Climate-adjusted Scenarios

3.2.6 Climate-adjusted Synthetic Flow Duration Curves

To generate the annual synthetic flow series for each climate-adjusted scenario, the simulated flow hydrographs for the Q_{bf}, $Q_{cr,}$ and $<Q_{cr}$ single storm events were multiplied by their associated annual frequency of occurrence for each climate variation (scenarios 1 to 4). Each annual synthetic flow series was plotted as a flow exceedance curve (Figure 9). Using these curves, we can identify:

- Around the 30th percentile, flow estimates diverge between existing and climate-adjusted scenarios, where lower flows are not sensitive to the adjusted climate inputs for lower flows and higher flows are more sensitive to the climate adjustments and generate a range in flow estimates.
- The 10th percentile flow estimates range from 1.9 to 3.3 m^3/s under the four climate-adjusted scenarios.
- The greatest change from existing flow exceedance estimates was under Scenario 4–fewer, much bigger, and much more intense storms.
- There were minimal changes from existing flow exceedance estimates under Scenario 2–more storms of the same size.
- Both Scenario 1(same number of bigger storms) and Scenario 3 (same number of bigger, more intense storms), produced similar flow exceedance estimates, with curves in between scenarios 2 and 4.

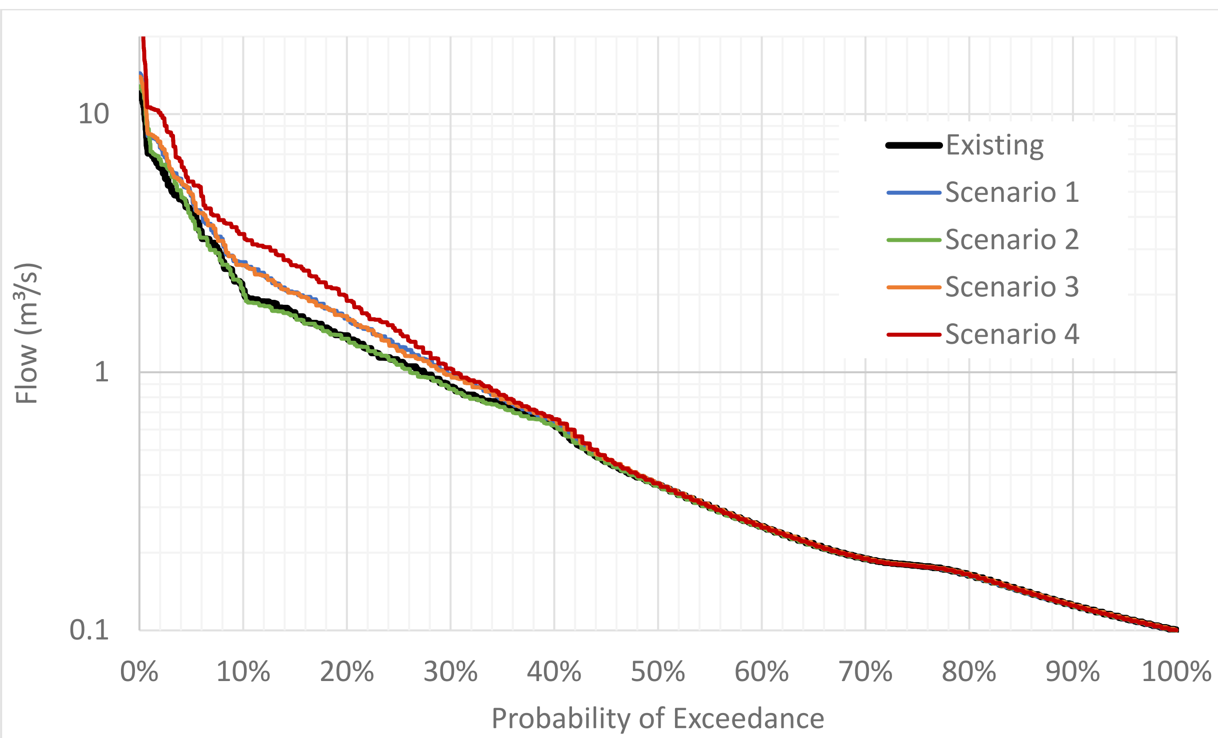


FIGURE 9 Annual Synthetic Flow Exceedance Curve for German Mills Creek under Adjusted Climates

3.2.7 Hydraulic Parameters

To quantify potential changes to key hydrogeomorphic indicators, rating curves for channel velocity, shear stress, and stream power (Figures 10 to 12) were generated at Reach 1 (Cross-section ID 442.77) in the 1D hydraulic model (HEC-RAS) that was developed by Matrix (Matrix 2022, 2021). These rating curves were used to assess geomorphic impacts (Section 4).

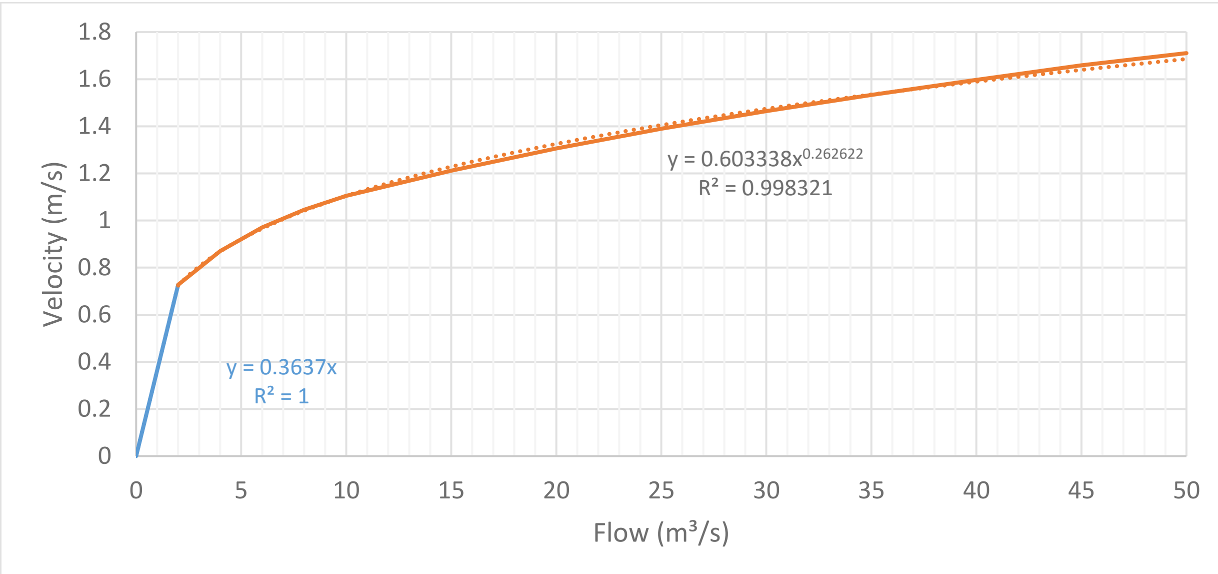


FIGURE 10 Rating Curve for Flow Velocity using One-dimensional HEC-RAS Model at Reach 1

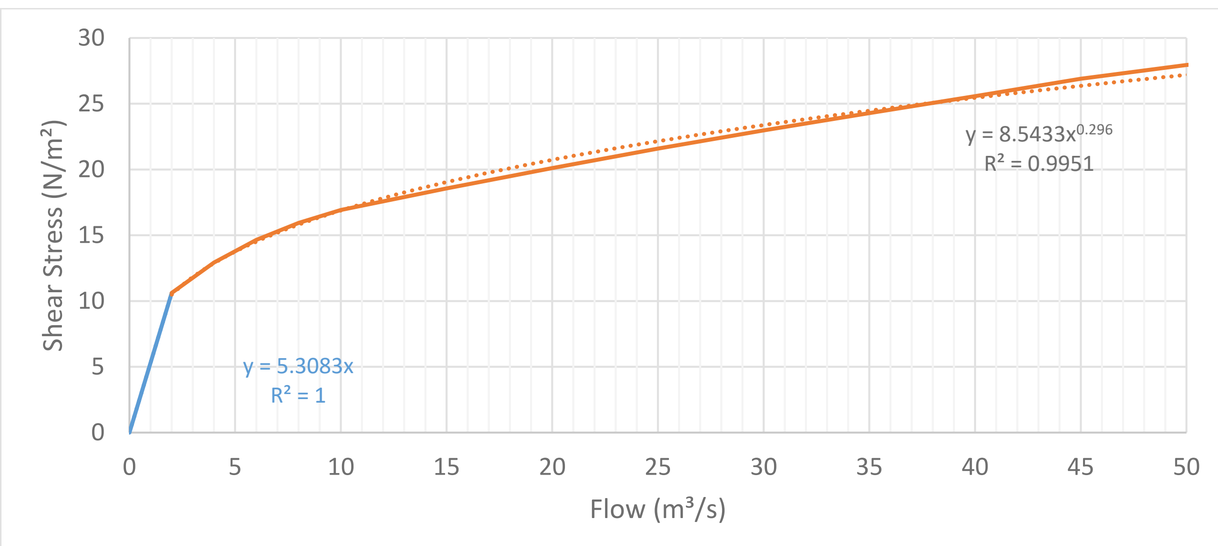


FIGURE 11 Rating Curve for Shear Stress using One-dimensional HEC-RAS Model at Reach 1

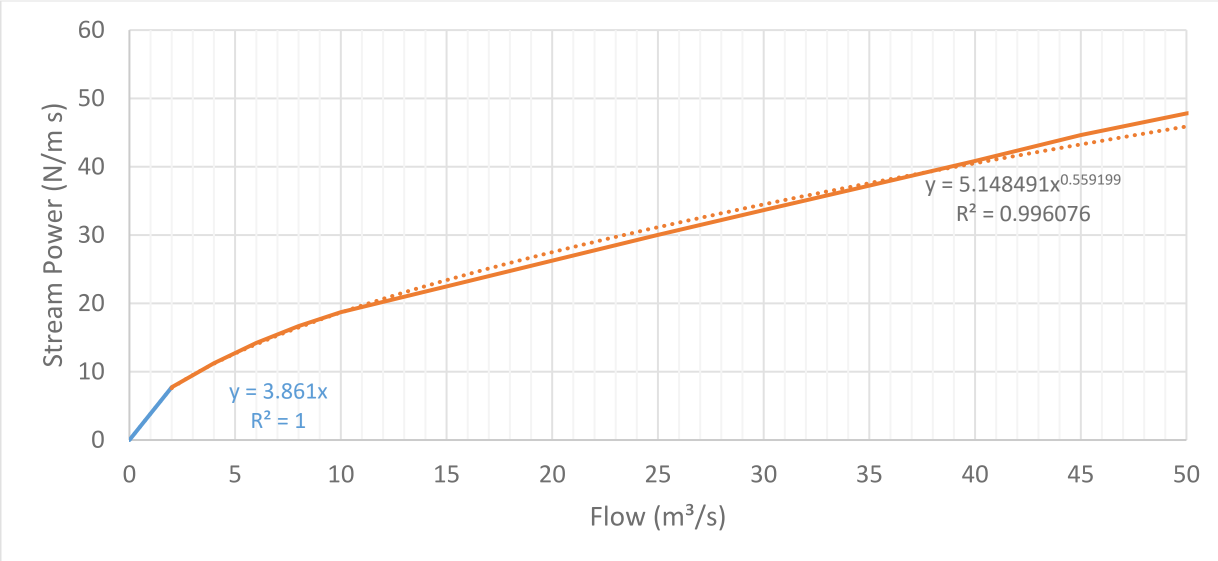


FIGURE 12 Rating Curve for Stream Power using One-dimensional HEC-RAS Model at Reach 1

3.3 Historic Development Impacts

Matrix evaluated the historical development impacts by modifying the PCSWMM hydrology model to simulate hydrologic output with an estimated range of “pre-development” rural land use conditions. This scenario provides background context and comparison between the hydrologic impacts associated with development-related land use changes and the projected hydrologic impacts associated with future climate projections. Note that existing climate is used for pre-development land use period (as opposed to using a “pre-development climate”), which allows the hydrological changes due to land use change can be assessed in isolation.

To represent the pre-development land use scenario in the hydrology model, Matrix updated the following subcatchment parameters in the PCSWMM model to reflect pre-development land use conditions.

- Manning’s n value for pervious area (N Perv) = 0.13 (average of Manning’s n for overland flow for cultivated land cover)
- depth of depression storage on pervious area (DStore Perv) = 7 mm (standard depression storage for cultivated land use per EWRG [2017])
- percent impervious (Imp. %) ranging from 5% to 30%, with 5% increments
- all other parameters stayed the same as the existing model

3.3.1 Peak Flood Historic Impacts

Figure 13 shows the relative percent differences in design storm peak flow results at German Mills outlet compared to existing conditions for a range of future climate change and historic rural land use conditions (5% to 30% impervious). The relative percent differences for each peak discharge value were calculated as:

$$Percent\ Difference = \frac{Q_{i\ Scenario} - Q_{i\ Existing}}{Q_{i\ Existing}} \times 100$$

Where $Q_{i\ Scenario}$ is the discharge at return interval i for each future and historic scenario and $Q_{i\ Existing}$ is the existing condition discharge at return interval i. These values allow for standardized comparison of historic land use conditions with the existing climate and land use condition (47% impervious), and the future climate scenarios presented in Figure 3 (Section 3.1).

For the development-related land use changes, peak flows change linearly with incremental changes according to the impervious percent (i.e., curves in Figure 13 are flat and equally spaced). Based on this analysis, the effect of land use on the hydrological response in the watershed compared to the potential predicted response from the future climate scenarios depends on the return period of the flood discharge. As presented in Figure 13, the relatively small percent increases in smaller return period floods (e.g., Q_5 increases of 9 to 17%) are equivalent to relatively small decreases in imperviousness (e.g., from about 47% to 40% imperviousness, not shown on figure). By comparison, the larger percent increases of 50% at the 50-year flood discharge modelled for the SSP5-8.5 (maximum) future climate scenario are roughly equivalent to the effect of land use change going from 47% to 25% imperviousness (i.e., equivalent decreases in flood discharges). This trend continues for the approximately 100% increase at the 100-year flood discharge for the SSP5-8.5 (maximum) future climate scenario compared to existing, that is roughly equivalent to the effect of land use change going from 47% to less than 5% imperviousness (i.e., equivalent decreases in flood discharges).

The historical impact analysis suggests that for peak flood discharges on German Mills Creek, the effect of climate change on the 100-year flood hydrological response is approximately equivalent to the effect of land use change going from pre-urban (Imp. 5%) to the existing condition (Imp. 47%). However, the hydrological response of lower return period events due to predicted climate change effects are substantively less than the effect of land use change. In other words, pre-urban to urban land use change would have much larger effect on the hydrological response of the watershed for the more frequent flood events compared to climate change effects.

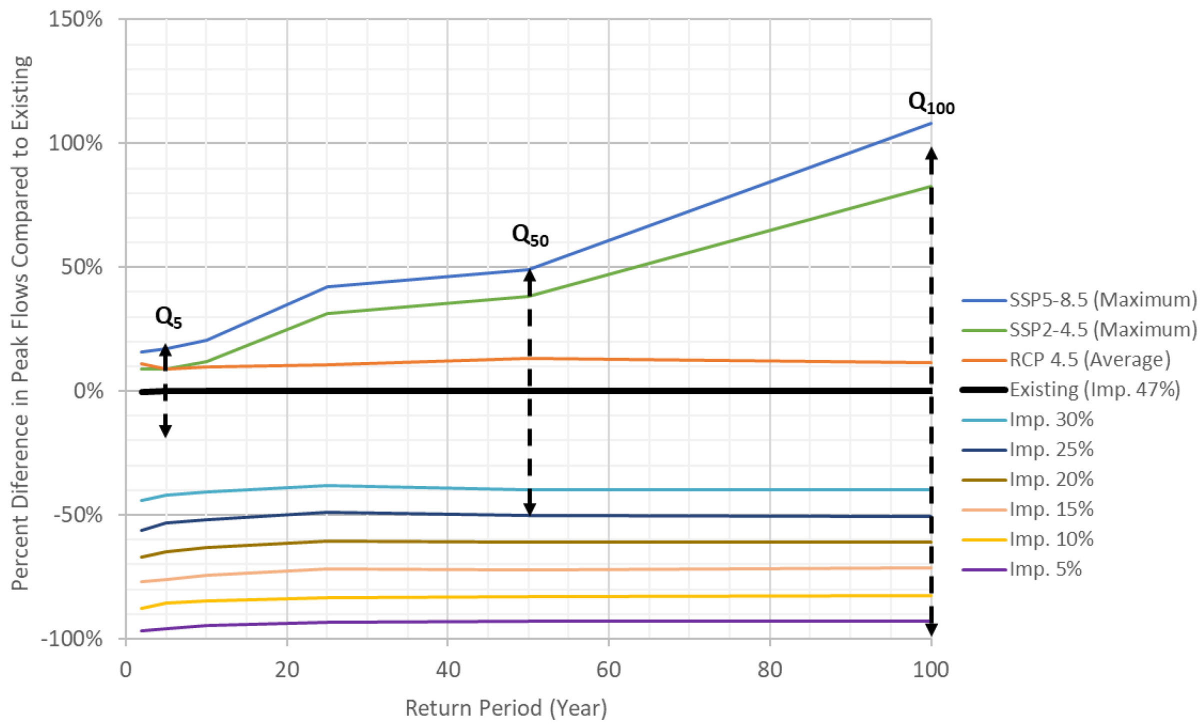


FIGURE 13 Percent Difference in Peak Flows by Return Period for Climate-Adjusted and Historical Land Use Scenarios Compared to Existing

3.3.2 Flow Duration Historic Impacts

The upper and lower range in simulated impervious pre-development land use conditions (5% and 30% impervious scenarios) were used to develop the annual synthetic flow duration curves (FDCs) using the method outlined in Section 3.2. To generate the annual synthetic flow series for the historical development scenarios, simulated flow hydrographs for the Q_{bf}, Q_{cr}, and $<Q_{cr}$ single storm events were multiplied by the annual frequency of occurrence as under the existing conditions scenario (i.e., 3, 13, and 35, respectively). This annual synthetic flow series was then plotted as a flow exceedance graph (Figure 14). This maintains imperviousness as the only changing parameter against the existing scenario. Results indicate that 5% impervious curve is substantial lower than all other curves. As a first-order approximation, this analysis indicates that annual flow exceedance curve is significantly sensitive to development-related land use changes, and degree of sensitivity is greater than future climate impacts.

With the exception of the 5% impervious curve, all other curves show little deviation between probability of exceedances in the range of 50% to 100% (the very righthand side of Figure 14). Between 50% and 1% probability of exceedance the 30% impervious curve and the future scenarios diverge from the existing conditions curve. For example, at 1% probability of exceedance the historical 30% impervious curve and the future scenario 4 curve are about 50% lower and higher than the existing conditions curve (i.e., 10.6 and 3.4, compared to 7.1 m^3/s, respectively). The other three future scenarios (1 to 3) fluctuate within the band between existing conditions and future scenario 4. This pattern of divergence into lower probability of exceedance below 0.7% becomes more pronounced for future scenario 4, where at 0.1% probability of exceedance the future scenario 4 discharge is twice the existing condition discharge, and the historical 30% impervious curve is about half (i.e., 24.7, 12.0, and 6.4 m^3/s, respectively).

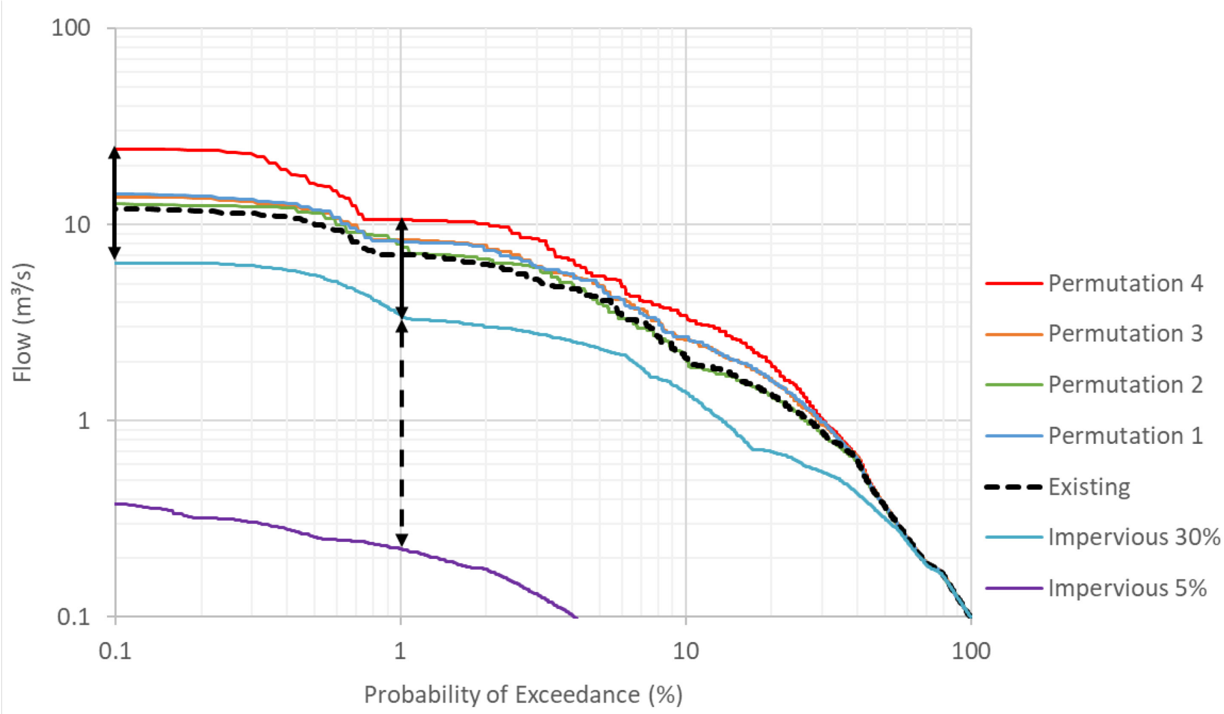


FIGURE 14 Annual Synthetic Flow Exceedance Curve for German Mills Creek under Adjusted Climates and Historical Development Scenarios

The historical impact analysis suggests that for the FDCs on German Mills Creek, the effect of climate change on the hydrological response is most pronounced for Scenario 4 (fewer much bigger and much more intense storms) for the rarer flows below about 0.5% probability of exceedance. This effect is likely similar to an intermediate land use condition between 5% and 30% imperviousness, but is less than the effect complete land use change from pre-urban (5% impervious) to urban (47% impervious). The other three future hydrological scenarios (1 to 3) plot on slightly higher than the existing conditions FDC, and thus based on this analysis are not considered to have as much of an effect on the hydrological response compared to land use change. In all cases, the differences between future, existing, and historic hydrological responses becomes the lower, more frequent, flows, with the exception of the pre-urban (5% impervious) FDC (reference limitations?). Overall, a future climate that emphasizes fewer, but larger and more intense storms, may rival historic land use change impacts for the range of lower flows represented in the flow duration analysis, but generally land use impacts are much greater.

3.3.3 Sensitivity Analysis Without SWM Ponds

A sensitive analysis was completed without SWM ponds and the results were not considered sensitive to the pond storage with respect to significantly changing the climate change assessment results and interpretation. The results of this sensitivity analysis are presented in Appendix C.

4 GEOMORPHIC IMPACT ANALYSIS

Building on the hydrologic and hydraulic modelling analyses developed in Section 3, the geomorphic impacts on German Mills Creek from future climate changes are evaluated further based on percent changes in peak flood frequency (from Section 3.1) and by the percentage changes in hydrogeomorphic indictors derived from the flow duration analysis (from Section 3.2). The corresponding sections for geomorphic impacts associated with the peak flood and flow duration analyses are presented in Sections 4.1 and 4.2, respectively.

4.1 Peak Flood Analysis

With reference to climate change assessment approach in Figure 1, the peak flood analysis is intended to assess the impact of changes due to climate change on erosion thresholds, especially as they might affect erosion control methods.

Geomorphically significant, channel forming flows are introduced above in Section 3.2.2 and Table 10 as representative for the German Mills Creek study area, including bankfull discharge, critical discharge, and sub-critical discharge. As detailed in the GSMP Phase 2 report (Matrix 2022), erosion threshold estimates for effective sediment transport (i.e., critical discharge) within German Mills Creek were developed from the existing geomorphic conditions assessment using surveyed cross-sectional, long profile, and channel substrate data and representative minimum, average and maximum critical discharge values. Grain sizes varied throughout German Mills Creek, but were generally within the gravel to small cobble range, therefore the Komar (1987) approach for critical velocity was applied in this case as it is suitable for gravel bed streams. Based on the range in median grain size (30 to 80 mm), critical discharge values ranged from 3 to 11 m^3/s, with the average selected value being 7 m^3/s. The field estimated bankfull discharge of the study area ranged from 9 to 15 m^3/s, with an average of 12 m^3/s used for they hydrology studies. Compared with the peak flood discharges reported in Section 3.1, Table 3, the critical and bankfull discharges are substantively lower than the 2-year (Q_2) discharge reported at 21 m^3/s. Therefore, it has been assumed that all peak floods are more than competent to mobilize the median grain sizes of the bed material in German Mills Creek.

The above analyses suggest that critical discharge is exceeded frequently and multiple times annually, so peak flood analysis is less relevant to the issue of general sediment entrainment and transport, or geomorphic work, but is still applicable to evaluate erosion control methods. The changes in annual probability and frequency (i.e., return period) for select flood discharges are presented in Table 15 as compared to a range of substrate mobilization classifications. From the climate change scenarios described in Sections 2 and 3.1, the annual probabilities of each design flood increase from the existing condition to the possible average and maximum predicted climate conditions (i.e., return periods decrease for a given flood discharge). As selected examples, the annual probability of the 2-year flood increases from 50% to 72% (i.e., 21 m^3/s becomes the 1.4-flood) and the 100-year flood increases from 1% to 4% (i.e., 69 m^3/s becomes the 25-year flood) under the maximum climate change scenario.

Despite the predicted increases in annual probabilities of floods due to climate change, the associated velocities for the flood series of Q_2 to Q_{100} are still within the range of the erosion thresholds for coarse gravel to cobble (64 to 128 mm) as presented in Table 15 (permissible velocities from Komar (1987) and velocity rating curve in Figure 10). For river engineering and natural channel design purposes, these substrate mobility classifications are appropriate (e.g., roughly in the 6 to 12-inch stone size range) and larger sizes of cobbles, boulders, riprap, and armourstone (e.g., 12 to 24-inch stone and greater) may be specified for specific erosion control designs. However, the hydraulic design criteria and approaches for integration of erosion control structures within the channel will need to be confirmed at detailed design given that the representative cross-section used in this assessment does not consider the variability in local and reach-scale slopes, or the variability in cross-section form and boundary conditions between project sites.

TABLE 15 Changes in Annual Probability and Frequency of Floods

Flood Discharge	Substrate Mobilization Classification (1)	Statistic	Existing Conditions	Future RCP 4.5 (Average)	Future SSP5-8.5 (Maximum)
Q_2 20.7 m^3/s	Coarse Gravel 64 mm	Probability (%)	50%	61%	72%
		Return Period (yr)	2-year	1.6-year	1.4-year
Q_5 30.4 m^3/s	Small Cobble 80 mm	Probability (%)	20%	24%	29%
		Return Period (yr)	5-year	4.25-year	3.5-year
Q_{10} 37.9 m^3/s	Medium Cobble 90 mm	Probability (%)	10%	13%	17%
		Return Period (yr)	10-year	8-year	6-year
Q_{25} 47.1 m^3/s	Medium Cobble 100 mm	Probability (%)	4%	6%	9%
		Return Period (yr)	25-year	18-year	11-year
Q_{50} 57.8 m^3/s	Medium Cobble 115 mm	Probability (%)	2%	3%	5%
		Return Period (yr)	50-year	36-year	19-year
Q_{100} 68.9 m^3/s	Coarse Cobble 128 mm	Probability (%)	1%	2%	4%
		Return Period (yr)	100-year	60-year	25-year

Notes:
(1) Based on Komar (1987) critical velocity methods and rating curve for typical cross-section in Figure 10.
RCP - Representative Concentration Pathway
SSP - Shared Socioeconomic Pathway

Notwithstanding the general condition that round stone materials in the cobble size range are predicted to be stable under most flood conditions, these sizes are larger than the dominant gravel materials within the existing channel, and overall stability would require a coarsening of channel at the reach scale, and possibly within the entire study area, which is not practical. Further, the predicted increases in the frequency of flood events are expected to more quickly degrade erosion control structures that are supported by the surrounding boundary materials, bioengineering, and channel morphology. For example, the potential for the 25-year flood to occur in the future on average every 11 years is likely to have destabilizing effects in channel that could put erosion control structures at greater risk and/or will require more frequent maintenance to ensure ongoing protection. This highlights the issue of balancing requirements for static erosion controls structures (i.e., “hard” engineering) with the recognition that long-term sustainable solutions may be better achieved through integration with “softer” and flexible fluvial systems that allow geomorphic processes to continue within the corridor. This issue will be discussed further in Section 5.4 with respect to the development of conceptual site designs.

4.2 Flow Duration Analysis

The flow duration analysis for possible future climate change scenarios as documented in Section 3.2 provides a basis to assess how changes in the range of normal annual flows might affect the amount of geomorphic work in the fluvial system. As the channel forming discharge is lower than the 2-year flood, and typically in the range of the critical and bankfull discharge, climate changes impacts have also been assessed for sub-Q_2 flows that are responsible for sediment transport on an annual basis. As such, geomorphic impacts were further assessed by percentage changes in hydrogeomorphic indices over annualized hydrographs generated from the synthetic years (Section 3.2), including cumulative hours of flow exceedance, cumulative excess shear stress, and cumulative effective work (i.e., excess stream power). These changes helped assess expected flood event impacts to erosion controls in response to climate change using the four future rainfall scenarios outlined in Section 3.2.5:

- **Scenario 1:** same number of bigger storms
- **Scenario 2:** more storms of the same size
- **Scenario 3:** same number of bigger, more intense storms
- **Scenario 4:** fewer much bigger and much more intense storms

4.2.1 Exceedance Analysis Methods

The synthetic year approach outlined in Section 3.2 is important because hydrogeomorphic indicators are conventionally assessed on an annual basis and are to be subsequently translated into annual erosion rate impacts (Section 5.2.1). The hydrogeomorphic indicators were evaluated for existing and future scenarios to determine the factor change increase between existing conditions rainfall and the four future rainfall scenarios in response to climate change. Hydrogeomorphic indicators were selected using the methods outlined in the TRCA *Stormwater Management Criteria* (2012). The *Stormwater Management Criteria* outlines erosion analysis through the use of three indices: time of exceedance, cumulative erosion index, and cumulative effective work index (i.e., excess stream power).

The time of exceedance defines the cumulative time that flow exceeds the average erosion threshold in German Mills Creek (i.e., critical discharge, Q_{cr} = 7 m^3/s) based on modelling flow in 15-minute time steps derived from the annual synthetic flow series for the existing and future climate change scenarios. To quantify potential changes to key hydrogeomorphic indicators, rating curves for channel velocity, shear stress, and stream power (Figures 10 to 12) were generated in the 1D hydraulic model (HEC-RAS) that was developed by Matrix (2022, 2021). These rating curves were used to assess the following geomorphic indices.

4.2.1.1 Cumulative Erosion Index

The erosion index is calculated as follows when flow was modelled to exceed the erosion threshold:

$$E_i = \sum (V_t - V_c)\,\Delta t$$

Where E_i is the erosion index, V_t is velocity in the channel at time t (m/s), V_c is critical velocity where particle entrainment occurs (m/s), and Δt is the time step (hour). The critical velocity is selected off the velocity rating curve developed by Matrix corresponding to the critical discharge being used. Velocities at each time step are then computed using the rating curve equation(s).

4.2.1.2 Cumulative Effective Work Index

The work index is calculated as follows when flow was modelled exceed the erosion threshold:

$$W_i = \sum (\tau - \tau_c) V\,\Delta t$$

Where W_i is the work index, τ is shear stress (N/m^2) in the channel at time t, τ_c is critical shear stress (N/m^2), V is the mean channel velocity at time t (m/s), and Δt is the time step (hour). The critical shear stress is selected off the shear stress rating curve developed by Matrix corresponding to the critical discharge being used. Shear stress at each time step are then computed using the rating curve equation(s). It is important to note that cumulative effective work, as the product of excess shear stress and velocity, is in theory equivalent to cumulative effective stream power (i.e., both can be expressed in units of Watts per m^2, where a Watt is equal to Nm/s).

The above calculations of each hydrogeomorphic parameter provide an indication of the frequency at which the erosion threshold is exceeded in German Mills Creek as well as quantifying overall erosive forces through the erosion and work indices. As such, they represent indices of geomorphic work in the form of sediment transport that will govern the dynamic stability of the channel, its prevailing morphology, and the associated rates of morphological changes (e.g., bank erosion, bed degradation).

4.2.2 Exceedance Analysis Results

Each of the hydrogeomorphic indices were evaluated based on the synthetic FDC data generated as part of the hydrology analysis detailed in Section 3.2. The FDCs are presented again in Figure 15 including the critical discharge line at Q_{cr} = 7 m^3/s. The exceedance analysis results are presented in Table 16 with the changes presented as both the percent changes and the factor increases of the future climate change scenarios compared to existing (e.g., a percent increase of 100% is equal to a factor increase of times 2). Historic scenarios of 5% and 30% imperviousness are included, but the FDCs fall below the critical discharge in Figure 15, so all exceedance values are zero. The factor increase results for each of the hydrogeomorphic indices are also presented in Figure 16.

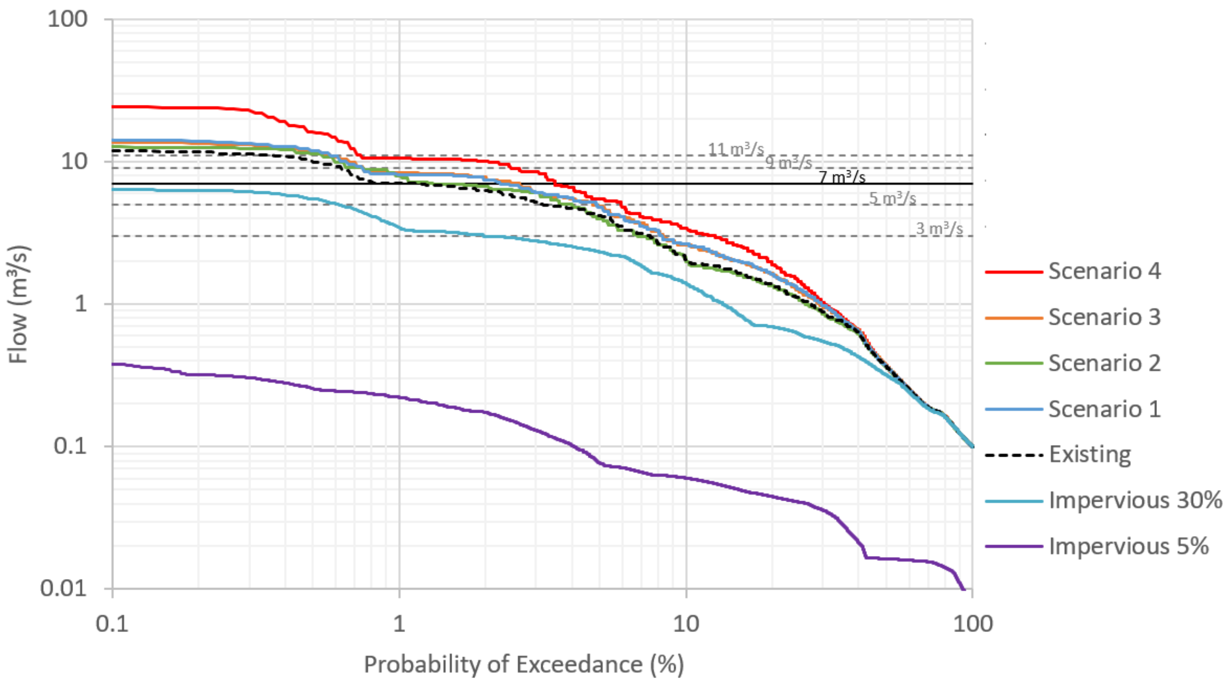


FIGURE 15 Annual Synthetic Flow Exceedance Curve for German Mills Creek under Adjusted Climates and Historical Development Scenarios with Critical Discharge Plotted (Q_{cr} = 7 m^3/s)

TABLE 16 Hydrogeomorphic Exceedance Indices from Flow Duration Curve Climate Change Analysis

Cumulative Index	Parameter	Historic Land use		Existing	Future Climate Change Permutations			
		Imp. 5%	Imp. 30%	Imp. 47%	P1	P2	P3	P4
Flow (Q)	Discharge (m³/s) hours	0	0	20.8	38.5	24.5	45.0	52.5
Erosion (E_i)	Velocity (m/s) hours	0	0	1.41	2.86	2.22	2.94	6.68
Effective Work (W_i)	Shear Stress x Velocity (W/m²) hours	0	0	26.4	53.5	42.0	54.4	136.3
Percent Changes of Cumulative Indices Compared to Existing								
Flow (Q)	Discharge	0	0	0	86%	18%	117%	153%
Erosion (E_i)	Velocity	0	0	0	103%	58%	109%	375%
Effective Work (W_i)	Shear Stress x Velocity	0	0	0	103%	59%	106%	417%
Average		**0**	**0**	**0**	**97%**	**45%**	**111%**	**315%**
Factor Changes of Cumulative Indices Compared to Existing								
Flow (Q)	Discharge	0	0	0	1.9	1.2	2.2	2.5
Erosion (E_i)	Velocity	0	0	0	2.0	1.6	2.1	4.8
Effective Work (W_i)	Shear Stress x Velocity	0	0	0	2.0	1.6	2.1	5.2
Average		**0**	**0**	**0**	**0**	**2.0**	**1.5**	**2.1**

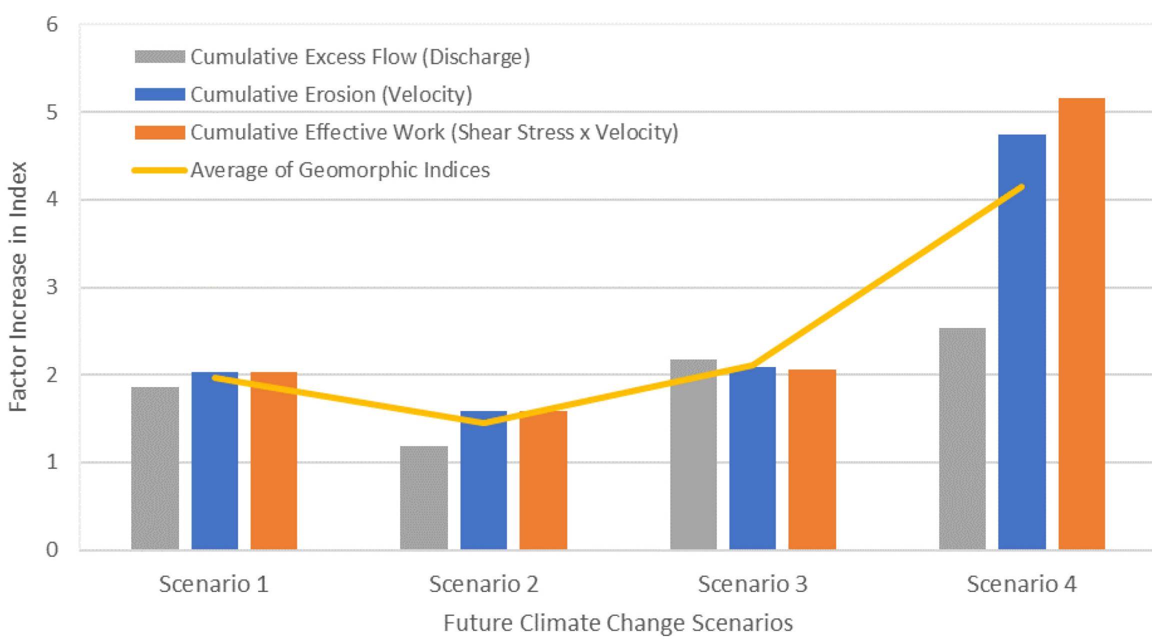


FIGURE 16 Factor Change Increases in Geomorphic Indices Between Existing and Future Scenarios

The exceedance hours in Table 16 are intended to be scaled to annual values, but it is noted that the FDCs are actually synthetic as described in Section 3.2; therefore, the absolute values should be judged with caution. The percent changes between future scenarios and existing conditions are presented as first-order approximation of the relative changes in geomorphic work that might be expected due to climate change. The percent changes in the flow exceedances above the critical discharge threshold are the lowest of the hydrogeomorphic indices, between 86 and 153% for scenarios 1 to 4, respectively, but this index tends to be less correlated with sediment transport as it does not account for the magnitude of the exceedances.

The two key hydrogeomorphic indicators of cumulative erosion and cumulative effective work both show similar patterns in scenarios 1 to 3, with percentage change that can be simplified to about 100% (or a factor increase of ×2; Table 16 and Figure 16). However, scenario 43 predicts a much larger increase in cumulative erosion and effective work of about 400% (or a factor increase of ×5). What this means is that significantly increasing the size and intensity of the normal series of annual storm events-while keeping the total annual rainfall constant for future conditions-has the most significant impact on geomorphic work in terms of erosion and sediment transport (i.e., Scenario 4). While there is some suggestion in the scientific literature that climate change will bring larger and more intense storm events, there is now basis within the current analysis to predict which of the four scenarios modelled is more likely.

Given that there is also some uncertainty embedded in the exceedance analysis with respect to the estimated critical discharge, as the average value within the study area, and its potential variability between reaches, and additional sensitivity analysis was completed as presented in Figure 17. The analysis indicates that between the critical discharge values of 5 to 9 m^3/s the factor increases in Table 16 only vary by about ±25% for scenarios 1 to 3 (i.e., zone of sensitivity), but that above and below these values, and for scenario 4 the sensitivity of the selected critical discharge can vary much more.

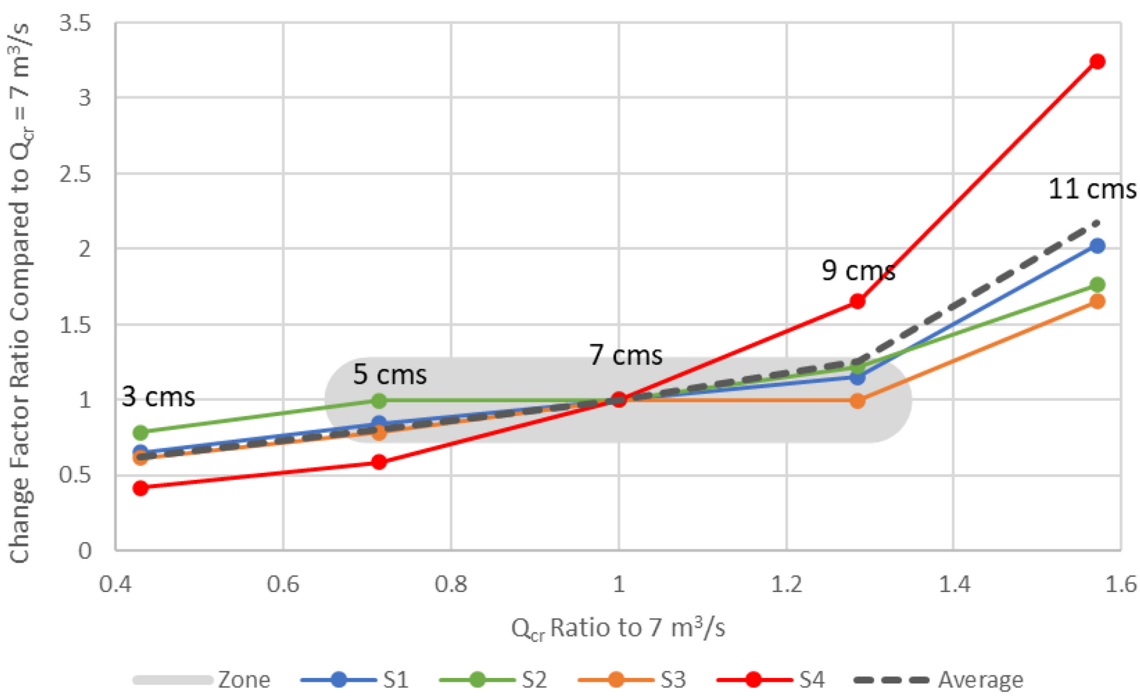


FIGURE 17 Sensitivity Analysis for Geomorphic Indices Over Range of Critical Discharges

5 GEOMPRPHIC SYSTEM MASTER PLAN EVALUATION OF IMPACTS

The results of the projected hydrologic, hydraulic, and geomorphic impacts of climate change as evaluated above are expected to generate future changes in the morphology and fluvial processes of German Mills Creek, and as such are to be considered as part of the GSMP study. The following impacts were identified by the City for consideration and are discussed further in the following sections:

- key hydraulic parameters
- geomorphic and erosion processes (including in terms of changes in select geomorphic indices)
    - rates of vertical and lateral erosion impacts
- estimated times to exposure to Toronto Water infrastructure
    - prioritizing the order of intervention
- implications for design and management of erosion controls in conceptual site designs

5.1 Changes in Key Hydraulic Parameters

Based on the projected changes in future climate in terms of rainfall (annual and IDF; Section 2) and the consequent changes in peak flood frequency (Section 3.1), and flow duration (Section 3.2), commensurate changes in key hydraulic parameters are also expected and have been presented in the above analyses. From the rainfall and peak flow results, the key hydraulic parameters assessed include velocity, shear stress, and stream power. Future changes in the flow duration for sub-Q_2 flows are also expected to result in changes to the cumulative threshold exceedance of velocity and stream power which can increase erosion and sediment transport, potentially transforming geomorphic processes and channel morphology.

As summarized in Figure 18, the percent changes in hydrologic and hydraulic parameters for the peak flood series Q_2 to Q_{100} (left graph) have median value of close to 10% (median = 9%), with half the hydraulic parameter data falling between 5% and 11%. For comparison, the percent change data for the peak flood series Q_2 to Q_{25} (right graph) are also presented below as the more frequent flood events tend to plot lower, with and average value of 9%).

The shaded bands and black bars presented in Figure 18 (left graph) have been added to show a comparison of the range of percent change values calculated from the FDC threshold exceedance analysis (Section 4.2, Table 16). While the FDC results vary from 18% to 417%, the median value is about 100% (actually 105%), and half the data falls between 79% and 126%.

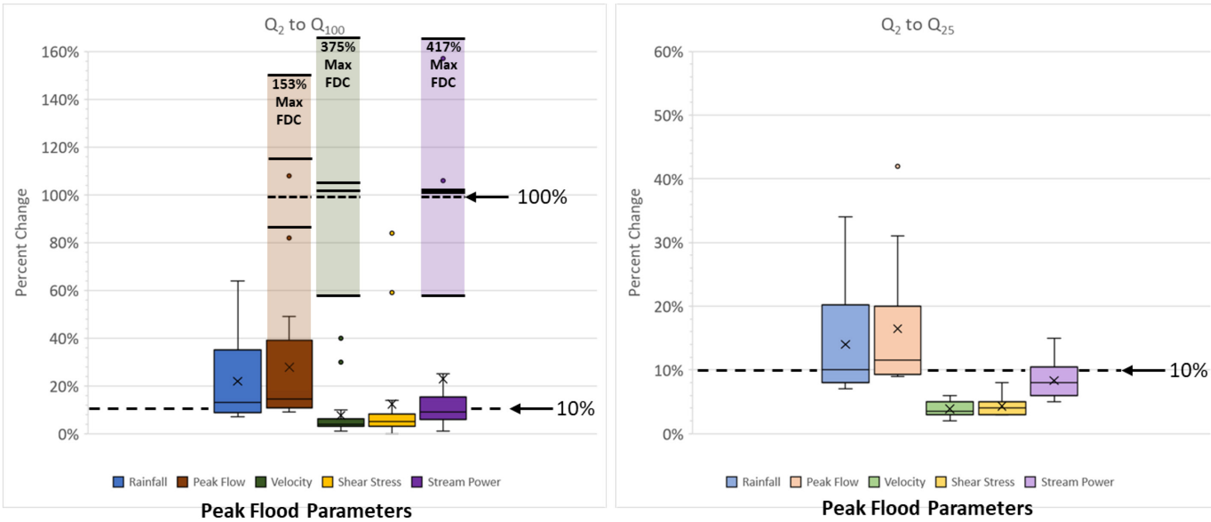


FIGURE 18 Summary Statistics (Boxplots) of Key Hydraulic Parameter Changes

For the purposes of the GSMP study, a simplified approach has been adopted to translate the hydrologic and hydraulic results, in terms of percent changes due to climate change, whereby representative values have been selected. From the results and analysis presented in this study, **the values of 10% of 100%** are considered representative of erosion (hydraulic forces from peak floods) and sediment transport (geomorphic work from sub-Q_2 flow duration), respectively. In other words, a 10% increase on average in the erosional forces that entrain channel bed materials (i.e., velocity, shear stress) and a 100% increase on average in sediment transport work (i.e., momentum transfer) may be expected due to climate change impacts on future rainfall to German Mills Creek.

5.2 Geomorphic and Erosion Processes

The increases in potential erosion and sediment transport due to climate change are expected to increase channel dynamics, alter morphological changes and fluvial processes (e.g., wide to depth ratio, sediment bar development), and further accelerate vertical and lateral erosion rates. While the peak flood (Q_2 to Q_{100}) and FDC (sub-Q_2) analyses are complementary and in theory should be combined into a single, integrated geomorphic response to climate change impacts, the two methods have been kept separate as a simplified approach for the current GSMP study. It is understood that erosion and sediment transport are not mutually exclusive in driving channel dynamics in terms of vertical scour and degradation or lateral channel migration; however, vertical and lateral process can be considered discretely for practical purposes based on the dominant constraints.

For the current study, the dominant constraints of erosion and sediment transport are rationalized to the primary drivers of vertical and lateral channel dynamics, respectively. Based on this theory, the dominant constraint on vertical scour and degradation is the erosional forces required to entrain coarse bed material, and especially the lag of gravel cobble that tends to concentrate in lower layers of floodplain alluvium. While bed erosion also plays a role in bank erosion, the dominant constraint on lateral migration is the capacity of the channel transport entrained sediment through the system over a contingent series of erosional and depositional events (i.e., geomorphic work). It is noted that geomorphic work in terms of sediment export from the system plays a long-term role in degradation processes, it has been assumed for German Mills Creek that resistant gravel and cobble lag will be the dominant control on vertical channel adjustments.

Therefore, the projected increases in erosional forces (peak floods) and sediment transport (sub-Q_2 FDC) due to climate change have been translated into discrete predictions of vertical and lateral changes in geomorphic erosion rates, respectively. With reference to the summary of representative changes in Section 5.1, the recommended value of 10% increases in vertical erosion rates and 100% increases in lateral erosion rates have been advanced to test the potential changes in German Mills Creek due to climate change.

5.2.1 Rates of Vertical and Lateral Erosion Impacts

Historical rates of vertical and lateral erosion were evaluated in the GSMP Phase 2 report (Matrix 2022). Specifically, the vertical rates were measured using historic channel elevations taken from historic 1969 as-builts of the sanitary sewer from 1969 compared to 2021 field surveys, with an average historical bed degradation rate of 0.016 m/year presented. It has been noted that the measured historical degradation rates are likely conservatively high for long-term predictions, given that they represent a response to land use hydromodification. The lateral erosion rates were measured based on analysis of a series of historical aerial photographs from 1954 to 2018, with an average historical bank erosion rate of 0.3 m/year presented. To assess lateral risk a range of lateral erosion rates were used for straight channels (0.2 m/year), typical channel bends (0.3 m/year), and actively migrating bends (0.6 m/year). A summary of the erosion rate results and recommendations for climate change assessment of impacts is presented in Table 17.

TABLE 17 Summary of Measured Historical and Tested Future Erosion Rates for German Mills Creek

Erosion Type	Historical Rates (m/year)	Historical Rate Notes	Tested Climate Change Increase		Tested Future Rates (m/year)
			%	Factor	
Vertical	0.016	Calculated from 1969 to 2018 bed elevation differences (1)	10	×1.1	0.0176
Lateral (Avg)	0.3	Calculated from bank erosion measurements from 1954 to 2018 aerial photographs	100	×2	0.6
Lateral (Range)	(0.2-0.6)		100	X2	(0.4-1.2)

Notes:
(1) Historical degradation from channel expansion in response to land use hydromodification, as such considered to be conservatively high estimate of long-term degradation.

5.3 Estimates of Times to Exposure with Toronto Water Infrastructure

As presented in Table 18, the adjusted future rates of vertical and lateral erosion due to potential climate change impacts were tested on the estimated times to exposure (TTE) of Toronto Water infrastructure as calculated in the risk assessment presented in the GSMP Phase 2 report (Matrix 2022). Given the existing exposure, or near exposure, of Toronto Water infrastructure for the top 6 priority project sites, the revised TTE does not change the high priority of these sites to be urgently repaired. For comparison, projects 7 through 12 have reduced TTE, with projects 7 and 8 in the 20-to-25-year range and projects 9 to 12 in the 50-to-75-year range. The effect of these changes to the TTE on the risk assessment and prioritization of projects is presented in Section 5.3.1.

TABLE 18 Revised Time to Exposure for Top 12 Priority Sites from Geomorphic System Master Plan Risk Assessment

Project No.	Priority Risk Site ID	Reach	Distance to Structure (m)	Erosion Credit (years)	Initial Erosion/ Scour Rate (m/year)	Initial TTE for Priority Site (years)	Revised Erosion/ Scour Rate (m/year)	Revised TTE for Priority Site (years)
1	16.1	GM-3	0	0	0.5	0	1	0
2	18.1	GM-3	0	0	0.5	0	1	0
3	21.1	GM-3	0	0	0.5	0	1	0
4	5.2	GM-1	1	0	0.6	2	1.2	1
5	7.1	GM-2	1	0	0.6	2	1.2	1
6	11.1	GM-2	1	0	0.3	3	0.6	2
7	8.2	GM-2	0.37 (1)	0	0.016	23	0.0176	21
8	1.1	GM-1	5	10	0.2	35	0.4	23
9	3.1	GM-1	1.22 (1)	0	0.016	76	0.0176	69
10	24.2	GM-4	10	30	0.2	80	0.4	55
11	26.1	GM-4	4	60	0.2	80	0.4	70
12	28.1	GM-BV-1	20	0	0.2	100	0.4	75

Notes:
(1) Depth of cover from existing channel grade
TTE - time to exposure

5.3.1 Prioritizing the Order of Intervention

Risk assessments are typically structured based on an evaluation of the probability of an occurrence and its severity. The German Mills GSMP risk assessment score is the product of the risk probability (TTE classifications = 1 to 5) and the risk severity (asset ranking 1 to 5, with Toronto Water sewers and watermains scoring 5) with final values ranging from 1 to 25. The revised TTE, risk assessment scores, and risk site rankings due to tested climate change impacts are presented in Table 19. Following the risk assessment methodology presented in the GSMP Phase 2 report (Matrix 2022) for 56 risk sites, there are no changes to the site rankings for projects 1 to 8. The revised lateral migration rates that factor in climate change have resulted in different priority risk sites within projects 8 and 9. This is due to the factor increase resulting from climate change being larger for lateral erosion sites (factor ×2) as opposed to a factor of 1.1

for vertical risk sites. These changes do not effect the project rankings as the scoring between primary and secondary risks sites in close proximity result in the same final project prioritization.

TABLE 19 Revised Climate Changed Assessment Time to Exposure for 12 Priority Projects from Geomorphic System Master Plan Risk Assessment

Project No.	Priority Risk Site ID	Risk For Priority Site	TTE with Erosion Credit (Years)		Risk Assessment Score (/25) (1)		Risk Site Ranking (1 - 56)	
			Initial	Revised	Initial	Revised	Initial	Revised
1	16.1	Maintenance Hole	0	0	25	25	1	1
2	18.1	Maintenance Hole	0	0	25	25	3	3
3	21.1	Maintenance Hole	0	0	25	25	4	4
4	5.2	Pipe Adjacent	2	1	20	20	5	5
5	7.1	Pipe Adjacent	2	1	20	20	6	6
6	11.1	Maintenance Hole	3	2	20	20	7	7
7	8.2	Pipe Crossing	23	21	20	20	15	15
8	1.1 (2)	Maintenance Hole	35	23	15	20	20	16
9	4.1 (2)	Maintenance Hole	95	48	10	10	29	35
10	24.2	Pipe Adjacent	80	55	10	10	30	32
11	26.1	Maintenance Hole	80	70	10	10	31	36
12	28.1	Private Property	100	75	1	1	55	55

Notes:
(1) Risk assessment score based on risk probability score (TTE classification scores 1 to 5) multiplied by risk severity scores (Toronto Water asset type scores 1 to 5) for maximum possible score of 25.
(2) Different priority risk site ID within project governs with updated erosion/scour rates.
TTE - Time to Exposure

5.4 Conceptual Site Designs

Alternative solutions and conceptual site designs have been developed for the German Mills Creek GSMP study to specifically address the erosion concerns documented in the top 12 erosion mitigation project sites, as identified and evaluated in the Phase 2 report (Matrix 2022) and Phase 3 report (Matrix 2023; see reports for detailed descriptions):

- Alternative 1: Do Nothing (monitoring, emergency Works)
- Alternative 2: Local Works (sub-reach scale, less than 200 m length)
- Alternative 3: Local Works with Reach-scale Floodplain Connections
- Alternative 4: Reach Works (greater than 200 m length)

A variety of erosion mitigation approaches are available to address the erosion risks identified in this study, including structural bank treatments (e.g., armourstone, vegetated rock buttresses, rock toe protection), in-stream treatments and grade controls (e.g., armoured riffles and rocky ramps, rib structures, flow deflectors), bioengineering (e.g., live staking and brush layering, log crib-walls, sod matts and vegetated coir-warp soils), and channel realignments (e.g., meandering, terraced floodplain, stream training). Specifically for Alternatives 2 and 3 (local works) and Alternative 4 (reach works), there is a spectrum of design options ranging from “harder” to “softer” approaches, but also hybrid and mixed combinations of approaches are possible:

- “harder” river engineering approaches relying heavily on in-channel structures to balance fluvial dynamics more toward channel stability

- “softer” channel realignments relying more strategically on channel realignments, buried erosion control structures (set within the floodplain, between the active channel and Toronto Water infrastructure), and bioengineering to balance fluvial dynamics more toward channel flexibility

Alternatives 2 through 4 propose a nested “bankfull” channel with a constructed, accessible floodplain, set within a larger cross-section as slopes grade up to the existing floodplain elevation. This results in a varying top width and substantial material removal (soil and vegetation), and considerations for disposal (excess soil), and tree plantings (onsite and offsite), respectively. The intent of the larger cross-section is to provide attenuation of in-stream stresses on the bankfull channel under less frequent events, allowing for a more sustainable bankfull channel and stabilization measures.

5.4.1 Climate Change Considerations for Conceptual Site Designs

The climate change assessment in this report documents the potential future effects on hydrologic, hydraulic, and geomorphic parameters, and tests the possible geomorphic impacts in terms of changes to the frequency of erosion threshold exceedances and erosion rates. Following the approach in Section 5.2, the analysis has defined increases in peak flood erosion impacts (i.e., hydraulic forces) and increases in sub-Q_2 flow duration impacts on sediment transport (i.e., geomorphic work). As such, the following considerations have been identified for mitigating climate change impacts in the conceptual site designs:

- impacts of flood level erosional forces on erosion control structures
- impacts of increased channel dynamics (sediment transport and erosion rates)

The potential impacts due to flood level erosional forces on erosion control structures can be addressed in the conceptual site designs by planning for more robust design options with added factors of safety where appropriate, and by integration of erosion control structures with natural channel morphology (i.e., alluvial flexibility with buried structures). The potential to mitigate the increased frequency and competence of large floods with structural resiliency using larger rounded stone materials that may be strategically buried is considered a viable based on the results presented in Section 4.1. For example, the substrate mobilization classifications for the 100-year flood event has been predicted to be in the range of coarse cobble sizes (128 mm), which is a common material used for natural channel design and stream restoration with erosion control objectives.

Reference to the same approach of integrating strategically placed erosion control structures with natural channel design methods within a flexible alluvial corridor is also appropriate for addressing the impacts of increased channel dynamics in terms of increased sediment transport and erosion rates due to climate changes. It is important to highlight that this approach is considered viable in large part because the existing and future risks to Toronto Water infrastructure with the German Mills Creek GSMP study area are primarily lateral risks (e.g., exposed manholes) and no imminent vertical risks have been documented for the main sanitary trunk sewer. Two vertical risks have been identified for smaller lateral sewer pipes, but these can effectively be mitigated through sewer relocations rather than requiring extensive channel hardening. With a reduced emphasis vertical grade controls and hard instream structures that directly control the channel hydraulics, a more flexible design approach can be planned that will buffer increased channel dynamics due to climate change while still providing structural protection of the existing TW infrastructure. The selected preliminary preferred alternatives 2 and 3, and the associated concept design development (Matrix 2023, 2022), can accommodate this approach to balance both hard and soft natural channel design approaches.

The selected preliminary preferred alternative solutions and proposed design approach have also been evaluated within the Phase 3 GSMP report with respect to long-term planning and management criteria (Matrix 2023). Specifically, it is understood that alternatives 2 and 3, and the associated design options to integrate hard and soft engineering approaches, balances capital works investments with operations, maintenance, and monitoring requirements, while also optimizing long-term life-cycle costs.

6 CONCLUSION

This GSMP climate change assessment applies a novel methodology to test the potential impacts of future changes in rainfall on the hydrology, hydraulics, and geomorphology of German Mills Creek. The subject report supplements the GSMP Phase 2 characterization and risk assessment study (Matrix 2022) and helps to inform the development and evaluation of alternatives in the Phase 3 report (Matrix 2023), including the consideration of conceptual design options that will help to mitigate future climate change impacts.

As part of the development of alternatives for the study, several design approaches will be considered and evaluated based on potential for added climate resilience and/or redundancy, to protect Toronto Water infrastructure over the intermediate and long term. The alternative concepts, and the recommended timelines for intervention, will also be evaluated based on potential for climate changes to impact the design life and maintenance requirements of any new erosion mitigation assets. Following adaptive management approaches, designing to shorter-time periods (e.g., 2050) may be considered appropriate to balance the cost of migration for managing creek erosion with the uncertainty of longer-term climate outcomes. As such, the design approach needs to consider how erosion mitigation infrastructure can be maintained, adapted, and effectively modified to meet future climate conditions with ongoing monitoring and watershed planning activities by the City and TRCA. This GSMP climate change assessment report provides detailed analyses and results that support the selection of preferred alternative solutions and conceptual design options that have been advanced in the Phase 2 and 3 reports (Matrix 2023, 2022).

7 REFERENCES

AECOM Canada Ltd. (AECOM). 2018. *Don River Hydrology Update*. Prepared for Toronto and Region Conservation Authority. Richmond Hill, Ontario. December 2018.

City of Toronto. 2019. *Toronto Resilience Strategy*. Toronto, Ontario. 2019. https://www.toronto.ca/ext/digital_comm/pdfs/resilience-office/toronto-resilience-strategy.pdf

City of Toronto. 2006. *Wet Weather Flow Management Guidelines*. Toronto, Ontario. November 2006.

Climate Action Tracker. 2021. *Temperatures*. Accessed July 2021. https://climateactiontracker.org/global/temperatures/

Environmental Water Resources Group Ltd. (EWRG). 2017. *Technical Guidelines for Flood Hazard Mapping*. Prepared for Central Lake Ontario Conservation, Credit Valley Conservation, Ganaraska Conservation, Grand River Conservation Authority, Nottawasaga Valley Conservation Authority, and Toronto and Region Conservation Authority. March 2017.

Komar P. 1987. "Selective gravel entrainment and the empirical evaluation of flow competence." *Sedimentology 34* (*6*): 1165–1176. 1987.

Matrix Solutions Inc. (Matrix). 2023. "German Mills Creek Geomorphic Systems Master Plan, Phase 3 Technical Memorandum, Evaluation of Alternatives and Preferred Options." Version 0.1. Draft prepared for the City of Toronto. Mississauga, Ontario. February 2023.

Matrix Solutions Inc. (Matrix). 2022. "German Mills Creek Geomorphic Systems Master Plan, Phase 2 Technical Memorandum, Development of Alternative Solutions." Version 0.1. Draft prepared for City of Toronto. Mississauga, Ontario. July 2022.

Matrix Solutions Inc. (Matrix). 2021. "German Mills Creek Geomorphic Systems Master Plan, Phase 1 Technical Memorandum, Issue Assessment and Problem Confirmation." Version 0.1. Draft prepared for the City of Toronto. Mississauga, Ontario. August 2021.

Toronto and Region Conservation Authority (TRCA). 2012. *Stormwater Management Criteria*. Version 1.0. August 2012. 2012.

WSP. 2022. *German Mills Creek Geomorphic Systems Master Plan, Climate Change Assessment - Future Rainfall Scenarios*. Prepared for Matrix Solutions Inc. September 20, 2022.

APPENDIX A
Technical Memorandum: German Mills Creek Geomorphic Systems Master Plan Climate Change Assessment Future Rainfall Scenarios by WSP

Technical Memorandum

To:	Matrix Solutions	Shaina Blue	Senior Water Resources Engineer
	Matrix Solutions	Ziyang Zhang	Water Resources EIT
From:	WSP	Peter Nimmrichter	Technical Lead – CC Rainfall Assessment
cc:	WSP	Brian Bishop	Associate Water Resources Engineer
	Matrix Solutions	Roger Phillips	Senior Geomorphologist
	Matrix Solutions	Steve Braun	Principal Water Resources Engineer

Wood Project #: WW21011051

Date: September 20, 2022

RE: German Mills Creek Geomorphic Systems Master Plan
Climate Change Assessment - Future Rainfall Scenarios

1.0 INTRODUCTION

A climate change assessment approach was developed in consultation with City staff to chart an acceptable path forward to meet the project objectives. The work plan is outlined with reference to the assessment components, base scope, and additional scope, as well as the expected outcomes in terms of the City's list of impacts to be evaluated.

The proposed climate change assessment is comprised of the following tasks:

1. Future Rainfall Scenarios: three (3) scenarios proposed based on consideration of three RCPs and a future time period of 2050, including total annual rainfall for each scenario.
2. Hydrological Modelling: climate adjusted flood event series (Q2 to Q100).
3. Geomorphic Impact Analysis: changes in annual frequency and probability of critical discharge exceedances to evaluate expected flood event impacts to erosion controls.
4. GSMP Evaluation of Impacts: impacts to key hydraulic parameters, geomorphic and erosion processes, and implications for design and management of erosion controls in conceptual site designs.

A diagram of the workplan components, tasks, and expected outcomes is provided as Figure 1.

This Technical Memorandum documents the preliminary assessment of Task 1 - Future Rainfall Scenarios.

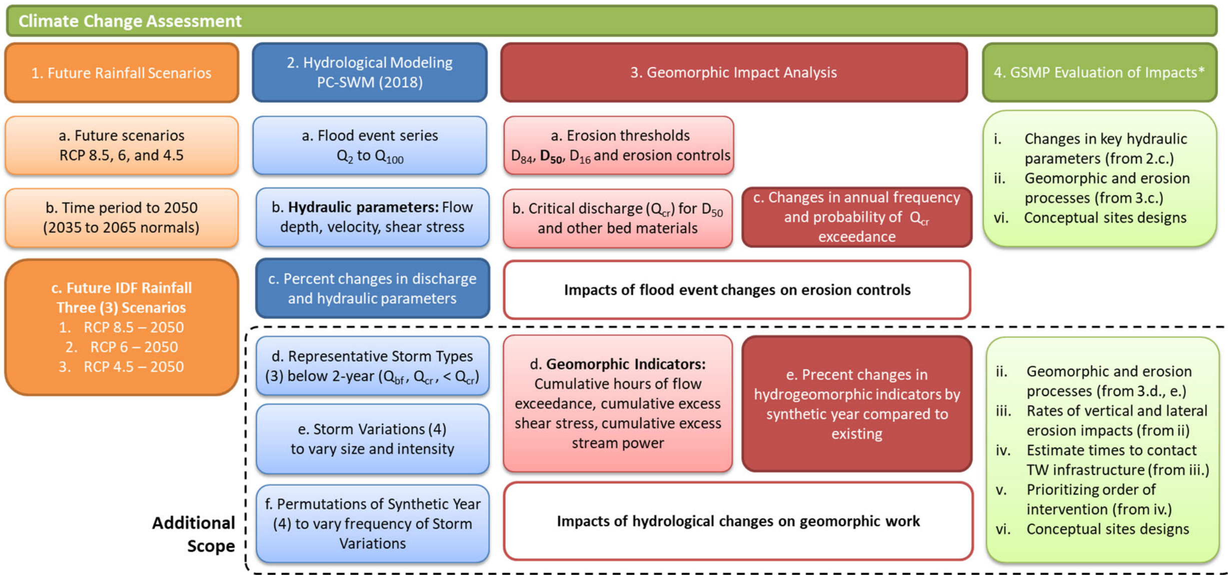


Figure 1 Climate Change Assessment Approach

1.1 TOOLS FOR ESTIMATING FUTURE RAINFALL

In Ontario, there are a variety of publicly accessible tools for estimating projected rainfall as intensity duration frequency (IDF) data. Examples include Environment and Climate Change Canada (ECCC), University of Western Ontario (IDF_ CC Tool), Ontario Climate Change Data Portal (OCCDP), and the Ontario Ministry of Transportation (MTO) Trending Tool. Added to this list is the notion of a simple offset (typically on a percentage basis) of a base (read "current") IDF relationship.

Central to structured assessments of the impacts of climate change on rainfall is use of an "ensemble" of estimates. This approach is advocated because each Global Climate Model provides a slightly different conceptualization of the earth atmosphere system, which has led the Intergovernmental Panel on Climate Change (IPCC) to recommend using an ensemble approach which incorporates a range of climate projections. The estimates in an ensemble provide a more encompassing characterization of the future and its uncertainty than a single model used in isolation.

As precipitation is a key driver for the health of German Mills Creek, the first component of the climate change assessment will involve compiling a long list of alternate future IDF rainfall estimates. For existing rainfall, the standard deviations provided with the ECCC IDF data are typically applied to establish an upper and lower bound. Additional online tools (such as MTO, IDF_ CC, OCCDP) are also available to establish a point IDF relationship at the centroid of the study watershed or other relevant but ungauged point. If the IDF_ CC Tool is used as a basis for estimating future rainfall, both the Gumbel and generalized extreme value (GEV) distributions may be assessed, using GEV as the expected higher estimate, with the required 50-year band around a named year.

The international climate modelling community has adopted four Representative Concentration Pathways[1] (RCPs) through the Intergovernmental Panel on Climate Change (IPCC). The long list of alternate future IDF rainfall estimates will consider various RCPs and various future periods. Trends, if any, will be assessed to determine if a critical future period exists, which can then be used as a basis for assessment. If no clear trend can be determined, then a target future time period will be established in discussion with the City and project team.

The RCP scenarios range from RCP 8.5, which corresponds to a "non-climate policy" scenario translating into high severity climate change impacts, to RCP 2.6, which is a future requiring aggressive climate policy to limit greenhouse

1 Refer to https://www.ipcc-data.org/guidelines/pages/glossary/glossary_r.html

gas emissions, translating into low severity impacts. Two middle scenarios, RCPs 4.5 and 6.0, were selected by the IPCC to be evenly spaced between RCPs 2.6 and 8.5. As an intermediate scenario, results generated using RCP 6.0 are similar to those generated using RCP 4.5. Further, as not all GCMs include runs for RCP 6.0, use of this RCP would limit the number of available GCMs for use in this assessment. The suggested RCPs for this study are the current trend of RCP 8.5 and the optimistic case of RCP 4.5, reflecting implementation of climate change mitigation measures globally. The base scope analysis has not considered RCP 6.

The IPCC's most recent Sixth Assessment Report (AR6[2]) released in August 2021 will also be reviewed for consideration of latest climate change recommendations and the associated Shared Socioeconomic Pathways (SSPs).

Figure 2 illustrates estimated emissions over time associated with RCPs along with associated expectations for temperature change into the future. This information has been integrated with anticipated emissions and warming recognizing various mitigation pledges and current policies to develop a comparative view (ref. Figure 3). This information postulates that mitigation pledges and current policies have the potential to limit warming to about the +3ºC range with some alignment to the RCP 4.5 curve.

Time periods of 2050s and 2080s, defined as normals over the periods 2035 to 2065 and 2065 to 2095, respectively. The base scope analysis has considered the 2050s time horizon only.

Rainfall estimates developed for this assessment will focus on the key frequencies (e.g., 2-year to 100-year return period) and durations, as relevant to the study area. The long list of future IDF rainfall estimates will be reviewed to establish a short list spanning a range of values for the modelling-based climate change assessment, with reference to work completed by Wood for the Town of Oakville Stormwater Master Plan (89 narrowed to 6 IDFs). Determination of the short list of rainfall scenarios will be based on criteria developed by the study team, in consultation with City staff, to reasonably frame the upper and lower limits that are most relevant to the objectives of the German Mills Creek GSMP objectives.

2 Source: IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896.

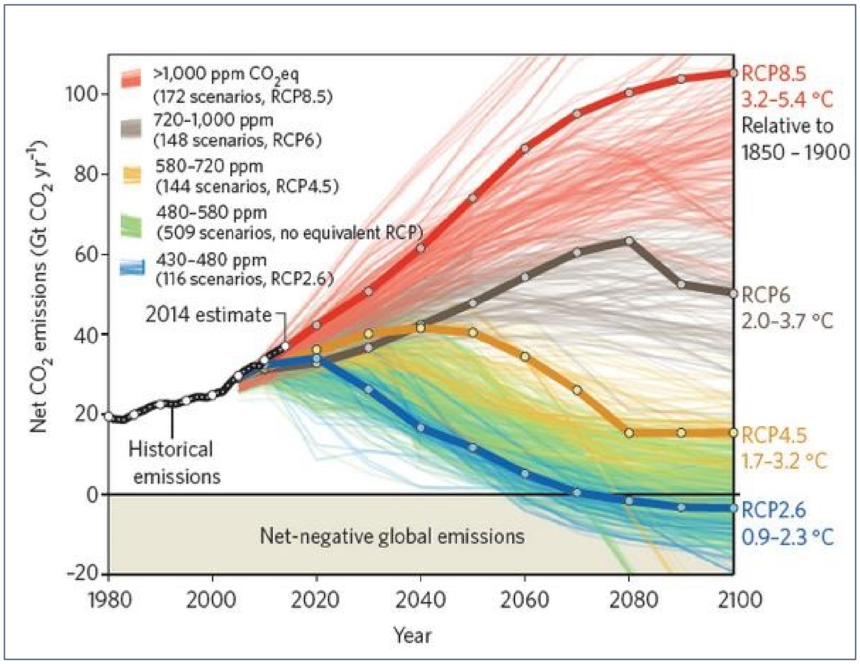


Figure 2 RCP Emission Scenarios

(Source: https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change/)

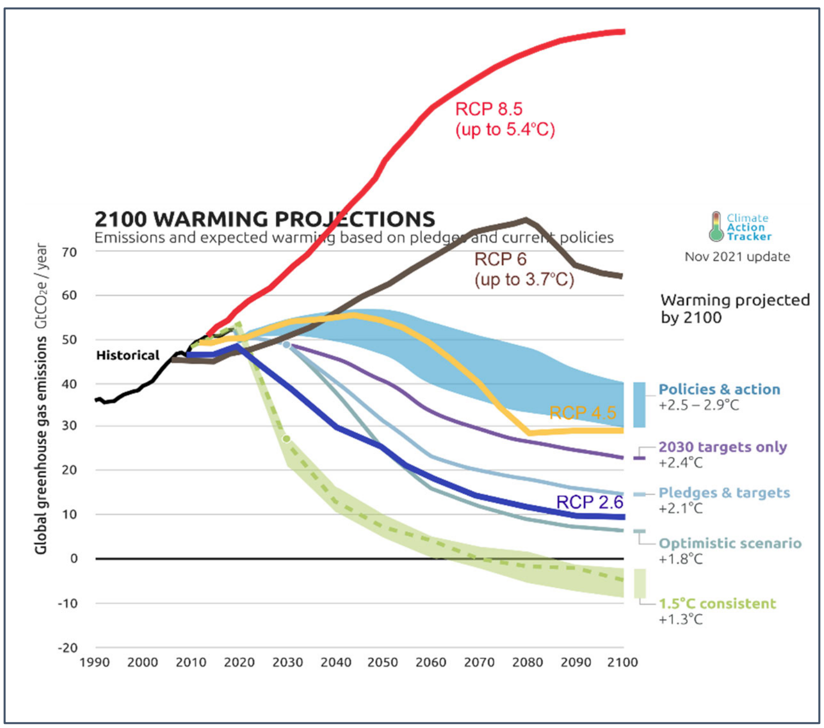


Figure 3 RCP Emission Scenarios Integrated with Mitigation Pledges and Policies

(Source: https://climateactiontracker.org/global/temperatures/)

1.2 WATERSHED LAYOUT AND AVAILABLE RAINFALL STATIONS

Figure 2 illustrates the general orientation and extent of the German Mills Creek Watershed. The watershed encompasses portions of the municipalities of Markham, Richmond Hill, Toronto and Vaughan. It is a tributary of the East Branch Don River. It originates in Vaughan (near Bathurst Street and the King–Vaughan Town Line), flows south through Richmond Hill and Markham, and empties into the East Branch Don River in the East Don Parklands in Toronto, south of Steeles Avenue between Bayview Avenue and Leslie Street. The main German Mills Creek channel is 26 km long and has a drainage area of approximately 40 km^2.

Figure 3 illustrates, approximately, the study reach and nearby rainfall gauging stations. Additional information for these stations is summarized in Table 1. It is noted that no rainfall stations are located within the immediate study area. It is also noted that modelling of the Don River has used TRCA gauges and supplemented data gaps with municipal gauges.

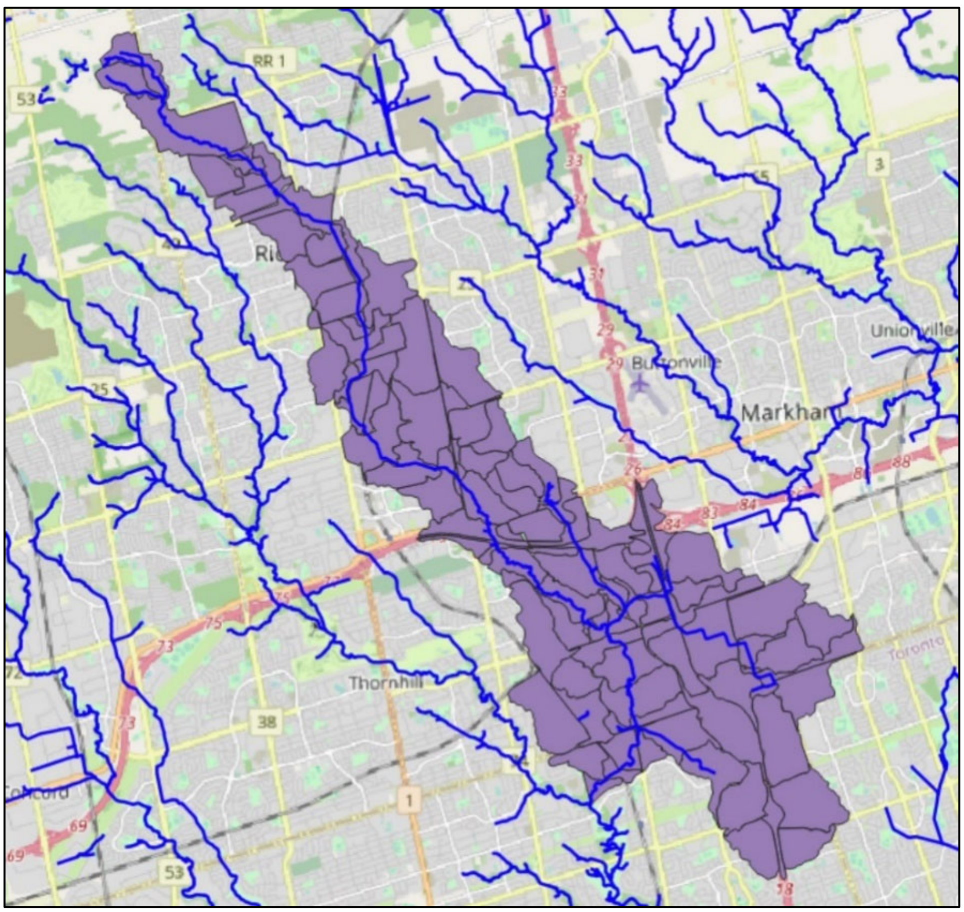


Figure 4 German Mills Creek Watershed

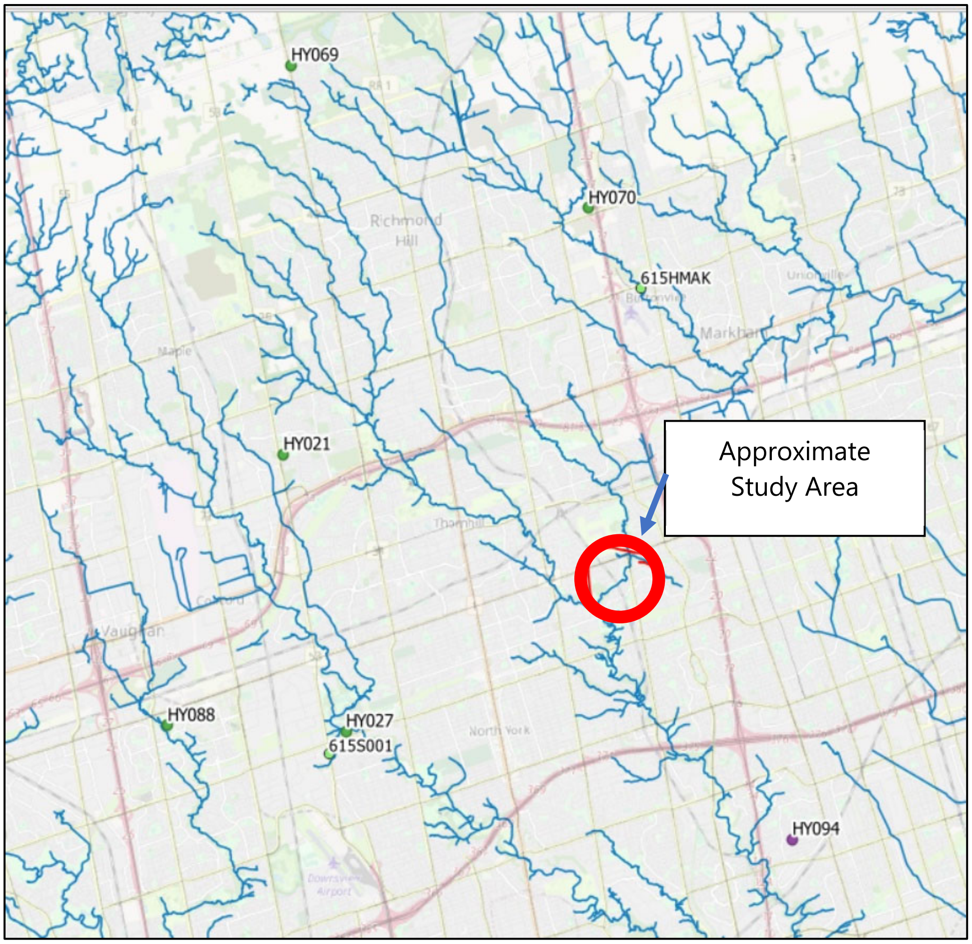


Figure 5 Approximate extent German Mills Creek Study Area with local Rain Gauges Identified

Table 1 Summary of Rain Gauges Local to the Study Area

Station ID	Station Name	Owner	Latitude	Longitude	Recording Interval	Years of Data Available	Distance to Study Area
HY070	York Regions Work Yard	TRCA	43.884	-79.383	5 minutes	8	9.5 km
HY021	Dufferin Reservoir	TRCA	43.832	-79.479	10 minutes	16	8.8 km
HY027	G Ross Lord Dam	TRCA	43.771	-79.461	5 minutes	13	7.3 km
HY094	Broadlands	TRCA	43.746	-79.323	5 minutes	6	7.4 km
HY036	Kennedy Pump Station	TRCA	43.819	-79.306	5 minutes	15	6.4 km
HY069	York Pump Station	TRCA	43.917	-79.475	5 minutes	8	15.2 km
HY088	Pioneer Village	TRCA	43.773	-79.517	5 minutes	6	11.4 km
615HMAK	Toronto Buttonville A	ECCC	43.861	-79.369	hourly	29	7.0 km
615S001	Toronto North York	ECCC	43.780	-79.468	daily	27	7.5 km
6158355	Toronto City	ECCC	43.670	-79.400	hourly	83	14.4 km

2.0 IDF RAINFALL ANALYSIS

2.1 CURRENT CONDITIONS RAINFALL ANALYSIS

The 100-year 24-hour duration rainfall design event for all the rainfall stations noted in Table 1 have been summarized in Table 2. The IDF data for the ECCC stations has been abstracted from the most recent ECCC edition of published IDF data for Ontario (dated March 26, 2021). It is noted that the ECCC IDF data is based on a Gumbel statistical distribution. The IDF data for the TRCA stations has been estimated using the University of Western Ontario IDF_ CC Tool[3] functionality for ungauged locations. It is noted that the IDF CC Tool data is based on a Generalized Extreme Value (GEV) statistical distribution.

For existing IDF data, the 95% upper and lower bounds of the rainfall intensity estimates provided with the ECCC IDF data can be applied as a means of establishing the range of estimates reflected in the statistical analysis founding the IDF results. This information is also summarized in Table 2.

Table 2 Summary of Rain Gauges Local to the Study Area

Station ID	Station Name	95% Confidence Limit	100-year 24 hour IDF Total Precipitation (mm)		
			Lower	Estimated Value	Upper
IDF CC Tool Existing IDF based on GEV estimates					
HY070	York Regions Work Yard	n/a	n/a	127.5	n/a
HY021	Dufferin Reservoir	n/a	n/a	134.3	n/a
HY027	G Ross Lord Dam	n/a	n/a	132.9	n/a
HY094	Broadlands	n/a	n/a	126.2	n/a
HY036	Kennedy Pump Station	n/a	n/a	119.5	n/a
HY069	York Pump Station	n/a	n/a	135.8	n/a
HY088	Pioneer Village	n/a	n/a	132.9	n/a
615HMAK	Toronto Buttonville A	n/a	n/a	117.6	n/a
615S001	Toronto North York	n/a	n/a	160.8	n/a
6158355	Toronto City	n/a	n/a	103.6	n/a
IDF CC Tool Existing IDF based on published ECCC data					
615HMAK	Toronto Buttonville A	±26.4	78.5	104.9	131.3
615S001	Toronto North York	±31.2	97.7	128.9	160.1
6158355	Toronto City	±14.4	83.7	98.1	112.5

2.2 FUTURE CONDITIONS RAINFALL ANALYSIS

Precipitation is a key driver for the health of German Mills Creek. As such, a long list of alternate future IDF rainfall estimates have been developed using readily available tools and data sources. These include:

- University of Western Ontario (IDF_ CC Tool v6) – ref. Table 3
- Ontario Climate Change Data Portal (OCCDP) – ref. Table 4
- Ontario Ministry of Transportation (MTO) Trending Tool – ref. Table 5

3 Ref: Simonovic, S.P., A. Schardong, R. Srivastav, and D. Sandink (2015), *IDF_CC Web-based Tool for Updating Intensity-Duration-Frequency Curves to Changing Climate – ver 6.0*, Western University Facility for Intelligent Decision Support and Institute for Catastrophic Loss Reduction, open access https://www.idf-cc-uwo.ca.

The following future IDF estimation methods have been explored using these tools:

- The online tools support functionality to establish a point IDF relationship at the centroid of the study watershed or other relevant but ungauged point.
- If the IDF_ CC Tool is used as a basis for estimating future rainfall, using the Generalized Extreme Value (GEV) distribution, with the required 30-year band around a named year.
- Added to this list is the notion of a simple offset (typically on a percentage basis) of a base (read "current") IDF relationship. This latter approach is used by a few municipalities in Ontario (e.g., Barrie, Ottawa).

2.2.1 UNIVERSITY OF WESTERN ONTARIO (IDF_ CC Tool v6)

The following information has been abstracted from the IDF CC Tool website:

- Tool available via https://www.idf-cc-uwo.ca/
- CMIP5 used RCPs to describe different levels of greenhouse gases and other radiative forcings that might occur in the future. Three of these RCPs are used by IDF_CC tool. Parallel modelling is concentrated on how socioeconomic factors may change over the next century. These include changes to population, economic growth, education, urbanization, and the rate of technological development. Shared Socioeconomic Pathways (SSPs) consider five different ways in which the world might evolve in the absence of climate policy and how different levels of climate change mitigation could be achieved, when the mitigation targets of RCPs are combined with the SSPs. These two efforts are designed to be complementary. The RCPs set pathways for greenhouse gas concentrations and, effectively, the amount of warming that could occur by the end of the century. The SSPs set the stage on which reductions in emissions will – or will not – be achieved.
- CMIP6 represents a substantial expansion over CMIP5, in terms of the number of modelling groups participating, the number of future scenarios examined, and the number of different experiments conducted. In the lead up to the IPCC Assessment Report 6, the energy modelling community has developed a new set of emissions scenarios driven by different socioeconomic assumptions described using SSPs. A number of these SSP scenarios have been selected to drive climate models for CMIP6. The IDF_CC tool offers to its users an opportunity to use CMIP6 climate models. Thirty models have been added to the tool's database under CMIP6.
- Users should note that the climate modelling community does not "compare" global climate models to identify superior/inferior models for specific locations. Thus, users should note that there is no "right" GCM for any given location. Users are provided access to all available models in the IDF_CC tool to allow them to understand uncertainty associated with potential climate change impacts.

Review of the Table 3 IDF rainfall estimates identified several anomalous results comparing the SSP2-4.5/ RCP4.5 results to the SSP5-8.5/RCP8.5 results within each future dataset whereby the SSP5-8.5/RCP8.5 estimate was less than the SSP2-4.5/RCP4.5 estimate. These anomalies were most associated with the CMIP5 dataset (ref. Table 4). These anomalies could generally be resolved by selecting a revised time base of 2035 to 2066, but this approach was considered inconsistent with the selected base time for other scenarios. As such, SSP5-8.5/RCP8.5 IDF rainfall estimates associated with anomalous results were not carried forward.

Table 3 University of Western Ontario (IDF_ CC Tool v6) Future IDF Rainfall Estimates

Station ID	Station Name	100-year 24-hour IDF Total Precipitation (mm) for the Period 2035 to 2065 using the IDF CC Tool							
		CMIP6 GCMs SSP2-4.5	PCIC Bias Corrected CMIP6 SSP2-4.5	CMIP5 GCMs RCP 4.5	PCIC Bias Corrected CMIP5 RCP 4.5	CMIP6 GCMs SSP5-8.5	PCIC Bias Corrected CMIP6 SSP5-8.5	CMIP5 GCMs RCP 8.5	PCIC Bias Corrected CMIP5 RCP 8.5
HY070	York Regions Work Yard	138.86	143.54	139.99	145.02	141.93	149.75	142.83	154.35
HY021	Dufferin Reservoir	145.09	153.45	148.02	147.62	147.50	161.79	146.62	159.68
HY027	G Ross Lord Dam	147.12	151.60	146.29	143.40	149.79	162.88	144.67	154.33
HY094	Broadlands	138.24	148.50	141.22	139.74	141.95	152.84	138.71	144.05
HY036	Kennedy Pump Station	131.83	138.15	131.73	131.19	132.93	143.29	135.20	135.80
HY069	York Pump Station	147.24	151.52	148.73	153.35	149.03	157.13	149.63	164.64
HY088	Pioneer Village	147.09	151.10	146.12	147.51	147.40	158.66	143.77	156.83
615HMAK	Toronto Buttonville A	126.54	132.76	124.54	131.22	127.21	140.31	127.07	144.84
615S001	Toronto North York	157.64	182.52	165.69	173.61	162.89	194.24	164.70	185.48
6158355	Toronto City	113.66	122.80	114.99	120.87	112.63	126.31	109.80	124.39

Statistical Metrics based on the IDF_CC Tool Rainfall Estimates				
Metric	SSP2-4.5 and RCP 4.5 based estimates		SSP5-8.5 and RCP 8.5 based estimates	
	Based on all estimates	Not including Toronto City	Based on all estimates	Not including Toronto City
Average	143.9	146.6	144.7	147.6
Median	145.6	146.3	147.0	148.3
Maximum	182.52		194.24	
Std Deviation	14.6	12.6	23.3	22.6

Table 4 Anomalies associated with IDF_ CC Tool (v6) Rainfall Estimates

Station ID	Station Name	100-year 24-hour IDF comparison SSP2-4.5/RCP4.5 results less than SSP5-8.5/RCP8.5 results			
		CMIP6 GCMs	PCIC Bias Corrected CMIP6	CMIP5 GCMs	PCIC Bias Corrected CMIP5
HY070	York Regions Work Yard				
HY021	Dufferin Reservoir			Yes	
HY027	G Ross Lord Dam			Yes	
HY094	Broadlands			Yes	
HY036	Kennedy Pump Station				
HY069	York Pump Station				
HY088	Pioneer Village			Yes	
615HMAK	Toronto Buttonville A				
615S001	Toronto North York			Yes	
6158355	Toronto City	Yes		Yes	

An approach for hydrological modelling of future rainfall conditions would be to simply model all scenarios. However, given the similarity of rainfall estimates, hydrologic modelling outcomes would also be expected to be similar. To be efficient, the Statistical Metrics outlined in Table 3 were used as guidance for selecting four (4) stations, to be used as input to the hydrologic modelling effort, which are reflective of average and maximum climate change influenced rainfall conditions (not including the Toronto City station). The average represented by a middle climate change scenario (i.e., RCP 4.5 or SSP2-4.5) and the maximum represented by a high scenario (i.e., RCP 8.5 or SSP5-8.5). Based on this approach yielded the following station data was selected:

- RCP 4.5 (Average based on CMIP5) – Station HY027 at G Ross Lord Dam
- SSP2-4.5 (Maximum based on PCIC Bias Corrected CMIP6) – Station 615S001 at Toronto North York
- SSP5-8.5 (Average based on CMIP6 GCMs) – Station HY069 at York Pump Station
- SSP5-8.5 (Maximum based on PCIC Bias Corrected CMIP6) – Station 615S001 at Toronto North York

A review of the four IDF relationships noted above was also completed, yielding the following comments:

- Comparison of the RCP 4.5 Average and SSP2-4.5 Maximum results indicates that the RCP 4.5 Average results are generally less than the SSP2-4.5 Maximum results (for individual return periods and durations) with only a few exceptions, namely the 2-year 12 hr, and the 24 hour 2,5 and 10-year events. However, the total rainfall depths for these events are very similar.
- The SSP5-8.5 Maximum results represent the upper bound of the noted estimates.
- Comparison of the SSP5-8.5 Average and the SSP2-4.5 Maximum results indicates that the SSP5-8.5 Average results (147.6 mm) are generally less than the SSP2-4.5 Maximum results (182.5 mm). Further, the SSP5-8.5 Average results (147.6 mm) are very similar to the RCP 4.5 Average results (146.6 mm).
- From this review, it has been concluded that the SSP5-8.5 (Average based on CMIP6 GCMs) – Station HY069 at York Pump Station results are inconsistent across the suite of IDF rainfall estimates selected for evaluation. As such, this IDF rainfall relationship will not be carried forward in this analysis.
- **The following IDF rainfall relationships are recommended to be carried forward for further analysis**:
    - RCP 4.5 (Average based on CMIP5) – Station HY027 at G Ross Lord Dam
    - SSP2-4.5 (Maximum based on PCIC Bias Corrected CMIP6) – Station 615S001 at Toronto North York
    - SSP5-8.5 (Maximum based on PCIC Bias Corrected CMIP6) – Station 615S001 at Toronto North York

2.2.2 ONTARIO CLIMATE CHANGE DATA PORTAL (OCCDP)

The following information is relevant to future IDF rainfall estimates using the OCCDP[4]:

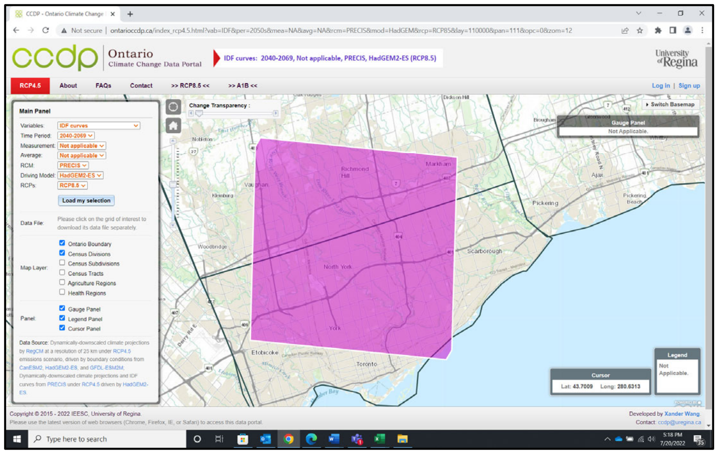
- Tool available via http://ontarioccdp.ca/
- The OCCDP uses the AR5[5] (i.e., CMIP5) climate data only.
- The database has a 25 km resolution.
- The OCCDP has incorporated the high-resolution (25 km x 25 km) climate projections developed by the IEESC at the University of Regina using the PRECIS model and the RegCM model under RCP4.5, RCP8.5, and SRES A1B emissions scenarios.[6]
- Refer to Table 5 for rainfall estimates.
- Refer to Figure 4 for an illustration of the grid cell used for IDF data determination.

4 Ref: Wang, Xiuquan and Gordon Huang (2013). "Ontario Climate Change Data Portal". Website: http://www.ontarioccdp.ca
5 Ref: IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.
6 For further information reference http://ontarioccdp.ca/Technical_Report_RCP85.pdf

Table 5 Ontario Climate Change Data Portal Future IDF Rainfall Estimates

Regional Climate Model	100-year 24-hour IDF Total Precipitation (mm) for the 2040 to 2069 Period using the OCCDP	
	RCP 4.5	RCP 8.5
PRECIS	102.0	150.7
RegCM	143.0	256.6

Figure 6 OCCDP Grid Reference used for IDF Estimation



2.2.3 ONTARIO MINISTRY OF TRANSPORTATION (MTO) IDF CURVE LOOKUP TOOL

The following information is relevant to future IDF rainfall estimates using the MTO IDF Lookup Tool:

- Tool available via http://www.eng.uwaterloo.ca/~dprincz/mto_site/map_acquisition.shtml
- The tool uses Environment Canada station data for Ontario, Manitoba, and Quebec up to 2013. The Manitoba and Quebec stations used are within 150 km of Ontario.
- The currently available version of the tool was released September 2016.
- Refer to Table 6 for rainfall estimates.

Table 6 MTO IDF Curve Lookup Tool Future IDF Rainfall Estimates

Station ID	Station Name	Confidence Limits	100-year 24 hour IDF Total Precipitation (mm) using the MTO method
HY070	York Regions Work Yard	±38.4	129.6
HY021	Dufferin Reservoir	±38.4	132.0
HY027	G Ross Lord Dam	+40.8 / -38.4	129.6
HY094	Broadlands	±38.4	129.6
HY036	Kennedy Pump Station	±38.4	129.6
HY069	York Pump Station	±38.4	132.0
HY088	Pioneer Village	±38.4	132.0
615HMAK	Toronto Buttonville A	±38.4	129.6
615S001	Toronto North York	±38.4	132.0
6158355	Toronto City	±38.4	129.6

2.2.4 SIMPLE OFFSET METHOD

Table 7 summarizes the future estimates 100-year 24-hour duration IDF rainfall for the various rainfall stations using the simple offset method. In comparison to the rainfall estimates generated using the other methods, these results are aligned with those generated using the University of Western Ontario IDF_ CC Tool (v6).

Table 7 Simple Offset Method Future IDF Rainfall Estimates

Station ID	Station Name	100-year 24 hour IDF Total Precipitation (mm)		
		Base Value	Base Value +10%	Base Value +20%
HY070	York Regions Work Yard	127.5	140.3	153.0
HY021	Dufferin Reservoir	134.3	147.7	161.2
HY027	G Ross Lord Dam	132.9	146.2	159.5
HY094	Broadlands	126.2	138.8	151.4
HY036	Kennedy Pump Station	119.5	131.5	143.4
HY069	York Pump Station	135.8	149.4	163.0
HY088	Pioneer Village	132.9	146.2	159.5
615HMAK	Toronto Buttonville A	104.9	115.4	125.9
615S001	Toronto North York	128.9	141.8	154.7
6158355	Toronto City	98.1	107.9	117.7
		Average	*136.5*	*148.9*

2.2.5 CONCLUSIONS

Future 100-year 24-hour rainfall estimates have been determined for gauges in proximity to the German Mills Creek study area using a variety of methods. Comparison of the results indicates a broad range of estimates from 98.1 mm to 256.6 mm for the 2050s future time horizon.

It has also been noted that the climate modelling community does not “compare” global climate models to identify superior/inferior models for specific locations and general recommendations are to access many available models to better understand uncertainty issues.

Of the tools explored, the versions of the OCCDP and MTO IDF Curve Lookup Tool used have not been updated in many years. Whereas the IDF_CC Tool’s latest version (v6) was released in 2021 and provides access to the most current global modelling data based on AR6. As well, this tool provides access to the most current ECCC IDF data in comparison to the other tools.

It is recommended that the IDF_CC Tool v6 be used as the basis for future rainfall estimation in support of this evaluation.

Further, it has been found that the rainfall estimates for stations in proximity to the study area are generally consistent and there is no specific basis to choose an estimate from one station over another.

It is recommended that two rainfall estimates be adopted for evaluation, namely an IDF relationship that is consistent with the average across all stations and the maximum IDF estimate to be used as a stress test.

In this manner, a range of streamflow modelling outcomes can be evaluated, and the uncertainty associated with rainfall estimation, and its resultant impacts on streamflow, can be better understood.

A long list of rainfall IDF relationships was reviewed in the context of supporting the German Mills Creek hydrologic modelling effort, namely:

- RCP 4.5 (Average based on CMIP5) – Station HY027 at G Ross Lord Dam
- SSP2-4.5 (Maximum based on PCIC Bias Corrected CMIP6) – Station 615S001 at Toronto North York
- SSP5-8.5 (Average based on CMIP6 GCMs) – Station HY069 at York Pump Station
- SSP5-8.5 (Maximum based on PCIC Bias Corrected CMIP6) – Station 615S001 at Toronto North
- RCP 4.5 (mid-Range based on PCIC Bias Corrected CMIP5) – Station 6158355 at Toronto City
- RCP 8.5 (mid-Range based on PCIC Bias Corrected CMIP5) – Station 6158355 at Toronto City

The full IDF relationships, for the above noted scenarios, are provided in Appendix A.

The IDF rainfall estimates for Station 6158355 (Toronto City) were included in the long list given the use of this station's data to support the Don River Hydrology Update[7] study. However, recognizing that station data more local to the study area is readily available, the more local study area data was deemed more relevant to the morphological assessment of German Mills Creek.

Further comparative review of the remaining IDF rainfall relationships was completed to determine consistency of results across the various relationships. Based on this review the SSP5-8.5 (Average based on CMIP6 GCMs) – Station HY069 at York Pump Station was removed from further consideration.

It is recommended that the following short-listed rainfall IDF relationships be considered for evaluation in the context of the morphological assessment of German Mills Creek.

- **RCP 4.5 (Average based on CMIP5) – Station HY027 at G Ross Lord Dam**
- **SSP2-4.5 (Maximum based on PCIC Bias Corrected CMIP6) – Station 615S001 at Toronto North York**
- **SSP5-8.5 (Maximum based on PCIC Bias Corrected CMIP6) – Station 615S001 at Toronto North York**

This list of future IDF estimates developed through this assessment will be used as input to the hydrologic and hydraulic modelling developed for other project purposes to quantify potential future changes to watershed flow response (i.e., Task 2 - Hydrological Modelling).

3.0 TOTAL ANNUAL RAINFALL ANALYSIS

Hydrological Modelling (i.e., Task 2) will also include an assessment of the future annual hydrological impacts of climate change based on a synthetic year of typical rainfall events. The synthetic year of typical rainfall events will be

7 Ref: Don River Hydrology Update, prepared by AECOM on behalf of the Toronto and Region Conservation Authority, December 2018 available via the following URL:
chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://trca.ca/app/uploads/2020/01/Don_Hydrology-Study-Update-_FINAL-12-18.pdf

developed from a statistical analysis of the typical number of each event type per year based on historical IDF data. The cumulative outputs for the synthetic hydrological year will then be used to provide quasi-absolute values on annual basis for changes in select hydrological parameters.

To inform the development of the synthetic year of typical rainfall events, an assessment of average annual rainfall in the study area was completed.

The Toronto and Region Conservation Authority (TRCA) supported the development of climate projections for a variety of time horizons; namely: short- (2011–2040), medium- (2040–2070), and long-term (2071–2100)[8]. It was generally concluded that the Toronto region is expected to experience a warmer and wetter climate, along with more variable weather patterns including higher intensity storms. The expected impacts include:

- An overall increase to total precipitation:

  The TRCA study concluded that the Toronto region is expected to see up to 20% changes compared to the historical climate period:

  - Up to 10% increase by 2011–2040
  - Up to 10% increase by 2041–2070
  - 10–20% increase by the end of 2100

  An independent review of changing total rainfall in the vicinity of the study area was completed for this assessment. The projected average annual total precipitation information was abstracted from ClimateData.ca and historic information was sourced from climate normal data[9]. The ClimateData.ca information, in his regard, suggests a less significant overall increase in average annual total precipitation.

- No significant decrease to the number of dry days:

  Both the TRCA study and the independent review came to similar conclusions ion this regard. This outcome suggests that the Toronto area will still experience a similar number of rainfall events, on average, over a year.

The data summary associated with the independent review completed for this assessment are summarized in Table 8.

8 Ref. https://storymaps.arcgis.com/stories/6bdd5b1d96c94792bf5eba5a73c2d6d0
9 Ref. available from the Government of Canada website at https://climate.weather.gc.ca/climate_normals/index_e.html

Table 8 Total Annual Precipitation Data

Climate Normal Period	Climate Normal Data for Buttonville Airport / Richmond Hill			Climatedata.ca			
				RCP 4.5		RCP 8.5	
	Total Annual Rainfall (mm)	Total Annual Precipitation (mm)	# of Wet Days (>= 10mm)	Total Annual Precipitation (mm)	# of Wet Days (>= 10mm)	Total Annual Precipitation (mm)	# of Wet Days (>= 10mm)
2031 - 2060	n/a	n/a	n/a	832 to 917	26 to 29	830 to 914	26 to 29
2021 - 2050	n/a	n/a	n/a	821 to 892	25 to 28	832 to 912	25 to 29
2011 - 2040	n/a	n/a	n/a	827 to 879	26 to 28	823 to 890	25 to 28
2001 - 2030	n/a	n/a	n/a	825 to 869	26 to 27	813 to 879	25 to 28
1991 - 2020	n/a	n/a	n/a	802 to 853	24 to 27	819 to 856	25 to 27
1981 - 2010	717.4	852.9	24.0	799 to 833	24 to 25	807 to 834	24 to 26
	744.6	895.2	24.5				
1971 - 2000	735.6	892.4	24.1	786 to 823	23 to 25	786 to 822	23 to 25
1961 - 1990	689.0	847.4	n/a	793 to 813	23 to 25	792 to 811	24 to 25
1951 - 1980	646.7	804.7	n/a	787 to 816	23 to 25	787 to 817	23 to 25
1941 - 1970	628.9	776.5	n/a	n/a	n/a	n/a	n/a

Notes:

- Red text estimates from ClimateData.ca for Buttonville Airport climate station
- Blue text estimates from ECCC climate normal data for Richmond Hill climate station (nearest available station). References:
  - 1981 – 2010: https://climate.weather.gc.ca/climate_normals/index_e.html via Station Name lookup
  - 1971 – 2000: https://climate.weather.gc.ca/climate_normals/index_e.html via Station Name lookup
  - 1961 – 1990: https://climate.weather.gc.ca/climate_normals/index_e.html via Station Name lookup
  - 1951 – 1980: Canadian Climate Normals 1951-1980 Volume 3 Precipitation via URL https://drive.google.com/file/d/1Nujco00lfiT0aBZHfW1Gs2P4MLFguxHR/view
  - 1941 – 1970: Canadian Normals Volume 2 1941-1970 via URL https://drive.google.com/file/d/1VNhfBLv97uGa8Iyhaa8Zh8rpZVZLe43K/view

4.0 CLOSURE

Should you have any questions regarding this memo, please do not hesitate to contact the undersigned.

Sincerely,

WSP E&I Canada Limited

Peter Nimmrichter, M.Eng., P.Eng., IRP
Climate, Resilience and Sustainability Lead for Canada
Mobile: (289) 242-3343
Email: peter.nimmrichter@wsp.com

Jonas Roberts, PhD, P.Eng.
Operations Manager, Digital Environment
Mobile: (709) 765-2884
Email: jonas.roberts@wsp.com

APPENDIX A

RAINFALL ESTIMATES

RCP 4.5 (Average based on CMIP5) – Station HY027 at G Ross Lord Dam

Duration	T (years)						
	2	5	10	20	25	50	100
5 min	9.41	12.52	14.5	16.15	16.57	18.43	20.03
10 min	13.53	18.07	20.96	23.38	23.99	26.72	29.11
15 min	16.57	22.2	25.81	28.75	29.61	33.02	35.97
30 min	21.31	28.95	34.02	38.35	39.57	44.54	48.96
1 h	24.72	34.72	42.05	49.15	51.23	60.01	68.98
2 h	28.82	40.89	50.69	61.08	64.31	78.06	93.20
6 h	37.61	53.23	66.27	80.38	84.81	103.76	124.94
12 h	42.78	59.28	72.84	87.34	91.86	111.36	133.07
24 h	48.83	66.97	81.74	97.37	102.22	123.15	146.29

SSP2-4.5 (Maximum based on PCIC Bias Corrected CMIP6) – Station 615S001 at Toronto North York

Duration	T (years)						
	2	5	10	20	25	50	100
5 min	9.57	12.71	15.01	18.32	19.52	23.57	28.44
10 min	14.21	19.35	23.24	28.83	30.92	37.99	46.75
15 min	16.97	23.69	29.29	37.95	41.28	53.52	70.41
30 min	22.84	33.97	42.81	55.18	59.93	75.66	96.26
1 h	27.31	41.32	52.51	68.25	74.25	94.19	120.59
2 h	31.50	46.51	59.24	77.39	84.57	109.83	144.31
6 h	38.09	55.26	70.02	91.69	100.22	131.05	173.74
12 h	42.09	59.35	74.07	96.86	105.67	138.46	182.52
24 h	48.30	65.58	79.64	101.61	110.18	140.73	182.52

SSP5-8.5 (Average based on CMIP6 GCMs) – Station HY069 at York Pump Station

Duration	T (years)						
	2	5	10	20	25	50	100
5 min	9.85	12.87	14.89	16.56	17.02	18.8	20.58
10 min	14.00	18.39	21.27	23.62	24.25	26.73	29.2
15 min	17.23	22.66	26.33	29.34	30.26	33.57	36.94
30 min	21.74	28.71	33.62	37.87	39.14	43.94	48.98
1 h	24.52	33.41	40.17	46.58	48.54	56.14	64.52
2 h	28.52	38.88	47.99	58.000	61.24	74.63	91.07
6 h	38.34	51.99	63.49	75.43	79.28	94.57	112.51
12 h	43.01	58.12	70.91	84.28	88.58	105.81	126.15
24 h	49.03	66.35	81.25	97.23	102.38	123.46	149.03

SSP5-8.5 (Maximum based on PCIC Bias Corrected CMIP6) – Station 615S001 at Toronto North

Duration	T (years)						
	2	5	10	20	25	50	100
5 min	9.99	13.51	16.39	19.82	21.14	25.49	31.13
10 min	14.86	20.55	25.35	31.19	33.43	40.97	51.11
15 min	17.84	25.29	32.25	41.25	44.57	57.03	74.47
30 min	23.93	36.05	46.45	59.59	64.39	81.43	104.05
1 h	28.63	43.83	56.95	73.62	79.67	101.32	130.02
2 h	33.12	49.53	64.33	83.67	90.93	117.24	153.12
6 h	40.06	58.97	76.41	99.33	107.88	139.54	183.30
12 h	44.27	63.44	81.56	105.26	114.02	147.22	193.66
24 h	50.75	69.99	87.87	110.64	119.04	150.26	194.24

RCP 4.5 (mid-Range based on PCIC Bias Corrected CMIP5) – Station 6158355 at Toronto City

Duration	T (years)						
	2	5	10	20	25	50	100
5 min	9.16	12.51	15.25	18.28	19.39	23.52	28.75
10 min	13.03	17.18	20.47	23.94	25.32	29.92	35.76
15 min	15.49	21.04	25.57	30.56	32.41	39.18	47.76
30 min	20.09	27.99	34.07	40.93	43.15	51.45	61.71
1 h	25.21	34.76	41.69	49.36	51.73	59.93	70.09
2 h	29.61	40.57	48.76	57.87	60.76	71.15	84.04
6 h	36.29	48.71	58.69	69.49	73.56	87.94	106.08
12 h	43.32	57.08	67.63	78.83	83.07	97.10	114.70
24 h	49.28	64.17	75.11	86.6	90.84	104.11	120.87

RCP 8.5 (mid-Range based on PCIC Bias Corrected CMIP5) – Station 6158355 at Toronto City

Duration	T (years)						
	2	5	10	20	25	50	100
5 min	9.600	13.4	16.18	19.42	20.52	24.27	28.68
10 min	13.65	18.4	21.72	25.5	26.74	31.05	36.01
15 min	16.23	22.54	27.14	32.48	34.28	40.46	47.70
30 min	21.07	30.05	36.29	43.18	45.50	53.40	62.83
1 h	26.41	37.36	44.40	51.93	54.50	62.72	72.59
2 h	31.03	43.58	51.93	60.98	63.99	74.200	86.39
6 h	38.01	52.19	62.29	73.88	77.73	91.04	106.53
12 h	45.36	61.14	71.88	83.72	87.61	101.07	116.63
24 h	51.58	68.81	79.98	91.77	95.74	108.94	124.39

APPENDIX B
Future Climate Rainfall Hyetographs

Appendix B - Rainfall and Hyetographs for Existing and Future Climate Scenarios

Rainfall Depth (mm)

Return Period	Existing (Buttonville station GEV distribution)		RCP 4.5 (Average based on CMIP5) – Station HY027 at G Ross Lord Dam		SSP2-4.5 (Maximum based on PCIC Bias Corrected CMIP6) – Station 615S001 at Toronto North York		SSP5-8.5 (Maximum based on PCIC Bias Corrected CMIP6) – Station 615S001 at Toronto North York	
	Rainfall Depth (mm)	Apply 0.905 Areal Reduction Factor	Rainfall Depth (mm)	Apply 0.905 Areal Reduction Factor	Rainfall Depth (mm)	Apply 0.905 Areal Reduction Factor	Rainfall Depth (mm)	Apply 0.905 Areal Reduction Factor
2	39.1	35.4	42.8	38.7	42.1	38.1	44.3	40.1
5	54.8	49.6	59.3	53.6	59.4	53.7	63.4	57.4
10	67.0	60.6	72.8	65.9	74.1	67.0	81.6	73.8
25	85.0	76.9	91.9	83.1	105.7	95.6	114.0	103.2
50	100.0	90.5	111.4	100.8	138.5	125.3	147.2	133.2
100	118.0	106.8	133.1	120.4	182.5	165.2	193.7	175.3

Hyetographs with 12-hour AES Distribution

Existing Scenario

Time (H:M)	2-year	5-year	10-year	25-year	50-year	100-year
0:00	0.0	0.0	0.0	0.0	0.0	0.0
1:00	4.6	6.5	7.9	10.0	11.8	13.9
2:00	9.2	12.9	15.8	20.0	23.5	27.8
3:00	7.1	9.9	12.1	15.4	18.1	21.4
4:00	5.3	7.4	9.1	11.5	13.6	16.0
5:00	5.0	6.9	8.5	10.8	12.7	15.0
6:00	2.8	4.0	4.9	6.2	7.2	8.5
7:00	1.1	1.5	1.8	2.3	2.7	3.2
8:00	0.4	0.5	0.6	0.8	0.9	1.1
9:00	0.0	0.0	0.0	0.0	0.0	0.0
10:00	0.0	0.0	0.0	0.0	0.0	0.0
11:00	0.0	0.0	0.0	0.0	0.0	0.0
12:00	0.0	0.0	0.0	0.0	0.0	0.0

RCP 4.5 Scenario (Average based on CMIP5) – Station HY027 at G Ross Lord Dam

Time (H:M)	2-year	5-year	10-year	25-year	50-year	100-year
0:00	0.0	0.0	0.0	0.0	0.0	0.0
1:00	5.0	7.0	8.6	10.8	13.1	15.7
2:00	10.1	13.9	17.1	21.6	26.2	31.3
3:00	7.7	10.7	13.2	16.6	20.2	24.1
4:00	5.8	8.0	9.9	12.5	15.1	18.1
5:00	5.4	7.5	9.2	11.6	14.1	16.9
6:00	3.1	4.3	5.3	6.7	8.1	9.6
7:00	1.2	1.6	2.0	2.5	3.0	3.6
8:00	0.4	0.5	0.7	0.8	1.0	1.2
9:00	0.0	0.0	0.0	0.0	0.0	0.0
10:00	0.0	0.0	0.0	0.0	0.0	0.0
11:00	0.0	0.0	0.0	0.0	0.0	0.0
12:00	0.0	0.0	0.0	0.0	0.0	0.0

SSP2-4.5 Scenario (Maximum based on PCIC Bias Corrected CMIP6) – Station 615S001 at Toronto North York

Time (H:M)	2-year	5-year	10-year	25-year	50-year	100-year
0:00	0.0	0.0	0.0	0.0	0.0	0.0
1:00	5.0	7.0	8.7	12.4	16.3	21.5
2:00	9.9	14.0	17.4	24.9	32.6	42.9
3:00	7.6	10.7	13.4	19.1	25.1	33.0
4:00	5.7	8.1	10.1	14.3	18.8	24.8
5:00	5.3	7.5	9.4	13.4	17.5	23.1
6:00	3.0	4.3	5.4	7.7	10.0	13.2
7:00	1.1	1.6	2.0	2.9	3.8	5.0
8:00	0.4	0.5	0.7	1.0	1.3	1.7
9:00	0.0	0.0	0.0	0.0	0.0	0.0
10:00	0.0	0.0	0.0	0.0	0.0	0.0
11:00	0.0	0.0	0.0	0.0	0.0	0.0
12:00	0.0	0.0	0.0	0.0	0.0	0.0

SSP5-8.5 Scenario (Maximum based on PCIC Bias Corrected CMIP6) – Station 615S001 at Toronto North York

Time (H:M)	2-year	5-year	10-year	25-year	50-year	100-year
0:00	0.0	0.0	0.0	0.0	0.0	0.0
1:00	5.2	7.5	9.6	13.4	17.3	22.8
2:00	10.4	14.9	19.2	26.8	34.6	45.6
3:00	8.0	11.5	14.8	20.6	26.6	35.1
4:00	6.0	8.6	11.1	15.5	20.0	26.3
5:00	5.6	8.0	10.3	14.4	18.7	24.5
6:00	3.2	4.6	5.9	8.3	10.7	14.0
7:00	1.2	1.7	2.2	3.1	4.0	5.3
8:00	0.4	0.6	0.7	1.0	1.3	1.8
9:00	0.0	0.0	0.0	0.0	0.0	0.0
10:00	0.0	0.0	0.0	0.0	0.0	0.0
11:00	0.0	0.0	0.0	0.0	0.0	0.0
12:00	0.0	0.0	0.0	0.0	0.0	0.0

APPENDIX C
Hydrological Modelling Sensitivity Analysis without Stormwater Management Ponds

Appendix C – SWM Ponds Sensitivity Analysis

Sensitivity Analysis on Q2-100 Flows

Below table shows peak flow results at the Watershed outlet, for different land use impervious scenarios, and for scenarios of SWM ponds included/excluded in the model.

T	Peak Flow at Node J295 (m^3/s)					
	SWM Ponds Including in the Model			SWM Ponds Excluding in the Model		
	Existing Condition (47% Impervious)	Impervious 5%	Impervious 30%	Existing Condition (47% Impervious)	Impervious 5%	Impervious 30%
2	20.7	0.7	11.6	22.3	0.7	12.5
5	30.4	1.3	17.7	32.6	1.5	19.2
10	37.9	2.0	22.5	41.0	2.3	24.3
25	47.1	3.1	29.2	52.5	3.5	31.6
50	57.8	4.0	34.7	62.4	4.4	37.8
100	68.9	5.0	41.5	73.7	5.4	45.0

Below table compares peak flow results between including SWM ponds scenario and excluding SWM ponds scenario, which show insignificant peak flow increases in the excluding SWM ponds scenario.

T	Percent Change compared "SWM Ponds Excluding in the Model" to "SWM Including in the Model " (Exclude Q - Include Q)/(Include Q)		
	Existing Condition (47% Impervious)	Impervious 5%	Impervious 30%
2	8%	6%	8%
5	7%	18%	8%
10	8%	14%	8%
25	12%	12%	8%
50	8%	10%	9%
100	7%	9%	9%

Below table compares peak flow results between existing scenario (including SWM ponds) and different impervious scenarios (for both including and excluding SWM ponds). The results show that SWM ponds in the model or not do not generally alter the overall peak flow reduction results caused by the reduction in imperviousness. For example, 100-yearpeak flow with 5% impervious landuse is reduced by 93% (compared with existing condition) when including SWM ponds, and when excluding SWM ponds, the flow is reduced by 92%.

T	Percent Change compared with "Existing Condition including SWM Ponds" (Q - Existing Include Q)/(Existing Include Q)			
	SWM Ponds Including in the Model		SWM Ponds Excluding in the Model	
	Impervious 5%	Impervious 30%	Impervious 5%	Impervious 30%
2	-97%	-44%	-96%	-40%
5	-96%	-42%	-95%	-37%
10	-95%	-41%	-94%	-36%
25	-93%	-38%	-93%	-33%
50	-93%	-40%	-92%	-35%
100	-93%	-40%	-92%	-35%

Sensitivity Analysis on Sub Q2

Below figure shows the Flow Exceedance Curves for existing landuse, 30% impervious landuse, 5% impervious landuse, and for both including and excluding SWM ponds scenario. The including SWM ponds scenario lines are solid, while the excluding SWM ponds scenario lines are dashed. The results indicate that including or excluding SWM ponds do not generally change the overall shape of the Flow Exceedance Curves for all landuse scenarios.