Study of the Impacts of Climate Change on Precipitation and Stormwater Management

Prepared for:
Greater Vancouver
Sewerage and Drainage
District

August 2018

August 3, 2018 Reference No. 11140666

Ms. Lillian Zaremba
Greater Vancouver Sewerage and Drainage District
Metro Vancouver
4730 Kingsway St.
Burnaby, BC V5H 4J5

Dear Ms. Zaremba:

Re: Study of the Impacts of Climate Change on Precipitation and Stormwater Management Final Report

GHD is pleased to provide the Greater Vancouver Sewerage and Drainage District with the attached Final Report for the Study of the Impacts of Climate Change on Precipitation and Stormwater Management. Should you have any questions or comments, please do not hesitate to contact me at the number listed below.

Yours truly,

GHD

Juraj M. Cunderlik, Ph.D., P.Eng.
Project Manager

JC/aj/2

Encl.

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Executive Summary

Climate change adaptation is one of the most important issues facing municipal, provincial, and federal governments today. Increased frequency and intensity of extreme rainfall events will have a significant impact on existing sewerage and stormwater collection infrastructure. Municipalities must adapt to changing rainfall regimes to ensure that adequate levels of service for infrastructure are maintained in the future.

The Greater Vancouver Sewerage and Drainage District (GVS&DD) has initiated this project for the purpose of advancing its knowledge and capabilities to adapt to the effects of climate change and to ensure that adequate levels of service for sewerage and stormwater collection infrastructure are maintained. There were four main objectives for this project:

- Define new homogeneous rainfall zones for Metro Vancouver and derive updated Intensity Duration Frequency (IDF) curves for each zone
- Quantify uncertainty surrounding future climate IDF projections and generate future climate IDF curves
- Determine the potential effect of climate change on the level of service of sewerage and stormwater collection infrastructure using three case studies, and
- Develop adaptation practices (good practice recommendations) for incorporating climate change into infrastructure planning and design

Current Climate Analysis

Engineers, planners, and policy makers utilize IDF curves in municipal planning and infrastructure design. IDF curves characterize the relationship between the intensity of rainfall occurring over a specified period and its frequency of occurrence. They are based on historical observations of rainfall. In order to plan for climate change, future climate IDF curves are desired.

An IDF curve update was performed for the Metro Vancouver region. A total of 126 rainfall monitoring stations were considered for the analysis, and 74 stations that had 10 or more years of data were retained in the analysis. Quality Assurance/Quality Control (QA/QC) was performed on the rainfall data, using a process based on the QA/QC process performed by Environment Canada.

A regional rainfall frequency analysis (RRFA) was used to produce regional IDF curves. The RRFA method consists of: identifying homogeneous rainfall zones, fitting a regional distribution, and estimating dimensionless IDF curves. Seven homogeneous rainfall zones were developed for this project. The dimensionless IDF curves must be scaled by the index rain to obtain the IDF curves for the area of interest.

An estimate of the index rain for the duration of interest is required for the study area, which can be determined from nearby station data, contour maps, or a regional regression. A set of contour maps was developed for all IDF durations as part of this project. The index rain is read from the maps and then utilized to scale the dimensionless IDF curve.

There were differences identified in the rainfall between the different Pacific Decadal Oscillation (PDO) phases. The IDF curves decreased for the warm phase PDO data, and increased for the cool phase PDO data. The level of sensitivity to PDO varied from location to location.

Future Climate Analysis

Future climate IDF curves are required for sustainable and resilient infrastructure planning and design. Currently, there is no standard or accepted methodology to derive IDF curves for future climate conditions. There are also many challenges in future climate IDF modelling.

One of the main technical challenges preventing the adoption of existing approaches for the development of future climate IDF curves arises from the inadequate temporal and spatial resolution of Global Circulation Model (GCM) outputs. A new downscaling methodology for deriving future climate IDF curves was developed for this project to address this issue. The methodology incorporates changes in sub-daily rainfall intensities and bias correction to preserve the temporal variability in IDF intensities for different rainfall durations. It also addresses the use of different spatial scales of rainfall data (climate stations, GCM grids, and homogeneous rainfall zones) in future climate modelling.

Projections of future climate IDF curves are subject to uncertainties in the prediction of the future (economy, population), limitations due to existing climate modelling, and other factors. In this project, uncertainties in future prediction were addressed by considering two greenhouse gas (GHG) emission scenarios. A suite of twelve GCMs addressed the uncertainties due to limitations in climate modelling techniques. Finally, the PDO phases and different frequency distributions addressed other sources of uncertainty.

A sensitivity analysis was used to evaluate the relative importance of the various sources of uncertainty in the definition of future climate IDF curves. The scaling factor, which defines the rate at which sub-daily rainfall intensities will increase in the future relative to daily rainfall, was found to be the most sensitive factor. Using a constant scaling factor of 1.0, it was found that the 95th percentile of the projections from the 12 GCMs approximated the effect of the scaling factor.

The moderate and high change future climate scenarios for the time horizons 2050 and 2100 were derived from the sensitivity analysis. The moderate and high scenarios were based on the median and 95th percentile projections of future climate, respectively. The moderate scenarios assumed that the scaling factors will remain unchanged while the high scenarios accounted for potential changes in the scaling factors in the future. The results suggested that the future climate rainfall intensities are expected to increase by 21% in 2050 and 41% in 2100 for the moderate change scenario, and by 44% in 2050 and 75% in 2100 for the high change scenario. The

Increase in IDF for:	Moderate future climate change	High future climate change
2050 Time Horizon	21%	44%
2100 Time Horizon	41%	75%

moderate and high change scenario results also suggested that a storm of a certain magnitude will become more frequent in the future.

Infrastructure Case Studies

Three case studies were analyzed to determine the effects of increased rainfall on the level of service of sewerage and stormwater collection infrastructure. The cost of infrastructure upgrades to maintain the level of service was also evaluated.

The first case study was the Glenbrook combined and separated trunk sewer. The level of service will decrease due to a combination of three factors: population growth (combined trunk sewer only), sea level rise, and increased rainfall. Pipe upsizing was required for the 2050 scenarios, and future upsizing was required for the 2100 scenarios. The infrastructure upgrade cost for the 2050 and 2100 scenarios was three and four times the cost to upgrade the system to meet the current level of service, respectively. The increase in cost between the high and moderate scenarios in each time horizon was relatively small: approximately 10 to 15 percent.

The second case study examined the Port Moody-Coquitlam Drainage Area (PMCDA). The scenarios examined sea level rise and increased rainfall. The current source control guidelines restrict the current peak flow, but the increased rainfall in the future climate change scenarios caused the peak flow to increase even with the source controls. As a result, infrastructure upgrades will be required. The cost for the 2050 and the 2100 scenarios was two times and three to four times the cost to upgrade the system to meet the current level of service. The increase in cost between the high and moderate scenarios in each time horizon was similar to the Glenbrook study: approximately 10 to 20 percent.

The third case study was the Collingwood sanitary trunk sewer. Two factors will impact the capacity of the sanitary trunk sewer: population growth (increased sanitary sewage flow) and increased rainfall-derived inflow and infiltration (RDII). The infrastructure upgrade cost was low for the 2050 scenarios because the sanitary sewer flow was generally less than the capacity of the trunk sewer and there was additional capacity to accommodate the increased RDII. For the 2100 scenarios, the trunk sewer was flowing near the maximum capacity according to the design requirement, and performing infrastructure upgrades to accommodate the increased RDII resulted in a cost increase of five to seven times the cost of upgrading for population growth alone. The increase in cost between the moderate and high scenarios in each time horizon was relatively high: approximately 40-50 percent.

Climate Change Adaptation Practices

Climate change considerations must be integrated into the business process framework, including planning, design, support services, and performance management. A formal Climate Change Policy (CCP) will provide guidelines, consistency, and context for climate change adaptation planning. For instance, performance expectations for infrastructure will set climate change objectives and level of service targets. The CCP is a priority for the GVS&DD as it will guide the adaptation planning process and assist in the creation of a "climate change culture".

There is no "one size fits all" future climate scenario to use for infrastructure planning and design. Identifying the current or future climate scenario to use for planning and design should consider the level of risk due to failure of the infrastructure and the planning horizon/design life:

- In general, there are three approaches to climate change adaptation: do nothing (no climate change adaptation), middle of the road (moderate change in climate), and worst-case (high change in climate). It is recommended that the do nothing approach be used for temporary infrastructure or infrastructure near its end of life (less than five years of service). It is recommended that the worst-case approached be used for high-risk infrastructure (i.e. with catastrophic or high consequences of failure). The middle of the road approach is appropriate for other infrastructure.
- It is recommended that the time horizon be selected based on the planning horizon or design life of the infrastructure. Interpolation between the 2050 and 2100 time horizons can also be considered.

A vulnerability assessment and risk analysis will help to evaluate existing infrastructure based on the level of consequence and the likelihood of failure. The infrastructure can then be ranked to reflect the risk thresholds of GVS&DD and allow for prioritization of climate change adaptation. The selection of preferred adaptation measures for the infrastructure can consider a number of alternatives, including pipe upsizing and peak flow reduction measures. Decision making methods can incorporate cost-benefit analysis or multi-criteria analysis to select the preferred adaptation measures. The results of the cost-benefit and/or multi-criteria analyses can then form the basis of the 10-year infrastructure capital plan.

Design standards and guidelines have historically not accounted for climate change. It is recommended that climate change be explicitly accounted for in design by incorporating future climate IDF curves and future sea level. It is recommended that the regulatory framework, such as stormwater source control guidelines and wastewater design guidelines, be reviewed to introduce measures for adaptation to climate change.

Maintaining climate change adaptation over the long-term is key to success. To achieve success in long-term climate change adaptation, it must be supported within the organization, and the performance must be monitored and managed. For instance, formalizing climate change knowledge and skills throughout the organization ensures that key climate change competencies are not lost when a staff member leaves the organization. A data management strategy that specifies how key climate change variables will be monitored and the data archived is required for ensuring that climate change adaptation efforts are successful and meeting the needs of infrastructure/users. For instance, the data management strategy can incorporate thresholds that trigger a new analysis of potential climate change impacts (e.g. a new future climate IDF curve analysis), a greater level of climate change adaptation, or a strategic change in the organization's approach to climate change adaptation. In addition, it is recommended that the GVS&DD continue to actively acquire knowledge about new climate change adaptation practices, tools, and techniques.

List of Abbreviations

AEP | Annual Exceedance Probability

AES | Atmospheric Environment Service

AM | Annual Maximum

AR | Atmospheric River

BARC | Building Adaptive and Resilient Communities

BC | British Columbia

BCCAQ | Bias Correction/Constructed Analogues with Quantile mapping reordering

BCSD | Bias-Corrected Spatial Disaggregation

C-C | Clausius-Clapeyron relation

CCP | Climate Change Policy

CDF | Cumulative Distribution Function

CSA | Canadian Standards Association

EC | Environment Canada

ENSO | El Niño Southern Oscillation

EQM | Equidistant Quantile Mapping

FSA | Fraser Sewerage Area

GCM | Global Circulation Model

GEV | Generalized Extreme Value frequency distribution

GI | Green Infrastructure

GHG | Greenhouse Gas

GLO | Generalized Logistic frequency distribution

GNO | Generalized Normal frequency distribution

GPA | Generalized Pareto frequency distribution

GVS&DD | Greater Vancouver Sewerage and Drainage District

IDF | Intensity Duration Frequency

IPCC | Intergovernmental Panel on Climate Change

LID | Low Impact Development

NAO | North Atlantic Oscillation

PCIC | Pacific Climate Impacts Consortium

PDO | Pacific Decadal Oscillation

PE3 | Pearson Type III frequency distribution

PMCDA | Port Moody-Coquitlam Drainage Area

QA/QC | Quality Assurance/Quality Control

RCP | Representative Concentration Pathway

RDII | Rainfall-Derived Inflow and Infiltration

RFD | Regional Frequency Distribution

RRFA | Regional Rainfall Frequency Analysis

TBRG | Tipping Bucket Rain Gauge

VSA | Vancouver Sewerage Area

WMO | World Meteorological Organization

Glossary of Terms

Adaptive Pathways Planning Process | A cyclical process that supports policy and decision making. It consists of five steps: Setting objectives, Assessing adaptation tipping points, Exploring and selecting policy responses, Combining the responses into combinations of alternative pathways, and Incorporating multiple stakeholder preferences.

Annual Exceedance Probability, AEP | The probability (expressed in percent) that an event of a particular magnitude will be exceeded in any year. AEP can be converted to **return period** by dividing 100% by the AEP.

Annual Maximum, AM | The largest rainfall depth or intensity observed at a station for a particular duration in a given calendar year.

Atmospheric River, AR | A thin band of moisture (also called a "**Pineapple Express**") in the atmosphere that transfers moisture from the tropical regions towards the North or South Poles. An AR results in large rainfall events when it reaches land. There are between 12 and 24 AR events that affect the western coast of North America in a year.

BARC Framework | A five-milestone framework developed by **ICLEI** to assist communities in adapting to the impacts of climate change and developing a climate change adaptation plan. The five milestones are: Initiate, Research, Plan, Implement, and Monitor/Review.

Bias | A systematic (i.e. not random) distortion of a set of data compared to the true distribution.

Bias Correction | This refers to the process of removing **bias** from the future **quantiles**. **Bias** can develop from the conversion between daily and sub-daily **quantiles**, especially when **scaling factors** are used. **Bias** can also develop when converting from the grid-level GCM **quantiles** to the **quantiles** at a station.

Boxplot | A statistical tool that graphically displays the range of values in the variable being plotted. A boxplot consists of a rectangle in the middle that spans from the first **quartile** to the third **quartile** of the data. A horizontal line inside the rectangle shows the location of the **median** value. There are two whiskers above and below the rectangle, which extend to 1.5 times the **interquartile range** beyond the rectangle. Values above or below the whiskers are considered to be outliers and are shown as dots outside of the whiskers.

Clausius-Clapeyron (C-C) Relation | A relationship between air temperature and saturated vapour pressure. Westra et al. (2014) proposed that this relationship could be used to predict the expected increase in sub-daily rainfall intensities.

Daily to Sub-Daily Ratios | A **temporal downscaling** method to convert daily GCM predictions to the sub-daily durations used in an IDF curve. Historical AM data are used to estimate the ratio between the AM for a duration and the AM for the 24-hr duration.

Delta Method | A method to describe the differences between the future climate and the current climate. The rainfall delta is the ratio between the future rainfall and the current rainfall for a time horizon of interest. A delta of one indicates no change in rainfall, while a delta greater (smaller) than one indicates an increase (decrease) in rainfall.

El Niño Southern Oscillation, ENSO | A two- to seven-year oscillation pattern that affects rainfall intensities and frequencies.

Freeboard | The distance between the highest level of water in a manhole and the ground level.

Frequency Distribution | A statistical relationship that describes the frequency of occurrence of different values of a variable.

Global Circulation Model, GCM | A climate model that mathematically models the general circulation patterns of the planetary atmosphere and ocean. They are used to model different future **GHG** concentrations and determine the possible effects of the **GHG** concentrations on the future climate.

Greenhouse Gas, GHG | A gas in the atmosphere that absorbs and/or emits thermal radiation. As the concentrations of GHGs rise, the Earth becomes warmer because thermal energy is trapped near the Earth's surface.

High Change Scenario| Future climate **IDF curve** that represents an extreme prediction of the future rainfall estimated by **GCMs**. It was estimated as the 95th **percentile** estimate of the **GCMs**, and used the RCP8.5 scenario.

Homogeneous Zone | A group of rainfall monitoring stations with **AM** data that display **statistical homogeneity**. The group of stations can be represented by a single regional **IDF curve**.

ICLEI | An association of local governments committed to achieving tangible improvements in environmental sustainability. See http://www.icleicanada.org/.

IDF curve | A mathematical relationship between the intensity, duration, and frequency of occurrence of rainfall.

IDF-CC | An online tool developed by Srivastav et al. (2015) to develop Intensity Duration Frequency curves under Climate Change.

Index Rain | A method to scale the dimensionless **IDF curves.** The index rain for a particular duration at a rainfall monitoring location is derived as the arithmetic average of the **AM** rainfall observations at that duration. When the location is not a rainfall monitoring station, it is an estimate taken from the index rain contour maps.

Interquartile Range | The difference between the third **quartile** and the first **quartile**.

Linear Moments, L-Moments | Analogues to standard moments that are linear combinations of the data and do not require exponentiation of the data residuals as in the estimation of standard moments. They are known to be robust and less sensitive to outliers than standard moments.

Mean of the Annual Maximum Rainfall | The arithmetic average of the **AM** rainfall at a given duration. Equivalent to the **index rain** at a rainfall monitoring location.

Median | The data value in a data set where half of the data are below, and half are above. If there are an odd number of values in the data set, it is the middle number when the values are ranked in order from lowest to highest. If there are an even number of values in the data set, it is the average of the two middle numbers.

Moderate Change Scenario | Future climate **IDF curve** that represents a mid-range but still conservative prediction of the future rainfall estimated by **GCMs**. It was estimated as the median estimate of the **GCMs** using the RCP8.5 scenario.

Pacific Decadal Oscillation, PDO | A long-term (40-70 year) cyclical variability in monthly sea surface temperature data. During a "cool" PDO phase, high intensity rainfall events occur more frequently and with higher amounts. The opposite is true during a "warm" PDO phase.

Percentile | A statistical measure of how much of the range of data is below the percentile. For instance, the 95th percentile is the data value where 95% of the data are below the value.

Pineapple Express | See **Atmospheric River**.

Quantile | One of a set of values that divide a variable into equal groups, with each group containing the same fraction of the population.

Quantile Mapping | A **bias correction** technique that develops a linear or non-linear mapping function between the **quantiles** of two data sets. It monotonically transforms the biased data to the "true" values based on the unbiased data set.

Quartile | A **quantile** that divides the data into four equal groups. There are three quartiles: the first quartile, the **median** (second quartile), and the third quartile. The first quartile is the data value where 25% of the data are below the value. The **median** is the data value where 50% of the data are below the value. The third quartile is the data value where 75% of the data are below the value.

Rainfall-Derived Inflow and Infiltration, RDII | Water (rainwater and/or groundwater) that enters the sewer system through cracks in the sewer pipes. Sump pumps and/or roof leaders can also be connected to the sewer system in some older developments.

Regional Rainfall Frequency Analysis, RRFA | The Hosking and Wallis (1997) method used to produce regional **IDF curves** for the Metro Vancouver region. The method consists of: identifying homogeneous rainfall zones, fitting a regional distribution, and estimating dimensionless IDF curves. The dimensionless IDF curves must be scaled by the **index rain** for the area of interest.

Representative Concentration Pathways, RCP | Trajectories of future **GHG** concentrations adopted by the Fifth Assessment Report of the IPCC (2013). RCPs are defined by the total radiative forcing (in Watts per square meter) and are used as input for **GCMs**.

Return Period | The average recurrence interval (in years) of an event greater than a particular magnitude. It can be converted to **AEP** by calculating one divided by the return period and converting the result to a percentage.

Scaling Factor | **Daily to sub-daily ratios** are estimated using historical data, which may or may not accurately represent the **daily to sub-daily ratios** under future climate change. The scaling factor is used to adjust the **daily to sub-daily ratios** in the future. A scaling factor of one indicates that the **daily to sub-daily ratios** are temporally invariant (constant), while a scaling factor higher than one indicates that the **daily to sub-daily ratios** increase under climate change (i.e. future short duration events become more intense relative to the future 24-hr event).

Sensitivity Analysis | A method to determine the relative importance of multiple sources of uncertainty by modelling combinations of the various sources of uncertainty. The results are evaluated and compared to determine the relative importance of each source of uncertainty.

Source Controls | A group of methods that capture stormwater. Some source controls infiltrate the stormwater so that it does not runoff, while other source controls retain the stormwater and release it into the environment over a long period of time (e.g. 24 hours). They can be used to achieve peak flow reduction targets during redevelopment of a parcel of land.

Spatial Downscaling | A collection of statistical techniques to convert **GCM** predictions on a grid scale of approximately one to three degrees (100 to 300 km) in size to predictions at a local scale (at a station).

Statistical Homogeneity | Samples from two or more groups of observations (e.g. at different rainfall monitoring locations) are said to be statistically homogeneous if they come from identical populations.

Temporal Downscaling | A collection of statistical techniques to convert **GCM**-scale predictions (generally daily or monthly) to sub-daily predictions.

Time Horizon | A future time period that is of interest for analysis. Two time horizons were examined in this project: 2050 and 2100. The 2050 time horizon uses **GCM** projections for 2036 to 2065. The 2100 time horizon uses GCM projections for 2070 to 2099.

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1. Introduction

1.1 Project Background

1.1.1 GVS&DD System

The Greater Vancouver Sewerage and Drainage District (GVS&DD) provides sewerage, drainage and stormwater collection services to 19 member municipalities. The sewerage collection system within the boundaries of Metro Vancouver consists of municipal sewers that are owned and managed by the municipalities and regional trunk sewers that are owned and managed by the GVS&DD. The GVS&DD is also responsible for 33 pump stations and five wastewater treatment plants.

Part of the regional sewerage system is a combined sanitary and storm sewer network that dates from the early 1900s. The GVS&DD and affected member municipalities plan to fully separate the combined sewer systems in the Vancouver Sewerage Area (VSA) by 2050 and in the Fraser Sewerage Area (FSA) by 2075.

The GVS&DD provides stormwater drainage services in two large areas (the Still Creek-Brunette River Drainage Area and the Port Moody-Coquitlam Drainage Area). The GVS&DD is responsible for maintenance of the open channel areas and regional storm trunk sewers. The municipalities are responsible for the local stormwater collection systems and developing stormwater management bylaws.

1.1.2 Climate Change Vulnerability and Risk in the GVS&DD System

Kerr Wood Leidal (2008 and 2009) identified the vulnerabilities in the VSA and the FSA. The main vulnerabilities were: combined sewer systems and pump stations (due to increased flows from rainfall events), and the wastewater treatment plants (due to increased flows and rising sea levels). There will be increased flows in combined sewer systems due to the increased rainfall intensities and volumes, and therefore combined sewer overflows will be more frequent and discharge greater volumes into the environment. Increased flows due to increased rainfall derived inflow and infiltration (RDII) in sewage–only systems can lead to pipe or pump station capacity concerns and overflows/basement backups/etc. The wastewater treatment plants can handle the increased flows but treatment performance may be degraded. The discharge facilities, which require sufficient hydraulic head to function efficiently, will be impacted by higher sea levels.

Metro Vancouver also commissioned a Climate Change Adaptation Risk Management Study (Black Shield Preparedness Solutions, Inc., 2010). The study identified three extreme risk events: increases in sewerage collection system overflows, increased stormwater flooding, and sea level rise damage to infrastructure and waterways.

Metro Vancouver initiated the ICLEI Building Adaptive and Resilient Communities (BARC) process in 2012. The BARC process is a straightforward approach to adaptation planning that uses a five-milestone framework (initiate, research, plan, implement, and monitor). Metro Vancouver has completed Milestones 1 and 2, and plans to complete Milestone 3 in 2018. This process will provide a suitable framework in which to plan for and adapt to climate change.

Metro Vancouver is currently developing a climate change strategy to 2050. The two main components of the strategy include ensuring that infrastructure, ecosystems and communities are resilient to climate change, and an 80% reduction in greenhouse gas (GHG) emissions by 2050. As part of the first component of the strategy, Metro Vancouver will ensure that their operations and assets are resilient to climate change, and assist member municipalities with their climate change adaptation efforts.

1.1.3 Climate Change Impact on Precipitation

In partnership with the Pacific Climate Impacts Consortium (PCIC), Metro Vancouver has developed climate projections for the region (Metro Vancouver, 2016). The total annual precipitation is expected to rise by 5% by the 2050s and 11% by the 2080s. However, the precipitation is expected to increase mainly in the fall, winter, and spring, and decrease in the summer. Since the majority of extreme events occur from October to April, the unequal distribution of precipitation throughout the year indicates that the increase in autumn precipitation may be as high as 11% by the 2050s and 20% by the 2080s (Metro Vancouver, 2016).

Engineers, planners, and policy makers use rainfall Intensity Duration Frequency (IDF) curves in municipal planning and infrastructure design. IDF curves characterize the relationship between the intensity of rainfall occurring over a specified period the time and its frequency of occurrence. They are based on historical observations of rainfall. In order to plan for climate change, future climate IDF curves are desired. Previously, BGC (2009a) developed regional IDF curves for the Metro Vancouver region. BGC (2009a) identified nine homogeneous rainfall zones using universal kriging on the average annual rainfall totals. BGC (2009b) also developed adjusted IDF curves for 2050 for 10 stations in Metro Vancouver. The analysis projected a 21% increase in rainfall intensity, which was utilized with regression equations to develop projected increases in rainfall intensities for durations from 1 hour to 24 hours.

1.2 Project Objectives

The GVS&DD initiated this project for the purpose of advancing its knowledge and adaptability to the effects of climate change to ensure that adequate levels of service for sewerage and stormwater collection infrastructure are maintained.

During past collaboration between GVS&DD and PCIC, it was found that future climate IDF curves were of interest to stakeholders to assist them with planning and adaptation. In response, GVS&DD initiated this project, which has four objectives.

- Define new homogeneous rainfall zones for Metro Vancouver and for each zone derive updated IDF curves.
- Quantify uncertainty surrounding future climate IDF projections and generate future climate IDF curves.

- Determine the potential effect of climate change on the level of service of sewerage and stormwater collection infrastructure using three case studies.
- Develop adaptation practices (good practice recommendations) for incorporating climate change into infrastructure planning and design.

1.3 Report Organization

There are three main sections in the remainder of this report: Methodology and Results (Section 2), Conclusions and Recommendations (Section 3), and Next Steps (Section 4). Section 2 is organized into four sub-sections that follow the four objectives of the project: current climate analysis, future climate analysis, infrastructure case studies, and climate change adaptation practices.

This report provides a summary of the main findings of the project. Detailed descriptions of the methodologies and results are included in five Technical Memoranda (TM), which are listed in Table 1.1 and attached at the end of the report.

Table 1.1 Technical Memoranda

Technical Memorandum Number	Technical Memorandum Name	Contents
1	Temporal Downscaling Methodology	• Methodology for temporal downscaling to derive future climate projections of sub-daily rainfall intensities
2	Rainfall Analysis and IDF Curve Update	• Rainfall data analysis • Derivation of updated IDF curves
3	Derivation of Future Climate IDF Curves	• Sensitivity analysis of sources of uncertainty in deriving future climate IDF curves • Derivation of future climate IDF curves for 2050 moderate change, 2050 high change, 2100 moderate change, and 2100 high change
4	Case Studies	• Analysis of case studies to determine effects of increased rainfall on sewerage and stormwater collection infrastructure
5	Good Practice Recommendations	• Good practice recommendations for Metro Vancouver • Literature review of good practices by Metro Vancouver and other jurisdictions to plan for and adapt to climate change

2. Methodology and Results

2.1 Current Climate Analysis

The current climate IDF curves for the Metro Vancouver region were updated with rainfall data up to 2016. The IDF curve update methodology adopted in this project (Figure 2.1) consists of four main steps: station selection, data QA/QC, developing homogeneous rainfall zones, and IDF fitting. The next four subsections describe each of the four steps in detail. The last subsection discusses the effect of the PDO on the IDF curves.

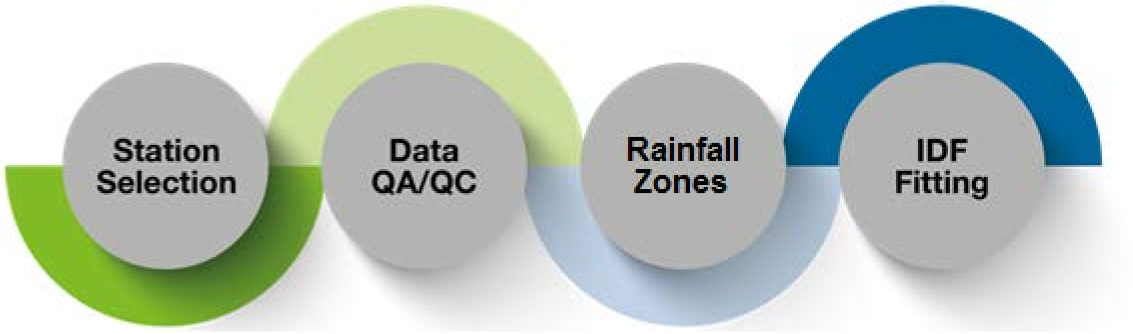


Figure 2.1 IDF Update Methodology

2.1.1 Station Selection

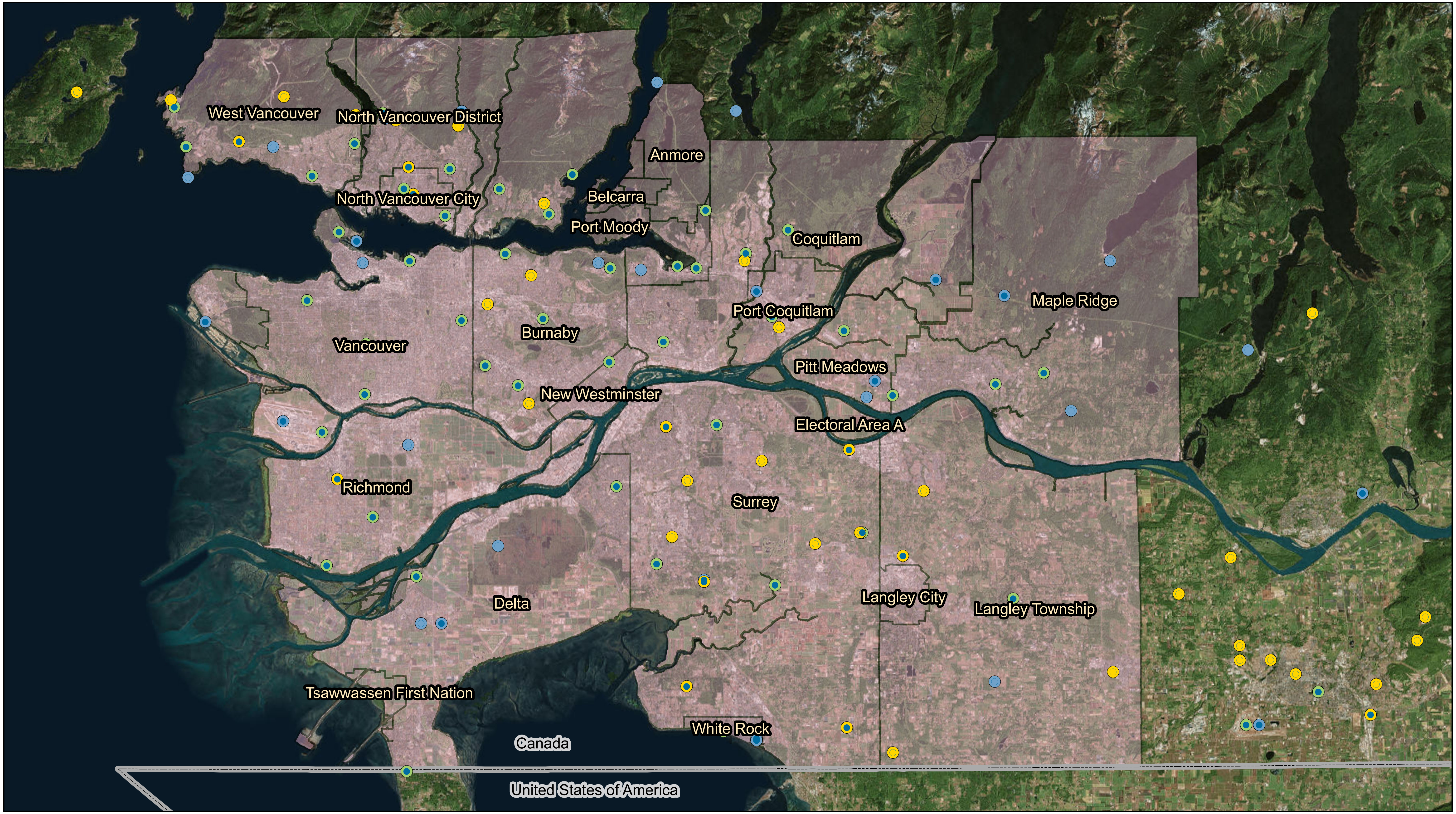
The first step of the IDF update methodology was station selection. There is a relatively dense rainfall monitoring network (126 rainfall monitoring locations) in the Metro Vancouver region (Figure 2.2). The stations are owned by Environment Canada (EC), Metro Vancouver, or by one of the member municipalities. The data quality at each station was ranked utilizing three criteria:

- **Record length |** EC requires a minimum time period of ten years for IDF curve analysis.
- **Measurement frequency |** IDF curves contain durations from five minutes to 24 hours.
- **Level of QA/QC |** EC applies QA/QC to their rainfall data, but the rainfall observations collected by Metro Vancouver or member municipalities are typically not subject to QA/QC.

The data quality ranking is summarized in Table 2.1. The stations with data quality rankings of "A" and "B" were retained in the IDF curve update analysis. A detailed description of the data ranking process is provided in Section 2.2 of TM2.

Table 2.1 Data Quality Ranking

Rank	Number of years ≥10?	Is rainfall measured at 5-min frequency?	Has QA/QC been applied?	Number of Stations
A	✓	✓	✓	15
B	✓	✓	✗	62
C	✓	✗		8
D	✗			41



Source: ESRI World Imagery Service.

0 2 4 6
Kilometres

Coordinate System:
NAD 1983 UTM Zone 10N

N

Legend

● Location Retained for Analysis
○ Location Omitted from Analysis
▭ Municipal Boundaries
● Environment Canada Station
● Metro Vancouver Station
● Local Municipality Station

GHD

METRO VANCOUVER
BRITISH COLUMBIA, CANADA

RAINFALL MONITORING NETWORK IN THE
METRO VANCOUVER REGION

11140666-01
Aug 1, 2018

FIGURE 2.2

GIS File: Q:\GIS\PROJECTS\11140000s\11140666\Layouts\MEMO002\11140666-01(MEMO002)GIS-WA001-Updated.mxd

2.1.1 Data QA/QC

The second step of the IDF update methodology, data QA/QC, was performed on the rainfall data for the Metro Vancouver and member municipality stations as part of the process of developing the annual maximum (AM) time series for each station. No QA/QC was performed on the EC rainfall data.

The QA/QC process was based on the QA/QC process performed by EC as described by the Canadian Standards Association (CSA, 2012), but additional checks were added for this analysis (e.g. checks for snowfall). A detailed description of the QA/QC process is in Section 2.3 of TM2.

2.1.2 Homogeneous Rainfall Zones

The third step of the IDF update methodology involved developing homogeneous rainfall zones. Within an IDF curve, there are nine durations from 5-min to 24-hr. The types of rainfall events that cause AM for short durations are different from the types of rainfall that cause AM for long durations (Figure 2.3). Zones that are homogeneous when tested with the 24-hr AM duration data may or may not be homogeneous for short duration rainfall. Using different variables to produce homogeneous zones will result in different zones. To obtain homogeneous zones for all nine durations of an IDF curve, the AM data for the nine durations were used to produced the homogeneous rainfall zones.

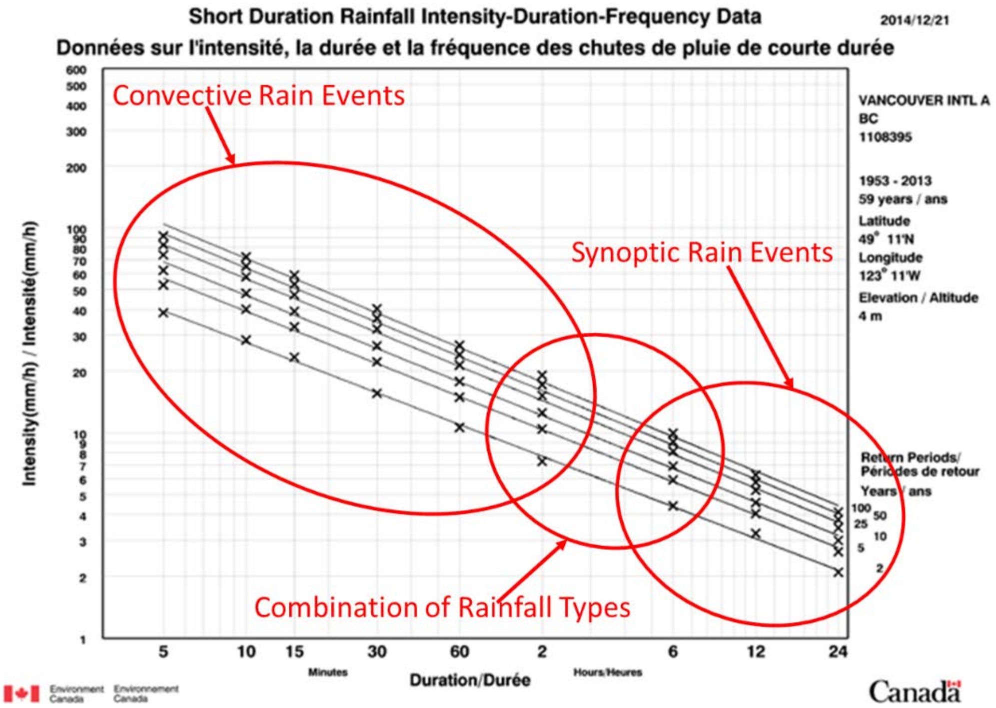


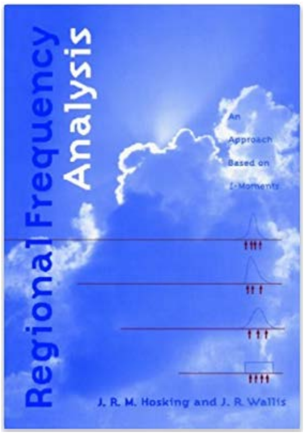
Figure 2.3 Rainfall Events for Different IDF Durations

The Hosking and Wallis (1997) homogeneity criterion was utilized to test the homogeneity of the zones with the AM data for all durations from 5-min to 24-hr. The process to develop homogeneous rainfall zones was an iterative process that involved K-means clustering and refinement of the zones. The following criteria were used to evaluate and optimize the zones:

- Inter-zone dissimilarity: the goal was to maximize the dissimilarity among the rainfall zones
- Intra-zone heterogeneity: the goal was to minimize heterogeneity (maximize homogeneity) within each zone
- Number of zones: the goal was to find an optimal number of stations in each zone (the zones are not too large or too small)

The final zones are shown in Figure 2.4. The zone boundaries are gradual and therefore approximate. The zones are representative of the data used to define them (a different data set will produce different zones/boundaries). A detailed description of the development of the homogeneous rainfall zones is provided in Section 3.1 of TM2.

2.1.3 IDF Curve Update

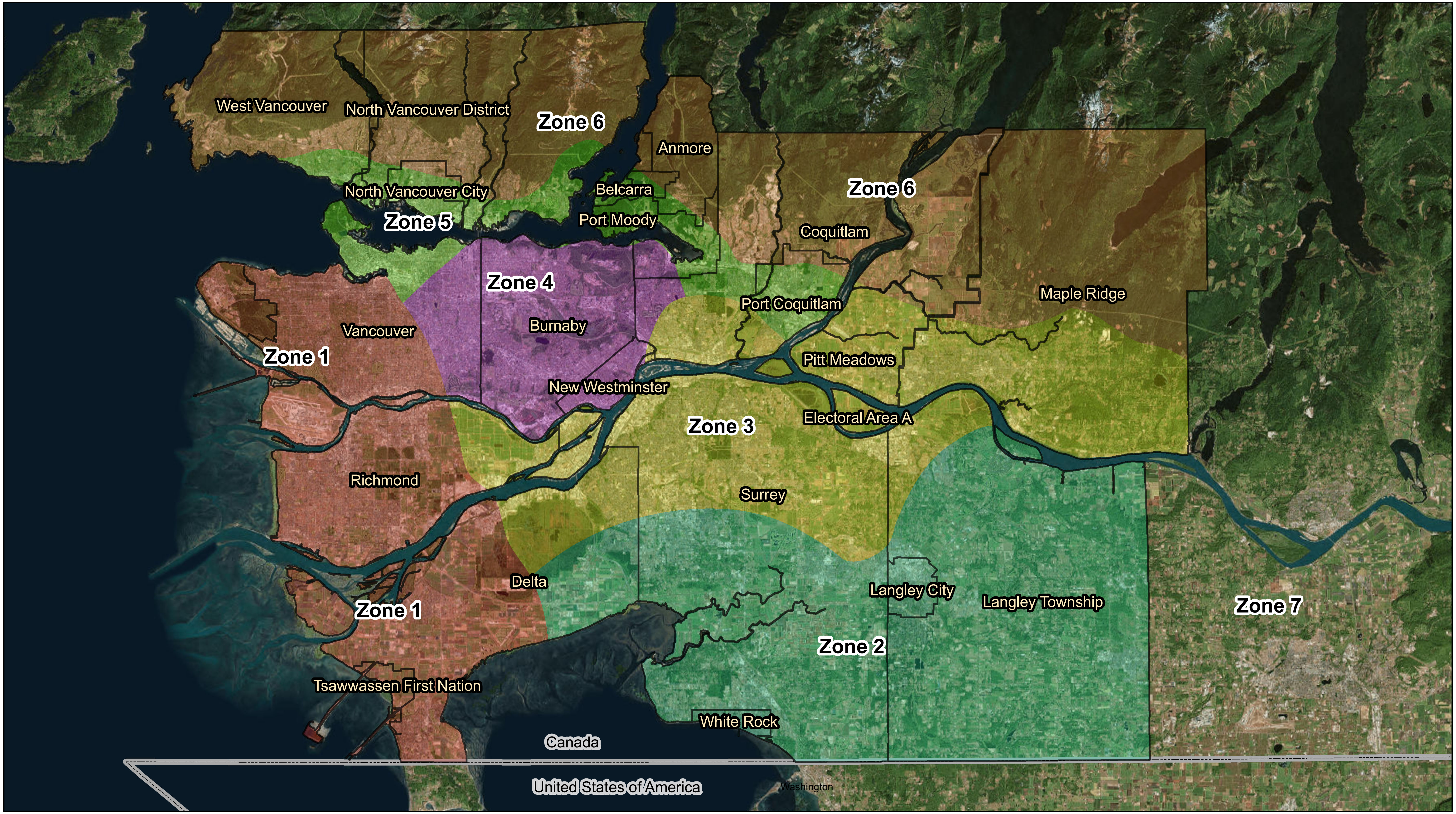


The fourth and last step of the IDF updated methodology was performing the IDF curve update. Regional IDF curves for the Metro Vancouver region were previously updated by BGC (2009a) to incorporate rainfall data up to, and including, the year 2008. The IDF curves were updated to incorporate data up to 2016. The Hosking and Wallis (1997) methodology was selected for the regional rainfall frequency analysis (RRFA). A detailed description of the IDF update is provided in Section 3.2 of TM2.

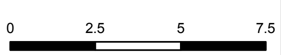
The RRFA method produces dimensionless IDF curves (with mean equal to one). The dimensionless IDF curves provide the shape of the IDF curve within each homogeneous zone.

The dimensionless IDF curves are scaled by the index rain. The index rain is the mean AM rainfall at each duration at a rainfall monitoring station or at a study area. Contour maps of the mean AM rainfall have been produced, and these can be used to estimate the index rain for the study area. The index rain can also be compared to data from a nearby rainfall monitoring station or local knowledge of the study area, where available.

If the study area is located across more than one zone, there will be one IDF curve for each part of the study area. If the user does not want to utilize multiple IDF curves, the most conservative IDF curve may be used. However, the IDF curves for each zone represent different rainfall regimes and selecting the most conservative option may provide biased results.



Source: ESRI World Imagery Service.



Coordinate System:
NAD 1983 UTM Zone 10N

METRO VANCOUVER
BRITISH COLUMBIA, CANADA

11140666-01
Aug 1, 2018

RAINFALL ZONES

FIGURE 2.4

GIS File: Q:\GIS\PROJECTS\11140000s\11140666\Layouts\MEMO002\11140666-01(MEMO002)GIS-WA014-updated-Brochure.mxd

Figure 2.5 describes the process of deriving the IDF curve to use for a study area. Each part of the figure has been labelled with a number. Detailed instructions for each part of the figure are provided below the figure.

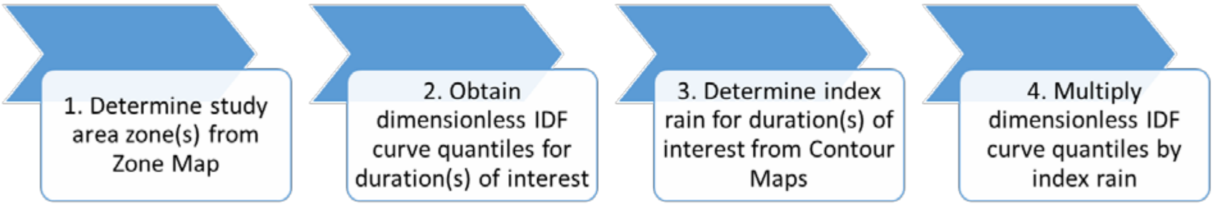


Figure 2.5 Development of Current Climate IDF Curves

1. The Zone Map has been provided in Figure 2.4. It is possible for a study area to cross multiple zones. In this case, follow the process for all zones, and account for multiple IDF curves in the analysis.
2. The dimensionless IDF curve values are included in Appendix C of TM2. Use the dimensionless IDF curve for the zone(s) of the study area and the duration(s) of interest.
3. Contour Maps for all durations have been provided in Appendix D of TM2. Read the index rain from the map for the duration(s) of interest.
4. Multiply the dimensionless IDF curve values by the index rain. For instance, if the dimensionless IDF curve quantile for a particular duration and AEP is 2 and the index rain for that duration is 4 mm, then the IDF curve rainfall depth for that duration and AEP is 8 mm.

2.1.4 Effect of Pacific Decadal Oscillation

The climate in Metro Vancouver is subject to long-term (low frequency) variability due to the PDO. The PDO phase is designated as either "cool" or "warm" depending on the sign of the PDO index (Figure 2.6). Significant differences in the rainfall regimes between the different PDO phases were identified in the Metro Vancouver region (Kerr Wood Leidal, 2002 and Murdock et al., 2007).

The IDF curve data were separated into warm and cool PDO index, and the effect on the IDF curves of separating the data is presented in Figure 2.7. Using only the data with warm PDO index, there is a general decrease in the IDF curves. The decreases range to more than 10%, but there are also stations with little or no decrease in the IDF curves. The IDF curves generally increase using the cool PDO index. The changes for cool data are smaller (absolute magnitude) than the changes for warm data. Given the high level of variability in the effect of PDO phase on IDF curves, it is preferable to use all data in the analysis. A detailed description of the PDO phase analysis is provided in Section 3.5 of TM2.

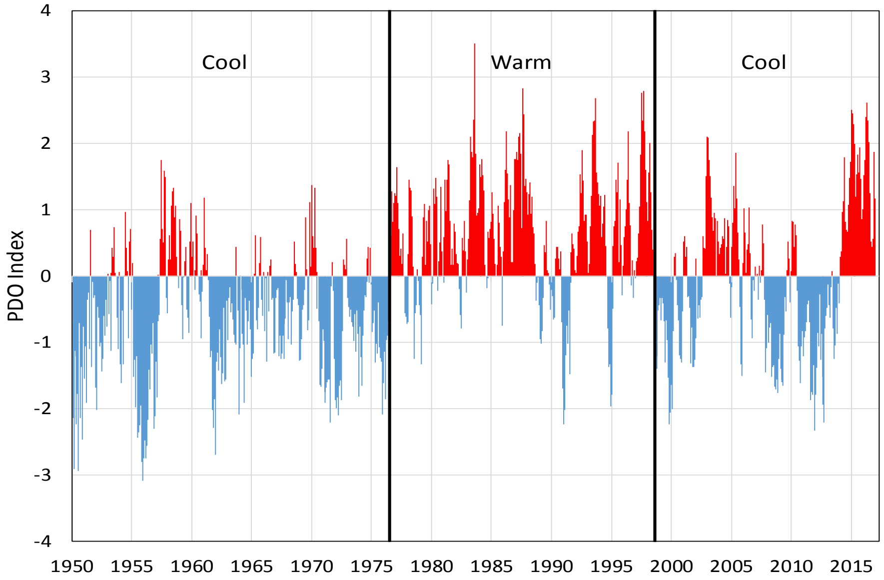


Figure 2.6 Pacific Decadal Oscillation Index

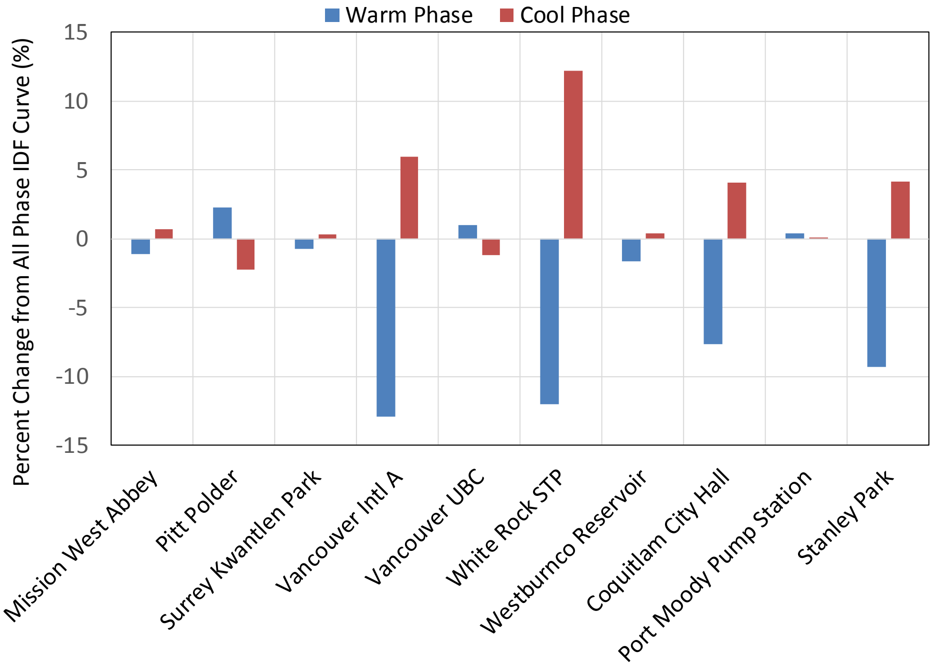


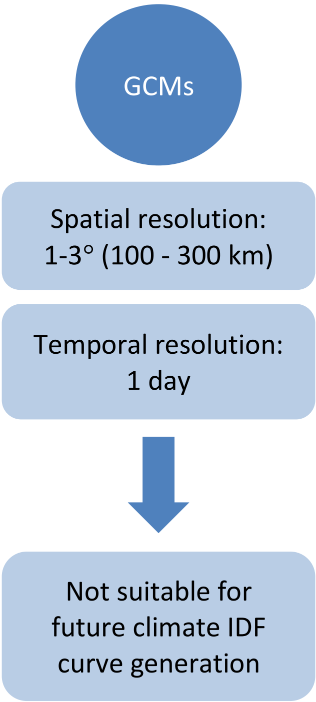
Figure 2.7 Change in IDF Curve for Warm Phase and Cool Phase PDO

2.2 Future Climate Analysis

Future climate IDF curves are required for sustainable infrastructure planning and design. Currently, there is no standard or accepted methodology to derive future climate IDF curves. The CSA (2012) provided a review of recent approaches that are potentially applicable to the development of future climate IDF curves. These approaches are expanded in this report with other approaches found in literature, which include:

- Extrapolation of trends in rainfall data
- Use of upper confidence intervals of current climate IDF curves
- Non-stationary frequency analysis
- Direct interpretation of GCM/RCM outputs
- Delta approach
- Statistical and stochastic modelling

The approaches summarized above differ in their levels of complexity, data requirements, ease of use, and cost of implementation, among other factors. Regardless of which approach is used, there are multiple challenges involved in future climate IDF modelling, which are discussed below.



- Projected future increases in extreme rainfall intensities are not always supported by historical observations. This often results from short observation records and/or monitoring networks having inadequate densities for capturing the variability/change in extreme rainfall.
- There are many uncertainties involved in projecting future climate. The main uncertainties include climate modelling (representation of atmospheric processes, model resolution, downscaling, etc.), climate scenarios (future greenhouse gas emissions, population growth, economy, etc.), and natural climate variability (low frequency oscillations, ocean-atmosphere interactions, etc.).
- Most current approaches for future IDF curves are based on GCM predictions and thus are limited by the accuracy of the GCMs. The spatial and temporal resolution of GCMs is inadequate for capturing localized short-duration extreme rainfall. Recent studies revealed that GCMs underestimate rainfall extremes (see e.g., Allan and Soden, 2008; Min et al., 2011). Uncertainties in future climate modeling result in large variation in projected changes.
- Climate change is a rapidly-evolving science; new research findings, tools, and techniques are constantly being introduced and require continuous re-evaluation and updating of practices.

This section describes the sensitivity analysis and derivation of the future climate IDF curves. The first subsection describes the downscaling methodology developed for this project to address some of the shortcomings listed above. The next two subsections describe the sources of uncertainty and the results of the sensitivity analysis. The final two subsections describe how the future climate scenarios were selected and the future climate IDF curves were developed.

2.2.1 Downscaling Methodology

New Methodology

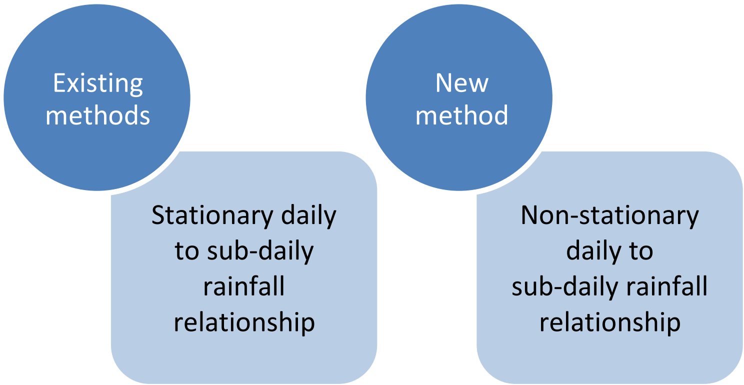
- Addresses multiple common limitations/shortcomings
- Directly incorporates uncertainties

One of the main technical challenges preventing the adoption of existing approaches for the development of future climate IDF curves arises from the temporal and spatial resolution of GCM outputs. A new methodology for deriving future climate IDF curves was developed for this project to address the limitations of existing approaches. The new methodology incorporated multiple features to address some of the shortcomings involved in future climate IDF modelling:

- Multiple spatial downscaling methodologies and conversion of spatial scales from single station to GCM grid square to homogeneous rainfall zone
- Statistical temporal downscaling with bias correction
- Non-stationary relationship between daily and sub-daily rainfall
- Ensemble of 12 GCMs to reduce uncertainties due to model selection
- Incorporation of uncertainties such as: multiple climate scenarios (representative concentration pathways, RCPs), low-frequency climate variations (PDO), and selection of rainfall frequency distribution

This project used the spatially downscaled GCM data provided by PCIC (PCIC, 2014). Two spatial downscaling methods were available: Bias-Correction Spatial Disaggregation (BCSD) and Bias Correction/Constructed Analogues with Quantile mapping reordering (BCCAQ). The data were available in 30 arc-second (approximately 10 km) grid squares, with a temporal resolution of 24 hours. In order to develop future climate IDF curves, the new methodology was used to temporally downscale the data to obtain sub-daily increases of rainfall intensities.

Current temporal downscaling approaches assume that the changes in sub-daily rainfall will increase at the same rate as the daily rainfall. However, as the CSA (2012) states, "changes in the atmospheric processes governing rainfall production will not likely be uniform for short to long time durations", which is supported by recent trends in regional precipitation (Intergovernmental Panel on Climate Change, IPCC, 2007).



The relationship between sub-daily and daily precipitation may vary with changing climate. Westra et al. (2014), as reviewed by PCIC (2015), identified that the observed daily rainfall extremes are increasing "between 5.9% and 7.7% per °C", which is close to the Clausius-Clapeyron (C-C) relation. The authors also mentioned that, at sub-daily time scales, especially at hourly or sub-hourly scales, extreme rainfall increases with air temperature at the C-C rate up to 12 °C, at twice the C-C rate between 12 °C and 24 °C, and at a reversed rate above 24 °C (Figure 2.8). This statement was reviewed and recommended by Zhang et al. (2017). The C-C relation in combination with global warming projections can be used to provide an upper limit for the scaling factors of the daily to sub-daily ratios.

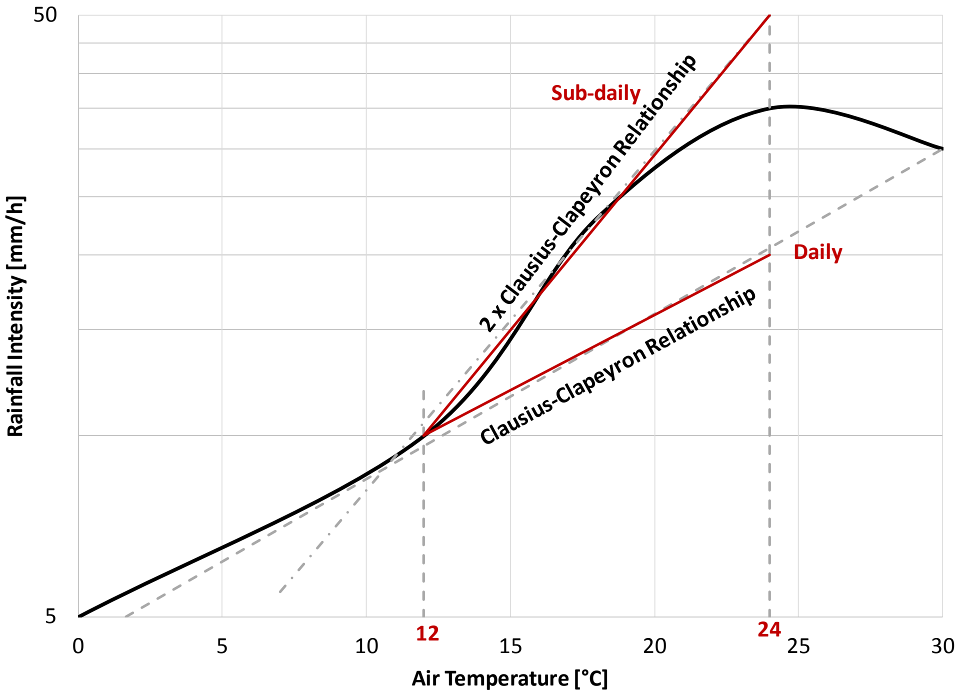


Figure 2.8 **Clausius-Clapeyron Relationship Between Observed Rainfall Intensity and Air Temperature**

The temporal and spatial downscaling methodology developed for this project is depicted in Figure 2.9. The temporal downscaling addresses low-frequency climatic variability (such as the PDO), changes in sub-daily ratios and scaling factors, and bias correction for preserving the temporal variability between IDF intensities of different durations in the future climate IDF curves. The methodology also addressed the different spatial scales of rainfall data used in the project (single climate stations, GCM grids, and homogeneous rainfall zones). A step-by-step description of the temporal and spatial downscaling methodology is provided in Section 3 of TM1.

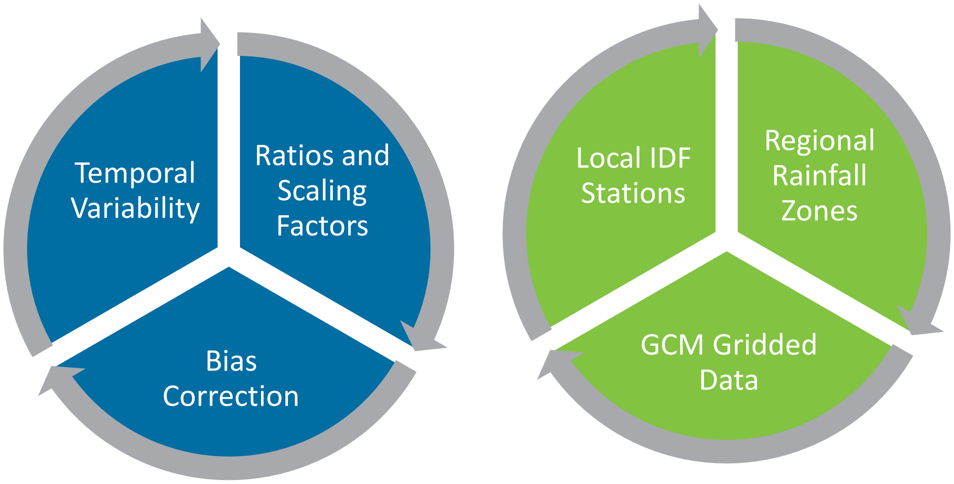


Figure 2.9 **Temporal and Spatial Downscaling**

2.2.2 Climate Change Uncertainty

The various sources of uncertainty (Figure 2.10) involved in projecting future climate IDF curves can be categorized into three general categories:

(1) Uncertainties in the prediction of the future

(2) Limitations of existing techniques

(3) Regional/project specific factors

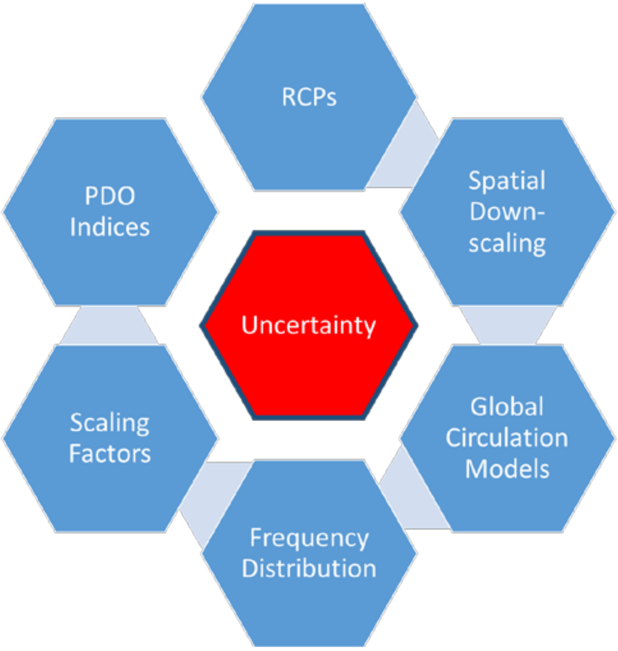


Figure 2.10 Sources of Uncertainty Analyzed in the Sensitivity Analysis

The uncertainties in the prediction of the future were addressed by incorporating two different GHG emission scenarios, known as RCPs (Figure 2.11), which are trajectories of GHG concentrations adopted by the Fifth Assessment Report of the IPCC (2013). Two RCP scenarios were selected: RCP 4.5, a scenario where the radiative forcing stabilizes after the 2050s, and RCP 8.5, a scenario where the radiative forcing increases throughout the century. These are prudent choices when planning for infrastructure with long service life, since global policy to date continues to reflect the RCP 8.5 pathway and sustained reductions appear improbable at present.

PCIC provided spatially downscaled outputs from 12 GCMs for the Western North America region. The data were available for the period of 1950 - 2100. Table 2.2 lists the 12 GCMs.

Table 2.2 GCMs Selected by PCIC for Western North America

CNRM-CM5-r1	CSIRO-Mk3-6-0-r1	HadGEM2-CC-r1
CanESM2-r1	CCSM4-r2	MRI-CGCM3-r1
ACCESS1-0-r1	MIROC5-r3	GFDL-ESM2-r1
Inmcm4-r1	MPI-ESM-LR-r3	HadGEM2-ES-r1

Temporal downscaling uncertainty was addressed by using different scaling factors. A scaling factor of 1.0 assumes temporally invariant or stationary daily to sub-daily ratios. The scaling factors varied from 1.0 (no change in daily to sub-daily ratios) to an upper limit derived from the C-C relation. The upper limit of the scaling factors was applied uniformly to sub-hourly rainfall durations (5, 10, 15, 30-min and 1-hr), and linearly decreased to 1.0 at the 24-h duration.

The selection of frequency distributions was considered a project-specific source of uncertainty since this step is not required in all climate change studies. The goodness-of-fit performance of the frequency distribution used to generate the IDF curve introduces uncertainties into rainfall intensity estimates. The Generalized Extreme Value (GEV), the Generalized Normal (GNO), and the Gumbel (GUM) distributions were included in the uncertainty analysis.

The second project-specific factor of uncertainty considered in this project was the PDO. The sensitivity analysis evaluated three PDO scenarios: years with PDO cool indices, with warm indices, and with all indices, designated as the factor levels of "Cool", "Warm", and "All".

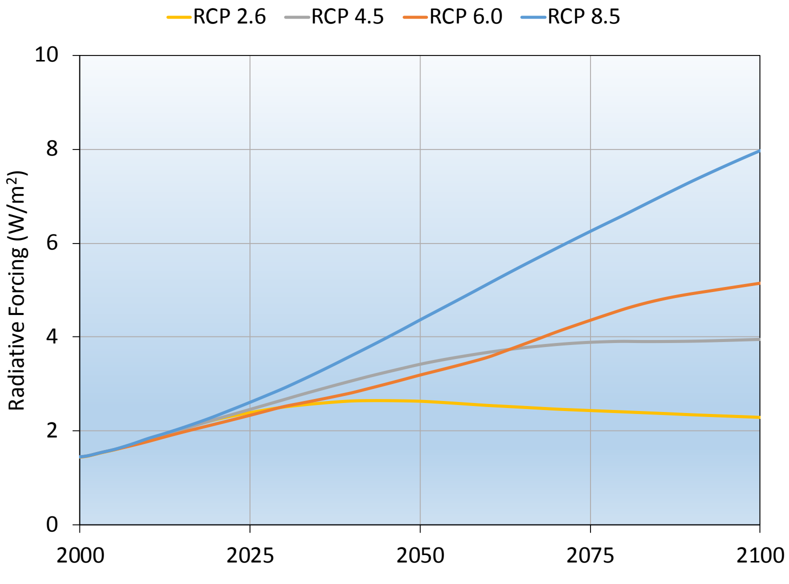


Figure 2.11 Representative Concentration Pathways

2.2.3 Sensitivity Analysis

A sensitivity analysis evaluated the relative importance of the various sources of uncertainty. Table 2.3 lists the different combinations of the uncertainty factors used in the sensitivity analysis. All 12 GCMs were used for all combinations of factors in the sensitivity analysis and therefore inter-GCM variability is common to all of the analyses conducted. It is noted that when including the seven AEPs (50%, 20%, 10%, 4%, 2%, 1%, and 0.5%) and nine rainfall durations (5-min, 10-min, 15-min, 30-min, 1-hr, 2-hr, 6-hr, 12-hr, and 24-hr) the sensitivity analysis consisted of 27,216 combinations for the 2050 time horizon, and 81,648 combinations for the 2100 time horizon.

Table 2.3 Factor Attributes Used for Future Time Horizons

Factor	Attributes Included in Sensitivity Analysis	
	2050 Time Horizon	2100 Time Horizon
RCPs	RCP 8.5	RCP 4.5, RCP 8.5
Downscaling Methods	BCCAQ, BCSD	
GCMs	12 GCMs [1]	
Frequency Distributions	GEV, Gumbel, GNO	
Scaling Factors	1.0, 1.2	1.0, 1.2, 1.4
PDO Indices	Warm, Cool, All	
Notes: [1] GCMs are an implicit factor in the sensitivity analysis		

Figure 2.12 shows the sensitivity results. The three colour-coded intervals represent the range (maximum difference) between the median increases in rainfall intensities obtained for each

category of a given uncertainty factor. For example, the 'warm' and 'cool' phases of PDO produced median increases of 1.39 and 1.56, which leads to a range of 0.17.

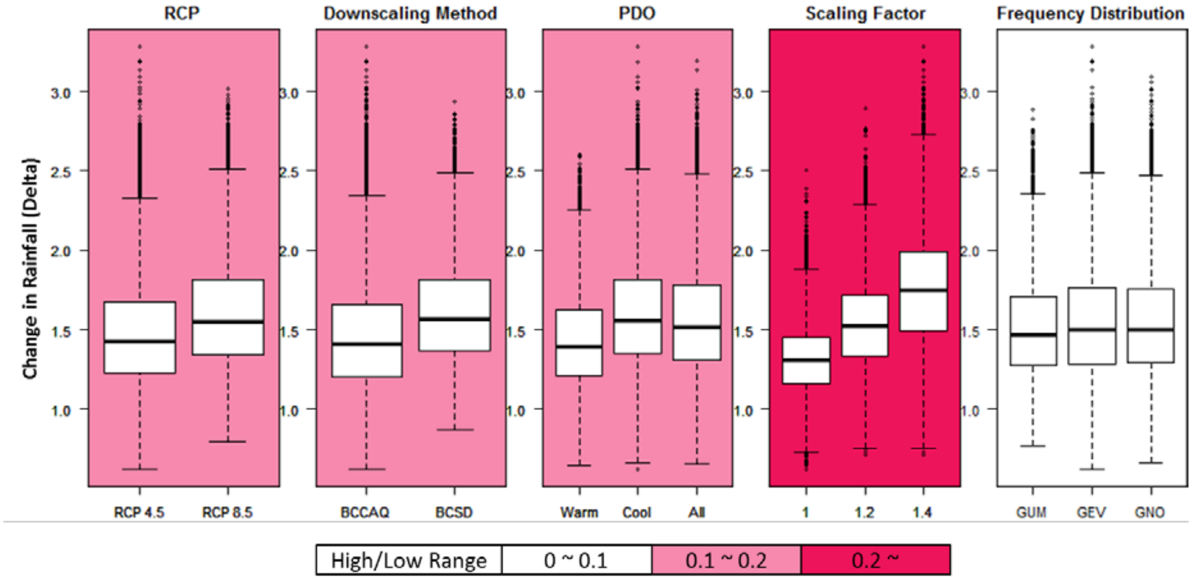


Figure 2.12 Sensitivity Analysis Results

The scaling factor was found to be the most sensitive factor. The median ranges obtained for PDO, downscaling methods, and RCP were very similar and the differences were too small to rank the factors separately. These factors were ranked second in the sensitivity analysis. The frequency distribution was found to be the least sensitive factor. Changing the frequency distribution will not affect the rainfall increase or the future climate IDF curves.

The rainfall increases (deltas) ranged from less than 1.0 to over 3.0 for both time horizons (i.e., from decreases to up to a triple increase in rainfall intensity). The large range of deltas was the result of simultaneous variations of multiple factors, especially when all factors were at the levels that can lead to large positive (or negative) changes in the IDF curves. The scaling factor, which is the least understood (and most uncertain) factor, introduced the most variability.

2.2.4 Derivation of Future Climate Scenarios

In consultation with PCIC, the uncertainty factors were selected from the results of the sensitivity analysis for use in estimating the future climate IDF curves for the moderate and high change scenarios (see Figure 2.13 and refer to TM3 for details). All 12 GCMs were included in the analysis, as shown in Figure 2.14.

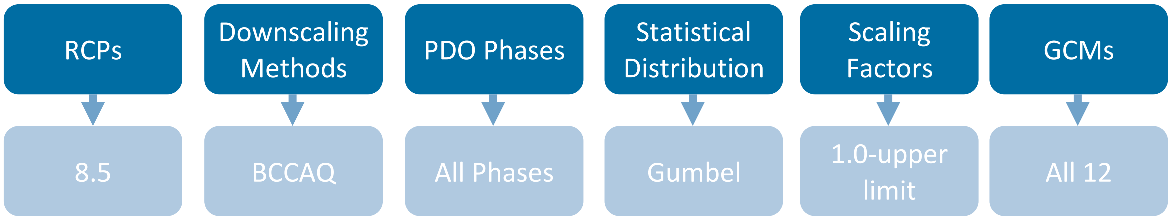


Figure 2.13 Factors Used for Deriving Future Climate IDF Curves

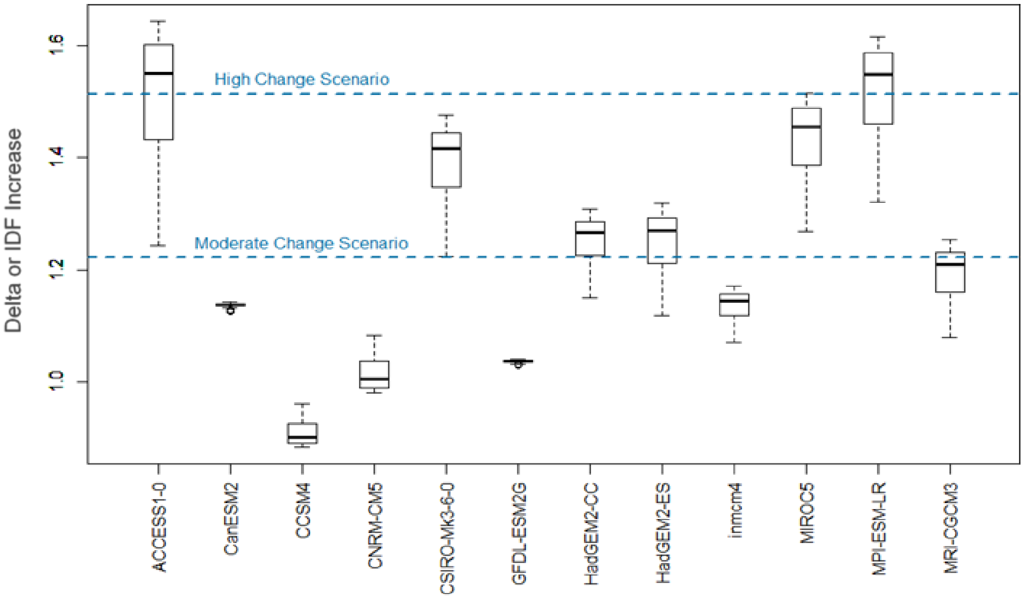


Figure 2.14 Variation of the IDF Increases for Different GCMs

The median of the deltas for the 12 GCMs with scaling factor equal to one (no change in sub-daily to daily scaling) was utilized to develop the moderate change future climate IDF curves. Development of the high change future climate IDF curves required that the upper limit of the scaling factor be defined, since it is the factor that introduced the most uncertainty. The scaling factor was selected using projected increases in air temperature (Metro Vancouver, 2016). The air temperature increases for the 2050s and 2080s time horizons were used with the C-C relation to derive the scaling factor for the 2050 and 2100 time horizon, respectively (Table 2.4).

Table 2.4 Derivation of Upper Bounds of Scaling Factor for Metro Vancouver

Time Horizon	Increase in Daytime Air Temperature (°C)	Increase in Nighttime Air Temperature (°C)	Average Increase in Air Temperature (°C)	Upper Bound for Scaling Factor Using C-C Relationship
2050s	2.9	2.9	2.9	1.2
2080s	4.9	4.8	4.9	1.3

The effect of high scaling factors can be achieved by selecting a simulation near the upper limits of the variation when the scaling factor was equal to one (Figure 2.15). For each scaling factor, a percentile can be selected to obtain the median delta derived with the scaling factor at the upper bound. This relationship indicates that the high change scenario can be defined either based on the theory that scaling ratios may change in the future, or based on the variation with stationary daily to sub-daily ratios. These two approaches are interrelated and different combinations of scaling factors and percentiles lead to similar increases in rainfall.

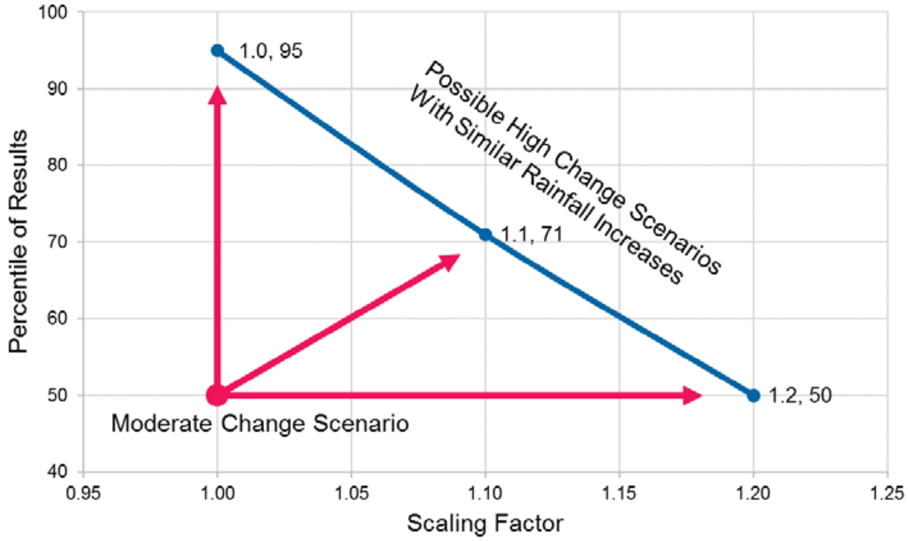
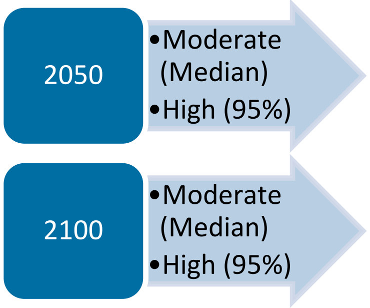


Figure 2.15 Relationship between Scaling Factors and Percentiles



The scaling factors are highly uncertain. For instance, it is unknown if the C-C relation will apply in the future. It is also unknown if the scaling factor will change or by what degree the scaling factor will change. The high change future climate IDF curves were selected as the 95th percentiles of the deltas for the scaling factor of 1.0, which captured the range in delta corresponding to the medians of the deltas for the scaling factor equal to the upper bounds.

2.2.5 Future Climate IDF Curves

Future climate IDF curves were generated for the moderate and high change scenarios for all homogeneous rainfall zones. The methodology to derive the future climate IDF curves is described in Figure 2.16, and detailed instructions are provided below the figure.

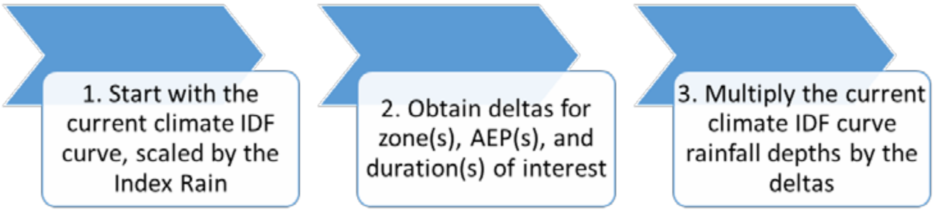


Figure 2.16 Development of Future Climate IDF Curves

1. The methodology to select the current climate IDF curve was presented in Figure 2.5.
2. The deltas are included in Appendix A of TM3. There are four sets of deltas, corresponding to the 2050 Moderate Change, 2050 High Change, 2100 Moderate Change, and 2100 High Change future climate IDF curves. Utilize the same zone(s), AEP(s), and duration(s) that were

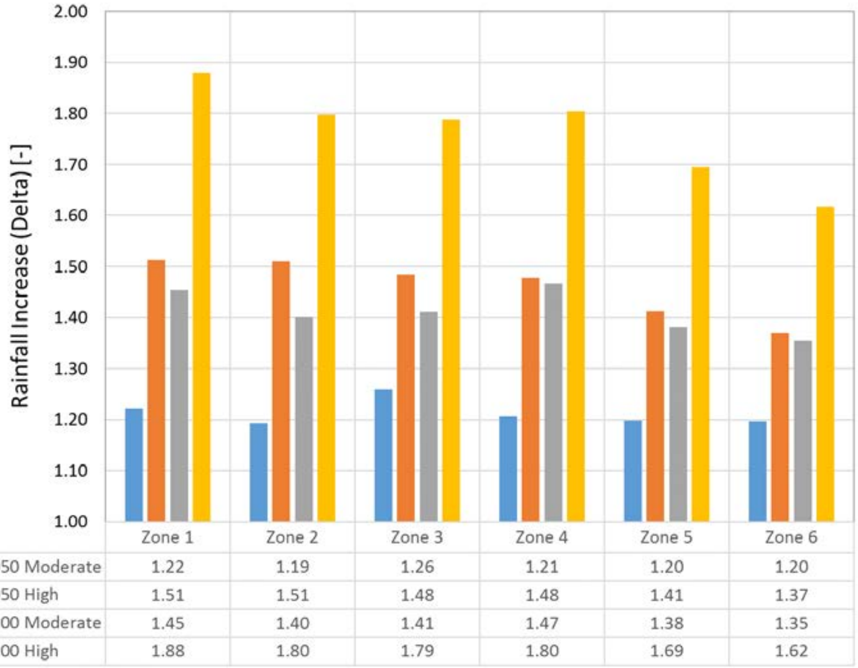
used for the current climate IDF curve. The deltas for each combination of AEP and duration are unique.

3. The future climate IDF curves are derived by multiplying the current climate IDF curve rainfall depths by the deltas. For instance, if the current climate IDF curve rainfall depth for a particular AEP and duration is 8 mm and the delta for that AEP and duration is 1.2, then the future climate IDF curve rainfall depth for that AEP and duration is 9.6 mm.

Figure 2.17 shows the average rainfall increase for each homogeneous rainfall zone, averaged over all durations and AEPs. The future climate IDF curves are expected to increase by 21% in 2050 and 41% in 2100 for the moderate change scenario, and by 44% in 2050 and 75% in 2100 for the high change scenario.

Increase in IDF for:	Moderate future climate change	High future climate change
2050 Time Horizon	21%	44%
2100 Time Horizon	41%	75%

The increase will vary spatially from zone to zone, with the lowest increase projected in Zone 6 and the highest increase projected in Zone 1 (Figure 2.17). Note that the absolute increases in AM daily rainfall in the GCM data are similar across all zones. However, the delta is a ratio of the future rainfall divided by the current rainfall. The current rainfall is lowest in Zone 1 and highest in Zone 6. As a result, the delta for Zone 1 is higher than the delta for Zone 6.



	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
🟦 2050 Moderate	1.22	1.19	1.26	1.21	1.20	1.20
🟧 2050 High	1.51	1.51	1.48	1.48	1.41	1.37
⬜ 2100 Moderate	1.45	1.40	1.41	1.47	1.38	1.35
🟨 2100 High	1.88	1.80	1.79	1.80	1.69	1.62

Figure 2.17 Average Rainfall Increase

The AEP of an event of a particular size increases substantially in the future climate change scenarios. The changes in AEP, averaged over all durations and homogeneous zones for the moderate and high change scenarios are summarized in Table 2.5 for the 20%, 10%, and 1% events.

Table 2.5 Predicted AEP for Future Climate Change Scenarios

Current AEP, % (Return Period, years)	2050 AEP, % (Return Period, years)	2100 AEP, % (Return Period, years)
Moderate Climate Change Scenario		
20% (5)	35% (3)	52% (2)
10% (10)	21% (5)	36% (3)
1% (100)	4% (25)	8% (12)
High Climate Change Scenario		
20% (5)	52% (2)	64% (1.6)
10% (10)	36% (3)	50% (2)
1% (100)	9% (11)	18% (5)

2.3 Infrastructure Case Studies

Increased rainfall will impact the existing level of service for sewerage and stormwater collection infrastructure. Adaptation measures will need to be implemented to maintain the level of service. The case studies addressed the following objectives:

- Determine the effects of the increased rainfall on the level of service of sewerage and stormwater collection infrastructure
- Estimate the cost of infrastructure upgrades to maintain adequate levels of service

Three different case studies were evaluated: a combined sewer system, a stormwater drainage network, and sanitary-only sewer system. Each case study is discussed in a separate sub-section below. The hydrologic and hydraulic modelling for the three case studies was performed with PCSWMM, a software program developed by CHI.

The pipe upsizing strategies selected to accommodate the higher rainfall events have not been tested for feasibility and may not represent the most efficient upsizing strategies (in terms of cost, construction staging, etc.). Alternative pipe upsizing or peak storage/reduction strategies may be preferable (e.g. to minimize flooding downstream). As such, the case study strategies are illustrative and the class D costing estimates provided are approximate and are provided for comparison purposes only. A detailed analysis is required for the identification and design of the preferred solution and associated costs.

2.3.1 Case Study 1: Glenbrook Combined and Separated Trunk Sewer

The Glenbrook combined trunk sewer is located in the Cities of Burnaby and New Westminster (Figure 2.18) and is currently a combined (sanitary and storm collection) sewer system. The trunk sewer is located in the FSA, and sewer separation will be performed by 2075. In total, the trunk sewer drains an area of 517.4 hectares. The Glenbrook diversion weir diverts sanitary flow during dry weather, and combines flows during wet weather up to the hydraulic capacity of the Glenbrook Diversion Extension into the New Westminster interceptor at McBride and East Columbia Street, which subsequently flows into the Annacis Wastewater Treatment Plant. The combined sewer overflow outfalls into the Fraser River at East Columbia Street at the bottom of the Glenbrook Ravine.

The scenarios that are discussed in this report are listed in Table 2.6. The scenarios varied according to sewer flow, rainfall event, and sea level (downstream boundary condition).

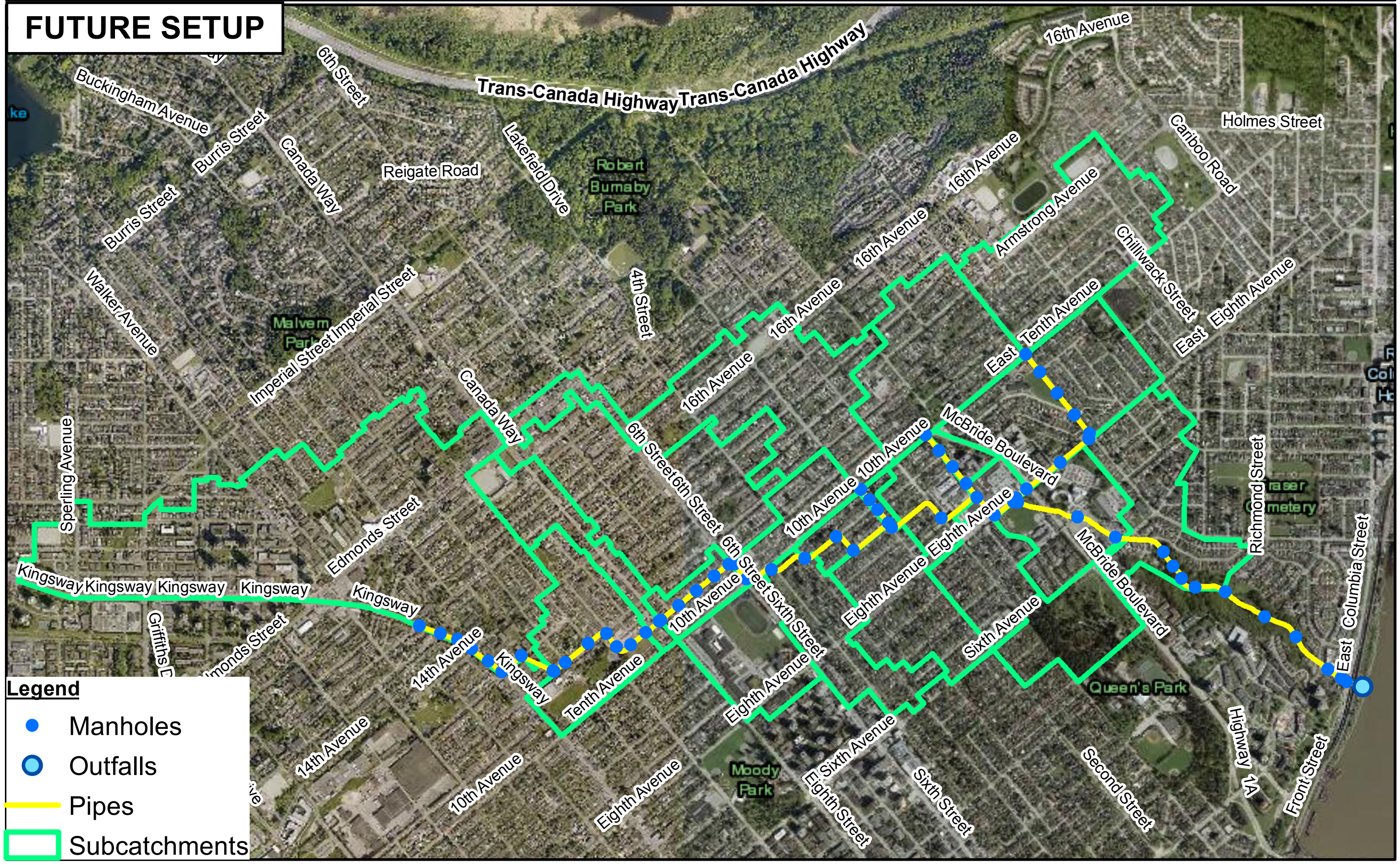
Table 2.6 Scenarios Analyzed for Case Study 1

Scenario Name	Sewer Configuration	Sanitary Flow	Rainfall Event	Sea Level
Current	Combined	Current	Current	Current
2050 Moderate	Combined	2050	2050 Moderate	2050
2050 High	Combined	2050	2050 High	2050
2100 Sea Level Rise Only	Separated	None	Current	2100
2100 Moderate	Separated	None	2100 Moderate	2100
2100 High	Separated	None	2100 High	2100

The combined trunk configuration was used to model the current and 2050 time horizons, while the separated trunk configuration was used to model the 2100 time horizons. The number of flooded manholes in each scenario at different AEPs is shown in Figure 2.19. The 1% AEP, 1-hr Rainfall Depth is expected to rise by 24% for the 2050 moderate change, and 53% for the 2050 high change scenario. The 2100 moderate change and 2100 high change 1% AEP 1-hr events were 51 and 92 percent higher than the current 1% AEP 1-hr event. There were increases in the number of flooded manholes but some of the flooding is due to the increased sanitary sewer flow (2050) and higher sea level (2050 and 2100). The volume of flooding also increased.

EXISTING SETUP

FUTURE SETUP



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Coordinate System:
NAD 1983 UTM Zone 10N

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11140666-01
Jun 6, 2018

EXISTING AND FUTURE MODEL SETUP FOR CASE STUDY #1: GLENBROOK COMBINED TRUNK SEWER AND SEWER SEPARATION

FIGURE 2.18

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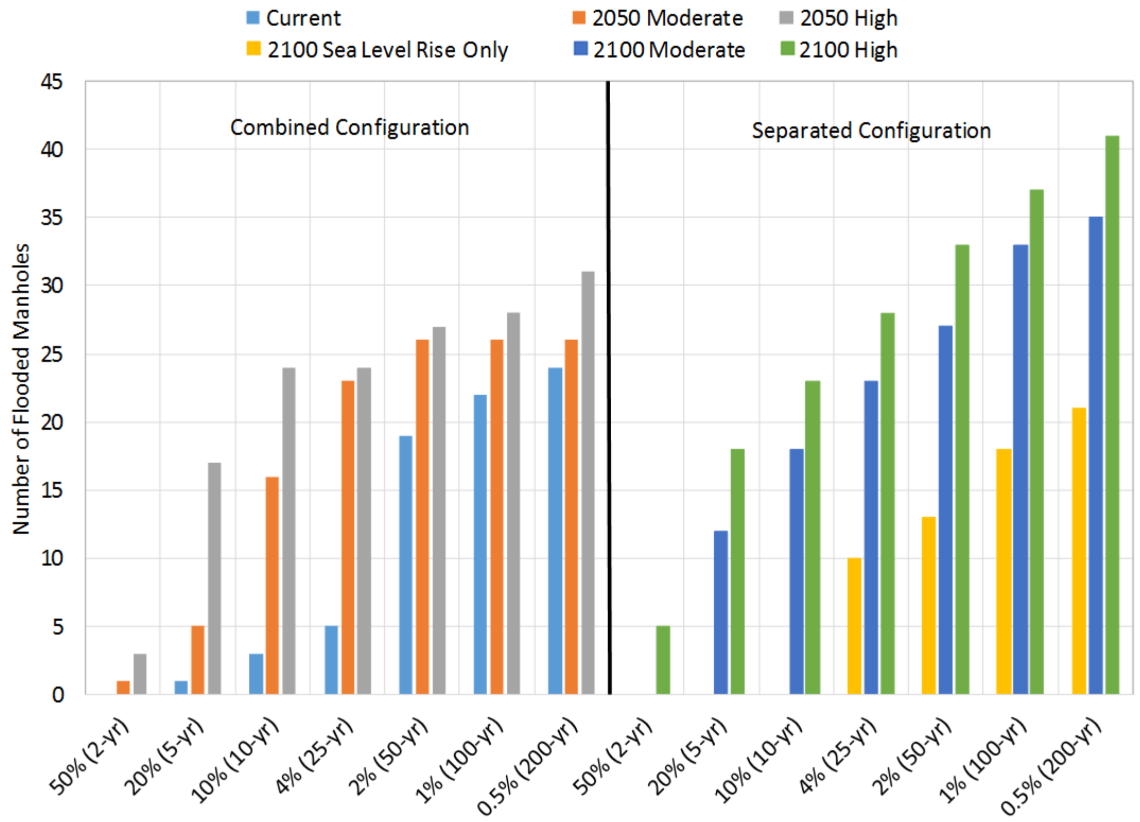


Figure 2.19 **Number of Flooded Manholes for Existing Combined and Future Separated Trunk Sewer**

To address the flooding associated with the current, 2050, and 2100 scenarios, pipes were upsized. For the 2050 scenarios, it was also necessary to increase the size of the diversion weir. The costs associated with upsizing for Case Study 1 are included in Table 2.7. The costs shown are for all changes from existing to the specified scenario (for the 2100 scenarios, it also includes the cost of the McElhanney (2014) upgrades). Note that there are scenarios where some pipes must be increased to accommodate a certain scenario, and then must be increased further to accommodate another scenario. Therefore, there can be some cost savings by selecting the final size and upgrading the pipes only once. The increase in cost to accommodate the larger rainfall events ranges from 150 to 250 percent of the cost to accommodate the current rainfall event. However, the incremental increase in cost to prepare for the more conservative high climate change instead of the moderate climate change is only 10 to 15 percent.

Table 2.7 Costing Summary for Case Study 1

Scenario	Trunk Sewer Configuration	Percent of Total Length that was Upsized (%)	Estimated Cost ($)	Percent Increase in Cost from Current (%)	Percent Increase in Cost from Moderate to High (%)
Current	Combined	33	10.9 million	N/A	N/A
2050 Moderate	Combined	63	29.1 million	167	17
2050 High	Combined	68	34.0 million	212	
2100 Moderate	Separated	68	35.3 million	224	10
2100 High	Separated	73	38.8 million	256	

The results of the analysis of Case Study 1 indicate that the Glenbrook combined trunk and separated sewers will be impacted by increased flow due to increased rainfall from climate change. Sea level rise and the increase in sanitary flow to 2050 also have an impact on the capacity of the trunk sewer. The flow rate for the 1% AEP is significantly higher in 2050 and 2100, and there were numerous locations along the trunk sewer where there were hydraulic constrictions.

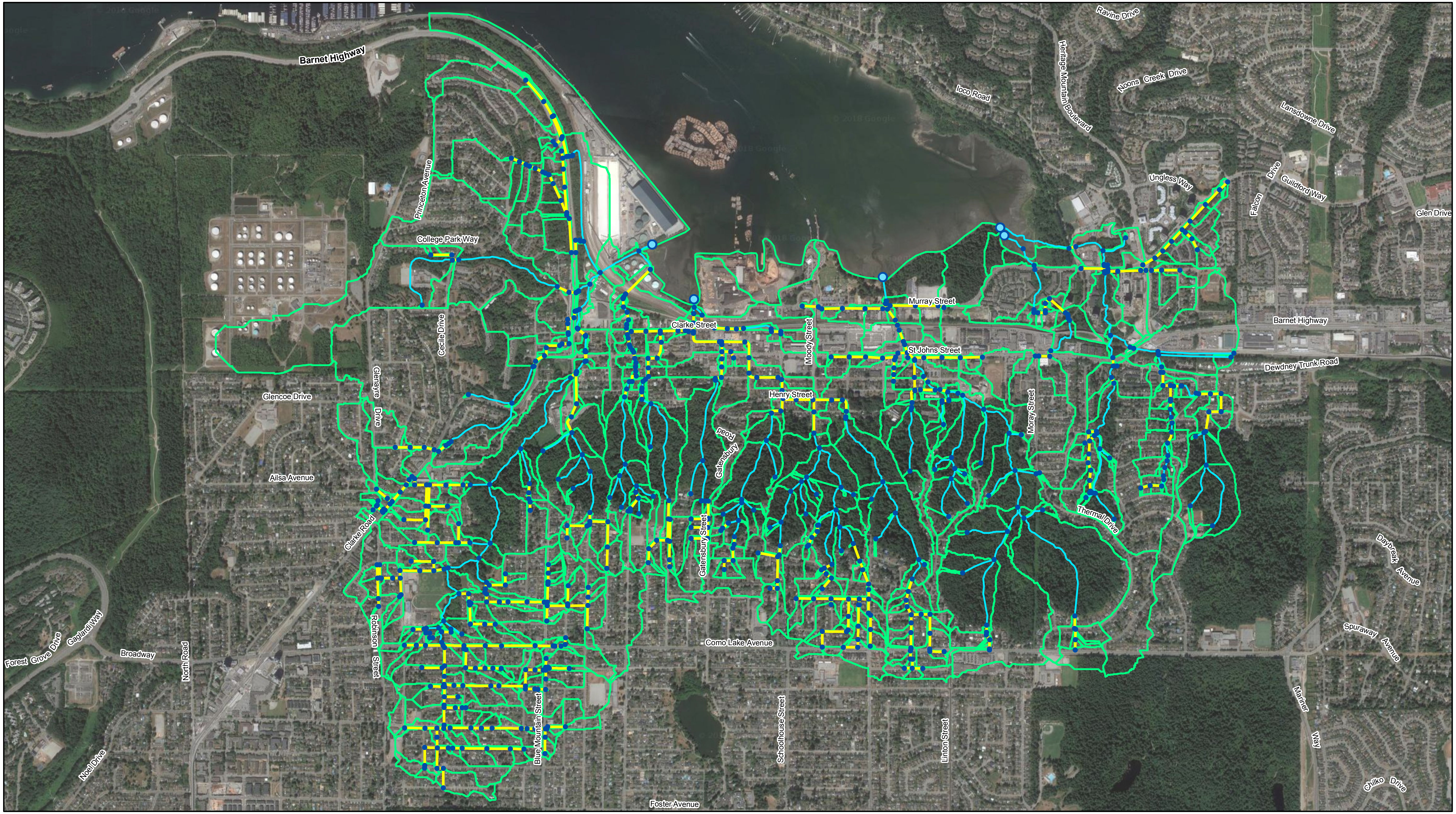
Accommodating the increased rainfall due to climate change will require the majority of the combined and separated trunk sewer to be re-designed. It is recommended that various re-design and staging scenarios be considered: including accelerating the sewer separation schedule. The cost to upsize the pipes was significant: the increase in cost to upsize the trunk sewer to accommodate the 2050 and 2100 future rainfall events ranged from 150 to 250 percent of the cost to accommodate the current 1% AEP 1-hr event. However, the incremental increase in cost to prepare for the more conservative high climate change instead of the moderate climate change is only 10 to 15 percent. Upsizing the pipes to accommodate the 2050 rainfall plus sanitary sewage flow is insufficient to pass the 2100 moderate or high change rainfall. A detailed description of the results for Case Study 1 is provided in Section 2 of TM4.

Infrastructure upgrades are required

- Upsizing for 2050 is insufficient for 2100
- Accelerated separation recommended
- Incremental cost of upgrades for high to moderate: 1015%

2.3.2 Case Study 2: Port Moody-Coquitlam Drainage Area

The Port Moody-Coquitlam Drainage Area (PMCDA) is located in the Cities of Port Moody and Coquitlam (Figure 2.20). It is a stormwater drainage system (no sanitary flow), covering 1,034 hectares. The PMCDA discharges into Burrard Inlet through five discharge locations. The PMCDA is composed of natural channels and closed conduit sections. Metro Vancouver is responsible for the main stems of the creeks and the major stormwater trunks receiving creek flows below the escarpment (in Port Moody). The Cities are responsible for the local stormwater systems on top of and below the escarpment. An Integrated Stormwater Management Plan (ISMP) for this area was developed by Associated Engineering, Ltd. in 2016 (Associated, 2016).



Source: Image ©2018 Google, Imagery date: 2017

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Legend

- ◎ Outfalls
- ● Junctions
- ― Piped Sections
- ― Natural Channels
- ▭ Subcatchments

GHD

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MODEL SETUP FOR CASE STUDY #2:
PORT MOODY-COQUITLAM DRAINAGE AREA

11140666-01
Jun 5, 2018

FIGURE 2.20

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The existing and future models were run with the current, 2050 moderate, 2050 high, 2100 moderate, and 2100 high rainfall scenarios. There were flooded junctions for all scenarios, for both the existing and future configurations (Figure 2.21). There were two main causes for flooded junctions. In the low areas of Port Moody, the flooding is mainly caused by the restricted flow capacity of the channels and pipes near the coast due to the rising sea level boundary condition. In the upper reaches, the flooding is mainly caused by piped sections with insufficient capacity.

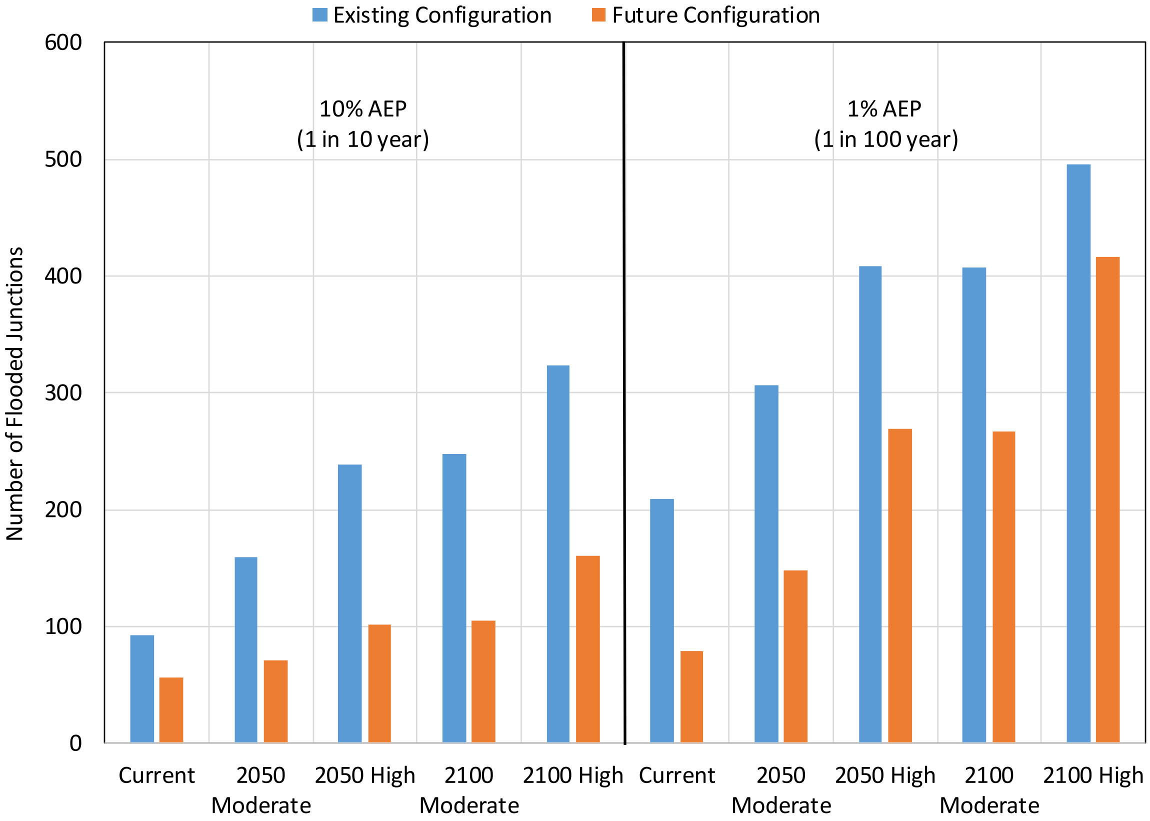


Figure 2.21 Number of Flooded Junctions for Existing and Future Configurations for Case Study #2

The preferred approach to reduce flooding in the watershed is through the application of source controls. The effect of adding source controls on the PMCDA was approximated by adjusting the parameters of each subcatchment to obtain a reasonable decrease in the 50% AEP 24-hr peak flow. The future climate 50% AEP peak flow rises in comparison to the current 50% AEP peak flow even with source controls (Figure 2.22).

The future mitigation model with the parameter changes to mimic the source controls was tested for lower AEP events (10% and 1%). The required levels of service for pipes and channels were the 10% AEP (City owned pipes) and 1% AEP (GVS&DD owned pipes and channels). The source controls decrease the future peak flows slightly, but the future peaks are still higher than the peak flow of the current event. The level of service will continue to decrease for low-AEP events.

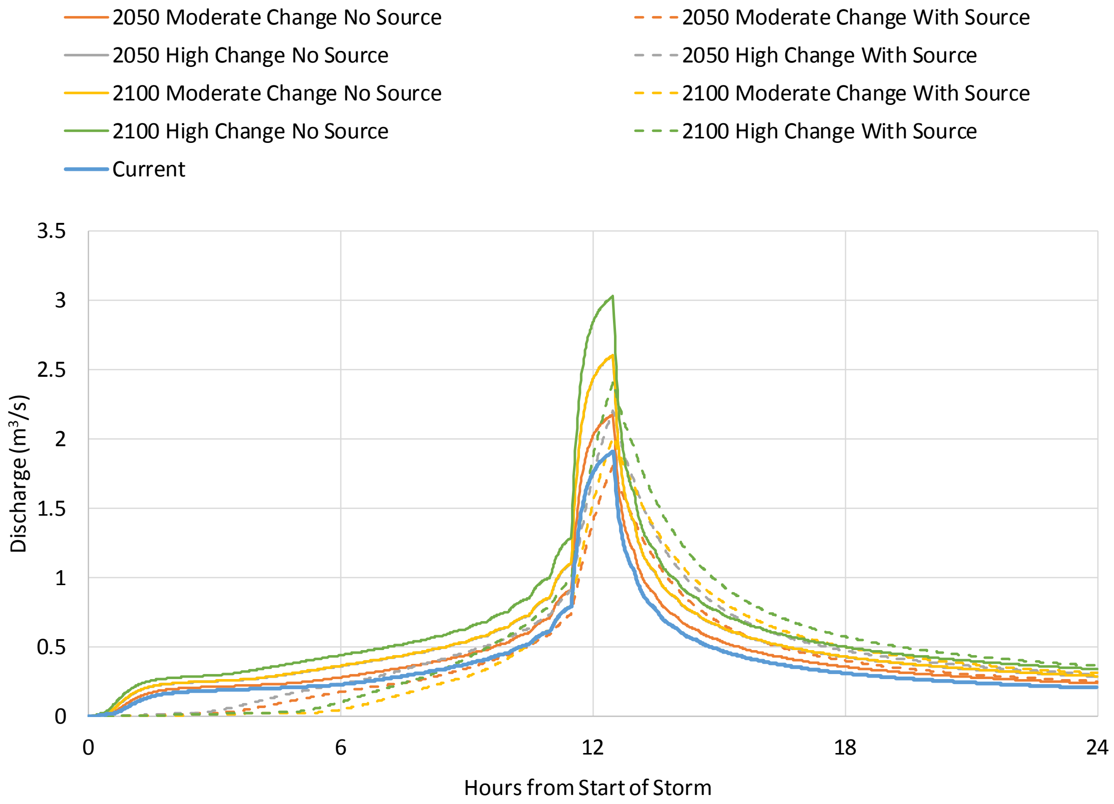


Figure 2.22 Comparison of Subcatchment Discharge With and Without Stormwater Source Controls for the 50% AEP Event

To address the decrease in level of service under future rainfall (even when source controls are applied), infrastructure upgrades will be required. Pipe upsizing to meet the 10% AEP and 1% AEP storm events, depending on the design requirement for the pipes, was performed. The costing summary for pipe upsizing for Case Study 2 is included in Table 2.8. The costs shown are for all changes from the future model setup to the specified scenario. The increase in cost to accommodate the future rainfall events ranges from 95 to 260 percent of the cost to accommodate the current rainfall event. The incremental costs to accommodate the high instead of the moderate change scenarios are 9% and 19% for the 2050 and 2100 time horizons.

Table 2.8 Costing Summary for Case Study 2

IDF Curve	Percent of Pipes Upsized (%)	Estimated Cost ($)	Percent Increase in Cost from Current (%)	Percent Increase in Cost from Moderate to High (%)
Current	5.3	4.2 million	N/A	N/A
2050 Moderate	5.7	8.2 million	95	9
2050 High	6.2	8.9 million	112	
2100 Moderate	6.5	12.7 million	202	19
2100 High	10.4	15.1 million	260	

The results of the analysis of Case Study 2 indicate that the PMCDA will be heavily impacted by increased rainfall from climate change. In addition, the sea level boundary condition also causes backwater effects in the sewers and surface flooding in Port Moody.

Source controls were examined as a method of reducing peak flows in the watershed. The current guideline, applied generally across each subcatchment (i.e. there is significant redevelopment across the watershed), may be sufficient to maintain the current peak flows for high AEP events. However, it is insufficient to maintain the current peak flows for low AEP events. Stricter guidelines will need to be implemented to maintain the current level of service.

Infrastructure changes in the stormwater system (e.g. pipe size increases, peak flow storage, redirecting flows) will be required. There are many end-of-pipe infrastructure improvement solutions that can be applied, which include (but are not limited to): stormwater detention ponds, subsurface stormwater storage, peak flow diversion, and pipe upsizing. Upsizing the pipes to accommodate climate change will cost an additional 100 to 250% on top of upgrades currently needed to maintain levels of service. The incremental cost of choosing the more conservative high change climate scenario is only 10% and 20% for 2050 and 2100 respectively. A detailed description of the results for Case Study 2 is provided in Section 3 of TM4.

Current source controls are insufficient

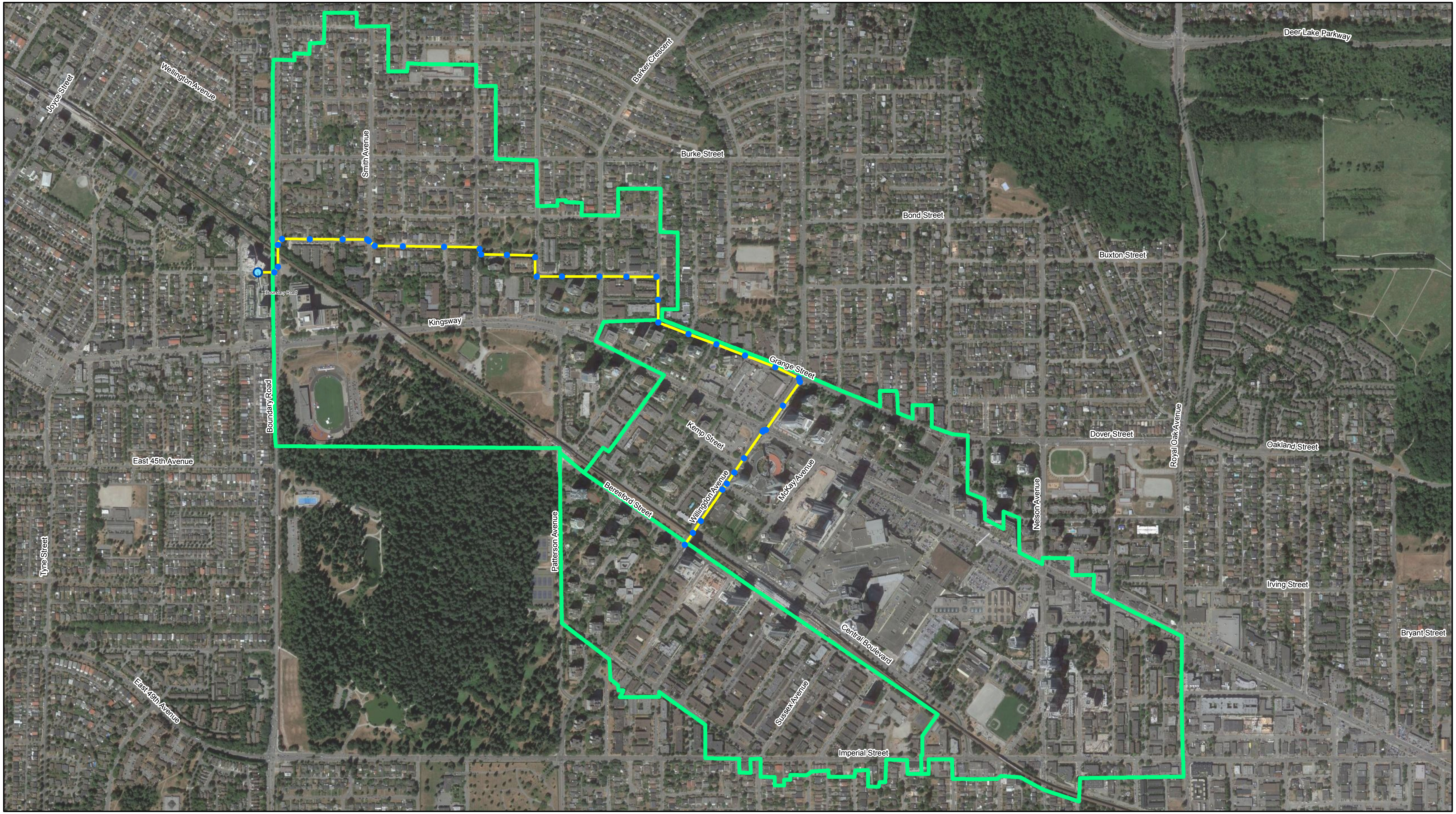
- Infrastructure upgrades required
- Stricter source controls recommended
- Incremental cost of upgrades for high to moderate: 1020%

2.3.3 Case Study 3: Collingwood Sanitary Trunk Sewer

The Collingwood Sanitary Trunk Sewer is located in the City of Burnaby (Figure 2.23). It is a sanitary collection system (no stormwater), which drains a total of 245.1 hectares. The level of RDII in the sewer, and its impact on the level of service for the trunk sewer as rainfall increases, was the focus of this case study. The Collingwood Sanitary Trunk Sewer starts at Willingdon Ave. and Beresford St., and proceeds north and west to Boundary Rd, near Vanness Ave. There is a sanitary flow measurement location at Boundary Road, which was the downstream boundary for the model.

The population in the sewer catchment area for the Collingwood sanitary trunk sewer is projected to more than double by 2100. Population growth will impact the sanitary trunk sewer capacity in addition to climate change. Population growth only scenarios were modelled (future sanitary flow for each time horizon with the current rainfall). Four pipes were upsized for the 2050 time horizon, and six pipes were upsized for the 2100 time horizon.

As rainfall depth increased in the future climate change scenarios, the level of service decreased (Figure 2.24). Even if the pipes were upsized to accommodate the population growth with the current rainfall, the increase in RDII in the climate change scenarios resulted in pipes that were more than 70% full by depth. However, even though pipes are more than 70% full by depth, there is low risk of basement flooding (few manholes have less than 1.8 m of freeboard). A criterion that is based on ensuring that there are no basement flooding or sewage backup concerns (e.g. a minimum freeboard requirement) is an alternate criterion for sanitary sewer systems that would reduce the need for pipe upsizing. Adding private-side measures to prevent basement flooding, such backwater valves, pumps or other controls are also recommended.



Source: Image ©2018 Google, Imagery date: 2017

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Meters

Coordinate System:
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Legend

- ◎ Outfalls
- ● Junctions
- ― Pipes
- ▭ Subcatchments

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MODEL SETUP FOR CASE STUDY #3:
COLLINGWOOD SANITARY TRUNK SEWER

11140666-01
Jun 5, 2018

FIGURE 2.23

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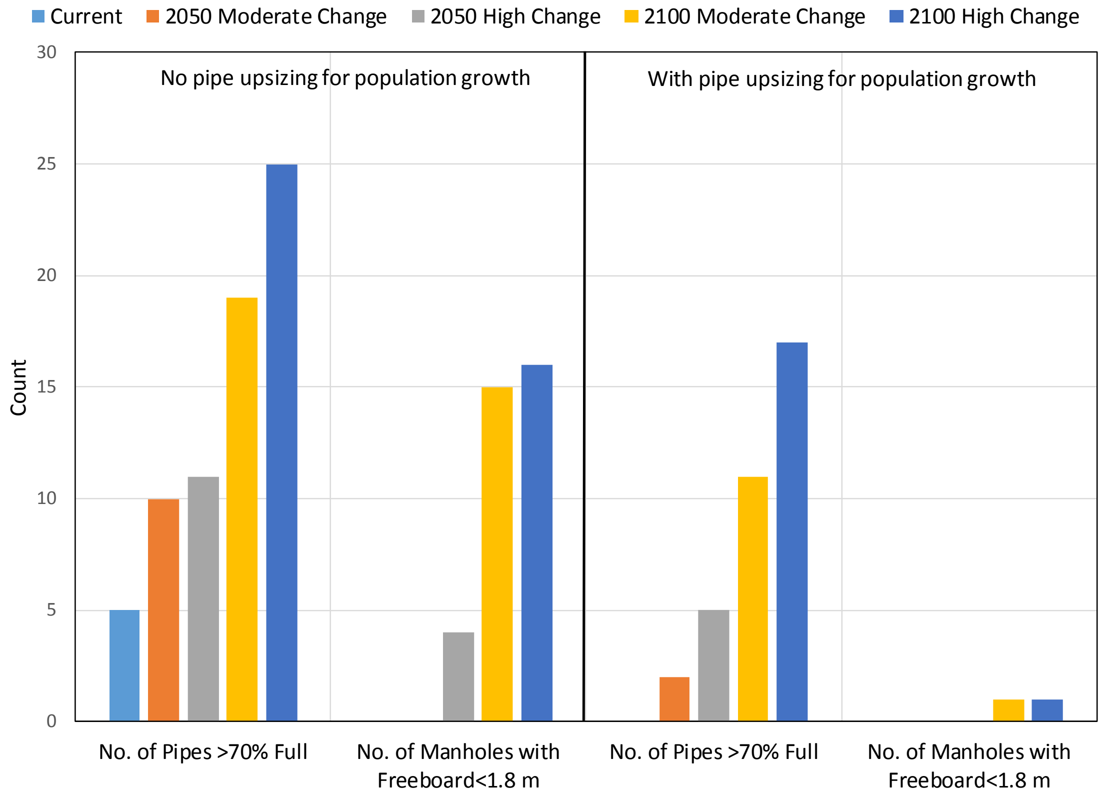

Figure 2.24 Number of Pipes more than 70% Full and Manholes with Freeboard less than 1.8 m for Case Study 3

Pipe upsizing was performed for the population growth scenarios and the future climate change scenarios (assuming that pipes must be less than 70% full by depth). A summary of how many pipes were upsized and the total cost of upsizing is provided in Table 2.9. Note that the summary provides the total number of pipes that were upsized and the total cost associated with upsizing them (not in addition to pipe upsizing for population growth). The 2050 sanitary flow rates are generally much less than the capacity of the trunk sewer. When the 2050 future rainfall scenarios were added to the model, there was sufficient capacity for the additional RDII in most pipes (relatively few pipes needed to be upsized to meet the level of service requirements in 2050). However, the 2100 sanitary flow rates were higher and the trunk sewer was flowing closer to the design requirement of 70% full by depth, which required more pipes to be upsized.

In addition to pipe replacement, RDII reduction strategies can also be implemented. Many of the existing pipes are concrete and develop cracks over time. When the pipes are replaced, there will be a reduction in RDII. RDII reductions of 10% to 30% can be achieved by lining/replacing the main trunk sewer alone (Kunay, et al., 2014). If RDII reduction is performed, there will be a decrease in the number of pipes that are greater than 70% full and it may be possible to avoid some of the additional pipe upsizing to accommodate the increased RDII due to climate change.

Table 2.9 Summary of Costing for Case Study 3

Population	IDF Curve	Percent of Total Length Upsized (%)	Estimated Cost ($)	Percent Increase in Cost from Current (%)	Percent Increase in Cost from moderate to high (%)
2050	Current	3.0	0.1 Million	N/A	N/A
2050	2050 moderate	3.0	0.1 Million	1.7	47
2050	2050 high	3.0	0.1 Million	2.5	
2100	Current	7.0	0.2 Million	N/A	N/A
2100	2100 moderate	35.3	1.2 Million	413	42
2100	2100 high	51.5	1.7 Million	663	

The results of the analysis of Case Study 3 indicate that the Collingwood sanitary trunk sewer will be impacted by both population increase and climate change. The current and 2050 sanitary flow are less than the capacity of the trunk sewer. However, for the 2100 sanitary flow, a larger number of pipes are flowing close to 70% full by depth. When the 2100 future rainfall scenarios are added to the model, a large number of pipes needed to be upsized.

Accommodating the increased RDII due to the climate change scenarios did not result in large increases in cost in 2050, but there were large increases in 2100. The increase in cost for the 2050 future rainfall scenarios was less than 5 percent. However, the increase in cost for the 2100 future rainfall scenarios ranged to over 600 percent. The large increase in cost for the 2100 scenarios occurs because the sanitary sewage flow is larger in 2100 and there is less capacity for increased RDII. Essentially, the trunk sewer in 2100 is flowing almost full during dry weather and a tipping point is reached: any increase in flow due to RDII results in a large amount of pipe upsizing. Performing pipe upsizing to accommodate increased RDII is inefficient, it is recommended that other adaptation measures be considered (e.g. private-side measures to protect against basement flooding and RDII reduction). A detailed description of the results for Case Study 3 is provided in Section 4 of TM4.

A "tipping point" occurs

- As population increases, vulnerability to increased RDII increases
- RDII reduction, privateside measures, and a review of design requirements are recommended
- Incremental cost of upgrades for high to moderate: 4050%

2.4 Climate Change Adaptation Practices

Climate change considerations were integrated into the components of a business process framework to create a systematic climate change process for GVS&DD, and spearhead a climate change culture. The framework is illustrated in Figure 2.25. There are four main components to the framework:

1. Planning
2. Delivery
3. Support services
4. Performance management

The recommendations for incorporating climate change considerations in each component of the framework are briefly summarized in the following sub-sections. A detailed description is included in TM5.

2.4.1 Planning

The first component of planning is to develop a formal Climate Change Policy (CCP). A formal CCP will assist the GVS&DD to remain 'on track' over the long-term timeframe of climate adaptation.

The CCP will explain Metro Vancouver's vision, strategic plans and other relevant policies, and explain how these apply to the practice of climate change adaptation. It is recommended that the CCP be approved by senior staff decision makers and (if possible) the Board. It is strategic to achieve consensus from senior decision makers before approaching the board for approval.

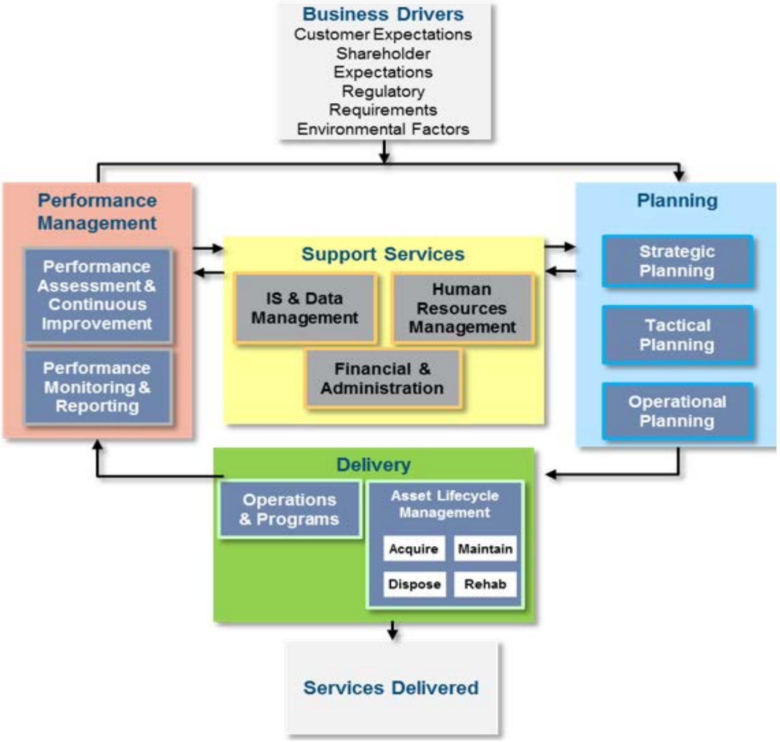

Figure 2.25 Business Process Framework

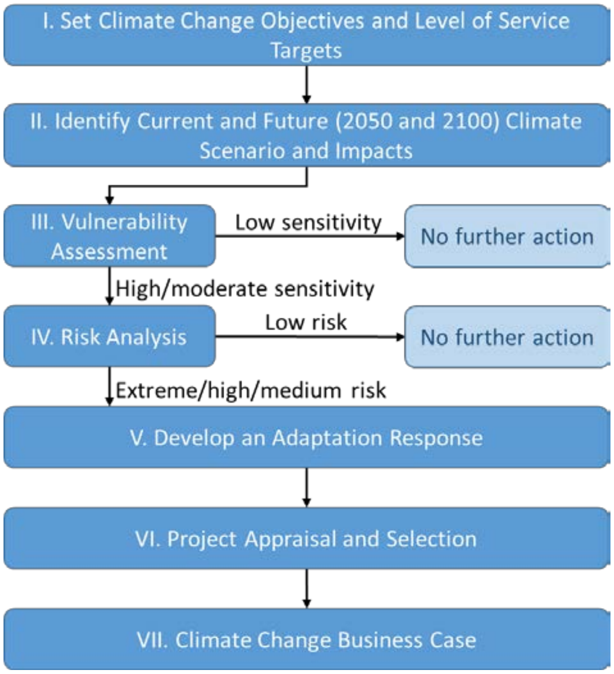

Figure 2.26 Step-by-Step Planning Framework

Review the CCP regularly (every 2-3 years) and after significant changes to the operational context of the organization. Within the context of the CCP, planning will follow a seven step framework (Figure 2.26).

I. Set Climate Change Objectives and Level of Service Targets

The level of service targets for stormwater and sewerage collection infrastructure are key to ensuring consistent climate change adaptation practices across the Metro Vancouver region. The objectives and targets will reflect strategic goals and shareholder expectations, and be measurable and clearly defined. The targets can be both quantitative and qualitative. Information to consider and collect in order to set proposed level of service targets are listed in Figure 2.27.

Storm Sewers	Combined Sewers	Sanitary Sewers
• Flow rates in drainage conveyance infrastructure (channels, storm sewers, culverts) • Surface water flooding frequency and severity (velocity x depth) • Property damage to drainage infrastructure, residences, and businesses • Number and/or cost of insurance claims related to water incurred losses	• The number and volume of combined sewer overflows per annum • The frequency and volume of surface flooding events from manholes • Property damage to drainage infrastructure • Number and/or cost of insurance claims related to water incurred losses	• Frequency of sewer backups • Relative contribution of I&I in sewer systems • Capacity of downstream infrastructure such as pumping stations and wastewater treatment plants • Number and/or cost of insurance claims related to water incurred losses

Figure 2.27 Level of Service Examples

II. Identify Current and Future (2050 and 2100) Climate Scenario and Impacts

Three approaches for climate change adaptation can be adopted for infrastructure planning and design under climate change uncertainties. Each approach has an associated risk of failure and adaptation cost (Figure 2.28). Balancing risk of failure and adaptation cost is a key aspect of climate change adaptation.

- **Do nothing/Business as usual** | This approach does not consider climate change, and continues to plan and design infrastructure for the current climate.
- **Middle of the road** | This approach uses the most likely future climate scenario, which is characterized by the moderate change future climate IDF curve developed in this project.
- **Worst-case** | This approach uses the extreme future climate scenario, which is characterized by the high change future climate IDF curve developed in this project.

Climate Scenario	Current Climate	Moderate Change Future Climate	High Change Future Climate
Risk of Failure	High	Medium	Low
Initial Cost	Low	Medium	High

Figure 2.28 Climate Scenarios and Associated Risk of Failure and Cost

The three approaches are all suitable for different infrastructure planning and design applications. The appropriate future climate scenario (Current/Moderate/High) to use for a particular type of infrastructure is shown schematically in Figure 2.29. The future climate scenario will vary depending on the level of risk due to failure.

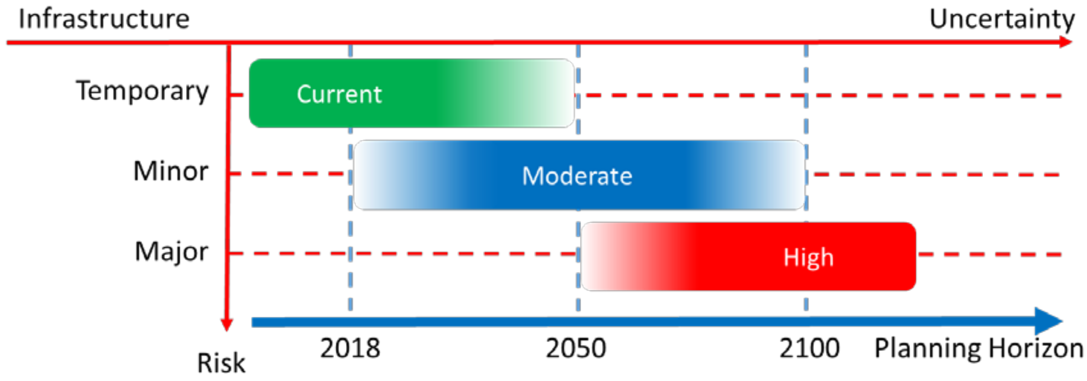

Figure 2.29 Selection of Future Climate Scenarios

The "Do nothing" approach (using the current climate IDF curve) is appropriate for temporary infrastructure (e.g. temporary water crossings), infrastructure near the end of its design life, or minor infrastructure repairs requiring immediate attention but with a major upgrade already scheduled in the near future. As the planning horizon increases to 2050, the number of projects that use this approach will decrease.

The "Middle of the road" approach (using the moderate change IDF curves) is appropriate for infrastructure with a minor level of risk due to failure. For instance, if flooding were to occur, there would be some, but relatively minor, impacts on property, the environment, and there would be no potential loss of life impacts. Infrastructure with a minor level of risk of failure will tend to have a planning horizon near the middle of the century. As the planning horizon increases, the usage of the moderate change IDF curves will decrease because infrastructure with a longer planning horizon is likely to have more major risks associated with failure. However, the moderate change IDF curves can be used for all planning horizons.

The "Worst-case" approach (using the high change IDF curves) is appropriate for infrastructure where the consequences of failure/loss of service are catastrophic (i.e. major infrastructure). Major infrastructure tends to have a longer design life (planning horizon is closer to 2100). As a result, the high change IDF curves will likely be applied only for infrastructure with a planning horizon greater than 2050, and mainly for infrastructure with a planning horizon near 2100.

For planning horizons between 2050 and 2100, the user can utilize the closer future climate IDF curve, or interpolate between the two time horizons.

III. Vulnerability Assessment

Climatic vulnerability is the degree to which a system is affected, either adversely or beneficially, by climate stressors. Vulnerability can be measured in terms of the consequences associated with failure of an asset due to the increased rainfall. There are several categories of consequences to consider; Table 2.10 provides examples of detailed criteria to consider for defining the consequence level in each category. These criteria can be adapted by GVS&DD to evaluate the impacts of climate change on their sewerage and stormwater collection infrastructure.

Table 2.10 Generic Consequences for Climate Change Impacts

Consequence Level	Asset Damage	Financial Loss	Loss of Service	Health and Safety	Reputation
Catastrophic	Permanent damage and/or loss of infrastructure	Above $10M	Disastrous service loss (for more than a day)	Potential for death(s) or probable permanent damage	Major ethics issue for multiple employees, major impacts to image
Major	Extensive infrastructure damage requiring repair	Up to $10M	Major service loss (less than a day)	Potential for serious injury(ies) with a possibility of loss of a life	Major accountability, minor ethics impacts to image
Moderate	Damage recoverable by maintenance and minor repair	Up to $5M	Service loss or major quality of service concern for critical users	Potential for serious injury or affects to health. disability	Minor accountability, minor impacts to image
Minor	No permanent damage, some minor restoration work required	Up to $625K	Reduced quality of service or service loss for critical users for less than an hour	Potential for minor injury to an individual. Full recovery is expected	Major communications issues impacting image
Insignificant	No Infrastructure damage	Up to $125K	Reduced quality of service or service loss for few residents	No obvious potential for injury or affects to health	Minor communications issue impacting image

IV. Risk Analysis

Formal risk analysis is used to combine the consequence of failure with the likelihood of failure of the asset. The risk analysis will categorize each infrastructure asset according to risk levels (extreme, high, moderate, low).

V. Prioritizing an Adaptation Response

The level of risk of an infrastructure asset will determine its priority for adaptation (Figure 2.30). High risk infrastructure has the highest priority for adaptation. As the level of risk decreases, the adaptation priority also decreases.

It is recommended that a range of adaptation measures to mitigate risk of failure from increased rainfall be investigated for each type of infrastructure. Selecting the right adaptation measures can be determined by the level of risk of the asset, a cost-benefit analysis, and/or by examining individual capabilities and resourcing. Table 2.11 highlights various adaptation measures that can be considered for stormwater and sewerage collection infrastructure.

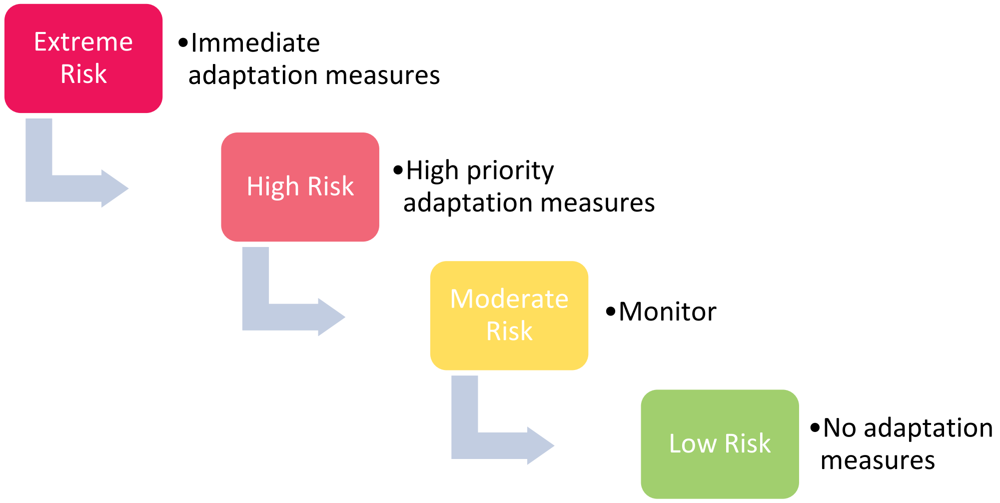

Figure 2.30 Prioritization of Adaptation Measures

Table 2.11 Example Stormwater and Sewerage Infrastructure Adaptation Measures

Stormwater Infrastructure	Sewerage Infrastructure
• Conserve naturally functioning watersheds to reduce stormwater runoff • Encourage Green Infrastructure/Low Impact Development (GI/LID) • Implement best stormwater practices • Add peak flow storage • Add an overland flow path and use the storm sewer for minor flows only • Maintain current level of service • Upsize pipes/culverts • Rehabilitate/upgrade part-way through the design life	• Reduce RDII • Add peak flow storage • Accept full pipes if hydraulic grade line is more than 1.8 m below ground • Upsize pipes • Private measures such as backwater valve requirements, pumps or other controls to prevent backflow into basements • Upgrade pump stations and wastewater treatment plants to increase resiliency

VI. Project Appraisal and Selection

Once a range of possible adaptation options has been identified, prioritize the options to create a shortlist of the most appropriate options for implementation. A number of decision-making approaches are available, some of which are listed below.

- **Best Judgement:** Utilizes engineering judgement only and does not include detailed analysis and justification.
- **Cost-Benefit Analysis:** Quantifies and assesses intervention costs against economic benefits. This option is preferred when costs and benefits can be quantified.
- **Multi-Criteria Analysis:** Prioritizes adaptation options with less tangible benefits and costs (the process is shown schematically in Figure 2.31). This option is preferred when costs and benefits are not quantifiable.

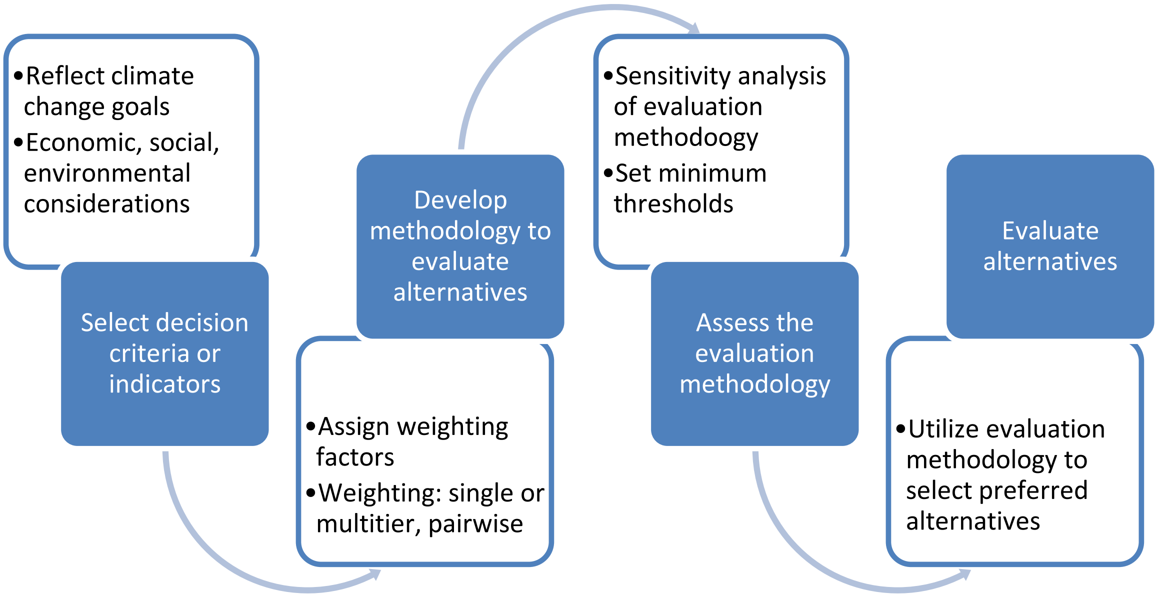

Figure 2.31 Multi-Criteria Analysis Decision-Making Process

VII. Climate Change Business Case

It is recommended that a business case be developed and approved that defines a 10-year capital program for climate change adaptation projects. The previous steps of the process will naturally prioritize the higher-risk infrastructure, and consider lower risk infrastructure as budgetary constraints/time allow.

2.4.2 Designing for Future Climate

As climate change progresses, rainfall intensity and frequency will increase. It is recommended that design practices be updated accordingly – it is imperative to consider climate change as part of design. The climate change adaptation design process is shown in Figure 2.32. Climate change factors must be evaluated and considered with other factors that are typically included in infrastructure design (e.g. population growth, land use change, catchment area, etc.).

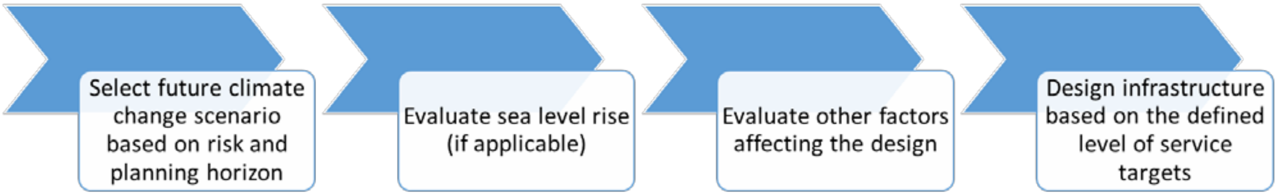

Figure 2.32 Climate Change Adaptation Design Process

It is important to consider that sewerage and stormwater collection infrastructure are part of a network system. It is recommended that the performance of the network be optimized by performing climate change adaptation in a way that minimizes problems in other parts of the network. Consider and test multiple adaptation measures and select the option that maximizes the level of service of the entire network.

It is recommended that the regulatory framework be reviewed and adapted to incorporate climate change impacts. Adjust/modify by-laws, design standards and guidelines, and other regulations to support climate change adaptation.

This project identified that the current stormwater source control guidelines will need to be updated to support climate change adaptation. The current guidelines will be insufficient to maintain the level of service. A proposed stormwater source control guideline includes ensuring that the proposed conditions peak flow do not exceed the current pre-development peak flow for a range of AEPs (Figure 2.33).

Existing	Proposed
• Pre-development conditions • Current rainfall • 50% AEP to 1% AEP	• Post-development conditions • 2050/2100 Moderate rainfall • 50% AEP to 1% AEP

Figure 2.33 Proposed Climate Change Stormwater Source Control Guideline

The guideline may not be achievable in all cases, but the level of service will degrade over time where it cannot be achieved. The stormwater source control may also be too stringent for the current time horizon (e.g. minimum ecological flow may not be achieved in the watercourses). Therefore, options to maintain water quantity and quality in the watercourses (e.g. plan to rehabilitate or upgrade part-way through the design life) are recommended for consideration. It is also recommended that retrofitting source controls onto existing properties be encouraged, but the effectiveness will likely be limited to high AEP events.

The current wastewater design guidelines will also need to be updated to support climate change adaptation. It may be appropriate to consider adding a provision regarding a maximum RDII allowance based on proportion of the sewage flow. Where the existing sewers experience RDII greater than the maximum RDII allowance (either in the current or the future climate), it is recommended that RDII reduction be mandated as part of the sewer system upgrades.

The design criteria for the sanitary sewers may also need to be adjusted/modified. Some guidelines specify a maximum flow depth during wet weather in the sewer (e.g. City of Burnaby, 2014). As climate change progresses, the increase in RDII will result in higher flow depths, which will require larger pipes. However, this will result in oversized pipes for the sanitary sewage flow.

2.4.3 Support Services

Climate change tasks, skills, and competencies are currently "ad hoc" within GVS&DD. It is recommended that climate change be formalized in job descriptions, and that succession planning be in place so climate change knowledge and initiatives do not diminish over time.

There is a significant amount of data to collect as part of climate change adaptation (Figure 2.34), including both observed data (e.g. monitoring rainfall) and projected climate data (e.g. GCM predictions). Continued monitoring is recommended for key climate variables (such as rainfall and sea level) and the existing level of service of infrastructure.

It is recommended that thresholds be established to trigger changes to climate change adaptation. Thresholds to set may include the following.

- If rainfall intensities are shown to be increasing (statistically significant trends), this is recommended as a suitable trigger for the development of new IDF curves.
- If the level of service of infrastructure is decreasing, it may be attributable to climate change. It is recommended that the cause of the decrease in level of service be investigated. If climate change adaptation efforts are not working effectively and/or climate change is progressing more rapidly than anticipated, then altering the approaches to climate change adaptation (for instance, a greater level of climate change adaptation) is recommended.
- As climate change science progresses, it may be necessary to generate new future climate IDF curves. For instance, when the sixth assessment report of the IPCC is published (due in 2021), it may contain new climate change scenarios with differences in climate change projections.
- Other external factors (e.g. changes in federal/provincial guidelines, the insurance sector or climate change legal liability) may also act as triggers to review and modify the GVS&DD's strategic approach to climate change adaptation.

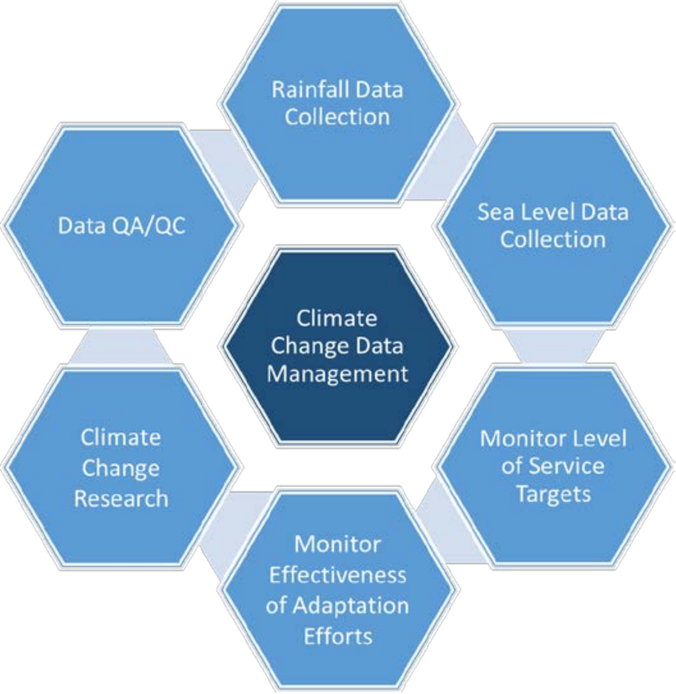

Figure 2.34 Data Collection for Climate Change Adaptation

2.4.4 Performance Management

It is recommended that GVS&DD establish, implement, and maintain processes for identifying opportunities to continually improve their climate change adaptation practices. Continual improvement is an iterative activity, and an annual audit to track climate change progress is recommended.

3. Conclusions and Recommendations

The conclusions presented in the following sections are organized into categories based on the main objectives of this project. Recommendations have also been provided in each section.

3.1 Current Climate Analysis

- New homogeneous rainfall zones were developed for this analysis. A total of seven homogeneous rainfall zones were delineated. The borders between the zones are to be interpreted as gradual and approximate. The homogeneous rainfall zones may change as additional data are collected.
- The index rain for the duration(s) of interest must be determined for the study area. The index rain can be read from the contour maps or estimated from data at nearby rainfall monitoring locations. The index rain can then be used to scale the dimensionless IDF curve.
- The effect of the PDO on the IDF curves was examined using long-term rainfall monitoring stations representative of the Metro Vancouver region. In general, there is a decrease in the IDF curves during warm years and an increase in the IDF curves during cool years. There is variability in this relationship: some stations were more sensitive and some were less sensitive to PDO. Given the level of variability in the effect of PDO on the IDF curves, it is recommended to use all data for the derivation of IDF curves.
- The rainfall monitoring network can be improved by ensuring that monitoring continues at all stations and (where necessary) adjusting the temporal frequency of the data to five minutes.
- It is recommended that the rainfall monitoring network be improved by adding stations in areas without rainfall measurement. Areas where the distance between stations is more than three kilometers are shown in Figure 3.1.
- Monitoring of trends in observed rainfall is recommended. In five years (2022), it is recommended that representative stations be examined to determine if there is a statistically significant increasing trend in rainfall. If there is a statistically significant trend, an IDF update is recommended. If there is no observed trend, the IDF update can be delayed for a further five years (2027) as there will be little change in the IDF curves.

3.2 Future Climate Analysis

- There is no standard or accepted methodology to derive IDF curves for future climate conditions. There are several approaches, which differ in their levels of complexity, data requirements, ease of use, and cost of implementation, among other factors.
- There are many challenges associated with future climate IDF modelling. A significant challenge preventing the adoption of existing approaches for the development of future climate IDF curves arises from the coarse or inadequate temporal and spatial resolution of GCM outputs.

Source: ESRI World Imagery Service.

0 2 4 6
Kilometres

Coordinate System:
NAD 1983 UTM Zone 10N

N

Legend

- 🟢 Stations with >10 yrs
- 🔴 Stations With <10 yrs
- ▭ Municipal Boundaries
- ▨ Suggested Regions for Additional Rainfall Monitoring

GHD

METRO VANCOUVER
BRITISH COLUMBIA, CANADA

11140666-08
Jun 5, 2018

SUGGESTED REGIONS FOR ADDITIONAL RAINFALL MONITORING FIGURE 3.1

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- A new downscaling methodology for deriving future climate IDF curves was developed for this project to address the limitations of existing approaches. The methodology addresses low-frequency climatic variability (PDO), derivation of changes in sub-daily rainfall intensities, and bias correction for preserving the temporal variability between IDF intensities of different durations in the future climate IDF curves. The methodology also addresses the different spatial scales of rainfall data (historical rainfall records available from climate stations, the GCM data provided at GCM grids, and the updated IDF curves derived for statistically homogeneous rainfall zones).
- The future climate analysis explored various sources of future climate uncertainty including uncertainties in the prediction of the future, limitations of existing climate modelling techniques, and regional/project specific factors. The scaling factor, which defines the rate that sub-daily rainfall intensities will increase relative to daily rainfall, was the most sensitive factor. While keeping other factors constant, it was found that the 95th percentiles derived from all simulated projections approximated well the effect of the scaling factor.
- The results of the sensitivity analysis were used to define moderate and high change future climate scenarios for Metro Vancouver for the time horizons 2050 and 2100. The moderate scenarios were based on median projections of future climate and the high scenarios on 95th percentile projections.
- Future climate IDF curves were generated for the moderate and high change scenarios for all homogeneous rainfall zones. The results suggested that the future climate IDF curves are expected to increase by 21% in 2050 and 41% in 2100 for the moderate change scenario, and by 44% in 2050 and 75% in 2100 for the high change scenario. The increase will vary spatially from zone to zone, with the lowest increase projected in Zone 6 and the highest increase projected in Zone 1.
- The results also suggested that the AEP of a storm of a certain magnitude will increase (return period will decrease) in the moderate and high change scenarios.
- Climate change science is rapidly evolving; research teams around the world are developing new tools, techniques, models, and future climate projections. New research findings constantly improve the understanding of climate change uncertainties and lead to more accurate predictions of future climate. To benefit from the new findings, it is necessary to regularly update future climate IDF curves. The release of the next IPCC report (scheduled for 2021) is recommended as the next milestone for revisiting the results generated in this project.
- It is recommended that a high-level study be initiated first to determine whether an update of future climate IDF curves is warranted for the recommended milestone (2021). If the update is found to be necessary, it is recommended to coordinate the future climate analysis with an update of current climate IDF curves.
- When new provincial and federal climate change guidelines are introduced they must be reviewed and integrated in the GVS&DD's climate adaptation process.

- It is also recommended that new developments in the insurance sector and climate change legal liability be periodically reviewed and reflected in the GVS&DD's climate adaptation process.

3.3 Case Studies

Stormwater Drainage Network

- Drainage networks are impacted by a combination of sea level rise and increased rainfall due to climate change. In the areas near the coast, sea level rise is the dominant factor affecting the level of service. In the upstream reaches, increased rainfall is the dominant factor.
- The current source control guidelines are insufficient to maintain the current level of service in the drainage area. The peak flows from future climate rainfall are higher than the current peak flow at the 50%, 10%, and 1% AEP. Maintaining the current level of service requires stricter source control guidelines.
- It is recommended that the source control guidelines currently in use across the Metro Vancouver region be re-examined to include climate change and various AEPs (return periods). It is recommended that the rainfall reduction strategy require that future peak flows (post-development land use with future climate IDF curve rainfall) do not exceed current peak flows (pre-development land use with current climate IDF curve rainfall) at a range of AEPs (e.g. 50% to 1% AEP).
- The rainfall reduction strategy can be modified based on the characteristics of the area where it will be applied. Factors to be included are: amount of redevelopment expected, watershed characteristics (e.g. infiltration capacity, amount of impervious area, slope, etc.), and capacity of the current drainage system.
- Retrofitting existing lots and/or encouraging private land owners to add source controls on their property is recommended. However, this will likely have limited impact as the retrofitting will be limited by the design of the existing developments.
- In areas where little or no redevelopment is anticipated, infrastructure upgrades will be required. There are multiple end-of-pipe solutions that can be used. Pipe upsizing may or may not be the preferred method for infrastructure upgrades: pipe upsizing can lead to flooding downstream. Consider peak flow reduction strategies (e.g. detention ponds, peak flow diversion, etc.).
- The infrastructure upgrade cost for the 2050 scenarios was approximately two times the infrastructure upgrade cost for the current scenario. For the 2100 scenarios, the infrastructure upgrade cost was three to four times the upgrade cost for the current scenario. The increase in cost between the high and moderate scenarios, however, was relatively small: 10-20 percent.

Sanitary Sewer System

- Sanitary sewer systems are impacted by a combination of population growth and increased RDII due to increased rainfall. The relative impact of each factor varies.

- Pipe upsizing may be required to accommodate population growth. It is recommended that additional pipe upsizing to accommodate increased RDII be avoided.
- The current sanitary sewer guideline requires that the sanitary sewer be less than 70% full by depth in the City of Burnaby. A different guideline will decrease the need for additional pipe upsizing while ensuring that basement flooding and/or sewer backups do not occur.
- The infrastructure upgrade cost for the 2050 scenarios was similar to the infrastructure upgrade cost to accommodate population. For the 2100 scenarios, the infrastructure upgrade cost to accommodate increased RDII was five to seven times the upgrade cost to accommodate population. For the 2100 scenarios, the sanitary sewer was flowing near full and the capacity for additional flow from RDII was low (a "tipping point" in vulnerability to increased RDII was reached).
- The increase in cost between the high and moderate scenarios was substantial: 40-50 percent. For the 2050 time horizon, this was due to the use of larger pipes for the high change scenario. For the 2100 time horizon, there was a significant increase in the number of pipes that needed to be upsized for the high change scenario.
- Continued sewer flow monitoring and assessment of levels of RDII in various parts of the sewerage network is recommended. RDII reduction strategies can be incorporated during sanitary sewer upgrades, and monitoring the level of reduction will provide feedback that can be used to further reduce RDII.
- Methods other than pipe upsizing are recommended for delivering the required level of service, such as RDII reduction, private-side measures, or peak flow storage. This will minimize the need to upsize pipes downstream and minimize overflows of downstream infrastructure such as pumping stations and wastewater treatment plants.

Combined Sewer Collection System

- Combined sewer systems will be impacted by a combination of population growth (prior to separation), sea level rise, and increased rainfall due to climate change. The relative impact of each factor varies.
- Increasing the combined sewer capacity to provide the level of service to 2050 may be insufficient to provide the required level of service for the separated sewer in 2100. As a result, an accelerated sewer separation schedule is recommended to avoid multiple upgrades.
- The infrastructure upgrade cost for the 2050 scenarios was approximately three times the infrastructure upgrade cost for the current scenario. For the 2100 scenarios, the infrastructure upgrade cost was more than three times the upgrade cost for the current scenario. The increase in cost between the high and moderate scenarios, however, was relatively small: 10-15 percent.
- There may be areas where population growth will impact the combined trunk design prior to sewer separation. These areas may need to be prioritized for sewer separation, depending on the level of impact of the population growth.

- It is recommended that the separated trunk sewer be designed for the flows due to the future rainfall estimates. For instance, selecting pipe sizes based on the future climate IDF curve is recommended.
- Methodologies to reduce pipe upsizing and downstream flooding are recommended where possible (e.g. overland flood route (minor-major system), peak flow storage, green infrastructure, and low impact development). This is particularly useful in areas where the separated sewer will flow into other infrastructure (instead of discharging to a river or the ocean).

3.4 Climate Change Adaptation Practices

- Currently, no 'gold standard' exists for climate change adaptation planning for sewerage and stormwater collection assets.
- It is important to aim and strive to create a climate change culture across all components of the organization's business process.
- It is recommended that a formal Climate Change Plan be developed and adopted to guide the progress of climate change adaptation and ensure consistency and completeness.
- Climate change objectives and level of service targets are foundational for future climate change adaptation, and it is recommended that the objectives and targets be established.
- The regulatory framework (by-laws, design standards and guidelines, and regulations) will need to be adjusted/modified to support climate change adaptation. Stricter stormwater source control guidelines will be required to maintain the current level of service. The wastewater design guidelines will need to be updated to encourage or require RDII reduction and ensure that pipes are not oversized due to increased RDII.
- It is recommended that a vulnerability/risk assessment be used to prioritize network upgrades. The assessment will include the consequences of failure and level of risk of failure. Higher risk areas are higher priority for upgrades than lower risk areas, which may simply maintain the current level of service.
- There are three approaches for climate change adaptation: Do nothing (current climate), Middle of the road (moderate future climate change), and Worst-case (high future climate change). For most applications, the moderate change scenarios may be acceptable, but for high-risk infrastructure the high change scenario is recommended.
- It is recommended that the selection of the 2050 or 2100 time horizon be based on the planning horizon/design life. If the planning horizon is between 2050 and 2100, either the closer time horizon or an interpolation between the 2050 and 2100 future rainfall events can be used.
- Design practices can be updated to explicitly incorporate climate change with an integrated planning approach. The following climate change factors are key to climate change adaptation planning: future climate IDF curves and sea level rise.
- There are multiple types of infrastructure upgrades that can be used to address capacity concerns. There are also different ways to stage the infrastructure upgrades. An "optimized

network approach" will consider multiple adaptation measures and select the option that minimizes adverse impact on the level of service of the entire network.

- It is recommended that climate change adaptation tasks be formalized through training, succession planning, and formal roles within job descriptions.
- It is important to have a data management strategy in order ensure that climate change data are being recorded, used, and updated when appropriate. It is recommended that threshold values be set to trigger changes to climate change adaptation.
- It is recommended that climate change adaptation progress be tracked and adjusted as necessary.

4. Next Steps

A number of recommendations have been provided for GVS&DD to develop adaptation practices and incorporate climate change into infrastructure planning and design. Current competencies exist within the organization, however there are multiple action items that will assist GVS&DD to successfully plan for an uncertain future.

Based on the good practice recommendations, a roadmap has been prepared to help GVS&DD achieve a well-executed climate change adaptation planning process (Figure 4.1). The roadmap has been set up as a ten-year plan. The first five years are instrumental in developing the climate change adaptation plan, so that the plan can be implemented in years six to ten.

The roadmap provides direction to incorporate climate change adaptation into the planning and design of infrastructure, but there is also flexibility to modify the climate change adaptation plan as the needs/requirements change. The climate change adaptation plan will incorporate climate change uncertainty and its effects on infrastructure. As GVS&DD proactively develops the climate change adaptation plan, consistent approaches across the Metro Vancouver region will be developed, and the organization will be able to help create a regional climate change 'culture'.

	Description	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6 to 10
PLANNING AND RESEARCH	Develop a formal climate change policy				Ongoing Improvements		
	Determine Overflow and Capacity Measures/Targets					Ongoing Improvements	
	Select adaptation responses based on risk assessments					Ongoing Improvements	
	Conduct cost-benefit analysis for project appraisal and selection						Ongoing Improvements
	Develop a ten year capital program for climate change adaptation						Ongoing Improvements
DESIGN AND DELIVERY	Propose draft version of design updates					Ongoing Improvements	
	Integrate climate change considerations through other capital delivery stages						Ongoing Improvements
	Implement and update final design updates						Ongoing Improvements
SUPPORT SERVICES	Create a climate change Data Management Strategy						Ongoing Improvements
	Create a Knowledge Management Plan, formalize climate change roles within job descriptions, and adopt succession planning.						Ongoing Improvements
PERFORMANCE MANAGEMENT	Create a formal audit process to benchmark climate change adaptation progress					Ongoing Improvements	

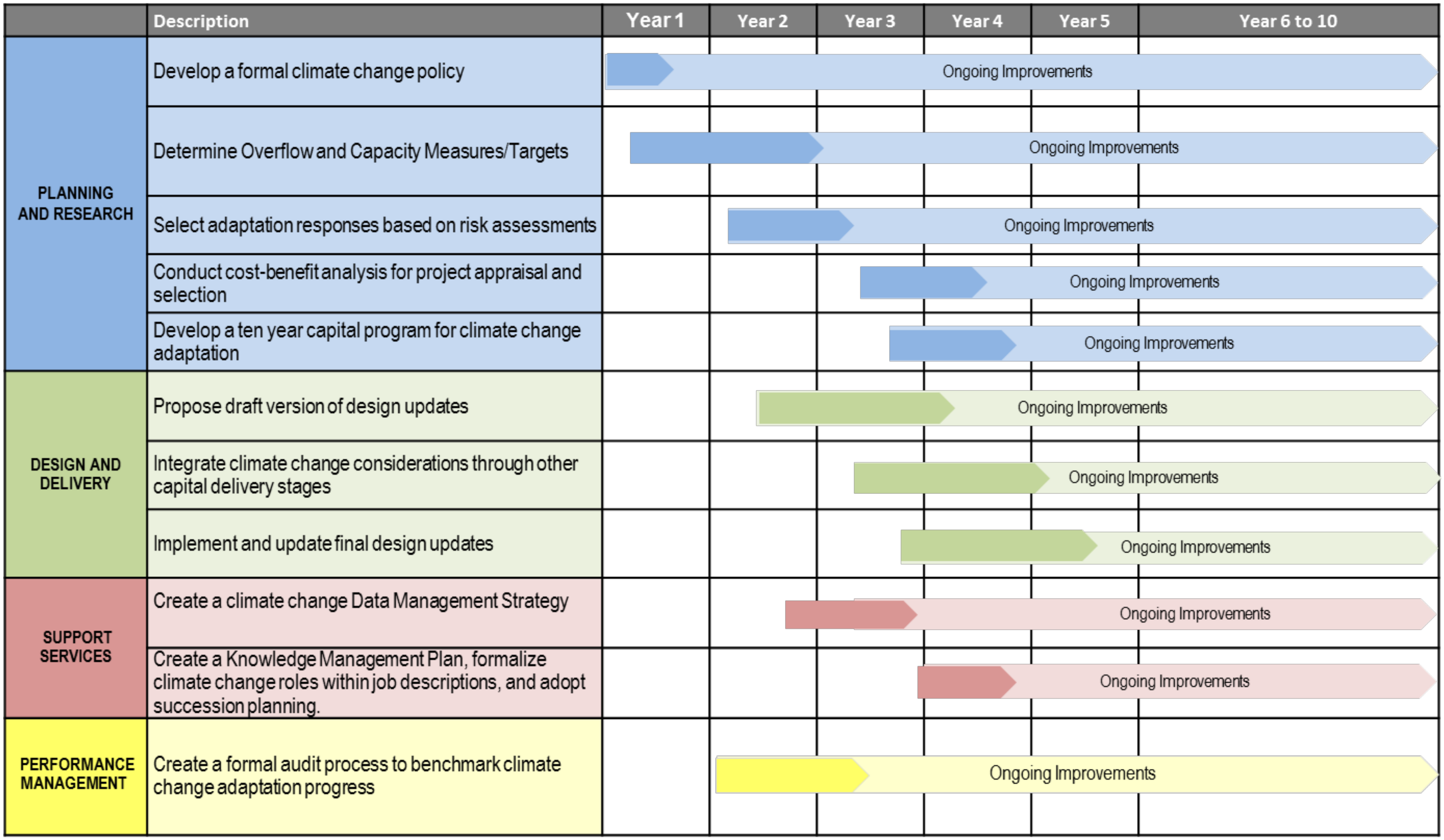

Figure 4.1 Ten-Year Roadmap for Climate Change Adaptation

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Technical Memorandum 1
Temporal Downscaling Methodology

GHD

Memorandum

August 3, 2018

To:	Lillian Zaremba	Ref. No.:	11140666
	JMC		
From:	Juraj Cunderlik, Allyson Bingeman, Yi Wang/aj/1	Tel:	519-884-0510

Subject: **Study of the Impacts of Climate Change on Precipitation and Stormwater Management Temporal Downscaling Methodology**

1. Introduction and Background

The Greater Vancouver Sewerage and Drainage District (GVS&DD) has initiated the above referenced project for the purpose of advancing its knowledge and capabilities to adapt to the effects of climate change to ensure that adequate levels of service for sewerage and drainage infrastructure are maintained. During past collaboration between the GVS&DD and the Pacific Climate Impacts Consortium (PCIC), it was found that many stakeholders were interested in future climate Intensity Duration Frequency (IDF) Curves. The objective of this project is to update the IDF curves for Metro Vancouver, quantify uncertainty surrounding future climate IDF projections, and determine the potential effect of climate change on infrastructure design.

The PCIC has performed spatial statistical downscaling of twelve Global Circulation Model (GCM) outputs which they recommended for North America. The twelve GCMs utilize the Representative Concentration Pathway (RCP) scenarios described in the 5th Annual Report of the Intergovernmental Panel on Climate Change (IPCC, 2013). PCIC used two different methodologies for spatial downscaling of the GCM outputs: Bias-Correction Spatial Disaggregation (BCSD) and Bias Correction/Constructed Analogues with Quantile mapping reordering (BCCAQ). The downscaled outputs are available in 300 arc-second grids (approximately 10 km by 10 km). The following data are available at the daily, monthly, seasonal, and annual time scales: maximum air temperature, minimum air temperature, and precipitation.

In order to develop future climate change IDF curves, the data must be temporally downscaled to obtain sub-daily increases in rainfall. There are various methodologies for temporal downscaling, most of which involve building statistical relationships between the GCM data and the historical data. In addition, temporal downscaling can change through time, as the relationship between sub-daily and daily precipitation may vary with changing climate. Westra et al. (2014), as reviewed by PCIC (2015), identified that the daily rainfall extremes are increasing “between 5.9 % and 7.7 % per °C”, which is close to the Clausius-Clapeyron (C-C) relation. Westra et al. (2014) also mentioned that, at sub-daily time scales, especially at hourly or sub-hourly scales, extreme rainfall increases with air temperature at the C-C rate up to 12 °C, at twice the C-C rate between 12 °C and 24 °C, and at a reversed rate above 24 °C. This statement was reviewed and recommended by Zhang et al. (2017).

The C-C relation in combination with global warming projections can be translated into scaling factors of the daily to sub-daily ratios. For rainfall events taking place in the 12 – 24 °C air temperature range, every Celsius degree increase in the air temperature will increase the rainfall intensity by 7 % to 14 % for the rainfall durations from daily to sub-hourly. If the air temperature increases from 12 °C to 24 °C, the daily to sub-daily ratio will increase by $(1 + 14\ \% \times 12)/(1 + 7\ \% \times 12) - 1 = 46\ \%$, which indicates the upper limit of the scaling factors.

The purpose of this technical memorandum is to present GHD's methodology for temporal downscaling of the daily GCM outputs. The proposed methodology is built upon the widely accepted and used delta change methodology for statistical downscaling. The proposed methodology represents a robust approach that is defendable in the scientific community.

This Technical Memorandum is organized as follows:

- Section 2 provides an overview of the temporal downscaling methodology
- Section 3 will provides a detailed description of the temporal downscaling methodology

2. Overview of Temporal Downscaling Methodology

Sub-daily temporal scales are not captured by the GCM models. However, except for 24-hour, all rainfall durations defining the standard IDF curve are sub-daily durations. Current approaches assume that the changes in sub-daily rainfall will increase at the same rate as the daily rainfall. However, as the CSA (2012) states, "changes in the atmospheric processes governing rainfall production will not likely be uniform for short to long time durations", which is supported by recent trends in regional precipitation (Intergovernmental Panel on Climate Change, IPCC, 2007).

A new methodology for deriving future climate IDF curves was developed for this project to address the limitations of existing approaches. In order to develop future climate IDF curves, the data must be temporally downscaled to obtain sub-daily increases of rainfall intensities. There are various methodologies for temporal downscaling, most of which involve building statistical relationships between the GCM data and the historical data. In addition, temporal downscaling can change through time, as the relationship between sub-daily and daily precipitation may vary with changing climate. Westra et al. (2014), as reviewed by PCIC (2015), identified that the daily rainfall extremes are increasing "between 5.9% and 7.7% per °C", which is close to the Clausius-Clapeyron (C-C) relation. The authors also mentioned that, at sub-daily time scales, especially at hourly or sub-hourly scales, extreme rainfall increases with air temperature at the C-C rate up to 12 °C, at twice the C-C rate between 12 °C and 24 °C, and at a reversed rate above 24 °C (Figure 2.1). This statement was reviewed and recommended by Zhang et al. (2017).

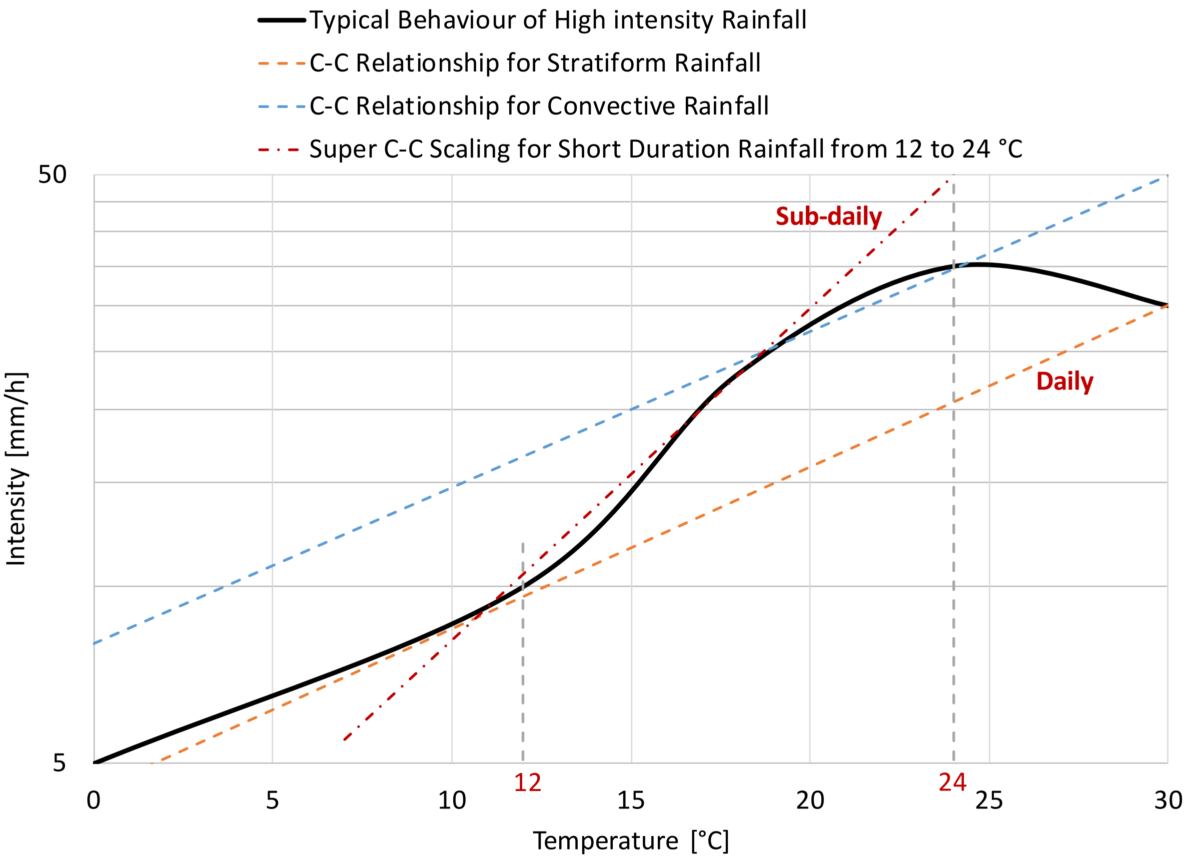

Figure 2.1 Clausius-Clapeyron Relationship Between Rainfall Intensity and Air Temperature

The C-C relation in combination with global warming projections can be translated into scaling factors of the daily to sub-daily ratios. For rainfall events taking place in the 12 – 24 °C air temperature range, every Celsius degree increase in the air temperature will increase the rainfall intensity by 7% to 14% for the rainfall durations from daily to sub-hourly. If the air temperature increases from 12 °C to 24 °C, the daily to sub-daily ratio will increase by 46%, which defines the upper limit of the scaling factors.

The temporal and spatial downscaling methodology developed for this project is depicted in Figure 2.2. The temporal downscaling addresses low-frequency climatic variability (such as the PDO), derivation of changes in sub-daily rainfall intensities (by means of sub-daily ratios and scaling factors), and bias correction for preserving the temporal variability between IDF intensities of different durations in the future climate IDF curves.

The spatial downscaling addresses the different spatial scales of rainfall data used in the project (historical rainfall records available from climate stations, the GCM data provided at GCM grids, and the updated IDF curves derived for statistically homogeneous rainfall zones). When implementing the temporal downscaling, the data must be interpolated/transferred between the three spatial scales.

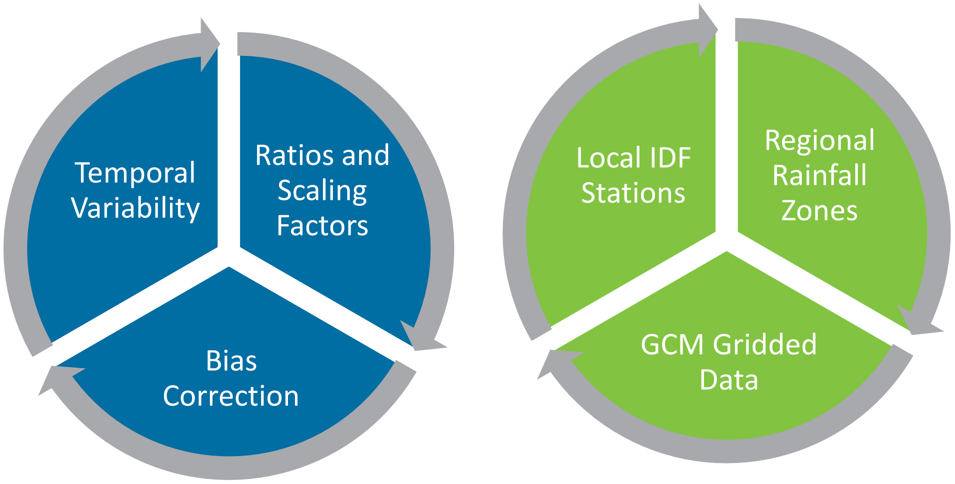

Figure 2.2 Temporal and Spatial Downscaling

The proposed approach integrates the three main components and transfers data between the three spatial scales. The overall methodology is shown in Figure 2.3. In the first step, the existing daily to sub-daily ratios are determined from historical rainfall records. Scaling factors are determined from observed changes over time in the historical daily to sub-daily ratios. In the second step, the annual maximum data at stations are used to estimate quantiles of return periods at each station, and interpolated into the grid level using gridding methods. In the third and fourth steps, the quantiles are estimated from the GCM daily annual maximum series for both the baseline and future time periods and converted to sub-daily quantiles using the daily to sub-daily ratios (baseline) or daily to sub-daily ratios and scaling factors (future time periods). In the fifth step, a quantile mapping technique is used to correct biases involved in the future GCM sub-daily quantiles. The sixth and seventh steps construct Regional Frequency Distributions (RFDs) from the gridded sub-daily quantiles and from the bias-corrected future GCM sub-daily quantiles, separately. In the eighth step, the two sets of RFD quantiles at the grid level are compared and the delta is applied to the RFD quantiles derived from station data.

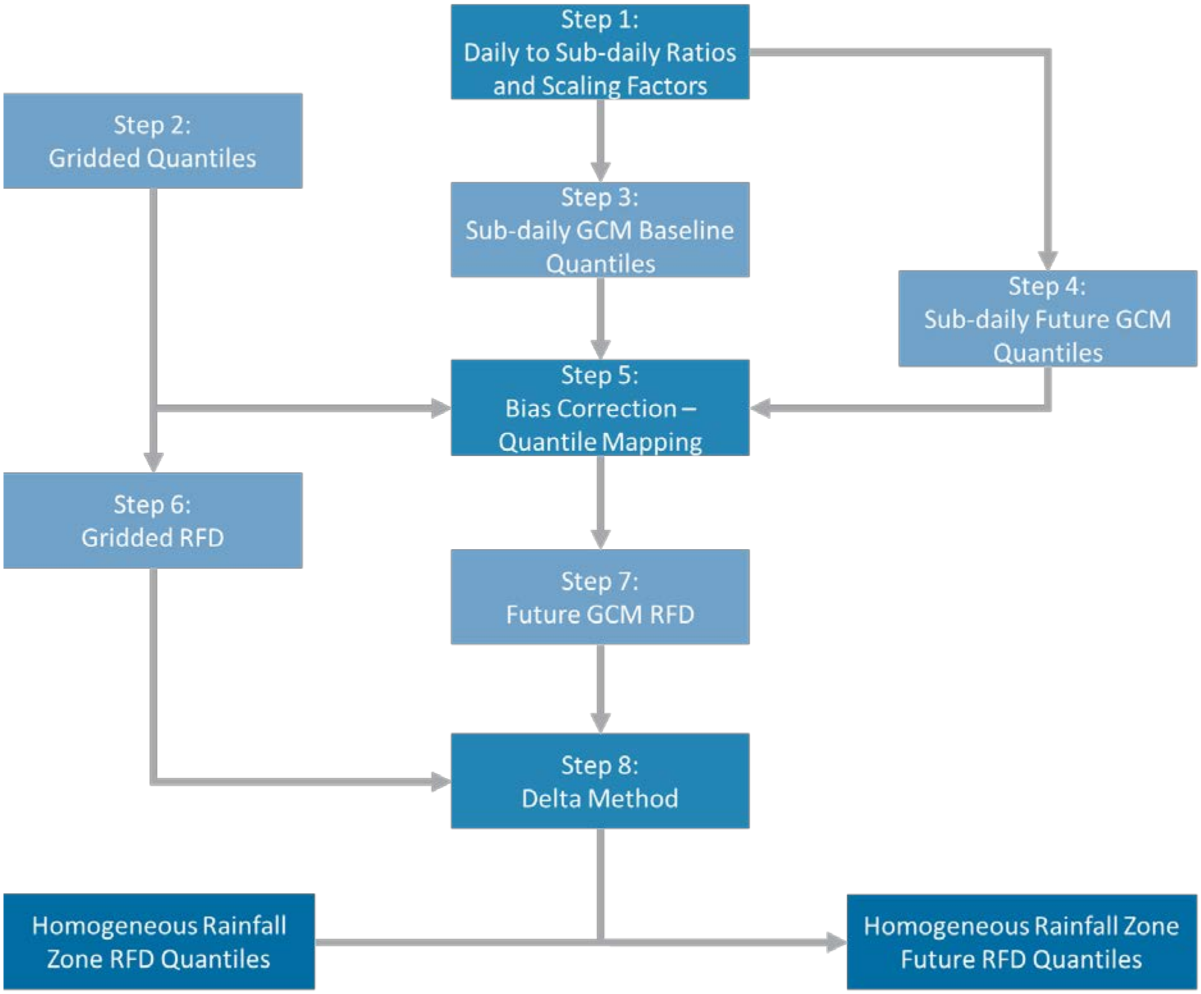

Figure 2.3 Methodology for Developing Future IDF Curves

3. Detailed Description of the Temporal Downscaling Methodology

3.1 Step 1: Daily to Sub-daily Ratios and Scaling Factors

The daily to sub-daily ratios will be derived using historical records. According to Hershfield (1961) ratios should be calculated from quantiles of the same return period, instead of from the annual maximum in each year. This is because the annual maxima from the daily and sub-daily time series for the same year do not necessarily come from the same storm event. Huff and Angel (1989) examined the variation of the ratios with respect to the length of return periods for stations in Illinois, and concluded that the same ratios could be used for all return periods. Spatial variations of ratios were investigated and excluded as well in Huff and Angel (1989).

In this project, daily to sub-daily ratios will be derived for all durations and return periods. Variations with respect to the length of return periods will be analyzed and excluded if appropriate. Spatial variations in the ratios won't be investigated since the statistically homogeneous rainfall zones will be used and that inherently warrants spatial invariance in the ratios. Finally, the ratios will be averaged among stations within homogenous rainfall zones to be used as the regional daily to sub-daily ratios.

More extreme rainfall intensities can be expected with climate warming. Recent research (e.g. Westra et al., 2014; PCIC, 2015; Zhang et al., 2017) suggests that there is some evidence that extreme daily rainfall will increase at the Clausius – Clapeyron rate, as discussed in section 1. For Western Canada, IPCC (2013) projected a 2-3 °C increase in surface air temperature for RCP 4.5 and 2-4 °C for RCP 8.5 for the 2046-2065 future period, compared to the 1986-2005 baseline period. An increase of 2-4 °C for RCP 4.5 and 4-7 °C for RCP 8.5 was projected for the 2081-2100 future period. If the C-C relationship holds in the future, assuming 12 °C base air temperature, sub-daily rainfall intensity will rise 12 % faster than the daily rainfall intensity at a 2 °C increase, 22 % faster at a 4 °C increase, and 33 % faster at a 7 °C increase. As PCIC (2015) noted, the C-C relation "emerges in a number of locations, it is not uniform and present everywhere, and it can vary by region and season."

Applying scaling factors to the daily to sub-daily ratios is an alternative to addressing the changes in sub-daily extreme precipitation. The scaling factors can be selected according to the C-C relationship, for example using one for no changes, 20% for moderate changes, and 40% for large changes. However, the scaling factors can be determined from historical rainfall data as well. For example, historical rainfall data can be divided into moving windows of 20 years, e.g. 1960-1979, 1961-1980, […], 2000-2017 and quantiles can be calculated by fitting Cumulative Distribution Functions (CDF) to the annual maxima (AM); then, daily to sub-daily ratios can be calculated from the quantiles for each time period, and compared to detect temporal and spatial trends in the ratios (see Figure 3.1). Assuming the rate of change in the ratios continues into the future, a possible range of changes for future time horizons can be explored in a sensitivity analysis. In addition, the scaling factors during warm and cool Pacific Decadal Oscillation (PDO) phases or the El Niño-Southern Oscillation (ENSO) years can be compared and used to inform the selection of values for the sensitivity analysis.

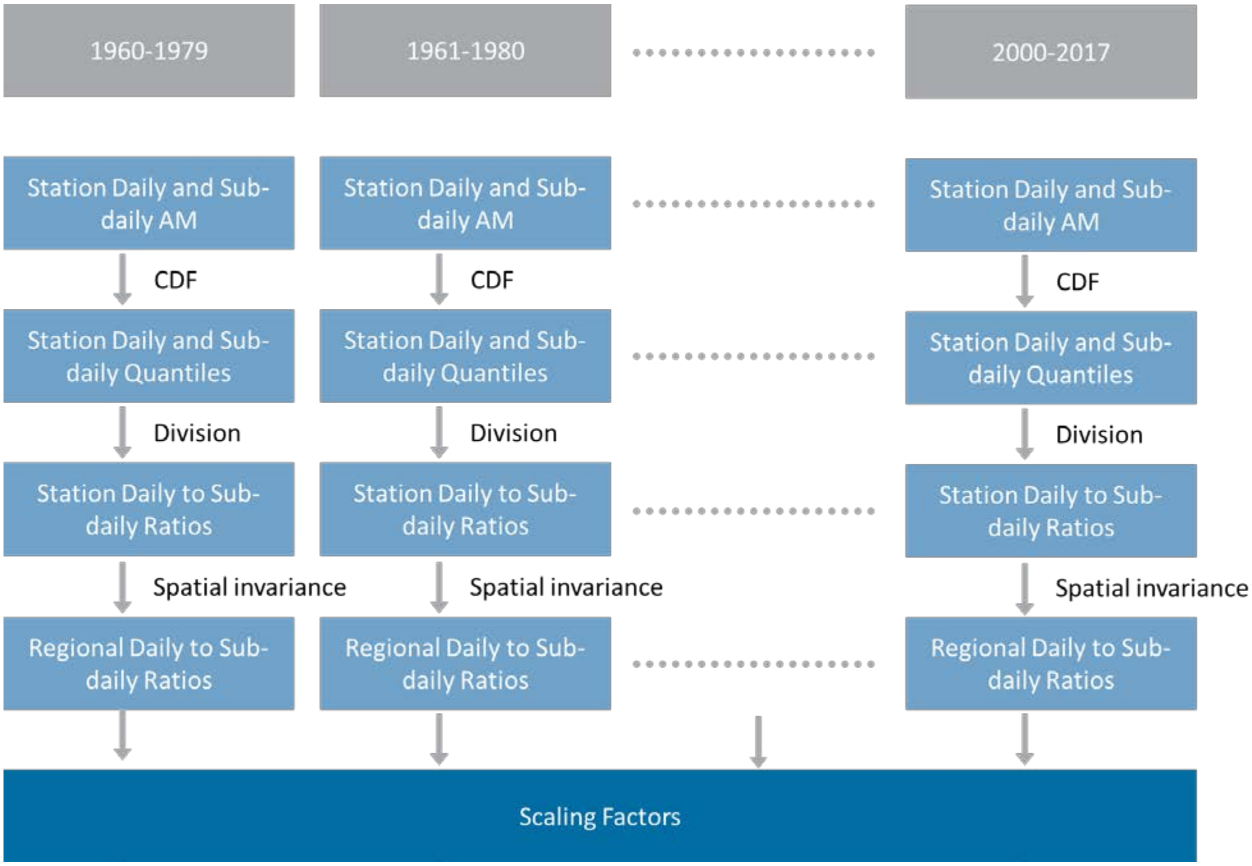

Figure 3.1 Derivation of Daily to Sub-daily Ratios and Scaling Factors

3.2 Step 2: Gridded Quantiles

Station-level daily and sub-daily rainfall quantiles (of various return periods) will be interpolated to get quantiles at the grid level, named "Gridded Quantiles" and denoted $X_{T,d}^{Gridded}$ herein (see Figure 3.2). In the interpolation technique (Castellano and DeGaetano, 2016), station-level quantiles within a given distance of the grid point, e.g. 10 km, will be averaged and weighted by the distances and the lengths of records at the stations.

The weighting factor (θ_k) is given by:

$$\theta_k = \alpha(\theta_d)_k + (1-\alpha)(\theta_n)_k \quad \text{........ Equation 1}$$

Where $(\theta_d)_k$ and $(\theta_n)_k$ are the distance component and the record length component at station (k), respectively, as shown below.

$$(\theta_d)_k = \frac{1}{d_k^2}\left(\sum_{i=1}^{N}\frac{1}{d_i^2}\right)^{-1} \quad \text{........ Equation 2}$$

$(\theta_n)_k = n_k\left(\sum_{i=1}^{N} n_i\right)^{-1}$ .... Equation 3

A weighting coefficient (α) is used to increase or decrease the distance component in the total weighting. The previous study used a weighting coefficient of 0.6 (Castellano and DeGaetano, 2016).

Revised homogeneous rainfall zones will be considered when selecting stations for the gridding process. The High-Resolution PRISM Climatology data, available from PCIC, provides average monthly totals for time periods of 1971-2000 and 1981-2010, and potentially can be used to validate the gridded quantiles, particularly the selection of the weighting coefficient (α).

Figure 3.2 Derivation of Gridded Sub-daily Quantiles

3.3 Step 3 and 4: Sub-Daily Quantiles

GCM daily AM data are available from PCIC, for both the baseline and future time periods. The selected frequency distribution will be used to extract quantiles of various return periods, noted as GCM baseline daily quantiles and future GCM daily quantiles. With the daily to sub-daily ratios determined (refer to Section 3.1), the GCM baseline daily quantiles can be converted to GCM baseline sub-daily quantiles, at each grid point. With the scaling factors, the future GCM daily quantiles can be downscaled to future GCM sub-daily quantiles (see Figure 3.3).

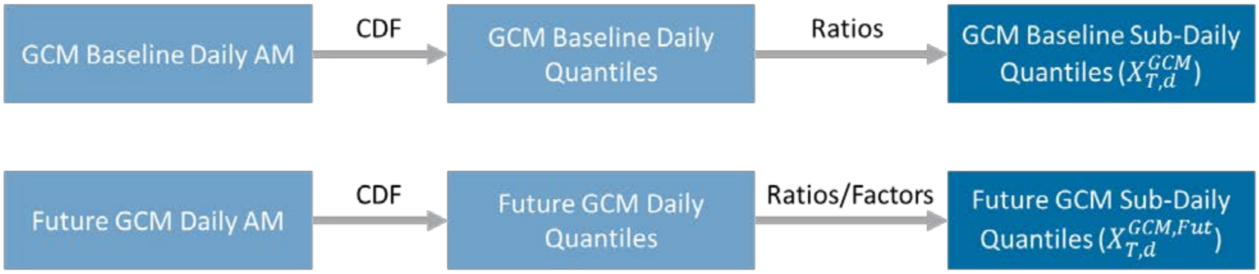

Figure 3.3 Derivation of GCM Sub-daily Quantiles

3.4 Step 5: Bias Correction – Quantile Mapping

The conversion between daily and sub-daily quantiles, especially when scaling factors are used, can introduce considerable amounts of uncertainties into the quantiles. In addition, biases exist between the grid-level GCM quantiles and the gridded quantiles from stations. Therefore, a quantile mapping method is proposed to correct biases in the future GCM quantiles (see Figure 3.4).

In the quantile mapping method, for a given rainfall duration (d) and return period (T), a linear relationship (Equation 4) will be established between the GCM baseline quantiles ($X_{T,d}^{GCM}$) and the gridded quantiles

($X_{T,d}^{Gridded}$), and used to transform the future GCM quantiles ($X_{T,d}^{GCM,Fut}$) to get bias-corrected future GCM quantiles ($X_{T,d}^{\widehat{GCM,Fut}}$) (Equation 5).

$$X_{T,d}^{Gridded} = a \times X_{T,d}^{GCM} + b \qquad \text{Equation 4}$$

$$X_{T,d}^{\widehat{GCM,Fut}} = a \times X_{T,d}^{GCM,Fut} + b \qquad \text{Equation 5}$$

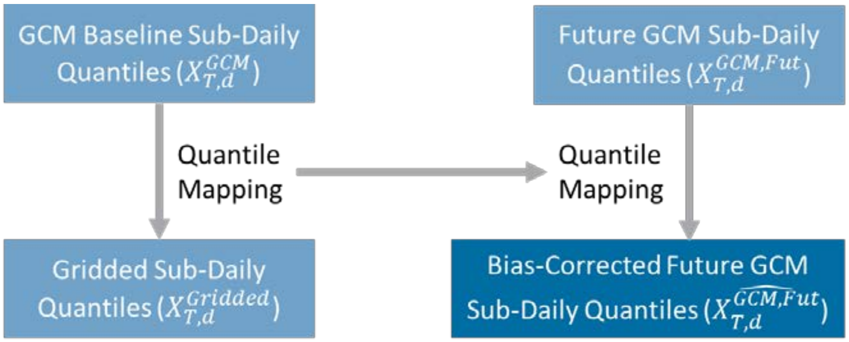

Figure 3.4 Bias Correction in Future GCM Sub-daily Quantiles

3.5 Step 6 and 7: Regional Frequency Distribution

Since the PCIC data are available at the grid level, the Regional Frequency Distributions (RFD) will be constructed and compared at the grid level, instead of the station level. At each grid point, L-moments (linear moments) will be estimated by fitting a selected probability distribution to the quantiles. Subsequently, the L-moments at grids within a homogeneous rainfall zone will be averaged in the calculation of the regional L-moments. Two sets of RFDs will be constructed for each homogenous rainfall zone: gridded RFD using gridded quantiles from stations, and future GCM RFD using the bias-corrected future GCM quantiles (see Figure 3.5).

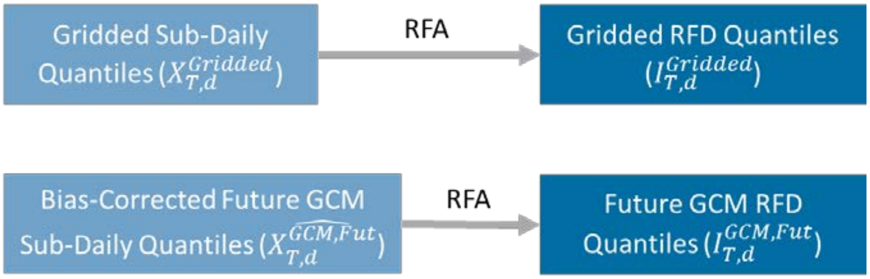

Figure 3.5 Derivation of Regional Frequency Distributions and Quantiles

3.6 Step 8: Delta Method

Although the future GCM RFDs will be constructed using bias-corrected quantiles, there are considerations prohibiting the use of these RFDs as future RFDs. In this project, existing RFDs will be updated using historical rainfall records at stations within homogeneous rainfall zones. Ideally, the future RFDs should be constructed using future projections at stations within same homogeneous rainfall zones, in order to compare with the updated RFDs under the same framework. However, the PCIC's GCM data are provided at the grid level, instead of the spatially downscaled station level.

The delta method will be used to derive homogeneous rainfall zone future RFD quantiles ($I_{T,d}^{Regional,Fut}$), by applying changes between gridded RFD quantiles ($I_{T,d}^{Gridded}$) and future GCM RFD quantiles ($I_{T,d}^{GCM,Fut}$) onto the updated homogeneous rainfall zone RFD quantiles ($I_{T,d}^{Regional,Updated}$) (see Equation 6 and Figure 3.6).

$$I_{T,d}^{Regional,Fut} = I_{T,d}^{Regional,Updated} \times \frac{I_{T,d}^{GCM,Fut}}{I_{T,d}^{Gridded}} \text{ .... Equation 6}$$

An additional benefit of using the delta method is that the variation between RFD quantiles of different return periods and rainfall durations are preserved in the updated RFDs.

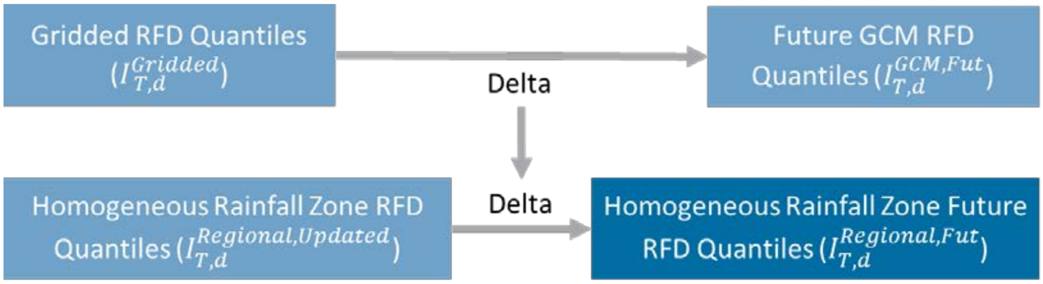

Figure 3.6 Delta Method for Future Regional Frequency Distribution Quantiles

3.7 Regional IDF curves

After steps 2 through 8 have been accomplished for all durations, future regional IDF curves can be constructed by assembling future RFDs of each duration into one set of future IDF curves (see Figure 3.7).

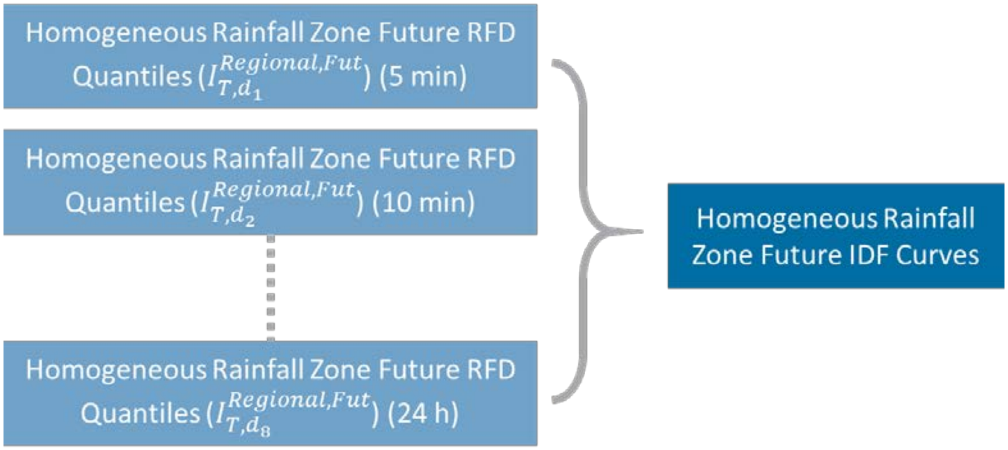

Figure 3.7 Derivation of Regional IDF Curves

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Technical Memorandum 2
Rainfall Analysis and IDF Curve Update

GHD

Memorandum

August 3, 2018

To: Lillian Zaremba　Ref. No.: 11140666

AB

From: Juraj Cunderlik, Allyson Bingeman/aj/2　Tel: 519-884-0510

Subject: **Study of the Impacts of Climate Change on Precipitation and Stormwater Management Rainfall Analysis and IDF Curve Update**

1. Introduction and Background

Increased frequency and intensity of extreme rainfall events will have a significant impact on infrastructure. The Greater Vancouver Sewerage and Drainage District (GVS&DD) has initiated this project for the purpose of advancing its knowledge and capabilities to adapt to the effects of climate change to ensure that adequate levels of service for sewerage and drainage infrastructure are maintained. During past collaboration between GVS&DD and the Pacific Climate Impacts Consortium (PCIC), it was found that many stakeholders were interested in future climate Intensity Duration Frequency (IDF) Curves. In response, GVS&DD initiated this project, which has the following objectives: update the IDF curves for Metro Vancouver, quantify uncertainty surrounding future climate IDF projections, and determine the potential effect of climate change on infrastructure design. The subject of this Technical Memorandum is the first stage of this study, namely updating the regional IDF curves to present day.

This study builds upon and updates previous work by BGC (2009) that developed regional IDF curves for the Metro Vancouver area. Across the region, there is a well-documented trend of increasing rainfall amounts from south to north. BGC (2009) noted an increase of 300% in annual rainfall from south to north, not including the North Shore zone. When the North Shore zone is included, there is a 400-500% increase in annual rainfall from south to north, indicating significant increase due to orographic uplift from the mountains. BGC (2009) identified nine homogeneous rainfall zones using universal kriging on the average annual rainfall totals. However, the ninth zone, which was located on the North Shore, was excluded from the IDF analysis because of the wide range in rainfall observed in this area (in part due to orographic uplift).

The statistical occurrence of extreme rainfall events is expressed in this Technical Memorandum (TM) as exceedance probability, as opposed to return period. Return periods (e.g. 100-year event, 1 in 100 year event) can be misunderstood to mean that the event occurs once every 100 years. In actuality, the event has a 1% probability of exceedance in any given year. This allows for a more clear description of potential changes due to climate change: the exceedance probability of an event of a certain magnitude increases as climate change affects the frequency of extreme rainfall events. The following terms are used interchangeably in this Technical Memorandum: 1% probability of exceedance and 1% annual exceedance probability (AEP).

This Technical Memorandum presents the results of a regional rainfall frequency analysis (RRFA) that was undertaken to redefine homogeneous rainfall zones for the Metro Vancouver area and develop updated IDF curves for the new rainfall zones. The Technical Memorandum is organized as follows:

- Section 2 describes the rainfall data sources, the methodology used to rank the quality of the rainfall data, and the quality assurance and quality control (QA/QC) procedures that were applied to the rainfall data.
- Section 3 describes the methodology for the RRFA, including the development of the homogeneous rainfall zones, investigation of the effect of the Pacific Decadal Oscillation (PDO) on the IDF curves, development of regional IDF curves, and development of regional envelope curves.
- Section 4 provides the conclusions and recommendations.

2. Rainfall Data

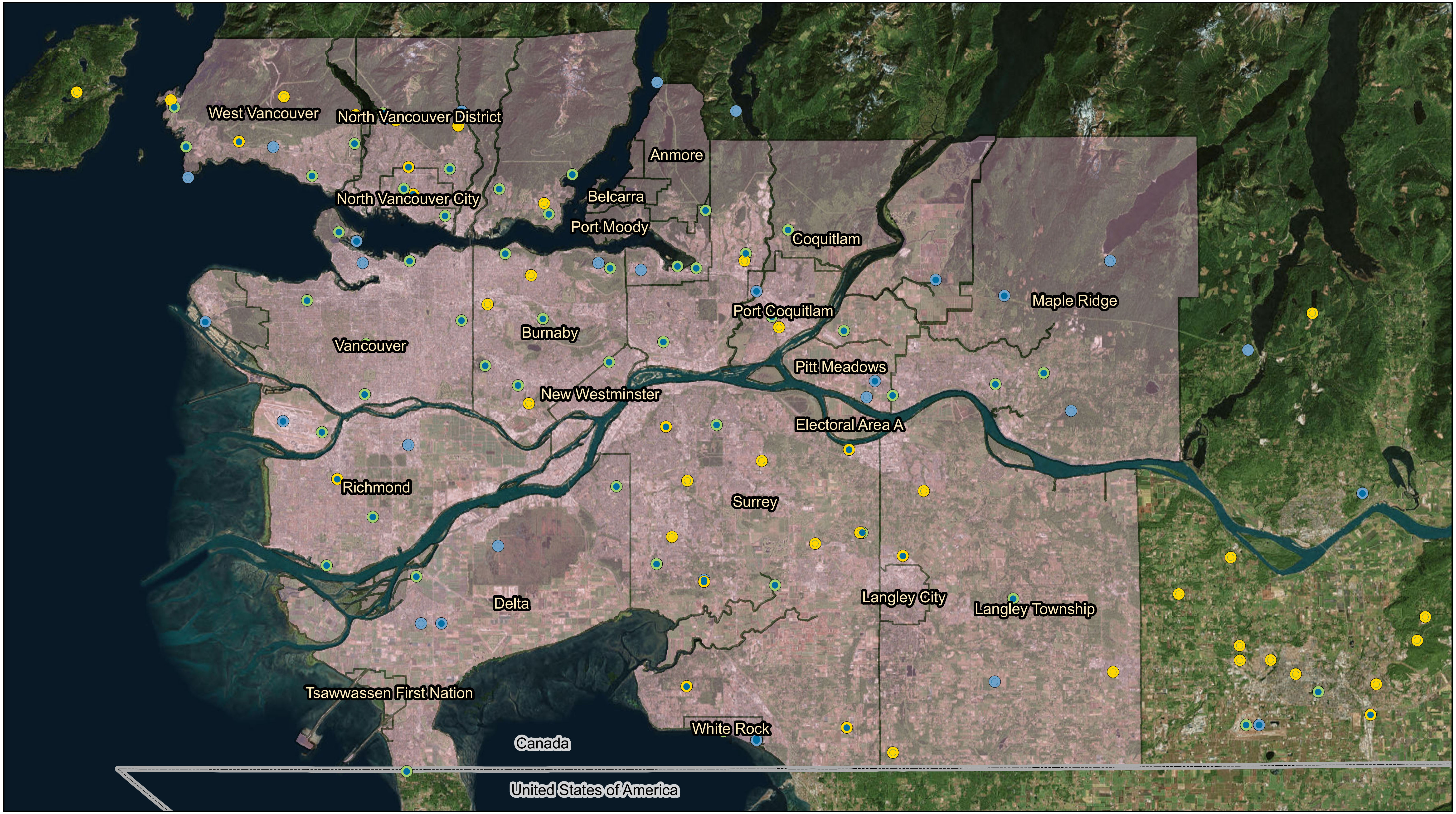
2.1 Rainfall Data Sources

There are numerous rainfall data stations across the Metro Vancouver region. Rainfall data are collected by multiple agencies: Environment Canada (EC), Metro Vancouver, and the member municipalities. The rainfall monitoring network is summarized in Table 2.1 and shown in Figure 2.1. Detailed information for all stations in the rainfall monitoring network is included in Appendix A.

Table 2.1 Metro Vancouver Rainfall Monitoring Network

Agency	Frequency of Data	Number of Stations
Environment Canada IDF stations	5-min	22
Environment Canada precipitation weighing gauges	15-min/1-hr	8
Metro Vancouver	5-min	52
Member Municipalities	Variable	43

Two different types of EC rainfall data were used for this study: 5-min data from IDF stations and 15-min/1-hr data from precipitation weighing gauges. There are 22 IDF stations in the Metro Vancouver Region. Generally, EC uses tipping bucket rain gauges (TBRG) for rainfall measurement for IDF curves. TBRGs are known to underestimate high intensity rainfall events (Hogg et al., 1989), and EC corrects the data using co-located daily rainfall measurements with standard manual gauges. Since 2000, EC has been updating the TBRG network with TB3 tipping buckets, which do not underestimate high intensity rainfall events to the same extent (Canadian Standards Association (CSA), 2012) and do not need to be adjusted by a co-located rain gauge. EC TBRGs only operate when the air temperature is above 0°C (they are not heated) and hence only record rainfall. EC performs thorough QA/QC on the TBRG data, in conformance with World Meteorological Organization (WMO) standards. For this project, the IDF data from EC’s V2.3 IDF update (December 2014) were utilized.



Source: ESRI World Imagery Service.

0 2 4 6
Kilometres

Coordinate System:
NAD 1983 UTM Zone 10N

Legend

- ● Location Retained for Analysis
- ○ Location Omitted from Analysis
- ▭ Municipal Boundaries
- ● Environment Canada Station
- ● Metro Vancouver Station
- ● Local Municipality Station

GHD

METRO VANCOUVER
BRITISH COLUMBIA, CANADA

RAINFALL MONITORING NETWORK IN THE
METRO VANCOUVER REGION

11140666-01
Aug 1, 2018

FIGURE 2.1

GIS File: Q:\GIS\PROJECTS\11140000s\11140666\Layouts\MEMO002\11140666-01(MEMO002)GIS-WA001-Updated.mxd

EC has also collected 15-min and 1-hr data at 8 stations in the Metro Vancouver region, using precipitation weighing gauges. The gauges are all-weather precipitation gauges, recording both liquid and solid precipitation. The 15-min and 1-hr data are archived by EC, with no QA/QC performed on the data.

Metro Vancouver operates a rainfall measurement network consisting of 52 active rainfall monitoring stations. The gauges are TBRGs, some have heaters or heat tape and some do not. The heaters are low power and there may be a delay in measurement for solid precipitation. Some of the gauges are part of the air quality monitoring network. The data are recorded at a 5-min or 15-min frequency, and no QA/QC is performed on the data.

The member municipalities operate a rainfall monitoring network consisting of 43 active rainfall monitoring stations. There are several rainfall measurement techniques utilized for rainfall data collection in the network. The stations record data at different temporal frequencies: 5-min, 15-min, and variable. No QA/QC is performed on the data.

2.2 Rainfall Data Quality

2.2.1 Data Quality Ranking Methodology

Four data quality ranks were utilized for this study. Three criteria were used in assigning the four data quality ranks.

EC requires that there are a minimum of ten years of data for the calculation of an IDF curve. Each year must be “complete” in order to ensure that the annual maximum was captured. CSA (2012) recommended a minimum of 180 days of measurement between April 1 and October 31 (no more than 15% of data are missing) as the criterion to determine if a year is “complete.” In Vancouver, the annual maximum may occur outside of this period due to its relatively warm and wet winters. Therefore, a criterion that no more than 15% of data are missing throughout the year was adopted instead. Most of the data records at the stations in the Metro Vancouver network had complete or nearly complete records each year. If a station had less than ten complete years of data, it received a data quality ranking of “D”.

The EC IDF curves are generally developed from 5-min TBRG data, which allows all nine IDF curve durations (from 5-min to 24-hr) to be analyzed. Therefore, it was considered that 5-min data would be preferred for the analysis, which would allow all IDF curve durations to be analyzed, resulting in complete IDF curves. Stations that did not record data at a 5-min frequency received a data quality ranking of “C”.

EC applies a significant amount of QA/QC to the data used in IDF curves. The QA/QC process is described in CSA (2012). The annual maxima are compared to nearby stations and the meteorological record. EC also corrects for TBRG under catch by applying daily rainfall correction factors where necessary. Therefore, the EC IDF curve data are considered as high quality. Stations that are not EC IDF curves received a data quality ranking of “B”, while EC IDF curve stations received a data quality ranking of “A”.

The data quality ranking for all stations is summarized in Table 2.2 and the full list for all stations is provided in Appendix A. Stations with data quality rankings of “A” and “B” were selected for the analysis. In total, 74 stations were selected to include in the analysis. Two category “B” stations, Chilliwack Airport (CK74) and Hope Airport (HP75), were also excluded from the analysis because they were too far away from the other stations. Three Surrey stations, SUR_White_Rock_STP, SUR_Municipal_Hall, and SUR_Kwantlen_Park, were replacement stations for earlier EC stations and were located in the same places. The EC and Surrey stations were combined into one station, and retained the Surrey name in the RRFA.

Table 2.2 Data Quality Ranking

Rank	Number of years >=10?	Is rain measured at 5-min frequency?	Has EC QA/QC been applied?	Number of Stations
A	✓	✓	✓	15
B	✓	✓	✗	62 [1]
C	✓	✗		8
D	✗			41

Note:

[1] Three Surrey stations combined with co-located EC-IDF stations.

2.3 Data Quality Assurance/Quality Control

Quality assurance and quality control (QA/QC) were applied to the stations with a data quality ranking of "B". No further QA/QC was applied to the EC IDF stations. The QA/QC process was based on the EC QA/QC process, modified for this study. A six-step QA/QC process was used (Figure 2.2).

The first step of the process involved removing any suspicious data in the time series. Any rainfall amounts greater than 20 mm in five minutes were considered suspicious and investigated further. Amounts greater than 10 mm in five minutes were verified by examining the time series at the station and at nearby stations to check if the amount was reasonable (e.g. a severe rain event was occurring). In addition, if the 5-, 10-, and 15-min annual maxima were all the same, this indicates a single 5-min interval with significant rainfall, which may indicate a suspicious data point. Finally, the automatic EC QA/QC checks flag any data with an hourly total greater than 25 mm. If the hourly annual maximum was greater than 25 mm, the time series was checked for suspicious data points.

The second and third steps involved checking for missing data. Any years with less than 85% of the data available were removed from the analysis. This was based on the CSA (2012) recommendation of 180 days from April 1 to October 31, but it was extended to the entire year. Approximately 2% of the years of data (across all stations) were rejected due to this criterion, and all years were considered to be complete at most stations. Secondly, any annual maxima for any duration with missing data within the duration were also removed from the analysis. For instance, if one or more data points are missing within the 24-hr annual maximum, then the annual maximum may be underestimated.

The fourth and fifth steps involved checking the data against nearby stations. In each case, the annual maxima were compared to daily rainfall totals at nearby EC climate stations, and further checked against the rainfall record at nearby Metro Vancouver or municipal stations. The annual maxima were also compared to daily snowfall and air temperature records from nearby EC climate stations. If the annual maxima could not be confirmed with nearby stations and/or the snowfall and air temperature records indicated that the event may have been a snow event, then the annual maxima was removed from the analysis. In summary, annual maxima were removed from the analysis for four reasons. The reasons and the frequency of occurrence of each removal are listed in Table 2.3. Overall, very few data were removed during these steps, and the effect on the analysis would be minimal.

Check for suspicious data	•If >20 mm in 5 minutes, mark the data as "missing" •If >10 mm, check time series for reasonableness •If 5-min=10-min=15-min, check time series for reasonableness •If hourly total > 25 mm, check time series for reasonableness
Check for significant periods of missing data	•If less than 85% of data for the year are available, do not include the year in the analysis
Check for missing data within a duration	•If the annual maximum contains missing data, mark the annual maximum as "missing" for that duration
Check the annual maxima with data from nearby stations/different durations	•Check nearby gauges to ensure that they also recorded rainfall on that date •Check daily rainfall totals from nearest EC stations •If annual maximum for a duration cannot be confirmed, mark the annual maximum as "missing" for that duration
Check for annual maxima that are snow or rain/snow events	•Compare to nearest EC stations daily maximum and minimum air temperatures, and daily rain and snow totals •If the annual maximum may be snow or rain/snow, mark annual maximum as "missing" for that duration
Check for consistency	•Confirm that annual maxima increase as duration increases •Rainfall amounts should be similar to the amounts observed in other years at the station

Figure 2.2 Quality Assurance/Quality Control Methodology

Table 2.3 Reasons to Remove Annual Maxima During QA/QC

Reason	Frequency of Occurrence (%)
Potential snow event	0.4%
Rain event could not be confirmed with nearby data	1.4%
Data are missing within the duration	0.2%
1-hr total was greater than 25 mm	0.4%

The sixth step involved consistency checks on the data. Multiple consistency checks were applied, such as: the rainfall amount should increase as the duration increases; and the rainfall amounts should be similar to other rainfall amounts in other years for each duration.

2.4 Filling-in of Missing Data

For single-station frequency analysis, it may be beneficial to extend a short record or fill-in missing years in a record using data from nearby stations (donor stations). However, there are multiple potential problems with filling-in missing data. Selecting potential donor stations is challenging in the Metro Vancouver region because of the orographic effects on rainfall. The donor stations should be located at a similar elevation with no significant changes of elevation between the donor and receiver stations (i.e. donor station should not be located on opposite sides of a hill or valley). Secondly, donor stations must be located very close to the receiving station (less than 3 km apart for transfer of short duration rainfall intensities). Short duration annual maximum rainfall events are generally local-scale convective storms, and therefore donor stations must be close to transfer short duration rainfall. Long duration annual maximum rainfall events are generally large-scale synoptic events, and donor stations can be farther away (Figure 2.3). Thirdly, combining data from two or more stations can introduce heterogeneity in the rainfall time series. The potential for the introduction of heterogeneity is increased when short duration rainfall event data are being transferred, when the stations are farther apart and when the stations have even relatively minor differences in elevation. In the Metro Vancouver region, these factors limit the effectiveness of using donor stations to fill-in missing data in a time series.

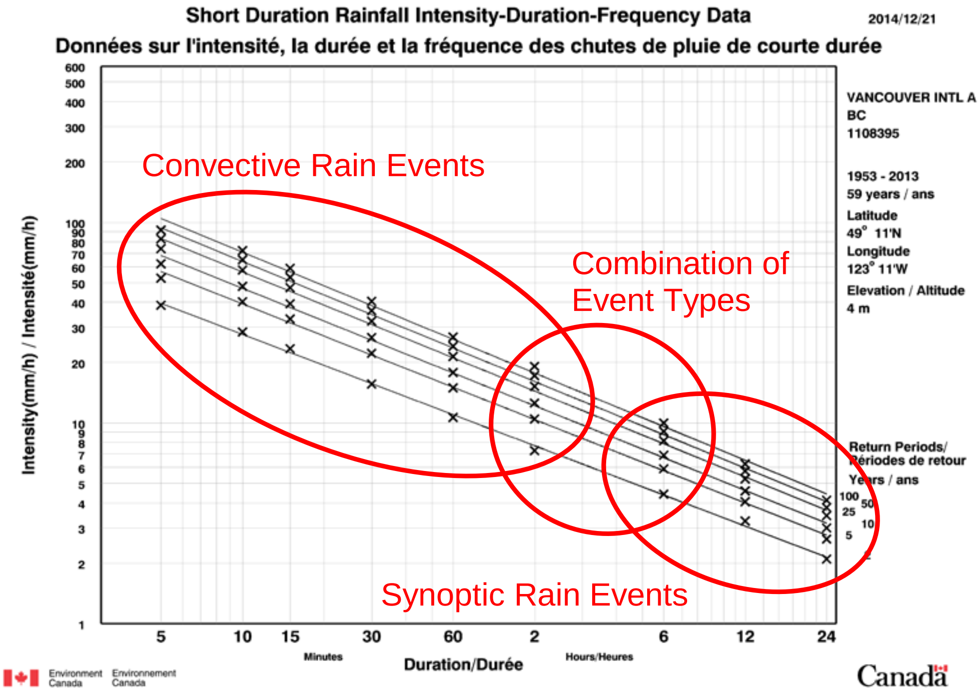


Figure 2.3 Type of Rain Events for Different Durations of the IDF Curve

For this analysis, an RRFA was performed. In regional frequency analysis, data from multiple stations are combined to generate a regional IDF curve. Filling-in missing data using the donor station method results in duplication of data within each zone (no new information is added). There is no benefit to using duplicate data in an RRFA. It may, in fact, affect the results negatively. For instance, combining data from multiple stations can result in heterogeneity at the receiver station, which may then impact the formation of homogeneous zones for RRFA. Additionally, using duplicate data can bias the regional IDF curve.

A total of 74 stations were included in the RRFA analysis. The number of stations with data in each year is shown in Figure 2.4. Many of the stations are relatively new; the number of stations with data in each year does not rise above 25 until after 1990. The older stations are spread throughout the Metro Vancouver region, and provide good areal coverage.

The objective of this analysis was to derive regional IDF curves through an RRFA. The RRFA methodology accounts for stations with differing record lengths and periods of observation. RRFA does not require that missing data be filled in. Missing data were therefore not filled-in.

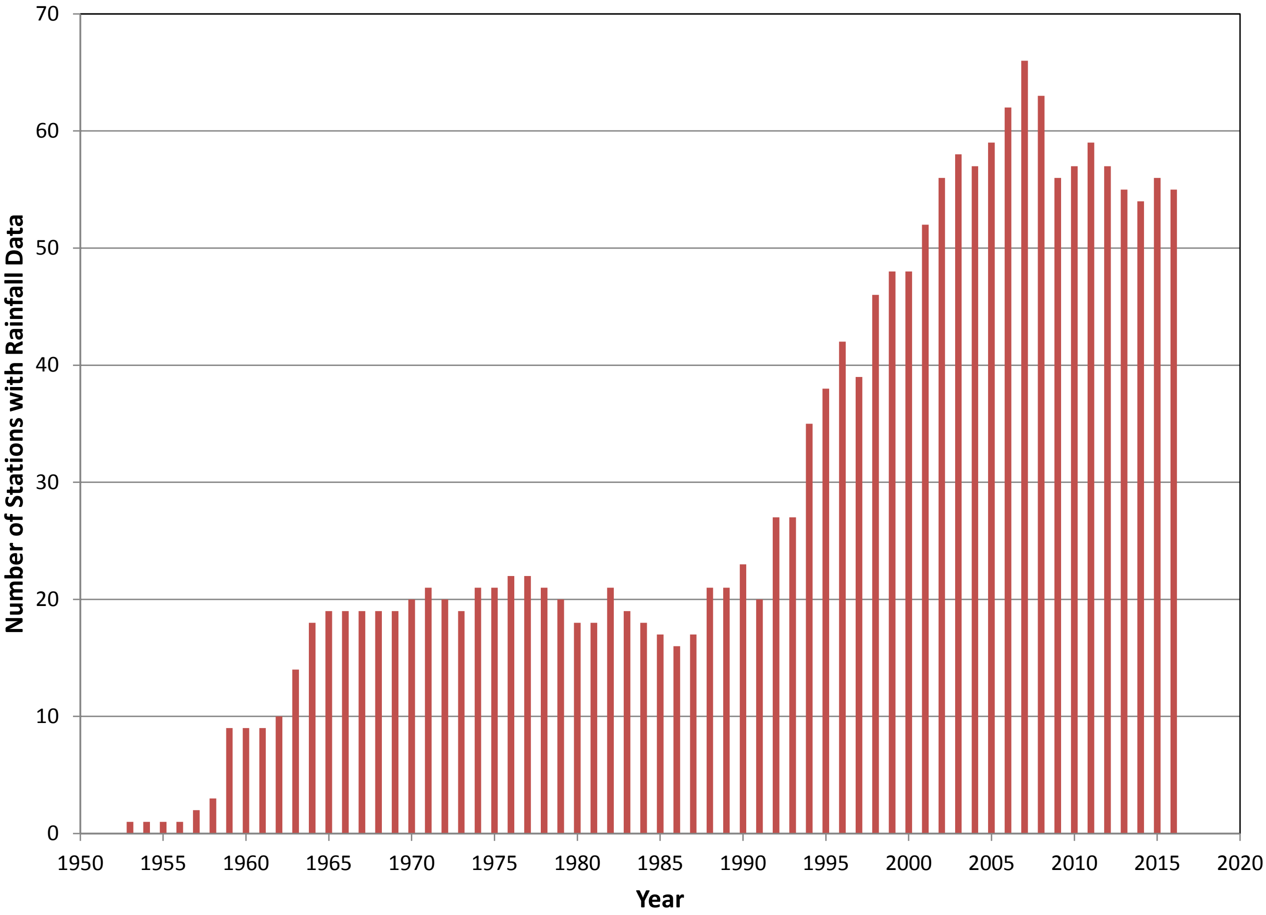


Figure 2.4 Number of Stations with Rainfall Data in each Year

3. Regional Rainfall Frequency Analysis

There are numerous advantages to the RRFA method:

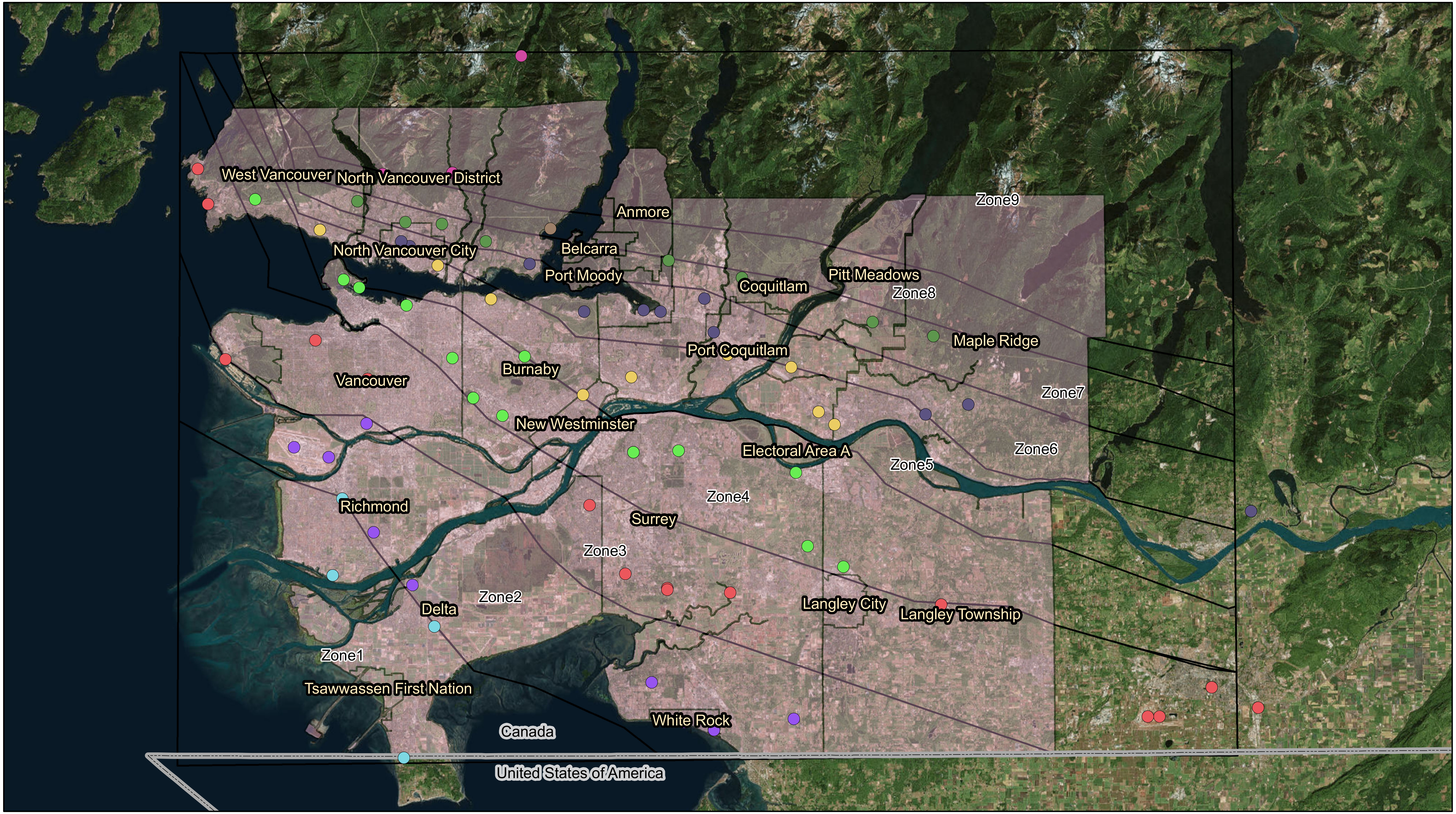
- Accuracy: decreased statistical uncertainty due to sampling variability; data from multiple stations increase effective record length
- Ease of use: one curve can be used anywhere within the homogeneous zone; usage of IDF curves can be standardized
- Flexibility: IDF curves can be scaled to match the index rain in different parts of each zone
- User input: user can scale IDF curves based on knowledge of the site, and customize the IDF curves to their needs (e.g. select how conservative to be in the design).

3.1 Delineation of Homogeneous Rainfall Zones

The first stage of an RRFA is the delineation of homogeneous rainfall zones. BGC (2009) developed homogeneous zones based on average annual rainfall at stations throughout the Metro Vancouver region (Figure 3.1). The station data were spatially interpolated using Universal Linear Kriging (ULK). Zone boundaries were selected according to the rainfall contour data. BGC (2009) used the Hosking and Wallis (1997) homogeneity criterion to test the homogeneity of the zones, but this test was applied to total monthly rainfall at the stations within each zone. Average annual rainfall and total monthly rainfall are climatological parameters, which may not be best suited for defining homogeneous rainfall zones in terms of extreme rainfall intensities. Therefore it is possible that the zones developed by BGC (2009) may not be homogeneous for the annual maximum time series (5-min to 24-hr).

The Hosking and Wallis (1997) homogeneity test uses L-moments. L-moments are analogous to standard moments (e.g. mean, standard deviation, skewness, kurtosis, etc.) but are less sensitive to outliers because they are based on linear combinations of the data instead of using exponents. They provide alternative measures of distribution shape. They are known to be robust and commonly used in statistical RRFA. The first L-moment is arithmetically equal to the mean of the data. L-moment ratios have been defined for the higher order moments, which are called L-scale (L-Cv), L-skewness (L-Cs), and L-kurtosis (L-Ck), respectively, because they are analogous to the standard moments.

The RRFA method proposed by Hosking and Wallis (1997) uses the “index flood” method. In this method, a frequency curve with an annual maximum mean of one is produced (dimensionless frequency curve), which is then scaled up by the estimate of the annual maximum mean at the site of interest. The homogeneity test proposed by Hosking and Wallis (1997) therefore only tests the higher-order moments and does not test for homogeneity of the mean. There are three variations of the Hosking and Wallis (1997) homogeneity test. The first test, H1, tests the L-Cv only. The second test, H2, tests the L-Cv and L-skewness. The third test, H3, tests the L-skewness and L-kurtosis. All three tests were applied, and the highest H was selected for that combination of zone and duration. The rainfall zones are “acceptably homogeneous” if H <1, and “possibly homogeneous” if H<2. Values of H<0 are associated with positive correlation between the sites in the zone, and a value of H<-2 is associated with significant correlation.



Source: ESRI World Imagery Service.

0 2.5 5 7.5
Kilometres

Coordinate System:
NAD 1983 UTM Zone 10N

N

Legend

Rain Station (BGC Zone)

- ● Zone 1
- ● Zone 2
- ● Zone 3
- ● Zone 4
- ● Zone 5
- ● Zone 6
- ● Zone 7
- ● Zone 8
- ● Zone 9
- ☐ BGC Zones
- ☐ Municipal Boundaries

GHD

METRO VANCOUVER
BRITISH COLUMBIA, CANADA

BGC ZONES USED FOR HOMOGENEITY TESTING

11140666-01
Jun 6, 2018

FIGURE 3.1

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The Hosking and Wallis (1997) tests were applied to the stations in each BGC zone. All three tests were applied for all nine IDF curve durations (5-min to 24-hr). There is little to no benefit in performing RRFA for a zone with less than five stations. The homogeneity testing was performed for zone 1 (four stations), but was not performed for the two zone 8 stations. BGC (2009) did not perform frequency analysis for zone 9, and therefore it was also not tested. The test results are summarized in Table 3.1. The results indicate that several zones have heterogeneity at one or more durations.

Table 3.1 Homogeneity Test Results for BGC (2009) Zones

Criteria	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9
Number of stations	4	10	15	14	10	11	8	2	3
Number of “Acceptably” Homogeneous Durations	4	5	7	7	9	6	6	Not tested	Not tested
Number of “Possibly” Homogeneous Durations	3	1	1	2	0	1	2		
Number of Heterogeneous Durations	2	3	1	0	0	2	1		

The results of the homogeneity testing of the BGC zones indicated that the short duration data have different characteristics from the long duration data. The average annual maxima for each duration were calculated for all stations. Although there is a general increase in annual maximum rainfall from south to north at all durations, the short duration data show considerable variability. In particular, there is a considerable variation from west to east as well.

New homogeneous zones were derived for this project. The process to develop homogeneous rainfall zones was an iterative process that involved K-means clustering and refinement of the zones. The following criteria were used to evaluate and optimize the zones:

- Inter-zone dissimilarity: the goal was to maximize the dissimilarity among the rainfall zones
- Intra-zone heterogeneity: the goal was to minimize heterogeneity (maximize homogeneity) within each zone
- Number of zones: the goal was to find an optimal number of stations in each zone (the zones should not be too large or too small)

The final clusters are shown in Figure 3.2. Table 3.2 provides a summary of the number of stations in each zone and the results of the homogeneity testing.

Table 3.2 Homogeneity Test Results for Final Homogeneous Zones

Criteria	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7
Number of stations	13	9	11	7	14	15	5
Number of "Acceptably" Homogeneous Durations	7	9	8	7	7	6	8
Number of "Possibly" Homogeneous Durations	2	0	1	2	2	3	1
Number of Heterogeneous Durations	0	0	0	0	0	0	0

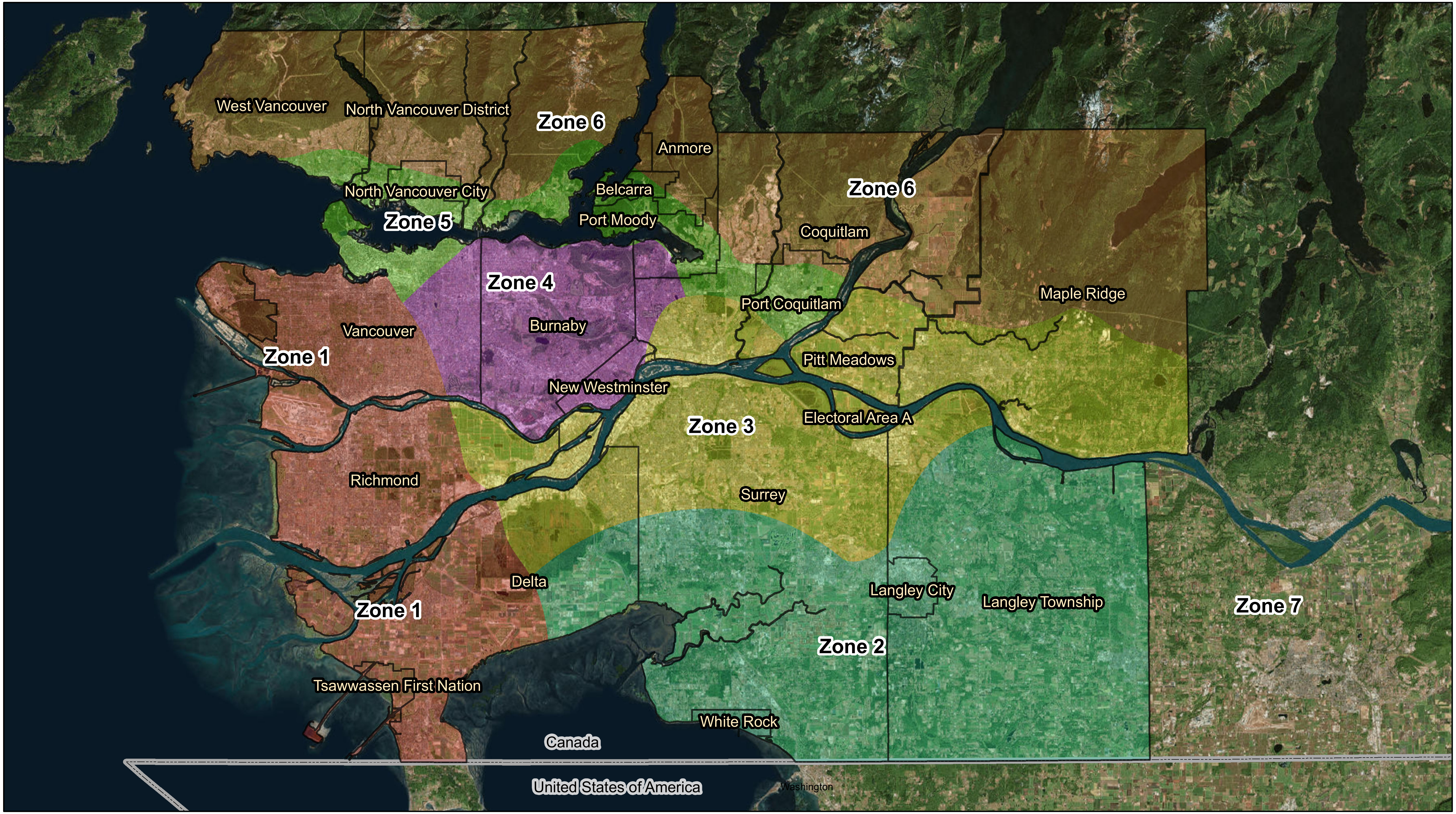
The number of rainfall zones decreased from nine BGC zones (BGC, 2009) to seven. There are three main reasons why the current seven zones are preferred over the nine BGC zones:

1. **Homogeneity** – The nine BGC zones were delineated based on annual rainfall, not extreme rainfall. Short duration extreme rainfall events do not correlate well with annual rainfall patterns and the nine BGC zones were not homogeneous at all durations. Extreme rainfall was used in the delineation of the seven homogeneous zones, and the new zones are homogeneous at all durations.
2. **Optimization**– The number of zones was optimized to balance the level of accuracy, the differences between IDF curves, and the number of stations in each zone. Increasing the number of zones allows for greater accuracy, but the IDF curves become similar across multiple zones. On the other hand, when there are fewer than approximately five stations in a zone, performing an RRFA becomes problematic.
3. **Practicability** – When there are a greater number of zones and/or the zones are small, it is more difficult to use the IDF curves. There is greater chance that the wrong IDF curve will be selected and/or that the watershed/sewershed of interest will overlap with more than one zone.

The BGC zones provide a useful description of the variation of mean annual rainfall across the Metro Vancouver region. However, they are not suited for the annual maximum rainfall variation, particularly for short duration intensities. The new rainfall zones were developed specifically for annual maximum rainfall intensities.

3.2 Derivation of Regional IDF Curves

Regional IDF curves were derived using the RRFA method for each homogeneous zone. The Hosking and Wallis (1997) goodness-of-fit criterion was used to test the following three-parameter frequency distributions: generalized logistic (GLO), generalized extreme value (GEV), generalized normal (GNO), Pearson type III (PE3), and generalized pareto (GPA). In addition, plots of L-kurtosis and L-skewness were also used to assess the goodness-of-fit. The plots also included two-parameter frequency distributions (e.g. Lognormal and Gumbel).



Source: ESRI World Imagery Service.

Coordinate System:
NAD 1983 UTM Zone 10N

METRO VANCOUVER
BRITISH COLUMBIA, CANADA

RAINFALL ZONES

11140666-01
Aug 1, 2018

FIGURE 3.2

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The goodness-of-fit test and plots were applied to all combinations of durations and zones (63 combinations). The test results are summarized in Table 3.3, and the plots are included in Appendix B. The RRFA method is typically applied with three-parameter distributions, and therefore only three-parameter distributions were considered. The GEV and GNO distributions were most commonly accepted across the study area and across all durations, and the difference between the two distributions was minor (only one combination of duration and zone). There were some combinations of duration and zone where none of the distributions were acceptable. The plots in Appendix B show that the GEV and GNO distributions are similar to each other. The GEV distribution was selected as the distribution for the analysis. The main reason for selecting the GEV distribution over the GNO distribution is that the Gumbel distribution (the distribution used by EC for all IDF curves) is a special case of the GEV distribution. This provides a theoretical basis for selecting the GEV distribution, since the GEV results should be similar to the Gumbel results. It is noted that the selection of frequency distribution will be included as part of the sensitivity analysis, and the relative impact of this selection on the regional IDF curves will be quantified in the next stage of the project.

Table 3.3 Summary of Goodness of Fit Criterion Results

Frequency Distribution	Percent of Duration and Zone Combinations Where Distribution is Accepted
Generalized Logistic	44
Generalized Extreme Value	76
Generalized Normal	75
Pearson Type III	65
Generalized Pareto	17

The RRFA method produces dimensionless IDF curves (with mean equal to one). The dimensionless IDF curves provide the shape of the IDF curve within each homogeneous zone. The dimensionless IDF curves are then scaled by the index rain (an estimate of the mean annual maximum rainfall for each duration). The RRFA method allows for greater flexibility in deriving the IDF curves, because the index rain can vary from location to location within the homogeneous zone.

There are two possibilities for deriving the index rain, which include:

- Index rains (at-site means) from a rainfall monitoring location
- Contour maps generated from the index rains (at-site means) for the rainfall monitoring locations

The at-site mean is calculated with Equation 1, and is the mean of the annual maximum data at a particular station. It is an accurate definition of the index rain at a station, assuming that the data record is long enough to produce a reasonable estimate. As part of this project, the index rain data were used to generate contour maps.

$$\overline{x_i} = \frac{1}{n_i}\sum_{j=1}^{n_i}\left(x_{i,j}\right) \quad \text{Equation 1}$$

where: N is the number of stations in the zone
n_i is the number of years of annual maximum data at station i
$x_{i,j}$ is the annual maximum for station i and year j

The effect of using different scaling factors is shown in Table 3.4. The example used is the 1-hr duration of the Vancouver Intl A station for the 1% AEP event. This station is located in Zone 1. In each case, the dimensionless IDF curve estimate (1% AEP, 1-hr) is the same. There are two estimates for the mean. The IDF Curve rainfall estimate is the dimensionless 1% AEP 1-hr IDF curve multiplied by the estimate for the index rain. This process is repeated for all other durations and frequencies.

Table 3.4 Example of Scaling of Dimensionless IDF Curves

	Index Rain (At-Site Mean) for Vancouver Intl A	Index Rain from 1-hr Contour Map
Dimensionless 1% AEP 1-hr IDF Curve (-)	2.30	2.30
Estimate of Index Rain 1-hr Rainfall (mm)	11.47	10.5
1% AEP 1-hr IDF Curve Rainfall Estimate (mm)	26.38	24.15

There are advantages to each option. When the index rain (at-site mean) for a station is known, this method allows for the most accurate definition of the IDF curve for the location (assuming the data record used for the estimating the index rain is sufficiently long). However, the index rain is only for a single point, and is most suitable when the study area is small and very close to a station. The contour maps are the preferred method of identifying the index rain and are suitable for all sizes of study area since they are a regional estimate of the index rain. The dimensionless IDF curves are included in Appendix C, and the index rain contour maps are included in Appendix D.

3.3 Comparison to Regional Envelope Curves

A second method for performing a regional analysis is to develop an envelope curve. This method was explored for this project by calculating the envelope curve for one pilot zone. The first rainfall zone was selected as the pilot zone, since it contains the station with the longest data record (Vancouver Intl A).

Envelope curves were originally developed to provide a worst-case regional frequency curve to be used at ungauged locations within a homogeneous zone. They do not represent the true frequency characteristics of the ungauged locations and tend to overestimate the rainfall intensities. Envelope curves are not preferred for locations with sufficient areal coverage of monitoring locations such as the Metro Vancouver region.

To develop the envelope curve, the largest annual maximum for each year and duration is selected from among the group of stations in the zone. A single-site frequency analysis is then performed on the envelope data. For this analysis, the GEV distribution was used, fitted by the method of L-moments, to match the RRFA results.

A disadvantage of this method is that the stations within the zone may have different record lengths and different overlapping periods and there will be a different number of events to choose from in each year. Therefore, the results will be highly sensitive to the period of record at each station.

To provide a suitable comparison, the dimensionless IDF curves were scaled by the station(s) with the largest at-site means for each duration in the zone. This would provide the largest IDF curve for the region. The envelope IDF curve for Zone 1 was compared to the largest regional IDF curve for Zone 1 (Figure 3.3). The percent differences in rainfall amount from the regional IDF curves were calculated for each duration and probability of exceedance. The regional IDF curve scaled by the regional maxima for all durations is similar to the envelope curve. Overall, the envelope curve is 1.3% higher than the largest regional IDF curve. The envelope curve is therefore comparable with the largest regional IDF curve in the zone, but would overestimate for all other locations in the zone.

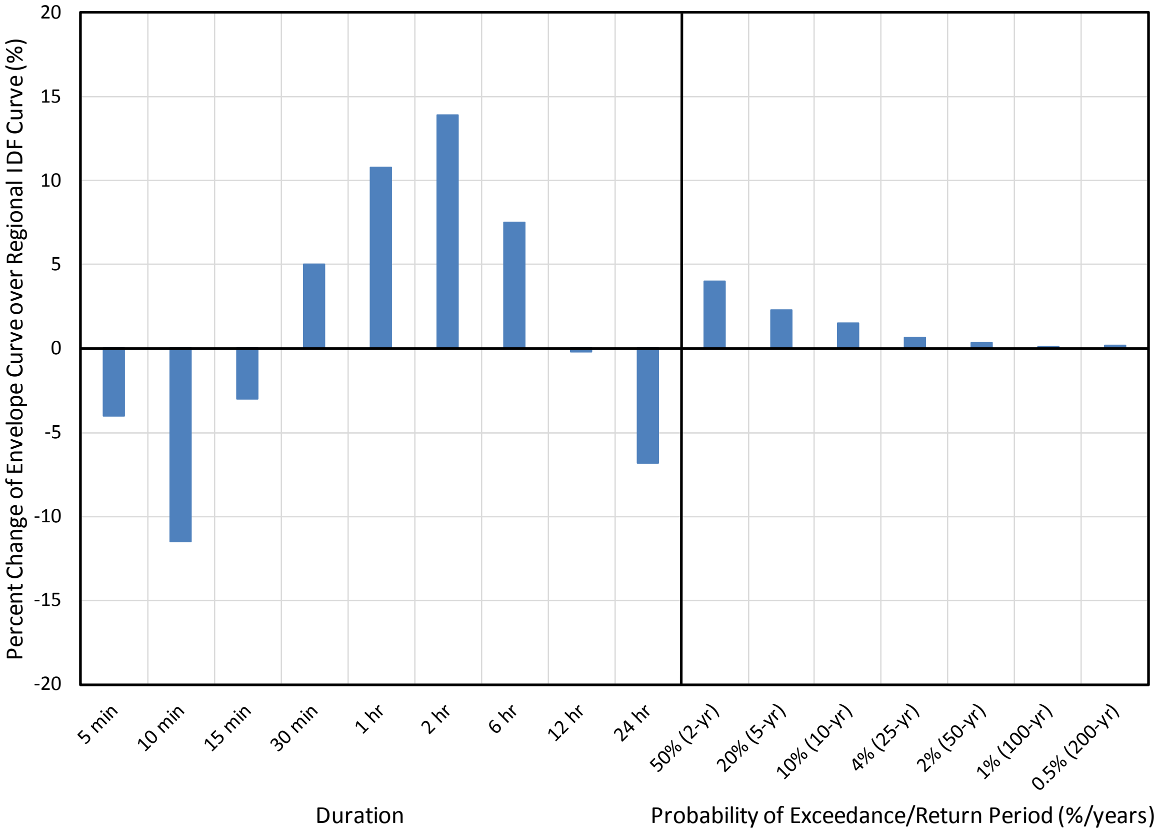

Figure 3.3 Comparison Between Envelope and Regional IDF Curves for Zone 1 for Each Duration or Probability of Exceedance

3.4 Comparison to Existing IDF Curves

The regional IDF curves (calculated with the RRFA method) were also compared to existing IDF curves. Zone 1 was chosen as the pilot zone for this comparison. Zone 1 crosses four BGC zones (BGC, 2009) and therefore provides a good comparison to multiple BGC IDF curves. As additional validation, four EC IDF curves in four different zones were also chosen as comparison locations. The BGC zone IDF curves pooled data from several stations and apply to the entire zone. The EC IDF curves are based on a single station.

3.4.1 Comparison to BGC IDF Curves

The comparison of the Zone 1 regional IDF curves (calculated with the RRFA method) to the BGC IDF curves (Zones 1 to 4) is summarized in Figure 3.4 and Figure 3.5. The dimensionless IDF curves were scaled by the index rain for the midpoint of the area of the BGC zone. The percent increase of the regional IDF curve over the BGC IDF curves has been calculated and averaged over all durations or probability of exceedance.

Figure 3.5 and Figure 3.6 indicate that scaling the regional IDF curve by the index rain near the middle of the BGC zone results in a similar IDF curve to the BGC IDF curves. The BGC IDF curves generally increase from Zone 1 to Zone 4. The differences are less than 20%, and there are several durations and AEP with differences less than 10%. The overall bias was low, the bias was -3%, -6%, 5% and 6% for BGC Zones 1 to 4, respectively.

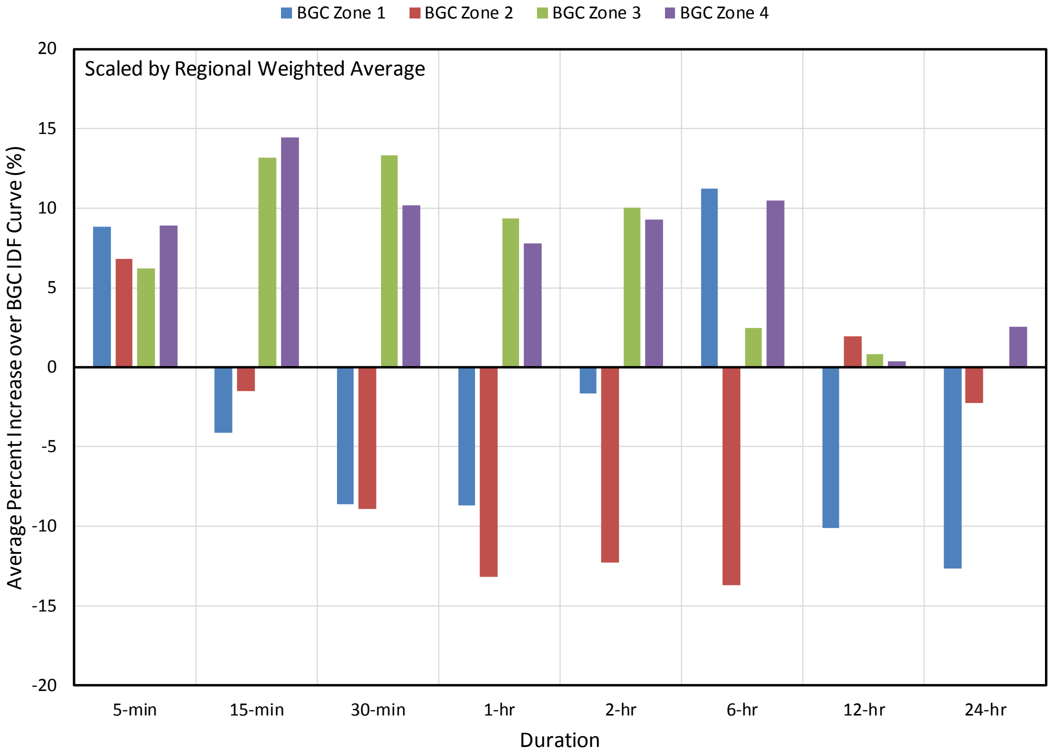

Figure 3.4 Percent Increase of Regional IDF Curve Scaled by the Midpoint of Index Rain over BGC IDF Curves for Each Duration, Averaged for all Probability of Exceedance

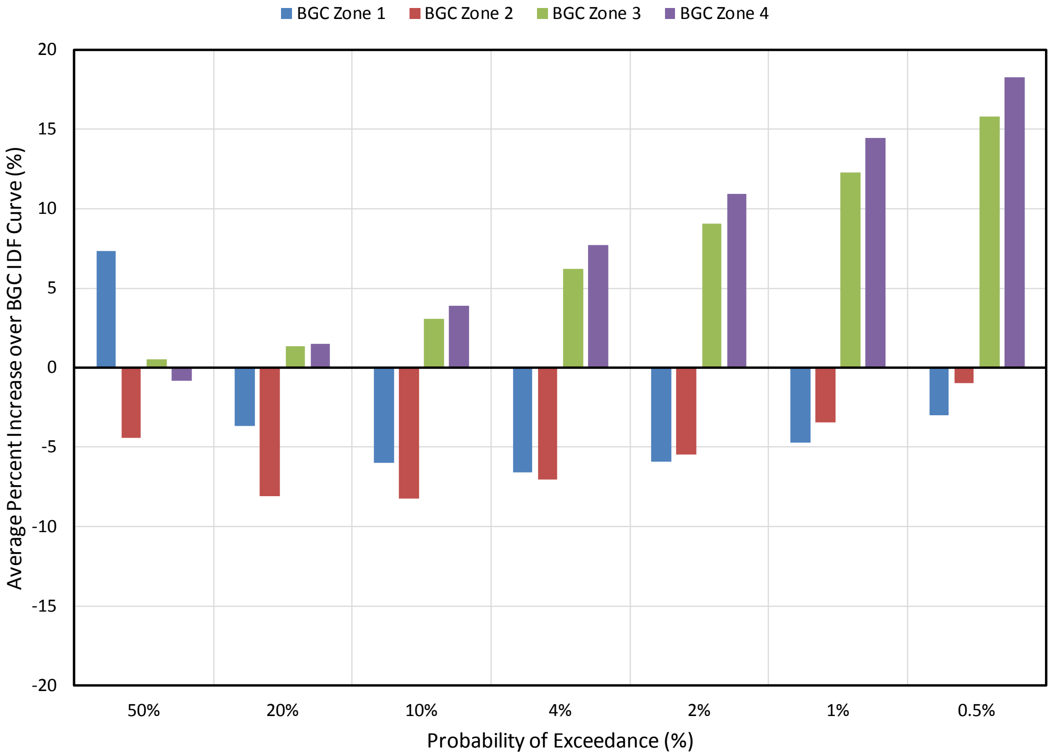

Figure 3.5 Percent Increase of Regional IDF Curve Scaled by the Midpoint of Index Rain over BGC IDF Curves for Each Probability of Exceedance, Averaged for all Durations

3.4.2 Comparison to EC IDF Curves

The regional IDF curves (calculated with the RRFA method) were compared to four EC IDF curves in Zones 1, 2, 3, and 5. For this comparison, the dimensionless IDF curves were scaled by the observed at-site mean for the station. The percent increase of the regional IDF curve over the EC IDF curves has been calculated and averaged over all durations or probabilities of exceedance. To minimize the number of figures, the averages for the durations (across all probabilities of exceedance) and the averages for the probabilities of exceedance (across all durations) have been shown on the same figure.

Figure 3.6 shows the comparison between the regional IDF curve and the EC IDF curve for Vancouver Intl A (Climate ID: 1108395). Vancouver Intl A is located in Zone 1, near the middle of the zone. The regional IDF curve is similar to the EC IDF curve. However, there are large decreases for the 2- and 6-hr durations. The EC IDF curve for these durations has been skewed by a large outlier in 2004. The effect of the outlier has been reduced by the RRFA method.

Figure 3.7 shows the comparison between the regional IDF curve and the EC IDF curve for White Rock STP (Climate ID: 1108914). White Rock STP is located in Zone 2, near the southern edge of the zone. The regional IDF curve is similar to the EC IDF curve, but there are large decreases for the 30-min, 1-hr, and 2-hr durations. A large outlier in 1975 skewed the EC IDF curve for these durations. The effect of the outlier has been reduced by the RRFA method.

Figure 3.8 shows the comparison between the regional IDF curve and the EC IDF curve for Surrey Kwantlen Park (Climate ID: 1107873). Surrey Kwantlen Park is located in Zone 3. The regional IDF curve similar to the EC IDF curve and differences are less than 10% on average.

Figure 3.9 shows the comparison between the regional IDF curve and the EC IDF curve for Vancouver Harbour CS (Climate ID: 1108446). Vancouver Harbour CS is located in Zone 5. The regional IDF curve is similar to the EC IDF curve, and the differences are less than 10%.

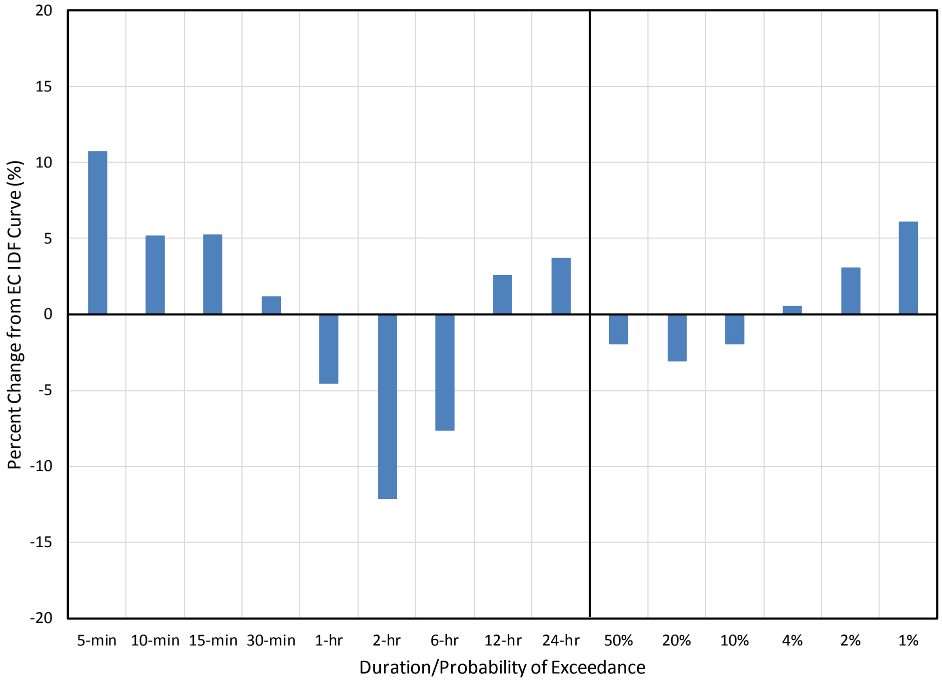

Figure 3.6 **Average Percent Changes of Regional IDF Curve (Zone 1) From EC IDF Curve for Vancouver Intl A (1108395)**

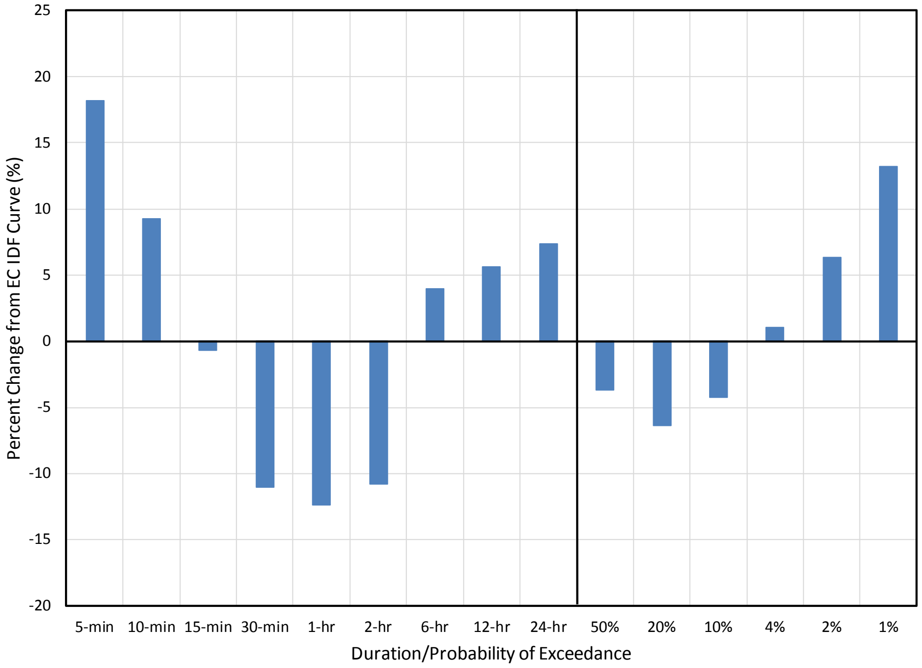

Figure 3.7 Average Percent Changes of Regional IDF Curve (Zone 2) From EC IDF Curve for White Rock STP (1108914)

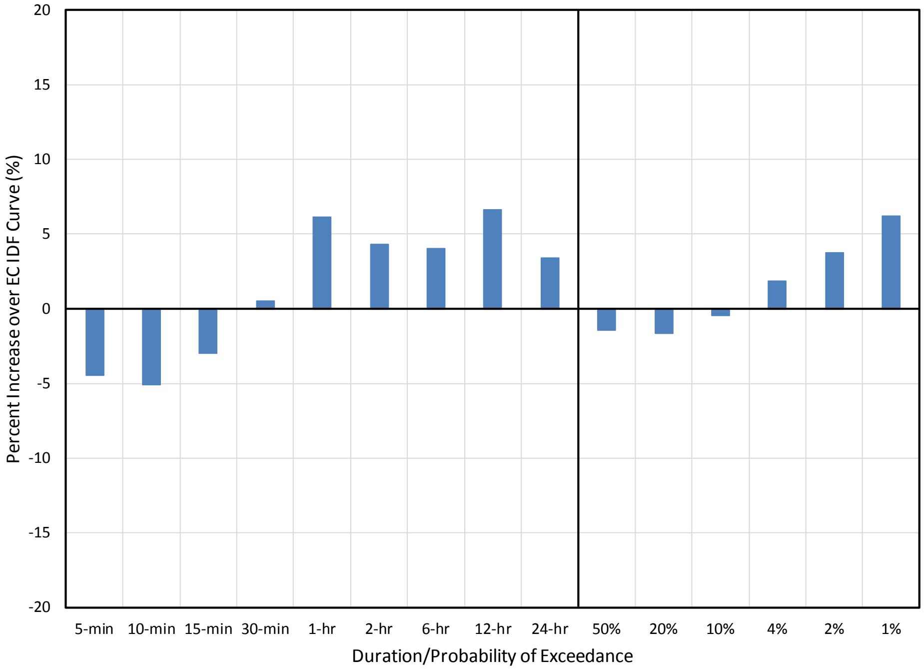

Figure 3.8 Average Percent Changes of Regional IDF Curve (Zone 3) From EC IDF Curve for Surrey Kwantlen Park (1107873)

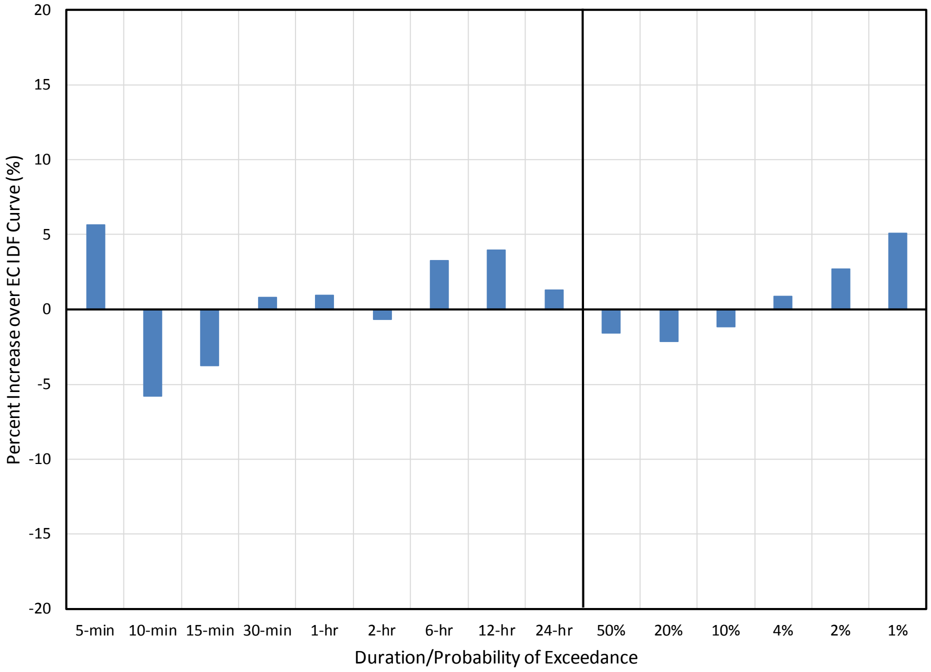

Figure 3.9 Average Percent Changes of Regional IDF Curve (Zone 5) From EC IDF Curve for Vancouver Harbour CS (1108446)

The regional IDF curves were similar to the EC IDF curves. When the at-site means are used for scaling the dimensionless IDF curves, the differences between the RRFA and EC IDF curves are generally low (less than 10%). There were high increases/decreases at some locations for some durations/probabilities of exceedance, which was attributed to the effect of the outliers in the data. The effect of outliers is reduced in regional IDF curves derived with the RRFA methodology. The differences between the EC IDF curves and the regional IDF curves (calculated with the RRFA method) were lower for probabilities of exceedance than for durations.

The RRFA regionalization methodology accounts for the differences between the regional and EC IDF curves. In RRFA, data from nearby locations can affect the IDF curves at the site of interest. The regional IDF curves are more robust and less sensitive to local outliers and extremes than single-site frequency analysis.

3.5 Pacific Decadal Oscillation

IDF curves in the Metro Vancouver region are subject to long-term (low frequency) variability in rainfall due to the Pacific Decadal Oscillation (PDO). PDO phases, which are classified as "cool" or "warm", persist for approximately 20 to 35 years. Significant differences in the rainfall regimes between the different PDO phases have been identified in the Metro Vancouver region. Kerr Wood Leidal (2002) and Murdock et al. (2007) investigated the rainfall intensity data for the Greater Vancouver Regional District (GVRD), and found relationships between PDO phases and rainfall intensity. The magnitude of the variability due to the PDO was greater than the magnitude shift due to climate change alone. During a cool phase, high intensity rainfall events occur more frequently and with higher rainfall amounts. The most recent PDO phase shifts are shown in Table 3.5. The PDO phase is determined from the PDO index, and represents the predominant range of the PDO index over a period. The PDO index is derived from monthly sea surface temperature data, and climate change signals are removed from the variability. The PDO index has varied from positive to negative within each historical phase since 1950 (Figure 3.10), but the 1999-Current period has shown a particularly high variability in the PDO index. For this analysis, an average annual PDO index was used to classify data as either "warm" or "cool" (PDO index values were downloaded from http://research.jisao.washington.edu/pdo/PDO.latest.txt).

Table 3.5 Pacific Decadal Oscillation Phases

Years	Pacific Decadal Oscillation Phase
1947-1976	Cool
1977-1998	Warm
1999-Current	Cool (relatively weak: has changed from cool to warm multiple times in this period)

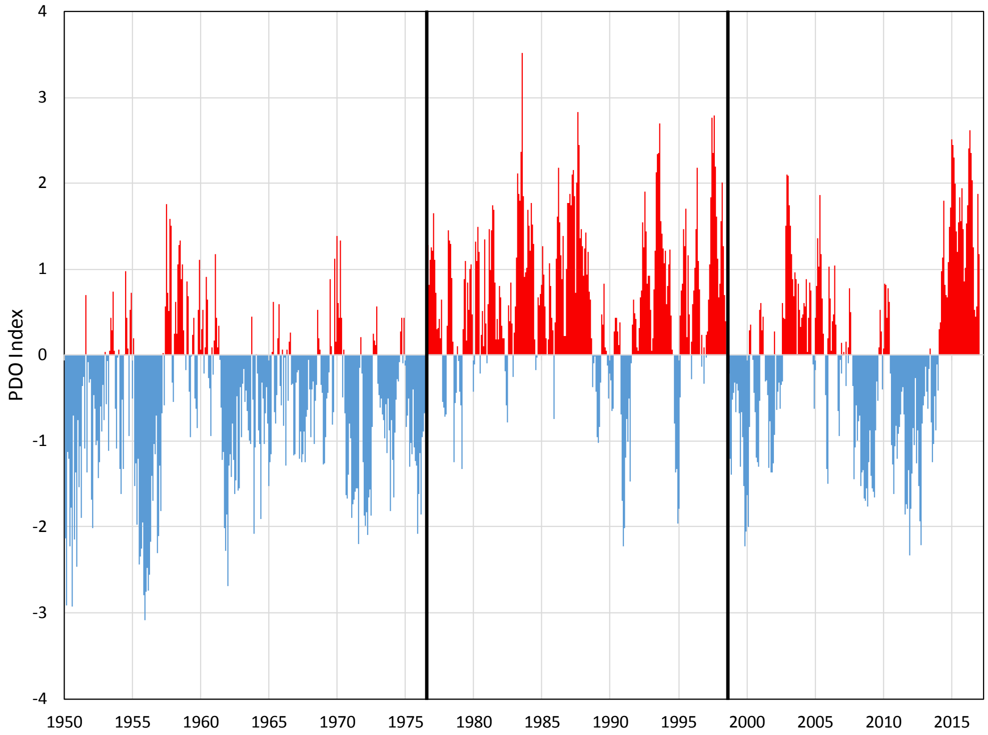

Figure 3.10 Monthly PDO Index Values

A second factor affecting IDF curves in the Metro Vancouver region are atmospheric river (AR) events (commonly referred to as "Pineapple Express" events). An AR is a thin band of moisture that transfers moisture from tropical regions towards the poles. The western coast of British Columbia is one of eight regions in the world that experience AR events, and there are between 12 and 24 events in a year (PCIC, 2013). Climate change is expected to cause AR events to intensify, move northward, and become more frequent. The tropical region where AR events originate is expected to expand. It is expected that increased AR activity will cause an increase of 28% in extreme precipitation days (Hagos, et al., 2016). Where an AR event results in the annual maximum precipitation for one or more durations, they are automatically included in the IDF curves. As AR events intensify, the IDF curves will shift accordingly. However, as AR events become more frequent, the IDF curves will not be affected, since only the annual maximum precipitation is used for each year. These variations are included within the IDF curves, and no analysis of AR events was performed.

IDF curves in the Metro Vancouver region are also subject to short-term variability due to the El Niño Southern Oscillation (ENSO). The ENSO is a two to seven year oscillation pattern that also affects rainfall intensities and frequencies. Since IDF curves are based on a minimum of ten years of data, the ENSO variations (El Niño years and La Niña years) are accounted for within the year-to-year variability of the IDF curves. The ENSO would not explain long-term trends in the rainfall data, unlike the PDO. Similarly, the ENSO would not explain differences in rainfall measured in different decades, unlike the PDO. Therefore, no analysis of the potential effect of the ENSO (including potential interaction with the PDO) was performed.

Eleven stations with a minimum of ten years of data in each PDO category were selected for the evaluation of potential PDO effects on the station's IDF curves. Single site frequency analysis, using the EC methodology (Gumbel distribution fit by the method of moments) was applied to three sets of data for each station: all data (entire record), warm phase data only, and cool phase data only. The warm phase and cool phase results were compared to the results calculated with all data. The percent differences were averaged across all exceedance probabilities to produce an "overall" change in the IDF curves for each duration. The warm and cool IDF curves had shorter data records than the all data IDF curves (due to the removal of data). Extrapolation to the low probability of exceedance events is less certain for shorter data records. The analysis showed that the largest changes from the all data case occurred for the 2% and 1% AEP events. This would bias the analysis towards indicating a higher sensitivity of IDF curves to PDO. However, the increases/decreases are also apparent for higher probability of exceedance events, so the bias relates mainly to the magnitude of the sensitivity of the IDF curves to PDO, not to whether there is an increase/decrease.

The results of the effect of the PDO on the IDF curves are presented in Figure 3.11 and Figure 3.12 and also in Table 3.6 and Table 3.7. In the tables, increases and decreases are colour-coded red and blue respectively, and large (greater than 5%) increases or decreases are marked with in bold font. The results vary widely. Using only the data with warm PDO index, there is a general decrease in the IDF curves, and the decreases are very large. However, there are some stations with either little change or an increase in the IDF curves. Using the data with cool PDO index, there is a general increase in the IDF curves, but the trend is less visible for this phase. The changes for cool data are smaller than the changes for warm data. For both warm and cool data, short duration events show greater sensitivity to PDO than long duration events. There is no obvious geographical pattern in sensitivity to PDO.

The changes in the IDF curves for the warm and cool PDO indices are partly related to sampling variability. Different years and different storms are represented in the IDF curves for each station. Although storms may tend to be more intense during cool PDO years, individual storms may not follow this trend. Secondly, storms may tend to be more frequent during cool PDO years, but only the annual maximum storm for each duration at each station is used for calculation of the IDF curve. In addition, splitting the IDF curve data into warm and cool data increases the uncertainty in the IDF curves because there are fewer years of data in the analysis.

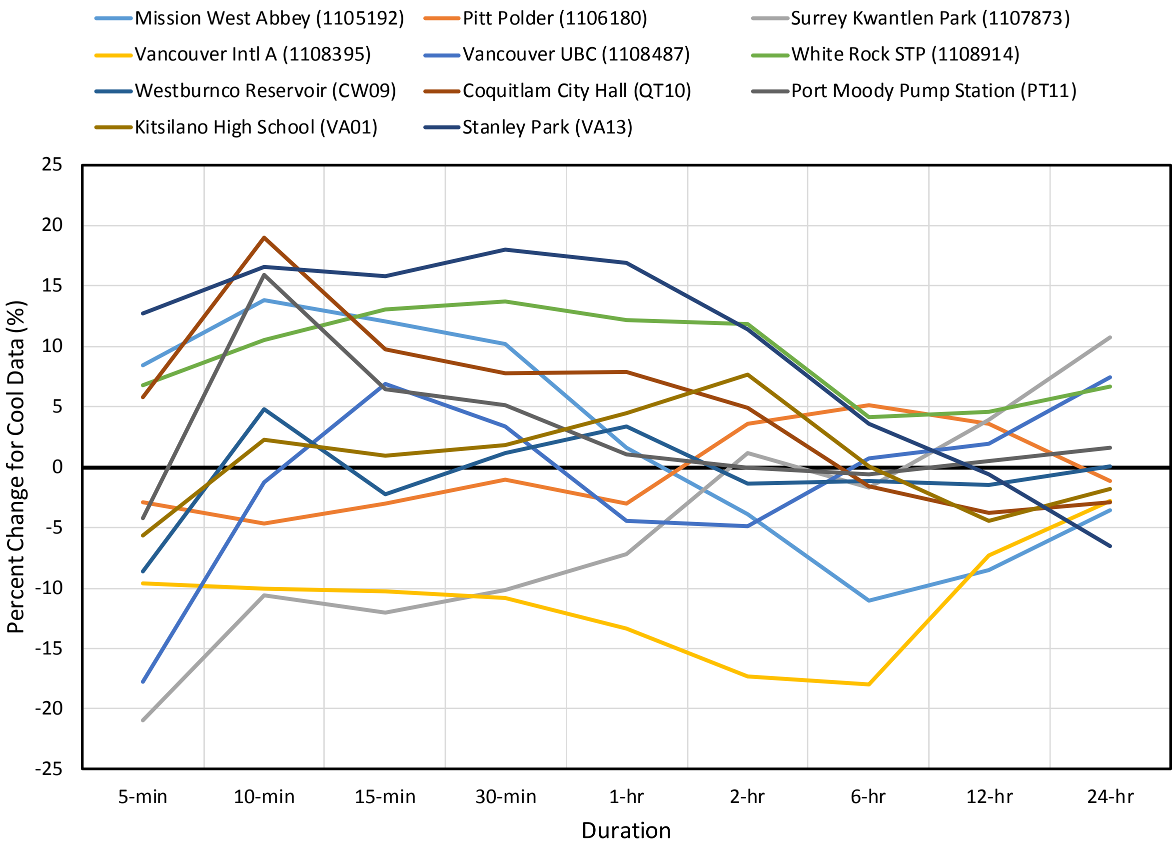

Figure 3.11 Percent Change in IDF for Different Durations Between the Cool PDO Data and All Data

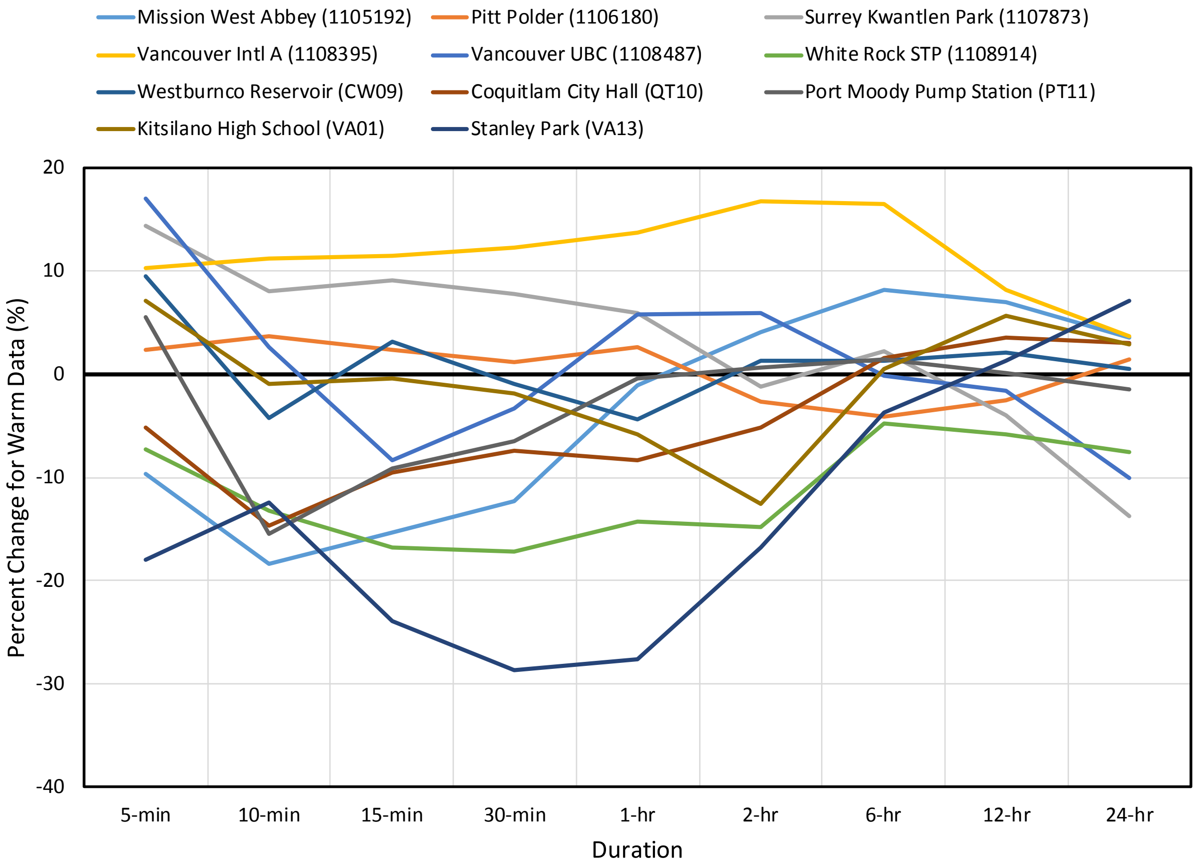

Figure 3.12 Percent Change in IDF for Different Durations Between the Warm PDO Data and All Data

Table 3.6 Comparison of Change in IDF for Different Durations Between the Warm PDO Data and All Data

Station Name and ID	Years of Data	Warm Years	Change for Warm Phase PDO Years (%)[1]								
			5-min	10-min	15-min	30-min	1-hr	2-hr	6-hr	12-hr	24-hr
Mission West Abbey (1105192)	1963-2010	1977-1998	**-9.6**	**-18.4**	**-15.4**	**-12.4**	-1.1	4.1	**8.2**	**7.0**	3.5
Pitt Polder (1106180)	1965-2007	1977-1998	2.4	3.7	2.3	1.2	2.5	-2.7	-4.2	-2.5	1.4
Surrey Kwantlen Park (1107873)	1962-1999	1977-1998	**14.3**	**8.1**	**9.1**	**7.7**	**5.9**	-1.3	2.2	-4.0	**-13.8**
Vancouver Intl A (1108395)	1953-2013	1977-1998	**10.3**	**11.2**	**11.4**	**12.3**	**13.7**	**16.7**	**16.5**	**8.2**	3.7
Vancouver UBC (1108487)	1958-1990	1977-1990	**17.0**	2.7	**-8.3**	-3.3	**5.8**	**5.9**	-0.2	-1.6	**-10.1**
White Rock STP (1108914)	1964-2001	1977-1998	**-7.2**	**-13.2**	**-16.7**	**-17.2**	**-14.3**	**-14.8**	-4.7	**-5.8**	**-7.5**
Westburnco Reservoir (CW09)	1960-2016	1980-1998	**9.4**	-4.3	3.2	-1.0	-4.4	1.2	1.3	2.1	0.5
Coquitlam City Hall (QT10)	1960-2016	1977-1998	**-5.2**	**-14.7**	**-9.6**	**-7.4**	**-8.3**	**-5.2**	1.5	3.5	3.0
Port Moody Pump Station (PT11)	1960-2016	1977-1998	**5.5**	**-15.5**	**-9.2**	**-6.5**	-0.5	0.7	1.5	0.1	-1.4
Kitsilano High School (VA01)	1958-2016	1977-1998	**7.0**	-0.9	-0.4	-1.8	**-5.8**	**-12.6**	0.4	**5.6**	2.8
Stanley Park (VA13)	1960-2016	1977-1998	**-17.9**	**-12.4**	**-23.9**	**-28.7**	**-27.6**	**-16.8**	-3.8	1.3	**7.1**

Note:

[1] Average change for all probabilities: 50%, 20%, 10%, 4%, 2%, and 1%.

Table 3.7 Comparison of Change in IDF for Different Durations Between the Cool PDO Phase and All Data

Station Name and ID	Years of Data	Cool Years	Change for Cool Phase PDO Years (%)[1]								
			5-min	10-min	15-min	30-min	1-hr	2-hr	6-hr	12-hr	24-hr
Mission West Abbey (1105192)	1963-2010	1963-1976, 1999-2010	**8.4**	**13.8**	**12.1**	**10.2**	1.6	-3.9	**-11.1**	**-8.5**	-3.6
Pitt Polder (1106180)	1965-2007	1965-1976, 1999-2007	-2.9	-4.7	-3.0	-1.0	-3.0	3.6	**5.1**	3.6	-1.2
Surrey Kwantlen Park (1107873)	1962-1999	1962-1976, 1999	**-21.0**	**-10.6**	**-12.1**	**-10.1**	**-7.1**	1.2	-1.7	3.9	**10.7**
Vancouver Intl A (1108395)	1953-2013	1953-1976, 1999-2013	**-9.6**	**-10.1**	**-10.3**	**-10.8**	**-13.4**	**-17.3**	**-18.0**	**-7.3**	-2.8
Vancouver UBC (1108487)	1958-1990	1958-1976	**-17.8**	-1.3	**6.9**	3.4	-4.4	-4.9	0.7	1.9	**7.4**
White Rock STP (1108914)	1964-2001	1964-1976, 1999-2001	**6.8**	**10.6**	**13.0**	**13.7**	**12.2**	**11.9**	4.2	4.6	**6.7**
Westburnco Reservoir (CW09)	1960-2016	1960-1976, 1999-2016	**-8.6**	4.8	-2.2	1.2	3.4	-1.4	-1.2	-1.5	0.0
Coquitlam City Hall (QT10)	1960-2016	1960-1976, 1999-2016	**5.8**	**19.0**	**9.8**	**7.7**	**7.9**	4.9	-1.6	-3.8	-2.9
Port Moody Pump Station (PT11)	1960-2016	1960-1976, 1999-2016	-4.3	**15.9**	**6.4**	**5.1**	1.0	-0.1	-0.6	0.5	1.6
Kitsilano High School (VA01)	1958-2016	1958-1976, 1999-2016	**-5.7**	2.3	0.9	1.8	4.5	**7.7**	0.0	**-4.5**	-1.8
Stanley Park (VA13)	1960-2016	1960-1976, 1999-2016	**12.7**	**16.6**	**15.8**	**18.0**	**16.9**	**11.4**	3.5	-0.6	**-6.6**

Notes

[1] Average change for all probabilities: 50%, 20%, 10%, 4%, 2%, and 1%.

The future climate uncertainty analysis will assess different IDF curves for each PDO category. If the PDO has a significant effect on the future climate change IDF curves, additional “PDO” IDF curves will be developed.

4. Summary and Recommendations

The rainfall data provided by Metro Vancouver were analyzed and ranked according to quality. Some stations were removed from the analysis because they had poor data quality. There were two main reasons for removing stations:

- The station had less than 10 years of data.
- The station did not record data at a five-minute (or shorter) temporal frequency.

The rainfall monitoring network could be improved by ensuring that monitoring continues at all stations and (where necessary) adjusting the temporal recording frequency of the data.

A total of 74 stations were used in an RRFA. An extensive QA/QC process was performed and annual maximum data were obtained for each station.

The rainfall zones developed by BGC (2009) were not homogeneous for all durations. Therefore, a k-means clustering analysis was performed to develop homogeneous rainfall zones. Geographic proximity was a key criterion for the delineation of the zones, in order to ensure that all durations would be homogeneous. A total of seven homogeneous rainfall zones were developed. The new zones correspond reasonably well with the BGC zones and with the south-north variation in rainfall in the Metro Vancouver region. Zone 7 will be omitted from further analysis because it is located in the Fraser Valley and is entirely outside of the GVS&DD service area.

A three-parameter distribution is generally used in RRFA. The GEV distribution was selected for the regional IDF curves. EC uses the Gumbel distribution (a two-parameter distribution) for IDF curves. The effect of the choice of distribution will be included in the sensitivity analysis, and will compare IDF curves generated with the Gumbel distribution with those generated with the GEV distribution.

The RRFA method produces dimensionless IDF curves. They must be scaled up according to the index rain. There are two possibilities for defining the means, which include: using the means from a nearby rainfall monitoring station, or using the means from the contour maps for each duration.

In order to compare the IDF curves across the Metro Vancouver region, the dimensionless IDF curves were scaled by the average index rain for the zone. The IDF curves are compared in Figure 4.1 and Figure 4.2. The regional IDF curves exhibit natural variation between the zones. The variation in rainfall across the zones for short duration events is minimal, with variability increasing as the duration increases. The southern zones have lower rainfall totals than the northern zones. The west-east precipitation “bands” observed by BGC (2009) become visible for durations longer than 6-hr. Short duration rainfall events show significant variability from west to east and south to north, which is captured in the regions derived for this study.

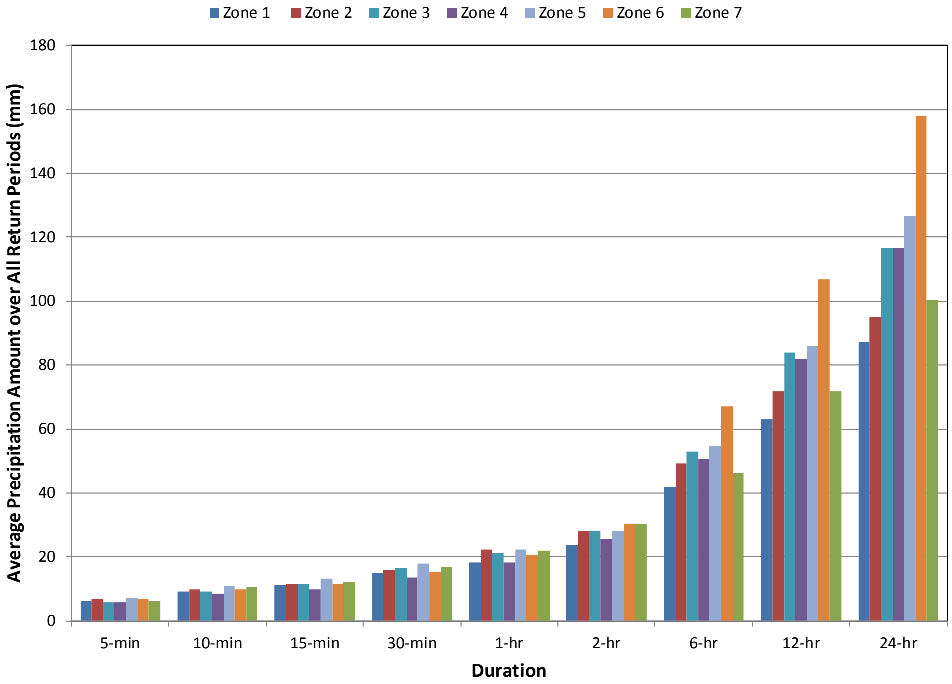

Figure 4.1 Variation Between Regional IDF Curves (Scaled by Average Index Rain for the Zone) for Each Duration, Averaged for All Probabilities of Exceedance

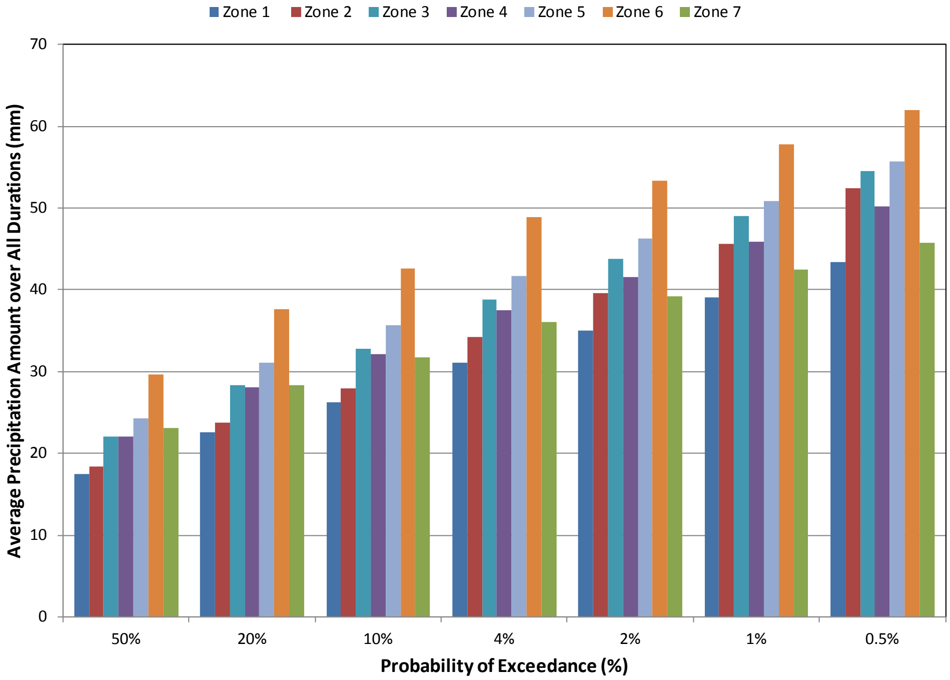

Figure 4.2 Variation Between Regional IDF Curves (Scaled by Average Index Rain for the Zone) for Each Probability of Exceedance, Averaged for All Durations

The regional IDF curves were compared to the BGC regional IDF curves and to individual EC IDF curves. The regional IDF curves were found to be similar to the existing IDF curves, with the differences attributed to the regionalization methodology. The regional IDF curves scaled by the regional maximum were in general larger than the earlier IDF curves, indicating that this is a conservative IDF curve estimate.

An additional analysis using the envelope curve methodology was also performed. The envelope curve method is not recommended for implementation in the Metro Vancouver region. Envelope curves do not represent the probability distribution characteristics of an area and tend to overestimate the rainfall intensities. The regional IDF curve scaled by the regional maximum was similar to the envelope IDF curve. This indicates that the envelope curve overestimates the rainfall. It is recommended that the regional IDF curves be used with the best-known estimate of the at-site means.

The effect of the PDO on the IDF curves was examined using a set of eleven long-term rainfall monitoring stations representative of the Metro Vancouver region. In general, there is a decrease in the IDF curves during warm years, and an increase in the IDF curves during cool years, but there is significant variability in this relationship. The effect of the PDO index on the future climate change IDF curves will be examined in detail during the future climate uncertainty analysis.

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Appendix A

Table of Contents

Table 1.1 Data Quality Ranking

Station ID	Station Name	Agency	Latitude	Longitude	Elevation	Sewerage Area	Temporal Frequency	QA/QC Level Applied	First Year	Last Year	Number of Years of Data	Number of Years with >85%	Data Quality Ranking
1100030	ABBOTSFORD A	EC	49.025	-122.360	59.13	N/A	5-min	IDF	1977	2001	25	25	A
1100032	ABBOTSFORD A	EC	49.025	-122.360	59.1	N/A	1-hr	None	2016	2017	2	<10	D
1100360	ALOUETTE LAKE	EC	49.283	-122.483	117.3	N/A	1-hr	IDF	1971	1982	12	12	C
1101140	BUNTZEN LAKE	EC	49.383	-122.867	10	N/A	1-hr	IDF	1969	1983	15	15	C
1101890	COQUITLAM LAKE	EC	49.367	-122.800	160.9	N/A	1-hr	IDF	1971	1982	12	12	C
1102415	DELTA BURNS BOG	EC	49.126	-123.002	3.11	N/A	15-min	None	2010	2017	8	<10	D
1102416	DELTA LADNER EAST	EC	49.083	-123.067	1.5	Fraser	5-min	None	1972	1974	3	<10	D
1103328	HANEY MICROWAVE	EC	49.200	-122.517	320	N/A	1-hr	IDF	1964	1984	21	21	C
1103332	HANEY UBC RF ADMIN	EC	49.264	-122.573	147	N/A	5-min	IDF	1963	2005	43	43	A
1104555	LANGLEY LOCHIEL	EC	49.050	-122.583	100.9	N/A	1-hr	IDF	1972	1986	15	15	C
1105192	MISSION WEST ABBEY	EC	49.153	-122.271	197	N/A	5-min	IDF	1963	2010	48	48	A
1105210	RICHMOND OPERATIONS CENTRE	EC	49.182	-123.078	16	Lulu	15-min	None	2010	2017	8	<10	D
1105660	N VANCOUVER LYNN CREEK	EC	49.367	-123.033	190.5	N/A	5-min	IDF	1964	1982	19	19	A
1106178	PITT MEADOWS CS	EC	49.208	-122.690	5	Fraser	15-min	None	2009	2017	9	<10	D
1106180	PITT POLDER	EC	49.273	-122.631	5	N/A	5-min	IDF	1965	2007	43	43	A
1106200	POINT ATKINSON	EC	49.330	-123.265	14	North Shore	15-min	None	2007	2017	11	<10	D
1106256	PORT COQUITLAM CITY YARD	EC	49.267	-122.783	6.7	Fraser	5-min	IDF	1971	1990	20	20	A
1107680	STAVE FALLS	EC	49.233	-122.367	110	N/A	5-min	IDF	1974	1982	9	<10	D
1107873	SURREY KWANTLEN PARK/ SUR_Surrey_Kwantlen_Park	EC/ Muni	49.192	-122.860	78	Fraser	5-min	IDF	1962	2017	56	55	A/B
1107876	SURREY MUNICIPAL HALL/. SUR_Surrey_Municipal_Hall	EC/ Muni	49.107	-122.828	76	Fraser	5-min	IDF	1963	2017	54	53	A/B
1108446	VANCOUVER HARBOUR CS	EC	49.295	-123.122	2.5	Vancouver	5-min	IDF	1970	1994	25	25	A
1108446	VANCOUVER HARBOUR CS	EC	49.295	-123.122	2.5	Vancouver	15-min	None	2007	2017	11	<10	D
1108465	VANCOUVER PMO	EC	49.283	-123.117	59.4	Vancouver	5-min	None	1969	1979	11	<10	D
1108487	VANCOUVER UBC	EC	49.250	-123.250	76	Vancouver	5-min	IDF	1958	1990	33	33	A
1108824	WEST VANCOUVER AUT	EC	49.347	-123.193	170.21	North Shore	15-min	None	2005	2017	13	11	C

Table 1.1 Data Quality Ranking

Station ID	Station Name	Agency	Latitude	Longitude	Elevation	Sewerage Area	Temporal Frequency	QA/QC Level Applied	First Year	Last Year	Number of Years of Data	Number of Years with >85%	Data Quality Ranking
1108910	WHITE ROCK CAMPBELL SCIENTIFIC	EC	49.018	-122.784	13	Fraser	1-hr	None	2013	2017	5	<10	D
1108914	WHITE ROCK STP/ SUR_White_Rock_STEP	EC/ Muni	49.019	-122.784	13	Fraser	5-min	IDF	1964	2017	51	50	A/B
1104470 / 1104473	LADNER BCHPA	EC	49.083	-123.050	1.5	Fraser	5-min	IDF	1963	1978	16	16	A
1106CL2	PORT MOODY GLENAYRE	EC	49.279	-122.881	129.5	Fraser	5-min	IDF	1971	2001	31	31	C
1108395 / 1108447	VANCOUVER INT'L A	EC	49.195	-123.184	4.3	Vancouver	5-min	IDF	1953	2013	61	61	A
110FAG9	PITT MEADOWS STP	EC	49.217	-122.683	4.9	Fraser	5-min	IDF	1974	1992	19	19	A
110JA54	BURNABY MTN BCHPA	EC	49.283	-122.917	464.8	Fraser	1-hr	IDF	1974	1991	18	18	C
110N6FF	N VANC SONORA DR	EC	49.363	-123.098	182.9	North Shore	5-min	IDF	1990	2010	21	21	A
AB76	ABBOTSFORD	MV	49.043	-122.310	80	N/A	5-min	None	2001	2016	16	15	B
BU07	Sperling Ave. Pump Station	MV	49.252	-122.964	46	Fraser	5-min	None	1987	2016	30	30	B
BU29	Central Park Reservoir	MV	49.226	-123.013	127	Vancouver	5-min	None	1989	2016	28	27	B
BU35	Burnaby Mountain, SFU	MV	49.280	-122.907	360	Fraser	5-min	None	1994	2016	23	22	B
BU70	Burnaby South	MV	49.215	-122.985	122	Fraser	5-min	None	1992	2016	25	24	B
BU80	North Burnaby	MV	49.288	-122.996	70	Vancouver	5-min	None	2001	2016	16	15	B
CK74	Chilliwack Airport	MV	49.321	-123.074	10	N/A	5-min	None	2002	2016	15	14	B
CW09	Westburnco Reservoir	MV	49.228	-122.908	127	Fraser	5-min	None	1960	2016	57	60	B
DM44	Katzie Pump Station	MV	49.209	-122.668	6	Fraser	5-min	None	1994	2016	23	26	B
DM45	Maple Ridge Reservoir	MV	49.221	-122.540	45	N/A	5-min	None	1995	2016	22	22	B
DM62	Golden Ears Elementary School	MV	49.215	-122.581	100	Fraser	5-min	None	1959	2016	58	55	B
DN16	AES Seymour Falls Dam	MV	49.440	-122.967	230	N/A	5-min	None	1960	2016	57	56	B
DN25	Dist North Van Municipal Hall	MV	49.336	-123.078	151	North Shore	5-min	None	1965	2016	52	52	B
DN53	Lynn Valley Firehall	MV	49.335	-123.043	142	North Shore	5-min	None	1995	2016	22	20	B
DN54	Seymour Golf and Country Club	MV	49.310	-122.959	80	North Shore	5-min	None	1996	2016	21	19	B

Table 1.1 Data Quality Ranking

Station ID	Station Name	Agency	Latitude	Longitude	Elevation	Sewerage Area	Temporal Frequency	QA/QC Level Applied	First Year	Last Year	Number of Years of Data	Number of Years with >85%	Data Quality Ranking
DN64	Blueridge Elementary School	MV	49.324	-123.001	134	North Shore	5-min	None	2001	2016	16	15	B
DN65	SeaCove Marina	MV	49.332	-122.939	10	North Shore	5-min	None	2001	2016	16	15	B
DN72	Mahon Park	MV	49.324	-123.082	80	North Shore	5-min	None	1964	2016	53	52	B
DN82		MV	49.366	-123.100	157	North Shore	5-min	None	1965	2008	53	52	B
DT34	Hellings Reservoir	MV	49.159	-122.902	111	Fraser	5-min	None	1993	2016	24	21	B
DT55	Ferry Road	MV	49.109	-123.071	0	Fraser	5-min	None	1997	2016	20	19	B
DT61	Pebble Hill Reservoir	MV	49.001	-123.079	54	Fraser	5-min	None	1998	2016	11	11	B
HP75	Hope Airport	MV	49.370	-121.499	131	N/A	5-min	None	2002	2016	15	14	B
PQ38	Port Coquitlam Pump Station	MV	49.253	-122.770	<15	Fraser	5-min	None	1959	2016	58	58	B
PT11	Port Moody Pump Station	MV	49.280	-122.834	4	Fraser	5-min	None	1960	2016	57	56	B
PT32	Rocky Point Park	MV	49.281	-122.850	20	Fraser	5-min	None	1959	2016	58	57	B
PW71	Meadowlands Elementary School	MV	49.245	-122.709	61	N/A	5-min	None	2001	2016	16	13	B
QT10	Coquitlam City Hall	MV	49.239	-122.862	13	Fraser	5-min	None	1960	2012	53	55	B
QT39	Burke Mountain Firehall	MV	49.301	-122.756	140	Fraser	5-min	None	1995	2016	22	17	B
QT57	Westwood Plateau	MV	49.312	-122.826	320	N/A	5-min	None	1998	2016	19	19	B
QT77	Douglas College	MV	49.288	-122.792	61	Fraser	5-min	None	1994	2016	23	20	B
RI60	Lulu Island WWTP	MV	49.115	-123.147	14	Lulu	5-min	None	2000	2016	17	16	B
RI81	Richmond	MV	49.142	-123.108	<15	Lulu	5-min	None	1992	2016	25	26	B
SU33	Surrey East	MV	49.133	-122.694		Fraser	5-min	None	1993	2016	24	23	B
SU42	Newton Reservoir	MV	49.116	-122.868	79	Fraser	5-min	None	1994	2016	23	23	B
SU48	Cloverdale Pump Station	MV	49.104	-122.768	100	N/A	5-min	None	1993	2016	24	23	B
SU56	Whalley Reservoir	MV	49.193	-122.817	1	Fraser	5-min	None	1959	2016	58	54	B
TL36	Langley Central	MV	49.096	-122.567	110	Fraser	5-min	None	1994	2016	23	22	B
TL78	31790 Walmsley Rd., Aldergrove	MV	49.025	-122.371		N/A	5-min	None	1957	2016	52	52	B
VA01	Kitsilano High School	MV	49.262	-123.164		Vancouver	5-min	None	1958	2015	58	57	B

Table 1.1 Data Quality Ranking

Station ID	Station Name	Agency	Latitude	Longitude	Elevation	Sewerage Area	Temporal Frequency	QA/QC Level Applied	First Year	Last Year	Number of Years of Data	Number of Years with >85%	Data Quality Ranking
VA04	Renfrew Elementary School	MV	49.251	-123.033		Vancouver	5-min	None	1960	2016	57	56	B
VA13	Stanley Park	MV	49.300	-123.137		Vancouver	5-min	None	1960	2016	57	53	B
VA28	Kent Ave. Pump Station	MV	49.210	-123.115		Vancouver	5-min	None	1989	2016	28	27	B
VA30	Kersland Reservoir	MV	49.238	-123.114		Vancouver	5-min	None	1988	2016	29	28	B
VA63	Harbour Pump Station	MV	49.284	-123.077	82	Vancouver	5-min	None	1999	2016	18	17	B
VA73	Vancouver International Airport	MV	49.189	-123.151	65	Vancouver	5-min	None	1994	2016	23	22	B
VN52	Lynn Pump Station	MV	49.309	-123.047		North Shore	5-min	None	1995	2016	22	20	B
VW14	West Vancouver Municipal Hall	MV	49.331	-123.160	34	North Shore	5-min	None	1992	2015	24	22	B
VW49	Gleneagles Pump Station No. 5	MV	49.347	-123.267	<15	North Shore	5-min	None	1995	2016	22	16	B
VW51	Capilano Golf and Country Club	MV	49.349	-123.124	4	North Shore	5-min	None	1996	2016	21	18	B
VW67	HORSESHOE BAY	MV	49.369	-123.277	20	North Shore	5-min	None	2007	2016	10	<10	B
WK47	White Rock Pump Station	MV	49.023	-122.812	61	Fraser	5-min	None	1959	2016	58	58	B
	ABB_Abby City Hall Rain	Muni	49.053	-122.329	13	N/A	5-min	None	2005	2017	13	<10	D
	ABB_Abby Maclure Rain	Muni	49.061	-122.350		N/A	5-min	None	2007	2017	11	<10	D
	ABB_Abby Old Yale Rain	Muni	49.061	-122.376		N/A	5-min	None	2007	2017	11	<10	D
	ABB_Bradner Rain Gauge	Muni	49.098	-122.427		N/A	5-min	None	2013	2017	5	<10	D
	ABB_Cannell Lake Station	Muni	49.253	-122.312		N/A	15-min	None	2012	2017	6	<10	D
	ABB_David Kandal Rain Gauge	Muni	49.069	-122.376		N/A	5-min	None	2013	2016	4	<10	D
	ABB_Ledgeview Rain	Muni	49.071	-122.226		N/A	5-min	None	2007	2017	11	<10	D
	ABB_Marshall Creek 2	Muni	49.030	-122.266		N/A	5-min	None	2003	2017	15	11	B
	ABB_McMillian Weather Station	Muni	49.047	-122.261		N/A	5-min	None	2013	2017	5	<10	D
	ABB_Mt Lehman Elementary Rain Gauge	Muni	49.118	-122.383		N/A	5-min	None	2013	2017	5	<10	D

Table 1.1 Data Quality Ranking

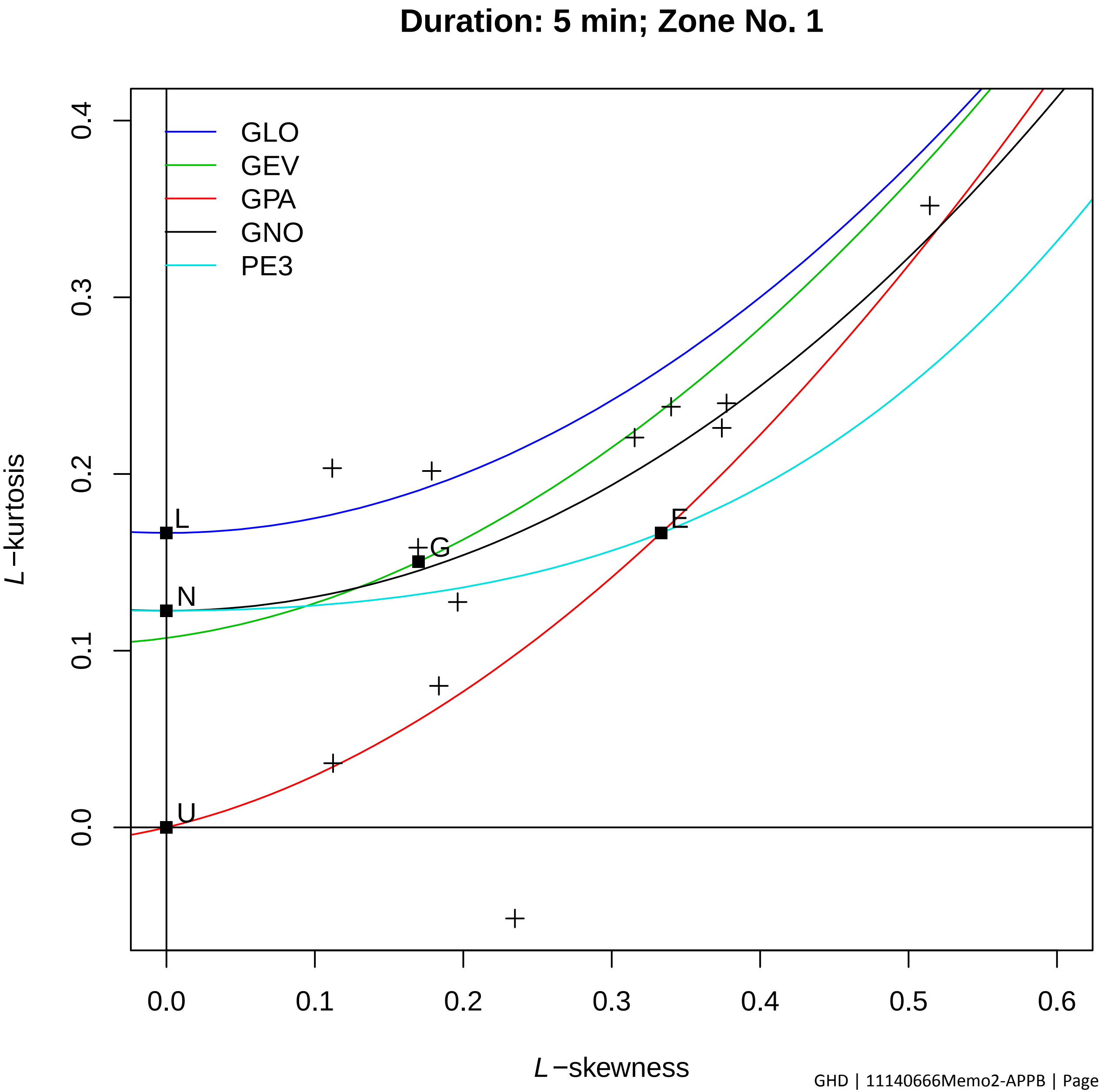
Station ID	Station Name	Agency	Latitude	Longitude	Elevation	Sewerage Area	Temporal Frequency	QA/QC Level Applied	First Year	Last Year	Number of Years of Data	Number of Years with >85%	Data Quality Ranking
	ABB_St. Auguston Rain Gauge	Muni	49.084	-122.219		N/A	5-min	None	2014	2017	4	<10	D
	BBY_Byrne Creek	Muni	49.205	-122.976		Fraser	5-min	None	2007	2017	11	<10	D
	BBY_Kensington Arena	Muni	49.276	-122.974		Fraser	5-min	None	2013	2017	5	<10	D
	BOW_Cove Bay Chlorination	Muni	49.377	-123.360		N/A	5-min	None	2016	2017	2	<10	D
	CNV_North Vancouver City Hall	Muni	49.321	-123.074		North Shore	5-min	None	1994	2017	24	18	B
	COQ_Coquitlam Rain Gauge	Muni	49.284	-122.793		Fraser	5-min	None	2013	2017	5	<10	D
	DNV_District of North Vancouver Rain Gauge	Muni	49.336	-123.078		North Shore	5-min	None	2013	2017	5	<10	D
	DNV_Fire Hall 4	Muni	49.316	-122.963		North Shore	5-min	None	2013	2017	5	<10	D
	DNV_Hastings Rain Gauge	Muni	49.359	-123.036		N/A	5-min	None	2013	2017	5	<10	D
	DNV_Mackay Debris Basin	Muni	49.362	-123.089		North Shore	5-min	None	2013	2017	5	<10	D
	DWV_Bonnymuir	Muni	49.365	-123.123		N/A	5-min	None	2007	2017	11	<10	D
	DWV_Cypress Mtn Ranger Station	Muni	49.375	-123.184		N/A	No data	None	N/A	N/A	0	<10	D
	DWV_DWV Municipal Hall	Muni	49.331	-123.160		North Shore	5-min	None	2007	2017	11	10	B
	DWV_DWV Works Yard	Muni	49.350	-123.222		North Shore	5-min	None	2007	2017	11	10	B
	DWV_Madrona	Muni	49.373	-123.280		North Shore	5-min	None	2007	2017	11	<10	D
	KWL_KWL Burnaby	Muni	49.260	-123.011		Vancouver	5-min	None	2012	2017	6	<10	D
	POC_Port Coquitlam Operations Centre	Muni	49.247	-122.764		Fraser	No data	None	N/A	N/A	0	<10	D
	RMD_Richmond City Hall	Muni	49.163	-123.138		Lulu	5-min	None	2005	2017	13	11	B
	SUR_68 Ave and 176 St	Muni	49.127	-122.734		Fraser	5-min	None	2011	2017	7	<10	D
	SUR_71A Ave at 190 St	Muni	49.133	-122.696		Fraser	1-min / 5-min	None	2011	2017	7	<10	D
	SUR_Chantrell Creek Elementary	Muni	49.048	-122.843		Fraser	5-min	None	2000	2017	18	11	B

Table 1.1 Data Quality Ranking

Station ID	Station Name	Agency	Latitude	Longitude	Elevation	Sewerage Area	Temporal Frequency	QA/QC Level Applied	First Year	Last Year	Number of Years of Data	Number of Years with >85%	Data Quality Ranking
	SUR_Hemlock Municipal Yard Rain Gauge	Muni	49.173	-122.779		Fraser	5-min	None	2012	2017	6	<10	D
	SUR_Port Kells Pump Station	Muni	49.179	-122.705		Fraser	5-min	None	2004	2017	14	12	B
	SUR_Semiahmoo Fish & Game Club	Muni	49.025	-122.708		N/A	5-min	None	2000	2017	18	15	B
	SUR_Surrey Arts Centre Rain Gauge	Muni	49.162	-122.842		Fraser	5-min	None	2012	2017	6	<10	D
	SUR_W.E. Kinvig Elementary School Rain Gauge	Muni	49.131	-122.855		Fraser	5-min	None	2012	2017	6	<10	D
	SUR_White Rock STP	Muni	49.018	-122.784		Fraser	5-min	None	1997	2017	21	17	B
	TOL_High Point	Muni	49.011	-122.669		Fraser	5-min	None	2009	2017	9	<10	D
	TOL_KinsRain	Muni	49.055	-122.483		Fraser	5-min	None	2007	2017	11	<10	D
	TOL_TOLRain	Muni	49.120	-122.660		Fraser	1-min / 5-min	None	2005	2017	13	10	B
	TOL_Yorkson Rain	Muni	49.156	-122.642		Fraser	5-min	None	2007	2017	11	<10	D

Appendix B

Figure Index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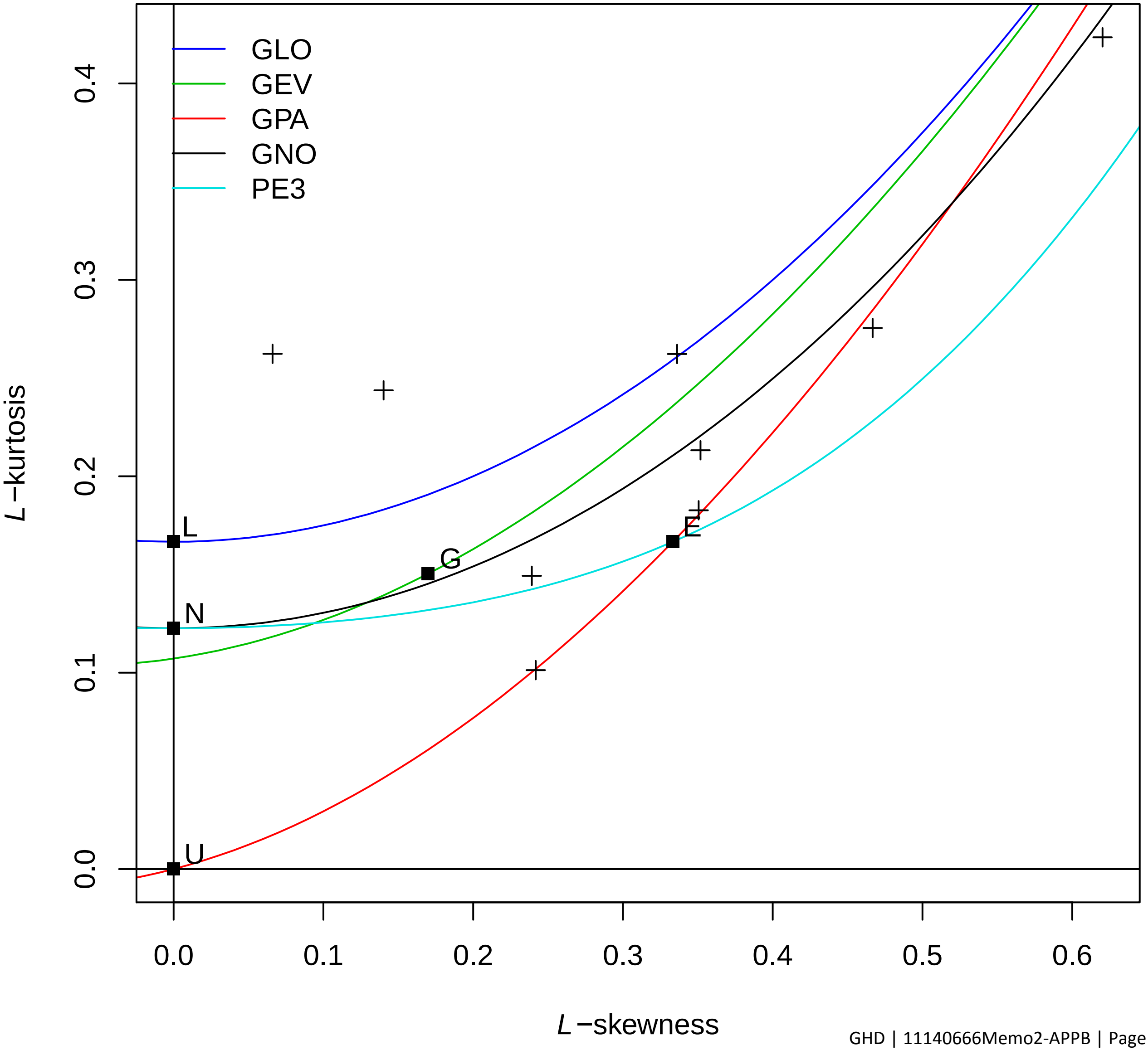

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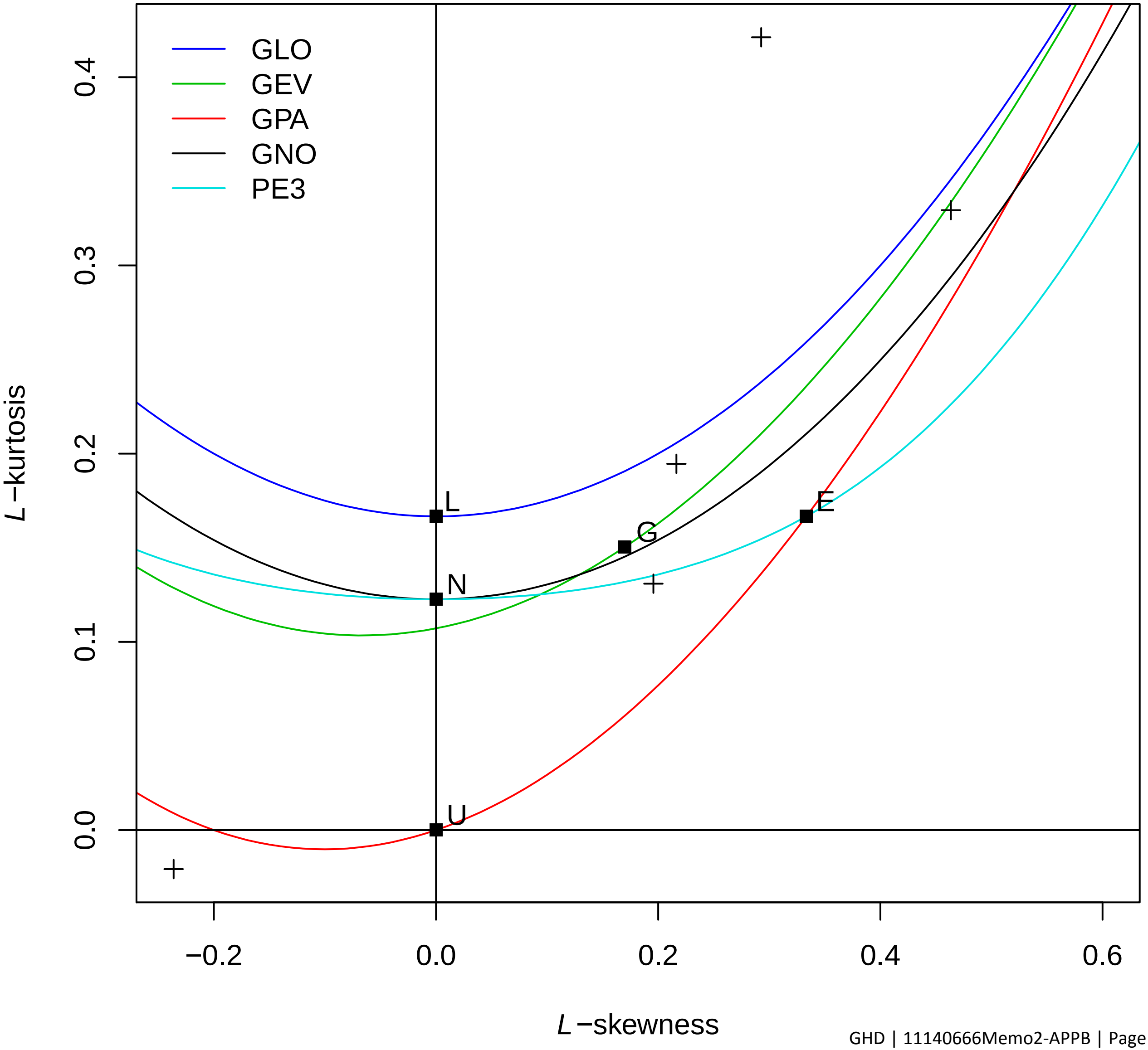

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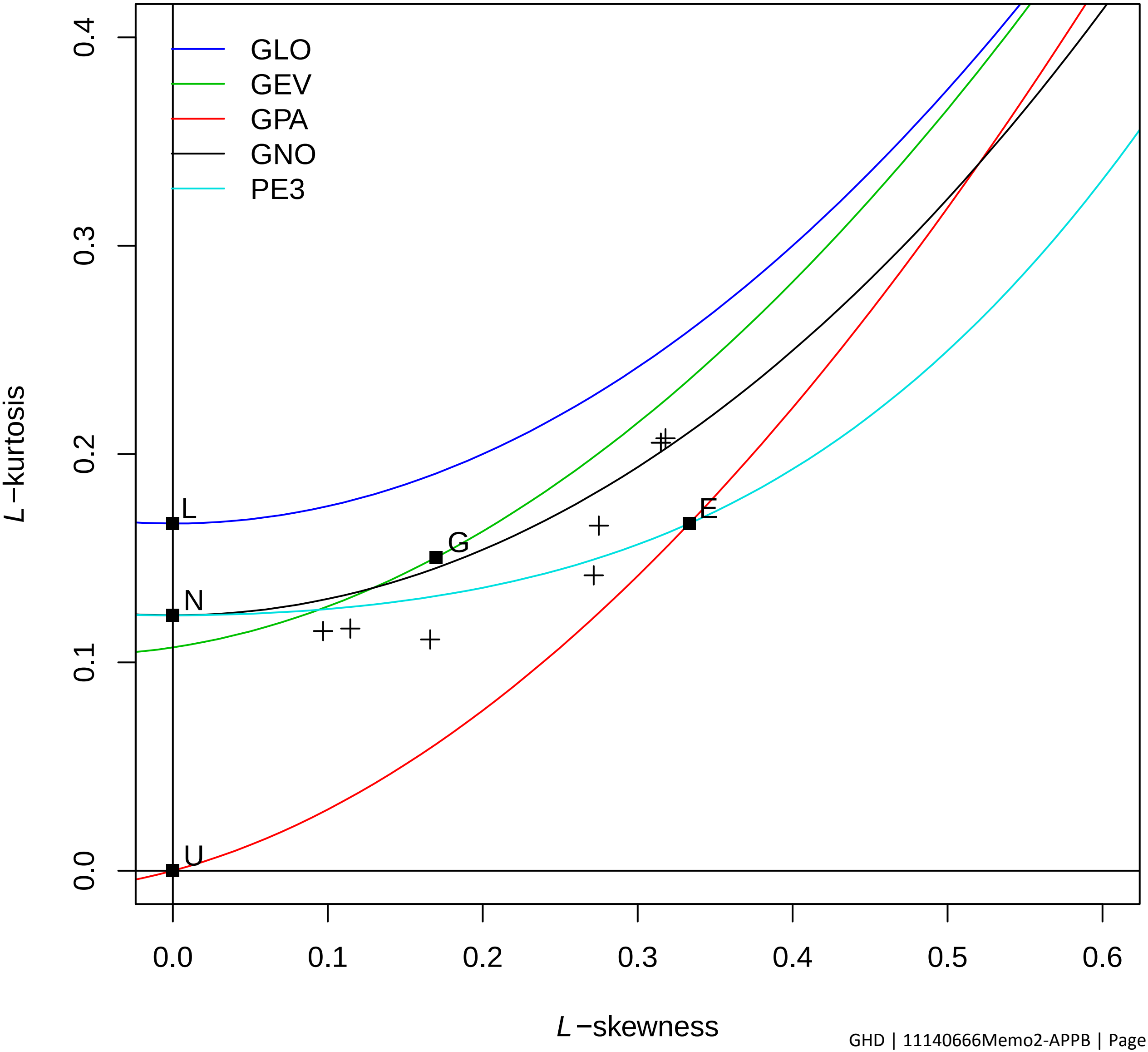

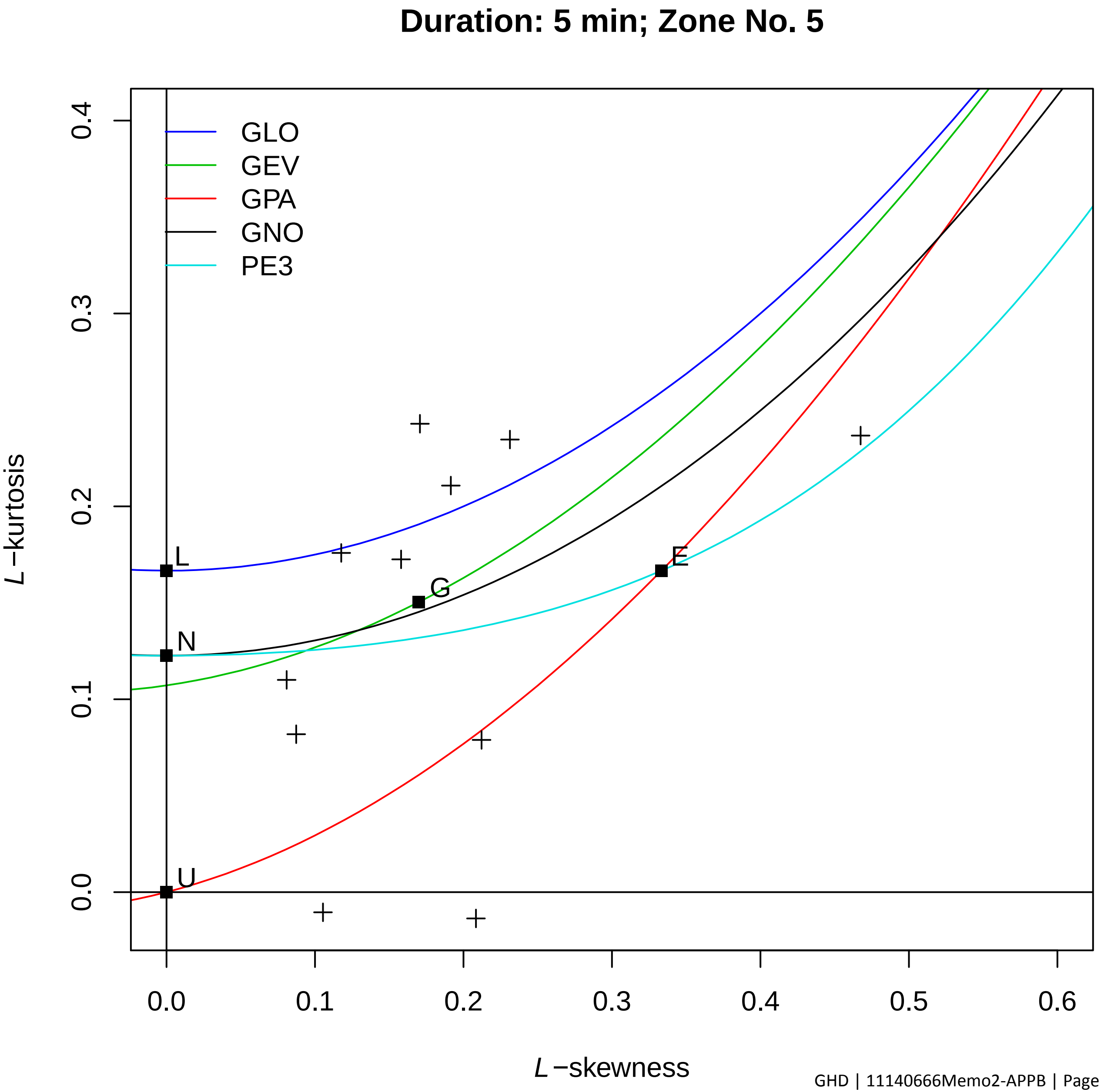
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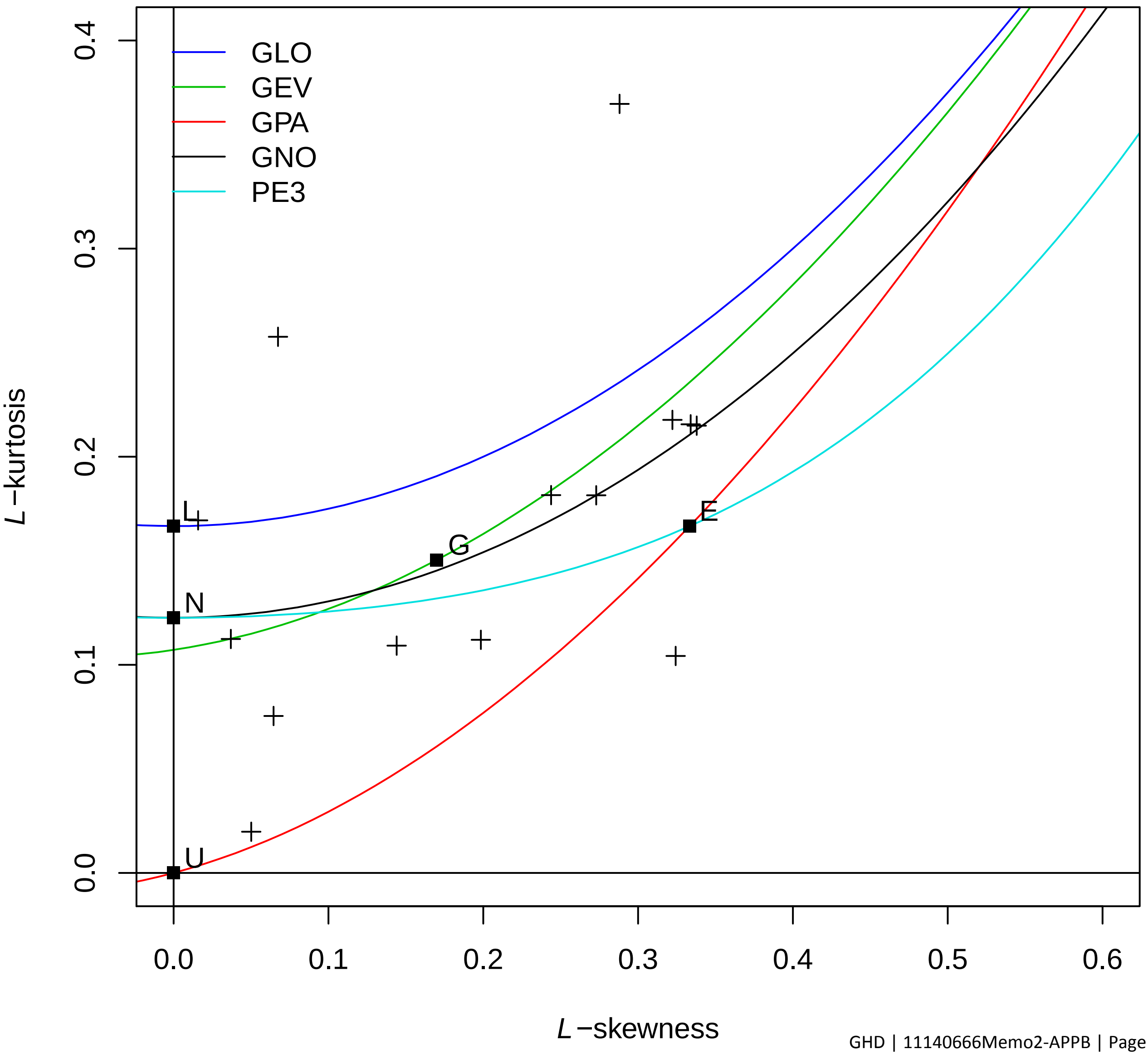

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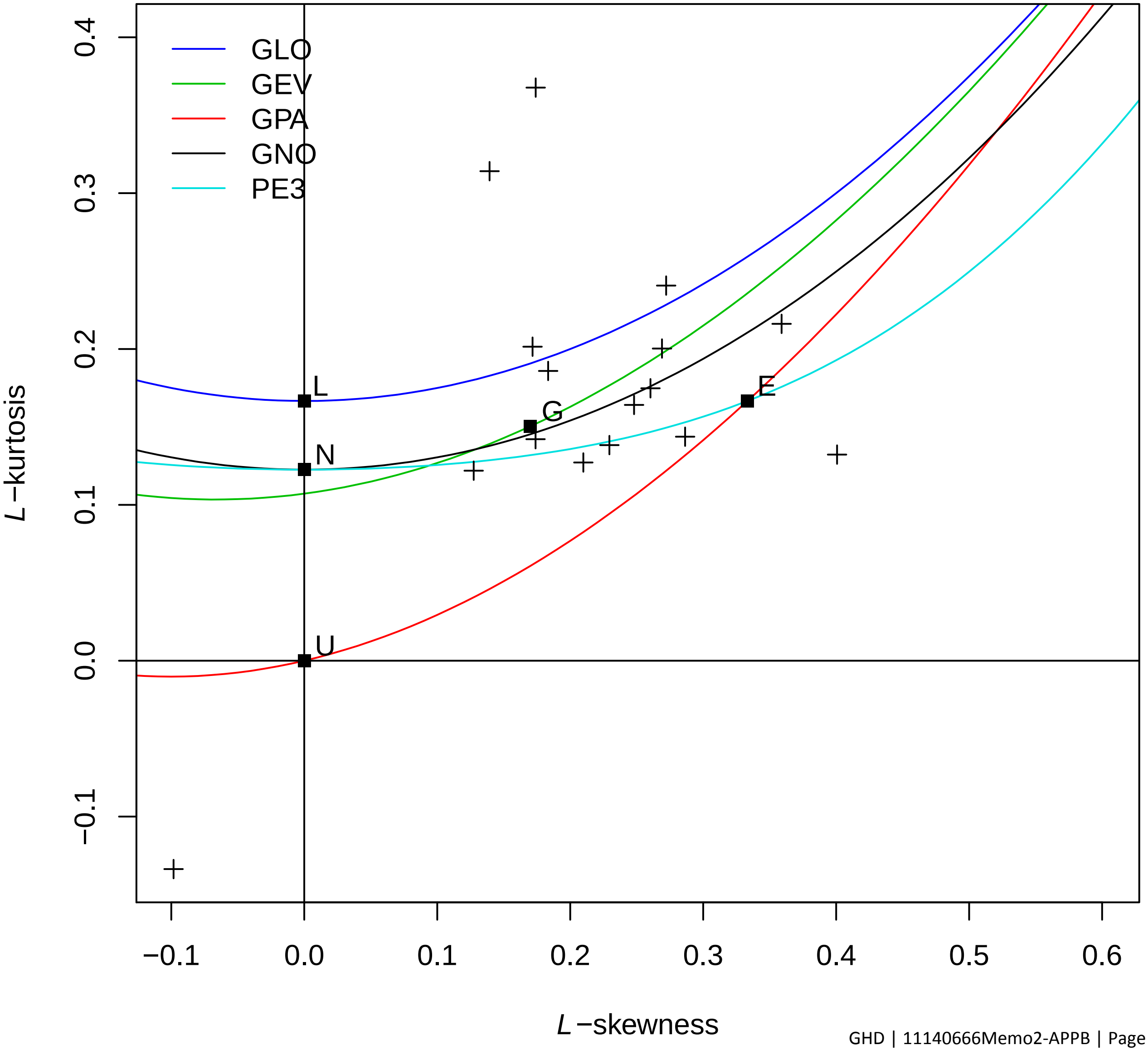

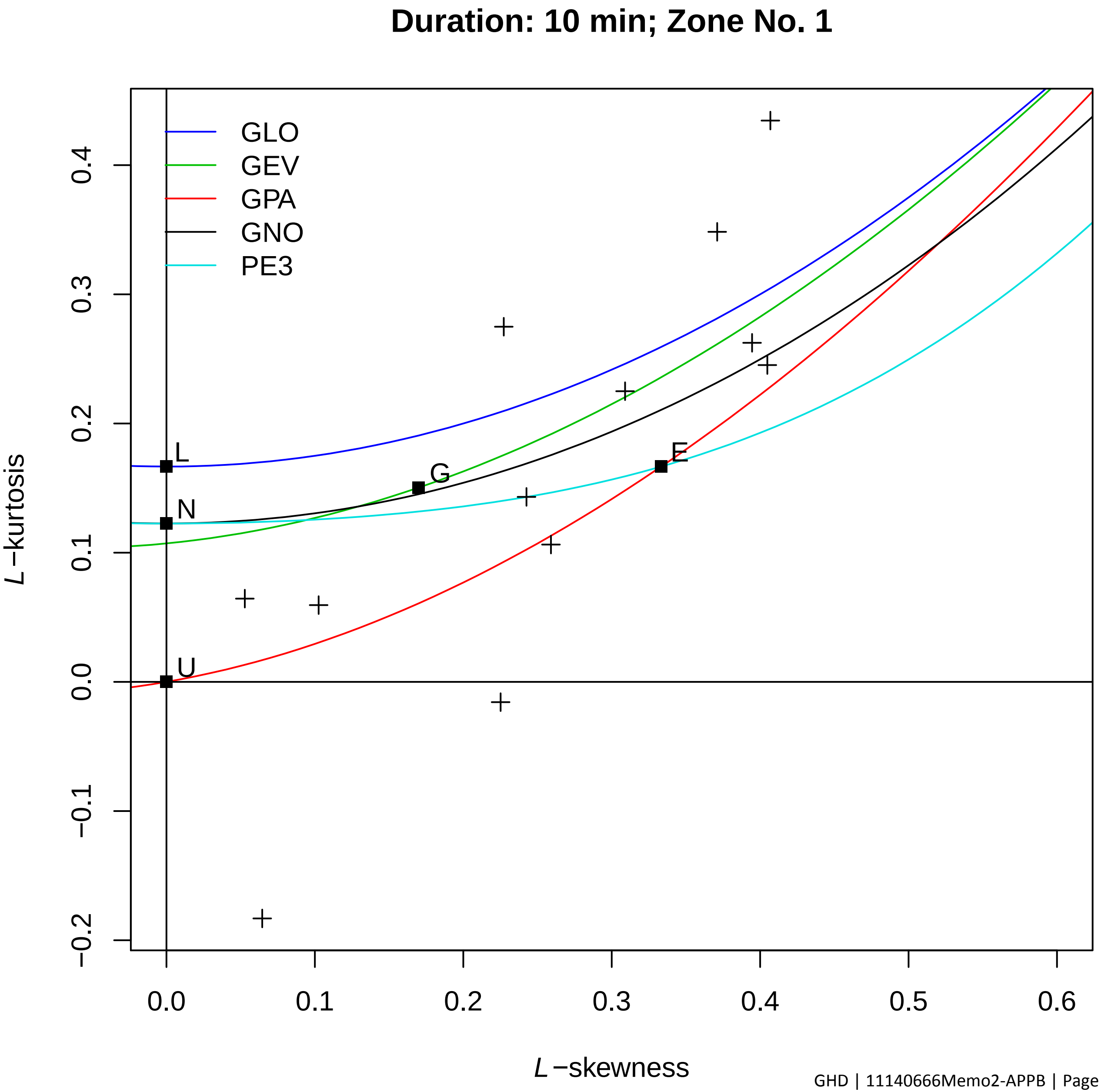
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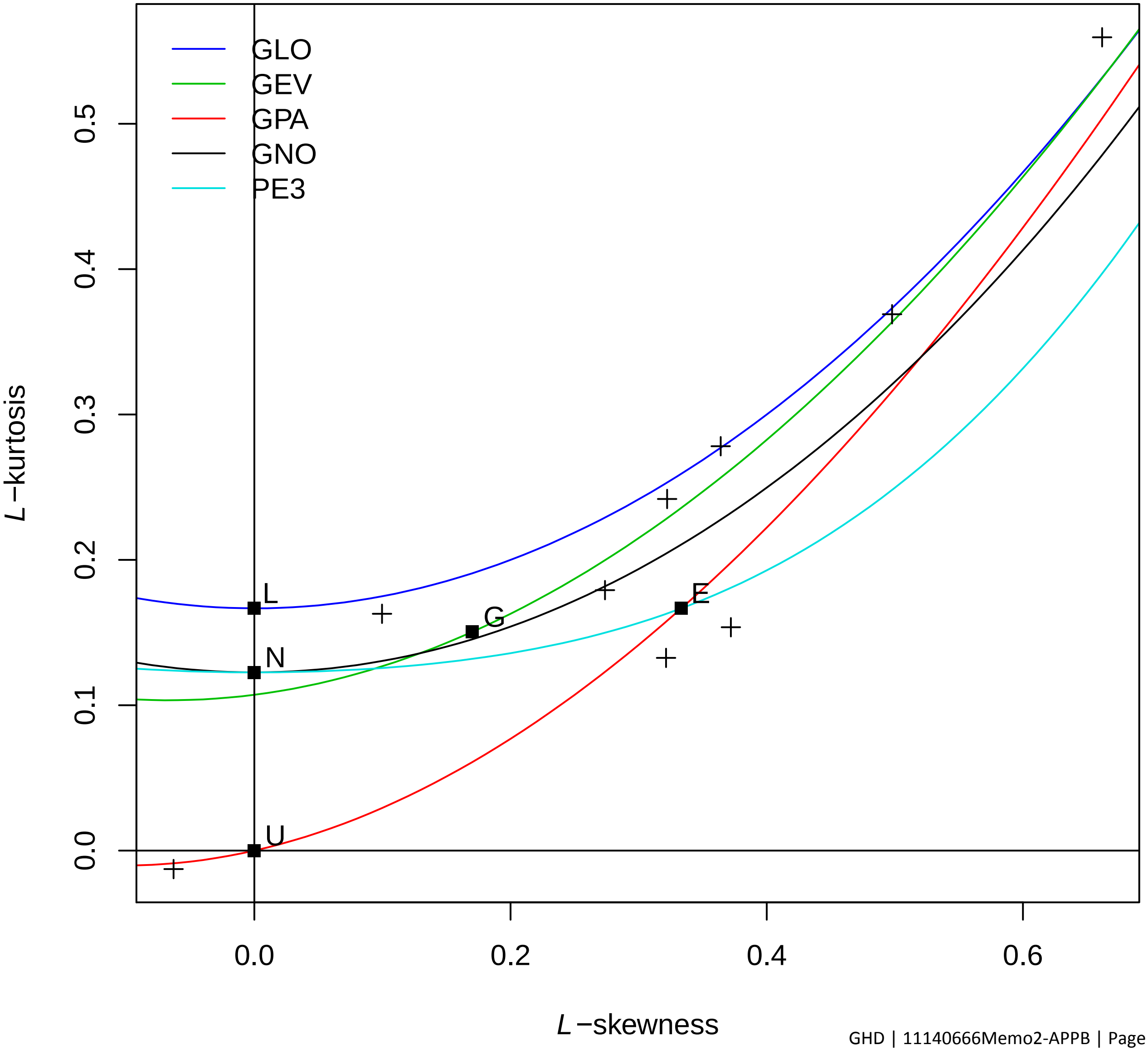

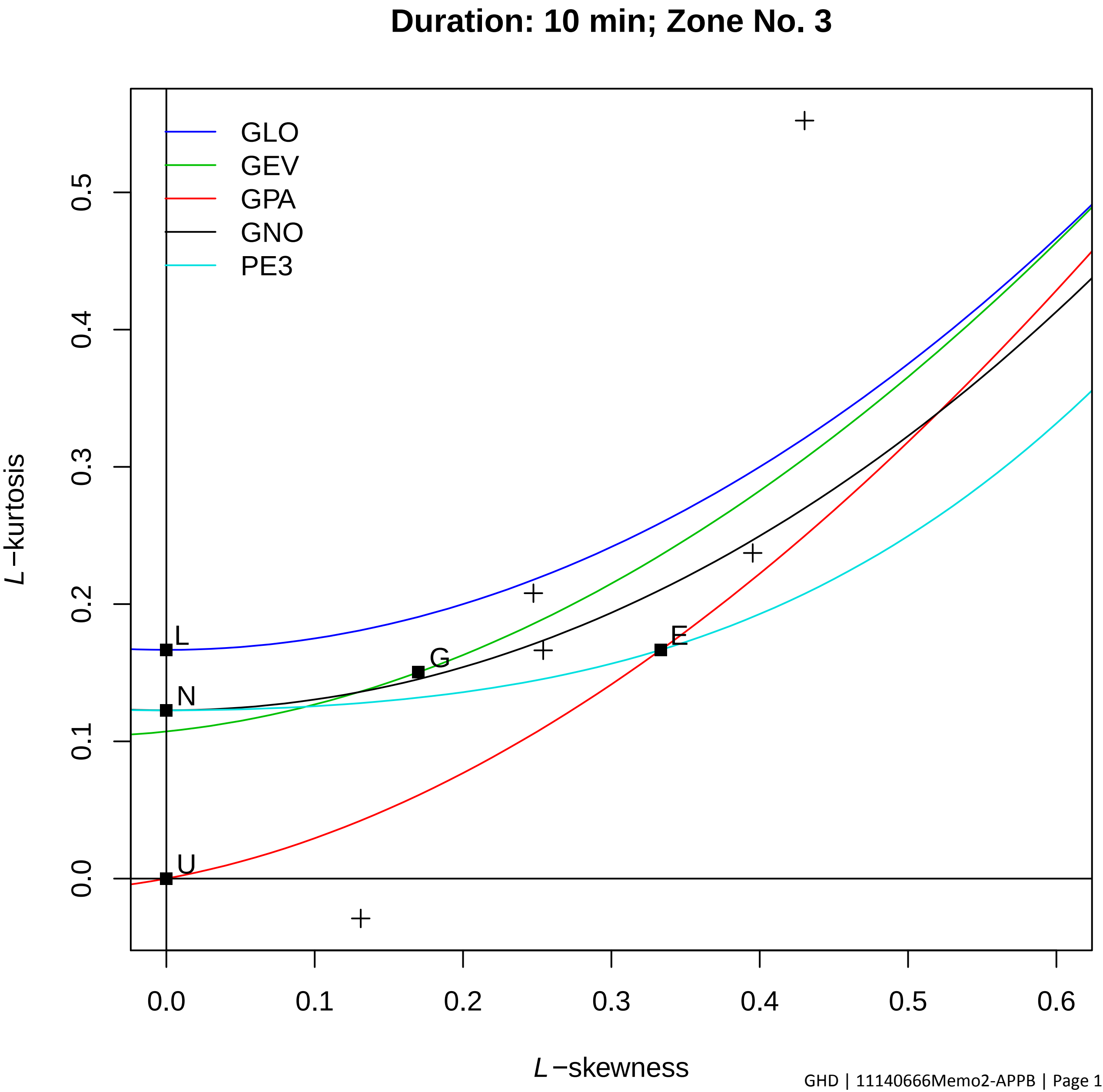
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L −skewness

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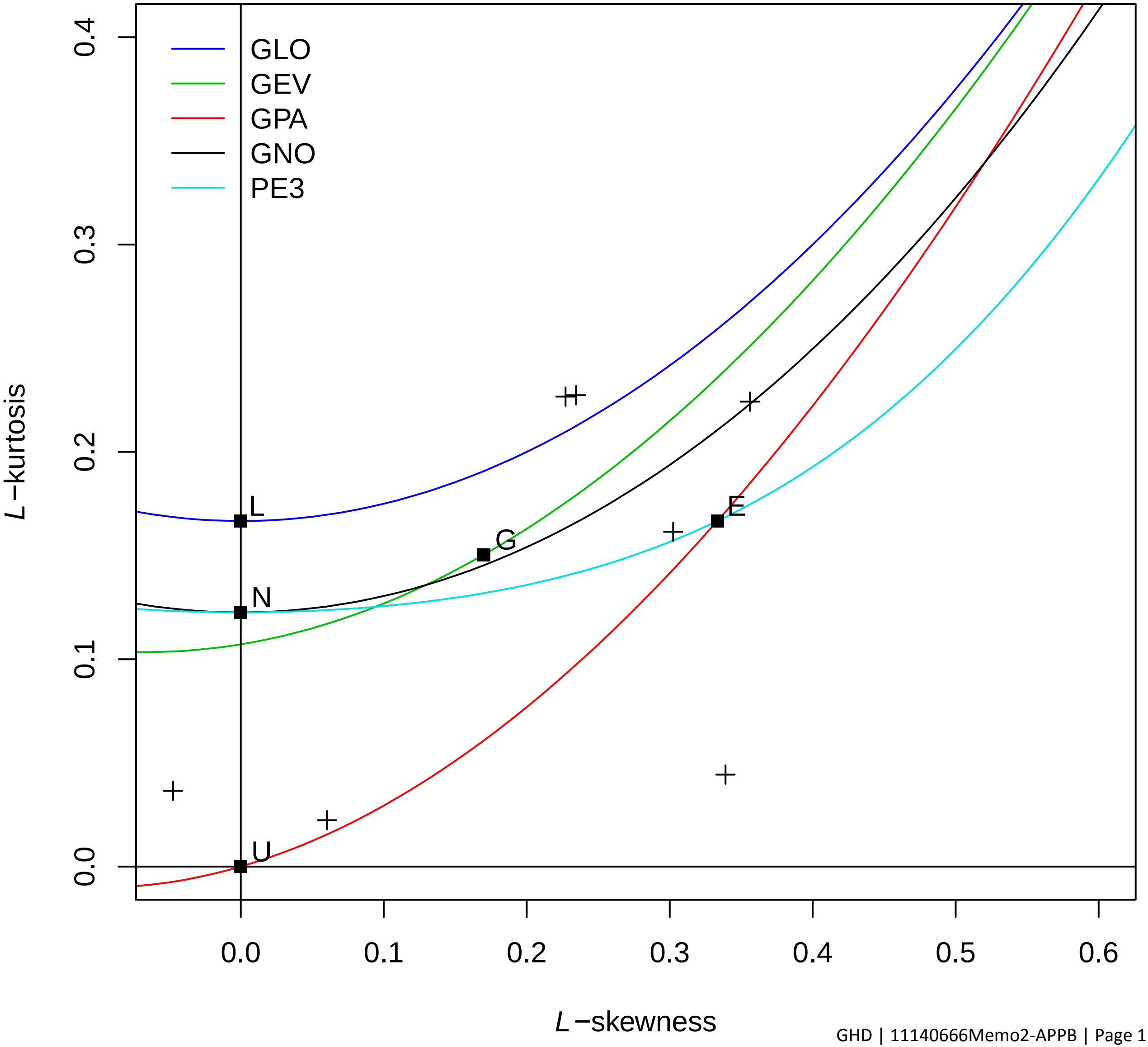

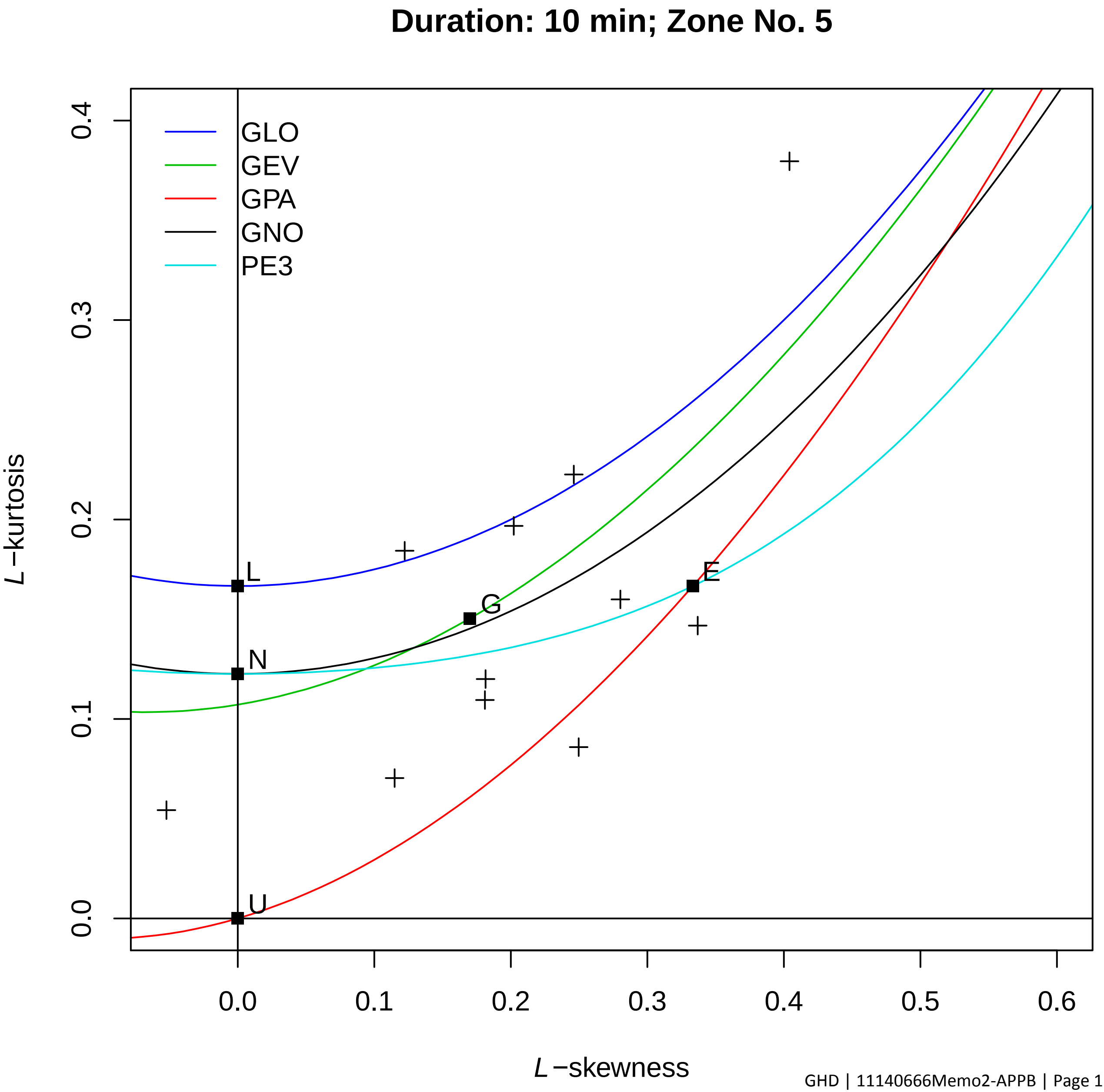
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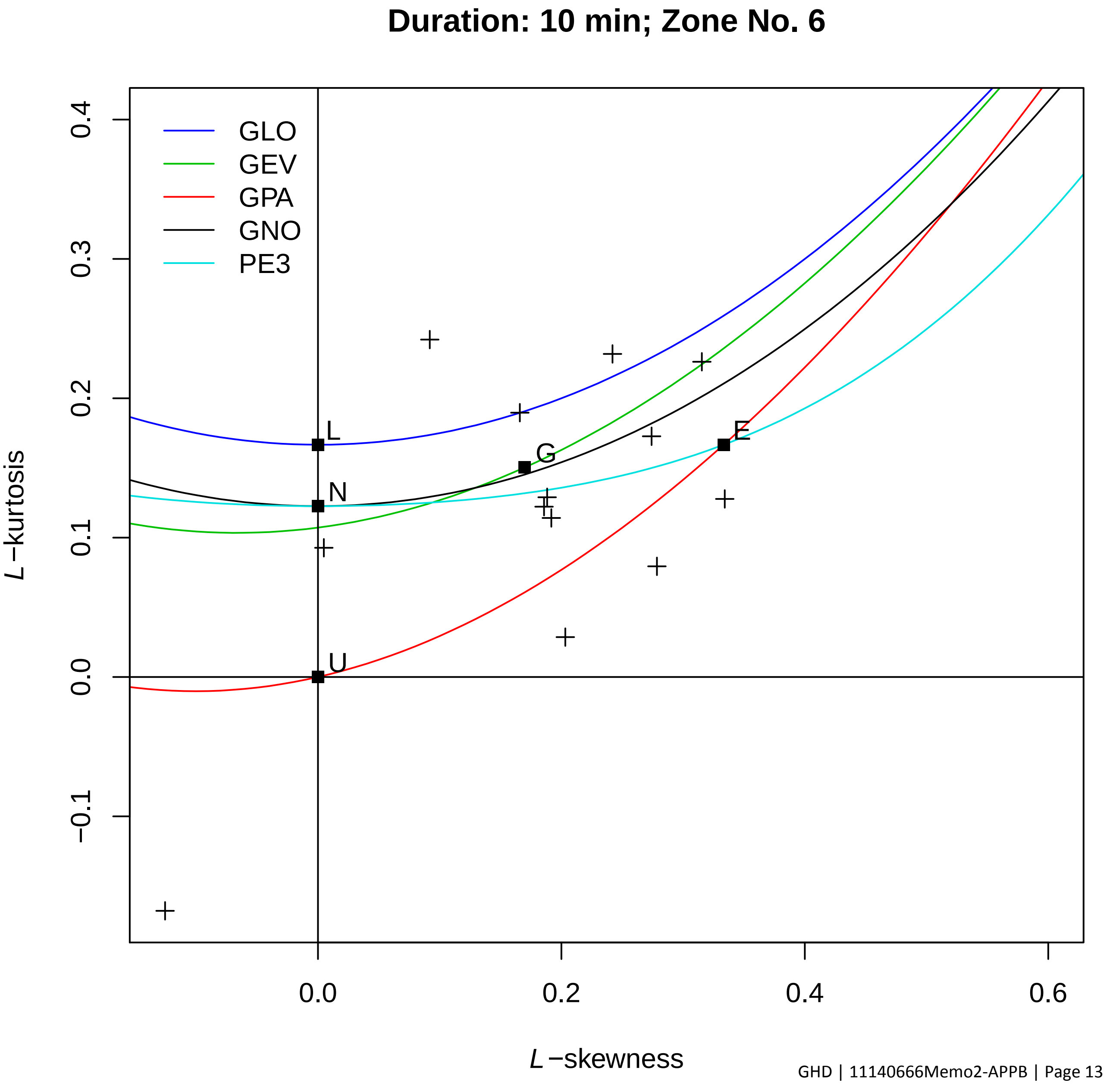
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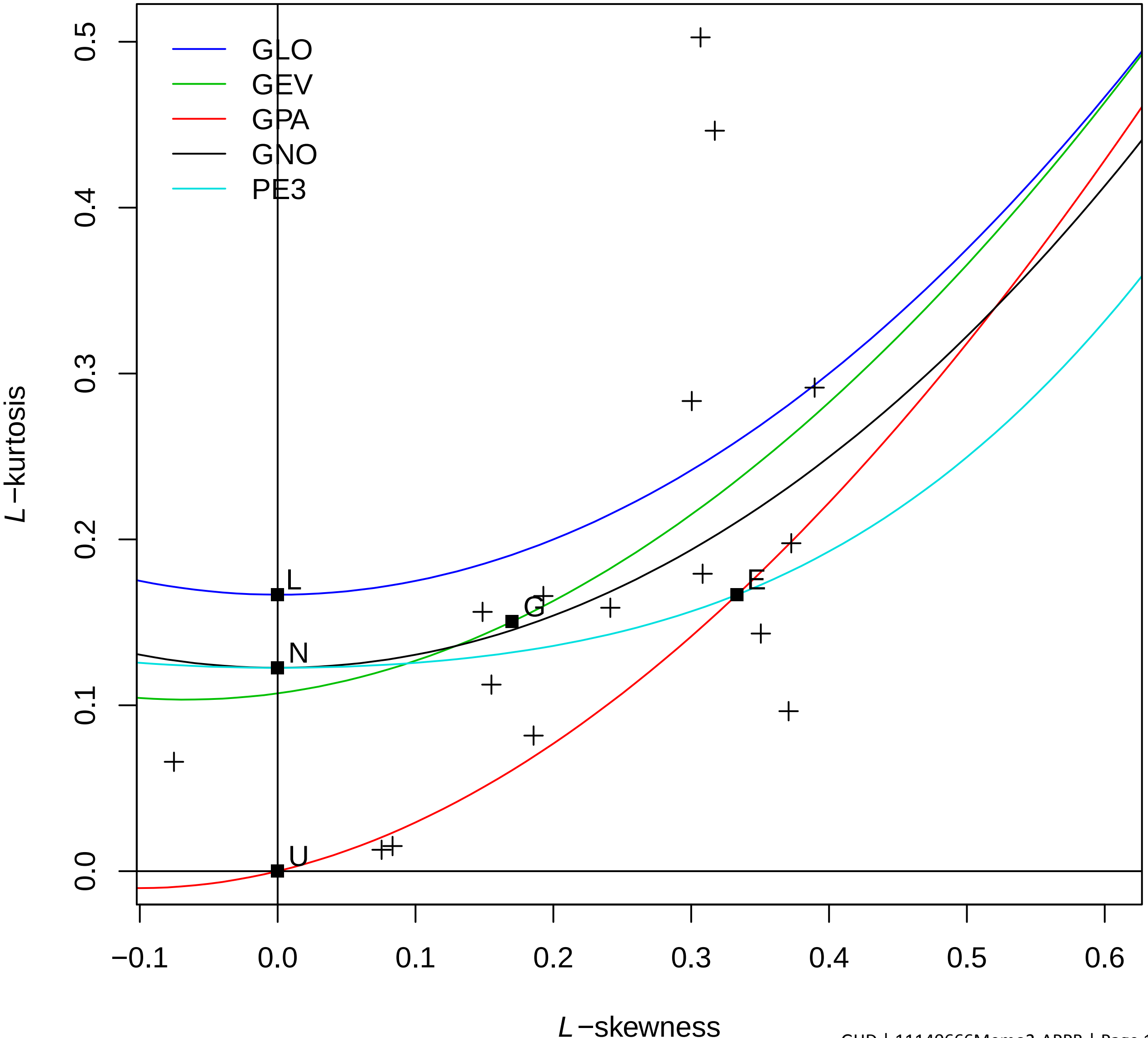

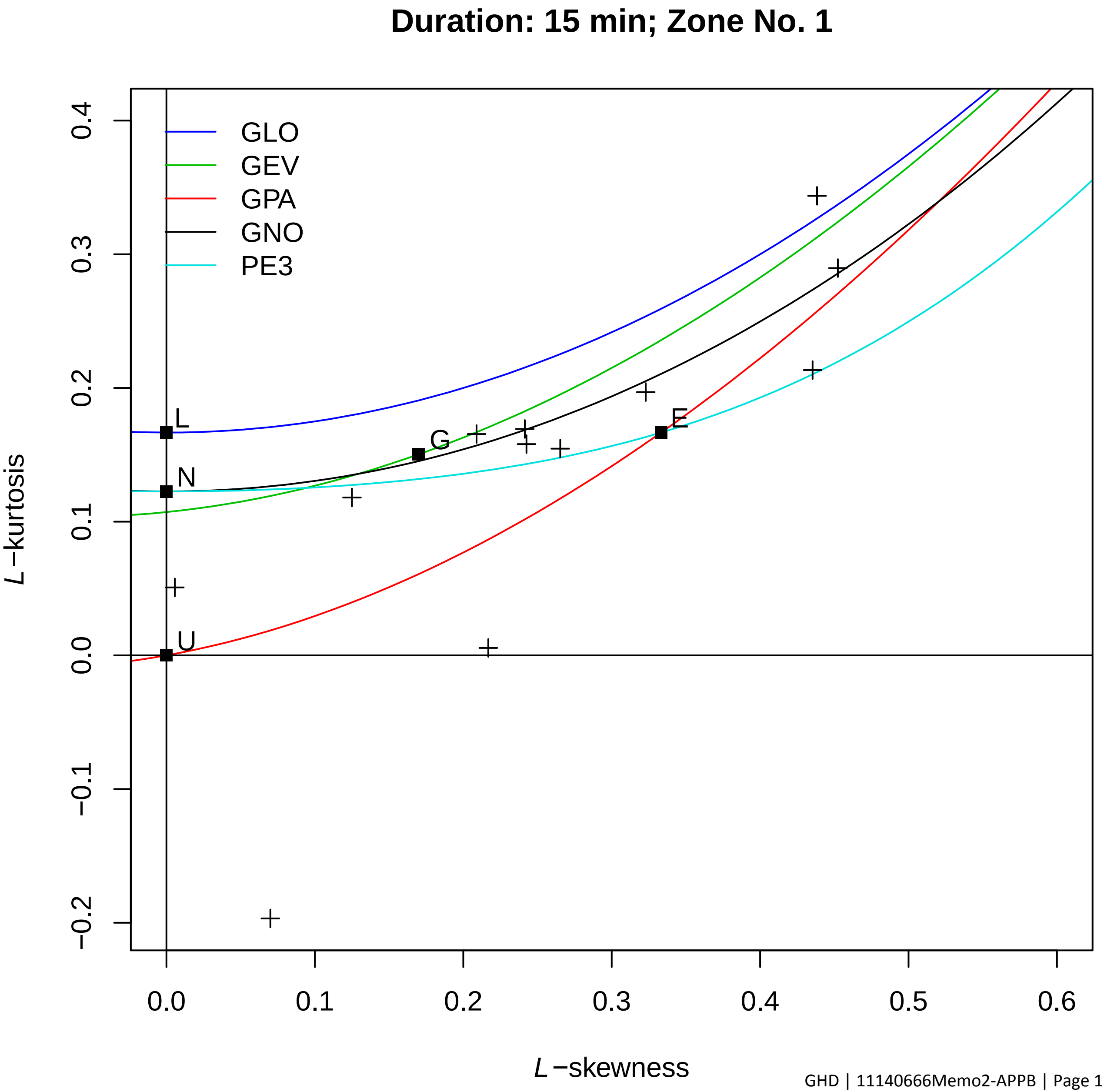
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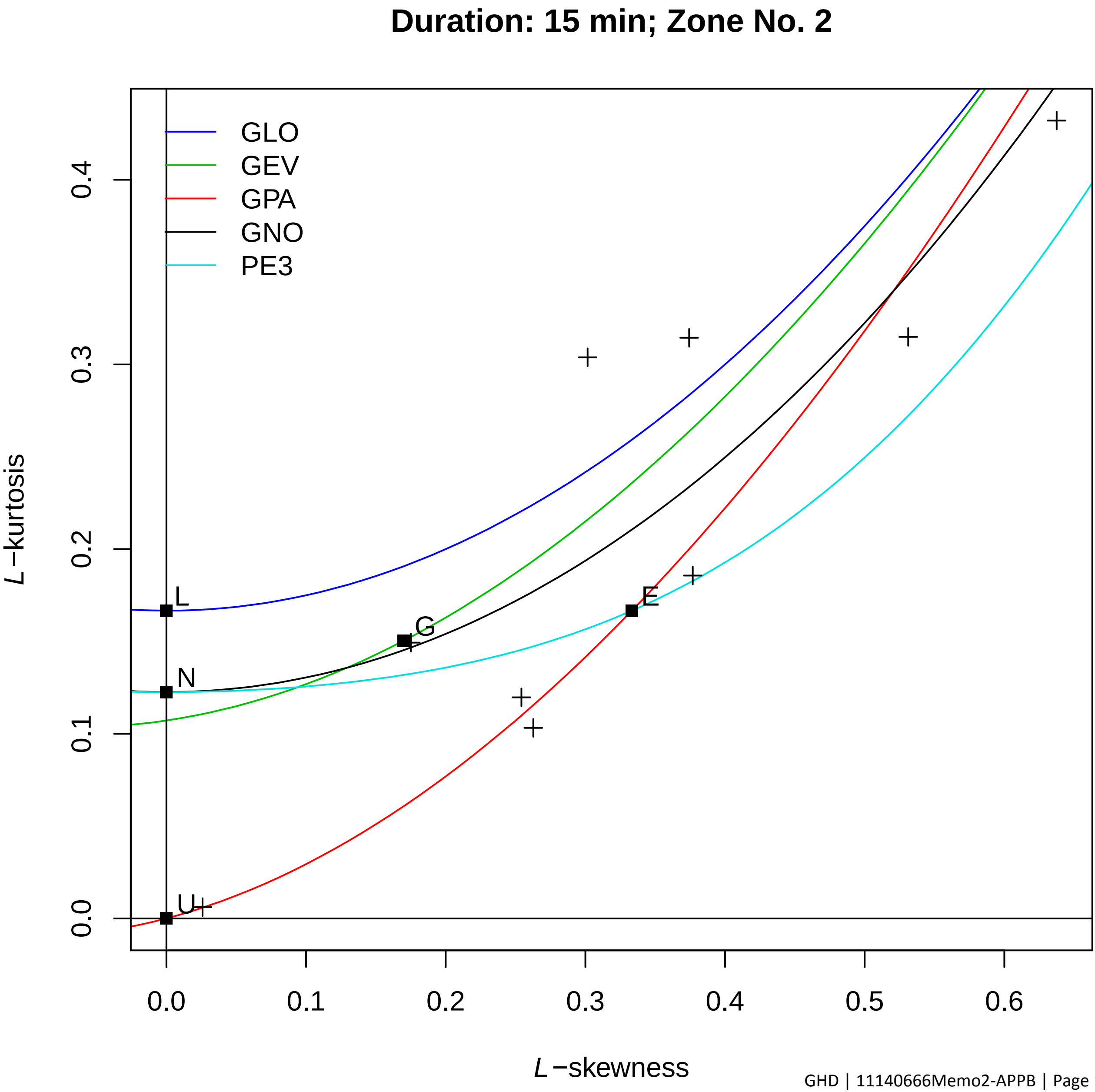
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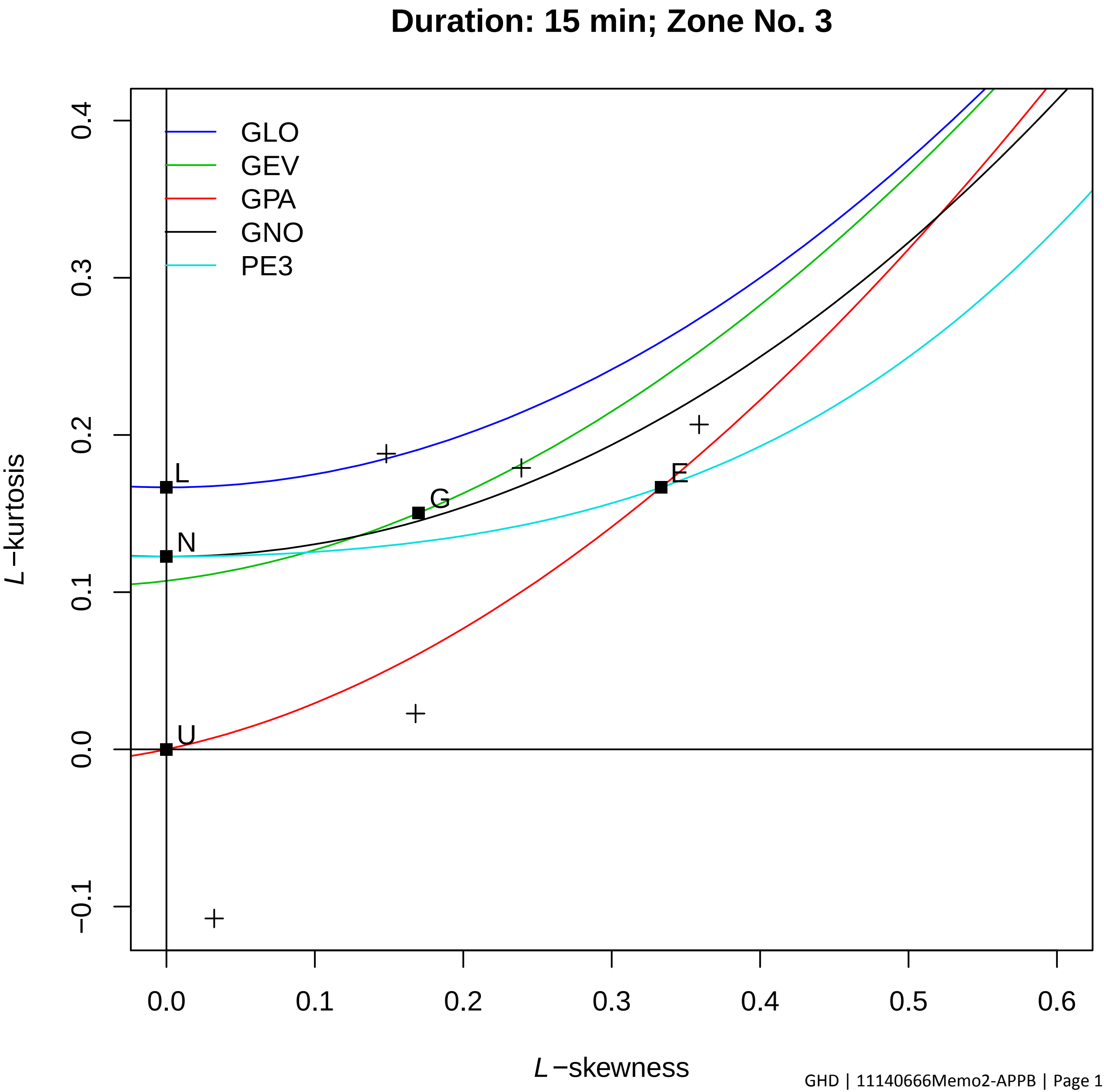
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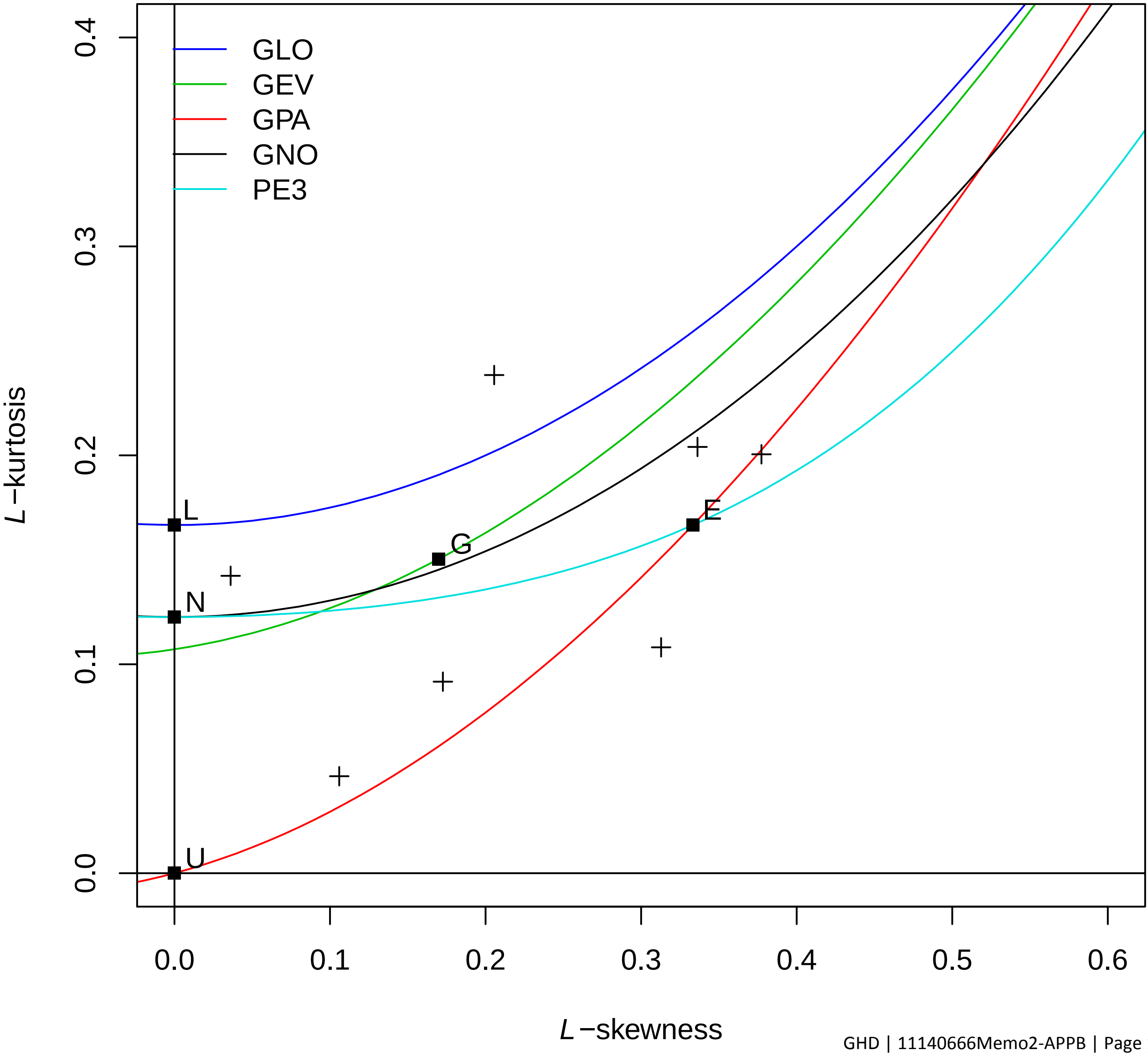

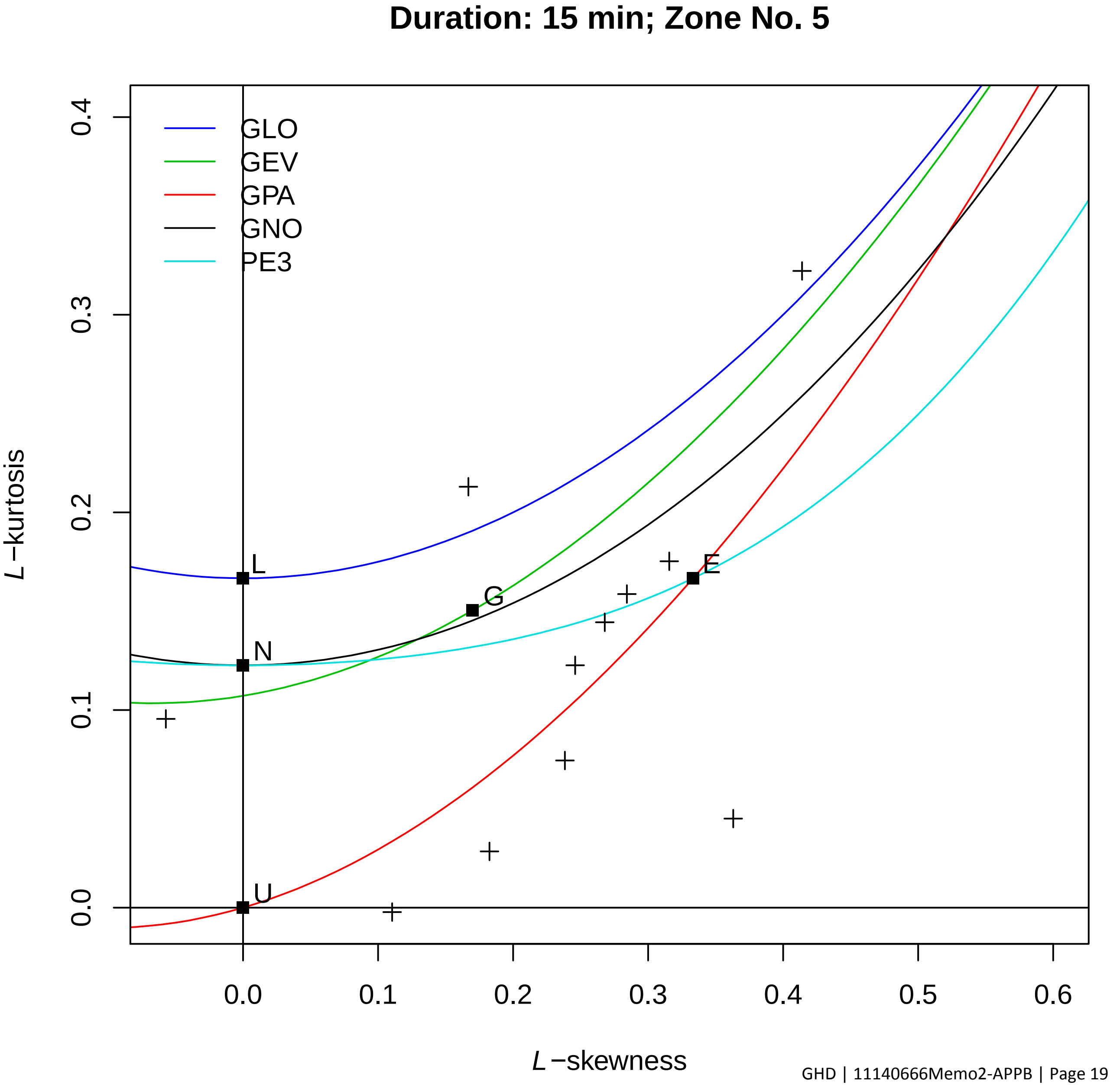
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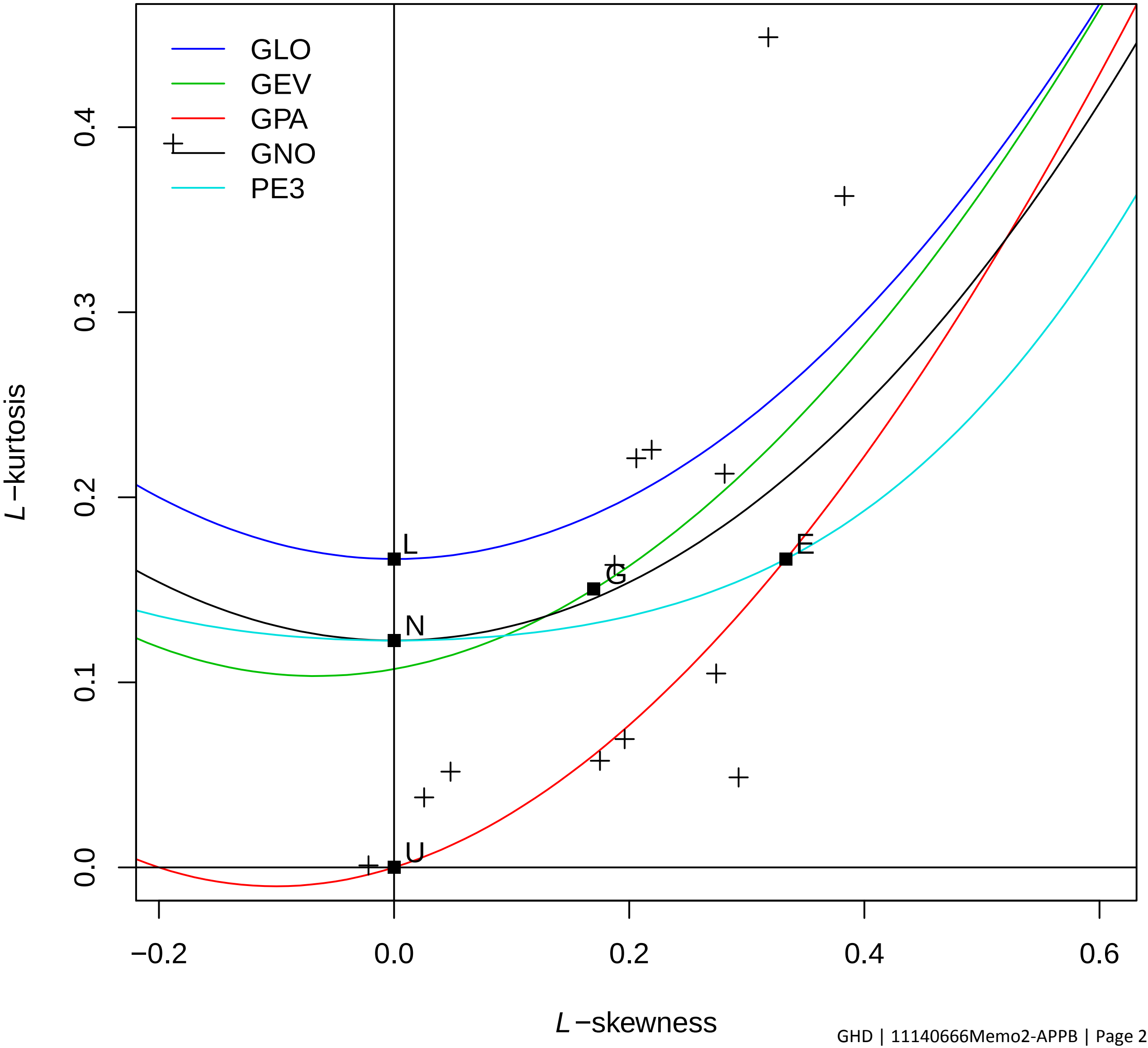

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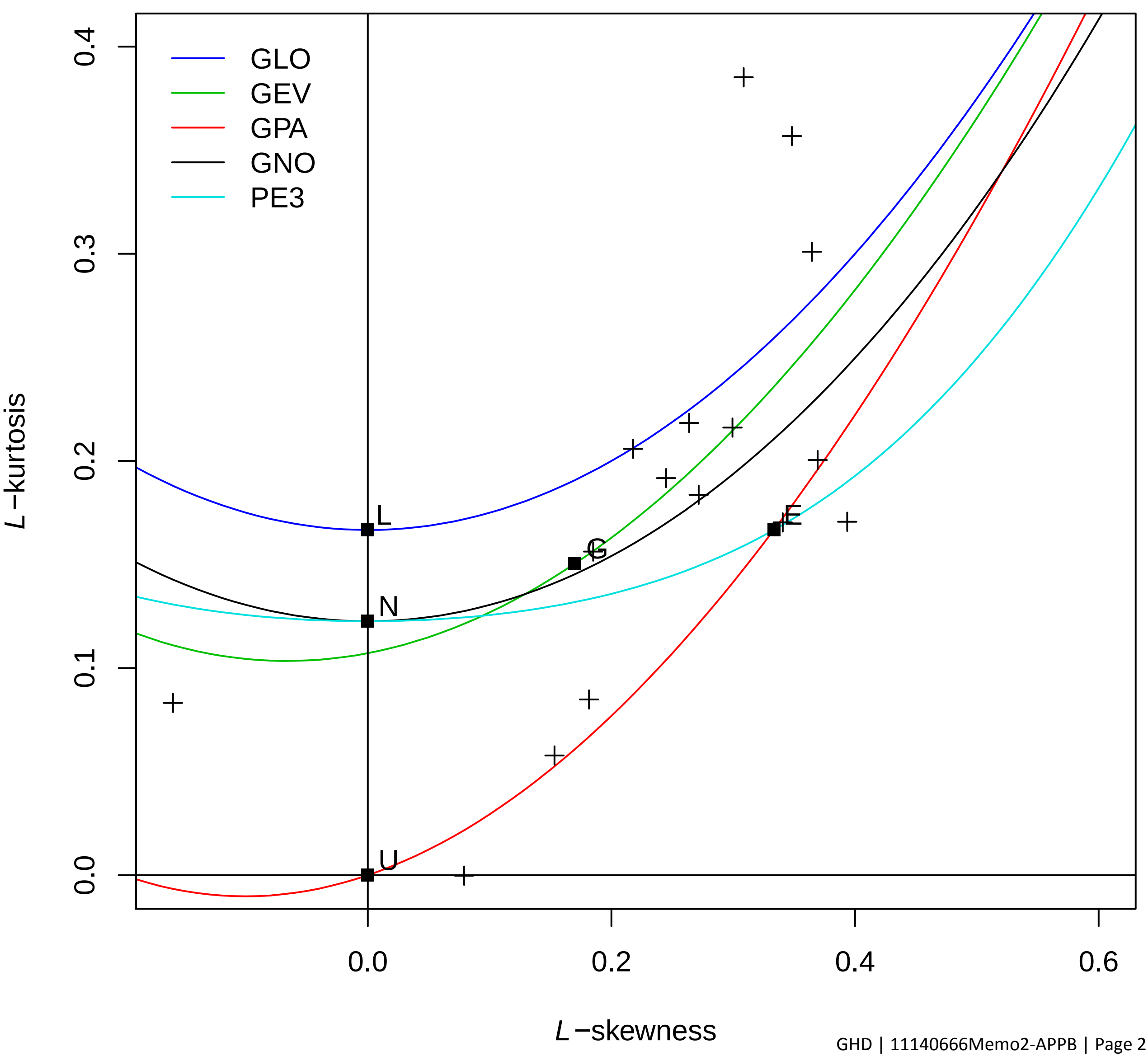

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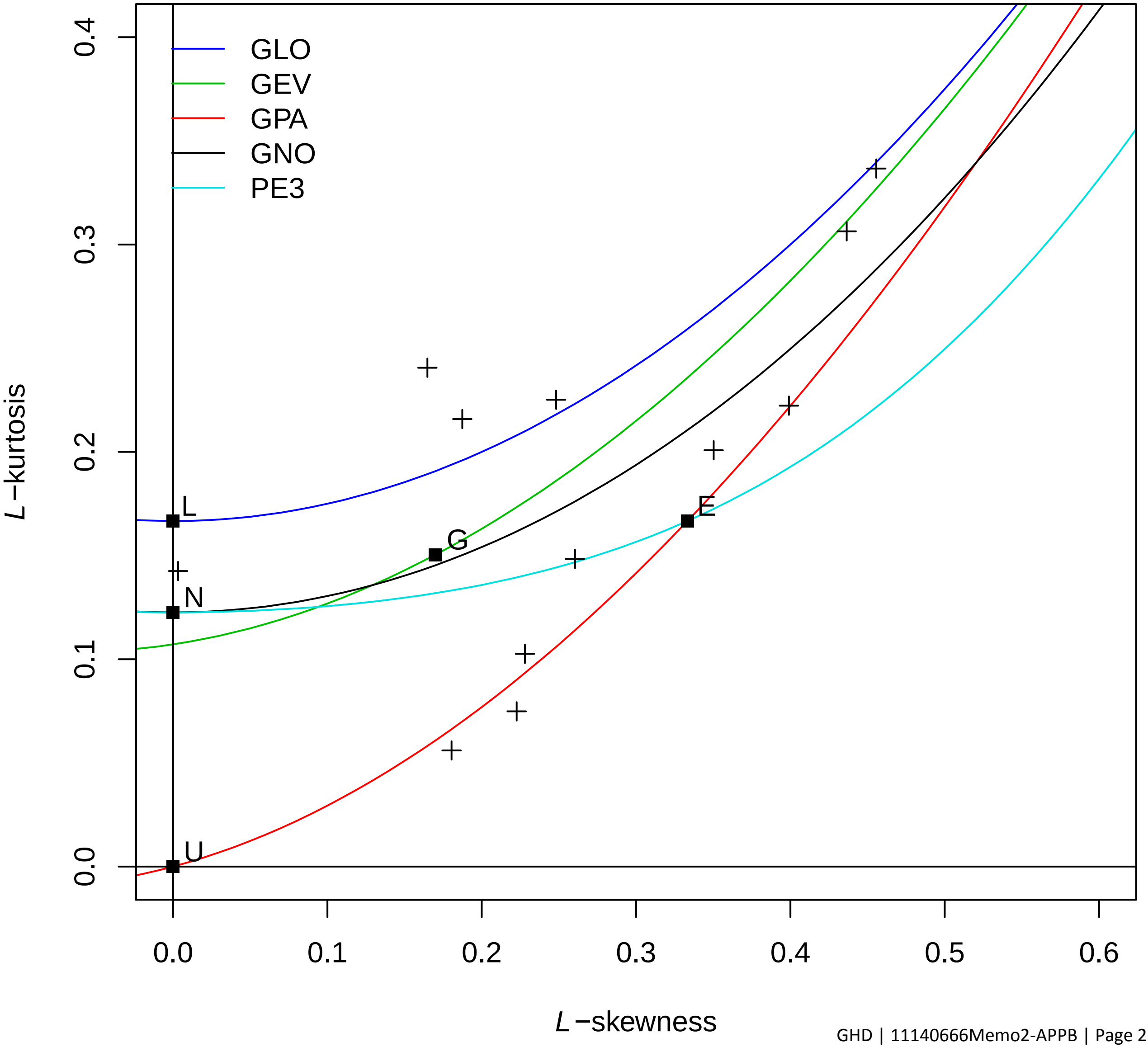

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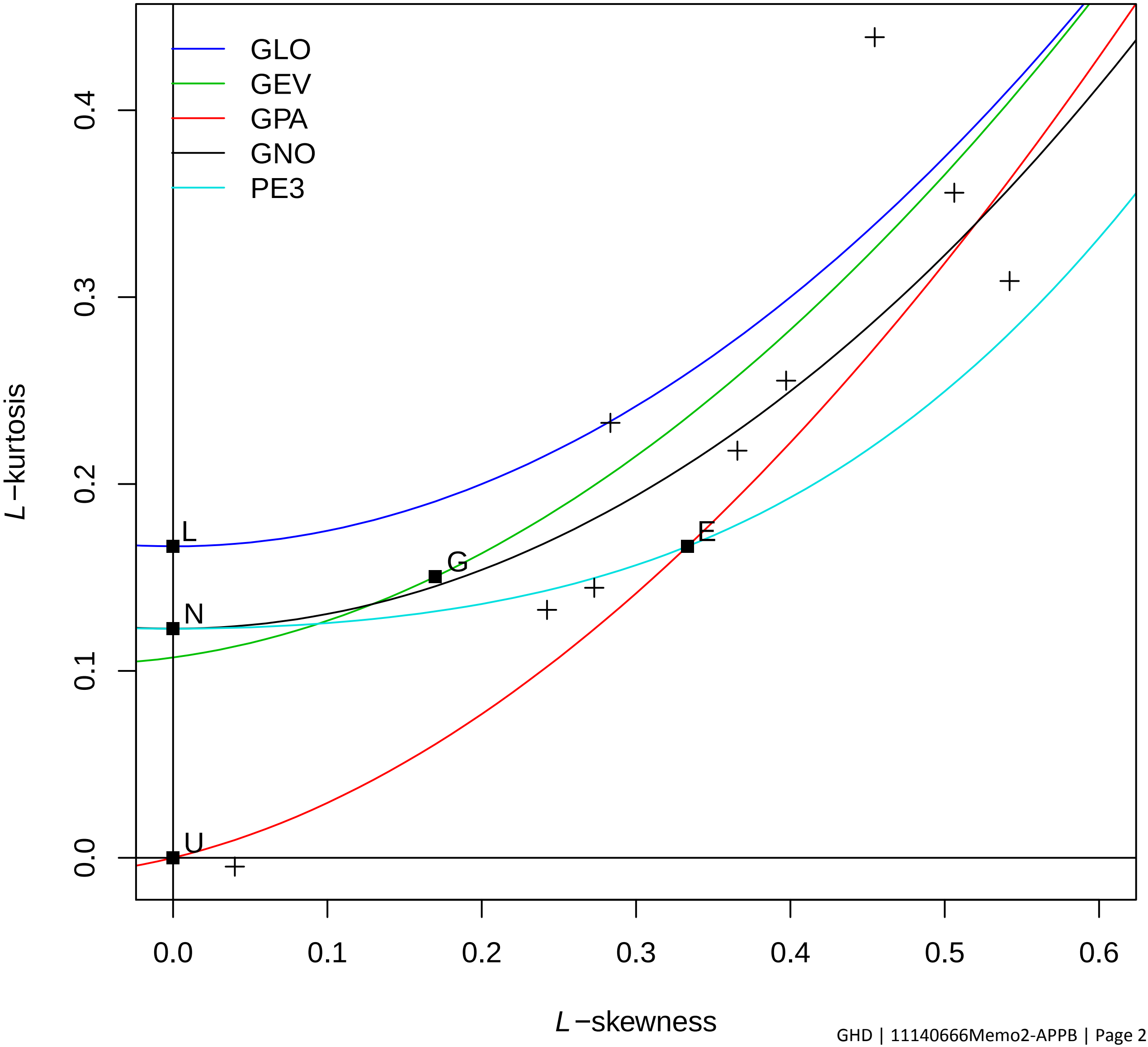

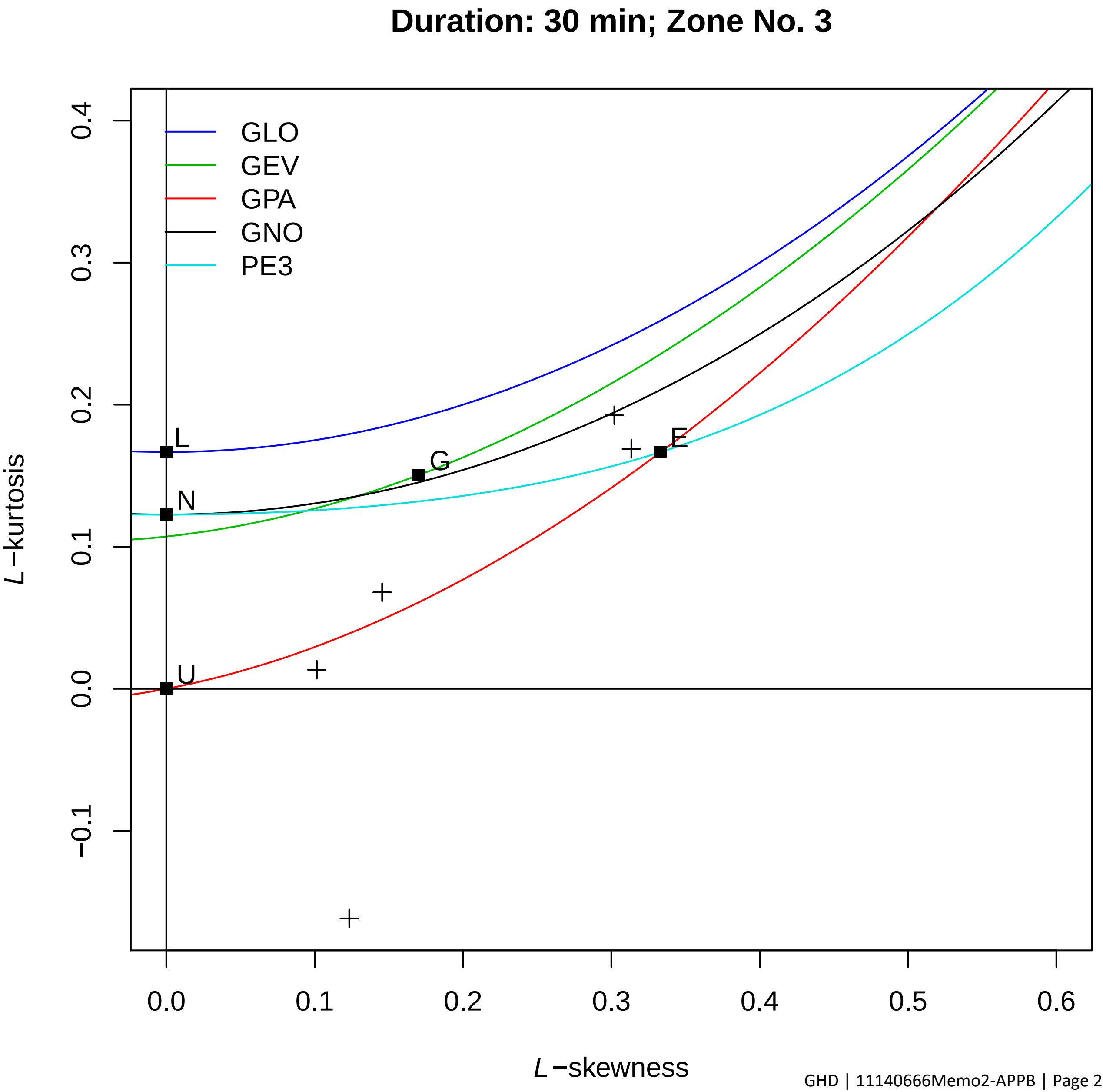
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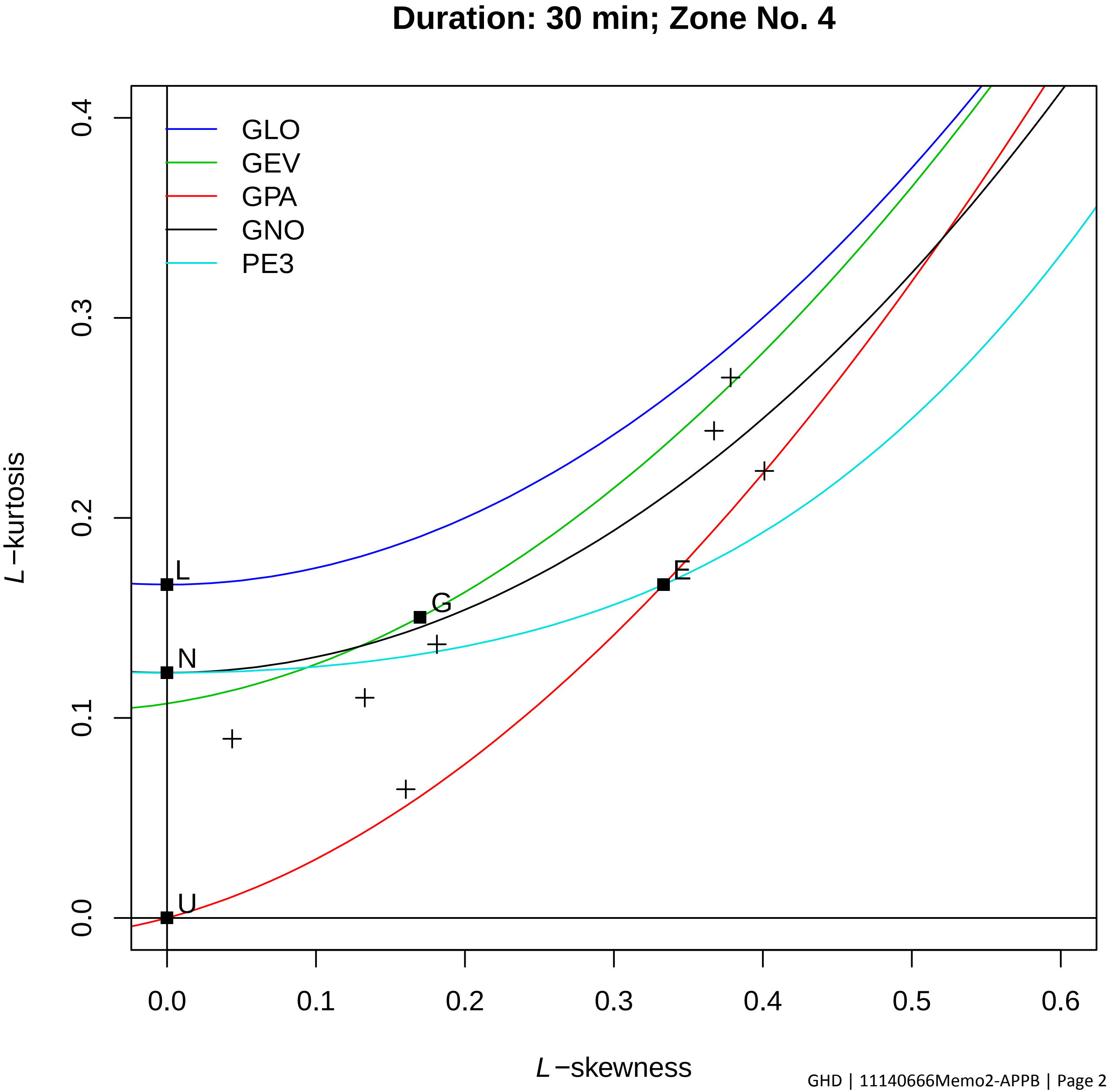
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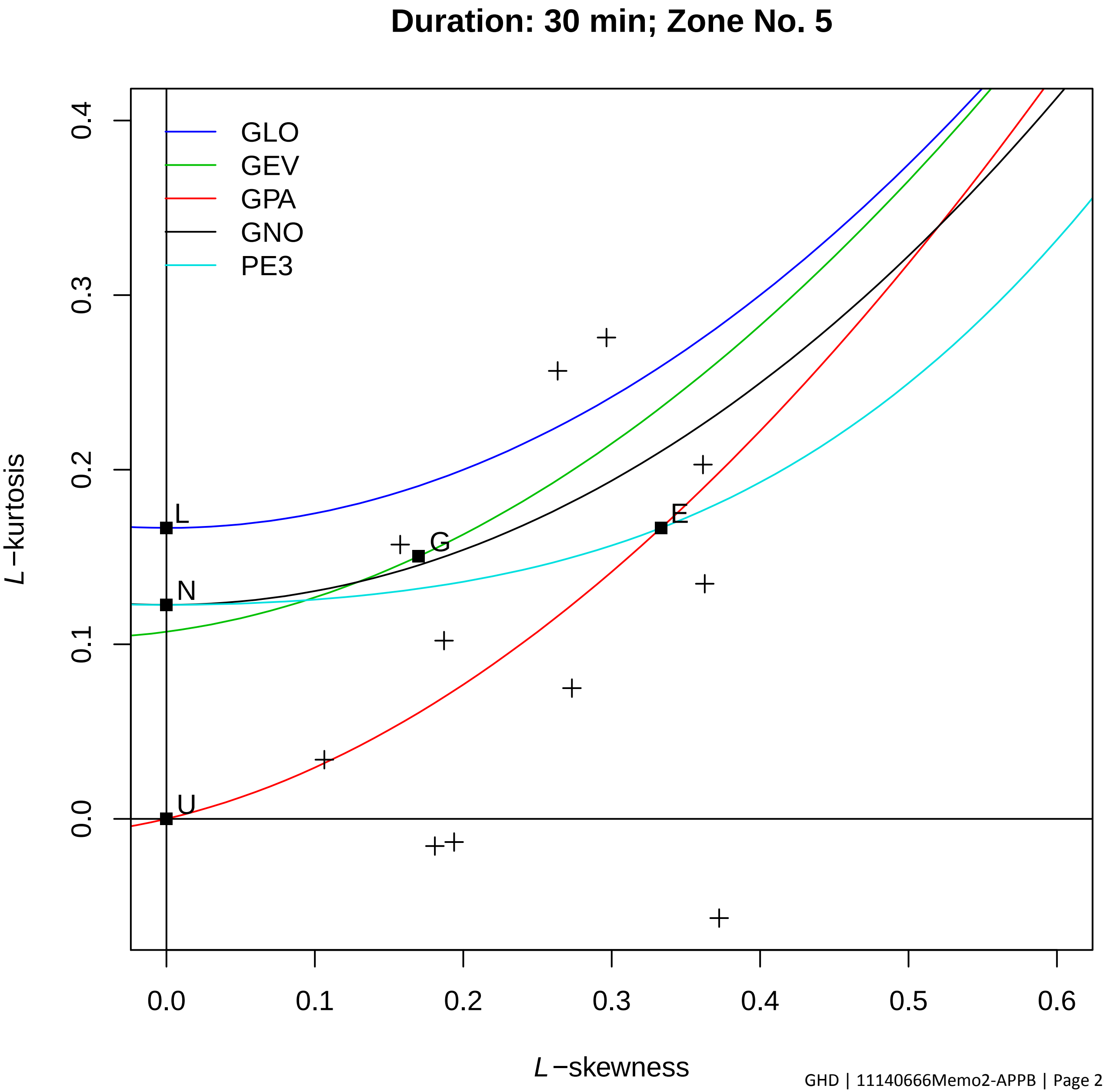
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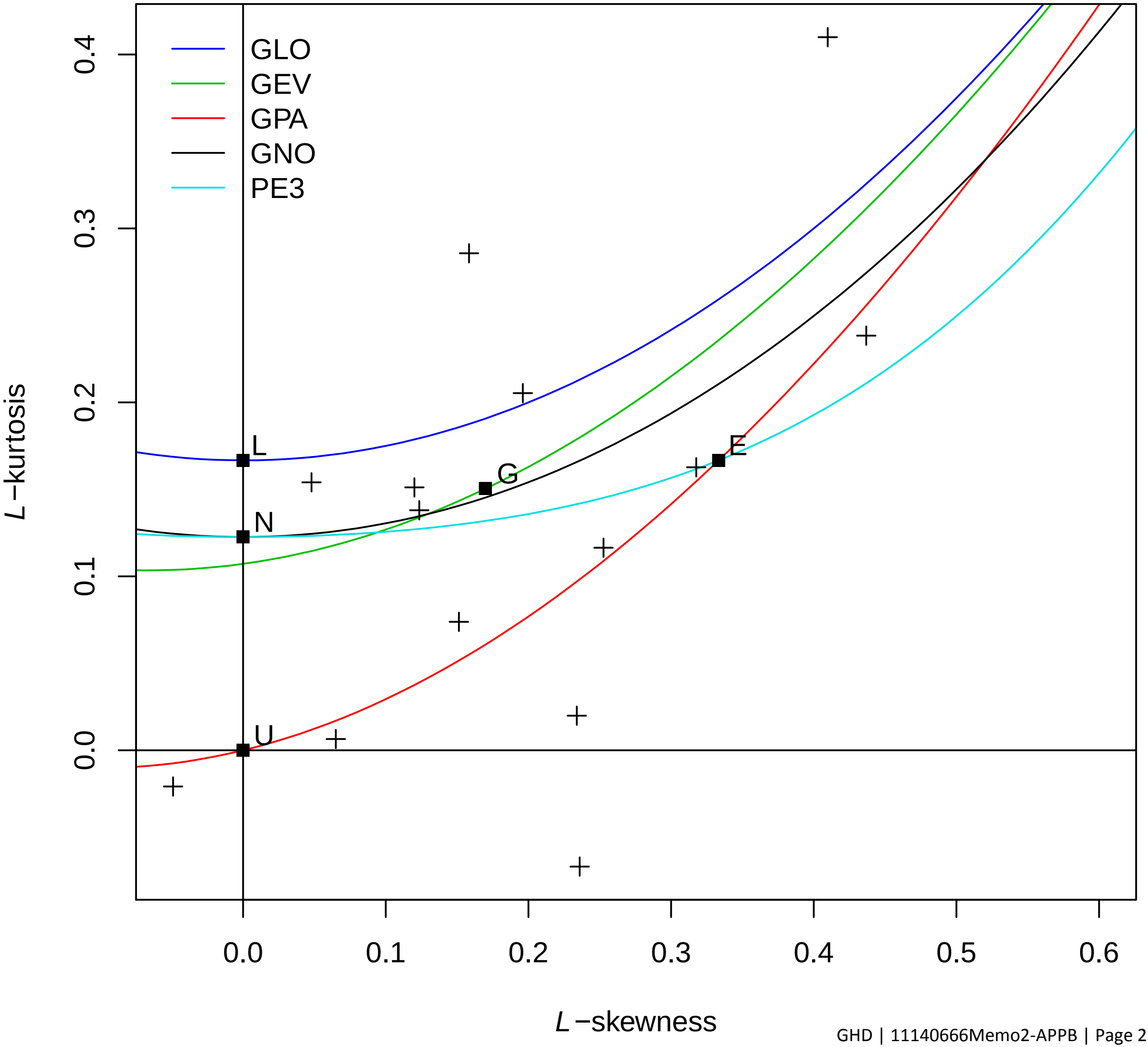

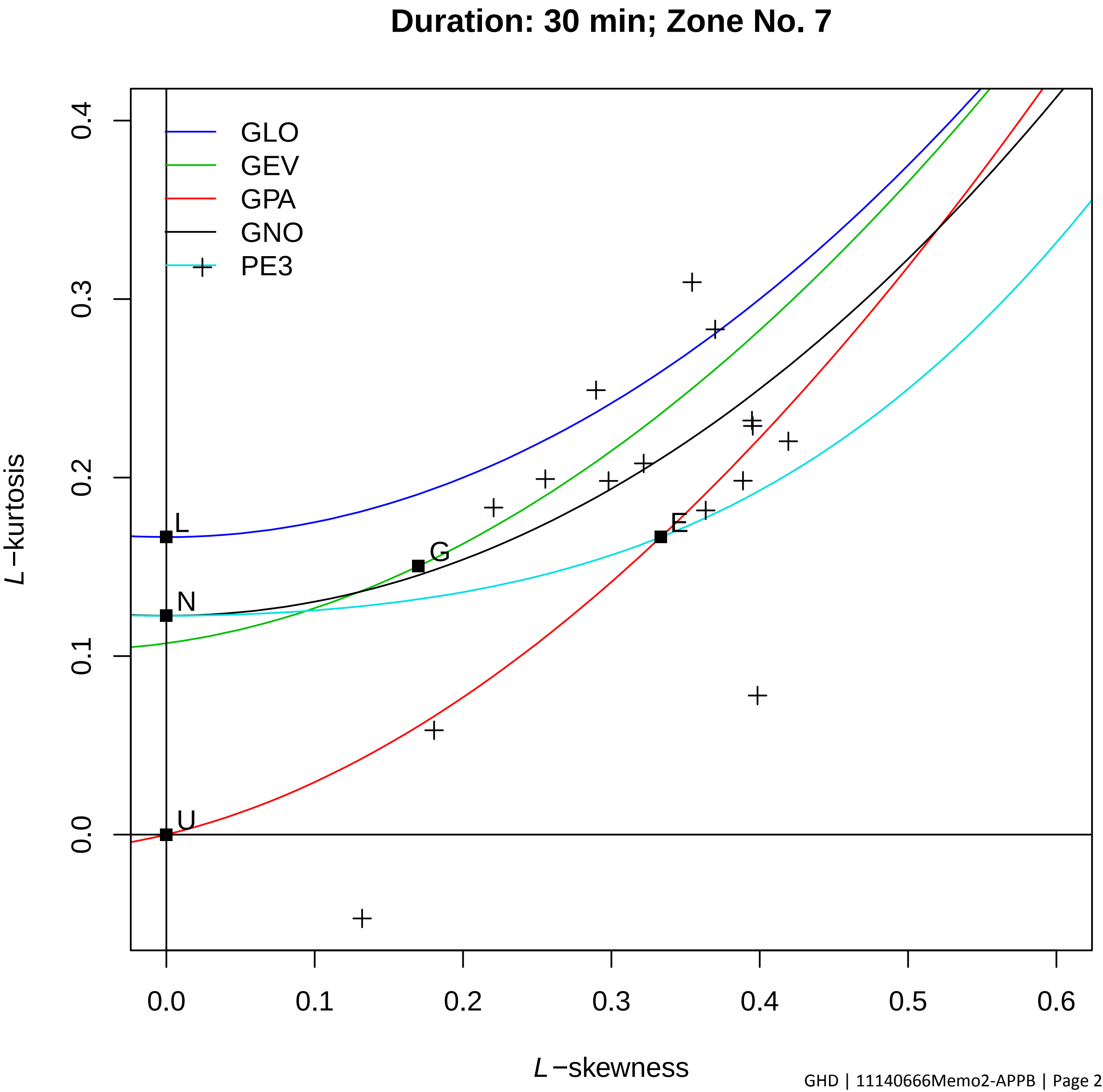
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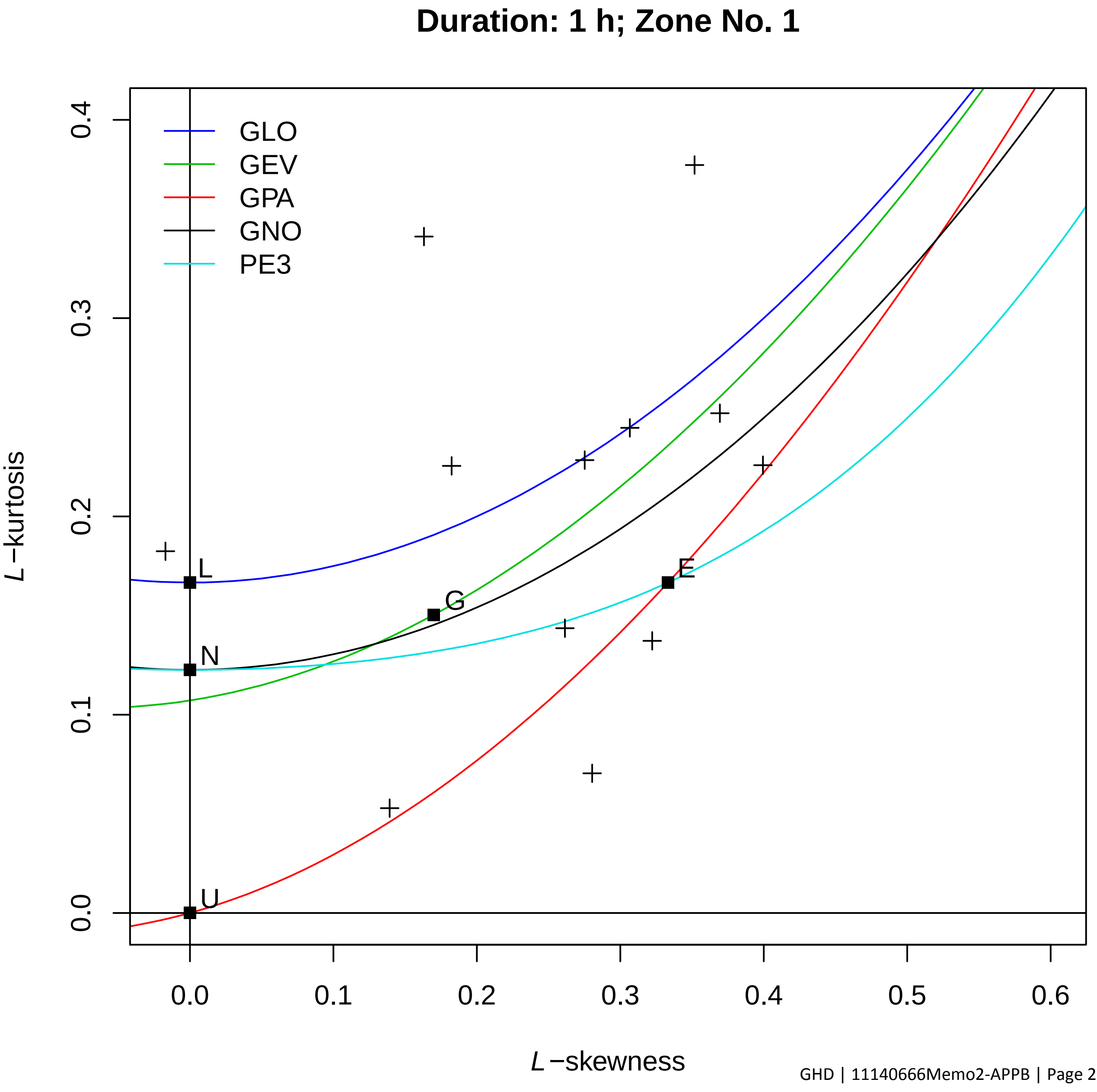
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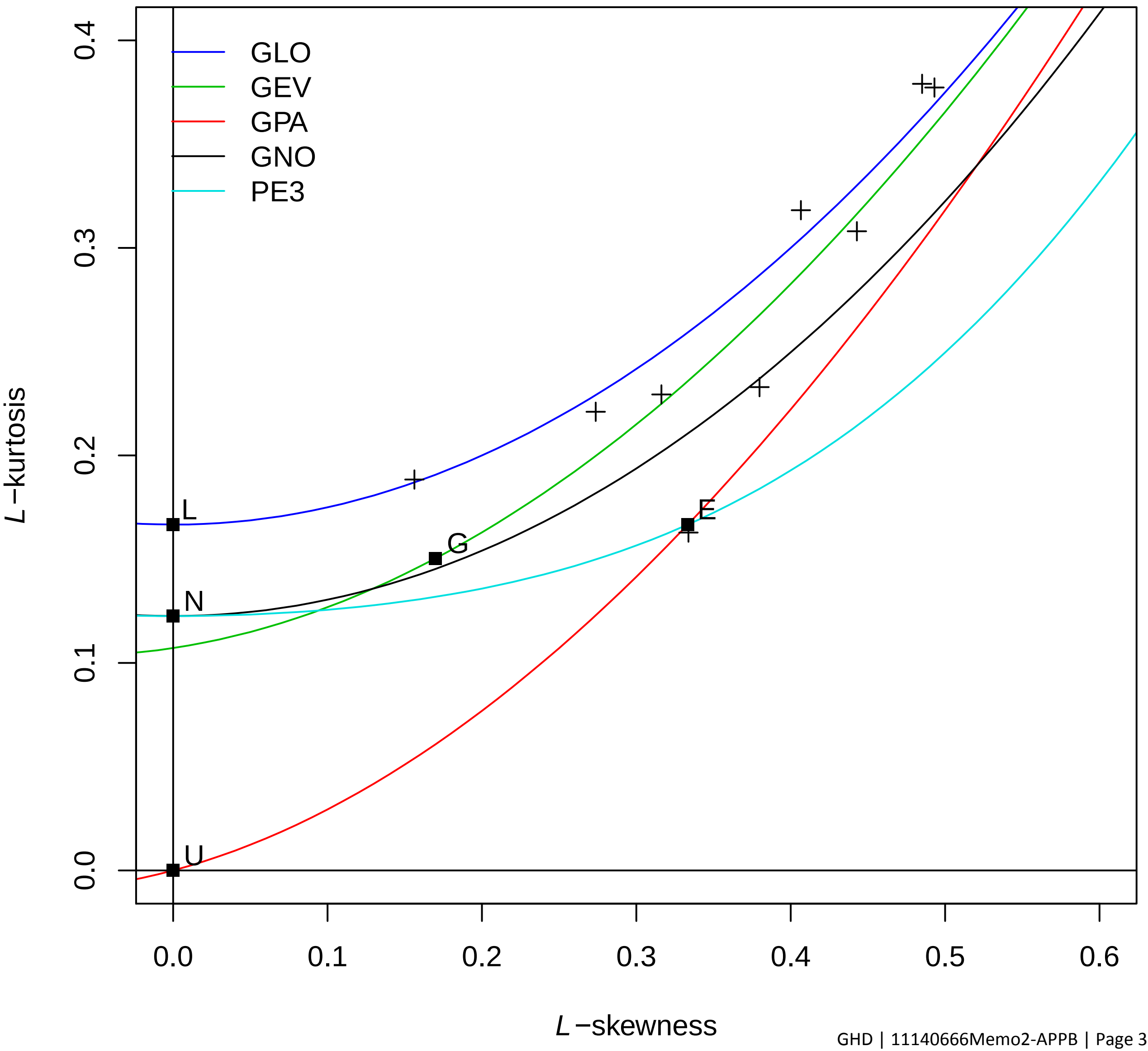

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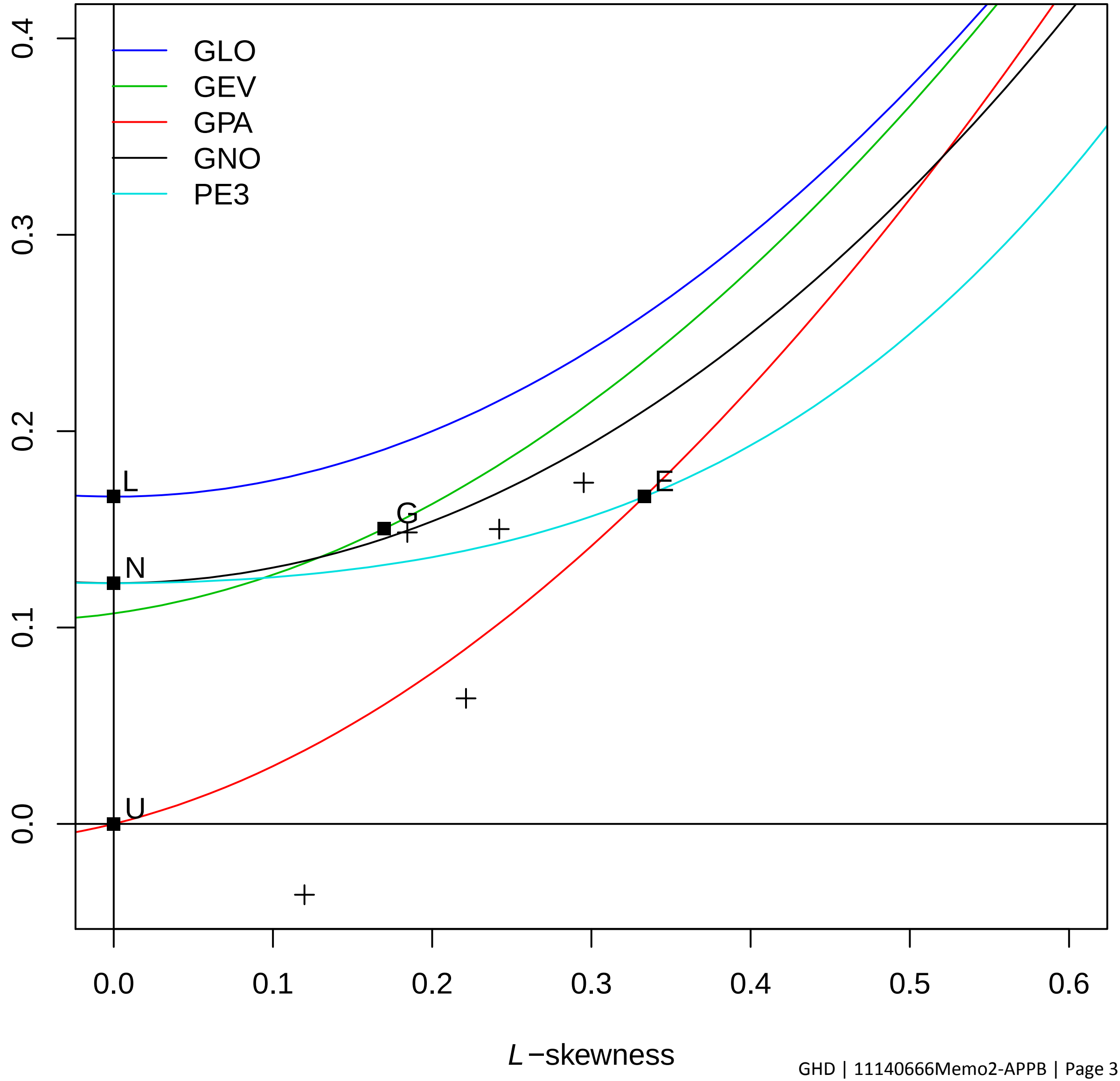

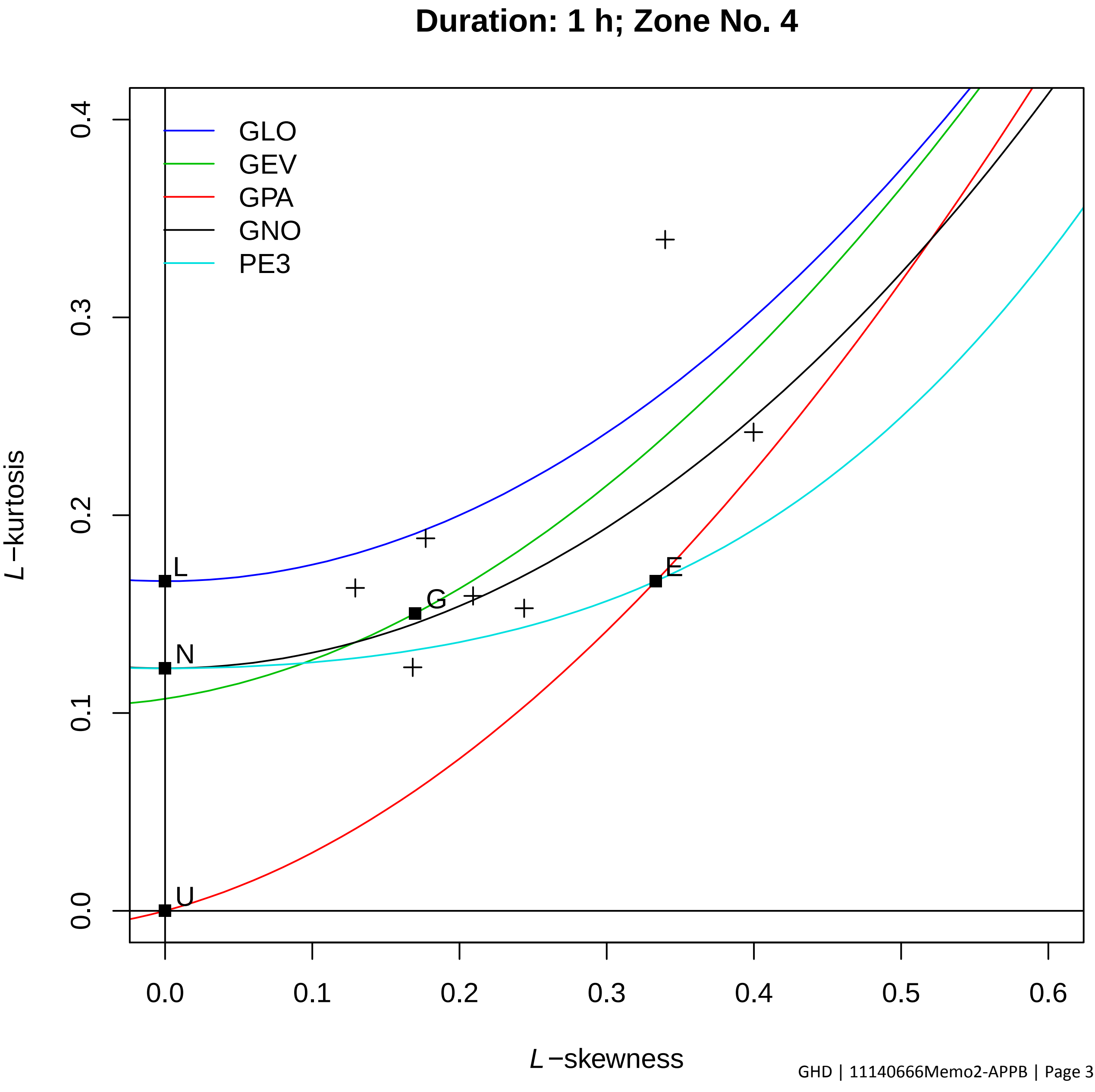
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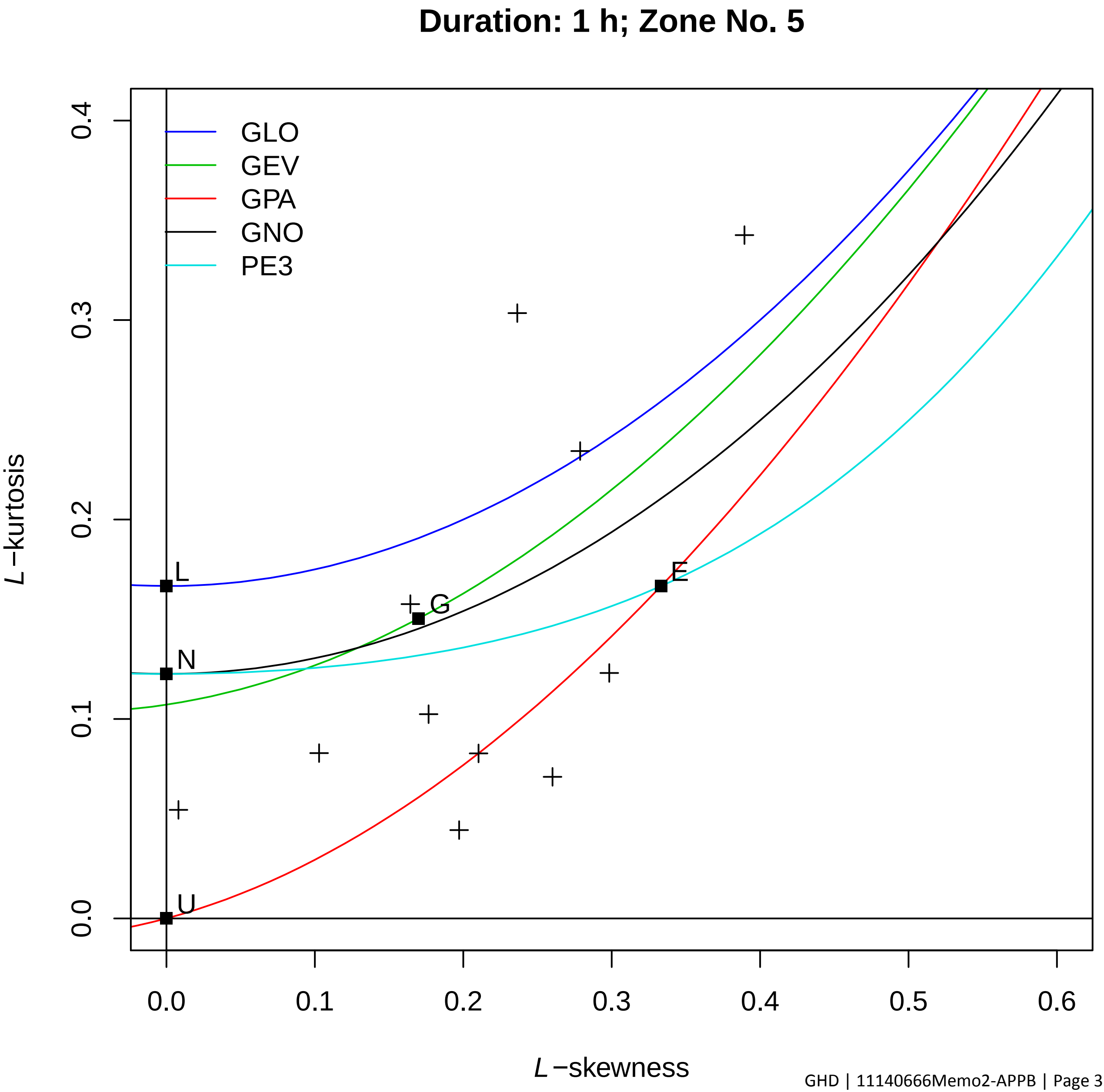
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PE3
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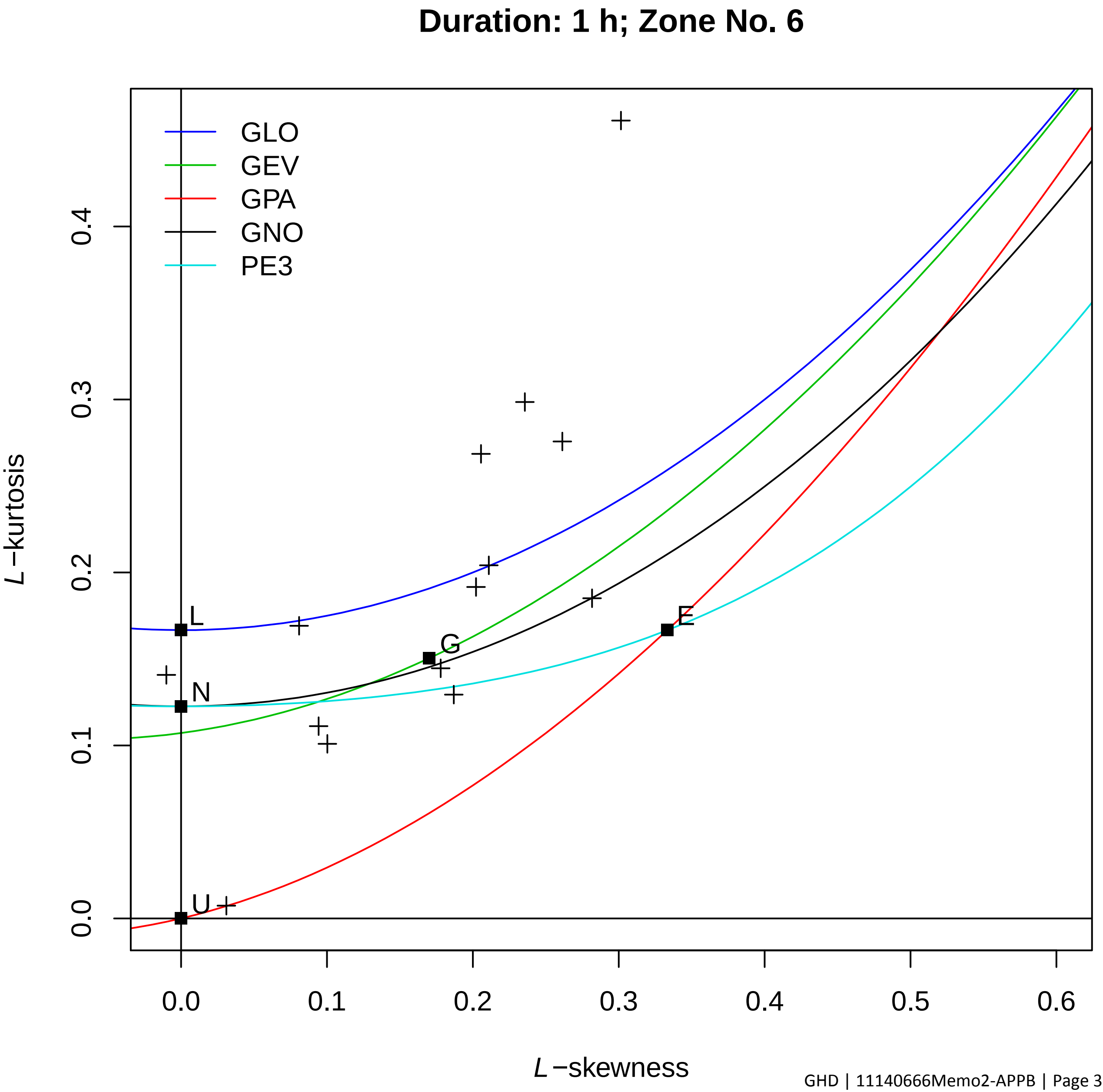
0.5
0.6
L −skewness
L −kurtosis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PE3
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G
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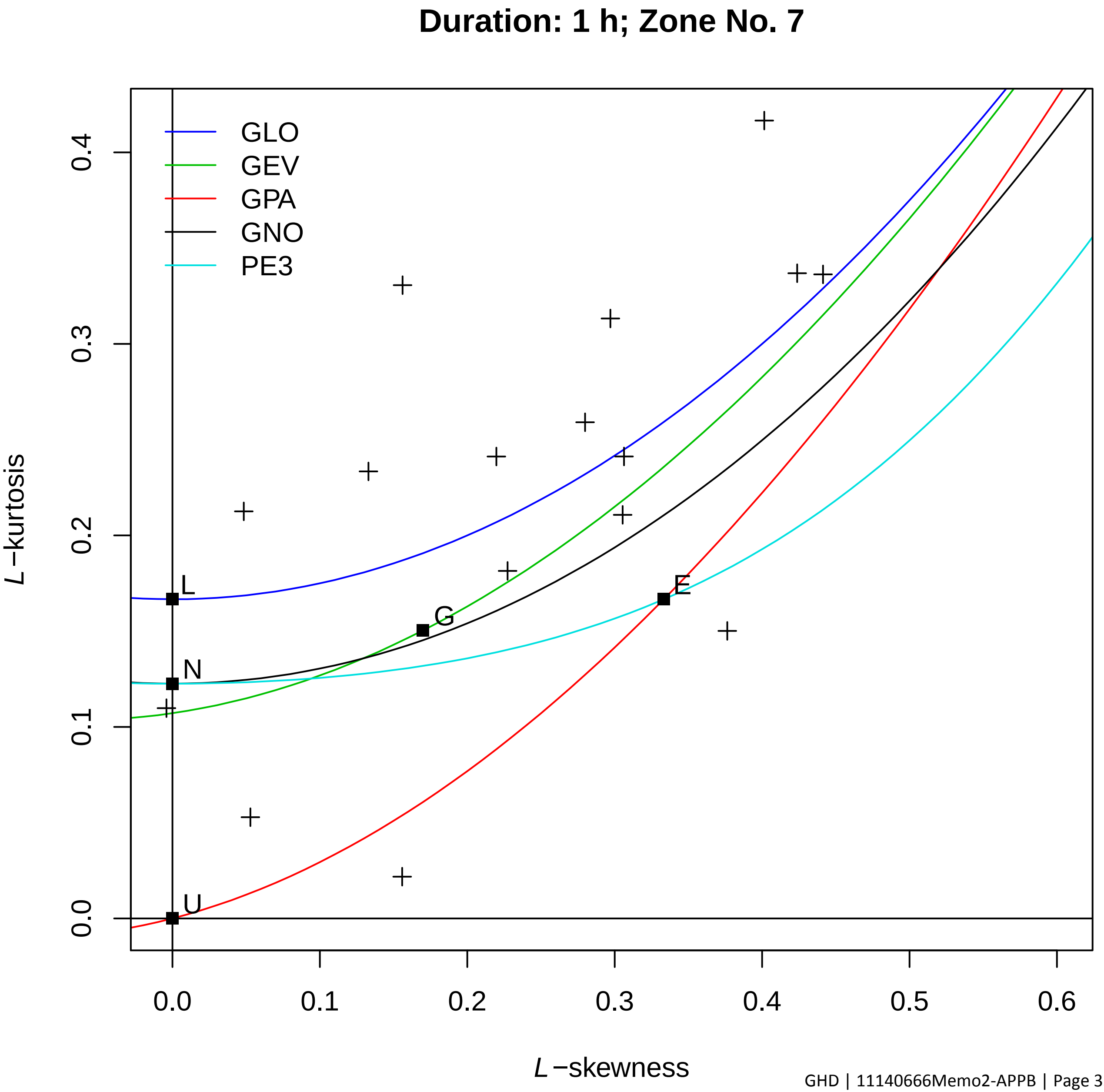
0.0
0.1
0.2
0.3
0.4
0.5
0.6
L −kurtosis
L −skewness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PE3
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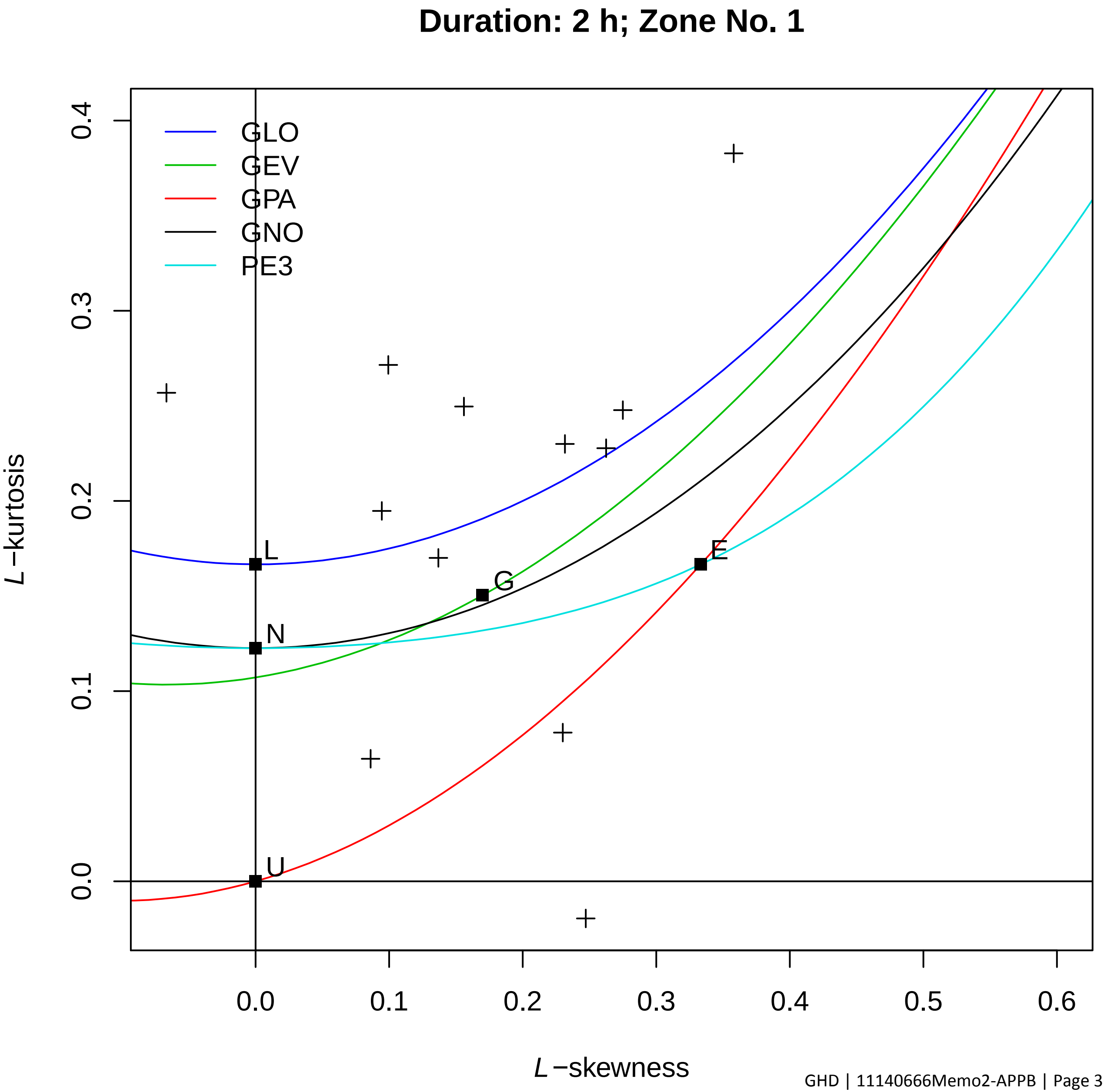
0.4
0.5
0.6
L −skewness
L −kurtosis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PE3
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G
E
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0.3
0.4
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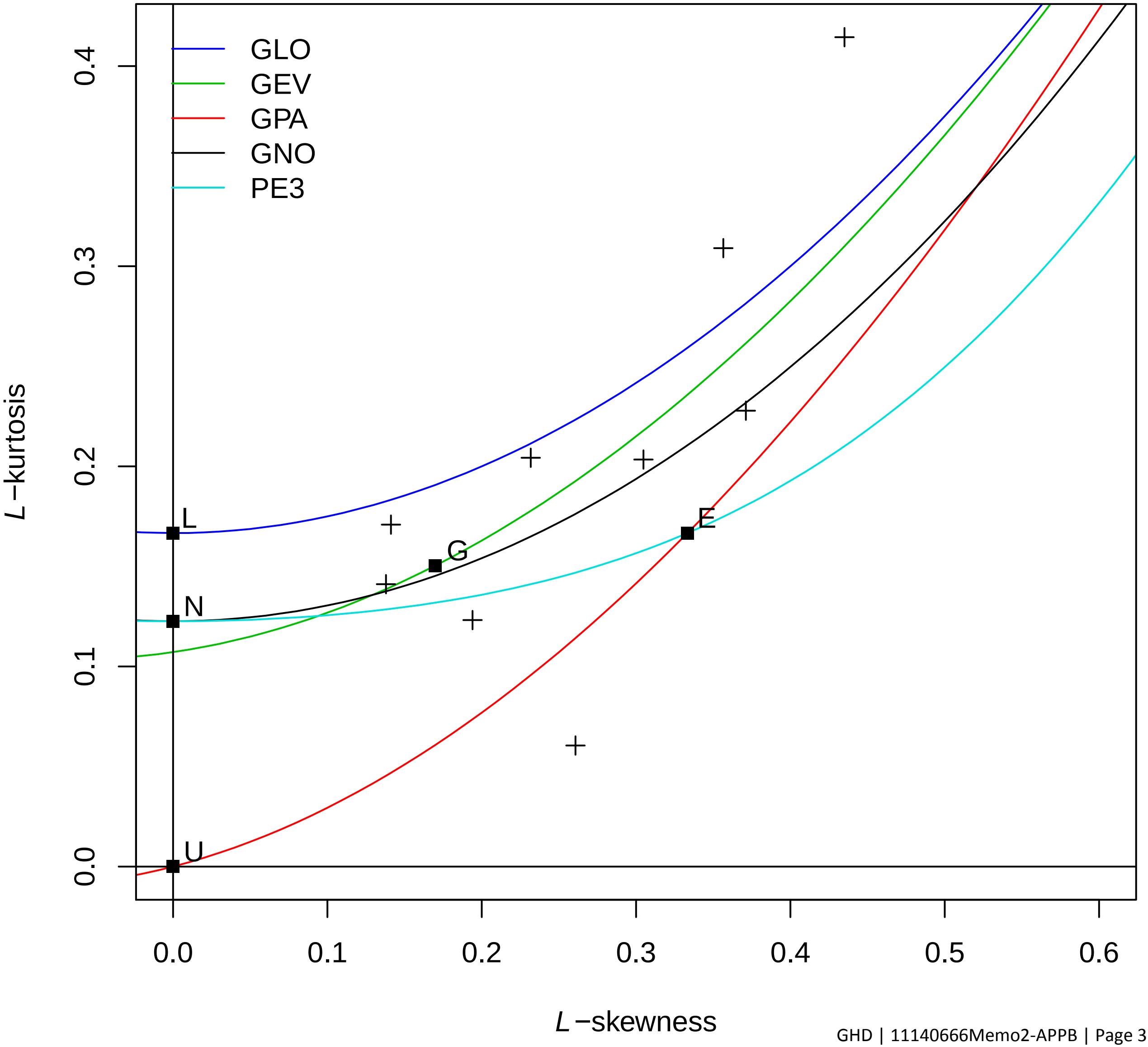
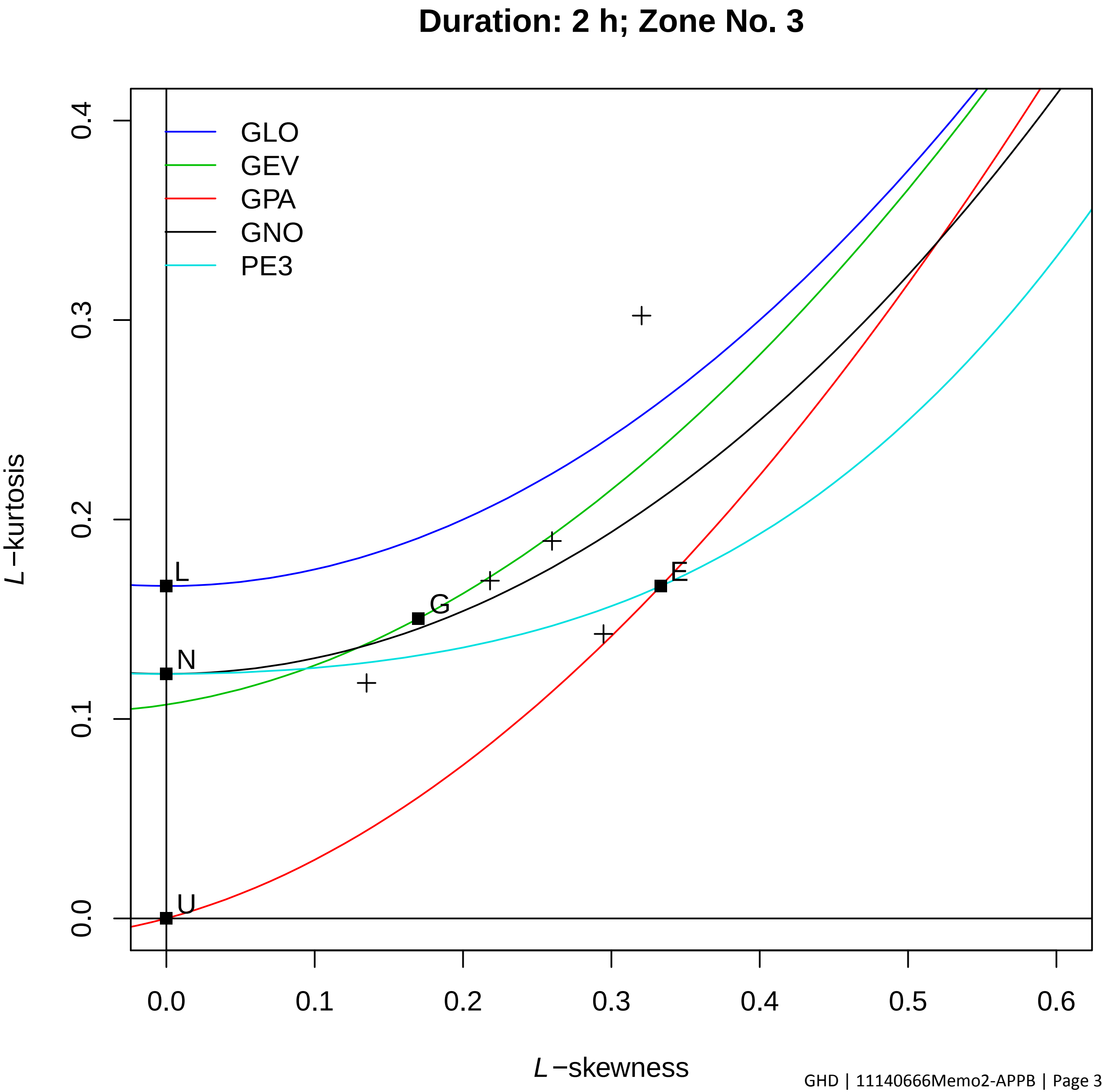
0.1
0.2
0.3
0.4
0.5
0.6
L −kurtosis
L −skewness

Duration: 2 h; Zone No. 2

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GNO
PE3
L
N
G
E
U
L −kurtosis
L −skewness
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0.1
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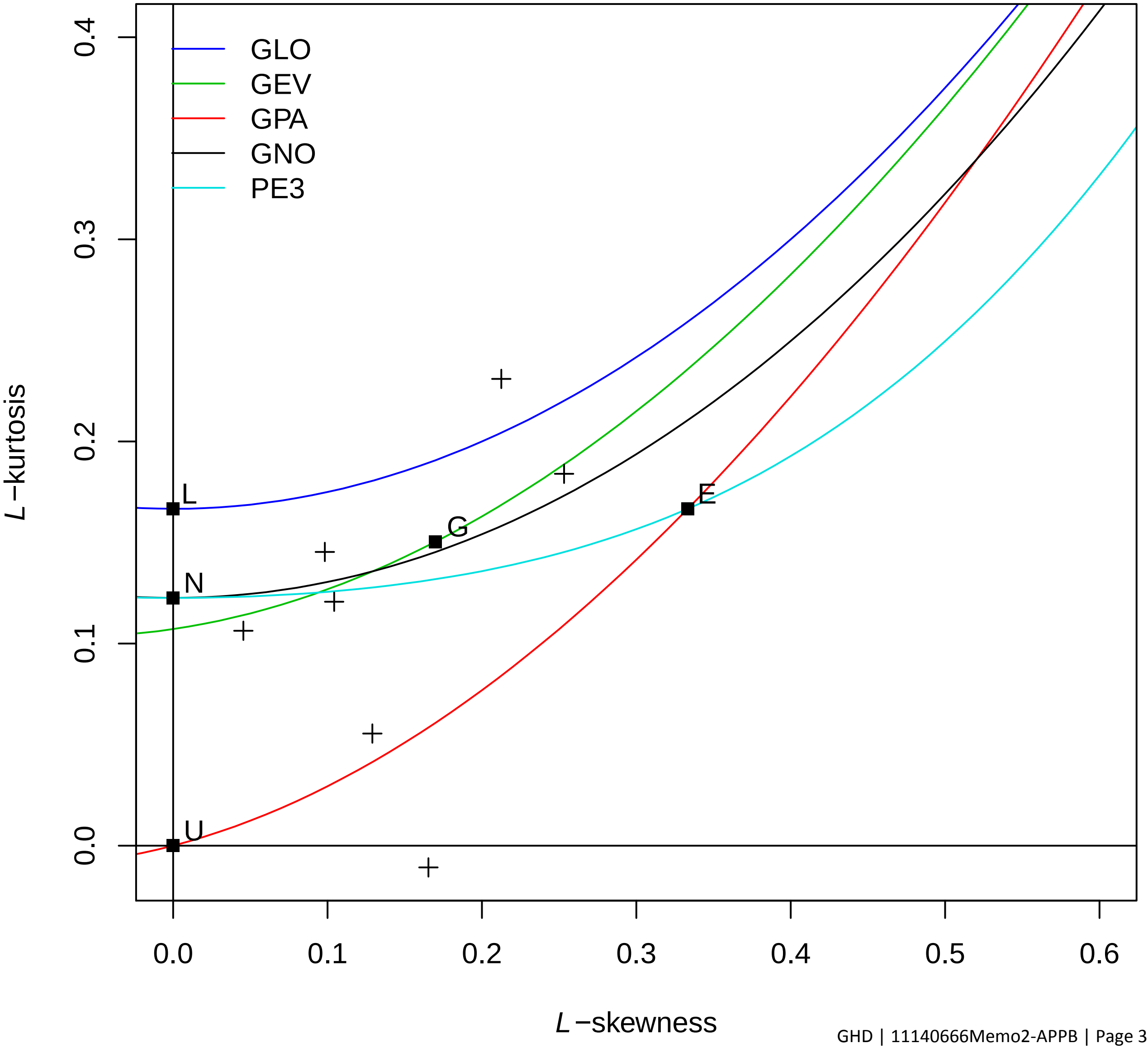
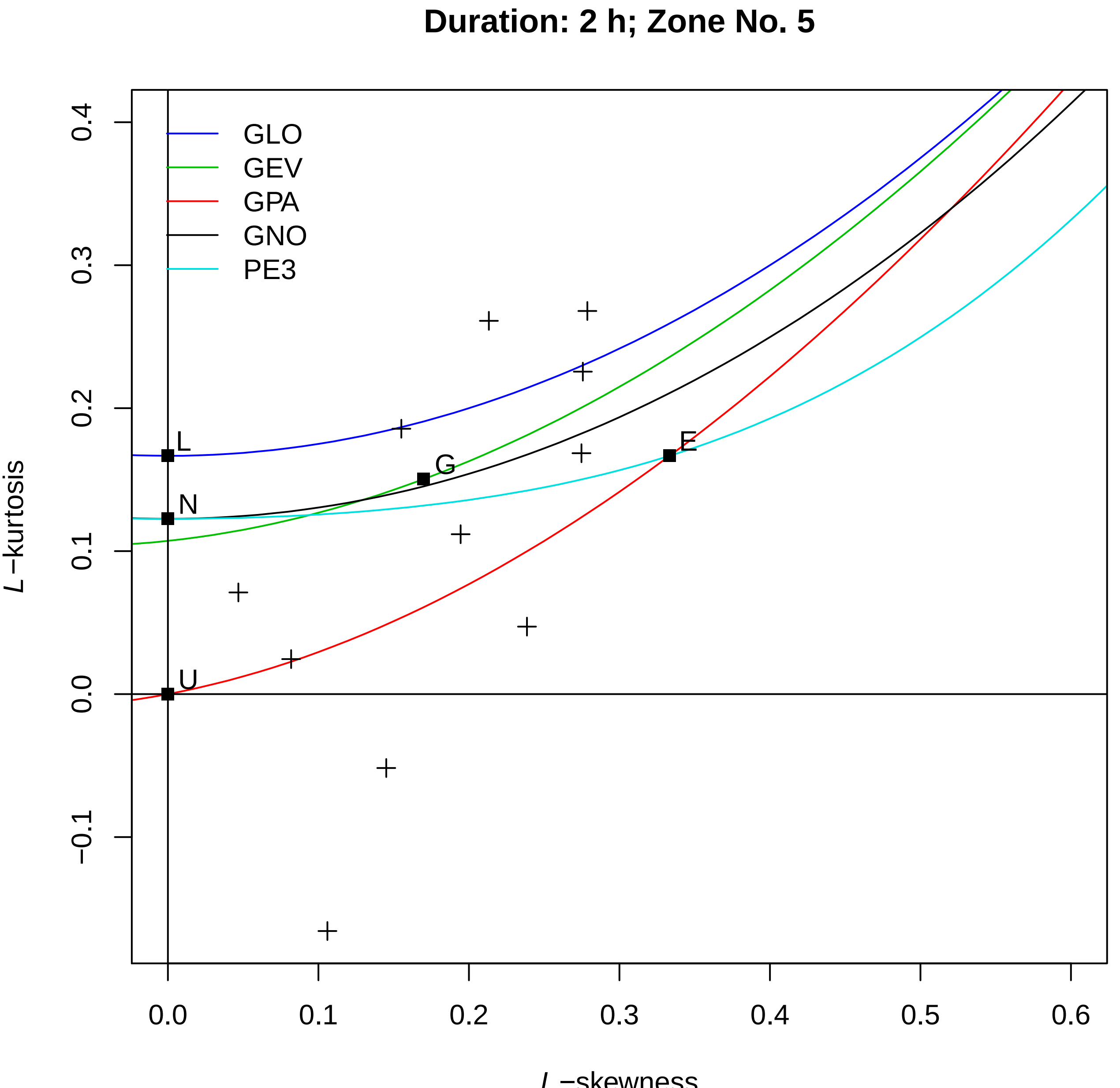
0.0
0.1
0.2
0.3
0.4
0.5
0.6

Duration: 2 h; Zone No. 4

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G
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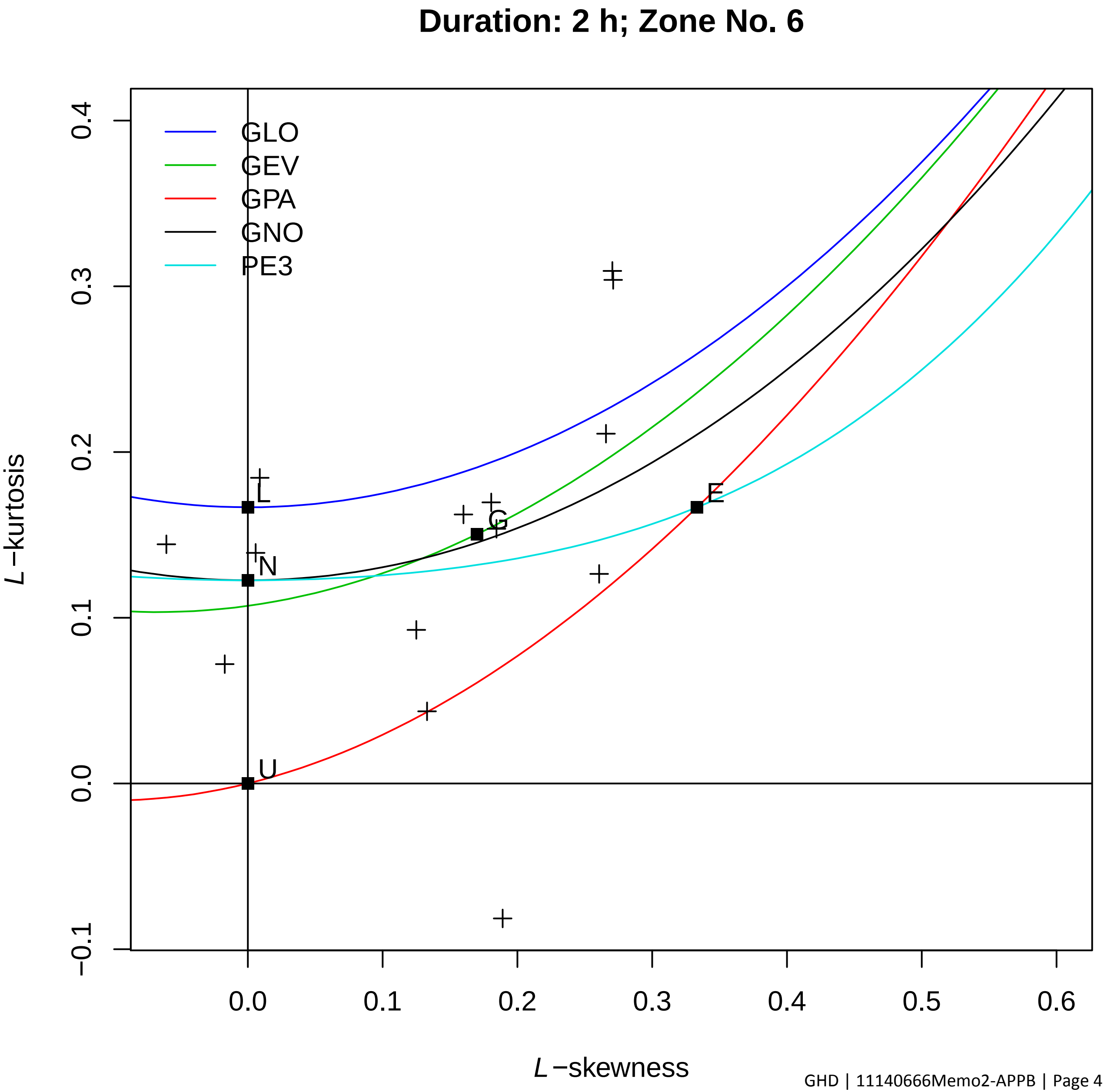
0.0
0.1
0.2
0.3
0.4
0.5
0.6
L −kurtosis
L −skewness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PE3
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G
E
U
L −kurtosis
L −skewness
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0.2
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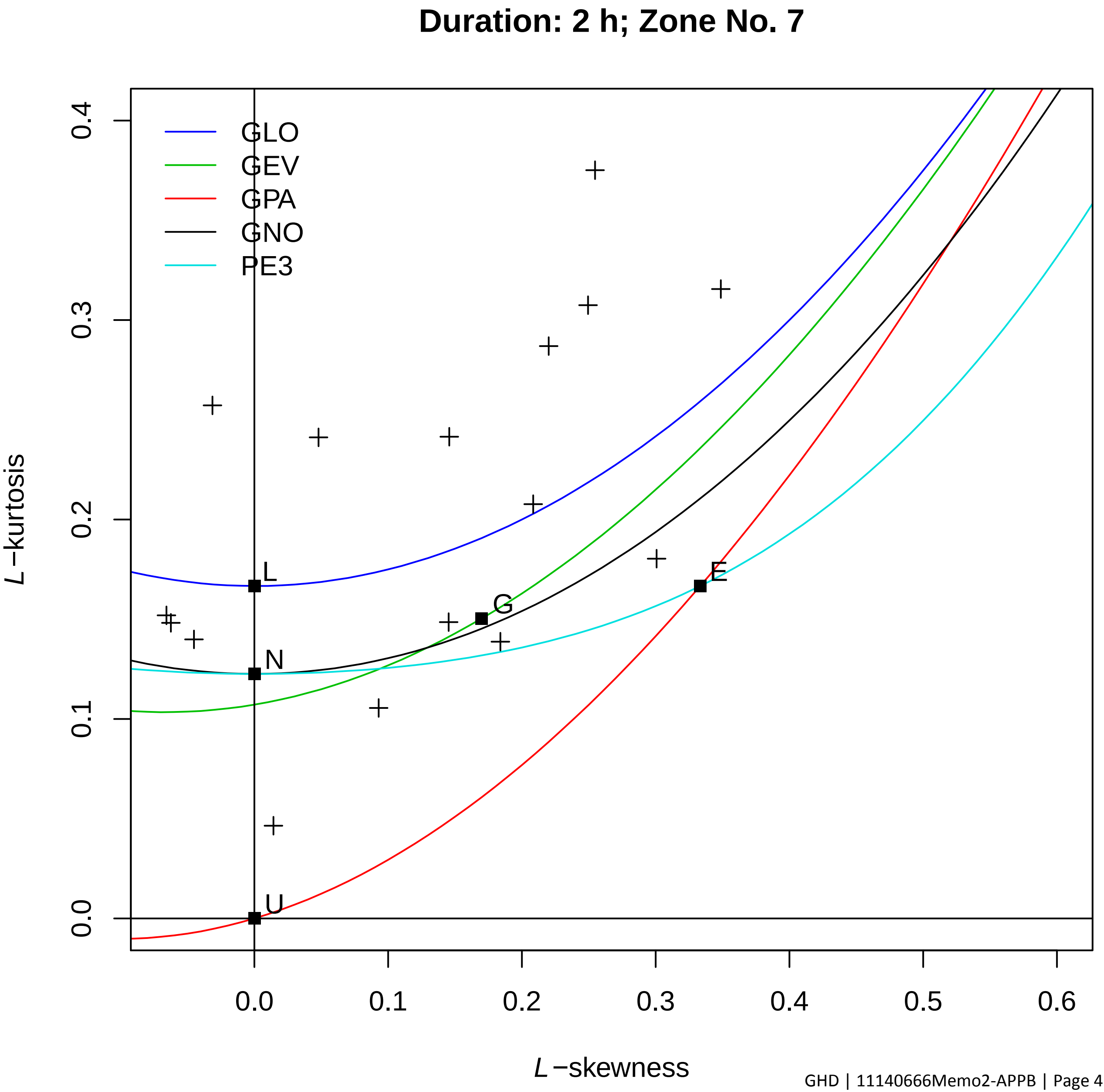
0.6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PE3
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G
N
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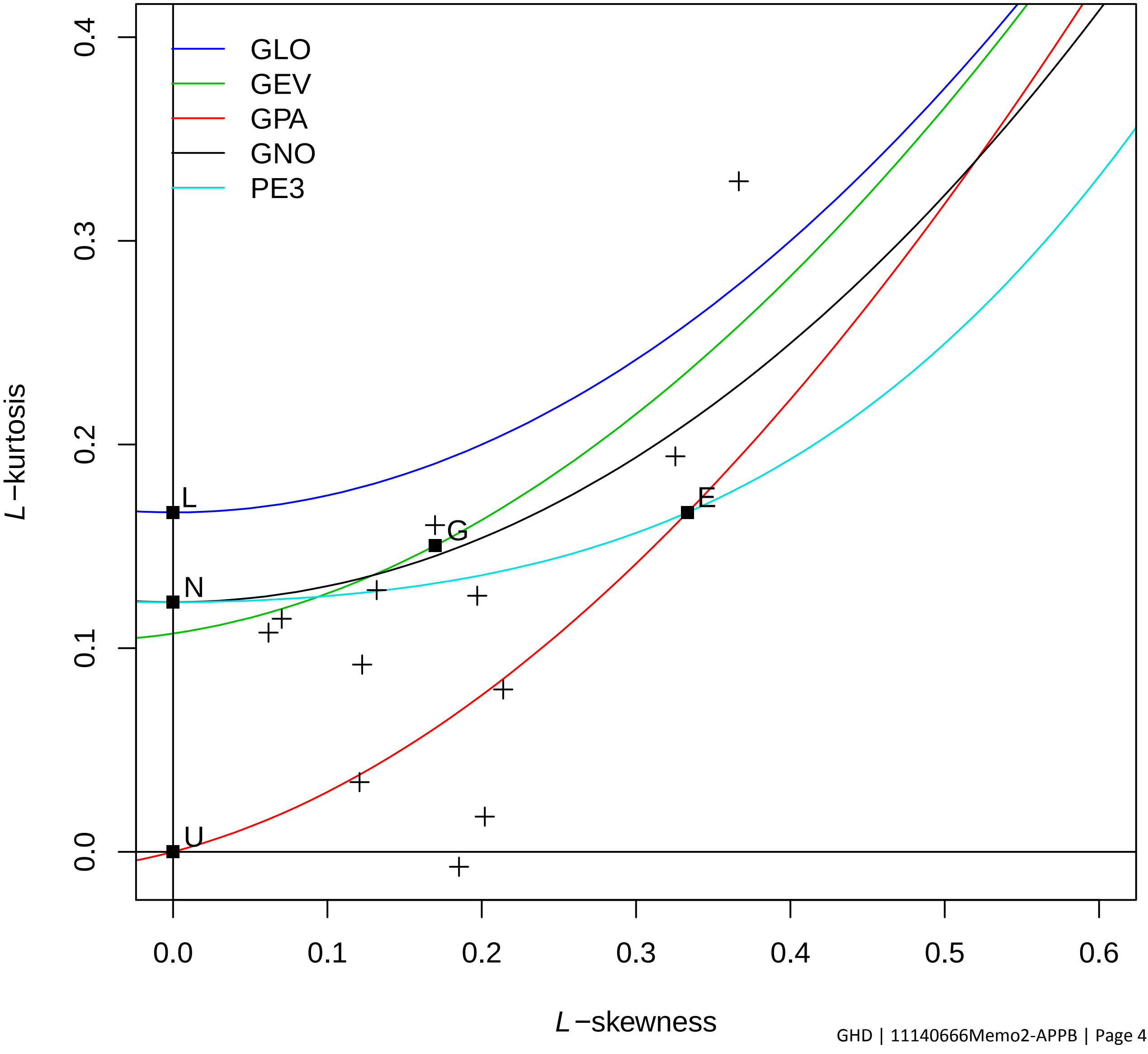
0.3
0.4
0.0
0.1
0.2
0.3
0.4
0.5
0.6
L−kurtosis
L−skewness

Duration: 6 h; Zone No. 1



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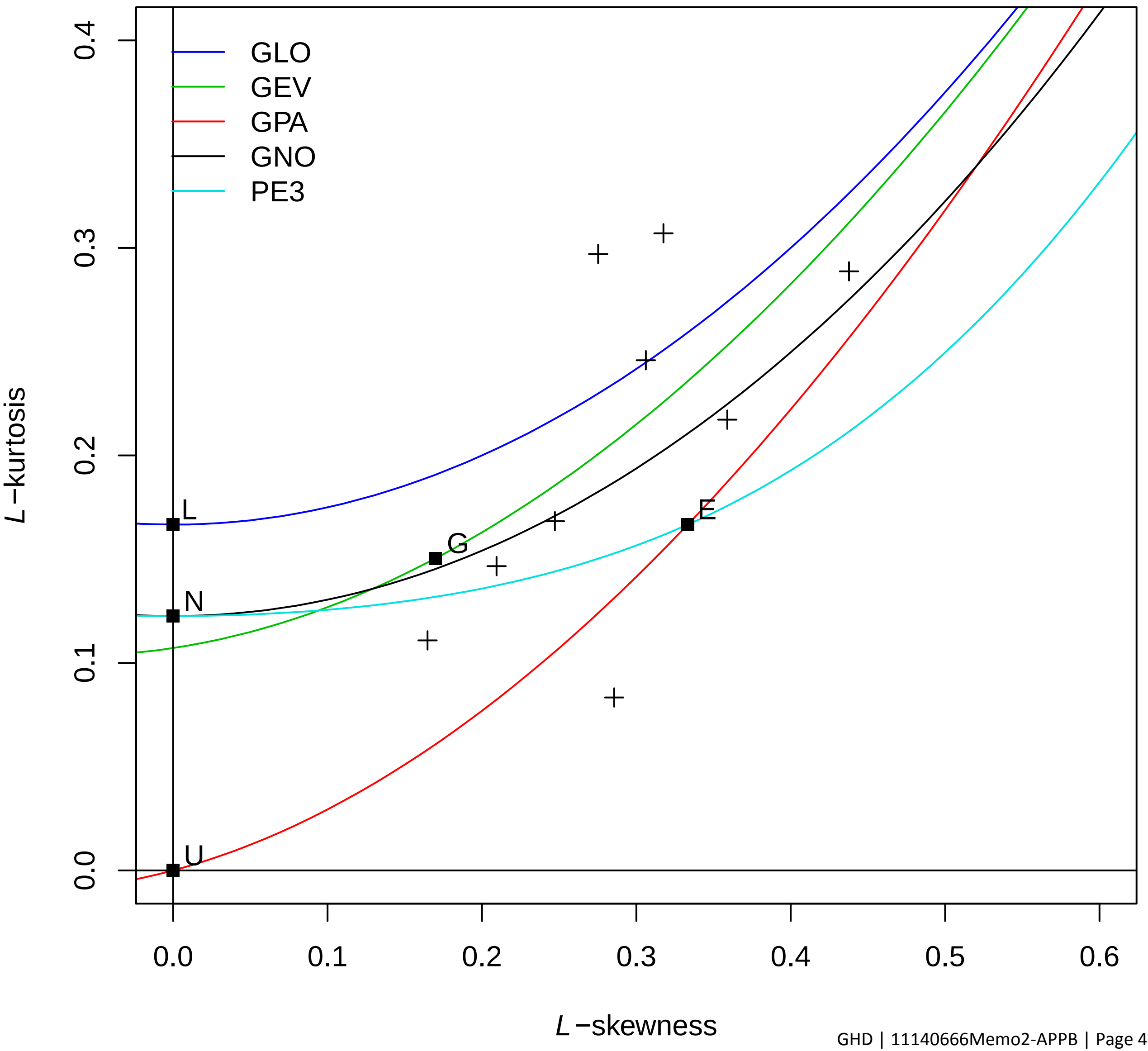

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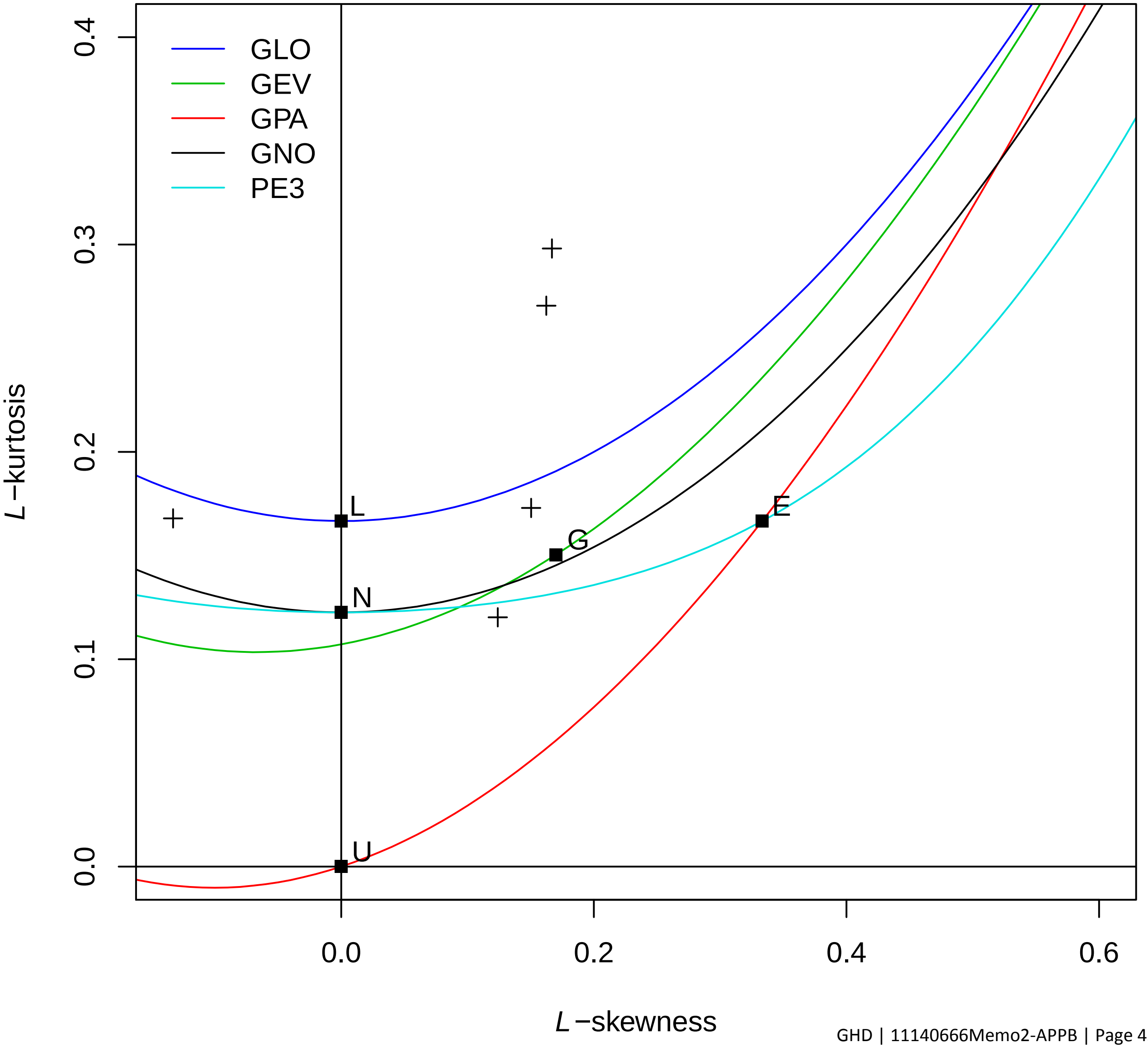

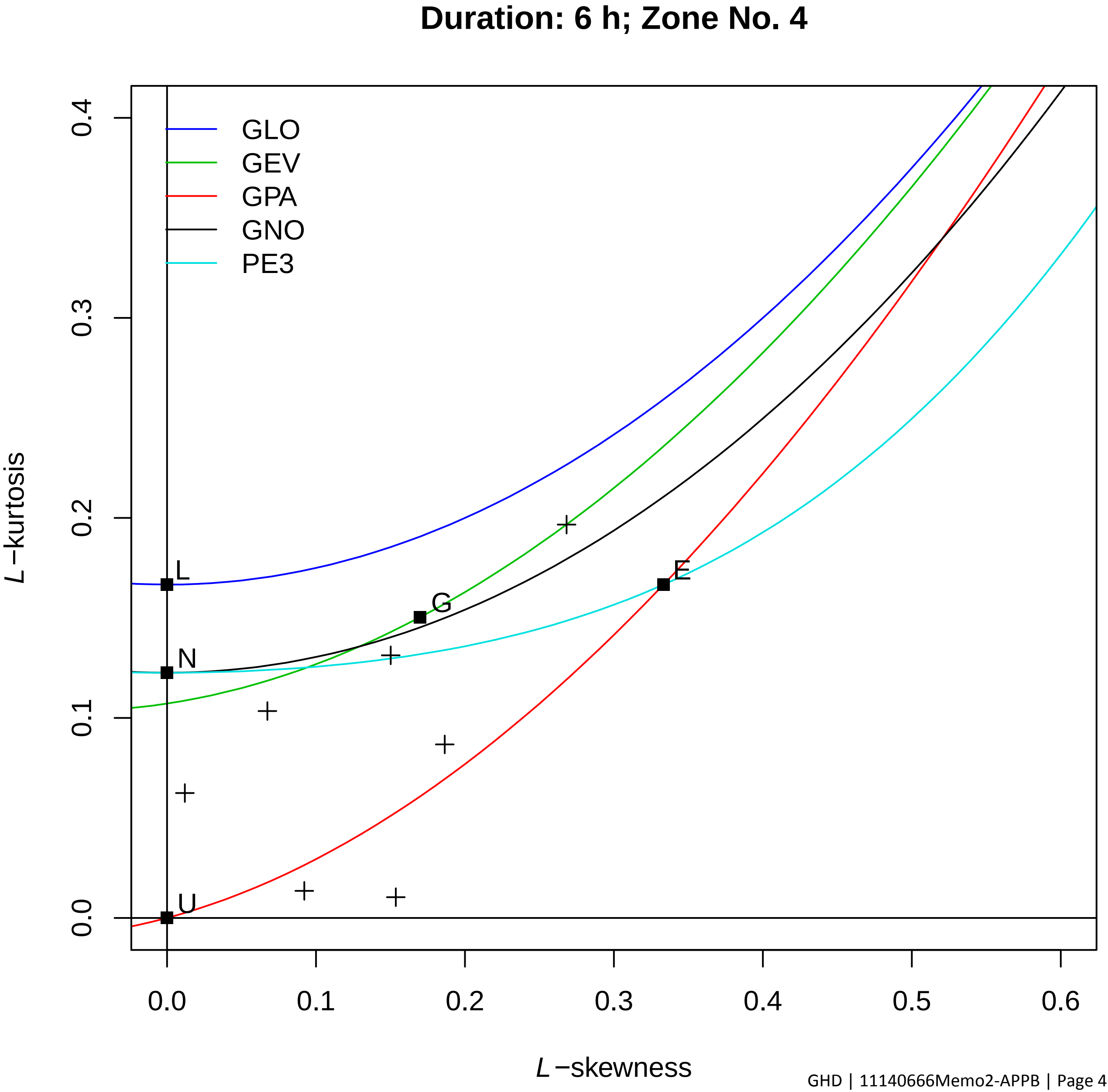
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PE3
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G
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N
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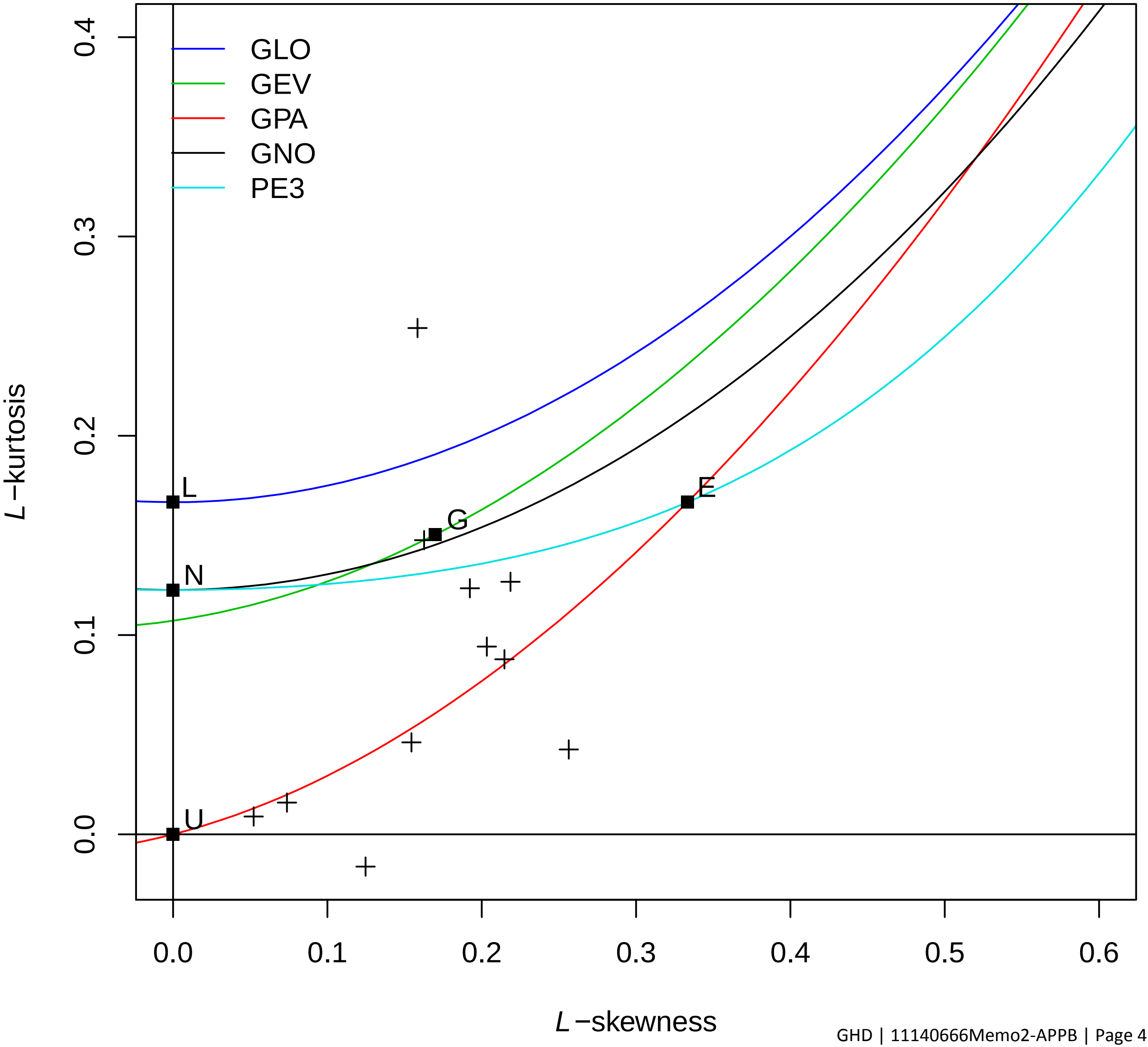
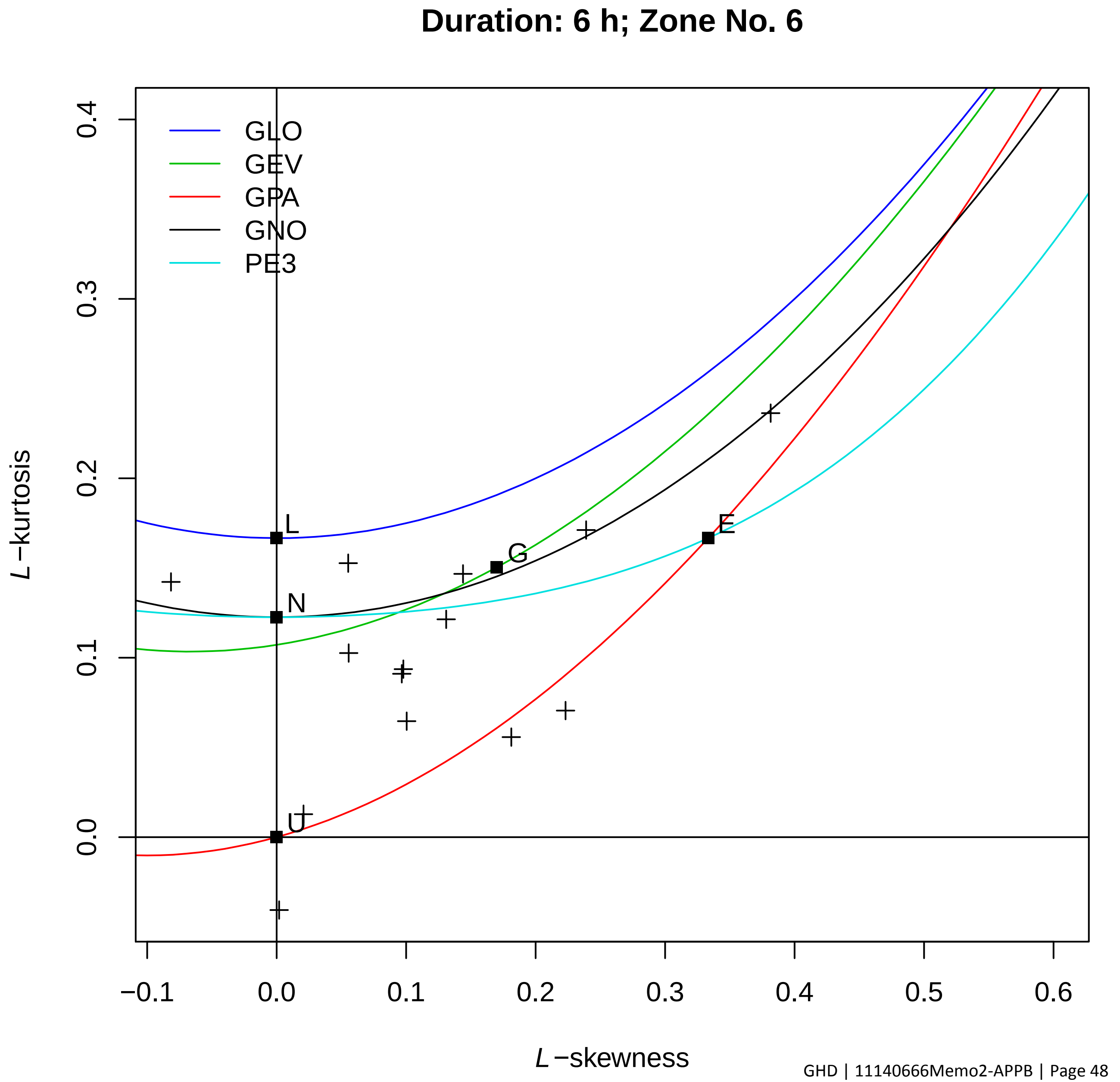
0.3
0.4
0.5
0.6
L −kurtosis
L −skewness

Duration: 6 h; Zone No. 5

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GNO
PE3
L
N
G
E
U
L −kurtosis
L −skewness
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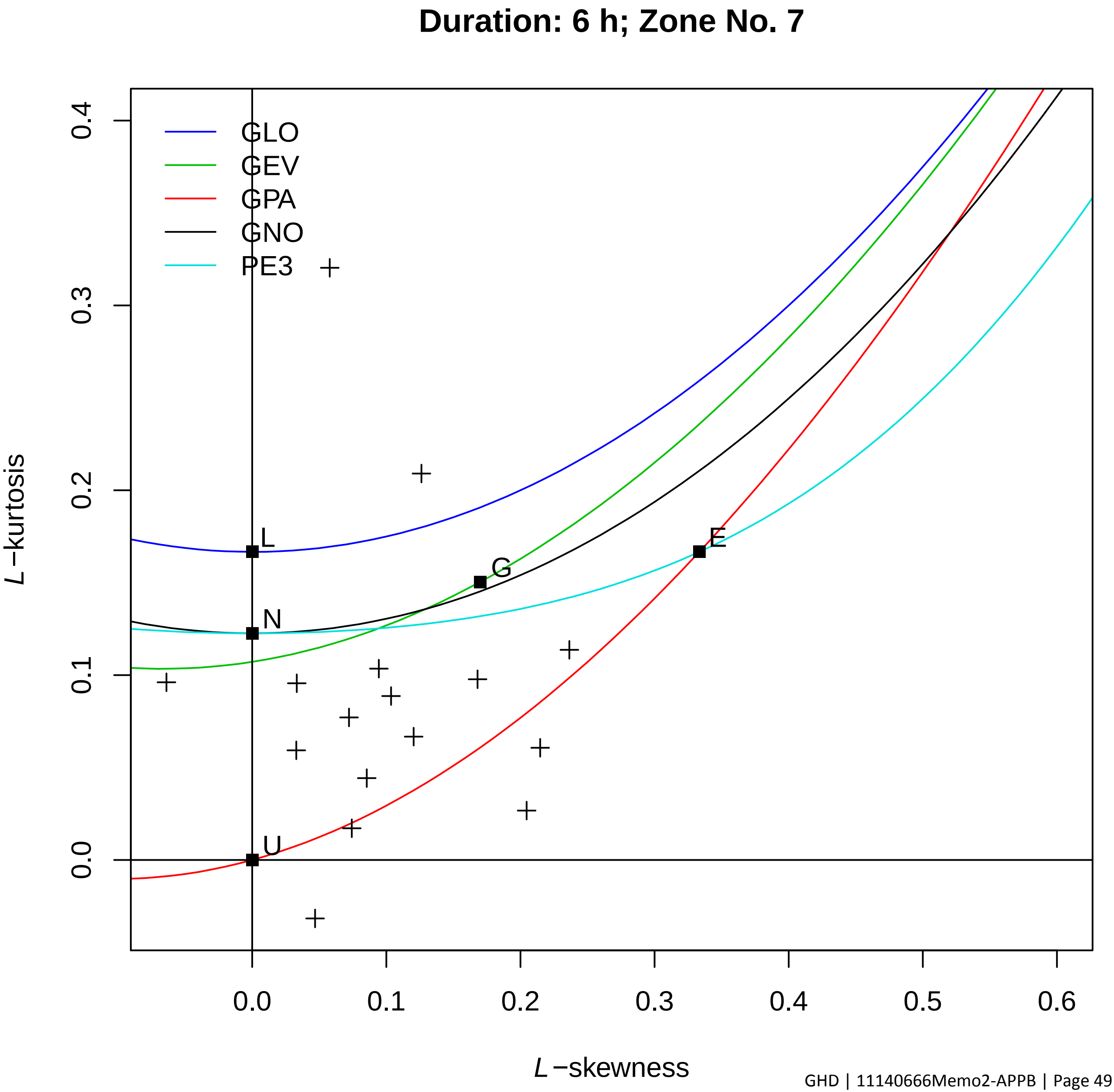
0.0
−0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6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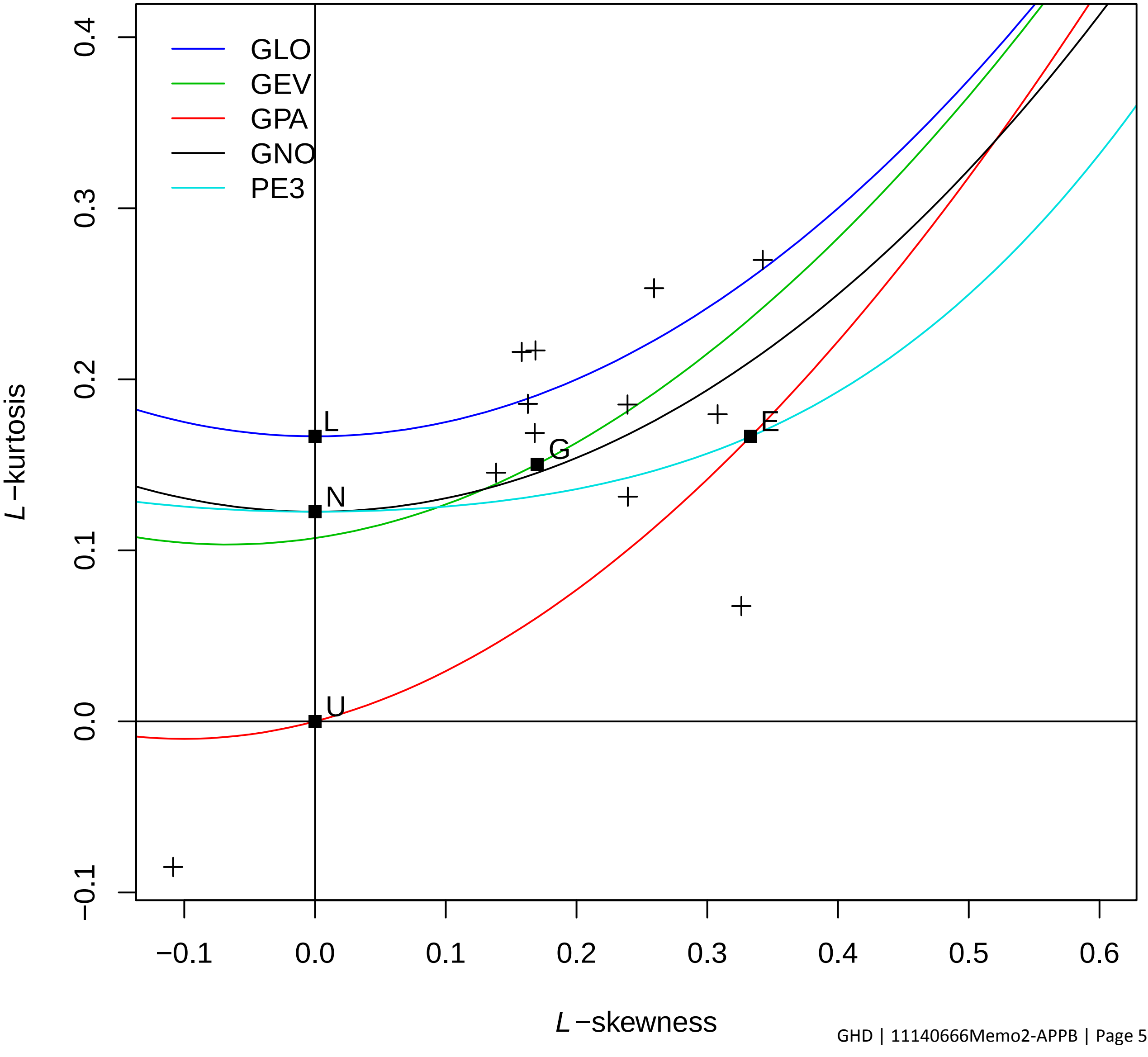
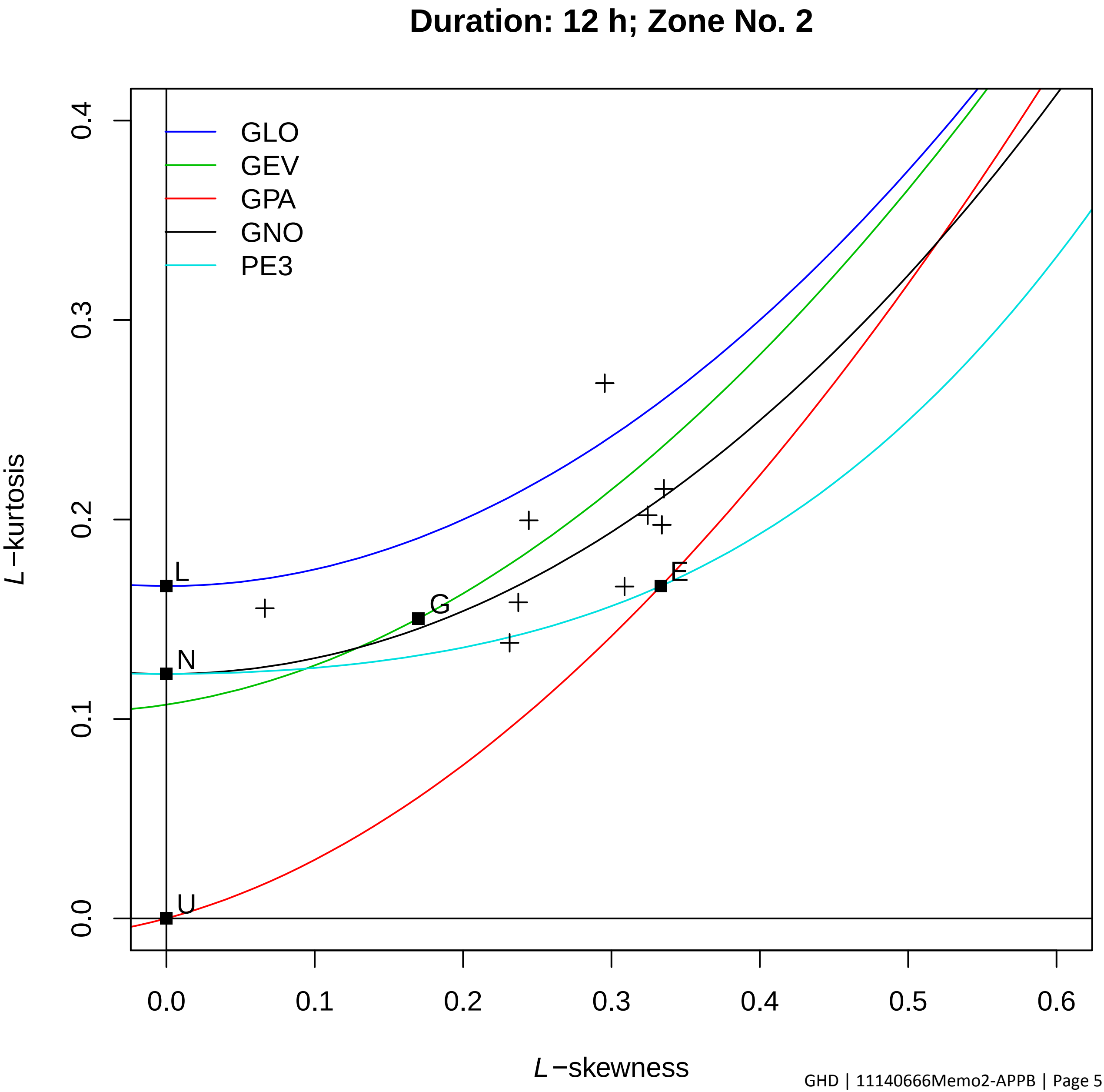
GEV
GPA
GNO
PE3
L
N
G
E
U
0.0
0.1
0.2
0.3
0.4
0.5
0.6
L −skewness
L −kurtosis

Duration: 12 h; Zone No. 1

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GNO
PE3
L
N
G
E
U
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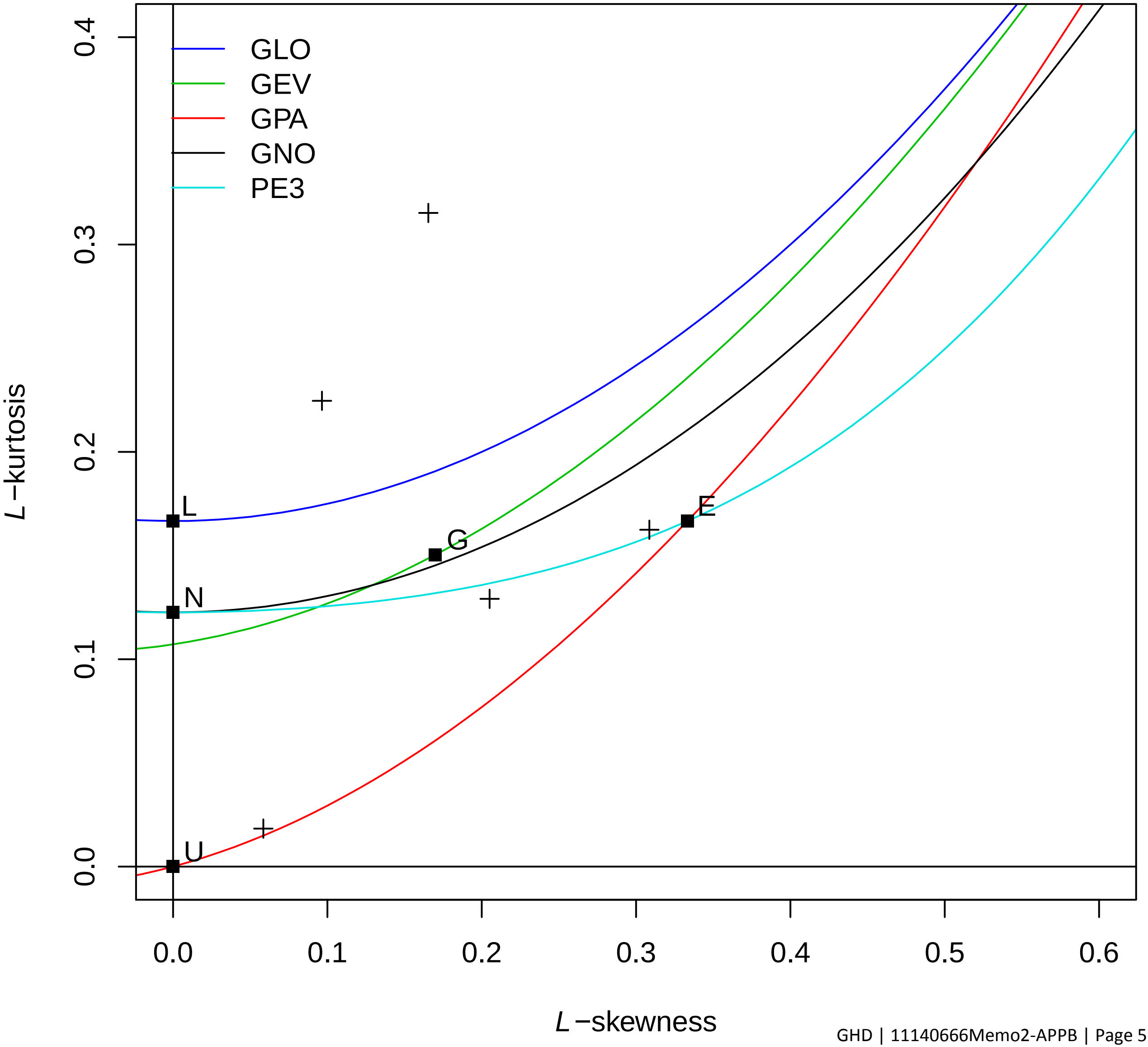
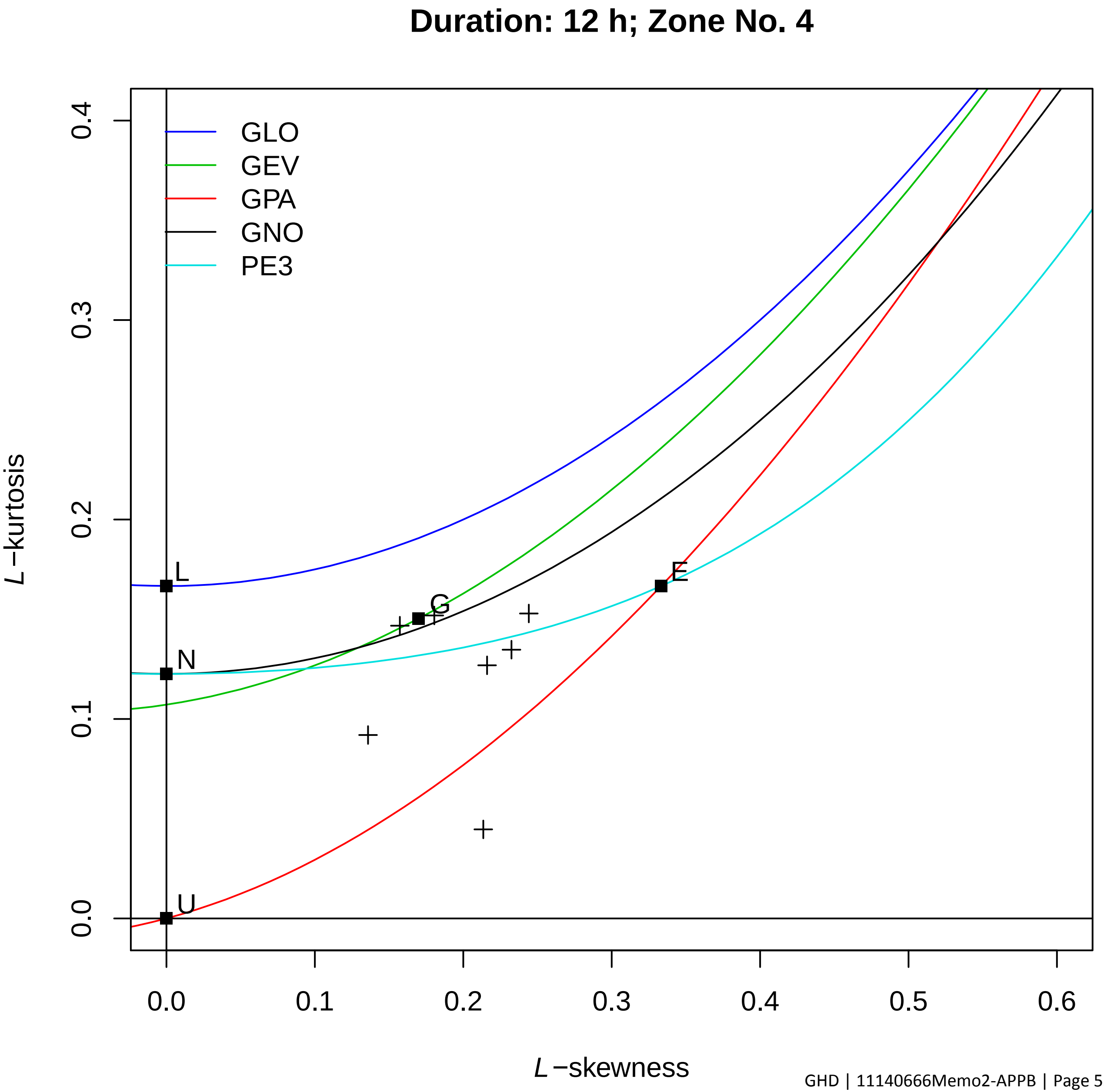
0.1
0.2
0.3
0.4
0.0
0.1
0.2
0.3
0.4
0.5
0.6
L −kurtosis
L −skewness

Duration: 12 h; Zone No. 3

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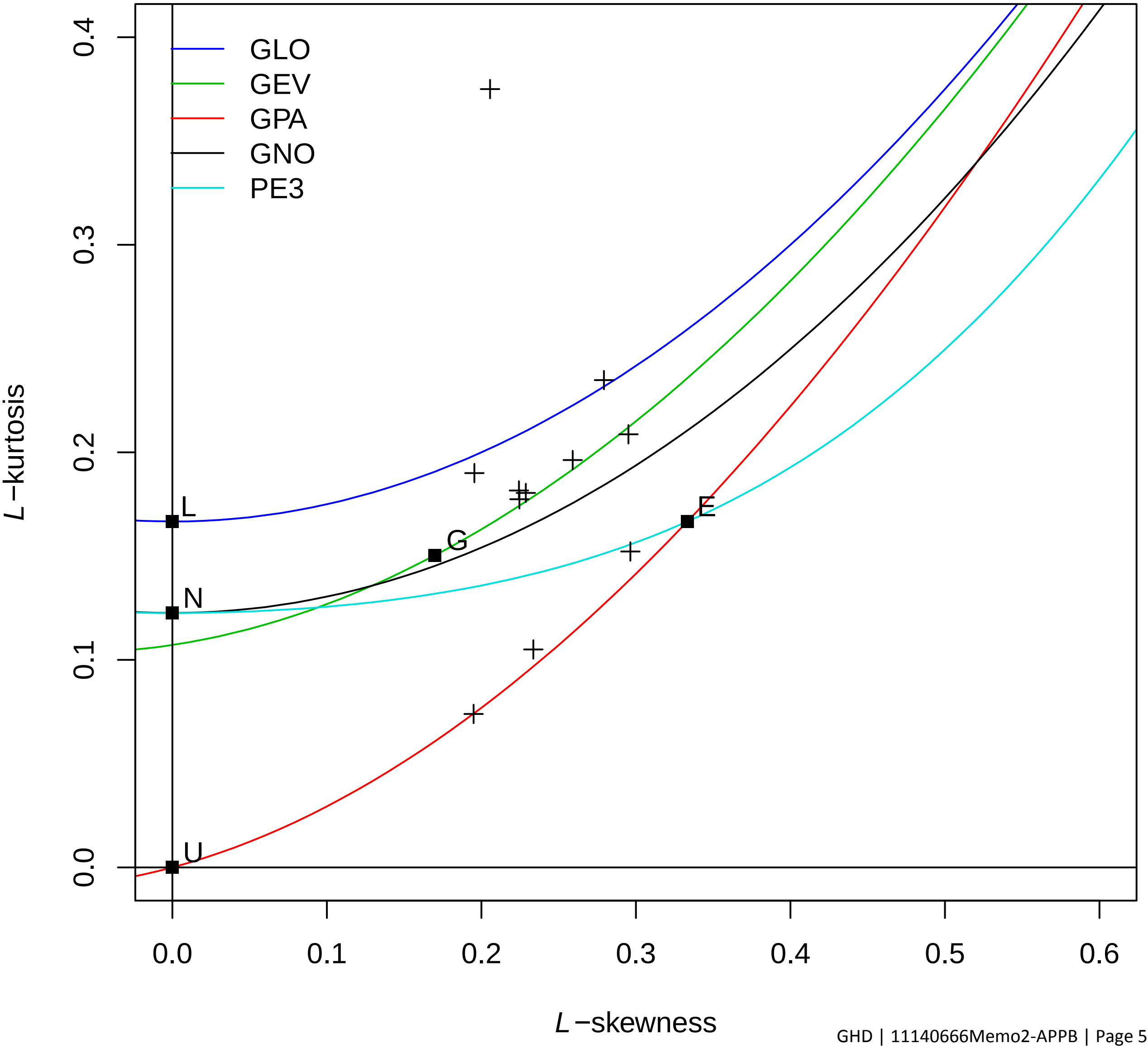
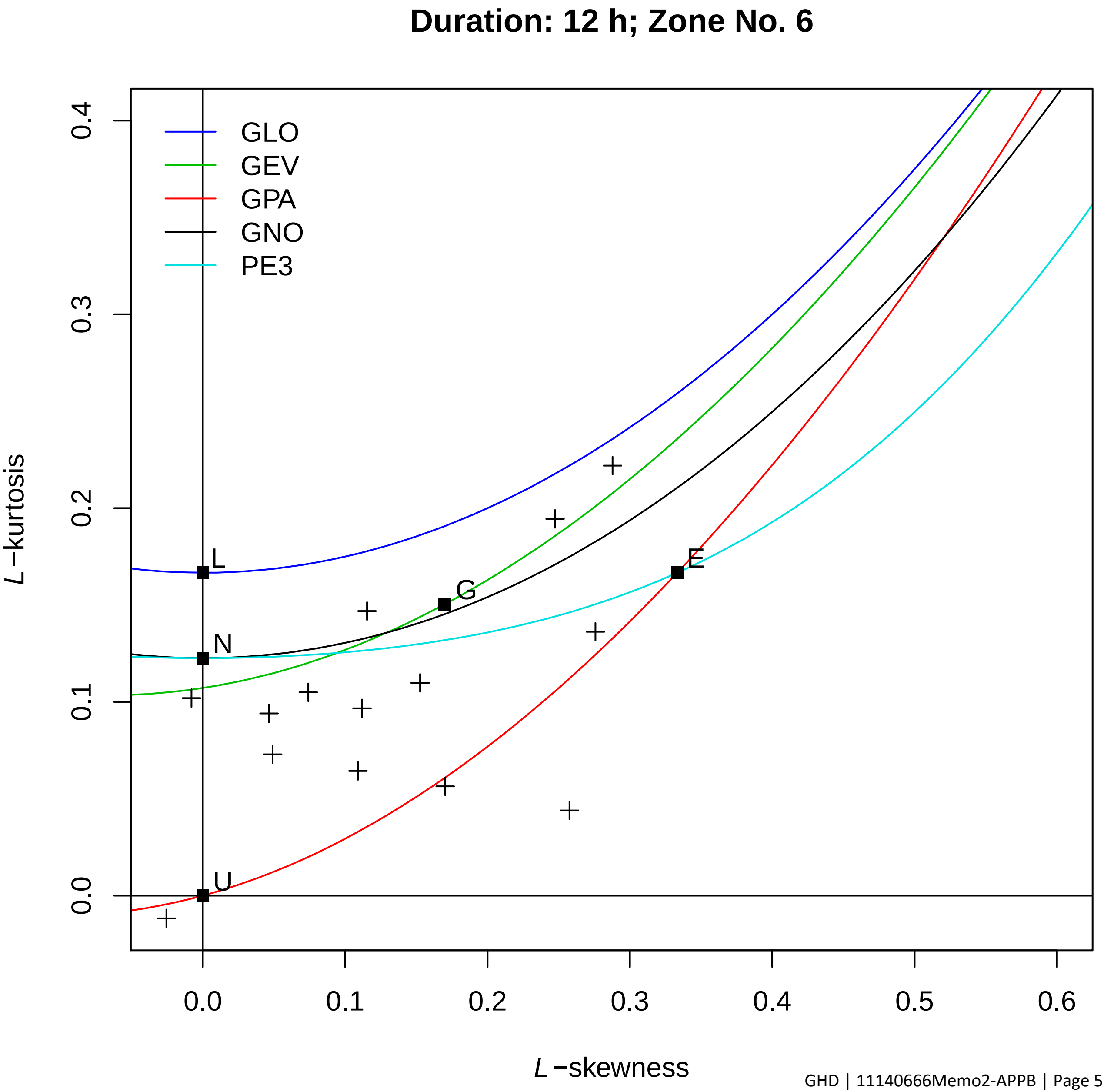
GEV
GPA
GNO
PE3
L
N
U
G
E
L −kurtosis
L −skewness
0.0
0.1
0.2
0.3
0.4
0.0
0.1
0.2
0.3
0.4
0.5
0.6

Duration: 12 h; Zone No. 5

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GNO
PE3
L
G
N
E
U
L −kurtosis
L −skewness
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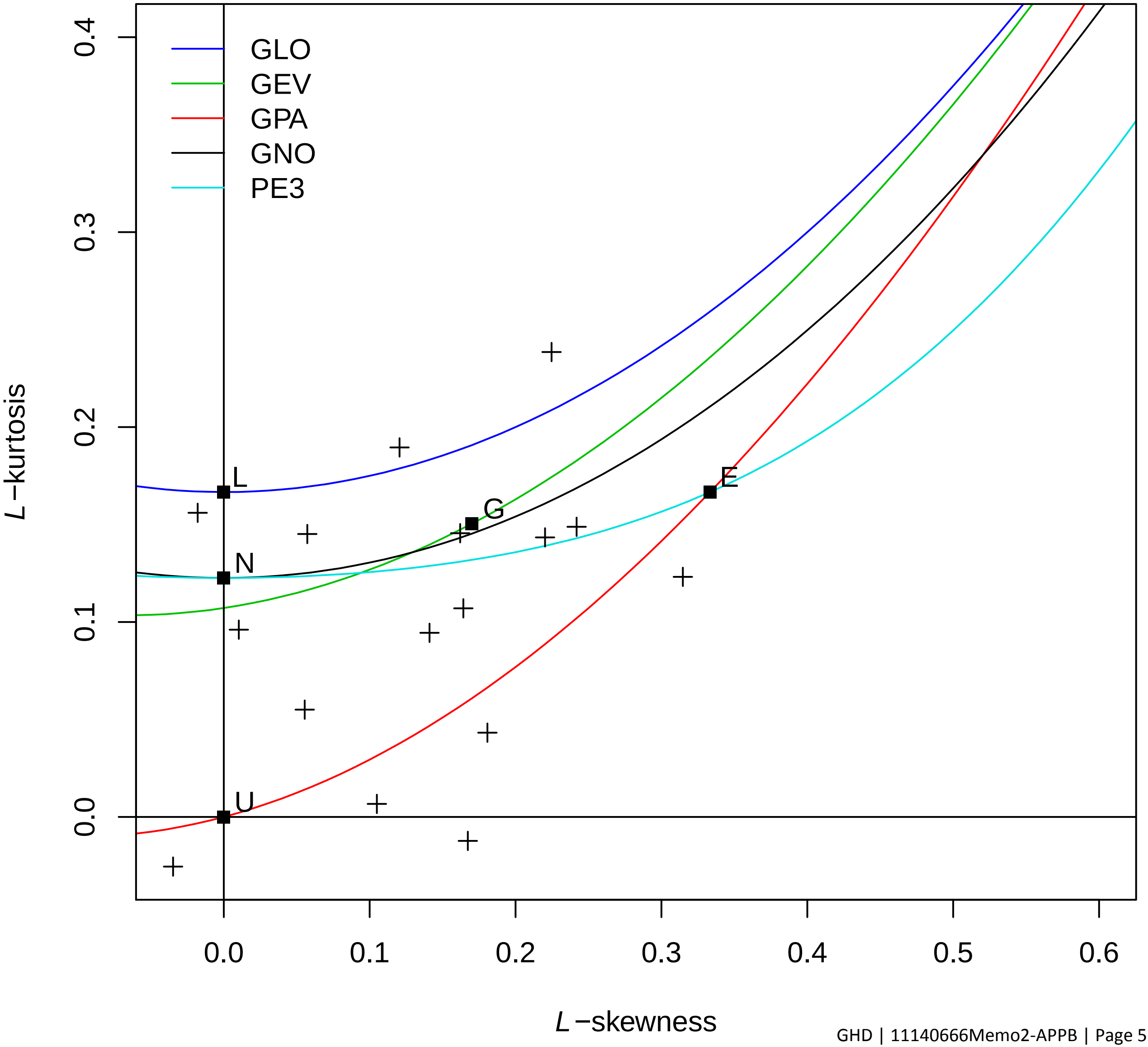
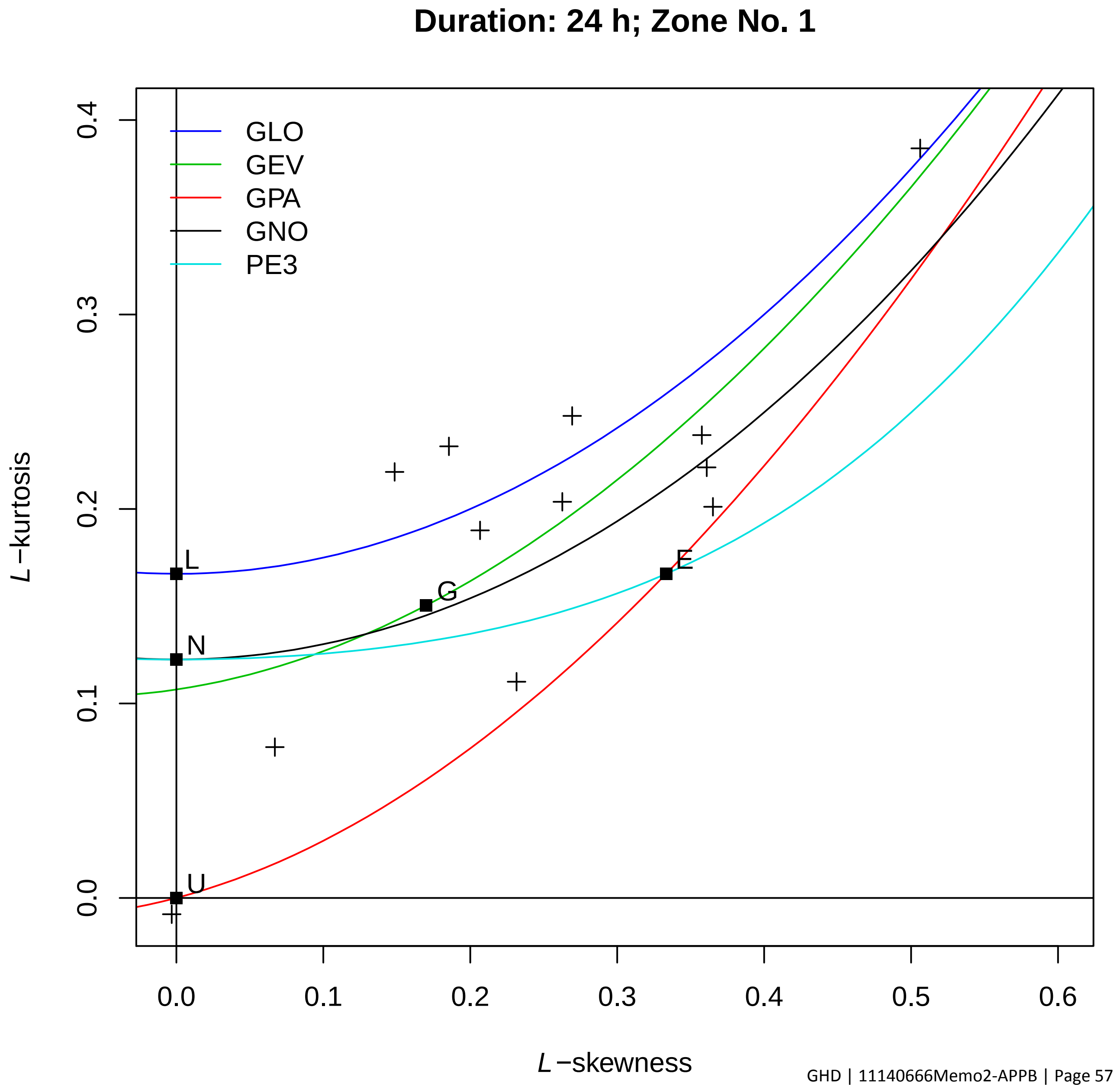
0.1
0.2
0.3
0.4
0.5
0.6

Duration: 12 h; Zone No. 7

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GNO
PE3
L
G
N
E
U
L −kurtosis
L −skewness
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0.1
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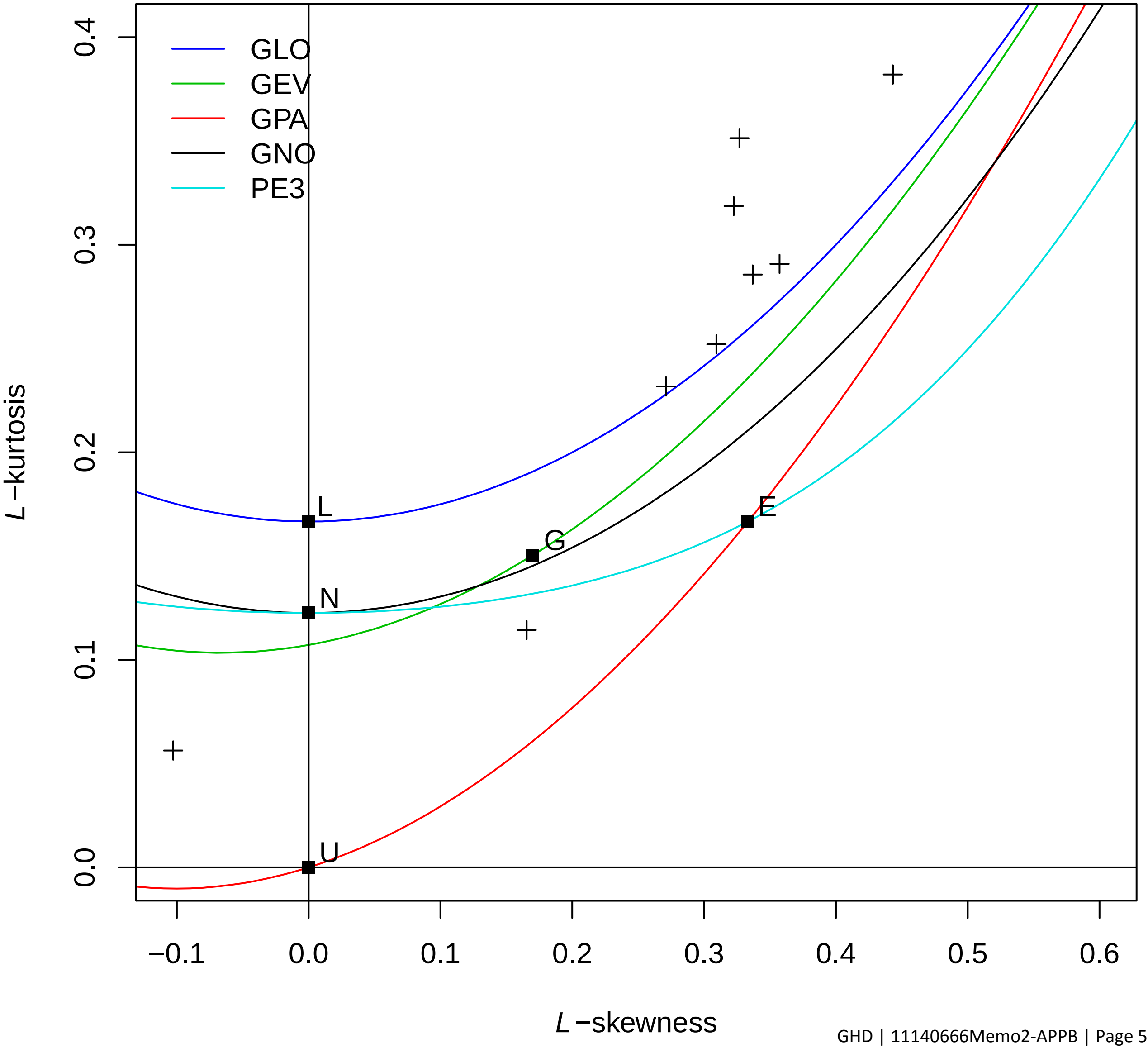
0.4
0.0
0.1
0.2
0.3
0.4
0.5
0.6

Duration: 24 h; Zone No. 2



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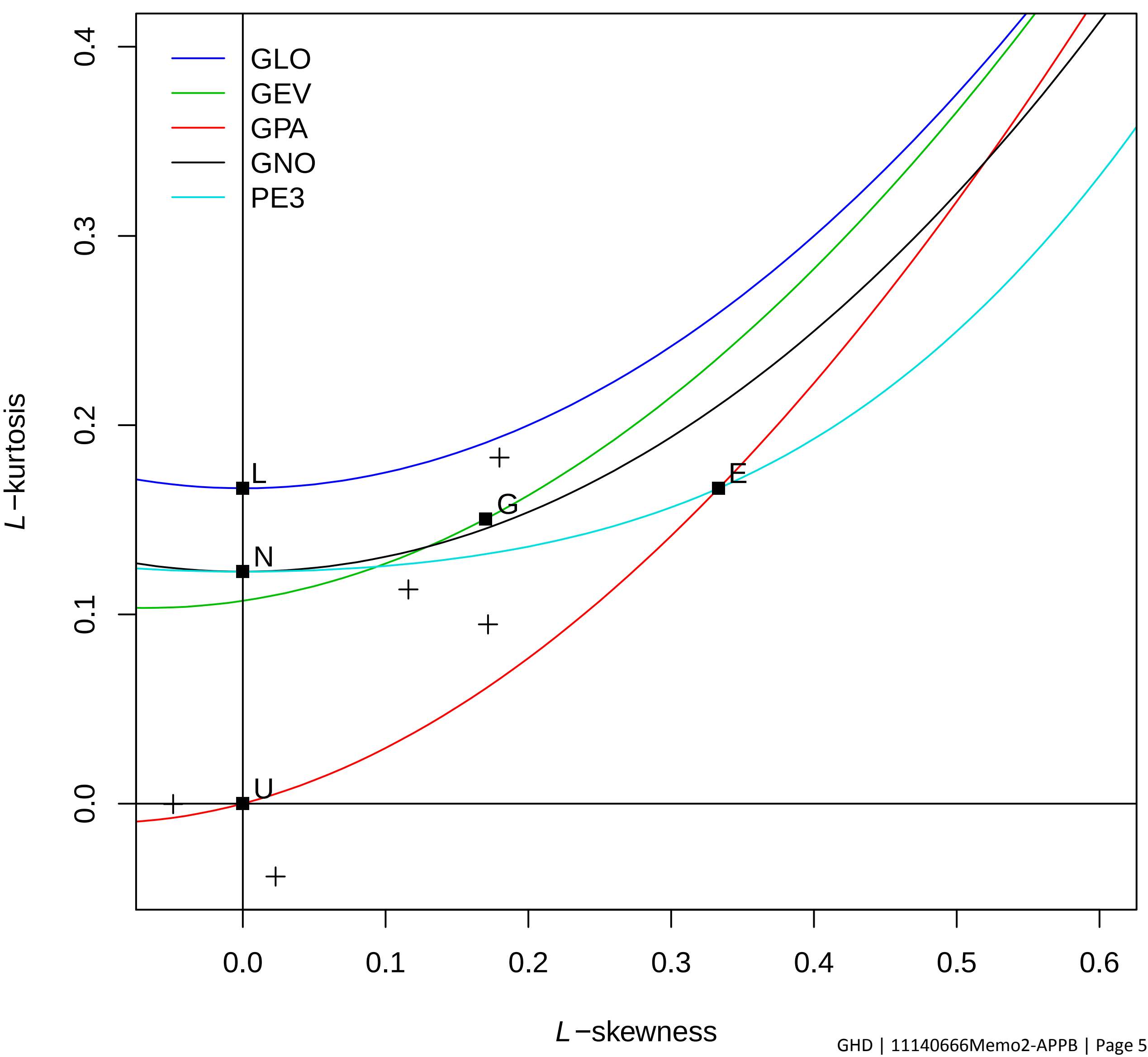

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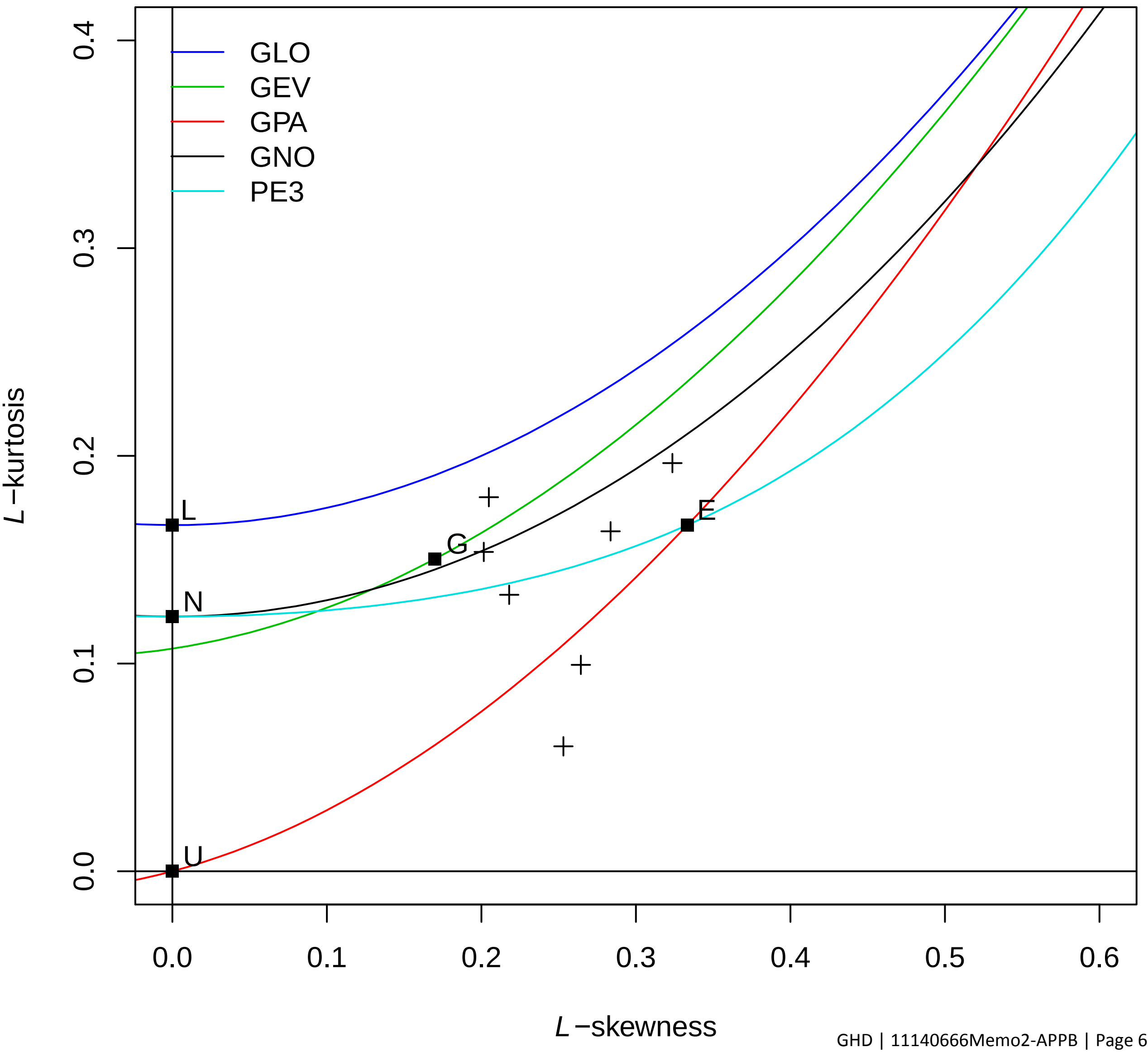

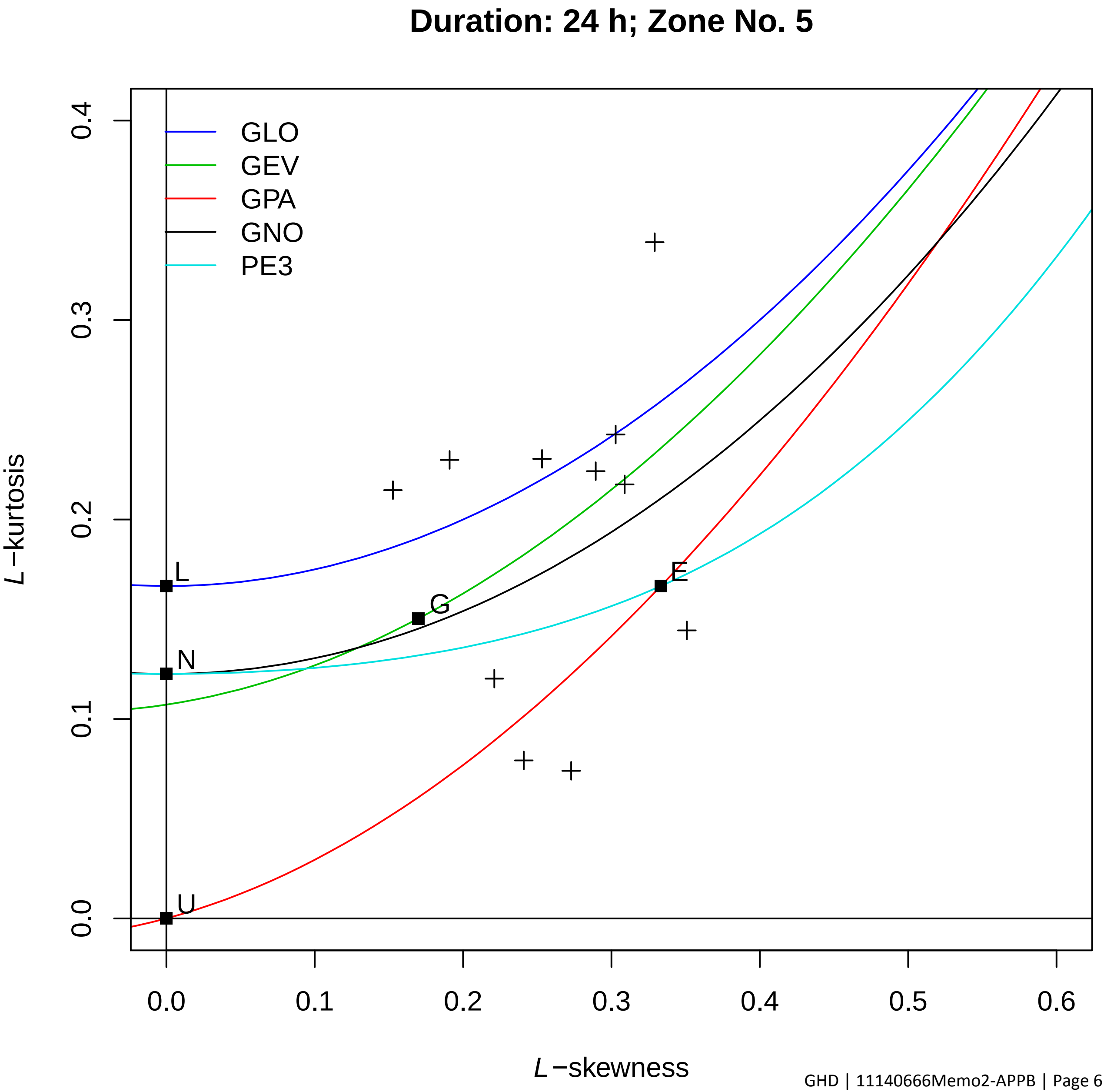
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GPA
GNO
PE3
L
G
E
N
U
L −kurtosis
L −skewness
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0.2
0.3
0.4
0.0
0.1
0.2
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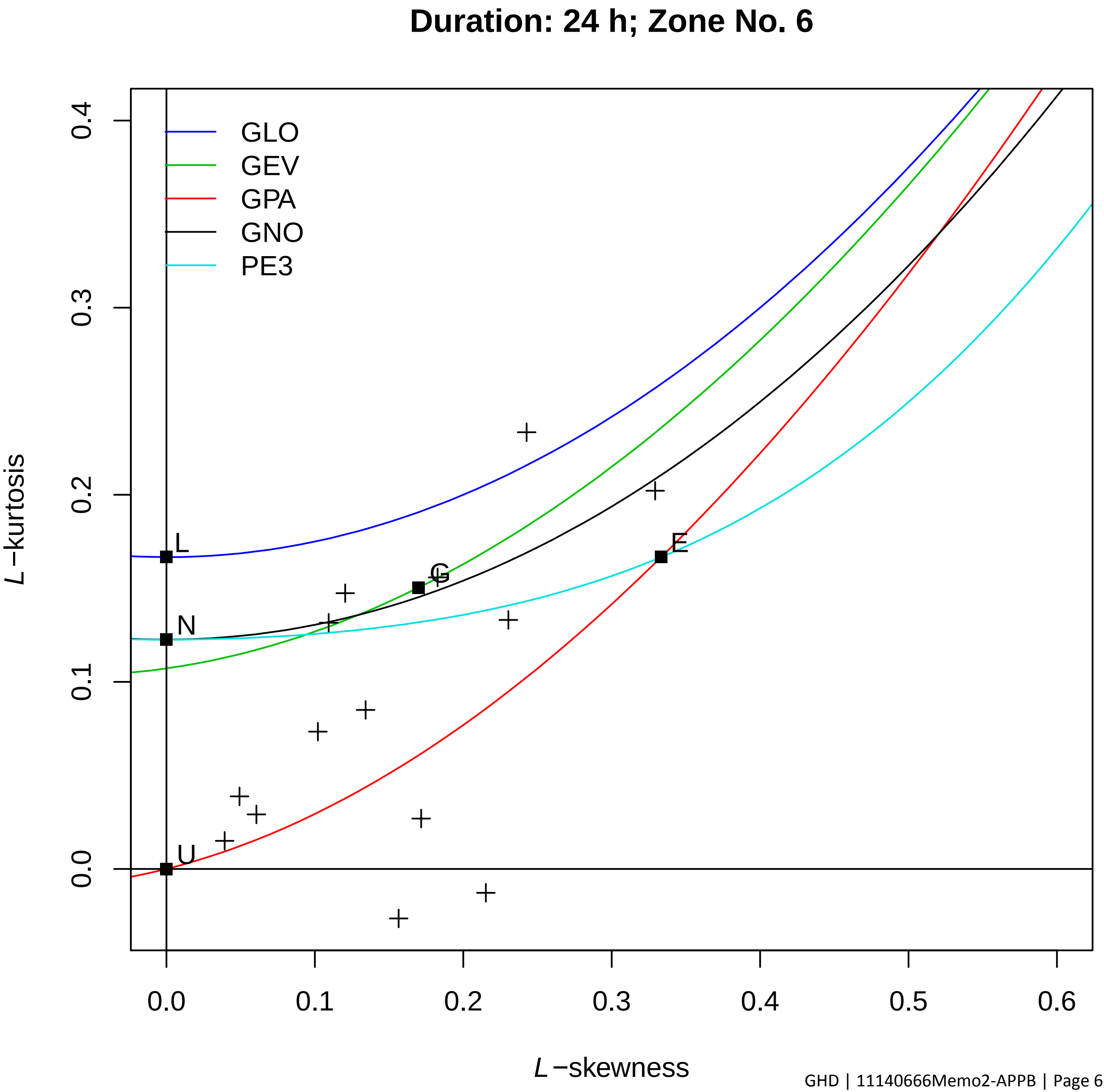
0.4
0.5
0.6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GNO
PE3
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N
G
E
U
L −kurtosis
L −skewness
0.0
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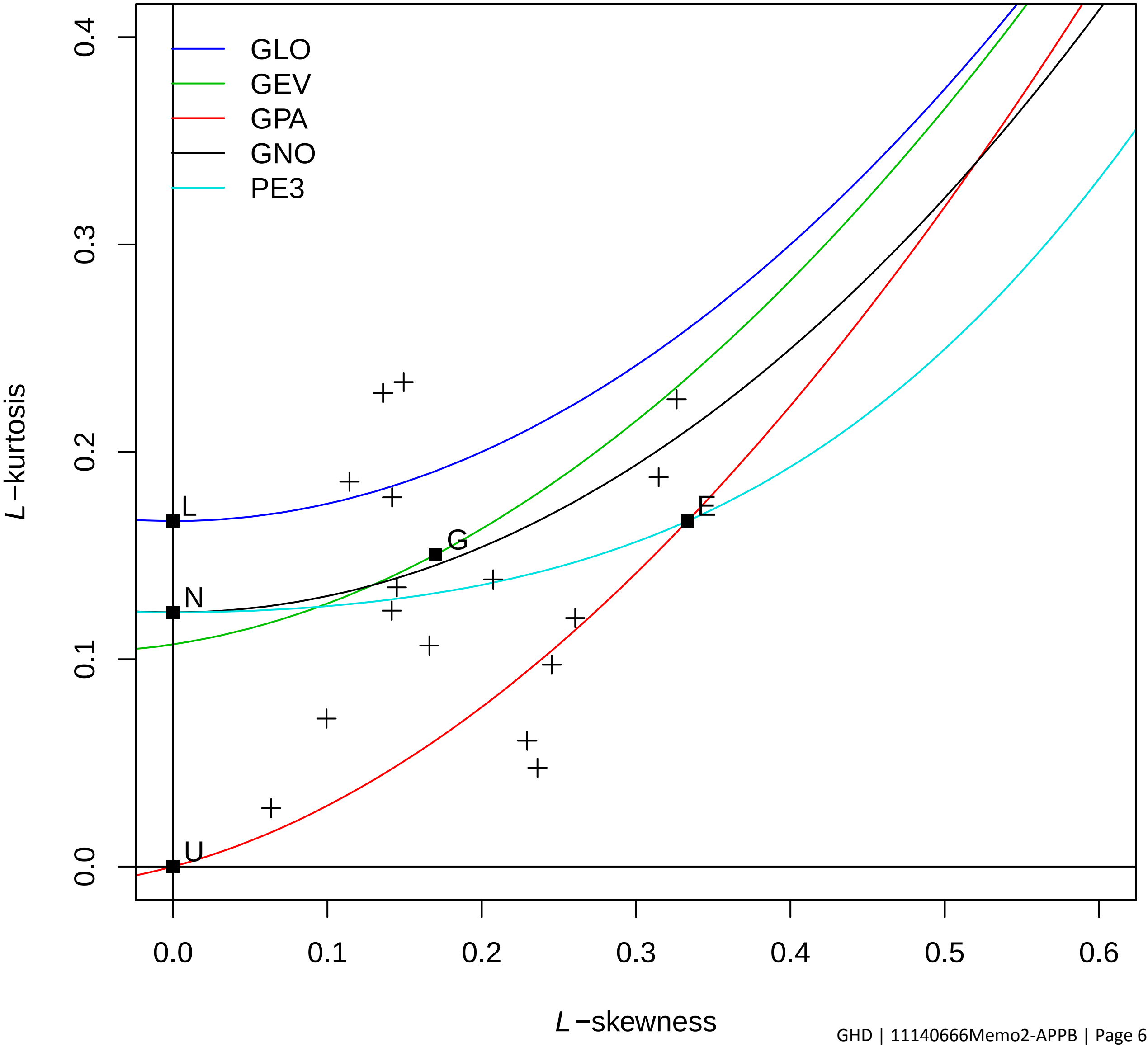
0.2
0.3
0.4
0.5
0.6

Duration: 24 h; Zone No. 7



Appendix C

Table Index

Table 1.1 Zone 1 Dimensionless IDF Curve

Duration	Dimensionless Quantiles						
	2 year	5 year	10 year	25 year	50 year	100 year	200 year
5-min	0.883	1.288	1.599	2.047	2.425	2.842	3.306
10-min	0.890	1.290	1.591	2.018	2.372	2.759	3.182
15-min	0.891	1.287	1.585	2.006	2.355	2.735	3.151
30-min	0.898	1.265	1.541	1.935	2.262	2.620	3.013
1-hr	0.920	1.221	1.445	1.759	2.017	2.295	2.598
2-hr	0.944	1.204	1.383	1.619	1.800	1.985	2.176
6-hr	0.952	1.190	1.350	1.557	1.714	1.872	2.032
12-hr	0.949	1.204	1.377	1.600	1.769	1.939	2.111
24-hr	0.935	1.197	1.387	1.647	1.855	2.076	2.312

Table 1.2 Zone 2 Dimensionless IDF Curve

Duration	Dimensionless Quantiles						
	2 year	5 year	10 year	25 year	50 year	100 year	200 year
5-min	0.870	1.260	1.576	2.055	2.479	2.967	3.532
10-min	0.874	1.239	1.539	1.999	2.410	2.891	3.452
15-min	0.882	1.225	1.507	1.940	2.328	2.781	3.309
30-min	0.884	1.215	1.488	1.910	2.292	2.738	3.264
1-hr	0.883	1.187	1.449	1.869	2.261	2.735	3.309
2-hr	0.919	1.189	1.397	1.702	1.961	2.251	2.576
6-hr	0.926	1.167	1.355	1.632	1.870	2.138	2.440
12-hr	0.928	1.184	1.378	1.655	1.885	2.138	2.417
24-hr	0.926	1.179	1.373	1.654	1.891	2.153	2.446

Table 1.3 Zone 3 Dimensionless IDF Curve

Duration	Dimensionless Quantiles						
	2 year	5 year	10 year	25 year	50 year	100 year	200 year
5-min	0.929	1.274	1.509	1.813	2.045	2.280	2.519
10-min	0.924	1.265	1.503	1.818	2.063	2.315	2.577
15-min	0.917	1.258	1.503	1.836	2.102	2.383	2.681
30-min	0.908	1.243	1.495	1.850	2.145	2.466	2.816
1-hr	0.927	1.220	1.432	1.724	1.958	2.207	2.472
2-hr	0.946	1.182	1.348	1.570	1.743	1.923	2.110
6-hr	0.957	1.179	1.328	1.519	1.662	1.805	1.949
12-hr	0.938	1.188	1.368	1.614	1.812	2.021	2.244
24-hr	0.927	1.194	1.394	1.676	1.909	2.163	2.440

Table 1.4 Zone 4 Dimensionless IDF Curve

Duration	Dimensionless Quantiles						
	2 year	5 year	10 year	25 year	50 year	100 year	200 year
5-min	0.919	1.274	1.524	1.856	2.117	2.387	2.669
10-min	0.924	1.254	1.487	1.800	2.045	2.300	2.567
15-min	0.938	1.245	1.454	1.723	1.926	2.132	2.340
30-min	0.939	1.217	1.410	1.667	1.865	2.070	2.282
1-hr	0.943	1.189	1.363	1.597	1.781	1.972	2.173
2-hr	0.966	1.187	1.326	1.494	1.613	1.727	1.837
6-hr	0.969	1.198	1.339	1.506	1.622	1.731	1.834
12-hr	0.949	1.202	1.373	1.594	1.761	1.931	2.102
24-hr	0.934	1.197	1.387	1.649	1.860	2.085	2.324

Table 1.5 Zone 5 Dimensionless IDF Curve

Duration	Dimensionless Quantiles						
	2 year	5 year	10 year	25 year	50 year	100 year	200 year
5-min	0.907	1.288	1.562	1.935	2.233	2.547	2.879
10-min	0.900	1.265	1.539	1.926	2.245	2.593	2.973
15-min	0.893	1.259	1.542	1.950	2.296	2.680	3.107
30-min	0.887	1.217	1.488	1.903	2.274	2.706	3.210
1-hr	0.918	1.204	1.421	1.734	1.997	2.287	2.609
2-hr	0.961	1.193	1.343	1.529	1.664	1.795	1.924
6-hr	0.972	1.205	1.344	1.504	1.613	1.714	1.807
12-hr	0.962	1.220	1.381	1.574	1.710	1.838	1.961
24-hr	0.943	1.218	1.405	1.648	1.833	2.020	2.211

Table 1.6 Zone 6 Dimensionless IDF Curve

Duration	Dimensionless Quantiles						
	2 year	5 year	10 year	25 year	50 year	100 year	200 year
5-min	0.921	1.269	1.514	1.841	2.097	2.364	2.641
10-min	0.930	1.252	1.475	1.768	1.994	2.227	2.467
15-min	0.942	1.241	1.441	1.698	1.890	2.082	2.276
30-min	0.953	1.216	1.387	1.602	1.759	1.914	2.066
1-hr	0.958	1.185	1.336	1.526	1.667	1.808	1.948
2-hr	0.969	1.178	1.309	1.465	1.575	1.680	1.780
6-hr	0.968	1.199	1.342	1.511	1.629	1.741	1.846
12-hr	0.961	1.216	1.377	1.573	1.712	1.845	1.973
24-hr	0.954	1.223	1.397	1.612	1.768	1.921	2.070

Table 1.7 Zone 7 Dimensionless IDF Curve

Duration	Dimensionless Quantiles						
	2 year	5 year	10 year	25 year	50 year	100 year	200 year
5-min	0.935	1.223	1.425	1.694	1.904	2.122	2.349
10-min	0.904	1.223	1.470	1.831	2.140	2.485	2.873
15-min	0.923	1.243	1.471	1.781	2.027	2.286	2.559
30-min	0.925	1.219	1.435	1.732	1.973	2.230	2.506
1-hr	0.936	1.198	1.387	1.644	1.849	2.066	2.295
2-hr	0.939	1.174	1.347	1.586	1.781	1.990	2.214
6-hr	0.977	1.143	1.245	1.366	1.450	1.529	1.603
12-hr	0.965	1.152	1.277	1.434	1.551	1.668	1.784
24-hr	0.976	1.188	1.314	1.458	1.554	1.643	1.724

Appendix D

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Figure Index

1. Methodology

The regional rainfall frequency analysis (RRFA) generated dimensionless Intensity Duration Frequency (IDF) curves. The dimensionless IDF curves must be scaled by the index rain, which is an estimate of the mean annual maximum rainfall. The index rain can be estimated using one of the following methods:

- Utilize the index rain from a nearby rainfall monitoring location. This method is limited to the area local to the rainfall monitoring location.
- Utilize the index rain from the index rain contour maps. This method provides a regional interpolation of the index rain, and can be used at any location.

The index rain contour maps are the preferred method of obtaining the index rain used for scaling the dimensionless IDF curves.

The index rain contour maps were developed by conducting a geostatistical analysis using the ArcGIS Geostatistical Analyst Extension[1]. The following steps were used.

1. Represent/Explore the Data
    - Historical rainfall data up to 2016 were used for the analysis (the dataset is described in Technical Memorandum 2). Rainfall data were explored and evaluated to determine the most appropriate interpolation method.
2. Select Spatial Interpolation Method
    - The kriging geostatistical interpolation method[2] was selected. The kriging method uses semivariogram models[3] of spatial autocorrelation to generate predicted values of the variable of interest.
    - The data were anisotropic[4] (the data show a higher autocorrelation in one direction than another). The index rain has a higher variability in the north to south direction than in the west to east direction; therefore the semivariogram function changes with direction as well as distance.
    - Ordinary kriging[5] was selected as the kriging method based upon the assumption that the sample mean of the data set was considered an estimate and not the true mean.
3. Fit the Model
    - The "optimize model" option within the geostatistical wizard of the Geostatistical Analyst Extension was used to find best-fitting parameters for the semivariogram model. This method uses the weighted least-squares fit to determine the most appropriate fit for the model. The model was then refined to account for anisotropy.
    - The search neighbourhoods functionality was used to identify data points to include in the analysis for a predicted value at a given location (i.e., ones in close proximity). A smoothing factor for the search neighbourhoods was used to ensure no sharp angles in the contour lines were present[6].

4. Map Predicted Values
   - A geostatistical layer in ArcMap was then created using the semivariogram models of spatial autocorrelation as a visual representation of the predicted values.
   - The geostatistical layer was then converted to a shapefile (.shp) and clipped to present predicted values within the municipal boundaries.
   - The contours were edited manually to ensure that the predicted values were reasonable and/or not skewed as the result of a single outlying station.

2. Evaluation

Cross-validation was used to evaluate the interpolation. Each data point was removed from the dataset one at a time and the kriging model was then used to predict its value. There were two purposes for the cross-validation:

1. Diagnostics of the reasonability of the model and its associated parameters.
2. Evaluation of the performance of the model and its ability to predict values at locations with no rainfall measurements.

Overall, the performance of the interpolation model was strong. The relative bias (or mean error) in the model was also low. The majority of durations, particularly the longer durations, had a slightly negative bias. The largest bias was obtained for the 24-hour duration rainfall event, which had a bias value of -0.1% (-0.345 mm); the index rain for the 24-hour duration rainfall event ranged from 39 to 157 mm. The largest relative bias was obtained for the 5-minute duration rainfall event, which had a relative bias value of 1.9% (0.015 mm). The contour maps are virtually unbiased for the majority of durations.

The average relative root-mean square (RMS) errors for each duration ranged from 5% to 9%, and typically decrease as the duration of the rainfall event increases. The predicted errors are normally distributed; which suggests that less accurate predictions occur significantly less often than predictions that are more accurate. In addition, stations with smaller sample sizes (i.e., less years of historical rainfall data) tend to have less accurate predictions than those with larger sample sizes.

A known property of kriging is its tendency to over-predict lower values and under-predict higher values; therefore a negative bias was expected. This tendency should be noted and taken into consideration when using these maps for engineering applications. The highest predicted errors typically occur at the stations with the highest or lowest observed annual maximum mean for any given duration. Higher rainfall intensities, and therefore under-predicted values, are more often observed at higher elevations of the Metro Vancouver region (mountainous areas). Lower observed rainfall intensities, and therefore over-predicted values, are typically observed at lower elevations.

The cross-correlation between index rain and elevation was also explored. The cokriging geostatistical interpolation method[7] was used to model the 24-hour duration rainfall event. The cross-covariance, along with the autocorrelation, of the two variables was used to produce a semivariogram model. The data set was explored to determine the rainfall duration event with the largest cross-correlation between index rain and elevation, which was the 24-hour rainfall duration event. The bias and root-mean square error for the model were 0.3% (-0.303 mm) and 5% (5.35 mm) respectively. In comparison, the bias and root-mean-square error for the kriging model (24-hour duration) were -0.1% (-0.345 mm) and 5% (5.76 mm) respectively. Although the cross-validation errors improved slightly using the cokriging method, the cokriging method required significantly more estimation and introduced more variability to model. It was therefore decided that the minor improvement in the model was not worth the increased variability, and the kriging results were used to generate the index rain contour maps.

It should also be noted that the model used to develop the isohyetal maps is dependent on spatial autocorrelation; coastal and mountainous effects on rainfall intensity are not explicitly accounted for in the interpolation model. Consequently, predictions may be less accurate in areas where these effects are pronounced.

3. References

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[1] http://desktop.arcgis.com/en/arcmap/latest/extensions/geostatistical-analyst/what-is-arcgis-geostatistical-analyst-.htm

[2] http://desktop.arcgis.com/en/arcmap/latest/extensions/geostatistical-analyst/what-are-geostatistical-interpolation-techniques-.htm

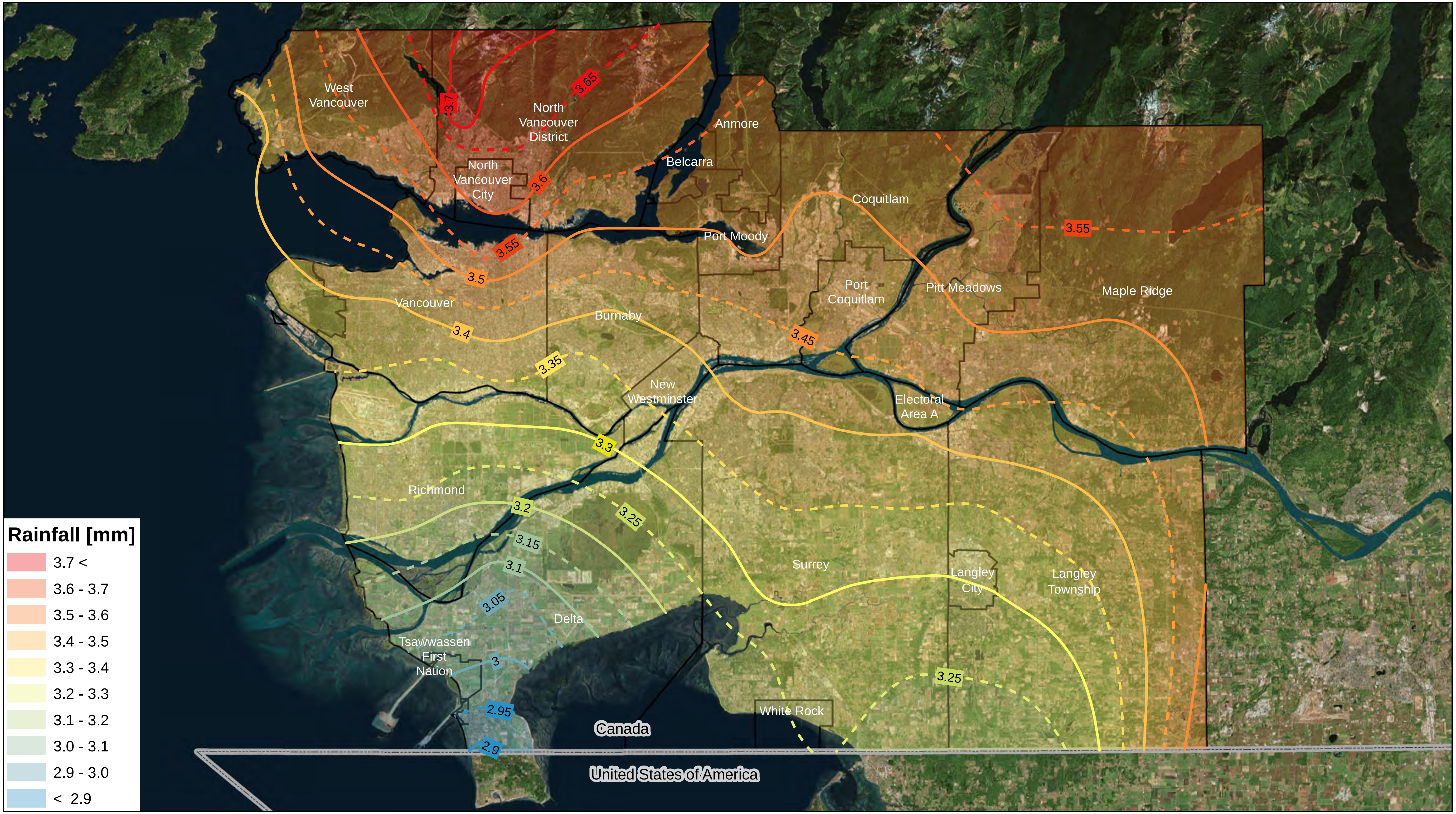
[3] http://desktop.arcgis.com/en/arcmap/latest/extensions/geostatistical-analyst/empirical-semivariogram-and-covariance-functions.htm

[4] http://desktop.arcgis.com/en/arcmap/latest/extensions/geostatistical-analyst/accounting-for-anisotropy-using-directional-semivariogram-and-covariance-functions.htm

[5] http://desktop.arcgis.com/en/arcmap/latest/extensions/geostatistical-analyst/understanding-ordinary-kriging.htm

[6] http://desktop.arcgis.com/en/arcmap/latest/extensions/geostatistical-analyst/search-neighborhoods.htm

[7] http://desktop.arcgis.com/en/arcmap/latest/extensions/geostatistical-analyst/understanding-cokriging.htm



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
ESRI World Imagery Service.

0 2 4 6
Kilometres

Coordinate System:
NAD 1983 UTM Zone 10N

N

Legend

▭ Municipal Boundaries

[mm] Isohyets

METRO VANCOUVER
BRITISH COLUMBIA, CANADA

5-MINUTE INDEX RAIN (MEAN ANNUAL MAXIMUM RAINFALL)
CONTOUR MAP

11140666
May 29, 2018

FIGURE 1.1

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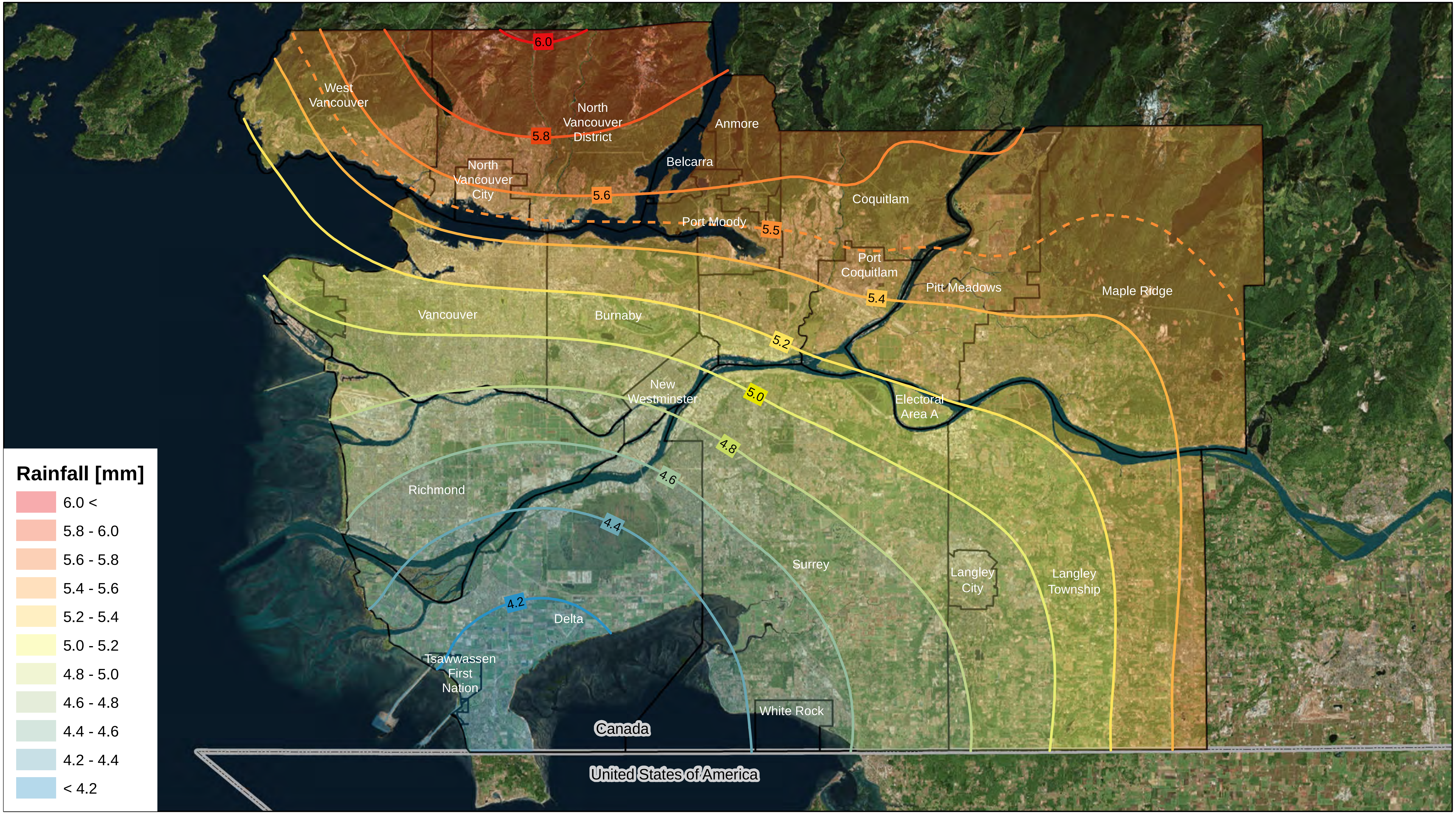

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
ESRI World Imagery Service.

0 2 4 6
Kilometres

Coordinate System:
NAD 1983 UTM Zone 10N

N

Legend

Municipal Boundaries

[mm] Isohyets

GHD

METRO VANCOUVER
BRITISH COLUMBIA, CANADA

10-MINUTE INDEX RAIN (MEAN ANNUAL MAXIMUM RAINFALL)
CONTOUR MAP

11140666
May 29, 2018

FIGURE 1.2

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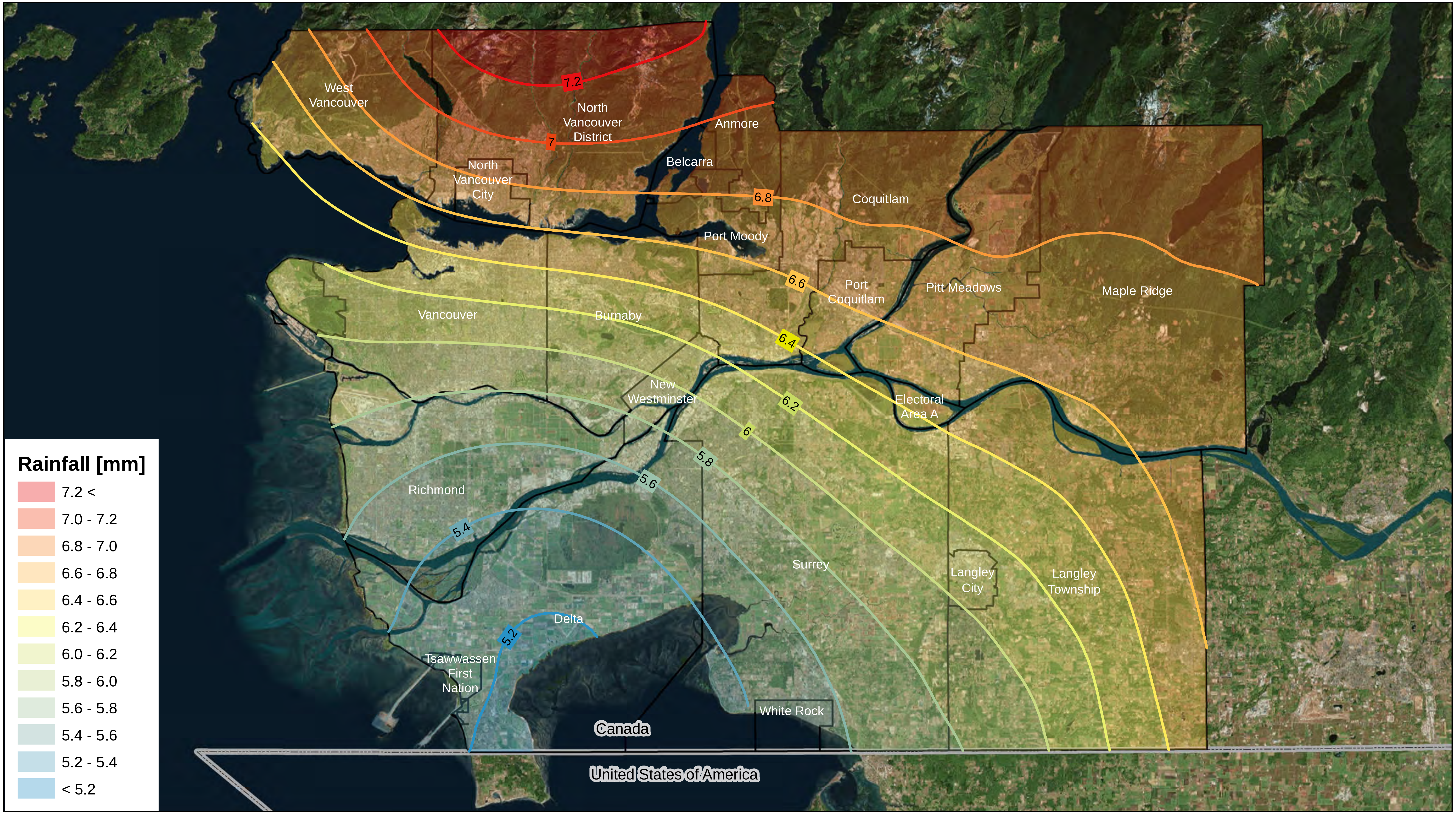

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
ESRI World Imagery Service.

0 2 4 6
Kilometres

Coordinate System:
NAD 1983 UTM Zone 10N

N

Legend

▭ Municipal Boundaries

[mm] Isohyets

METRO VANCOUVER
BRITISH COLUMBIA, CANADA

15-MINUTE INDEX RAIN (MEAN ANNUAL MAXIMUM RAINFALL) CONTOUR MAP

11140666
May 29, 2018

FIGURE 1.3

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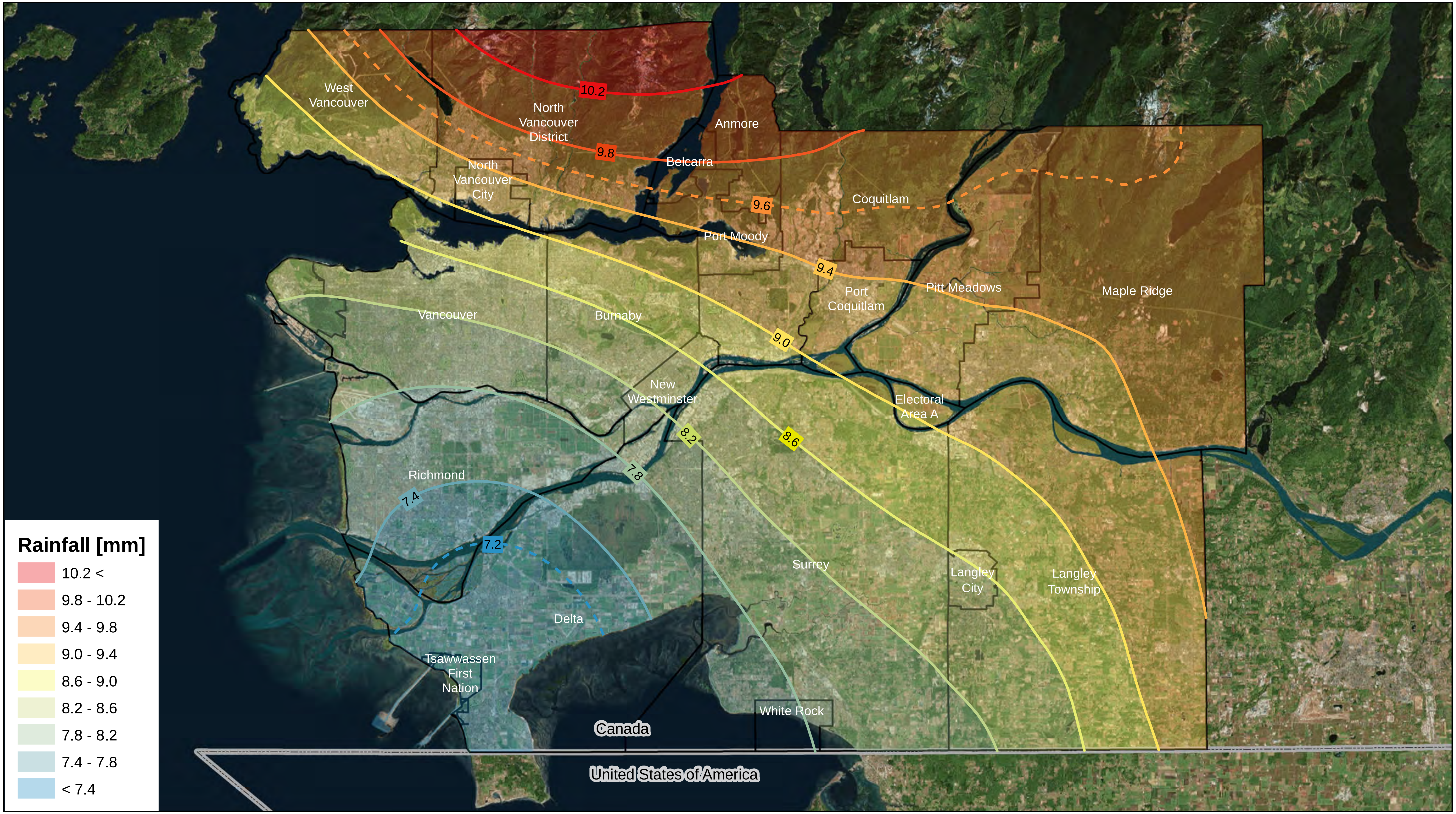

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
ESRI World Imagery Service.

0 2 4 6
Kilometres

Coordinate System:
NAD 1983 UTM Zone 10N

N

Legend

▭ Municipal Boundaries

[mm] Isohyets

METRO VANCOUVER
BRITISH COLUMBIA, CANADA

30-MINUTE INDEX RAIN (MEAN ANNUAL MAXIMUM RAINFALL) CONTOUR MAP

11140666
May 29, 2018

FIGURE 1.4

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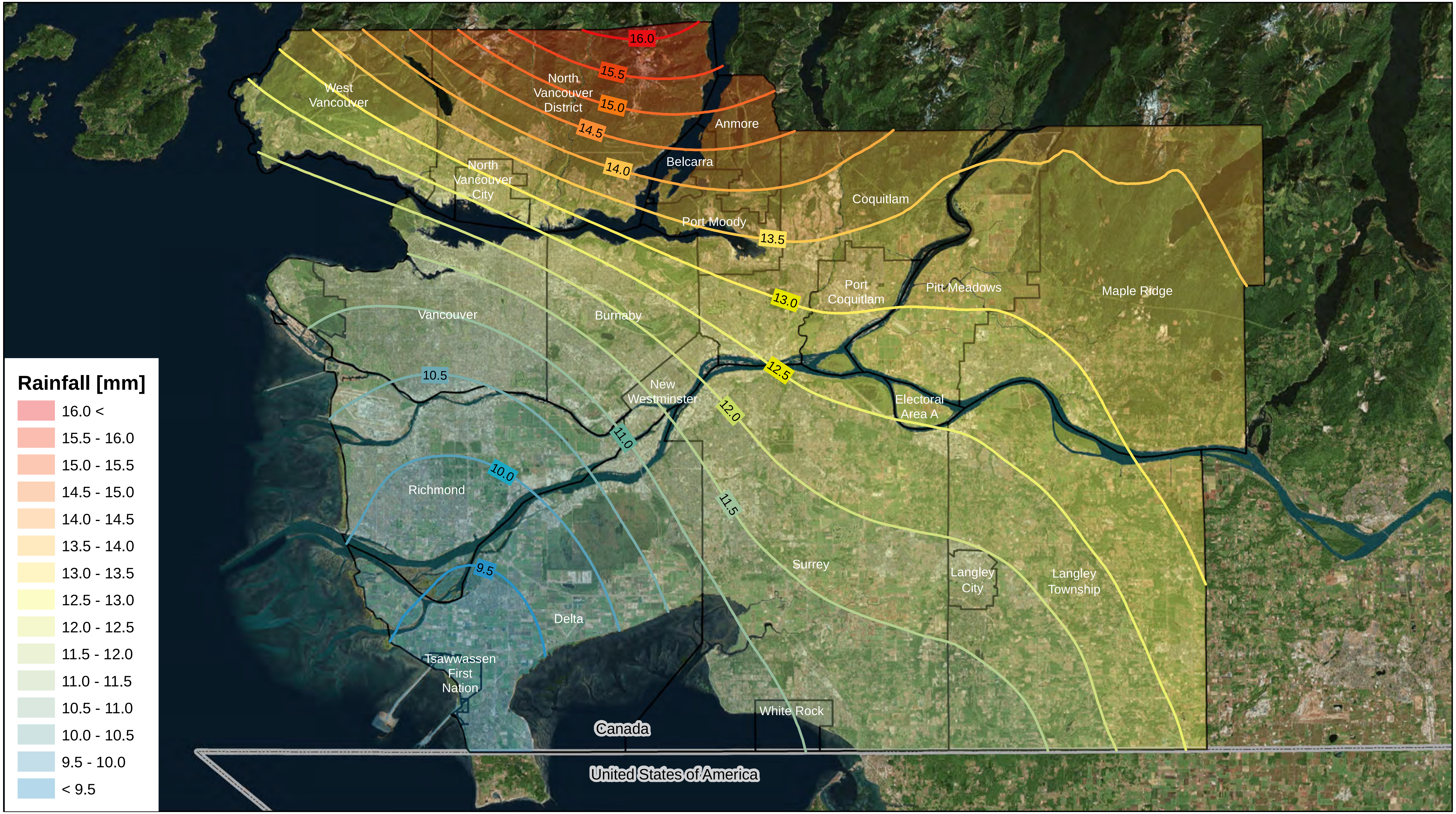

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
ESRI World Imagery Service.

0 2 4 6
Kilometres

Coordinate System:
NAD 1983 UTM Zone 10N

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Legend

▭ Municipal Boundaries

[mm] Isohyets

GHD

METRO VANCOUVER
BRITISH COLUMBIA, CANADA

1-HOUR INDEX RAIN (MEAN ANNUAL MAXIMUM RAINFALL)
CONTOUR MAP

11140666
May 29, 2018

FIGURE 1.5

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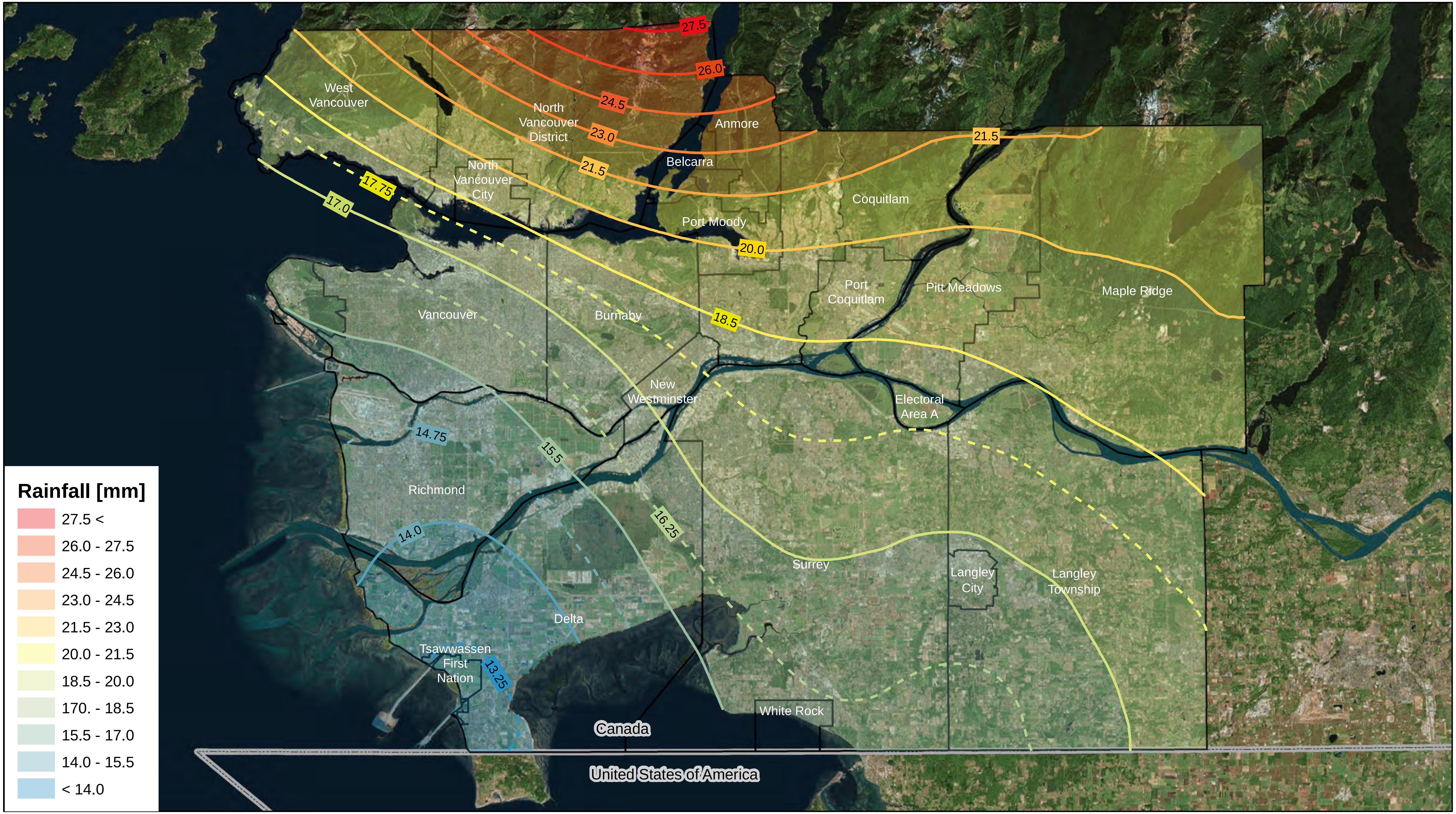

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Kilometres

Coordinate System:
NAD 1983 UTM Zone 10N

N

Legend

▭ Municipal Boundaries

[mm] Isohyets

METRO VANCOUVER
BRITISH COLUMBIA, CANADA

2-HOUR INDEX RAIN (MEAN ANNUAL MAXIMUM RAINFALL) CONTOUR MAP

11140666
May 29, 2018

FIGURE 1.6

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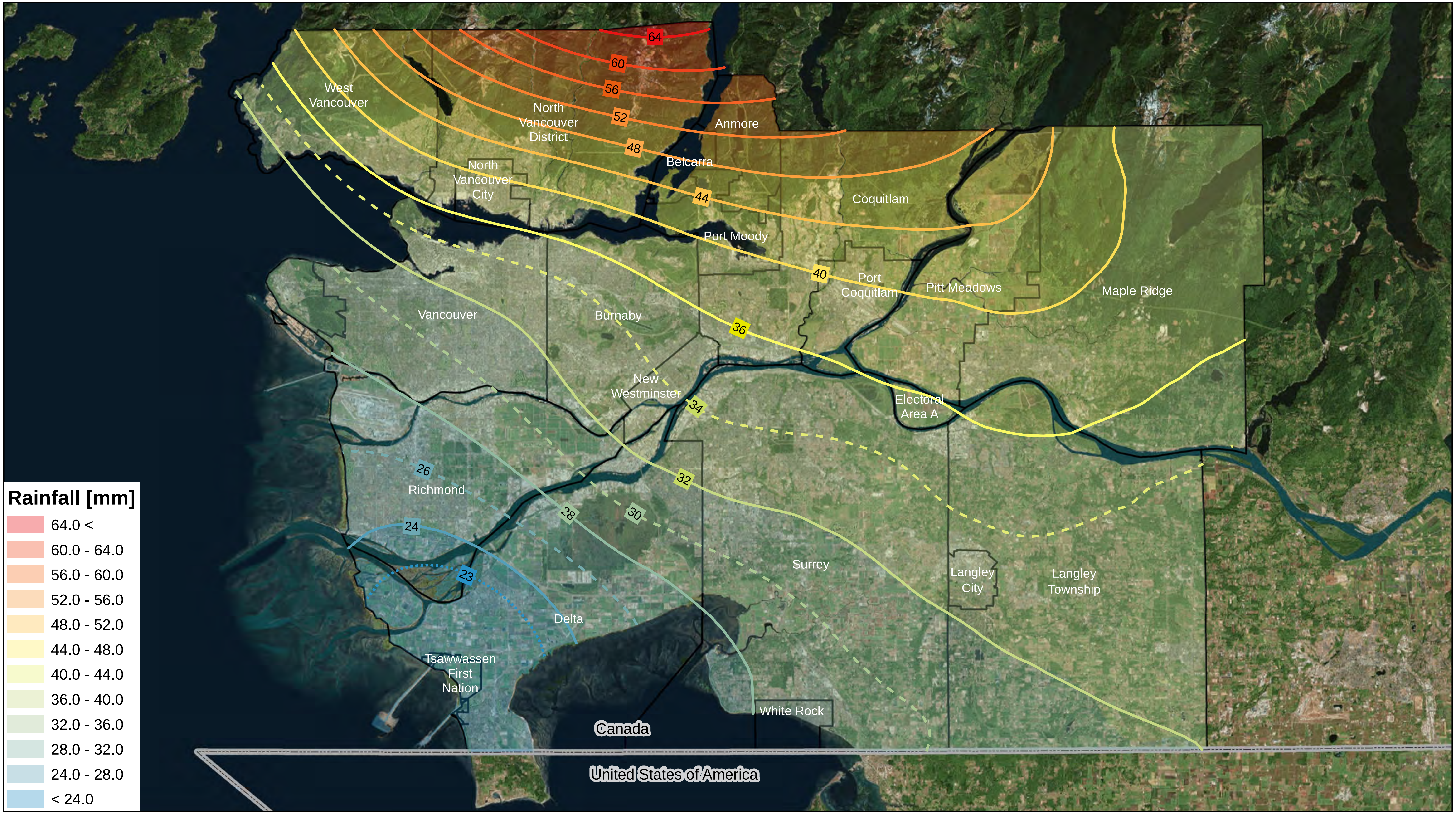

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
ESRI World Imagery Service.

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Kilometres

Coordinate System:
NAD 1983 UTM Zone 10N

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Legend

▭ Municipal Boundaries

[mm] Isohyets

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METRO VANCOUVER
BRITISH COLUMBIA, CANADA

6-HOUR INDEX RAIN (MEAN ANNUAL MAXIMUM RAINFALL)
CONTOUR MAP

11140666
May 29, 2018

FIGURE 1.7

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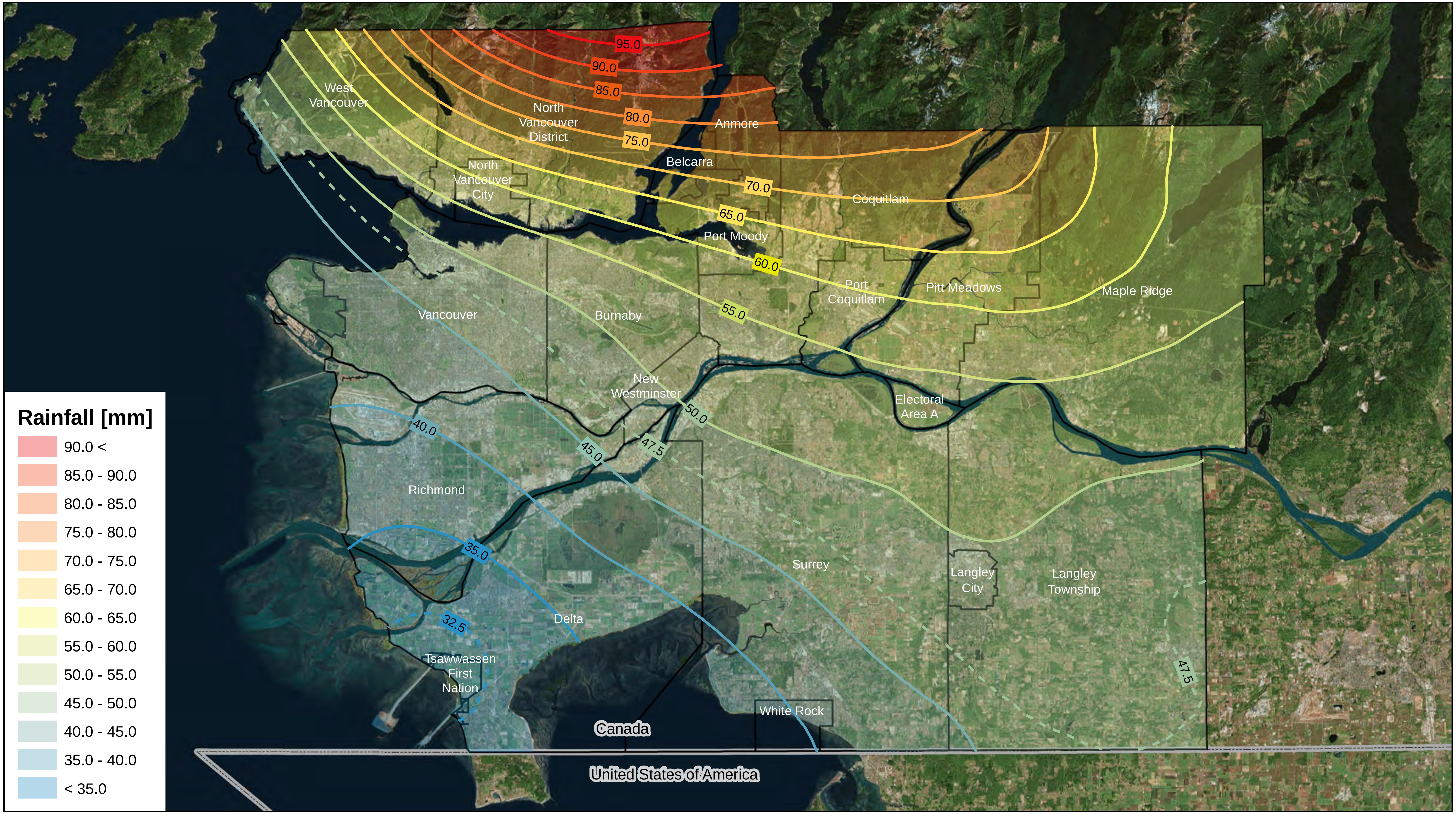

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
ESRI World Imagery Service.

0 2 4 6
Kilometres

Coordinate System:
NAD 1983 UTM Zone 10N

N

Legend

▭ Municipal Boundaries

[mm] Isohyets

METRO VANCOUVER
BRITISH COLUMBIA, CANADA

12-HOUR INDEX RAIN (MEAN ANNUAL MAXIMUM RAINFALL) CONTOUR MAP

11140666
May 29, 2018

FIGURE 1.8

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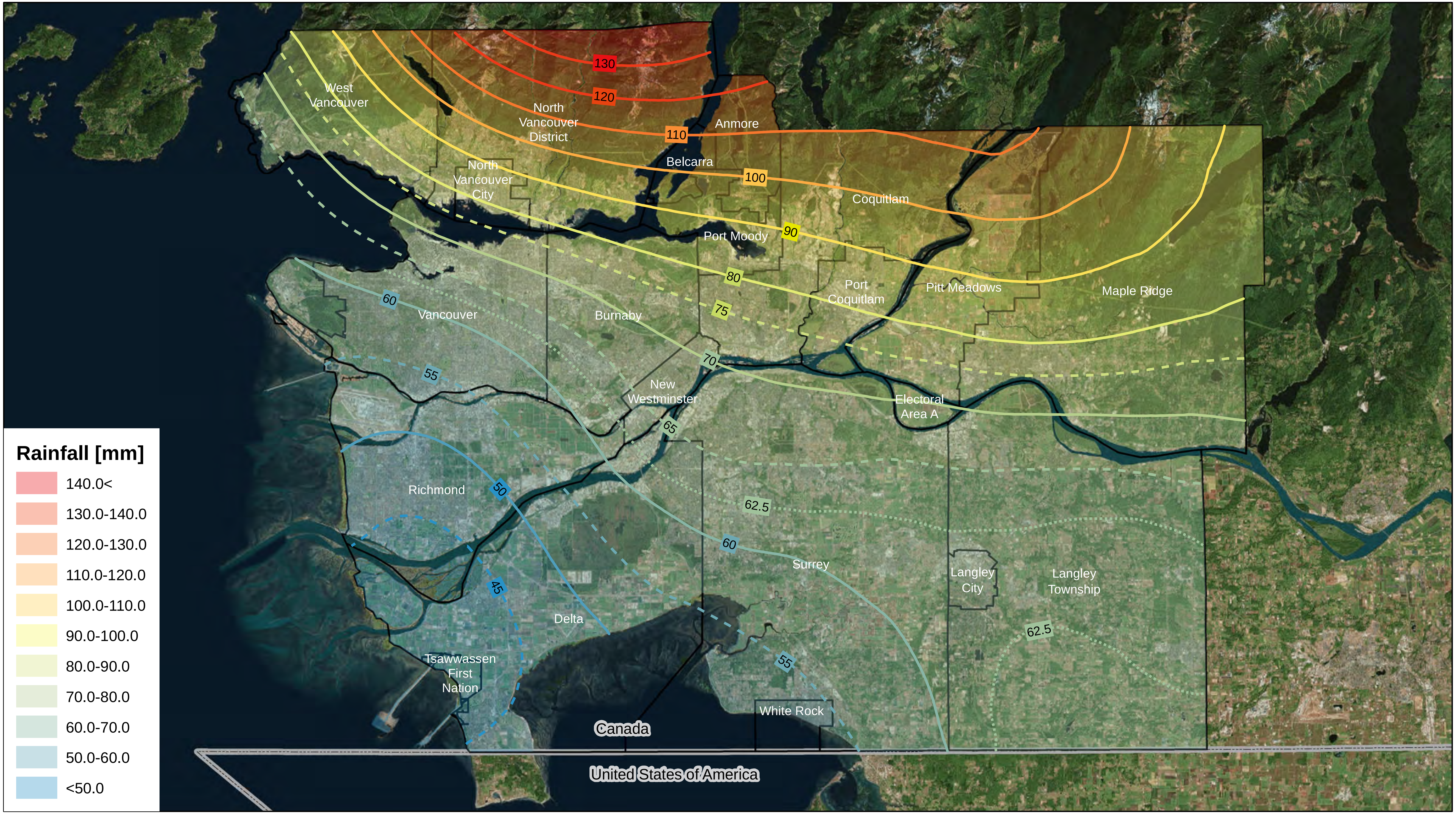

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
ESRI World Imagery Service.

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Kilometres

Coordinate System:
NAD 1983 UTM Zone 10N

N

Legend

▭ Municipal Boundaries

[mm] Isohyets

METRO VANCOUVER
BRITISH COLUMBIA, CANADA

24-HOUR INDEX RAIN (MEAN ANNUAL MAXIMUM RAINFALL)
CONTOUR MAP

11140666
May 29, 2018

FIGURE 1.9

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Technical Memorandum 3
Derivation of Future Climate IDF Curves

Memorandum

August 3, 2018

To: Lillian Zaremba, Ref. No.: 11140666

JMC

From: Juraj Cunderlik, Allyson Bingeman, Yi Wang/aj/3 Tel: 519-884-0510

Subject: **Study of the Impacts of Climate Change on Precipitation and Stormwater Management Derivation of Future Climate IDF Curves**

1. Introduction and Objectives

1.1 Introduction

Increased frequency and intensity of extreme rainfall events will have a significant impact on infrastructure. The Greater Vancouver Sewerage and Drainage District (GVS&DD) has initiated this project for the purpose of advancing its knowledge and capabilities to adapt to the effects of climate change to ensure that adequate levels of service for sewerage and drainage infrastructure are maintained. During past collaboration between GVS&DD and the Pacific Climate Impacts Consortium (PCIC), it was found that many stakeholders were interested in future climate Intensity Duration Frequency (IDF) Curves. In response, GVS&DD initiated this project, which has the following objectives: update the IDF curves for Metro Vancouver, quantify uncertainty surrounding future climate IDF projections, and determine the potential effect of climate change on infrastructure design. The subject of this Technical Memorandum (TM) is the second stage of this study, namely performing a sensitivity analysis of multiple factors affecting the derivation of future climate IDF curves and using the sensitivity analysis results to develop the future climate IDF curves for moderate change and high change for two future time horizons: 2036 to 2065 (2050 time horizon) and 2070 to 2099 (2100 time horizon). The year 2050 is a commonly used time milestone in climate change research studies. The PCIC data ends at the year 2100.

The statistical occurrence of extreme rainfall events is expressed in this TM as exceedance probability, as opposed to return period. Return periods (e.g., 100-year event, 1-in-100-year event) can be misunderstood to mean that the event occurs once every 100 years. In actuality, the event has a 1% probability of being exceeded in any given year. This allows for a clearer description of potential changes due to climate change: the exceedance probability of an event of a certain magnitude increases as climate change affects the frequency of extreme rainfall events. The following terms are used interchangeably in this TM: 1% probability of exceedance and 1% annual exceedance probability (AEP).

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Uncertainty is typically defined as a lack of exact knowledge. In climate change studies, uncertainties are inevitable. Projections of future climate IDF curves are subject to many sources of uncertainty. In this study, the following sources of uncertainty were evaluated:

- Assumptions about future greenhouse gas (GHG) emissions
- Differences between various General Circulation Models (GCMs)
- Spatial and temporal downscaling from large-scale, daily GCM outputs
- Assumptions about changes in the relationship between daily and sub-daily rainfall in the future
- Changes in rainfall caused by long-term atmospheric patterns such as the Pacific Decadal Oscillation (PDO)
- Assumptions about the frequency distribution used to define the IDF curve

Sensitivity analysis evaluates the amount of variability in the model output due to each source of uncertainty, and allows the uncertainty sources to be ranked by their relative importance.

1.2 Objectives

The first objective of this TM is to identify possible sources of uncertainty in generating future climate IDF curves, and develop levels for each factor. The second objective is to rank the sources of uncertainty according to their impacts on the future climate IDF curves, using a sensitivity analysis. The third objective is to define moderate and high change scenarios for the 2050 and 2100 time horizons, using the results of the sensitivity analysis. Future climate IDF curves are derived in this TM.

The remainder of this TM is organized as follows:

Section 2 describes the sources of uncertainty in the estimation of future climate IDF curves.

Section 3 contains the methodology of the sensitivity analysis and selection of the future climate scenarios.

Section 4 summarizes the sensitivity results and discusses the importance of each source of uncertainty.

Section 5 provides the future climate IDF curves and a discussion of future rainfall and uncertainty.

Section 6 provides conclusions of the study and recommendations for future work.

2. Uncertainty Factors and Levels

Projections of future climate IDF curves are subject to many sources of uncertainty. The various sources of uncertainty involved in projecting future climate can be categorized into three general categories:

(1) Uncertainties in the prediction of the future

(2) Limitations of existing techniques

(3) Regional/project specific factors

The uncertainty factors explored in this project and how they were defined are described in the next subsections.

2.1 Representative Concentration Pathways

In this project, uncertainties in the prediction of the future were addressed by two different GHG emission scenarios, known as representative concentration pathways (RCPs), which are trajectories of GHG concentrations adopted by the Fifth Assessment Report of the IPCC (2013). The four RCPs, RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5, are depicted in Figure 2.1. The differences between RCPs can be attributed to different assumptions on socioeconomics, land use, technology, and policy.

Two RCP scenarios were selected for the sensitivity analysis: RCP 8.5, the business-as-usual emission scenario, and RCP 4.5, a middle-of-the-road emissions reduction scenario. These are prudent choices when planning for infrastructure with long service life, since global policy to date continues to reflect the business-as-usual pathway and sustained reductions appear improbable at present. Only RCP 8.5 was used for the 2050 time horizon, due to the similarity in the radiative forcing between the two RCP scenarios at year 2050. The figure is produced using RCP scenario data from van Vuuren et al. (2007), Clarke et al. (2007), Smith and Wigley (2006), Wise et al. (2009), Fujino et al. (2006), Hijioka et al. (2008), and Riahi et al. (2007), downloaded from the IAMC database (http://www.iiasa.ac.at/web-apps/tnt/RcpDb).

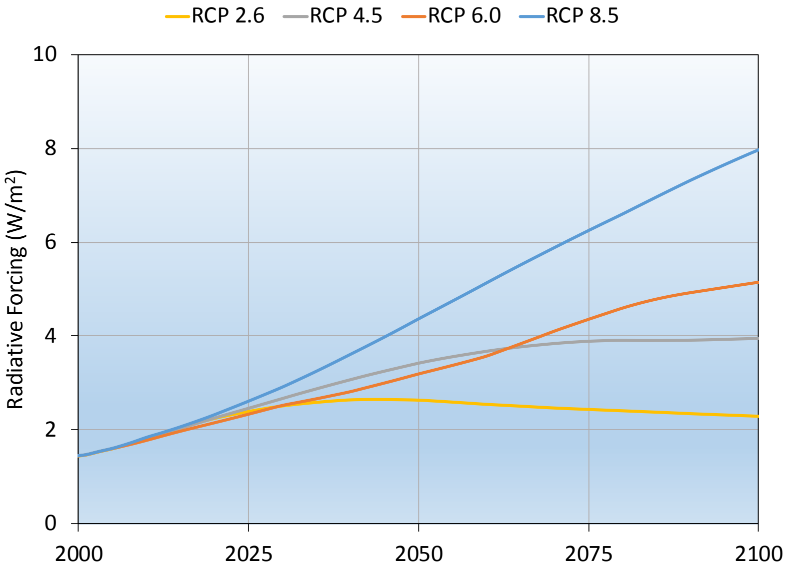


Figure 2.1 **Representative Concentration Pathway Projections of Radiative Forcing in the 21st Century (Produced Using Scenario Data from IAMC database)**

RCP2.6 is the "best case" scenario, where the radiative forcing peaks in the 2020s and then stabilizes. Both the RCP 4.5 and RCP 6 are stabilization without overshoot scenarios where a range of technologies and strategies for GHG emissions are adopted and the total radiative forcing stabilizes before 2100. The RCP 8.5 has total radiative forcing increasing over the entire 21st century and is representative of scenarios with few controls placed on GHG emissions. Two RCP scenarios were selected for the sensitivity analysis: RCP 8.5, the business-as-usual emission scenario, and RCP 4.5, a middle-of-the-road emissions reduction scenario. These are prudent choices when planning for infrastructure with long service life, since global policy to date continues to reflect the business-as-usual pathway and sustained reductions appear improbable at present. Only RCP 8.5 was used for the 2050 time horizon, due to the similarity in the radiative forcing between the two RCP scenarios at year 2050.

2.2 Spatial Downscaling Methods

GCMs are currently limited to large spatial (1 to 3 degrees) and temporal (daily) scale predictions and therefore spatial and temporal downscaling methods are utilized to obtain finer-scale outputs. Two different spatial downscaling methods were selected for this project: the Bias-Correction Spatial Disaggregation (BCSD) and the Bias Correction/Constructed Analogues with Quantile mapping reordering (BCCAQ). Both methods were used by PCIC to spatially downscale outputs from selected 12 GCMs for the Western North America region, and were both included in the analysis. The downscaled outputs are available in 300 arc-second grids (approximately 10 km by 10 km) for the period of 1950 - 2100. The Pacific Climate Impacts Consortium (PCIC) selected 12 GCMs for the Western North America region, according to the Giorgi Regions (Giorgi and Francisco, 2000, see Table 2.1). This selection provides the widest spread in projected future climate for a smaller subset of the full ensemble as defined by Cannon (2015).

Table 2.1 List of Global Circulation Models Selected for the Western North America Region

Name		
CNRM-CM5-r1	CSIRO-Mk3-6-0-r1	HadGEM2-CC-r1
CanESM2-r1	CCSM4-r2	MRI-CGCM3-r1
ACCESS1-0-r1	MIROC5-r3	GFDL-ESM2G-r1
inmcm4-r1	MPI-ESM-LR-r3	HadGEM2-ES-r1

2.3 Scaling Factors

The PCIC daily precipitation series must be temporally downscaled into sub-daily and sub-hourly durations. There are various methodologies for temporal downscaling, most of which involve building statistical relationships between the GCM data and the historical data. Many studies have assumed that the statistical relationship between sub-daily and daily precipitation is temporally invariant (for example the IDF-CC tool developed by Western University, which provides online access to projected IDF curves under climate change). However, climate change may introduce non-stationarity to the daily to sub-daily ratios,Westra et al. (2014), as reviewed by PCIC (2015), identified that the daily rainfall extremes are increasing "between 5.9% and 7.7% per °C", which is close to the Clausius-Clapeyron (C-C) relation. The authors also mentioned that, at sub-daily time scales, especially at hourly or sub-hourly scales, extreme rainfall increases with air temperature at the C-C rate up to 12 °C, at twice the C-C rate between 12 °C and 24 °C, and at a reversed rate above 24 °C (Figure 2.2). This statement was reviewed and recommended by Zhang et al. (2017).

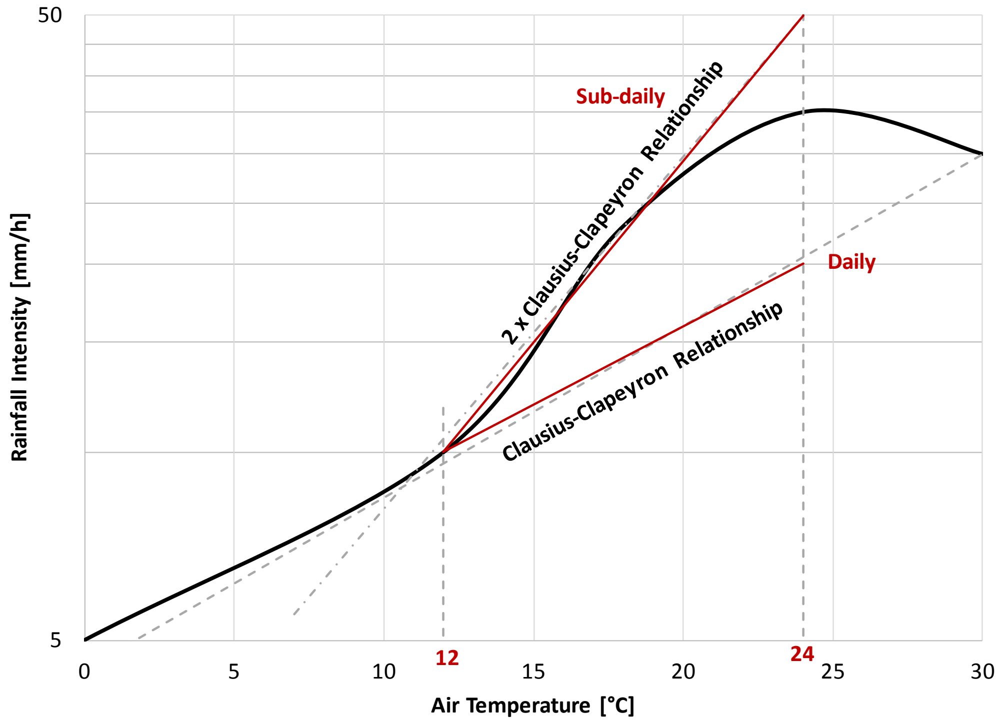


Figure 2.2 Clausius-Clapeyron Relationship Between Rainfall Intensity and Air Temperature

The C-C relation in combination with global warming projections can be translated into scaling factors of the daily to sub-daily ratios. For rainfall events taking place in the 12°C to 24°C air temperature range, every Celsius degree increase in the air temperature will increase the rainfall intensity by 7% to 14% for the rainfall durations from daily to sub-hourly. If the air temperature increases from 12°C to 24°C, the daily to sub-daily ratio will increase by 46%, which defines the upper limit of the scaling factors.

Temporal downscaling uncertainty was addressed by using different scaling factors. A scaling factor of 1.0 would assume temporally invariant or stationary daily to sub-daily ratios. An upper limit of 1.46 can be obtained from the C-C relation. The uncertainty analysis included factor levels of 1.0 (no change) and 1.2 for the 2050 time horizon, and 1.0, 1.2, and 1.4 for the 2100 time horizon. The scaling factors were applied uniformly to sub-hourly rainfall durations (5-, 10-, 15-, 30-min and 1-hr), and linearly decreased from 1.2 or 1.4 at the 1-hr duration to 1.0 at the 24-hr duration.

The scaling factor was applied uniformly to sub-hourly rainfall durations (5, 10, 15, 30-min and 1-hr), and linearly decreased from 1.2 or 1.4 at the 1-hr duration to 1.0 at the 24-hr duration. Table 2.2 lists the scale factors for different rainfall durations.

Table 2.2 Scale Factors for Rainfall Durations

Name	5-min	10-min	15-min	30-min	1-hr	2-hr	6-hr	12-hr	24-hr
Scale Factor 1.2	1.20	1.20	1.20	1.20	1.20	1.19	1.16	1.10	1.00
Scale Factor 1.4	1.40	1.40	1.40	1.40	1.40	1.38	1.31	1.21	1.00

2.4 Statistical Frequency Distributions

The selection of frequency distributions was considered a project-specific source of uncertainty since this step is not required in other climate change studies (such as those that utilize projections of daily or monthly rainfall and do not need to perform frequency analysis). The IDF curves are derived by fitting frequency distributions to the annual maximum rainfall data series and then estimating rainfall intensities of various Annual Exceedance Probabilities (AEPs). The goodness-of-fit performance of different frequency distributions (statistical estimation uncertainty) can introduce uncertainties into rainfall intensity estimates. The Generalized Extreme Value (GEV), the Generalized Normal (GNO), and the Gumbel (GUM) distributions were found to be the most accepted frequency distributions to develop regional IDF curves in the Metro Vancouver region and consequently were included in the uncertainty analysis.

2.5 Pacific Decadal Oscillation

The second project-specific factor of uncertainty considered in this project was the PDO. The PDO is a long-term atmospheric cycle that can affect the long-term variability in rainfall and subsequently the IDF curves in the Metro Vancouver region. "Cool" and "warm" PDO phases can persist for approximately 20 to 35 years, as seen in Figure 2.3. High intensity rainfall events occur more frequently with higher rainfall amounts during a cool phase. Another factor that may affect the analysis is the possible effect of the PDO on climate change. Biondi et al. (2001) found that climate change may be either enhanced or suppressed by changes in long-term climatic variability such as the PDO. This indicates that there is an interrelationship between climate change and PDO, which adds an additional source of uncertainty. The sensitivity analysis evaluated three PDO scenarios: years with PDO cool indices, with warm indices, and with all indices, designated as the factor levels of "Cool", "Warm", and "All".

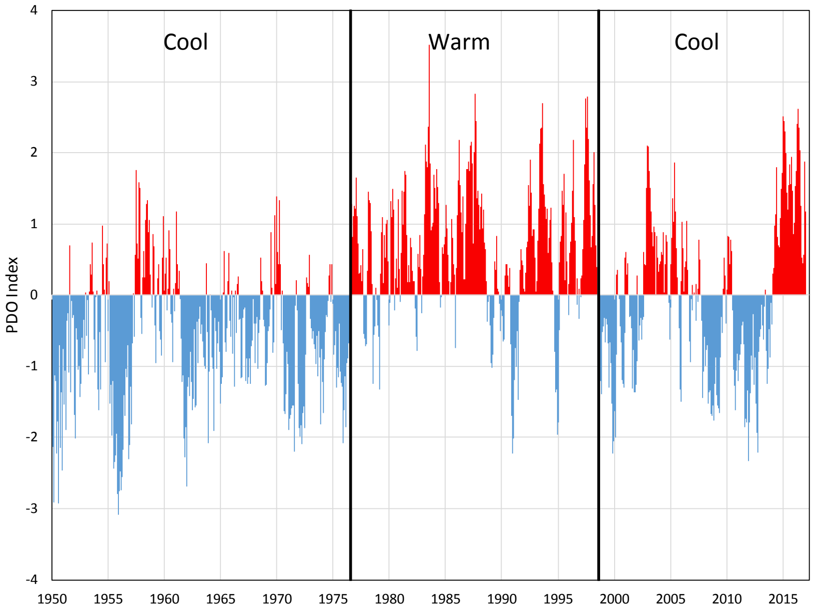


Figure 2.3 Pacific Decadal Oscillation Index from 1950 to Current

In addition to the PDO, Metro Vancouver region also experiences variation in rainfall from Atmospheric River (AR) events and El Nino-Southern Oscillation (ENSO) phenomena. As discussed in TM2, the AR events have multiple occurrences annually and thus are inherently included in the IDF curves, since the IDF curves were developed based on AM data. The ENSO phenomena have a cycle of two to seven years. The differences between ENSO phases were averaged out when developing IDF curves using records longer than 10 years. For these reasons, neither AR nor ENSO were evaluated in the uncertainty analysis.

3. Sensitivity Analysis Methodology

TM 1 presented the methodology to derive future climate IDF curves. The methodology was utilized in the uncertainty analysis. The downscaling method and the RCP scenario were used to select the GCM data series to analyze for each run. The PDO phase was used to screen the historical rainfall records and baseline GCM records based on the annual PDO index. The scaling factor was incorporated into the temporal downscaling process (multiplied by the daily to sub-daily ratios), and the frequency distribution was used to construct regional and at-site rainfall frequency distributions.

Zone 1 was selected as the pilot (initial) zone for the sensitivity analysis. The finalized methodology was then applied to the remaining rainfall zones.

3.1 Uncertainty Factors and Combinations

The combinations of factors and levels for the two horizons are listed in Table 3.1. It is noted that, including the seven AEPs (50%, 20%, 10%, 4%, 2%, 1%, and 0.5%) and nine rainfall durations (5-min, 10-min, 15-min, 30-min, 1-hr, 2-hr, 6-hr, 12-hr, and 24-hr) in the IDF curves, the uncertainty analysis consisted of 27,216 combinations for the 2050 time horizon, and 81,648 combinations for the 2100 time horizon.

Table 3.1 Factor Levels Used for Future Time Horizons

Factor Category	2050 Time Horizon	2100 Time Horizon
RCPs	RCP 8.5	RCP 4.5, RCP 8.5
Downscaling Methods	BCCAQ, BCSD	
GCMs	12 GCMs	
Frequency Distributions	GEV, Gumbel, GNO	
Scaling Factors	1.0, 1.2	1.0, 1.2, 1.4
PDO Indices	Warm, Cool, All	

3.2 Deltas

The "Deltas" in the delta method in TM1 (Equation 6 in TM1, and modified as Equation 1 below) are the ratios between the gridded regional frequency distribution (RFD) quantile ($I_{T,d}^{Gridded}$) and the future GCM RFD quantile ($I_{T,d}^{GCM,Fut}$). The deltas were used herein to quantify the impact of the various factor combinations on the variation of the future climate IDF curves.

$$Delta = \frac{I_{T,d}^{GCM,Fut}}{I_{T,d}^{Gridded}} \quad \text{Equation 1}$$

A set of deltas (seven AEPs and nine durations) were calculated for each combination of factors.

3.3 Boxplots

Customized boxplots were created to visualize the range of deltas for each set of factor levels. Generally, a boxplot consists of a rectangle in the middle that spans from the first quartile to the third quartile. A horizontal line inside the rectangle shows the location of the median value. There are two whiskers above and below the rectangle, which extend 1.5 times of the interquartile range beyond the rectangle. Deltas above or below the whiskers are considered to be outliers and are shown as dots outside of the whiskers.

Multiple boxplots were utilized to visually illustrate the changes in deltas between various factor levels. Figure 3.1 gives an example of how the factor sensitivity can be visually compared. The left part of the figure shows two boxplots of deltas when using the two RCP scenarios – RCP 4.5 and RCP 8.5, separately. Each boxplot represents half of the "large set" – the set of deltas of all factor combinations as an enclosure of all possibilities that were generated using the corresponding RCP. Similarly, the second rectangle illustrates the difference between downscaling methods BCCAQ and BCSD, and the third rectangle illustrates the range of deltas with different PDO indices, and so forth. Sensitivities to the factors can be perceived when examining the figures side by side, and with the aid of colour-coding. If the difference between the largest and the smallest medians is greater than 0.2, a red color background is used to highlight the figure. A pink background indicates a difference between 0.1 and 0.2; for all other values a white background is used. The colour-coding technique is especially helpful when analyzing the sensitivity of the factor over different rainfall durations and AEPs at the same time (Figure 3.2 through Figure 3.6). In these figures, the large set is split into subsets according to rainfall durations and AEPs (seven rows and nine columns of rectangles), and then split by the factor being investigated into sub-subsets and compared using the boxplots.

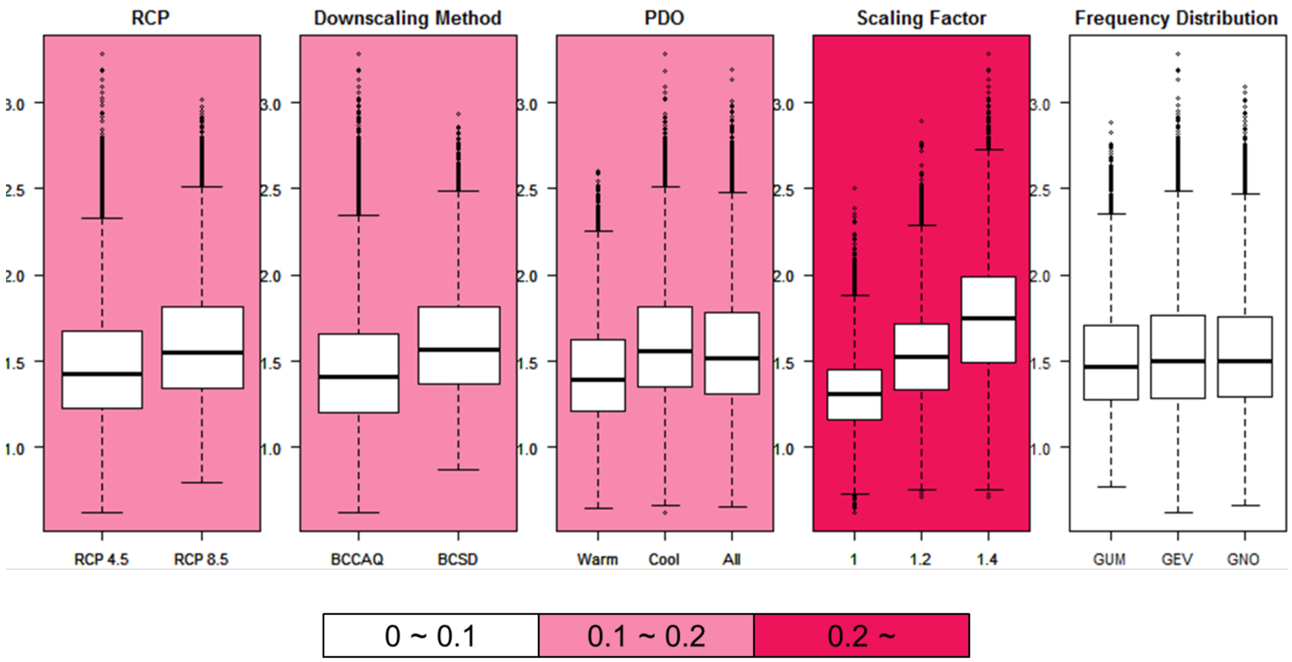


Figure 3.1 Boxplot Comparison of Deltas for the 2100 Time Horizon

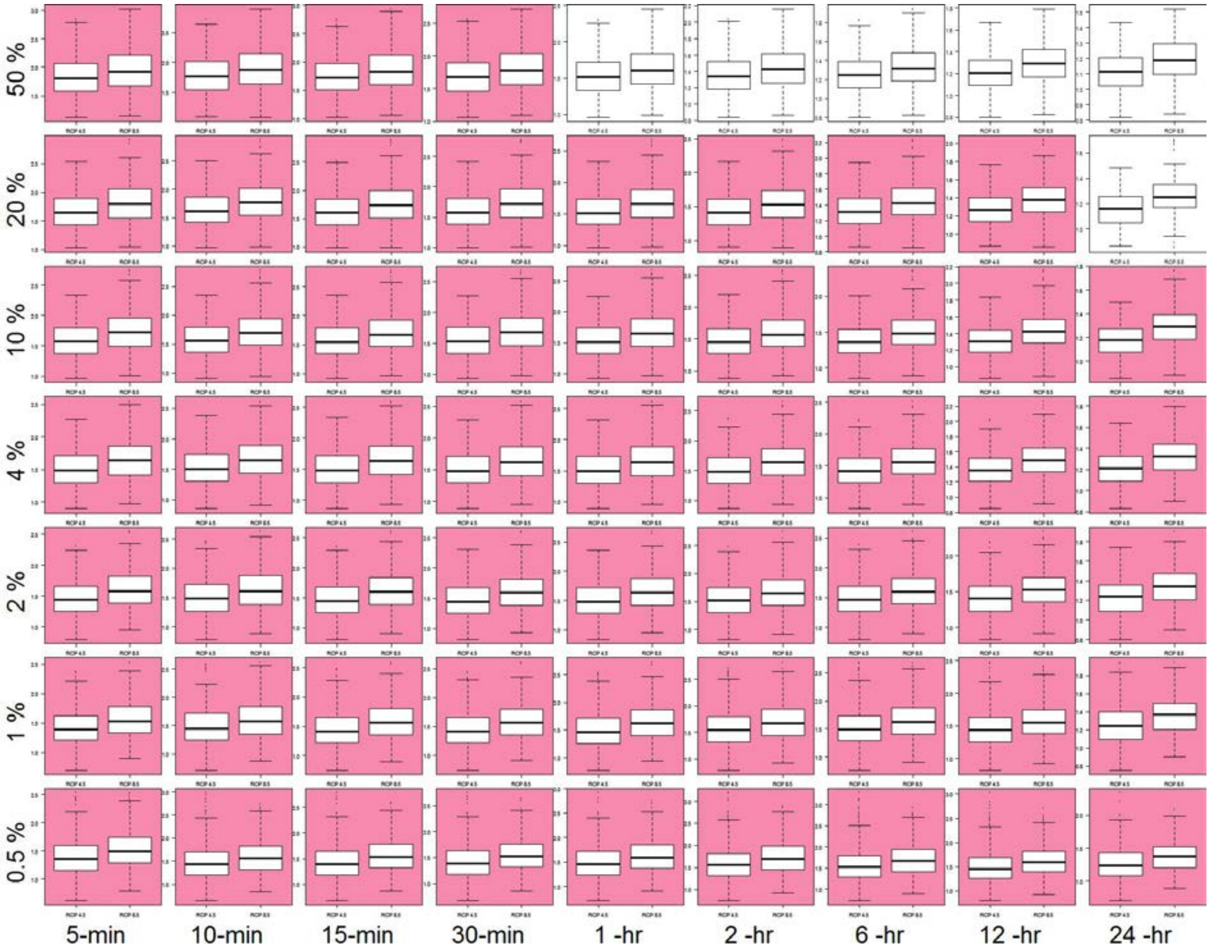


Figure 3.2 Boxplot Comparison of Deltas for the 2100 Time Horizon, Split by Durations (Horizontal), AEPs (Vertical), and RCP

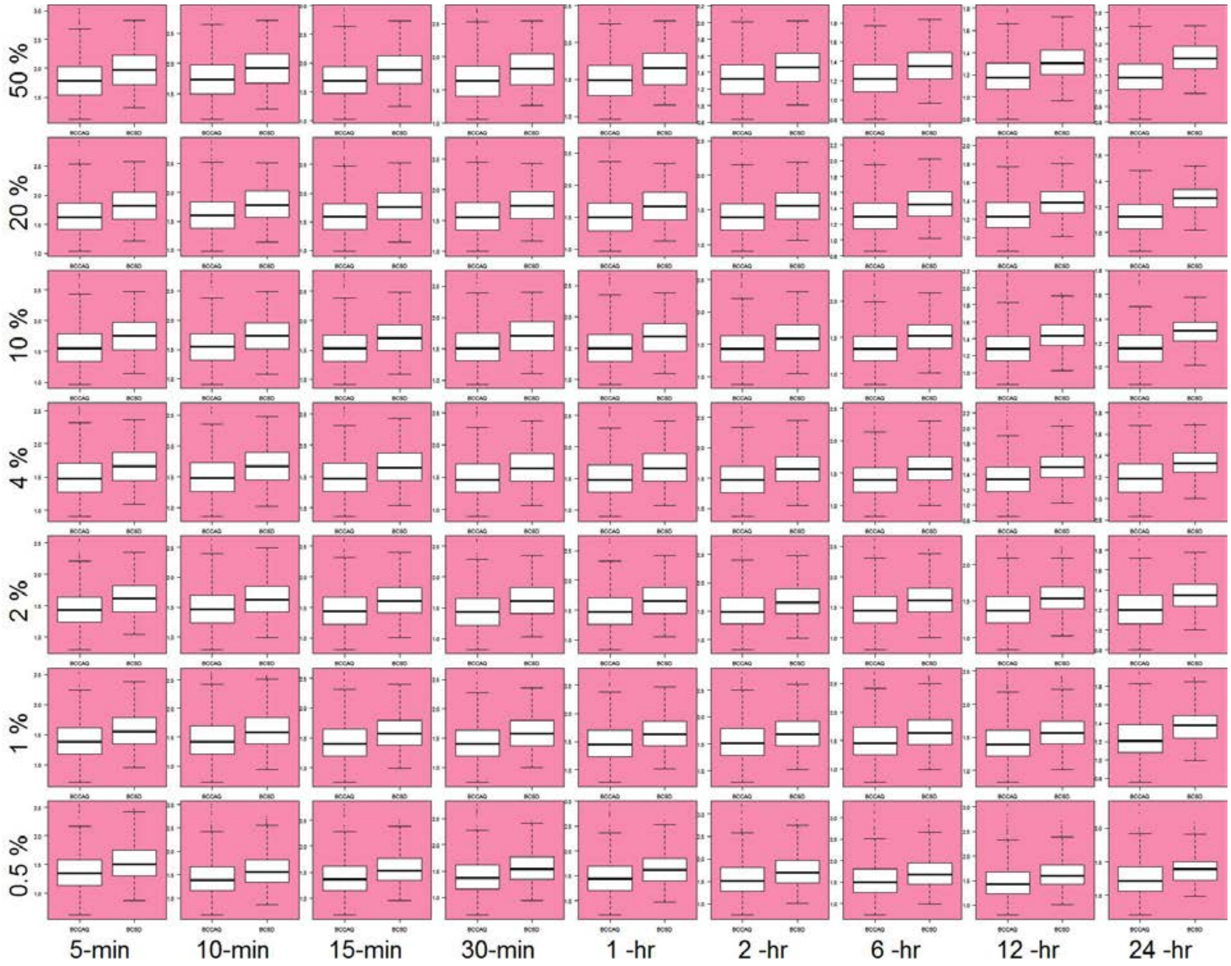


Figure 3.3 Boxplot Comparison of Deltas for the 2100 Time Horizon, Split by Durations (Horizontal), AEPs (Vertical), and Downscaling Method

Figure 3.4 **Boxplot Comparison of Deltas for the 2100 Time Horizon, Split by Durations (Horizontal), AEPs (Vertical), and PDO Index**

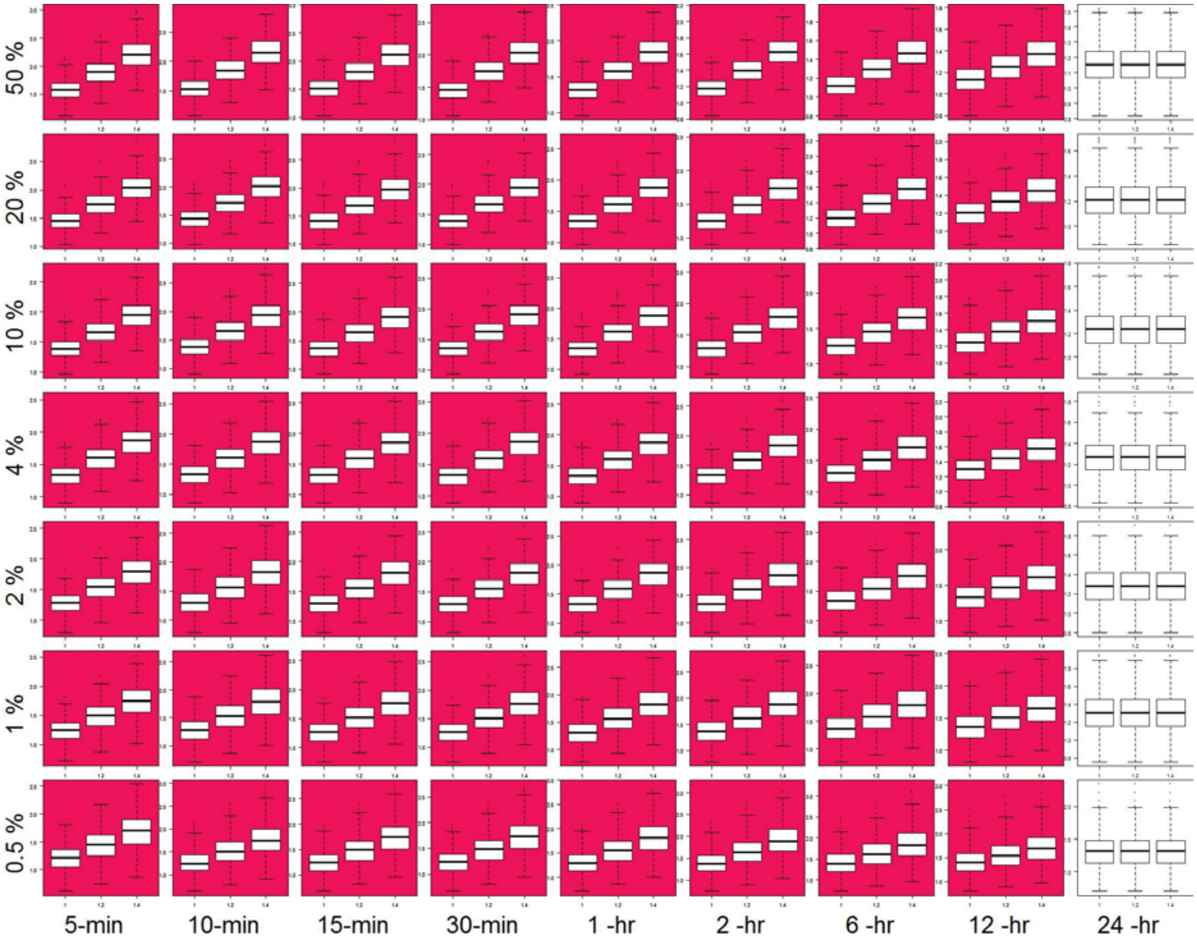


Figure 3.5 Boxplot Comparison of Deltas for the 2100 Time Horizon, Split by Durations (Horizontal), AEPs (Vertical), and Scaling Factor

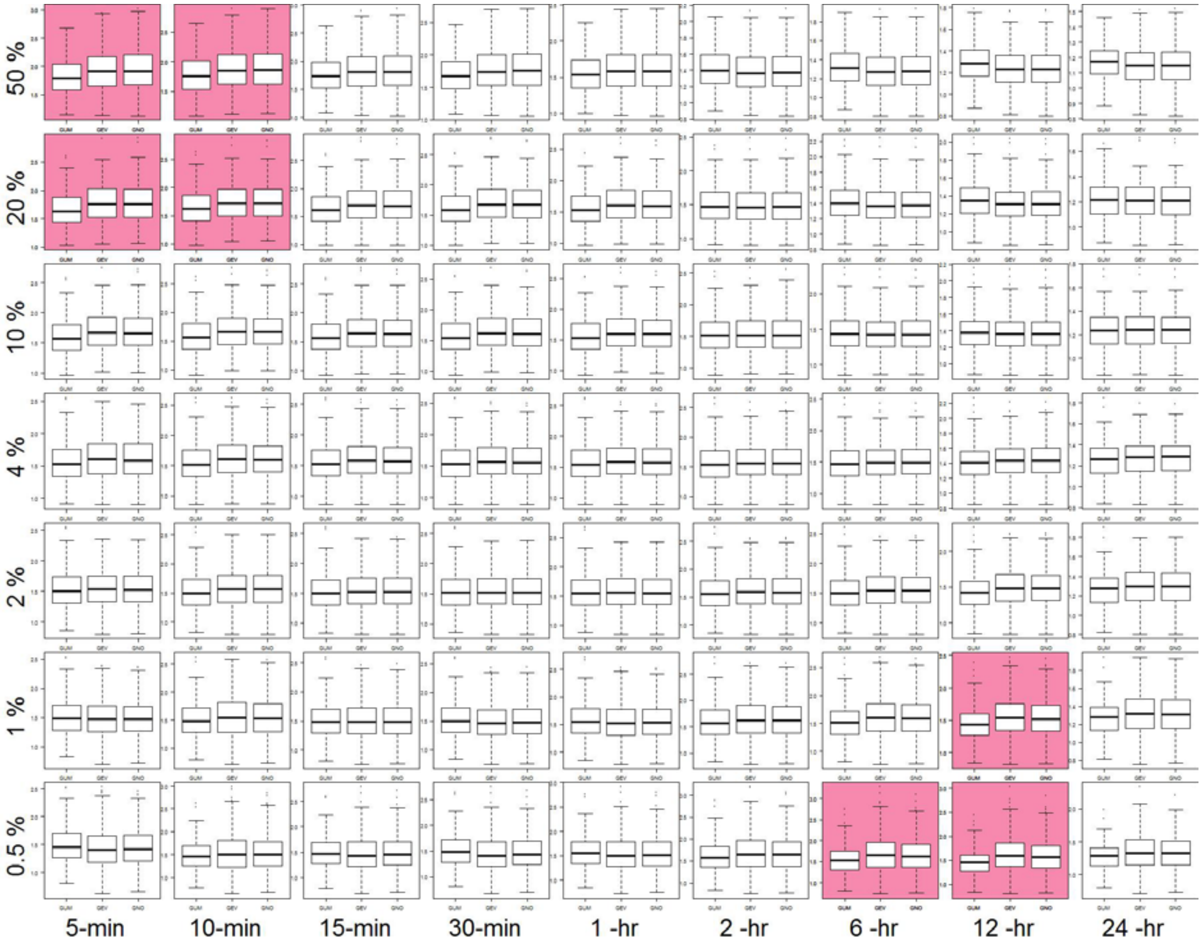


Figure 3.6 Boxplot Comparison of Deltas for the 2100 Time Horizon, Split by Durations (Horizontal), AEPs (Vertical), and Frequency Distribution

In the example shown in Figure 3.2 through Figure 3.6, the scaling factor has the most effect on the deltas, and the frequency distribution has the least effect on the deltas. Figure 3.5 shows that splitting the "large set" by the scaling factor produced almost all red boxplots (i.e., the difference between the largest and the smallest medians is greater than 0.2) except for the 24-hr column (because scaling factor was always 1.0 for the 24-hr duration). The methodology generated all pink boxplots for the downscaling method (Figure 3.3), almost all pink boxplots for RCP (Figure 3.2), and a mix of red, pink, and white boxplots for the PDO index (Figure 3.4). The frequency distribution (Figure 3.6) only showed a few pink boxplots and rest are all in white. Figure 3.2 through Figure 3.6 illustrated that the scaling factor introduced the largest amount of uncertainties into the deltas; therefore, it was considered as the most sensitive factor.

After identifying that the scaling factor was the most sensitive factor, the subsets of deltas corresponding to scaling factors of 1.0, 1.2, and 1.4 for the 2100 time horizon (1.0 and 1.2 for the 2050 time horizon) were separated from the "large set". Customized boxplots were created for the subset of deltas according to the remaining factors (downscaling method, RCP, PDO, and frequency distribution). The factor with the largest number of red boxplots was considered as the second most sensitive factor. After that, the deltas were further subdivided using the second most sensitive factor to find the third most sensitive factor, and the process was repeated until all of the factors were sorted according to sensitivity.

3.4 Selection of Future Climate Scenarios

The sensitivity analysis provided an understanding of the amount of uncertainty each factor introduced into the future climate IDF curves. Combinations of factors were selected from the results of the sensitivity analysis to represent the moderate and high change scenarios required for the project. The boxplot of the deltas using the combination of factors for the selected scenario was compared with the boxplot of the large set to provide an understanding of the range of deltas for the selected scenario compared to the range of all deltas for all factors. Combinations of factors close to the median of the large set indicate that these sets of combinations match the central tendency of the large set and can be appointed as moderate change scenarios. Combinations of factors located in the top range (e.g., 90th percentile) of the large set can be designated as high change scenarios.

4. Sensitivity Analysis Results

4.1 Ranking of Sources of Uncertainty and Selection of Factors

The sensitivity analysis was performed on the five factors and the boxplots, as shown in Figure 3.1 through Figure 3.6, were created and analyzed to rank the factors. For the 2100 time horizon, the scaling factor demonstrated the largest sensitivity. For the other factors (PDO, downscaling methods, and RCP), the ranges of deltas were largely overlapping and the differences in the ranges of deltas were not large enough to separate one factor from the rest. Therefore, they were all ranked the second place in the sensitivity analysis. For the 2050 time horizon, the scaling factor ranked the highest sensitive factor again, and the downscaling method and the PDO indices ranked second and third with minimal difference. The frequency distribution is an insensitive factor for both time horizons, which indicating switching from one frequency distribution to another will not significantly change the deltas or the future climate IDF curves. It should be noted that these results indicate that the selection of frequency distribution used in the calculation of the delta (change in rainfall due to climate change) does not greatly impact the value of the delta, however, they do not indicate that the current IDF curve is insensitive to the frequency distribution.

The deltas ranged from less than 1.0 to over 3.0 for both time horizons, i.e., from decreases to up to a triple increase in rainfall intensity. The large range of deltas was the result of simultaneous variations of multiple factors, especially when all factors were at the levels that can lead to large positive (or negative) changes in the IDF curves. The scaling factor, which is the least understood (and most uncertain) factor, introduced the most variability. For the 2050 time horizon, the deltas increased from an average of 1.22 at a scaling factor of 1.0 to an average of 1.42 at a scaling factor of 1.2. For the 2100 time horizon, the deltas increased from an average of 1.31 at a scaling factor of 1.0 to an average of 1.53 at a scaling factor of 1.2 and an average of 1.74 at a scaling factor of 1.4.

Shown in Figure 4.1 (a), the distribution of deltas of different scaling factors are significantly different. The deltas of scaling factor 1.0 are smaller and more centralized, while the deltas of scaling factor 1.4 are larger and more dispersed. As the most sensitive factor, the scaling factor can substantially change the future climate IDF curves. Using a large scaling factor can produce future climate IDF curves that are very different from those produced using a small scaling factor. However, the academic research is not yet sufficient to provide an understanding of how the scaling factor may vary as climate change occurs. This study has adopted a simplified scaling factor adjustment based on the Clausius-Clapeyron relation. The downscaling methods, RCP scenarios, and PDO phases were less sensitive factors and introduced limited amount of uncertainty. The distribution of the deltas of different factor levels are shown in Figure 4.1 (b)-(d). The frequency distribution was the least sensitive factor; therefore, the distribution of deltas of different frequency distributions is not shown.

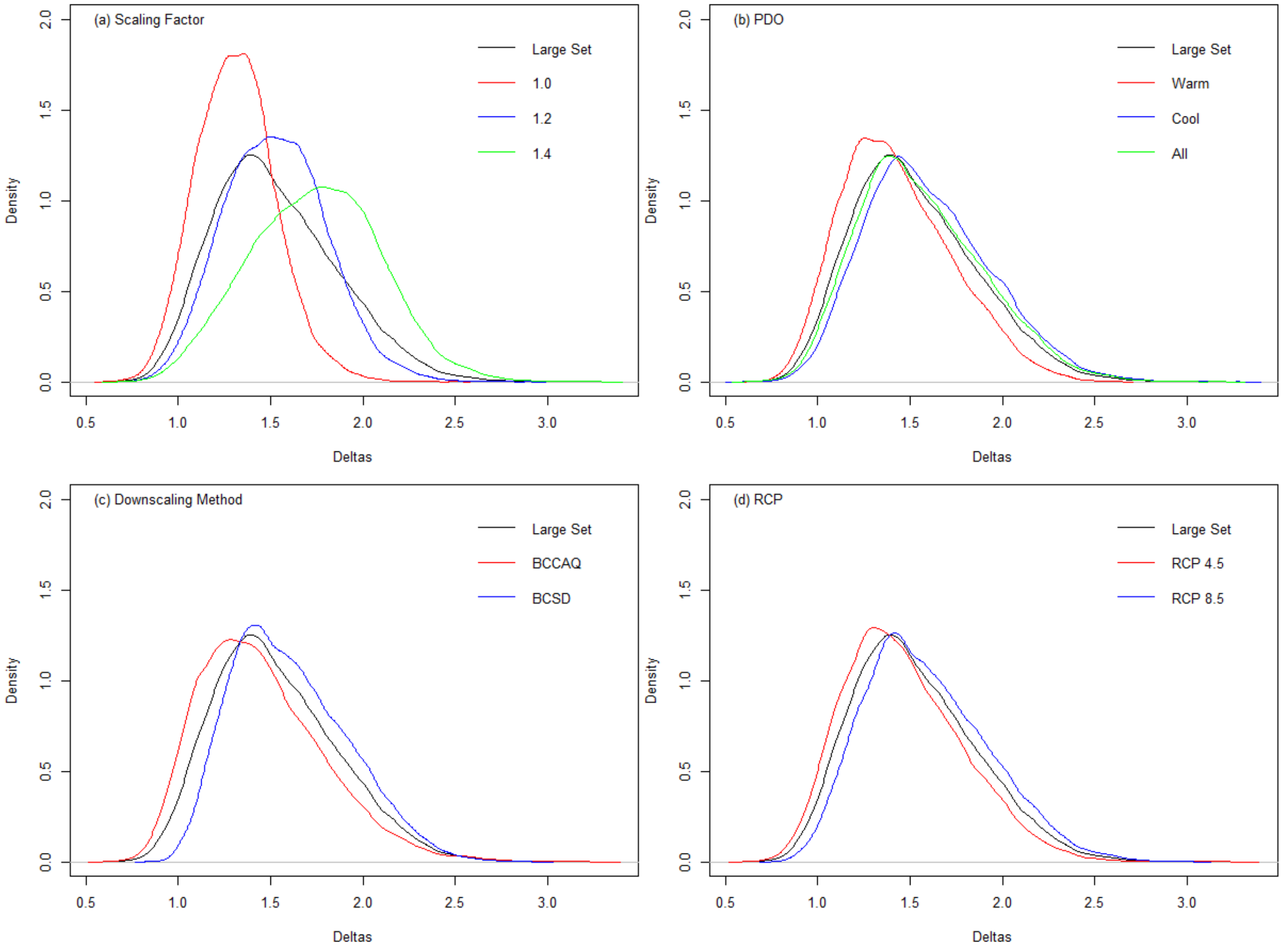


Figure 4.1 Distribution of the Deltas for Different Factors

Factor levels for PDO, spatial downscaling methods, RCP scenarios, and frequency distribution were selected during discussions with PCIC. PCIC explained that using PDO Cool with a high percentile (e.g., 95th percentile) may double-count climate change effects in the high change scenario. PCIC advised that the 95th percentile events tends to take place during PDO Cool; as a result, if the 95th percentile is selected, it is most likely already PDO Cool. The results of PDO Cool provided an understanding of how PDO indices were affecting the future climate IDF curves; however, in this project, it was not desired to overestimate or "double-count" changes in the future climate IDF curves. Since PDO All was selected for generating the future climate IDF curves for the moderate and high change scenarios, the PDO Cool phase was not explicitly accounted for in the generation of the IDF curves. However, it is implicitly accounted for in the selection of a 95th percentile event.

PCIC also provided feedback about the use of BCSD/BCCAQ. BCSD is known to be prone to inflation of large events. GHD's analysis has confirmed this fact, and quantified the degree of exaggeration to be approximately 20%. PCIC characterized BCCAQ as more robust and recommended it be used for generating the moderate and high change future scenarios in this study.

PCIC preferred the RCP 8.5 scenario over the RCP 4.5 for the 2100 time horizon, in order to be conservative and consistent with current climate commitments. PCIC accepted both GEV and Gumbel as suitable selections for the analysis. However, it was found that when fitting GEV to AM rainfall data series, inconsistent rainfall intensities, such as a 10-min rainfall intensity is larger than a 5-min rainfall intensity for the same AEP, were produced. Gumbel is a robust and simple distribution and was selected instead in the analysis.

4.2 Comparison with Other Techniques

Other existing techniques and tools, such as the IDF-CC tool (Srivastav et al., 2015), were compared to review the suitability of the methodology. The IDF-CC tool utilized an equidistance quantile matching (EQM) method to update IDF curves. In version 2.0 of the IDF-CC tool (Schardong et al., 2017), the EQM method predicted future sub-daily rainfall intensities directly from historical sub-daily data and GCM daily maximum data from PCIC, without using the daily to sub-daily ratios. In other words, the IDF-CC tool assumed a temporally invariant scaling factor of 1.0. As discussed in Section 2.3, allowing scaling factor > 1.0, as in this study, will create large differences in deltas compared to the IDF-CC tool.

Deltas were calculated using the IDF-CC tool for the Vancouver Intl A and the Vancouver UBC stations in the Metro Vancouver region for nine of the twelve GCMs (three of the GCMs are not available in the IDF-CC tool). The IDF-CC tool (Version 2.0) required a minimum time period of 50 years, which does not allow for a 2050 time horizon and a 2100 time horizon to be selected. Therefore the time period of 2036 – 2099 was selected to overlap with both the time horizons utilized in this study. The median of deltas are first calculated between all GCMs and then averaged over all AEPs and durations to derive the mean/min/max of the medians, and listed in Table 4.1. Using a scaling factor of 1.0, the deltas in homogeneous zone 1 for both the 2050 and 2100 time horizons from this study (referred to as the GHD method) are pooled together and shown in Table 4.1 as well. Additionally, the deltas from this study when using all scaling factors (1.0 and 1.2 for the 2050 time horizon, 1.0 and 1.3 for the 2100 time horizon) are also shown in Table 4.1. It is shown that the deltas from this study, when using scaling factor of 1.0, are similar to the range of deltas estimated by the IDF-CC tool. The deltas from this study when using all scaling factors are larger than the deltas from the IDF-CC tool, which was expected since the scaling factor was the most sensitive factor. Therefore, it was concluded that the scaling factor was the main source of the discrepancy between the GHD method and the IDF-CC tool output.

Table 4.1 Comparison of Deltas between IDF-CC Tool and GHD Method

Model	Station/Zone	Mean	Min.	Max.
IDF-CC Tool	VAN INTL A	1.32	1.17	1.47
	VAN UBC	1.31	1.18	1.43
GHD Method (12 GCMs)	Zone 1 (SF=1)	1.34	1.12	1.50
	Zone 1 (All SF)	1.48	1.12	1.94
Note: SF refers to scaling factor				

4.3 Additional Sensitivity Analysis on Scaling Factors

The uncertainty analysis initially used a coarse definition of the range for the scaling factor to account for the full range of possible deltas due to various scaling factors. After the scaling factor was found to be the most sensitive, this factor was further refined during discussions with GVS&DD. The upper boundary of the scaling factors was adjusted to 1.3 for the 2100 time horizon and 1.2 for the 2050 time horizon, according to the C-C relation and the average of the changes in daytime high and nighttime low air temperatures projected by PCIC for the 2050s and 2080s in the "Climate Projections for Metro Vancouver" (Metro Vancouver, 2016).

While keeping other factors constant (PDO All, BCCAQ, RCP 8.5, and GUM), the scaling factor was evaluated at 1.0 and 1.2 for the 2050 time horizon and 1.0 and 1.3 for the 2100 time horizon, for the six homogeneous zones. Listed in Table 4.2, the median and 95th percentile of deltas using various scale factors were examined for the 2050 time horizon. Medians of deltas were calculated from all of the GCMs, and averaged over all durations and AEPs to calculate the "Mean" in the table. The minimum and maximum medians of deltas are also listed in Table 4.2. Similarly, the 95th percentile of the deltas from all of the GCMs were calculated, averaged over AEPs and durations, and summarized in the table. It was found that the 95th percentiles of deltas using a scaling factor of 1.0 were slightly larger than the medians of deltas using a scaling factor of 1.2, for the 2050 time horizon (Table 4.2). A similar examination was performed for the 2100 time horizon (Table 4.3) and it was found that the 95th percentile of the deltas using a scaling factor of 1.0 were very close to the medians of the deltas using a scaling factor of 1.3.

Table 4.2 Deltas for 2050 Time Horizon

Homogeneous Zone	Scale Factor = 1						Scale Factor = 1.2					
	Median			95th Percentile			Median			95th Percentile		
	Mean	Min.	Max	Mean	Min.	Max	Mean	Min.	Max	Mean	Min.	Max
Zone 1	1.22	1.12	1.28	**1.51**	1.29	1.63	**1.42**	1.14	1.53	1.75	1.33	1.94
Zone 2	1.19	1.12	1.24	**1.51**	1.28	1.64	**1.38**	1.13	1.48	1.74	1.32	1.95
Zone 3	1.26	1.15	1.32	**1.48**	1.34	1.58	**1.48**	1.15	1.60	1.73	1.35	1.88
Zone 4	1.21	1.12	1.26	**1.48**	1.33	1.56	**1.41**	1.13	1.51	1.71	1.36	1.86

Table 4.2 Deltas for 2050 Time Horizon

Homogeneous Zone	Scale Factor = 1						Scale Factor = 1.2					
	Median			95th Percentile			Median			95th Percentile		
	Mean	Min.	Max	Mean	Min.	Max	Mean	Min.	Max	Mean	Min.	Max
Zone 5	1.20	1.13	1.24	**1.41**	1.30	1.48	**1.40**	1.15	1.51	1.65	1.34	1.78
Zone 6	1.20	1.13	1.23	**1.37**	1.28	1.43	**1.41**	1.14	1.49	1.60	1.32	1.73

Table 4.3 Deltas for 2100 Time Horizon

Homogeneous Zones	Scale Factor = 1						Scale Factor = 1.3					
	Median			95th Percentile			Median			95th Percentile		
	Mean	Min.	Max	Mean	Min.	Max	Mean	Min.	Max	Mean	Min.	Max
Zone 1	1.45	1.31	1.50	**1.88**	1.51	2.09	**1.81**	1.37	1.94	2.34	1.58	2.69
Zone 2	1.40	1.25	1.49	**1.80**	1.49	1.98	**1.73**	1.28	1.91	2.21	1.55	2.55
Zone 3	1.41	1.32	1.47	**1.79**	1.55	1.94	**1.78**	1.33	1.91	2.23	1.56	2.51
Zone 4	1.47	1.32	1.53	**1.80**	1.53	1.98	**1.84**	1.36	1.99	2.24	1.57	2.56
Zone 5	1.38	1.31	1.41	**1.69**	1.46	1.83	**1.73**	1.36	1.85	2.11	1.52	2.39
Zone 6	1.35	1.31	1.39	**1.62**	1.43	1.74	**1.71**	1.34	1.84	2.03	1.49	2.28

The interrelationship between scaling factors and the statistic (percentile) was further explored using a range of scaling factors between 1.0 and 1.2 for the 2050 time horizon (Figure 4.2). The median of the deltas for a scaling factor of 1.2 was calculated. Other scaling factors were also calculated, and the percentile with the same deltas as the scaling factor of 1.2 were determined. In each case, as the scaling factor decreased, a higher percentile was required to obtain the same deltas as the median of the deltas with a scaling factor of 1.2. This indicated that the high change scenario can be defined either based on the theory that scaling ratios may change in the future, or based on statistical probability analysis of the potential outcomes (percentiles) with stationary daily to sub-daily ratios. Scaling factors capture the temporal changes in the daily to sub-daily ratios, indicating how fast the short duration rainfall events will increase compared to the long duration rainfall events (the IDF curve is tilted and the slope from short duration intensity to long duration intensity gets steeper, as depicted in the "Deltas at 1.20, 50%" in Figure 4.2). To obtain a higher percentile, the methodology prefers the GCMs with higher output (higher estimates of rainfall). A larger GCM output leads to larger changes in the estimates of both short and long duration rainfall events (the entire IDF curve is increased, as depicted in the "Deltas at 1.00, 85%" in Figure 4.2). These two approaches are interrelated and different combinations of scaling factors and percentiles may lead to similar probability/extremity. The distribution percentile is preferred to the scaling factor due to the lack of confidence in the scaling factor – there is a lack of information regarding how much the IDF curve will tilt, instead the entire IDF curve is increased to cover the possible tilt.

A similar figure could be constructed for the 2100 time horizon and it will show that using the 95th percentile at a scaling factor of 1.0 will result in same possible high change scenarios as using the 50th percentile at a scaling factor of 1.3.

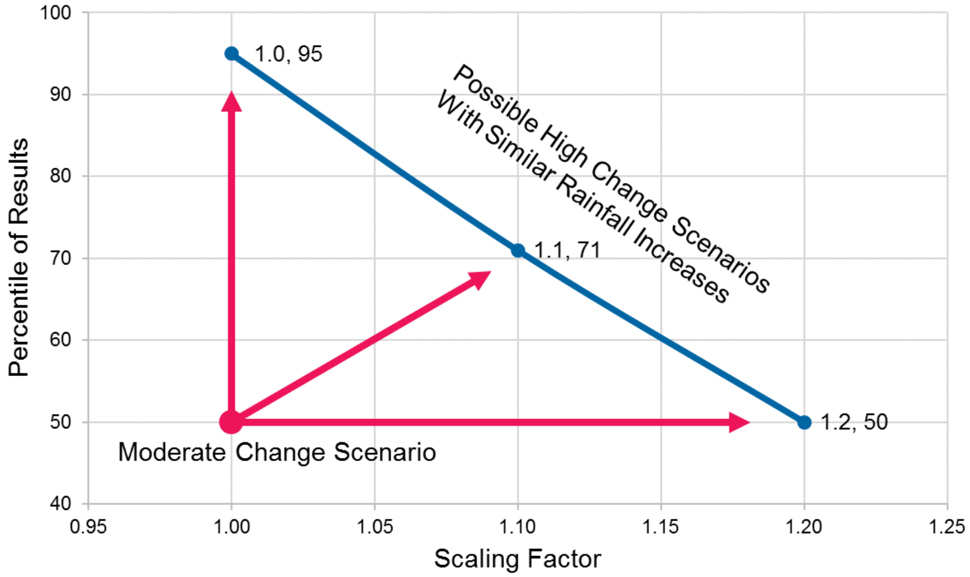


Figure 4.2 Possible High Change Scenarios Producing Similar Deltas for the 2050 Time Horizon

4.4 Selection of Scenarios

Based on the sensitivity analysis on the factors and the discussions with PCIC, the moderate and high change scenarios were selected from the deltas for the scaling factor equal to 1.0 (Table 4.4). This study did not simply adopt a scaling factor > 1.0 to capture the potential temporal changes in the future, because it is difficult to quantify the temporal changes directly. The sensitivity of the scaling factor was investigated and an alternative approach (based on selection of a high percentile) to address possible temporal changes in the daily to sub-daily ratios was adopted (in section 4.3). The moderate change scenarios were based on the median of the deltas for the scaling factor equal to 1.0. For the high change scenarios, the 95th percentile of the deltas for the scaling factor equal to 1.0 was selected. As recommended by PCIC, the other factor levels were kept at BCCAQ for the downscaling method, RCP 8.5 for the RCP scenario, PDO All for the PDO index. The Gumbel distribution was selected for the frequency distribution used to calculate the deltas.

Table 4.4 Moderate and High Change Scenarios

Scenario	2050 Time Horizon	2100 Time Horizon
Moderate Change	Median delta for scale factor =1.0	Median delta for scale factor =1.0
High Change	95th percentile delta for scale factor =1.0	95th percentile delta for scale factor =1.0
All	RCP 8.5, BCCAQ, PDO All, Gumbel	RCP 8.5, BCCAQ, PDO All, Gumbel

The scaling factors are highly uncertain and consequently, the scenarios using scaling factors > 1.0 were used as the supporting theory behind selecting the 95th percentile of the deltas using a scaling factor of 1.0 for defining the high change scenarios. It is unknown if the scaling factor will change or by what degree the scaling factor will change. However, if the scaling factor does change, it was desired that the high change scenario would account for the potential increase in rainfall. The 95th percentiles of the deltas for the scale factor of 1.0 correspond to the medians of the deltas for the scaling factor equal to 1.2 (2050 time horizon) or 1.3 (2100 time horizon). This reflects a balance between the likelihood of occurrence and the amount of conservativeness. The medians of the deltas for scaling factors of 1.2 and 1.3 (the upper boundaries for the scaling factors assuming that the C-C relation applies in the future) are the "most likely" estimates if the scaling factor does change. Choosing a higher percentile (greater than the median) of the deltas with the higher scaling factors would increase the amount of conservativeness but would also decrease the probability of occurrence.

For the 2050 time horizon high change scenario, the 95th percentile of deltas using a scaling factor of 1.0 was selected since it was slightly larger (conservative) than the medians of deltas using a scaling factor of 1.2. The 95th percentile of the deltas using a scaling factor of 1.0 was very close to the medians of the deltas using a scaling factor of 1.3, and it was selected for the high change scenario for the 2100 time horizon.

Table 4.5 lists the ranges of the deltas for the selected scenarios. The medians (or 95th percentiles) of the deltas in all combinations of the GCMs were averaged over all durations and AEPs as the means for the moderate (or high) change scenarios. The minimum and maximum of the averages are listed as well. The moderate change scenario for the 2050 time horizon leads to a 20 to 26% increase in future climate IDF curves, and for the 2100 time horizon it leads to a 35 to 47% increase. The changes for the moderate scenario are comparable to the changes calculated by the IDF-CC tool (Table 4.1). However, the changes in IDF curves in the high change scenarios are generally higher than the IDF-CC tool. There are variances in the outputs from the 12 GCMs, and the use of the 95th percentile for the deltas inclines the analysis towards the GCMs that predict high changes in the future.

It is noted that the 2050 time horizon high change scenario has slightly larger deltas compared to those for the 2100 time horizon moderate change scenario. If the climate is warming at a faster rate than anticipated, the extreme rainfall intensities should increase faster as well. That is, a given level of increase (delta) will occur either early in a high change scenario (the 2050 high change scenario) or late in a moderate change scenario (the 2100 moderate change scenario).

Table 4.5 Ranges of Deltas in Selected Scenarios

Homogeneous Zones	2050 Time Horizon Moderate			2050 Time Horizon High			2100 Time Horizon Moderate			2100 Time Horizon High		
	Mean	Min.	Max	Mean	Min.	Max	Mean	Min.	Max	Mean	Min.	Max
Zone 1	**1.22**	1.12	1.28	**1.51**	1.29	1.63	**1.45**	1.31	1.50	**1.88**	1.51	2.09
Zone 2	**1.19**	1.12	1.24	**1.51**	1.28	1.64	**1.40**	1.25	1.49	**1.80**	1.49	1.98
Zone 3	**1.26**	1.15	1.32	**1.48**	1.34	1.58	**1.41**	1.32	1.47	**1.79**	1.55	1.94
Zone 4	**1.21**	1.12	1.26	**1.48**	1.33	1.56	**1.47**	1.32	1.53	**1.80**	1.53	1.98

Table 4.5 Ranges of Deltas in Selected Scenarios

Homogeneous Zones	2050 Time Horizon Moderate			2050 Time Horizon High			2100 Time Horizon Moderate			2100 Time Horizon High		
	Mean	Min.	Max	Mean	Min.	Max	Mean	Min.	Max	Mean	Min.	Max
Zone 5	**1.20**	1.13	1.24	**1.41**	1.30	1.48	**1.38**	1.31	1.41	**1.69**	1.46	1.83
Zone 6	**1.20**	1.13	1.23	**1.37**	1.28	1.43	**1.35**	1.31	1.39	**1.62**	1.43	1.74

4.5 Uncertainties in GCMs

The variances of deltas in each of the 12 GCMs were explored after the moderate and high scenarios were selected to understand the preferences between GCMs when using medians or 95th percentiles of the deltas of the 12 GCMs. Figure 4.3 illustrates the variance of the deltas in each GCM for the 2050 time horizon in Zone 1. Each boxplot represents deltas of nine durations and seven AEPs. ACCESS1-0 produced the largest deltas with a large amount of variance, while CCSM4 resulted in the lowest deltas and GFDL-ESM2G had the smallest variance in deltas. Similar patterns are observed for the 2100 time horizon as well (Figure 4.4). The large variation of deltas between GCMs is consistent with the purposes behind the selection of the GCM ensemble for the Western North America, which were preferentially selected to capture the overall range of the ensemble (Cannon, 2015).

The deltas of the selected scenarios are compared with the spread of the deltas in each GCM as well. The moderate change scenario selected for the 2050 time horizon has a mean delta of 1.22 (bottom blue dash line drawn in Figure 4.3). This is a good representation of the central tendency of the deltas. In contrast, the high change scenario prefers the GCMs that produced large deltas, as the mean of the deltas was 1.51 (top blue dash line in Figure 4.3), and it only crosses the high end of a few boxplots. The selected scenarios for the 2100 time horizon demonstrated similar patterns (Figure 4.4).

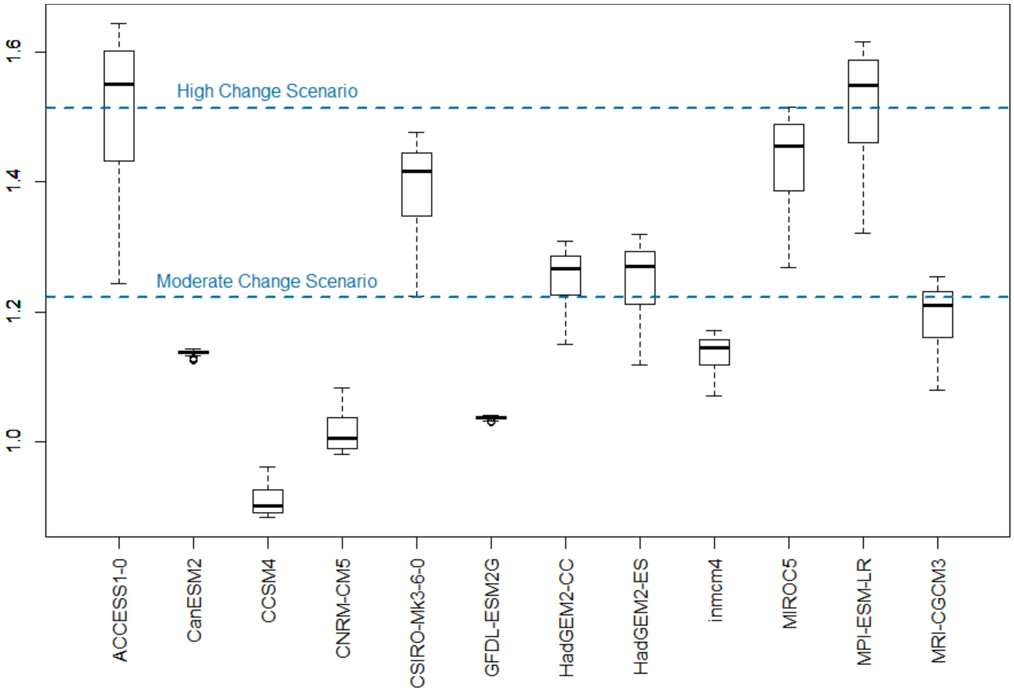


Figure 4.3 Boxplot Comparison of Deltas for the 2050 Time Horizon, Split by GCM

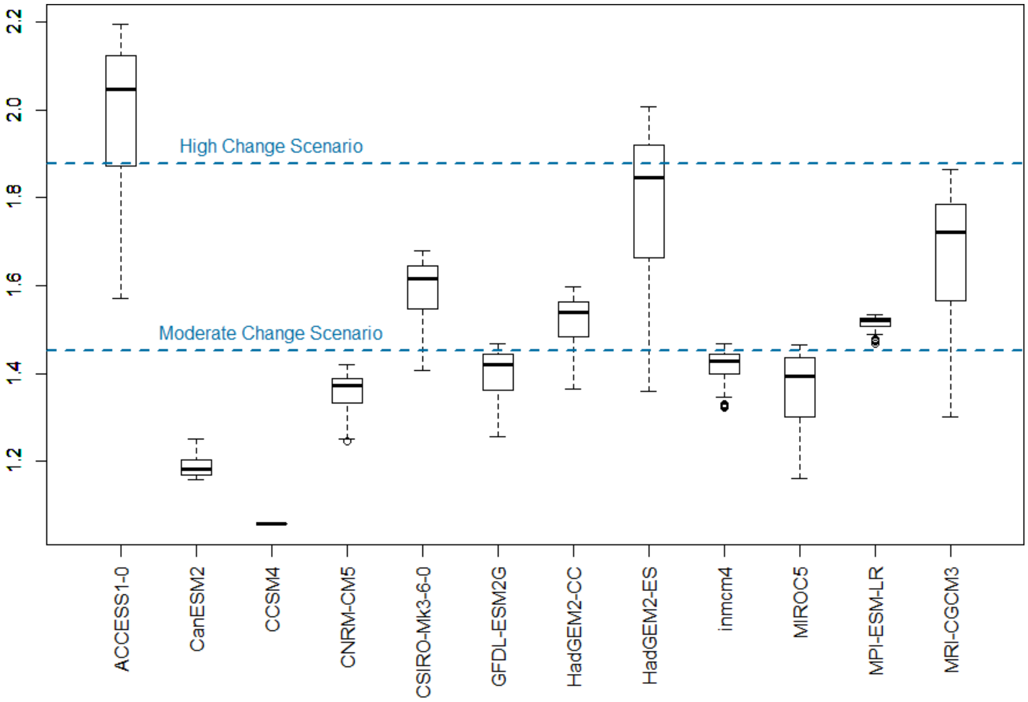


Figure 4.4 Boxplot Comparison of Deltas for the 2100 Time Horizon, Split by GCM

5. Future Climate IDF Curves

5.1 Methodology

Using the selected moderate and high change scenarios (Table 4.4), the delta was calculated from the 12 GCMs for each homogeneous zone, rainfall duration, and AEP. The delta was then applied to the corresponding updated homogeneous rainfall zone RFD quantile ($I_{T,d}^{Reg,Upd}$) to obtain the homogeneous rainfall zone future RFD quantile ($I_{T,d}^{Reg,Fut}$) (Equation 6 in TM1, and modified as Equation 2 below).

$$I_{T,d}^{Reg,Fut} = I_{T,d}^{Reg,Upd} \times Delta \qquad \text{Equation 2}$$

The updated homogeneous rainfall zone RFD quantiles were calculated in TM2 (updated to present-day). The regional rainfall frequency analysis (RRFA) in TM2 generated dimensionless IDF curves. The dimensionless IDF curves should be scaled by the index rain for each duration for the study area. The index rain is an estimate of the mean annual maximum rainfall in the study area. The deltas for the future climate scenarios should then be applied to scaled IDF curves. The deltas act as an additional scaling factor for the IDF curves, as shown in Equation 2. Four sets of deltas are included in Appendix A: two future climate scenarios (moderate and high) for two time horizons (2050 and 2100). The deltas for each of the six different zones are different: if the study area is in zone 1, then the dimensionless IDF curves for zone 1 and the deltas for zone 1 should be selected.

Quality Assurance and Quality Control (QA/QC) were applied to the delta factors. The dimensionless IDF curves for each zone were scaled by average index rains for each zone, and then the future climate IDF curves were generated by multiplying the IDF curves by the delta factors. Examples IDF curves are included in Appendix B. The QA/QC process checked for inconsistencies, such as rainfall depth decreasing as duration increases for the same AEP or rainfall depth decreasing as AEP increases for the same duration. The IDF curves were also verified to ensure that the regression lines for different AEP do not cross each other. Finally, the high change future climate IDF curves should be greater than the moderate change future climate IDF curves, and the 2100 time horizon IDF curves should be higher than the 2050 time horizon IDF curves. Such inconsistencies are possible due to the methodology of developing the future climate IDF curves: the delta is calculated for each combination of duration and AEP separately. The delta depends on multiple factors, sub-daily to daily ratios, and multiple GCMs that could result in inconsistencies. Applying a detailed QA/QC process ensures that the future climate IDF curves are suitable for design use.

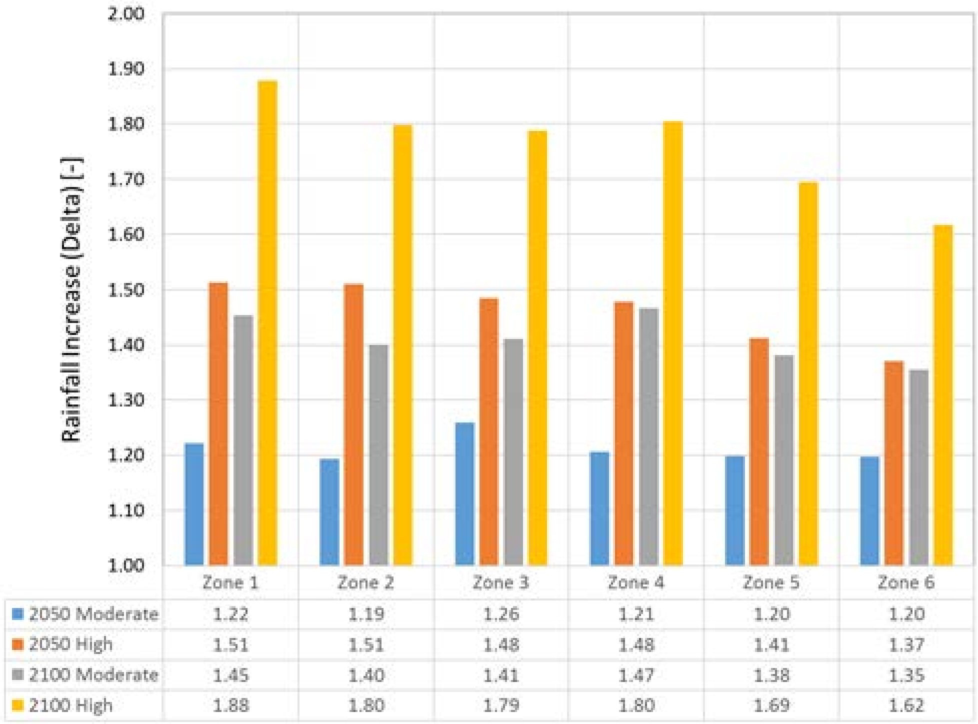
In the QA/QC process, it was identified that inconsistencies between rainfall intensities and AEPs were produced when the daily to sub-daily ratio used for a small AEP is smaller than that for a large AEP. The daily to sub-daily ratios were calculated from observations at climate stations, by dividing sub-daily and sub-hourly rainfall intensities by daily rainfall intensity for each AEP. Adjustment were made to correct the inconsistent ratios used for the small AEP. When fitting statistical distributions to rainfall AM, occasionally, the rainfall intensity estimated for a longer duration was larger than that for a shorter duration, for the same AEP. The Gumbel distribution was used instead. No other inconsistency issues were identified in the analysis.

The Gumbel distribution was utilized to generate the deltas. However, the deltas were applied to the updated IDF curves, which were generated using GEV. The deltas are essentially adjustments to an IDF curve and could be applied to any IDF curve constructed using any frequency distribution, since they are independent from and insensitive to the frequency distribution.

5.2 Discussion of Future Rainfall and Uncertainty

The deltas were utilized to change the updated IDF curves from TM2. For example, a delta of 1.2 indicates a change of 20% in the IDF intensity.

The deltas for each homogeneous zone were averaged over all durations and AEPs to provide a general summary of the changes, as shown in Figure 5.1. As expected, the 2050 moderate change scenario resulted in the lowest increase (approximately 21%) in IDF curves. The 2050 high change scenario has a 44% increase on average. An average increase of 41% was predicted for the 2100 moderate change scenario, and the largest change was predicted for the 2100 high change scenario, which was 67% on average, and ranged from 51% in zone 6 to 78% in Zone 1.

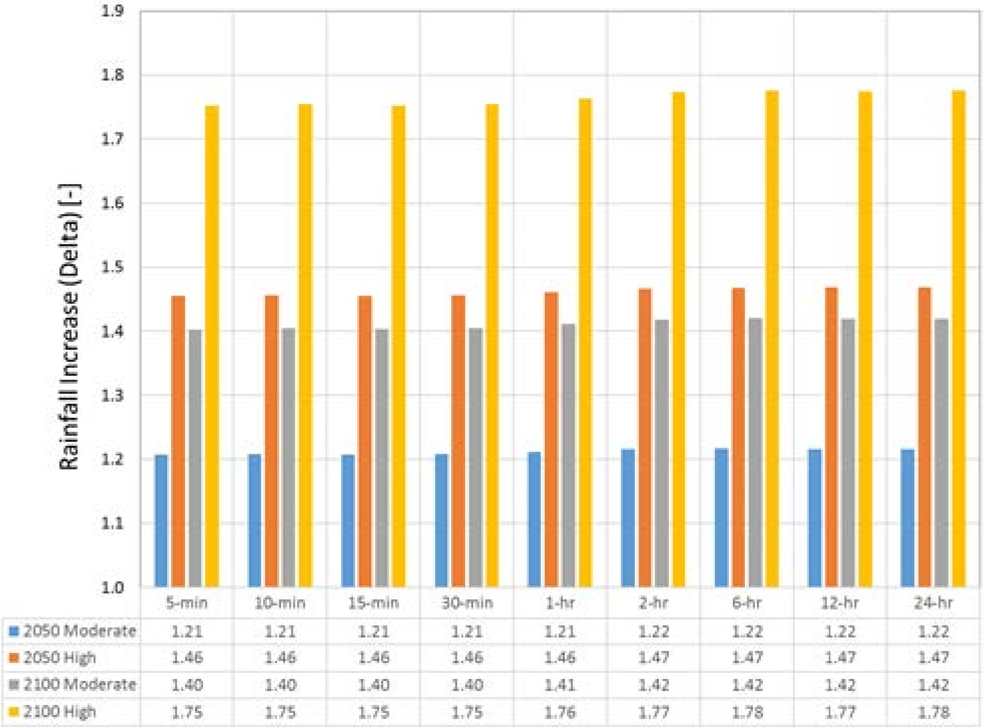


	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
🟦 2050 Moderate	1.22	1.19	1.26	1.21	1.20	1.20
🟧 2050 High	1.51	1.51	1.48	1.48	1.41	1.37
⬜ 2100 Moderate	1.45	1.40	1.41	1.47	1.38	1.35
🟨 2100 High	1.88	1.80	1.79	1.80	1.69	1.62

Figure 5.1 Changes in IDF Curves Averaged Over All Durations and AEPs

Differences in IDF curve changes were negligible between short and long rainfall durations. In Figure 5.2, the changes are averaged over all zones and AEPs and are relatively constant among all durations.

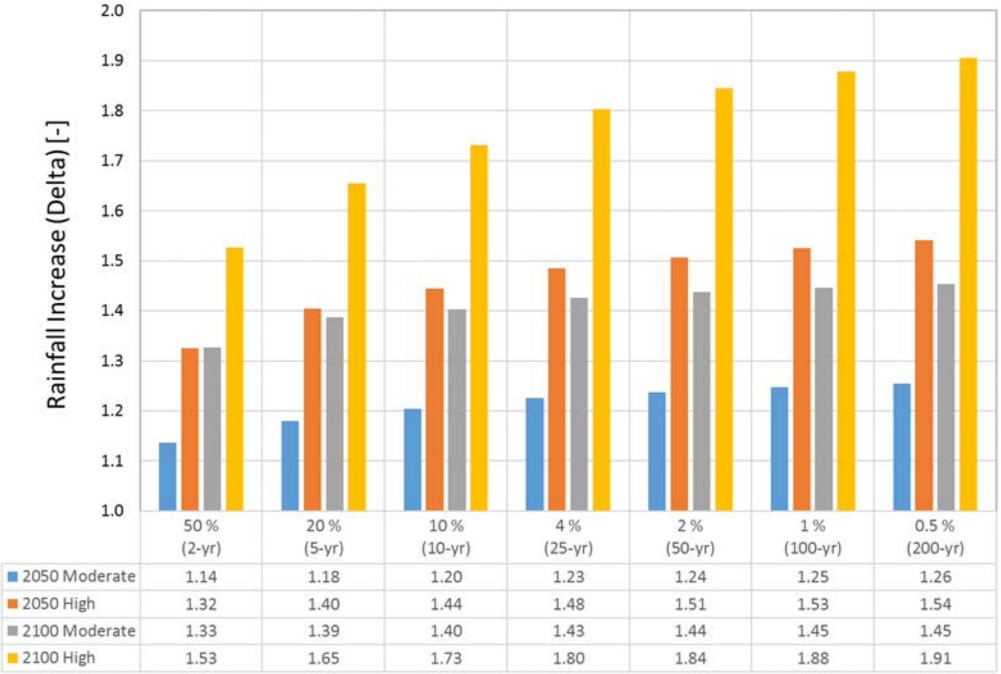
Comparisons of changes in IDF curves between rainfall durations for each homogeneous zone are shown in Figure 2.1 through 2.6 in Appendix B.



	5-min	10-min	15-min	30-min	1-hr	2-hr	6-hr	12-hr	24-hr
■ 2050 Moderate	1.21	1.21	1.21	1.21	1.21	1.22	1.22	1.22	1.22
■ 2050 High	1.46	1.46	1.46	1.46	1.46	1.47	1.47	1.47	1.47
■ 2100 Moderate	1.40	1.40	1.40	1.40	1.41	1.42	1.42	1.42	1.42
■ 2100 High	1.75	1.75	1.75	1.75	1.76	1.77	1.78	1.77	1.78

Figure 5.2 Changes in IDF Curves Averaged Over All AEPs and Homogeneous Zones

Differences in IDF curve changes were also observed between low and high AEPs. In Figure 5.3, the changes (averaged over all zones and duration) kept increasing for all four scenarios from AEP of 50% to 0.5% (return period of 2 years to 200 years). Greater increases are observed in the high change scenarios compared to the moderate change scenarios. It is noted that the deltas for the high change scenarios were the 95th percentiles among the 12 GCMs, and the GCMs that produce the largest increases in precipitation would be preferentially selected for the high change scenarios. Comparisons of changes in IDF curves between AEPs for each homogeneous zone are shown in Figure 2.7 through 2.12 in Appendix B.



	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
🟦 2050 Moderate	1.14	1.18	1.20	1.23	1.24	1.25	1.26
🟧 2050 High	1.32	1.40	1.44	1.48	1.51	1.53	1.54
■ 2100 Moderate	1.33	1.39	1.40	1.43	1.44	1.45	1.45
🟨 2100 High	1.53	1.65	1.73	1.80	1.84	1.88	1.91

Figure 5.3 Changes in IDF Curves Averaged Over All Durations and Homogeneous Zones

Shifts in AEP (or return period) were analyzed by comparing future climate IDF curves with the updated IDF curves. Appendix C provides figures comparing updated IDF curves and the future climate IDF curves from the moderate and high change scenarios, for each homogeneous zone for both the 2050 and 2100 horizons. Alternatively, the intensities from the updated IDF curves can be projected into the future climate IDF curves and the corresponding future AEPs reveal shifts in the likelihoods of occurrences of same rainfall intensities in the future.

Table 5.1 and Table 5.2 list the AEPs and return periods of the updated IDF intensities derived from future climate IDF curves respectively. For example, the current 50% AEP (2-year return period) event will become a 64% AEP (1.6-year return period) event under the moderate change scenario in 2050, and an 84.2% AEP (1.2-year return period) event under the high change scenario in 2100. Similarly, a 0.5% AEP (200-year return period) event in the updated IDF will become a 2.2% AEP (46-year return period) event under the 2050 moderate change scenario, and a 12.8% AEP (8-year return period) event in 2100 under the high change scenario.

Table 5.1 Changes in AEPs, Averaged Over All Durations and Homogeneous Zones

AEPs in Updated IDF	AEPs in 2050 IDF		AEPs in 2100 IDF	
	Moderate	High	Moderate	High
50%	64.2%	77.6%	79.8%	84.2%
20%	34.8%	51.6%	52.4%	64.2%

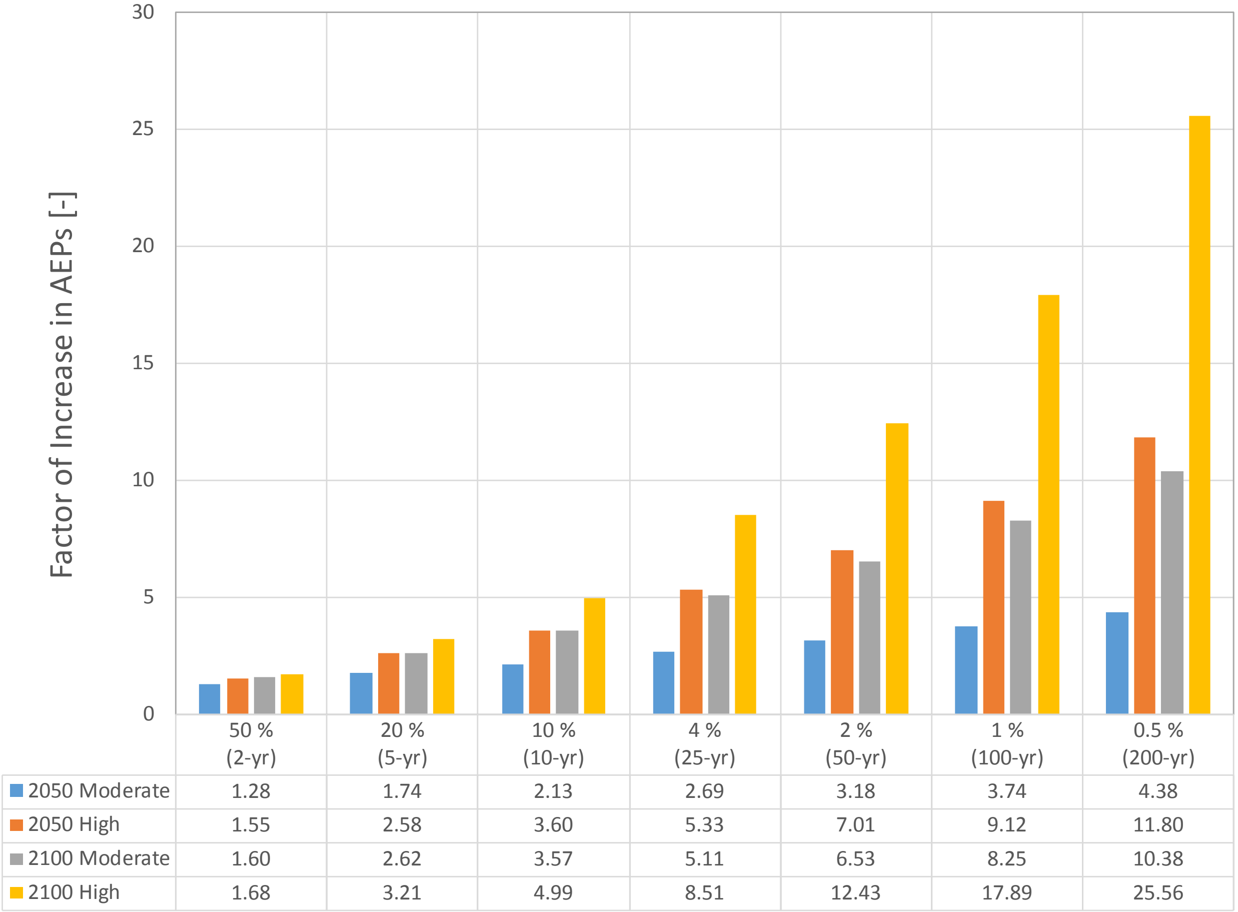
Table 5.1 Changes in AEPs, Averaged Over All Durations and Homogeneous Zones

AEPs in Updated IDF	AEPs in 2050 IDF		AEPs in 2100 IDF	
	Moderate	High	Moderate	High
10%	21.3%	36.0%	35.7%	49.9%
4%	10.8%	21.3%	20.4%	34.1%
2%	6.4%	14.0%	13.1%	24.9%
1%	3.7%	9.1%	8.3%	17.9%
0.5%	2.2%	5.9%	5.2%	12.8%

Table 5.2 Changes in Return Period, Averaged Over All Durations and Homogeneous Zones

AEPs in Updated IDF	AEPs in 2050 IDF		AEPs in 2100 IDF	
	Moderate	High	Moderate	High
2-yr	1.6-yr	1.3-yr	1.3-yr	1.2-yr
5-yr	2.9-yr	1.9-yr	1.9-yr	1.6-yr
10-yr	4.7-yr	2.8-yr	2.8-yr	2.0-yr
25-yr	9.3-yr	4.7-yr	4.9-yr	2.9-yr
50-yr	15.7-yr	7.1-yr	7.7-yr	4.0-yr
100-yr	26.8-yr	11.0-yr	12.1-yr	5.6-yr
200-yr	45.7-yr	16.9-yr	19.3-yr	7.8-yr

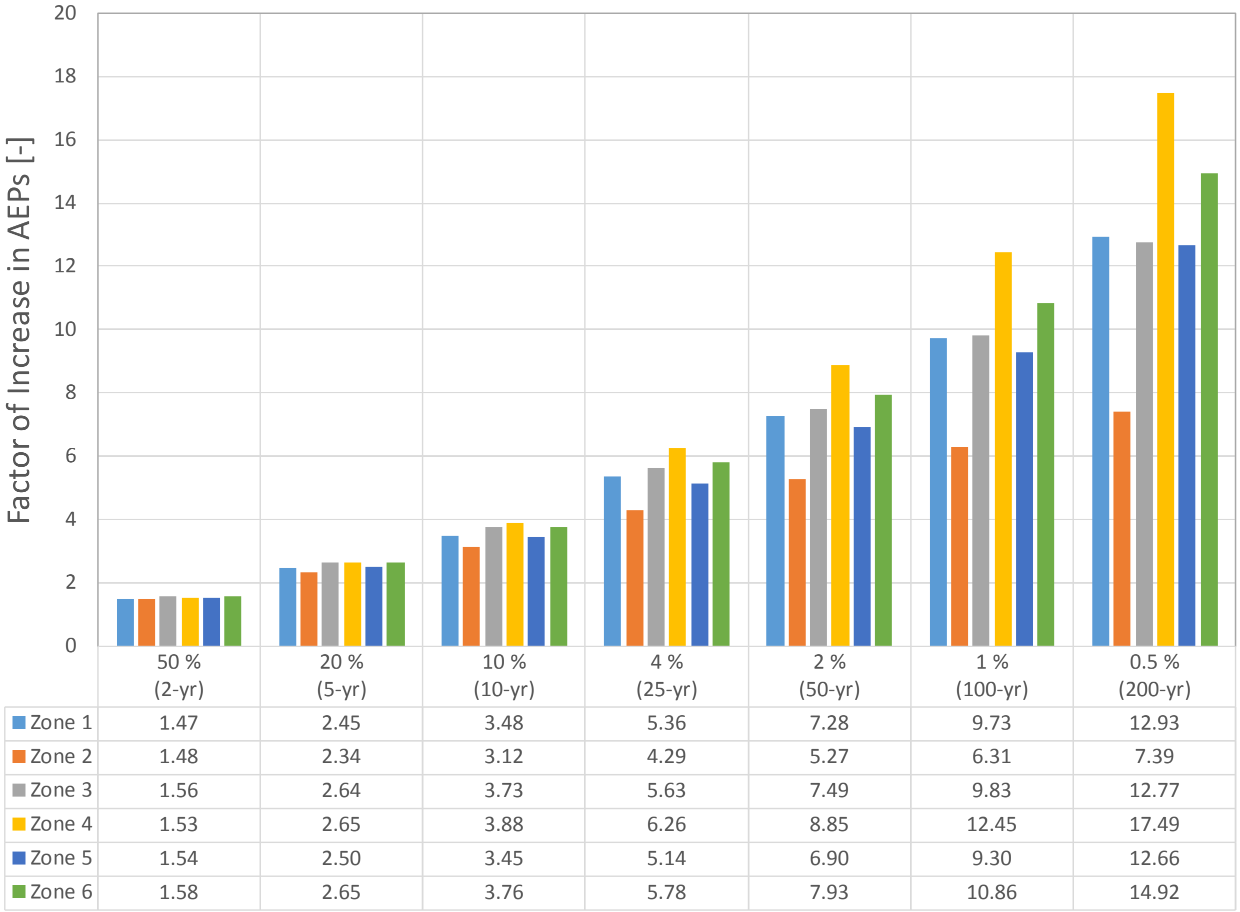
The changes in frequent events (high AEP or short return period) were minor. The AEP of the 50% AEP (2-year return) events increased to 64-84% (1.2 to 1.6-year return) for all future scenarios. However, high increases in AEPs were observed in infrequent events (low AEP or long return period), that is, they became significantly more frequent. Shown in Figure 5.4, the AEP of the 0.5% AEP (200-year return) events increased by 4 times (2.2%/0.5% ≈ 4) under the 2050 moderate scenario and increased by 26 times (12.8%/0.5% ≈ 26) under the 2100 high change scenario. This is because the high change scenarios include 90% of the variation with a scale factor of 1.0 and 50% of variation with scale factor of 1.2/1.3.



	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
🟦 2050 Moderate	1.28	1.74	2.13	2.69	3.18	3.74	4.38
🟧 2050 High	1.55	2.58	3.60	5.33	7.01	9.12	11.80
⬜ 2100 Moderate	1.60	2.62	3.57	5.11	6.53	8.25	10.38
🟨 2100 High	1.68	3.21	4.99	8.51	12.43	17.89	25.56

Figure 5.4 Factor of Increase in AEPs Averaged Over All Durations and Homogeneous Zones

The increase in AEPs were mostly similar between homogeneous zones, except for zones 2 and 4 (see Figure 5.5). The differences between the increases in AEP of zone 2 and the rest of the zones increased as the AEP decreased; while the differences between the increases in the AEP of zone 4 and the rest of the zones decreased as the AEP decreased. At an AEP of 0.5% (200-year return), zone 2 showed a factor of 7.4 and zone 4 showed a factor of 17.5, while the rest of the zones are between 12 and 15. An examination of the updated IDF curves revealed that the zone 2 has rainfall intensities larger than other zones, and zone 4 has rainfall intensities smaller than other zones, for short durations and low AEPs. This difference will change the shapes of the update and future climate IDF curves and eventually change the AEPs derived from them.



	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
🟦 Zone 1	1.47	2.45	3.48	5.36	7.28	9.73	12.93
🟧 Zone 2	1.48	2.34	3.12	4.29	5.27	6.31	7.39
⬜ Zone 3	1.56	2.64	3.73	5.63	7.49	9.83	12.77
🟨 Zone 4	1.53	2.65	3.88	6.26	8.85	12.45	17.49
🟦 Zone 5	1.54	2.50	3.45	5.14	6.90	9.30	12.66
🟩 Zone 6	1.58	2.65	3.76	5.78	7.93	10.86	14.92

Figure 5.5 Factor of Increase in AEPs Averaged Over All Durations and Future Scenarios

6. Conclusions and Recommendations

The downscaling methodology described in TM1 was implemented and applied to a sensitivity analysis. Five factors were examined: RCP scenario (RCP4.5 and RCP8.5), spatial downscaling methodology (BCCAQ and BCSD), PDO phase (Warm, Cool, and All), daily to sub-daily ratio scaling factor (1.0 to 1.4), and frequency distribution (generalized normal, generalized extreme value, and Gumbel). An ensemble of twelve GCMs selected for Western North America were used in the analysis.

A sensitivity analysis was performed to quantify the impact of multiple factors on the future climate IDF curves. The scaling factor was identified as the most important source of uncertainty in the future climate IDF curves. PDO, RCP, and downscaling methods were secondary to the scaling factor. The frequency distributions showed limited impact on the future climate IDF curves. The ranking of the various factors did not change between the 2050 time horizon and the 2100 time horizon.

The Clausius-Clapeyron (C-C) relation was an important assumption adopted in determining the upper limit of the daily to sub-daily ratio scaling factors. This methodology provided the means for defining an upper limit for the possible changes between the sub-daily and daily rainfall using the projected changes in air temperatures. Further research on the C-C relation and its application to the daily to sub-daily ratios are required. In addition, further research is required for defining how the intensities of short-duration events may change differently from the intensities of long duration events with increases in temperature, i.e., whether the daily to sub-daily ratios are non-stationary.

The scaling factors substantially changed the future climate IDF curves. A scaling factor of 1.2 increased the IDF by an additional 16% compared to a scaling factor of 1.0 in the 2050 time horizon, and a scaling factor of 1.3 increased the IDF by an additional 24% compared to a scaling factor of 1.0 in the 2100 time horizon.

In the selection of future scenarios, there is an interaction between the scaling factor and the percentile of the frequency distribution used for selecting deltas. Using a scaling factor > 1.0 and a low percentile (the median) will produce results similar to using a scaling factor of 1.0 and a high (95th) percentile. The future changes in daily to sub-daily ratios (scaling factors) are highly uncertain. The scenarios based on scaling factors > 1.0 should only be used as the supporting theory behind selecting the percentiles for defining the high change scenarios. Defining scenarios based on specific scaling factor values is less defensible and has not been used previously.

The final selected future climate scenarios all used PDO All, BCCAQ, RCP 8.5, GUM, and a scaling factor of 1.0. The moderate change scenario used the median of the deltas between the 12 GCMs, and the high change scenario used the 95th percentile. The 95th percentiles were selected to balance the conservativeness with the likelihood of occurrence. The selection of the 95th percentiles using a scaling factor of 1.0 for the high change scenarios is supported by their similarity to the medians of the deltas with scaling factors of 1.2/1.3, which are the "most likely" estimates if the scaling factor does change. Choosing a higher percentile (greater than the median) of the deltas with the higher scaling factors would increase the amount of conservativeness but would also decrease the probability of occurrence.

For the 2050 time horizon, rainfall intensity is projected to increase on average by 21% for the moderate change scenario and by 44% for the high change scenario. Changes up to 52% were predicted for low AEPs, and changes up to 14% were predicted for high AEPs. The difference between changes in long and short durations is negligible. By 2050, the current 1% AEP (100-year return) event becomes 3.7% (27-year return) event under the moderate change scenario, and 8.5% (11.8-year return) event under the high change scenario.

For the 2100 time horizon, rainfall intensity is projected to increase on average by 41% for the moderate change scenario and by 67% for the high change scenario. For low AEPs, changes up to 80% were predicted, and for high AEPs, changes up to 33% were predicted. The difference between changes in long and short durations is negligible. By 2100, the current 1% AEP (100-year return) event becomes 8.3% (12-year return) event under the moderate change scenario, and 14.7% (6.8-year return) event under the high change scenario.

This TM developed the moderate and high change scenarios for both the 2050 and 2100 time horizons. Four future climate IDF curves are created, and increases in rainfall are identified and discussed. The effect of the increased rainfall on the stormwater and wastewater infrastructures should be evaluated and a framework for best practice recommendations for planning for climate change impacts in infrastructure should be defined.

Research and development are recommended on the aggregation of rainfall records from climate stations to GCM grids. The regional IDF curves were updated and the daily to sub-daily ratios were estimated in this process. Uncertainties were introduced when weighting rainfall records of different lengths and from different distances. In addition, explorations on methods to downscale the daily data series and to account for temporal changes, such as non-stationary frequency distributions, artificial neural networks, etc., are recommended as well.

Climate change science is rapidly advancing, and the latest climate science should be utilized during the next IDF curve update and generation of future IDF curves. In particular, when the science and models have updated their predictions for the future and/or there is more information that will address the current knowledge limitations (e.g., the variation in the scaling factor is currently unknown) the approach to calculate the deltas should be revisited and revised.

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Appendix A

Table Index

Table 1.1 Zone 1 Delta Changes for Moderate Change 2050 Scenario

Duration\AEP	Deltas						
	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
5-min	1.122	1.179	1.209	1.234	1.246	1.255	1.263
10-min	1.123	1.180	1.210	1.236	1.249	1.258	1.266
15-min	1.125	1.181	1.211	1.235	1.247	1.256	1.264
30-min	1.127	1.181	1.211	1.234	1.247	1.257	1.265
1-h	1.134	1.183	1.213	1.238	1.252	1.262	1.271
2-h	1.140	1.186	1.215	1.240	1.254	1.265	1.275
6-h	1.142	1.188	1.217	1.245	1.259	1.271	1.282
12-h	1.138	1.185	1.215	1.240	1.253	1.265	1.275
24-h	1.141	1.189	1.218	1.244	1.258	1.269	1.279

Table 1.2 Zone 2 Delta Changes for Moderate Change 2050 Scenario

Duration\AEP	Deltas						
	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
5-min	1.117	1.154	1.178	1.200	1.212	1.222	1.230
10-min	1.120	1.156	1.181	1.203	1.215	1.225	1.233
15-min	1.123	1.160	1.185	1.207	1.219	1.229	1.237
30-min	1.121	1.157	1.182	1.204	1.216	1.227	1.235
1-h	1.123	1.157	1.181	1.204	1.216	1.227	1.235
2-h	1.124	1.157	1.181	1.204	1.217	1.228	1.237
6-h	1.124	1.156	1.179	1.202	1.215	1.227	1.236
12-h	1.129	1.161	1.184	1.207	1.220	1.231	1.240
24-h	1.132	1.164	1.187	1.210	1.223	1.234	1.243

Table 1.3 Zone 3 Delta Changes for Moderate Change 2050 Scenario

Duration\AEP	Deltas						
	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
5-min	1.151	1.214	1.248	1.278	1.292	1.302	1.311
10-min	1.148	1.210	1.243	1.274	1.288	1.299	1.308
15-min	1.150	1.211	1.244	1.275	1.290	1.301	1.310
30-min	1.152	1.214	1.247	1.278	1.292	1.303	1.312
1-h	1.153	1.214	1.248	1.279	1.293	1.304	1.313
2-h	1.160	1.220	1.253	1.286	1.301	1.313	1.323
6-h	1.157	1.216	1.249	1.282	1.299	1.312	1.323
12-h	1.159	1.219	1.253	1.284	1.299	1.311	1.321
24-h	1.153	1.214	1.247	1.278	1.293	1.304	1.314

Table 1.4 Zone 4 Delta Changes for Moderate Change 2050 Scenario

Duration\AEP	Deltas						
	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
5-min	1.124	1.166	1.192	1.216	1.229	1.240	1.248
10-min	1.130	1.170	1.196	1.220	1.233	1.244	1.253
15-min	1.127	1.167	1.193	1.217	1.230	1.242	1.251
30-min	1.128	1.167	1.193	1.218	1.232	1.243	1.253
1-h	1.126	1.164	1.190	1.215	1.230	1.242	1.253
2-h	1.129	1.166	1.192	1.217	1.232	1.245	1.256
6-h	1.133	1.171	1.197	1.222	1.236	1.249	1.259
12-h	1.132	1.170	1.196	1.221	1.236	1.247	1.258
24-h	1.135	1.173	1.199	1.224	1.238	1.250	1.259

Table 1.5 Zone 5 Delta Changes for Moderate Change 2050 Scenario

Duration\AEP	Deltas						
	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
5-min	1.127	1.156	1.178	1.198	1.209	1.217	1.225
10-min	1.134	1.162	1.184	1.203	1.214	1.223	1.230
15-min	1.135	1.164	1.185	1.204	1.215	1.224	1.231
30-min	1.136	1.164	1.185	1.204	1.215	1.224	1.232
1-h	1.149	1.174	1.194	1.214	1.224	1.233	1.241
2-h	1.145	1.170	1.191	1.211	1.223	1.233	1.242
6-h	1.147	1.172	1.193	1.213	1.225	1.235	1.244
12-h	1.148	1.173	1.194	1.214	1.225	1.234	1.242
24-h	1.146	1.173	1.193	1.213	1.224	1.234	1.241

Table 1.6 Zone 6 Delta Changes for Moderate Change 2050 Scenario

Duration\AEP	Deltas						
	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
5-min	1.138	1.185	1.201	1.208	1.211	1.214	1.216
10-min	1.131	1.177	1.194	1.201	1.205	1.209	1.212
15-min	1.126	1.170	1.187	1.196	1.200	1.204	1.207
30-min	1.130	1.172	1.190	1.198	1.203	1.207	1.210
1-h	1.138	1.180	1.198	1.206	1.210	1.214	1.218
2-h	1.152	1.193	1.212	1.220	1.224	1.227	1.230
6-h	1.153	1.194	1.214	1.222	1.226	1.229	1.231
12-h	1.146	1.189	1.209	1.217	1.221	1.224	1.226
24-h	1.142	1.185	1.205	1.213	1.217	1.220	1.223

Table 1.7 Zone 1 Delta Changes for Large Change 2050 Scenario

Duration\AEP	Deltas						
	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
5-min	1.292	1.433	1.492	1.542	1.568	1.589	1.606
10-min	1.296	1.435	1.493	1.544	1.570	1.591	1.608
15-min	1.297	1.439	1.497	1.548	1.575	1.596	1.613
30-min	1.302	1.439	1.497	1.548	1.576	1.597	1.615
1-h	1.318	1.442	1.498	1.549	1.578	1.601	1.620
2-h	1.330	1.445	1.500	1.552	1.581	1.605	1.626
6-h	1.335	1.444	1.498	1.550	1.580	1.605	1.626
12-h	1.325	1.441	1.496	1.549	1.578	1.603	1.624
24-h	1.333	1.448	1.503	1.554	1.584	1.608	1.628

Table 1.8 Zone 2 Delta Changes for Large Change 2050 Scenario

Duration\AEP	Deltas						
	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
5-min	1.278	1.424	1.490	1.549	1.581	1.606	1.627
10-min	1.286	1.426	1.491	1.550	1.582	1.608	1.629
15-min	1.294	1.430	1.494	1.553	1.585	1.611	1.632
30-min	1.291	1.425	1.489	1.548	1.580	1.607	1.629
1-h	1.296	1.426	1.489	1.548	1.581	1.608	1.631
2-h	1.301	1.421	1.483	1.542	1.576	1.605	1.628
6-h	1.301	1.414	1.475	1.533	1.568	1.597	1.622
12-h	1.311	1.427	1.487	1.546	1.580	1.608	1.633
24-h	1.319	1.435	1.495	1.553	1.587	1.616	1.640

Table 1.9 Zone 3 Delta Changes for Large Change 2050 Scenario

Duration\AEP	Deltas						
	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
5-min	1.347	1.428	1.469	1.510	1.532	1.551	1.566
10-min	1.338	1.418	1.459	1.501	1.524	1.543	1.559
15-min	1.342	1.422	1.463	1.505	1.528	1.547	1.563
30-min	1.346	1.426	1.468	1.510	1.533	1.552	1.568
1-h	1.345	1.422	1.465	1.508	1.532	1.552	1.568
2-h	1.359	1.428	1.469	1.512	1.537	1.558	1.576
6-h	1.353	1.422	1.461	1.505	1.530	1.552	1.571
12-h	1.357	1.429	1.469	1.512	1.536	1.557	1.574
24-h	1.346	1.420	1.461	1.503	1.528	1.548	1.565

Table 1.10 Zone 4 Delta Changes for Large Change 2050 Scenario

Duration\AEP	Deltas						
	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
5-min	1.331	1.425	1.464	1.498	1.517	1.532	1.545
10-min	1.347	1.436	1.473	1.507	1.526	1.541	1.553
15-min	1.339	1.427	1.464	1.499	1.518	1.534	1.547
30-min	1.342	1.425	1.462	1.497	1.517	1.534	1.548
1-h	1.337	1.415	1.452	1.488	1.509	1.527	1.542
2-h	1.344	1.419	1.455	1.491	1.512	1.530	1.547
6-h	1.355	1.432	1.468	1.503	1.523	1.540	1.555
12-h	1.352	1.432	1.469	1.503	1.523	1.540	1.554
24-h	1.360	1.441	1.477	1.511	1.530	1.546	1.560

Table 1.11 Zone 5 Delta Changes for Large Change 2050 Scenario

Duration\AEP	Deltas						
	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
5-min	1.298	1.349	1.376	1.407	1.424	1.438	1.450
10-min	1.316	1.363	1.389	1.419	1.436	1.449	1.460
15-min	1.318	1.364	1.390	1.420	1.436	1.450	1.460
30-min	1.320	1.363	1.389	1.419	1.436	1.450	1.461
1-h	1.347	1.381	1.406	1.435	1.451	1.464	1.475
2-h	1.338	1.371	1.398	1.428	1.446	1.461	1.474
6-h	1.342	1.376	1.403	1.433	1.451	1.465	1.478
12-h	1.344	1.378	1.404	1.434	1.451	1.465	1.477
24-h	1.342	1.377	1.403	1.433	1.450	1.463	1.475

Table 1.12 Zone 6 Delta Changes for Large Change 2050 Scenario

Duration\AEP	Deltas						
	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
5-min	1.314	1.337	1.359	1.380	1.391	1.400	1.408
10-min	1.298	1.321	1.345	1.366	1.379	1.389	1.397
15-min	1.284	1.309	1.333	1.355	1.368	1.379	1.388
30-min	1.290	1.313	1.336	1.359	1.372	1.383	1.392
1-h	1.305	1.327	1.350	1.372	1.385	1.396	1.406
2-h	1.333	1.355	1.377	1.399	1.412	1.422	1.432
6-h	1.339	1.361	1.383	1.404	1.416	1.426	1.435
12-h	1.329	1.351	1.373	1.393	1.406	1.416	1.424
24-h	1.320	1.342	1.364	1.385	1.398	1.408	1.416

Table 1.13 Zone 1 Delta Changes for Moderate Change 2100 Scenario

Duration\AEP	Deltas						
	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
5-min	1.311	1.418	1.446	1.465	1.472	1.480	1.487
10-min	1.317	1.422	1.450	1.468	1.476	1.482	1.489
15-min	1.317	1.422	1.451	1.470	1.477	1.485	1.492
30-min	1.323	1.423	1.451	1.470	1.478	1.486	1.493
1-h	1.348	1.432	1.459	1.475	1.482	1.489	1.496
2-h	1.365	1.439	1.465	1.479	1.486	1.492	1.500
6-h	1.376	1.445	1.470	1.482	1.489	1.495	1.501
12-h	1.360	1.436	1.462	1.476	1.483	1.490	1.497
24-h	1.369	1.444	1.470	1.482	1.489	1.495	1.501

Table 1.14 Zone 2 Delta Changes for Moderate Change 2100 Scenario

Duration\AEP	Deltas						
	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
5-min	1.247	1.341	1.384	1.421	1.441	1.457	1.470
10-min	1.254	1.345	1.387	1.423	1.443	1.460	1.473
15-min	1.261	1.351	1.392	1.428	1.448	1.464	1.477
30-min	1.257	1.346	1.387	1.424	1.444	1.461	1.474
1-h	1.259	1.348	1.388	1.424	1.445	1.462	1.476
2-h	1.263	1.347	1.386	1.422	1.444	1.461	1.476
6-h	1.265	1.345	1.381	1.418	1.440	1.458	1.474
12-h	1.274	1.355	1.392	1.428	1.449	1.467	1.481
24-h	1.281	1.362	1.398	1.434	1.455	1.472	1.487

Table 1.15 Zone 3 Delta Changes for Moderate Change 2100 Scenario

Duration\AEP	Deltas						
	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
5-min	1.328	1.388	1.400	1.416	1.432	1.445	1.455
10-min	1.320	1.380	1.393	1.410	1.426	1.440	1.451
15-min	1.323	1.384	1.397	1.414	1.430	1.443	1.454
30-min	1.327	1.388	1.400	1.417	1.433	1.447	1.457
1-h	1.329	1.386	1.399	1.416	1.433	1.446	1.458
2-h	1.349	1.397	1.409	1.423	1.441	1.456	1.468
6-h	1.345	1.393	1.405	1.419	1.437	1.453	1.466
12-h	1.345	1.395	1.407	1.422	1.439	1.453	1.465
24-h	1.332	1.385	1.398	1.414	1.431	1.445	1.457

Table 1.16 Zone 4 Delta Changes for Moderate Change 2100 Scenario

Duration\AEP	Deltas						
	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
5-min	1.319	1.432	1.457	1.480	1.492	1.503	1.511
10-min	1.337	1.444	1.468	1.490	1.502	1.512	1.520
15-min	1.331	1.436	1.461	1.483	1.496	1.507	1.515
30-min	1.338	1.438	1.462	1.485	1.499	1.510	1.519
1-h	1.337	1.431	1.456	1.480	1.494	1.506	1.516
2-h	1.347	1.437	1.462	1.486	1.500	1.512	1.523
6-h	1.356	1.449	1.472	1.495	1.509	1.520	1.529
12-h	1.351	1.447	1.471	1.493	1.507	1.517	1.527
24-h	1.357	1.455	1.478	1.499	1.512	1.522	1.531

Table 1.17 Zone 5 Delta Changes for Moderate Change 2100 Scenario

Duration\AEP	Deltas						
	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
5-min	1.305	1.349	1.353	1.375	1.384	1.385	1.385
10-min	1.324	1.364	1.366	1.386	1.394	1.394	1.393
15-min	1.327	1.366	1.367	1.386	1.394	1.394	1.393
30-min	1.329	1.366	1.366	1.384	1.393	1.393	1.392
1-h	1.361	1.389	1.384	1.397	1.404	1.405	1.402
2-h	1.356	1.384	1.378	1.389	1.398	1.401	1.399
6-h	1.362	1.389	1.382	1.393	1.402	1.406	1.403
12-h	1.362	1.389	1.383	1.395	1.403	1.405	1.403
24-h	1.358	1.387	1.382	1.394	1.402	1.404	1.402

Table 1.18 Zone 6 Delta Changes for Moderate Change 2100 Scenario

Duration\AEP	Deltas						
	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
5-min	1.343	1.338	1.337	1.360	1.365	1.367	1.364
10-min	1.325	1.323	1.325	1.348	1.354	1.358	1.357
15-min	1.309	1.311	1.312	1.338	1.346	1.349	1.348
30-min	1.317	1.316	1.316	1.343	1.351	1.354	1.352
1-h	1.337	1.330	1.329	1.356	1.366	1.367	1.364
2-h	1.368	1.354	1.353	1.381	1.390	1.391	1.387
6-h	1.371	1.359	1.357	1.384	1.392	1.394	1.390
12-h	1.357	1.349	1.347	1.373	1.380	1.382	1.379
24-h	1.346	1.341	1.339	1.366	1.371	1.374	1.371

Table 1.19 Zone 1 Delta Changes for Large Change 2100 Scenario

Duration\AEP	Deltas						
	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
5-min	1.514	1.728	1.831	1.920	1.968	2.005	2.036
10-min	1.520	1.731	1.834	1.924	1.972	2.010	2.041
15-min	1.524	1.736	1.838	1.927	1.976	2.014	2.045
30-min	1.531	1.736	1.838	1.928	1.977	2.016	2.048
1-h	1.554	1.746	1.845	1.937	1.989	2.031	2.066
2-h	1.571	1.756	1.853	1.946	2.000	2.045	2.082
6-h	1.576	1.759	1.856	1.951	2.006	2.053	2.093
12-h	1.564	1.749	1.847	1.940	1.995	2.040	2.078
24-h	1.575	1.762	1.860	1.952	2.006	2.050	2.088

Table 1.20 Zone 2 Delta Changes for Large Change 2100 Scenario

Duration\AEP	Deltas						
	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
5-min	1.490	1.664	1.760	1.844	1.891	1.928	1.958
10-min	1.502	1.669	1.763	1.848	1.894	1.932	1.963
15-min	1.515	1.676	1.770	1.854	1.901	1.938	1.969
30-min	1.509	1.668	1.761	1.846	1.893	1.932	1.964
1-h	1.516	1.669	1.762	1.847	1.895	1.934	1.966
2-h	1.522	1.664	1.754	1.840	1.890	1.931	1.965
6-h	1.520	1.654	1.742	1.827	1.878	1.920	1.956
12-h	1.537	1.674	1.762	1.846	1.896	1.937	1.972
24-h	1.552	1.687	1.774	1.859	1.908	1.949	1.984

Table 1.21 Zone 3 Delta Changes for Large Change 2100 Scenario

Duration\AEP	Deltas						
	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
5-min	1.563	1.684	1.759	1.828	1.866	1.896	1.921
10-min	1.547	1.669	1.745	1.814	1.853	1.884	1.910
15-min	1.555	1.675	1.751	1.820	1.859	1.890	1.916
30-min	1.562	1.683	1.758	1.827	1.866	1.897	1.923
1-h	1.560	1.679	1.754	1.824	1.864	1.897	1.924
2-h	1.580	1.690	1.763	1.834	1.876	1.911	1.940
6-h	1.569	1.678	1.752	1.824	1.867	1.904	1.934
12-h	1.577	1.689	1.763	1.834	1.875	1.909	1.937
24-h	1.559	1.675	1.749	1.820	1.861	1.894	1.922

Table 1.22 Zone 4 Delta Changes for Large Change 2100 Scenario

Duration\AEP	Deltas						
	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
5-min	1.529	1.678	1.763	1.840	1.882	1.916	1.944
10-min	1.553	1.695	1.779	1.855	1.897	1.931	1.960
15-min	1.539	1.681	1.765	1.842	1.886	1.921	1.951
30-min	1.544	1.681	1.764	1.843	1.888	1.926	1.957
1-h	1.534	1.668	1.750	1.831	1.878	1.918	1.952
2-h	1.544	1.675	1.757	1.837	1.886	1.926	1.961
6-h	1.562	1.694	1.776	1.856	1.903	1.942	1.975
12-h	1.559	1.694	1.776	1.855	1.901	1.939	1.971
24-h	1.571	1.707	1.789	1.867	1.911	1.948	1.979

Table 1.23 Zone 5 Delta Changes for Large Change 2100 Scenario

Duration\AEP	Deltas						
	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
5-min	1.456	1.571	1.639	1.699	1.733	1.759	1.782
10-min	1.482	1.595	1.660	1.719	1.752	1.778	1.799
15-min	1.485	1.597	1.662	1.720	1.752	1.778	1.799
30-min	1.487	1.595	1.659	1.718	1.751	1.777	1.800
1-h	1.527	1.624	1.685	1.742	1.774	1.801	1.823
2-h	1.513	1.610	1.671	1.731	1.766	1.796	1.822
6-h	1.521	1.618	1.679	1.739	1.774	1.804	1.829
12-h	1.524	1.621	1.682	1.740	1.774	1.802	1.826
24-h	1.520	1.618	1.680	1.738	1.772	1.799	1.822

Table 1.24 Zone 6 Delta Changes for Large Change 2100 Scenario

Duration\AEP	Deltas						
	50 % (2-yr)	20 % (5-yr)	10 % (10-yr)	4 % (25-yr)	2 % (50-yr)	1 % (100-yr)	0.5 % (200-yr)
5-min	1.478	1.548	1.597	1.642	1.666	1.686	1.702
10-min	1.450	1.523	1.575	1.621	1.648	1.669	1.687
15-min	1.431	1.502	1.554	1.602	1.630	1.653	1.672
30-min	1.443	1.510	1.560	1.609	1.637	1.661	1.680
1-h	1.470	1.533	1.583	1.631	1.660	1.684	1.705
2-h	1.519	1.575	1.623	1.671	1.700	1.724	1.745
6-h	1.529	1.580	1.628	1.674	1.702	1.725	1.744
12-h	1.510	1.565	1.610	1.656	1.683	1.705	1.724
24-h	1.494	1.552	1.597	1.644	1.670	1.692	1.711

Appendix B

Figure Index

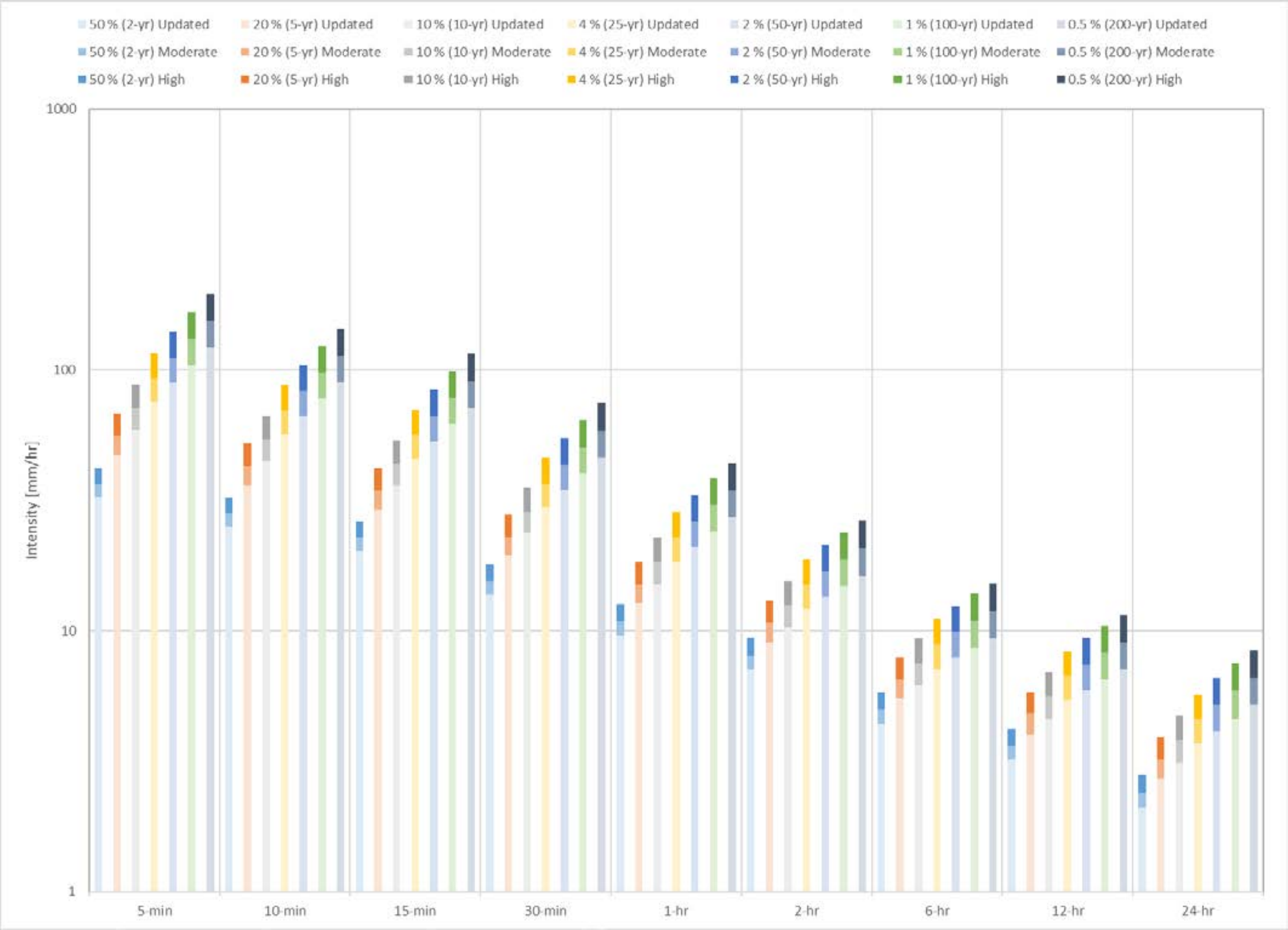


Figure 1.1 Zone 1 IDF Curve (Scaled by Average Index Rain for the Zone) for Moderate and High Change 2050 Scenario

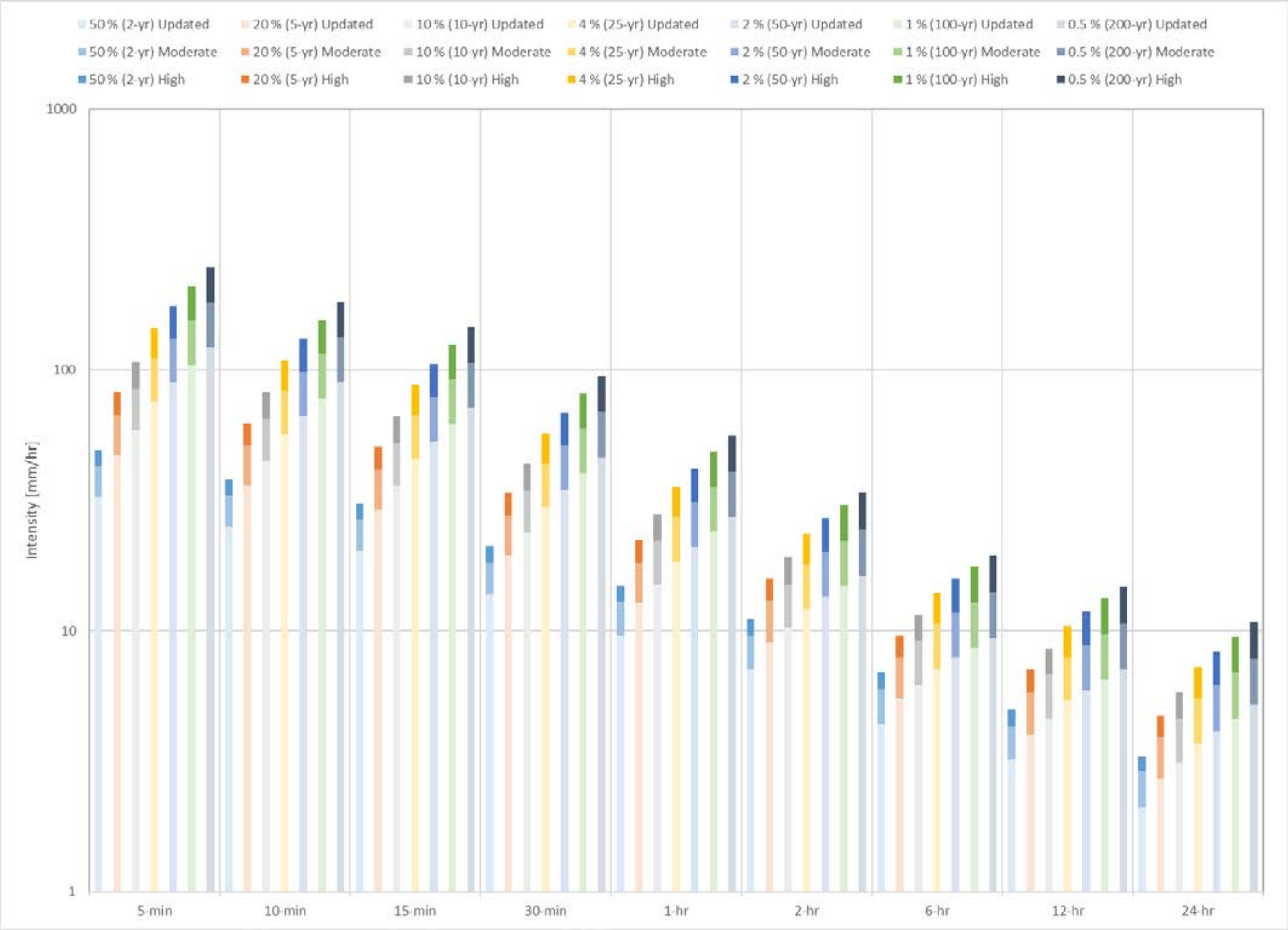


Figure 1.2 Zone 1 IDF Curve (Scaled by Average Index Rain for the Zone) for Moderate and High Change 2100 Scenario

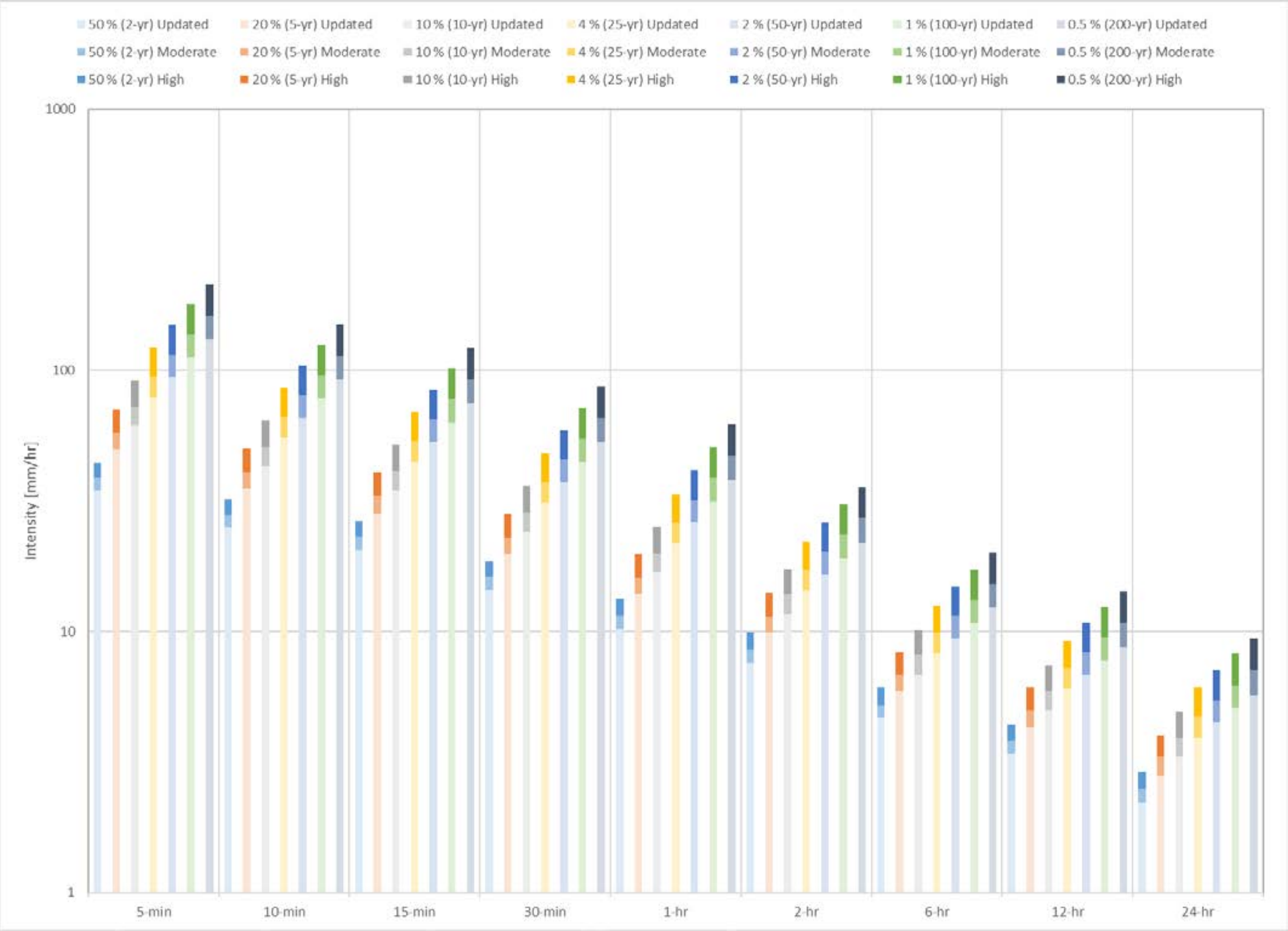


Figure 1.3 Zone 2 IDF Curve (Scaled by Average Index Rain for the Zone) for Moderate and High Change 2050 Scenario

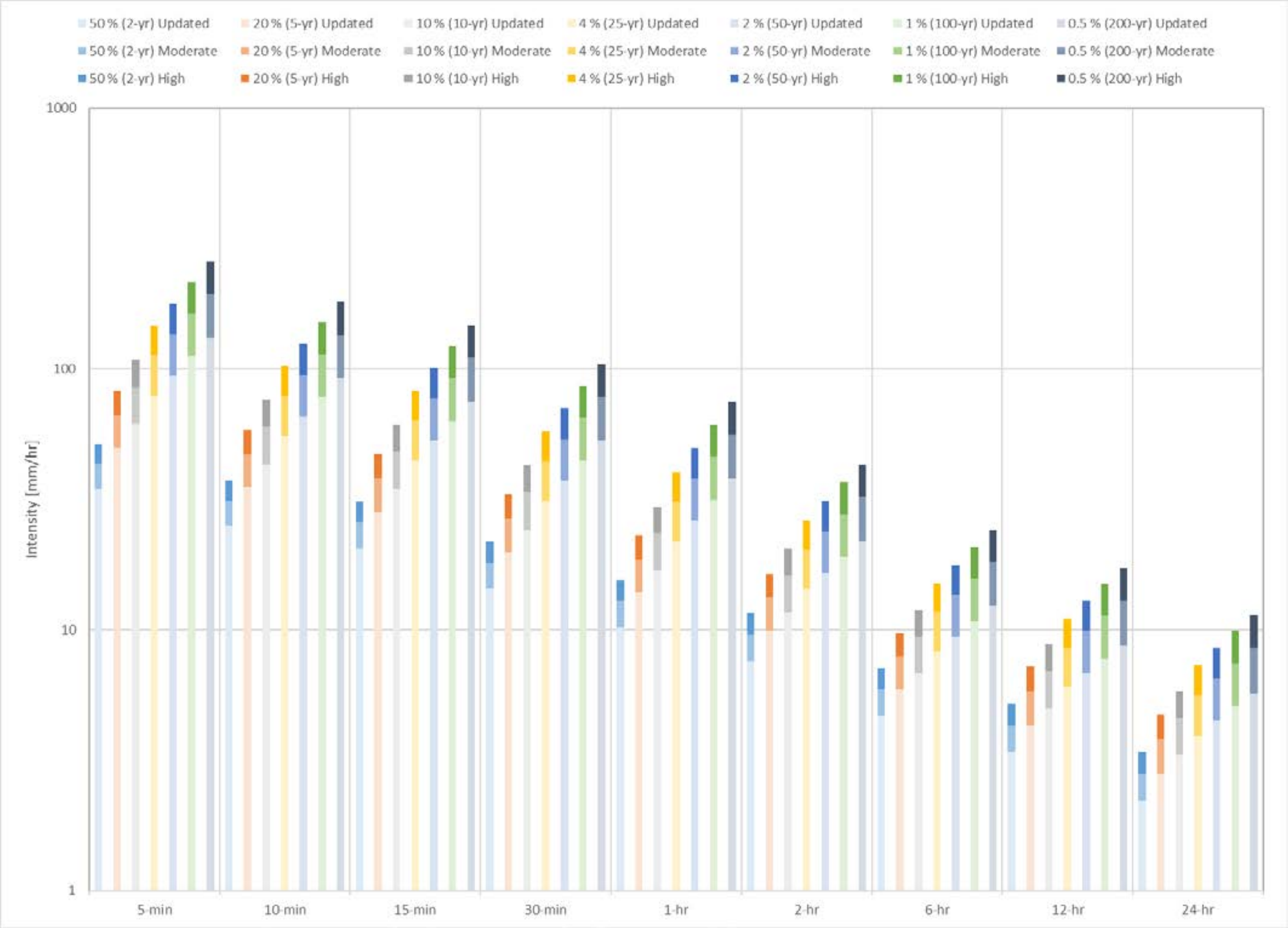


Figure 1.4 Zone 2 IDF Curve (Scaled by Average Index Rain for the Zone) for Moderate and High Change 2100 Scenario

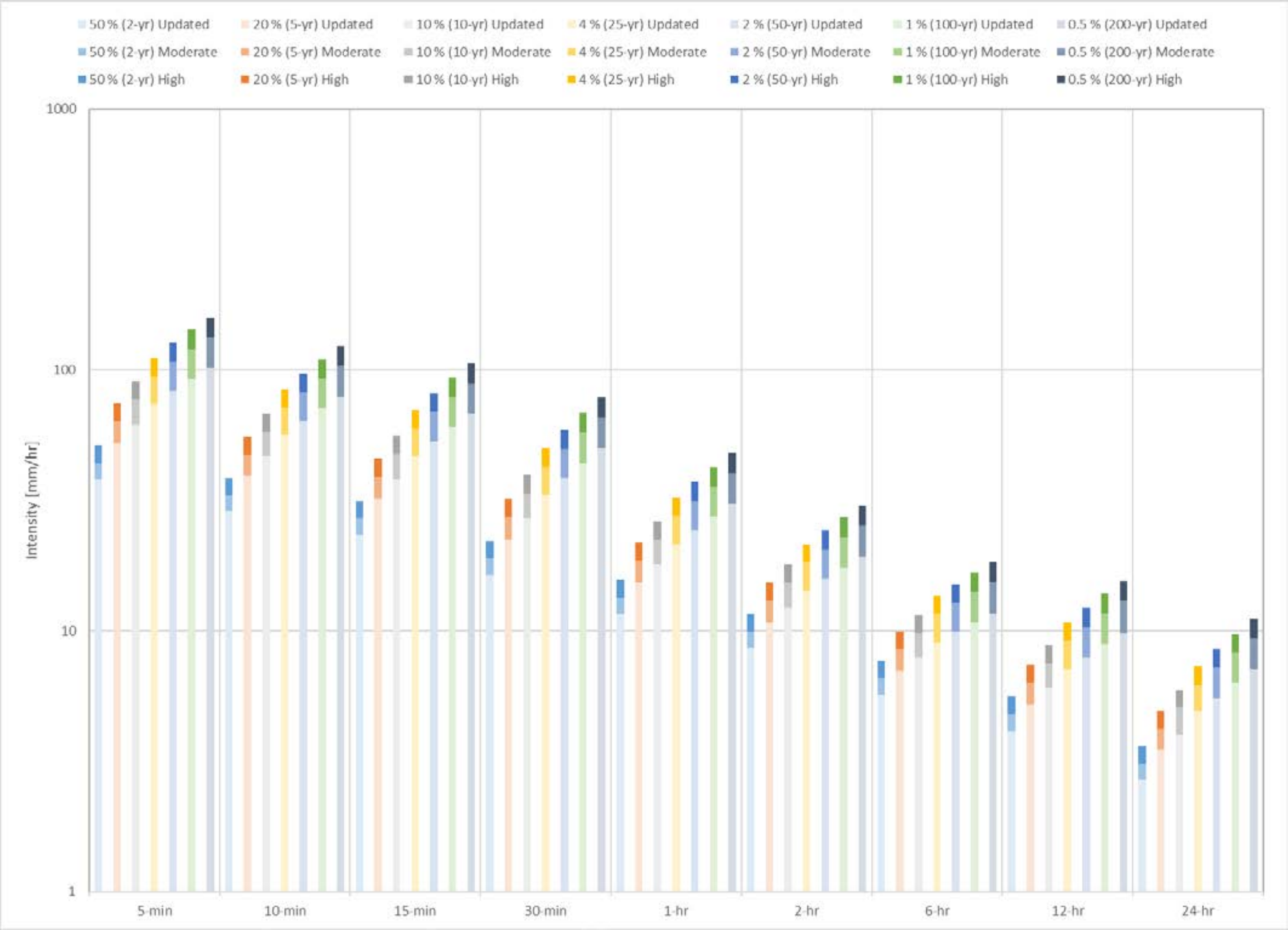


Figure 1.5 Zone 3 IDF Curve (Scaled by Average Index Rain for the Zone) for Moderate and High Change 2050 Scenario

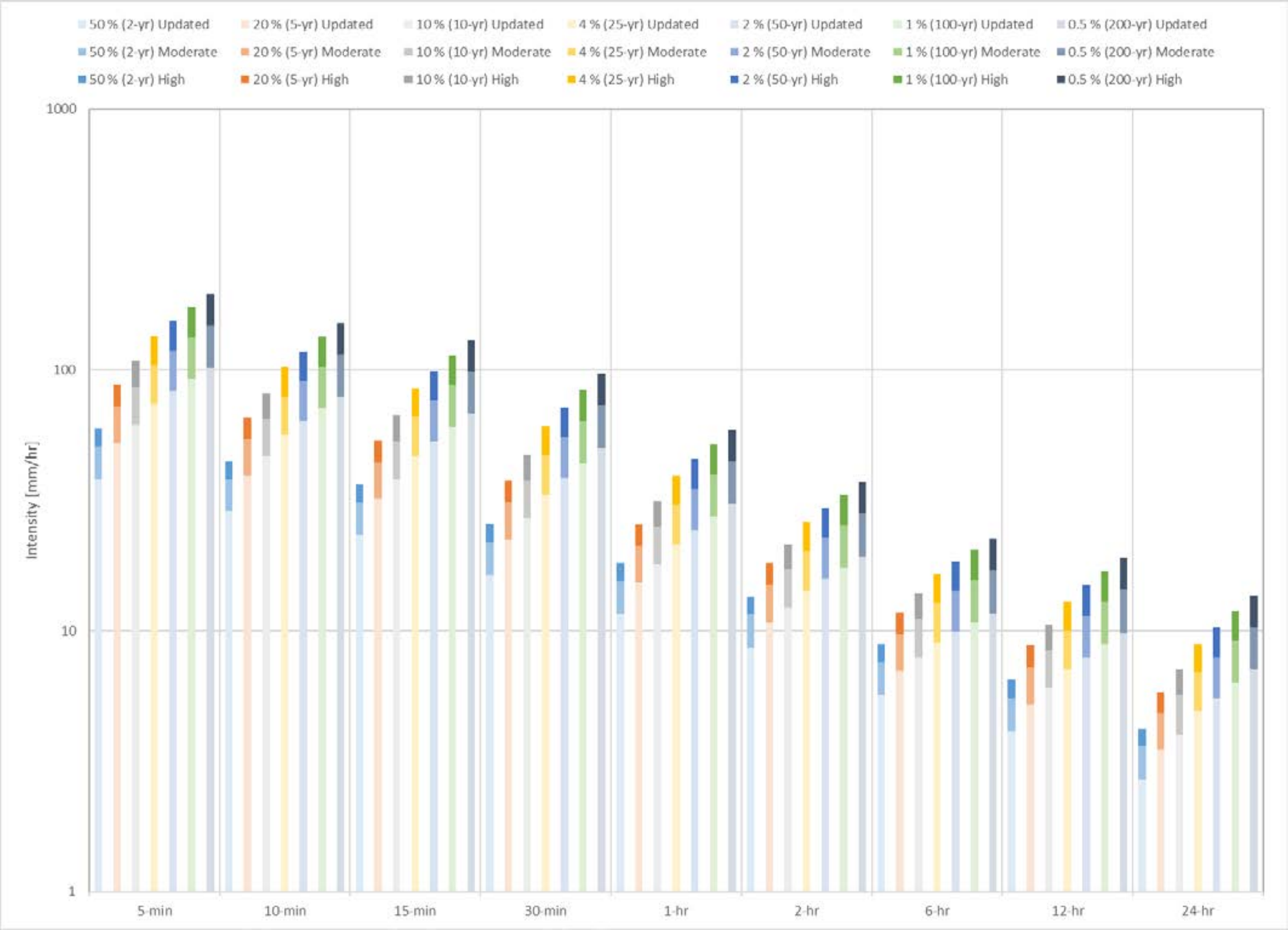


Figure 1.6 Zone 3 IDF Curve (Scaled by Average Index Rain for the Zone) for Moderate and High Change 2100 Scenario

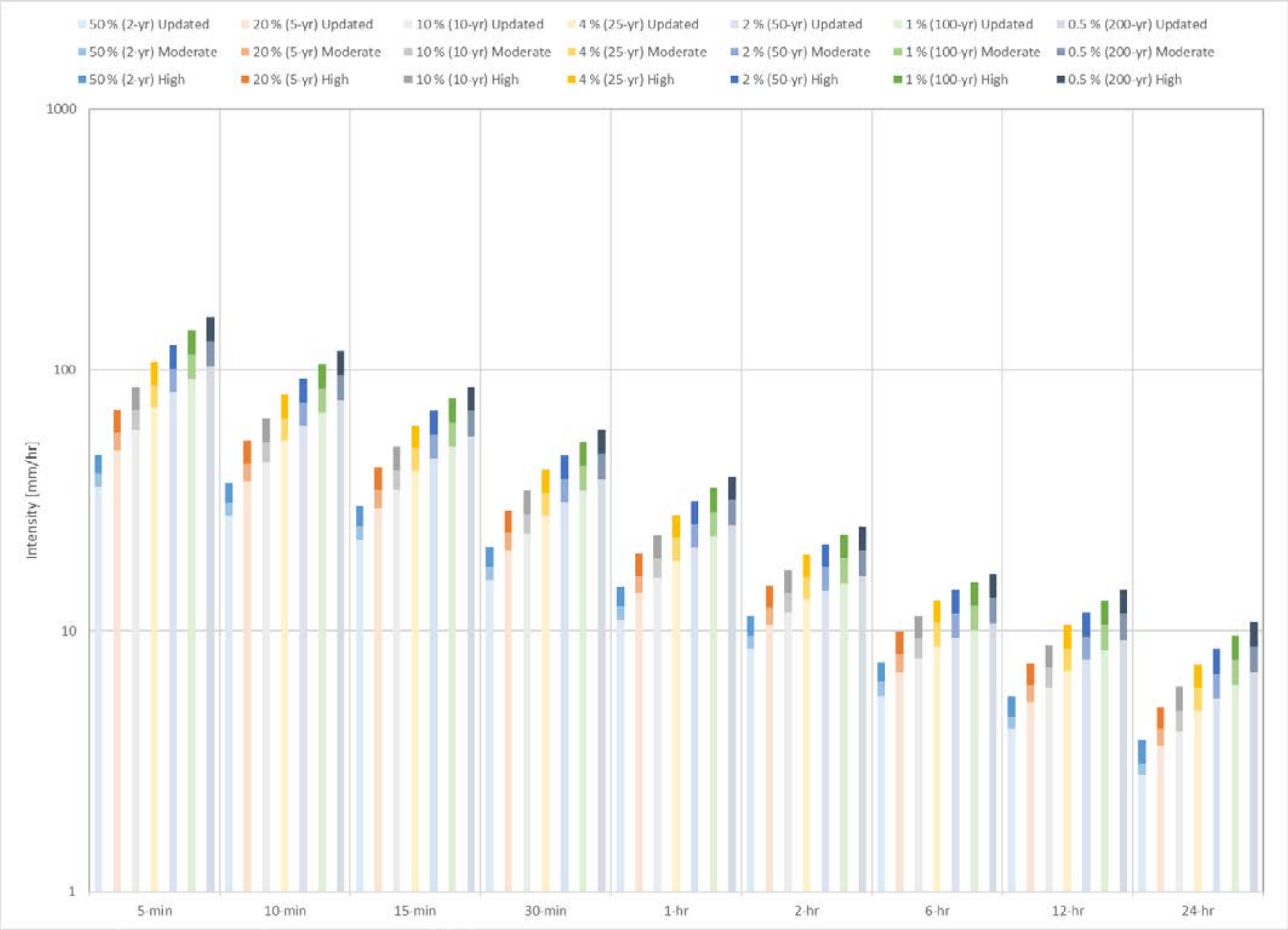


Figure 1.7 Zone 4 IDF Curve (Scaled by Average Index Rain for the Zone) for Moderate and High Change 2050 Scenario

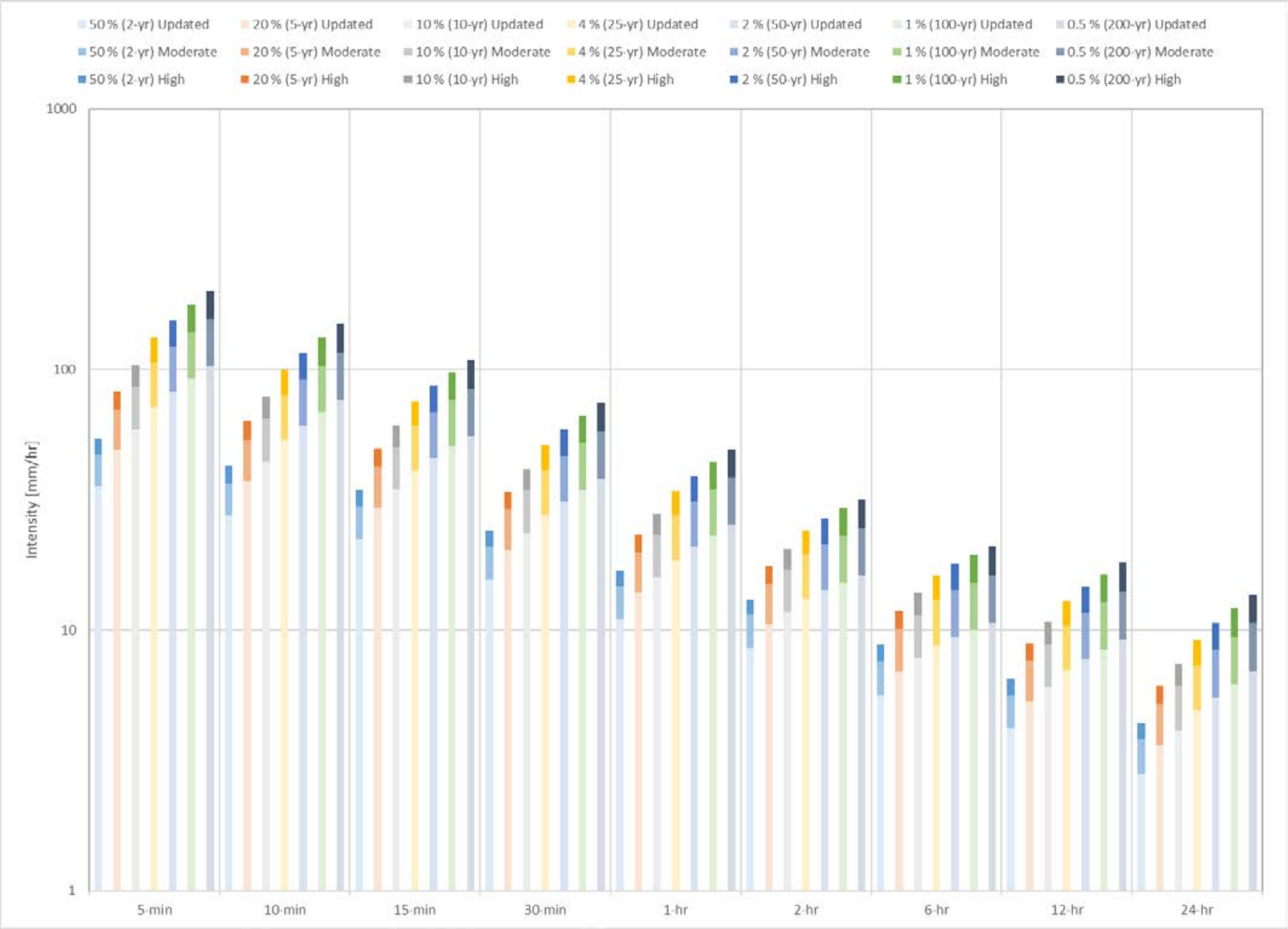


Figure 1.8 **Zone 4 IDF Curve (Scaled by Average Index Rain for the Zone) for Moderate and High Change 2100 Scenario**

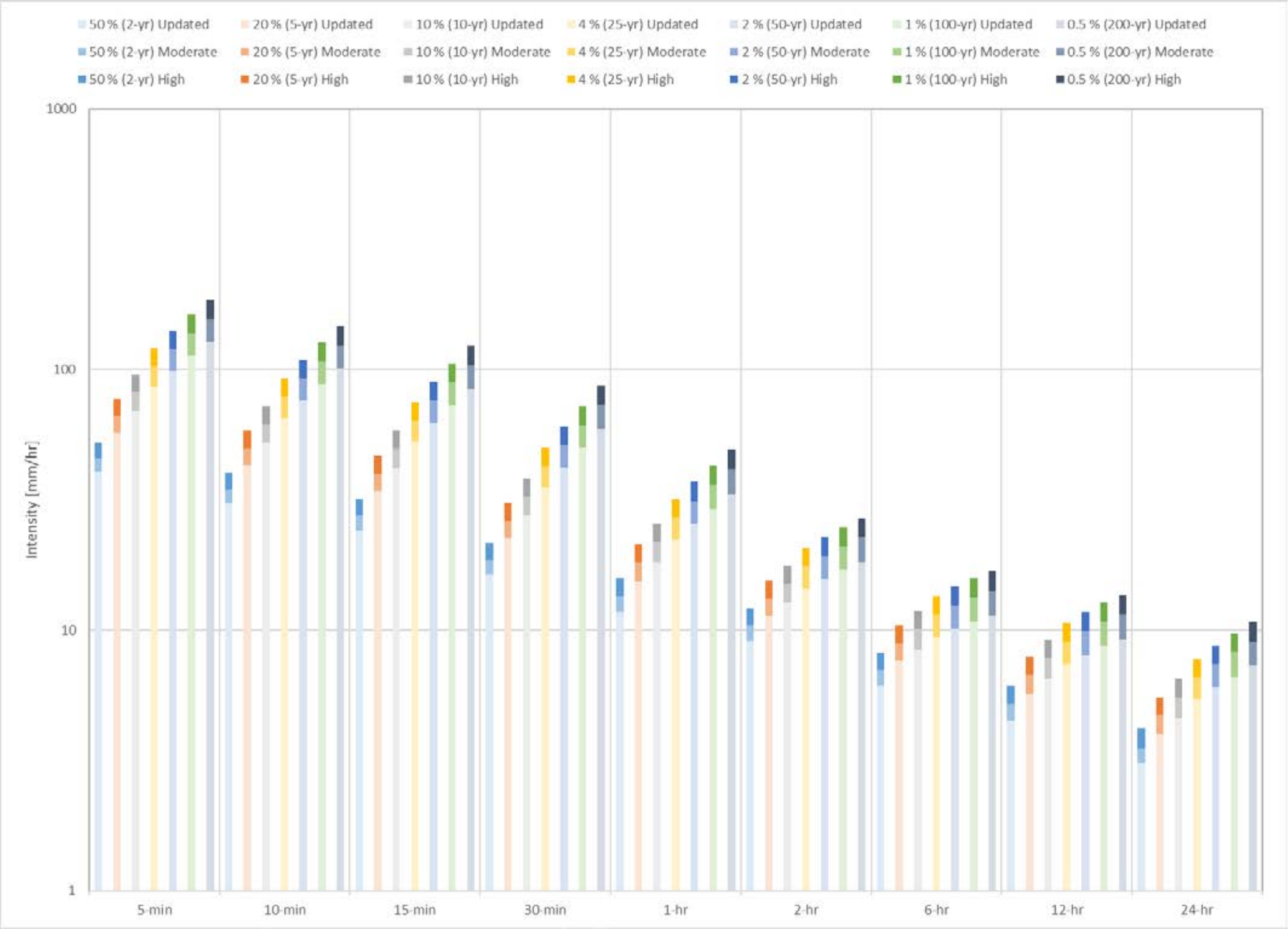


Figure 1.9 Zone 5 IDF Curve (Scaled by Average Index Rain for the Zone) for Moderate and High Change 2050 Scenario

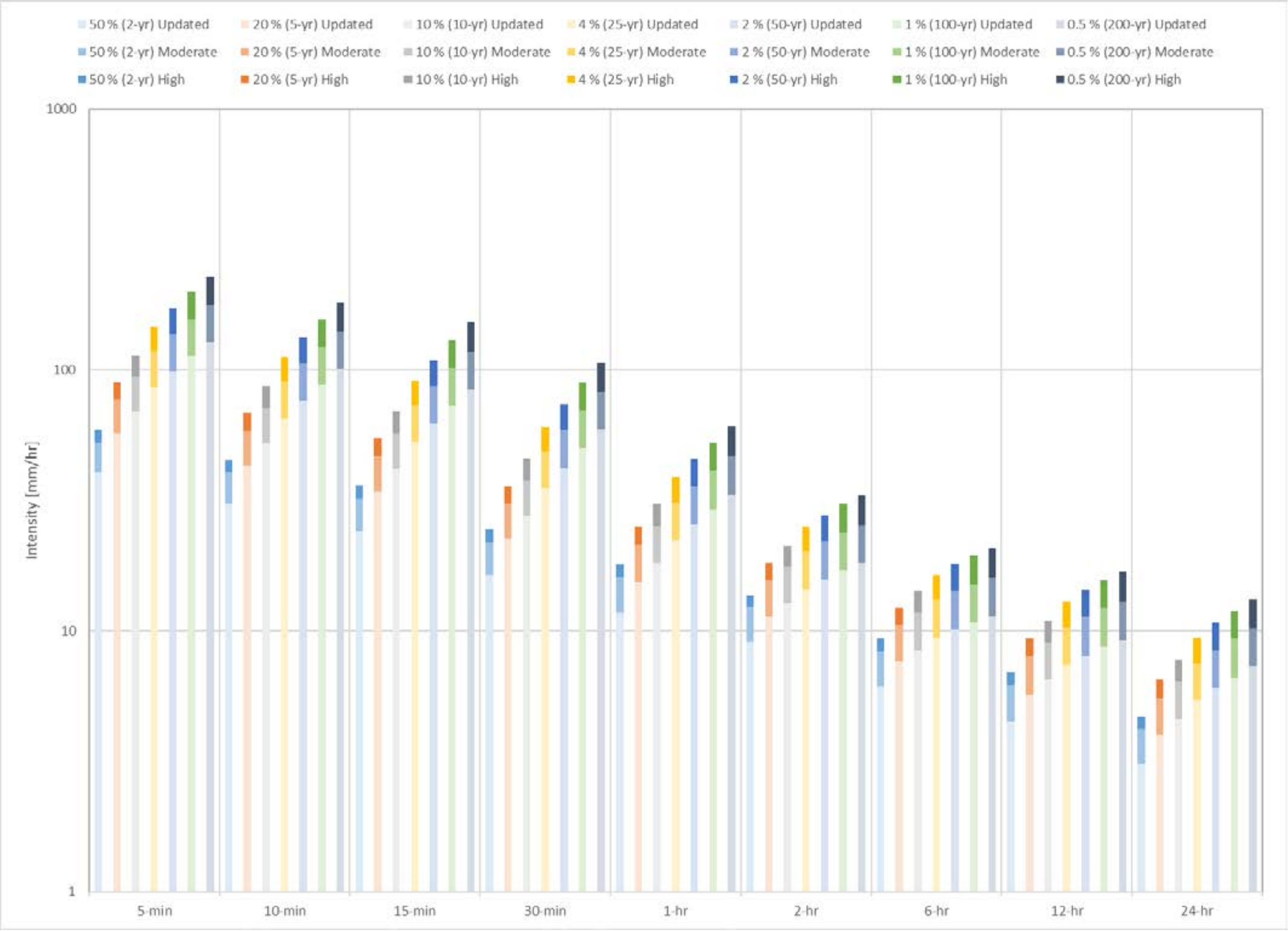


Figure 1.10 Zone 5 IDF Curve (Scaled by Average Index Rain for the Zone) for Moderate and High Change 2100 Scenario

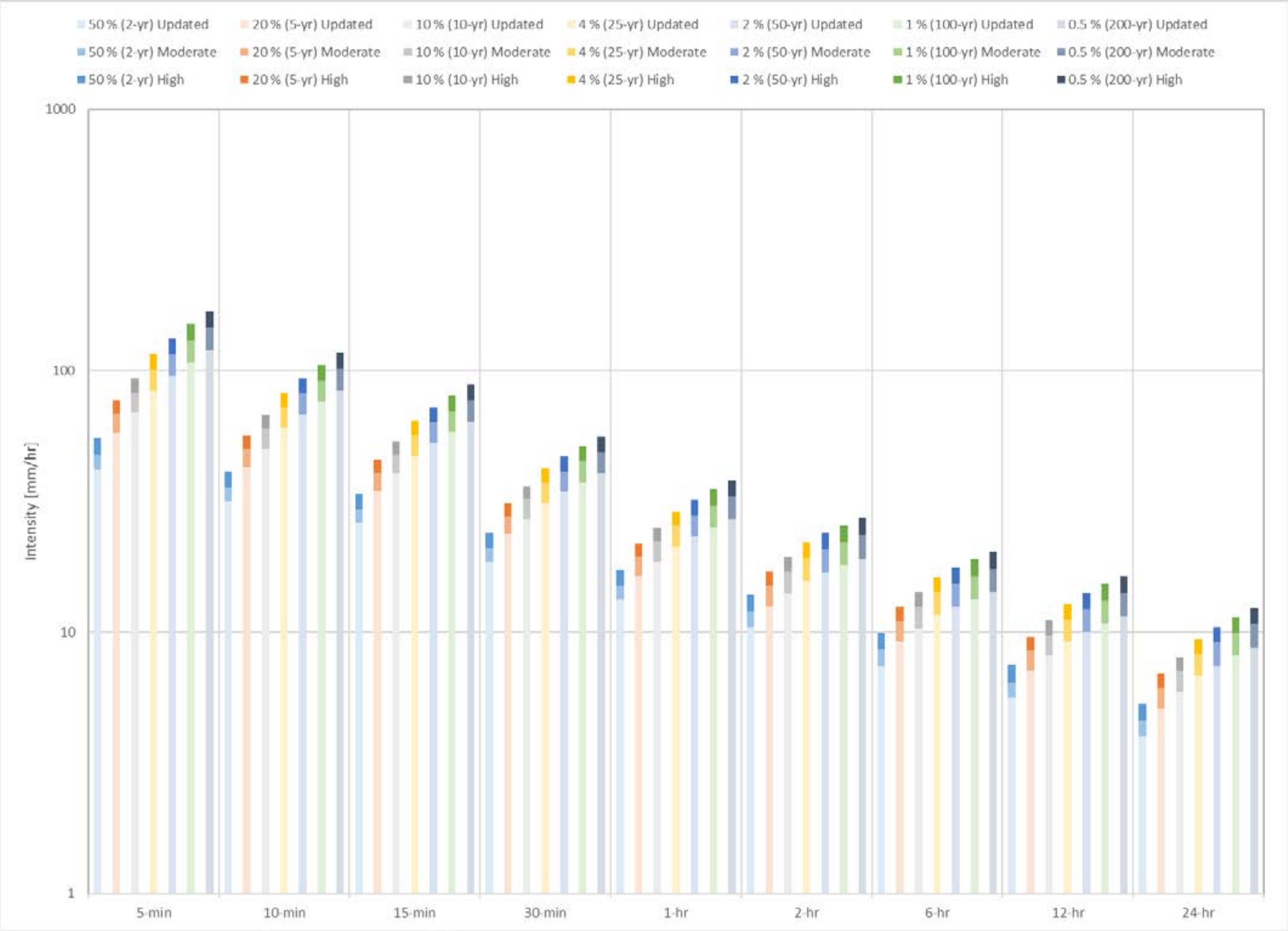


Figure 1.11 Zone 6 IDF Curve (Scaled by Average Index Rain for the Zone) for Moderate and High Change 2050 Scenario

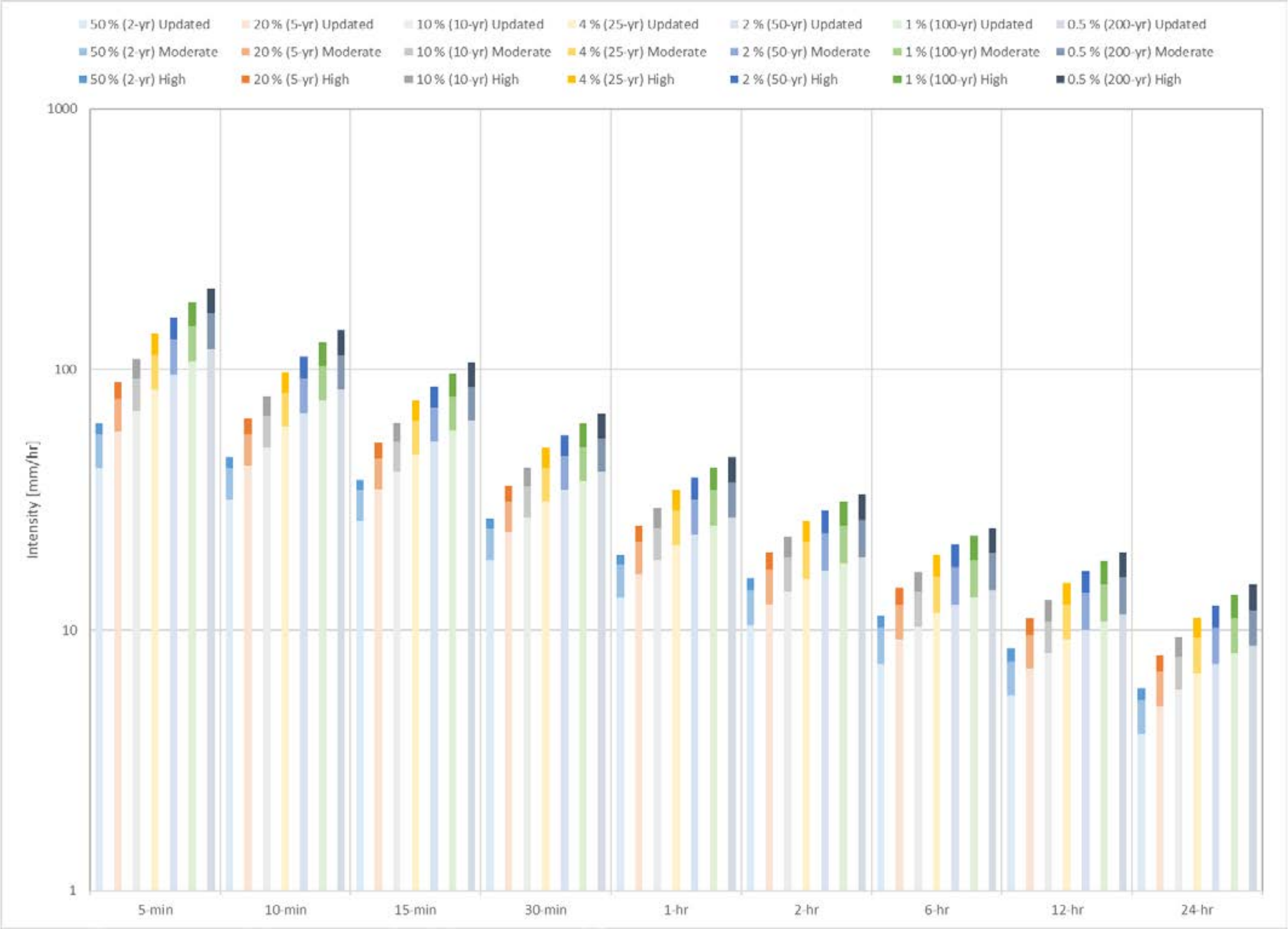


Figure 1.12 Zone 6 IDF Curve (Scaled by Average Index Rain for the Zone) for Moderate and High Change 2100 Scenario

Appendix C

Figure Index

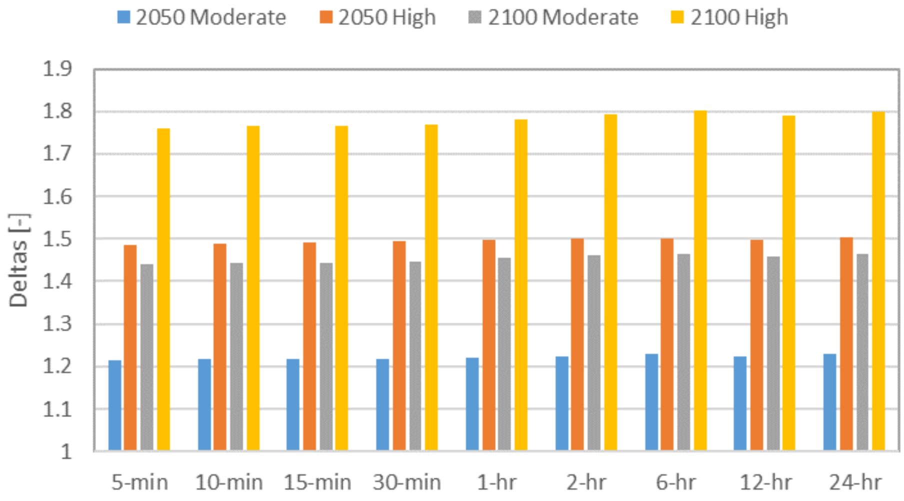


Figure 1.1 Changes in IDF Curves for Zone 1, Averaged Over All AEPs for Each Duration

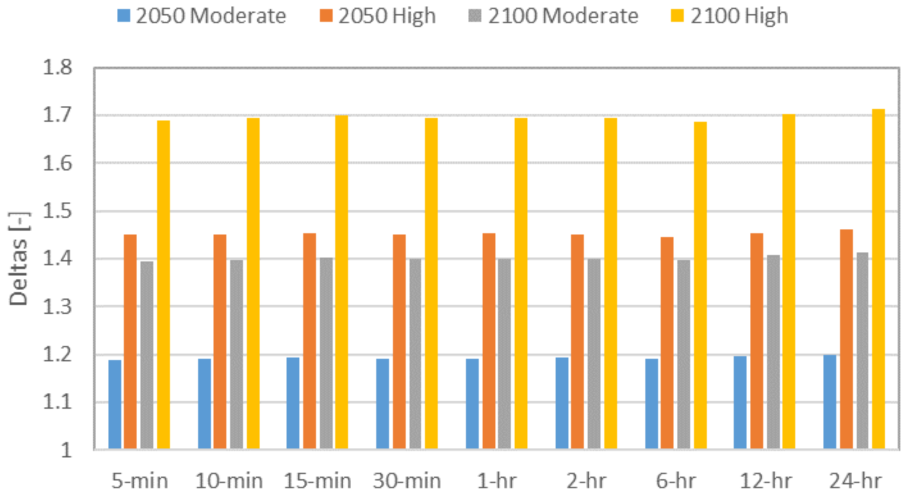


Figure 1.2 Changes in IDF Curves for Zone 2, Averaged Over All AEPs for Each Duration

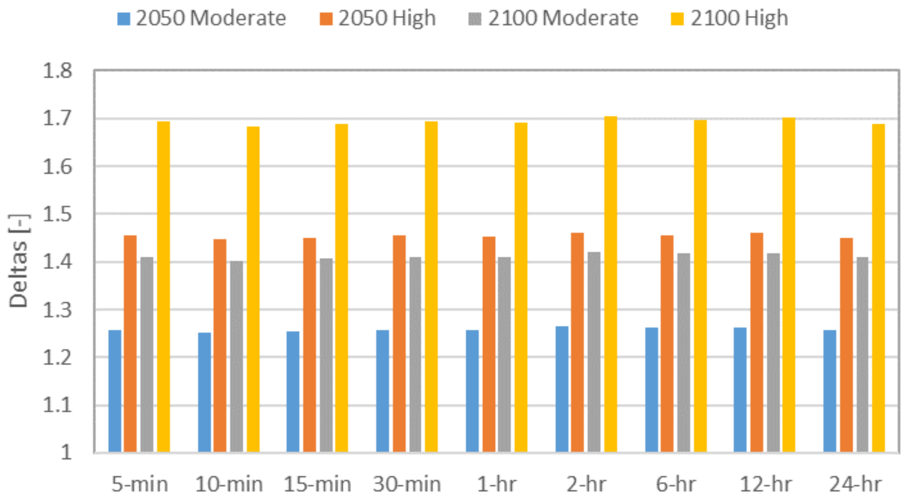


Figure 1.3 Changes in IDF Curves for Zone 3, Averaged Over All AEPs for Each Duration

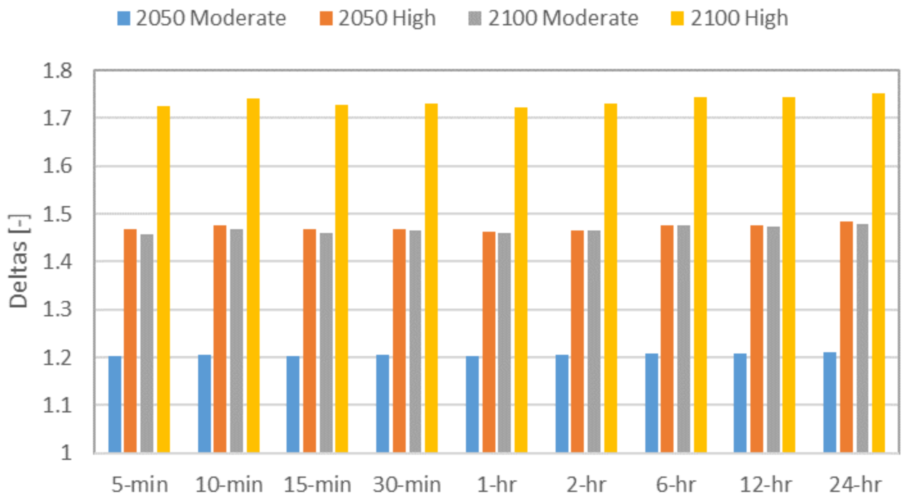


Figure 1.4 Changes in IDF Curves for Zone 4, Averaged Over All AEPs for Each Duration

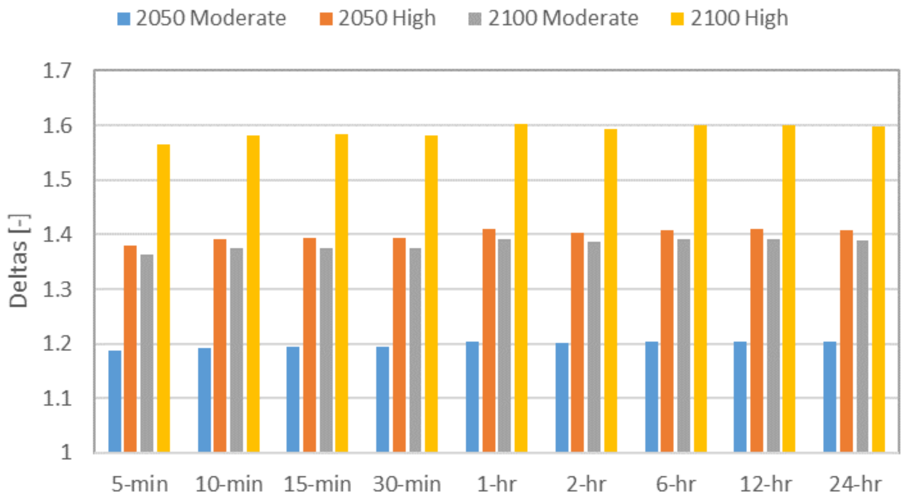


Figure 1.5 **Changes in IDF Curves for Zone 5, Averaged Over All AEPs for Each Duration**

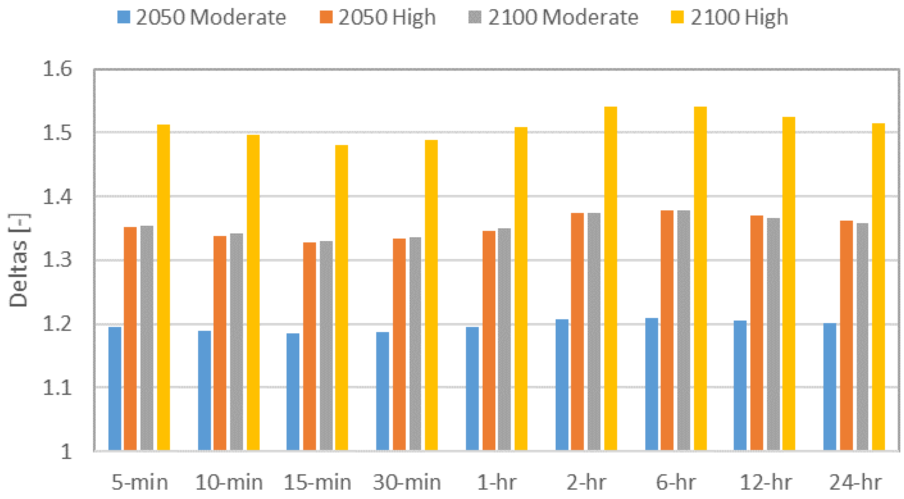


Figure 1.6 **Changes in IDF Curves for Zone 6, Averaged Over All AEPs for Each Duration**

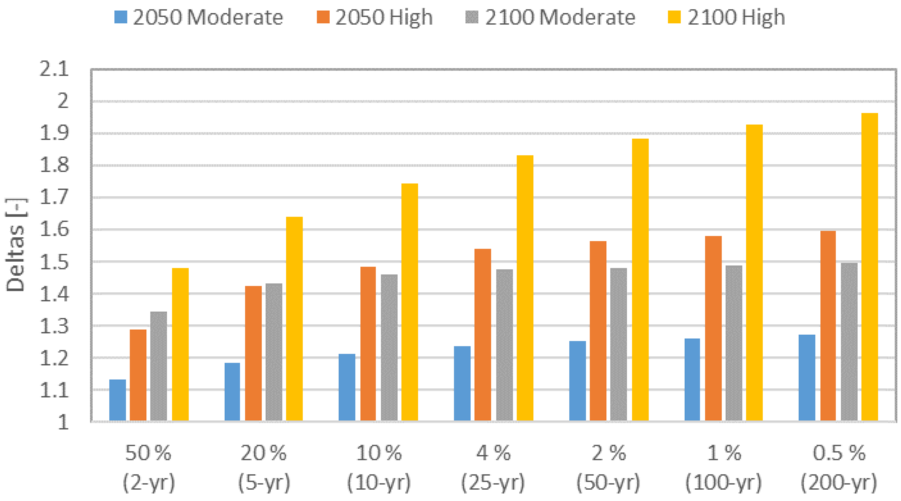


Figure 1.7 **Changes in IDF Curves for Zone 1, Averaged Over All Durations for Each AEP**

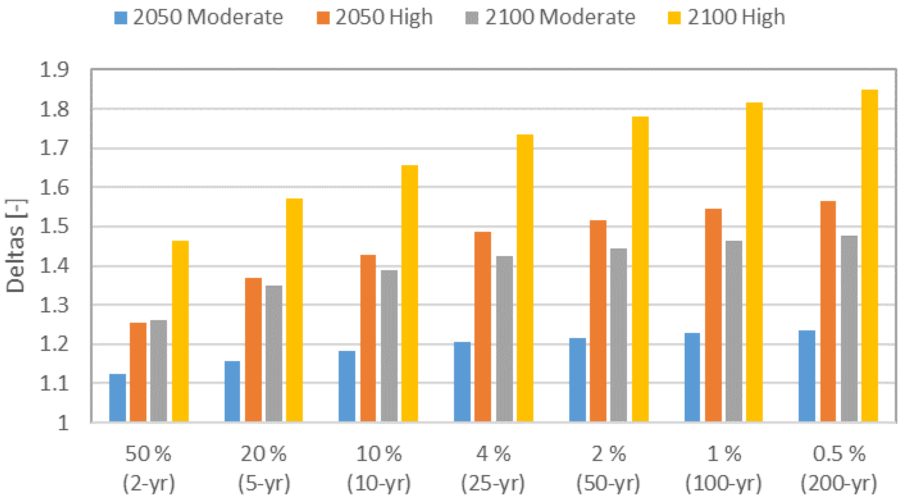


Figure 1.8 **Changes in IDF Curves for Zone 2, Averaged Over All Durations for Each AEP**

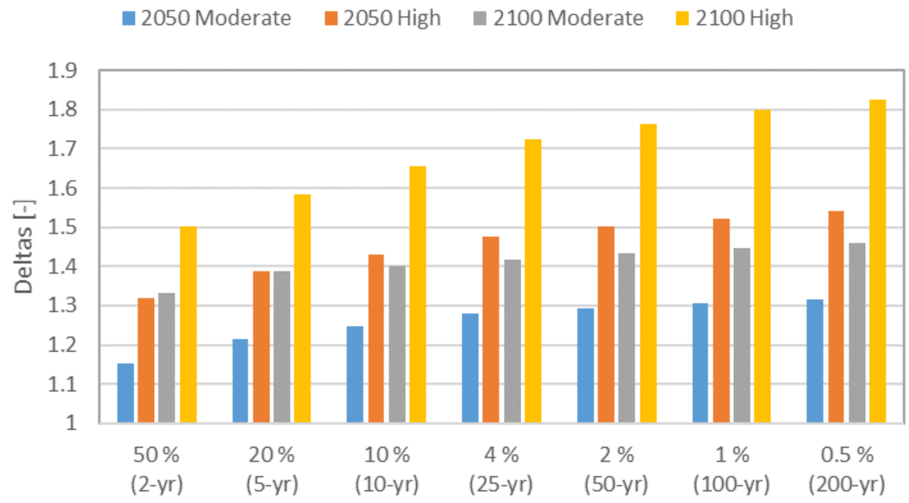


Figure 1.9 Changes in IDF Curves for Zone 3, Averaged Over All Durations for Each AEP

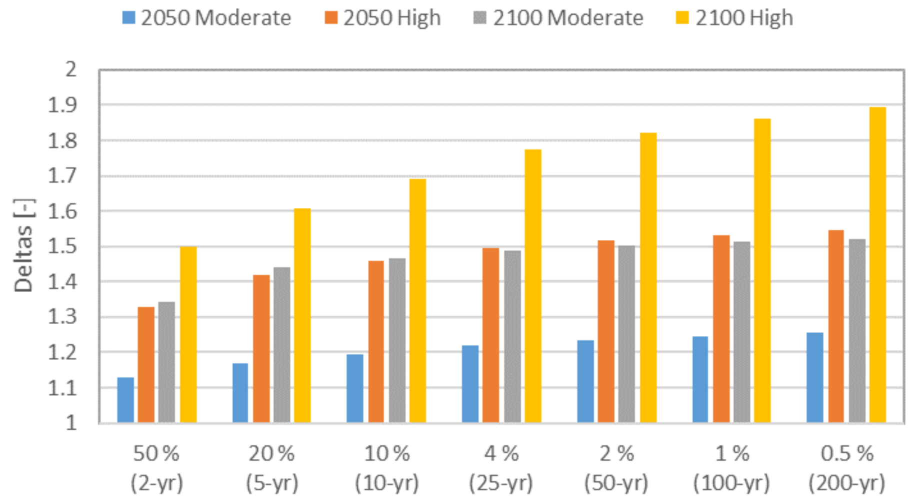


Figure 1.10 Changes in IDF Curves for Zone 4, Averaged Over All Durations for Each AEP

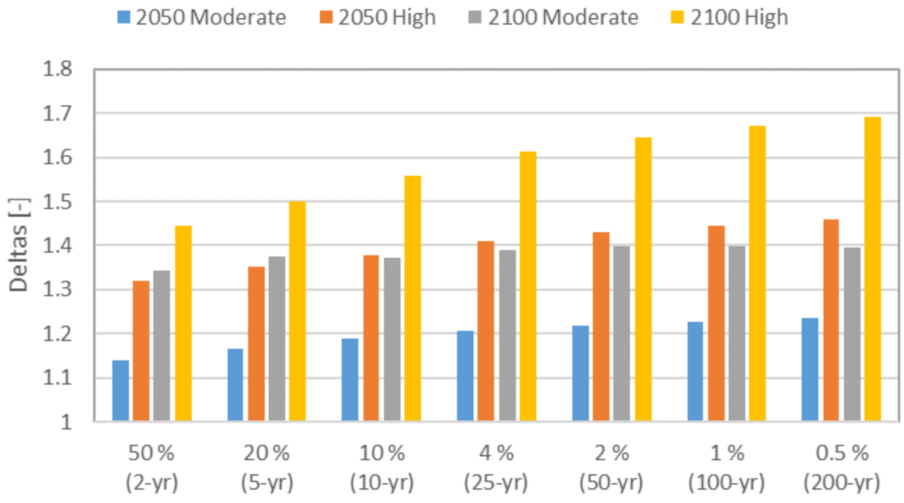


Figure 1.11 Changes in IDF Curves for Zone 5, Averaged Over All Durations for Each AEP

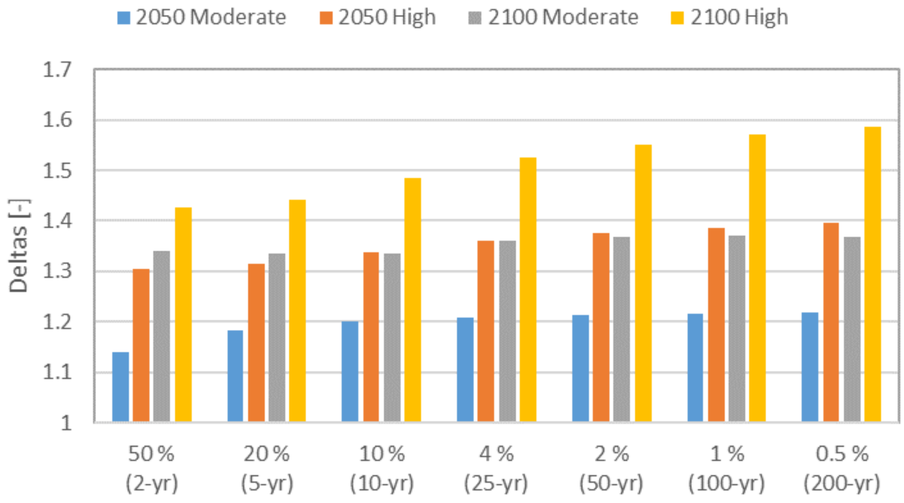


Figure 1.12 Changes in IDF Curves for Zone 6, Averaged Over All Durations for Each AEP

Technical Memorandum 4
Case Studies

Memorandum

August 3, 2018

To:	Lillian Zaremba	Ref. No.:	11140666
From:	Juraj Cunderlik, Allyson Bingeman/aj/4	Tel:	519-884-0510

AB

Subject: **Study of the Impacts of Climate Change on Precipitation and Stormwater Management Case Studies**

1. Introduction and Background

Increased frequency and intensity of extreme rainfall events will have a significant impact on wet infrastructure. The Greater Vancouver Sewerage and Drainage District (GVS&DD) has initiated this project for the purpose of advancing its knowledge and capabilities to adapt to the effects of climate change to ensure that adequate levels of service for sewerage and drainage infrastructure are maintained. During past collaboration between GVS&DD and the Pacific Climate Impacts Consortium (PCIC), it was found that future climate change Intensity Duration Frequency (IDF) Curves were of interest to stakeholders to assist them with planning and adaptation. In response, GVS&DD initiated this project, which has the following objectives: update the IDF curves for Metro Vancouver, quantify uncertainty surrounding future climate IDF projections, generate future climate IDF curves, determine the potential effect of climate change on infrastructure design, and develop good practice recommendations.

Technical Memorandum #1 (TM1) of this project described a temporal downscaling methodology that was developed to derive the rainfall increase (delta) from Global Climate Model (GCM) data. Technical Memorandum #2 (TM2) described the rainfall data analysis and derivation of updated IDF curves. Technical Memorandum #3 (TM3) performed a sensitivity analysis of various factors that affect the future climate change IDF curves (using the methodology in TM1), and derived four future climate change IDF curves: 2050 Moderate Change, 2050 High Change, 2100 Moderate Change, and 2100 High Change. The subject of this Technical Memorandum is the fourth stage of this study, namely the analysis of three case studies to determine how the future increases in rainfall would impact sewerage and stormwater drainage in the Metro Vancouver area.

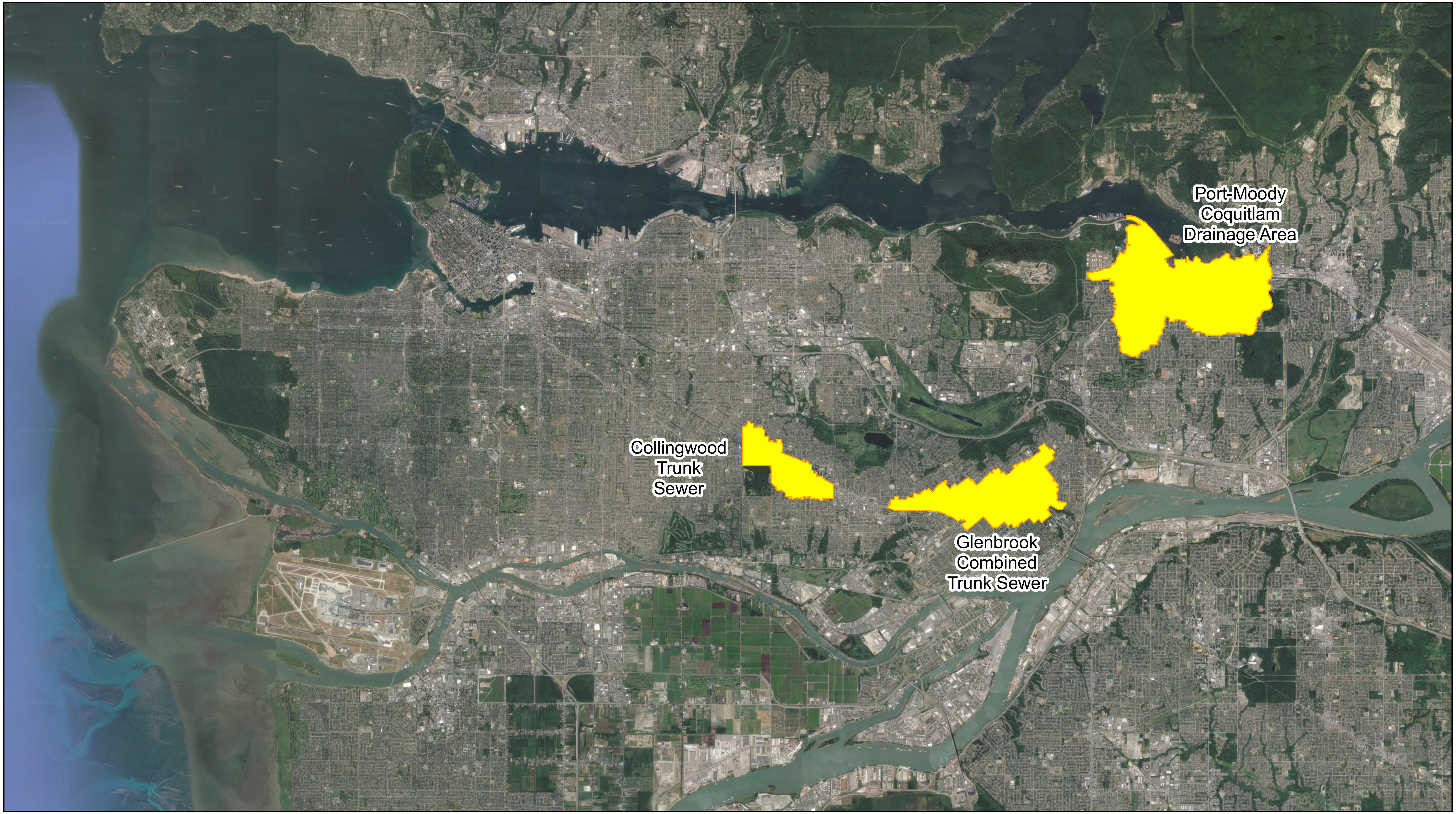
The three cases studies (Figure 1.1) are intended to showcase the vulnerabilities of different types of sewerage and stormwater drainage systems to increased rainfall from climate change. The first case study, the Glenbrook combined trunk and sewer separation study, consists of an existing combined trunk sewer that will be undergoing sewer separation by 2075. The capacity of the existing and future configurations of the sewer were investigated under the future climate change scenarios. The second case study, the Port Moody-Coquitlam Drainage Area (PMCDA), is a stormwater drainage system consisting of a combination of closed conduit sections and natural channels. The capacity of the closed conduit sections to pass the increased rainfall due to climate change was investigated. Additionally, the effectiveness of source control measures to maintain the current level of service in the watershed was also investigated. The third case study, the Collingwood sanitary trunk sewer, is a sanitary-only trunk sewer that is subject to inflow and infiltration (RDII) from rain events. The capacity of the trunk sewer to pass the increased RDII flow due to the increased rainfall in the future climate change scenarios was investigated. For each case study, potential adaptation measures have been applied to address the capacity issues. It is noted, however, that the potential adaptation measures proposed have not been tested for feasibility and are to be used for illustration only. The purpose of the case studies was to develop overall conclusions regarding the impacts of increased rainfall due to climate change on sewage and drainage infrastructure, to assist with the development of good practice recommendations. Less focus will be placed on individual results for a specific case study, but individual results are included to illustrate the types of changes that will be required and the relative costs of each change. This memorandum will focus on overall conclusions that can be applied generally.

The modelling for the three case studies was performed using PCSWMM (a hydrologic/hydraulic modelling package produced by Computational Hydraulics Inc.). PCSWMM can model both stormwater and wastewater collection systems. It can be used for conceptual design of drainage works such as pipes, open channels (rivers, creeks and ditches), weirs, dams, orifices, and storage/detention units. It can also incorporate Low Impact Development (LID) measures. The model requires input of a hyetograph, topographical features (catchment area, width, slope and hydraulic roughness), soil parameters (antecedent moisture condition, infiltration capacity and drying time), ground cover conditions (land use and vegetation cover) and drainage paths (rivers, pipes and storage units). PCSWMM models the hydrological processes to develop the flood from a given hyetograph, and then routes the flood through the pipes/channels. PCSWMM is capable of using the dynamic wave method to route non-steady flows through a general network of pipes and/or open channels with or without backwater effects.

The statistical occurrence of extreme rainfall events is expressed in this TM as exceedance probability, as opposed to return period. Return periods (e.g., 100-year event, 1 in 100 year event) can be misunderstood to mean that the event occurs once every 100 years. In actuality, the event has a 1% probability of being exceeded in any given year. This allows for a clearer description of potential changes due to climate change: the exceedance probability of an event of a certain magnitude increases as climate change affects the frequency of extreme rainfall events. Rainfall or flood events are referred to in this TM according to their respective annual exceedance probabilities (AEP), but return period language has often also been included in brackets as follows: 1% AEP (100-year return period).

The Technical Memorandum is organized as follows:

- Section 2 describes the model setup and results for the Glenbrook combined trunk sewer and sewer separation case study.
- Section 3 describes the model setup and results for the PMCDA case study.
- Section 4 describes the model setup and results for the Collingwood sanitary trunk sewer case study.
- Section 5 provides the conclusions and recommendations.



Source: Image ©2017 Google, Imagery date: 2017

Coordinate System:
NAD 1983 UTM Zone 10N

METRO VANCOUVER
BRITISH COLUMBIA, CANADA

CASE STUDY LOCATIONS

11140666-01
Dec 19, 2017

FIGURE 1.1

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2. Case Study 1: Glenbrook Combined Trunk Sewer and Sewer Separation

2.1 Model Setup

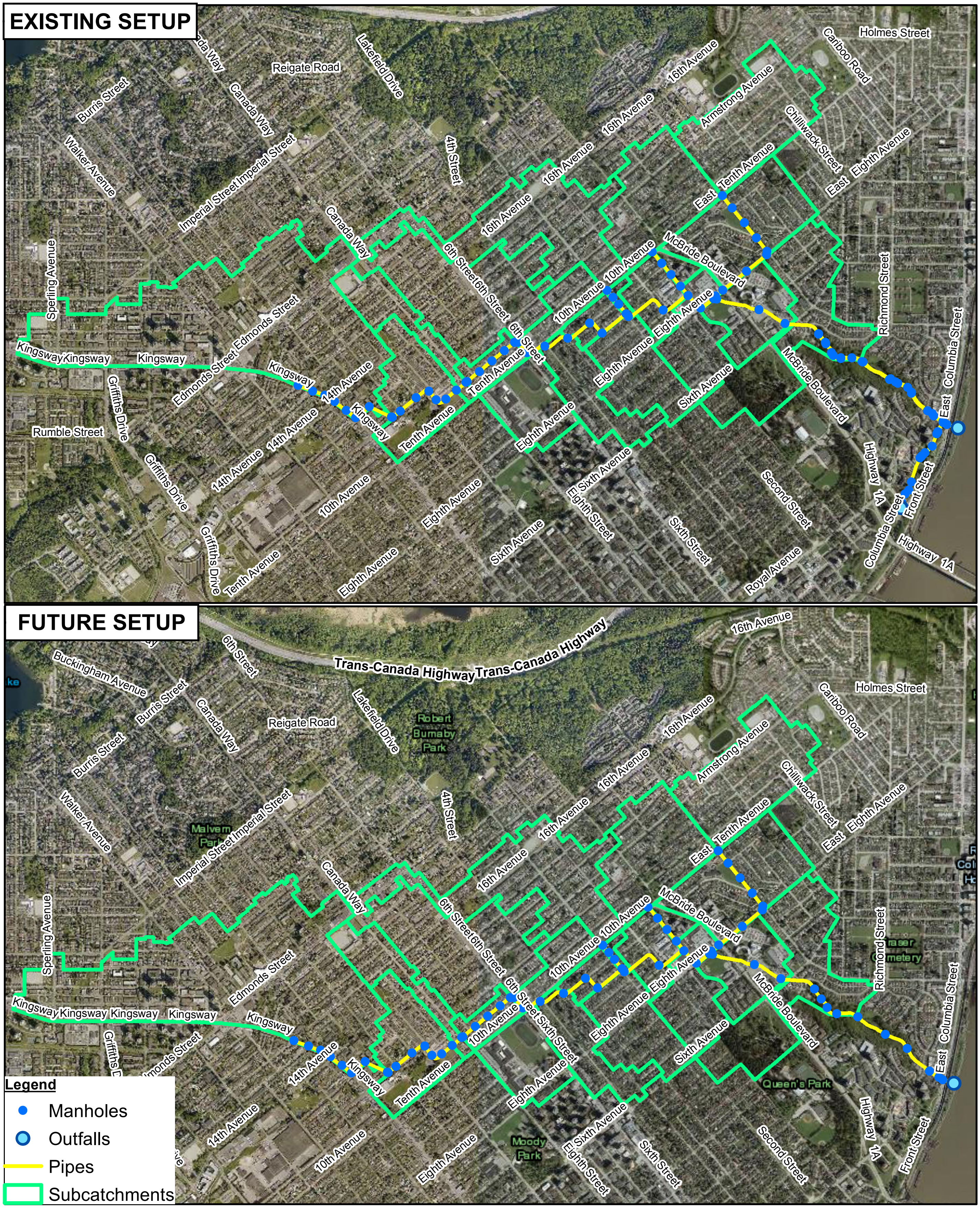
2.1.1 Model Description

The Glenbrook combined trunk sewer is located in the Cities of Burnaby and New Westminster. It is currently a combined (sanitary and storm collection) sewer system. In total, the trunk sewer drains an area of 517.4 hectares. The primary trunk system starts at Kingsway and 16th Avenue in Burnaby, and proceeds northeast to McBride Boulevard and 8th Avenue. The trunk system then proceeds southeast. The Glenbrook diversion weir diverts sanitary flow during dry weather, and diverts combined flows during wet weather up to the hydraulic capacity of the Glenbrook Diversion Extension into the New Westminster interceptor at McBride and East Columbia Street, which subsequently flows into the Annacis Wastewater Treatment Plant. The combined sewer overflow outfalls into the Fraser River at East Columbia Street at the bottom of the Glenbrook Ravine.

A report describing the Glenbrook trunk sewer separation strategy was prepared by McElhanney Consulting Services (McElhanney, 2014). McElhanney (2014) inventoried and inspected the trunk sewer system, and then developed a methodology to perform the sewer separation. The current combined trunk sewer will be used to convey stormwater flows. The existing trunk sewer in the Cumberland branch will be upsized, so that it can convey the storm event with an annual exceedance probability of 1% (100-year return period). The diversion weir will be removed, and all stormwater will outfall into the Fraser River at East Columbia Street at the bottom of the Glenbrook Ravine. A separate sewer system will convey the sanitary sewer flow; the separate sanitary sewer is not part of this case study and will not be discussed further.

As part of the analysis performed by McElhanney (2014), two PCSWMM models (existing and proposed) were developed. The existing and proposed networks are shown in Figure 2.1. The existing model was calibrated for stormwater flow only, as the purpose of the study was to estimate pipe sizes for the future stormwater only configuration.

The existing combined trunk sewer configuration was utilized for the current horizon and for the 2050 horizon. Sanitary flows were added to the model for each horizon, using sanitary flows observed at two monitoring locations and the sewer flow calculations performed by McElhanney (2014). The base model for the current horizon and 2050 horizon model used the current pipe sizes, as it was assumed that the upgrading of the Cumberland branch will be performed as part of the sewer separation. The proposed separated sewer configuration was utilized for the 2100 horizon. No sanitary flows were used in the model for the 2100 horizon.



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0 200 400 600
Meters

Coordinate System:
NAD 1983 UTM Zone 10N

N

GHD

METRO VANCOUVER
BRITISH COLUMBIA, CANADA

11140666-01
Jun 6, 2018

EXISTING AND FUTURE MODEL SETUP FOR CASE STUDY #1: GLENBROOK COMBINED TRUNK SEWER AND SEWER SEPARATION

FIGURE 2.1

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2.1.2 Sewer Flow Calculations for the Current and 2050 Horizons

McElhanney (2014) performed sanitary sewer loading calculations for each catchment for both 2011 and 2061. Metro Vancouver also provided sanitary flow data from two flow meter locations. These two data sources were combined to develop the dry weather flow in the model.

The first sanitary flow monitoring location, GL3, is located in Manhole #35 near the corner of 12th Avenue and Mary Avenue. The Kingsway subcatchment (# 785) is the only subcatchment upstream from this monitoring location. Sanitary flow monitoring data were provided for July and August of 2012 and 2013 (four months of data in total). The diurnal flow pattern was similar between both years, but the flow rates were (on average) lower for the month of July in 2013.

The second sanitary flow monitoring location, NW21, is located in a manhole near McBride Boulevard and East Columbia Street, just before the sanitary flow is discharged into the New Westminster Interceptor. Since this location is below the Glenbrook diversion weir, only dry weather flow is measured (combined sewer overflows are discharged directly into the Fraser River). Sanitary flow monitoring data were provided for the period June 20, 2017 to July 16, 2017 (approximately one month of data).

Sewer flow varies according to the day of the week and the hour of the day. Generally, weekdays have one diurnal flow pattern, and weekends have another pattern. Three time patterns were identified: hourly (weekday), hourly (weekend), and daily. The average dry weather flow and the diurnal patterns for both GL3 and NW21 were calculated with the time series editor in PCSWMM.

McElhanney (2014) provided sanitary sewer calculations for all subcatchments for both 2011 and 2061. These were converted to 2016 and 2050 using the updated residential, commercial, industrial, and institutional areas in each subcatchment (provided by the GVS&DD for this project). The values were scaled according to the observed dry weather flow, as shown in Table 2.1. The average dry weather flow for GL3 was applied to subcatchment 785, while the average dry weather flow for NW21 was split between the remaining subcatchments according to the calculated sewer flow. The flows were then increased for 2050, according to the increase in calculated sewer flow for each subcatchment. No sanitary flow data were included in the 2100 horizon model.

Table 2.1 Sanitary Flow Calculations for Case Study 1

Subcatchment(s)	Outlet Node	Calculated Sewer Flow 2016 (L/s) [1]	Scaled Flow 2016 (L/s) [2]	Calculated Sewer Flow 2050 (L/s) [3]	Scaled Flow 2050 (L/s) [4]
785	56001	73.00	40.47	112.33	79.80
801	56009	7.43	8.18	12.01	12.76
789	56015	3.76	4.14	6.39	6.76
784	56022	11.52	12.68	17.06	18.21
10020 & 806	56023	5.88	6.47	7.33	7.92
810	56030	4.56	5.02	7.00	7.46
792	56037	1.81	2.00	2.52	2.70

Table 2.1 Sanitary Flow Calculations for Case Study 1

Subcatchment(s)	Outlet Node	Calculated Sewer Flow 2016 (L/s) [1]	Scaled Flow 2016 (L/s) [2]	Calculated Sewer Flow 2050 (L/s) [3]	Scaled Flow 2050 (L/s) [4]
795	56041	1.02	1.12	1.58	1.68
782	56092	12.08	13.30	18.09	19.30
22222	56093	0.17	0.18	0.24	0.26
802	56049	16.31	17.95	24.52	26.15
790	56056	1.94	2.13	3.03	3.23
777	56097	6.45	7.10	9.83	10.48
10088	56100	1.96	2.16	2.71	2.91
10089	56059	9.78	10.76	13.91	14.89
800	56065	3.29	3.62	5.07	5.40
772	56103	6.33	6.96	9.68	10.32
10087	56107	6.07	6.68	9.45	10.06
791	56073	17.07	18.78	25.20	26.91
805	56075	0.50	0.55	0.72	0.77
786	56076	4.57	5.03	6.88	7.34
Total			**175.28**		**275.32**

Notes:

[1] Values from McElhanney (2014) – Sanitary Sewer Calculations (Existing, 2011).xlsx with updated residential, commercial, industrial, and institutional areas

[2] Scaled according to average dry weather flow measurements for GL3 (subcatchment 785) and NW21 (other subcatchments)

[3] Values from McElhanney (2014) – Sanitary Sewer Calculations (Future, 2061).xlsx with updated residential, commercial, industrial, and institutional areas

[4] Scaled Flow for 2011 + (Average Flow 2061 – Average Flow 2011)

2.1.3 Downstream Boundary Condition

The Glenbrook trunk sewer discharges into the Fraser River near its mouth. As such the downstream boundary condition for the modelling must account for high water levels due to sea level rise and/or Fraser River freshets. Typically, the highest sea level events occur during winter storms, while the Fraser River freshets result in high water level in the River during spring (Fraser Basin Council, 2016). GHD performed a seasonality analysis to determine if there is any interaction between sea level and the Fraser River flow (i.e. determine if the peak sea level and the peak Fraser River flow could combine to produce an even higher water level). The Vancouver sea level station data (Department of Fisheries and Oceans Station # 7735) were compared to the Fraser River at Mission Streamflow station (Water Survey of Canada Station # 08MH024) in Figure 2.2. The months when the annual maxima occurred have very low overlap between the two stations. Therefore, the annual maximum sea level and the annual maximum Fraser River flood level do not occur concurrently, and there is no need to consider a combined event as the downstream condition for the modelling.

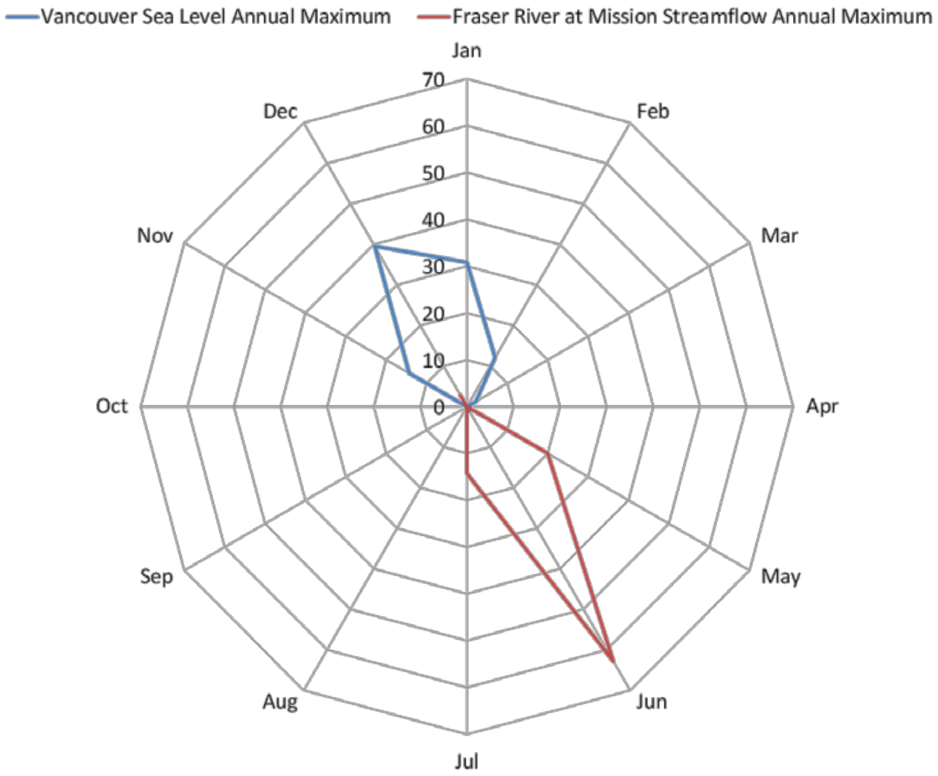

Figure 2.2 Seasonality Analysis of Annual Maximum for Vancouver Sea Level Station and Fraser River at Missing Streamflow Station

The downstream boundary conditions for the current, 2050, and 2100 horizons were selected based on potential Fraser River flooding and sea level rise. Worst-case conditions were assumed. The potential sea level rise was developed from the Flood Construction Level (FCL) methodology in Kerr Wood Leidal (2011). The FCL for the current, 2050, and 2100 horizons are calculated in Table 2.2.

Table 2.2 Sea Level Rise Calculations for Case Study 1

Sea Level Component	Current (m)	2050 (m)	2100 (m)	Reference
Higher High Water at Large Tide (HHWLT)	2.1 [1]	2.1 [1]	2.1 [1]	Communication with Canadian Hydrographic Service (CHS), 2017
Sea Level Rise	0	0.5	1.0	Kerr Wood Leidal (2011)
Land Subsidence (2 mm/year)	0	0.07	0.17	Kerr Wood Leidal (2008)
500-year Storm Surge	1.3	1.3	1.3	Kerr Wood Leidal (2011)

Table 2.2 Sea Level Rise Calculations for Case Study 1

Sea Level Component	Current (m)	2050 (m)	2100 (m)	Reference
Wave Setup	0.75	0.75	0.75	Calculated using Canadian Dam Association (2007) based on 500-year wind at Vancouver Intl A
Freeboard	0.6	0.6	0.6	Kerr Wood Leidal (2011)
Total	**4.75**	**5.32**	**5.92**	

Notes:

[1] HHWLT rounded to 2 m according to the Fraser River Stepped Datum (elevation expressed in Canadian Geodetic Vertical Datum 1928). Elevation was converted to Canadian Geodetic Vertical Datum 2013.

Current and future Fraser River flood estimates were calculated by Fraser Basin Council (2016) (Table 2.3). Since the sea level rise calculations resulted in higher estimates, the sea level rise values from Table 2.2 were utilized in the analysis.

Table 2.3 Fraser River Flood Estimates for Case Study 1

	Current (m)	2100 (m)
500-year Flood Level	4.22	5.24

Note:

Values from Fraser Basin Council (2016)

2.1.4 Rainfall Estimates for Current and Future IDF Curves

McElhanney (2014) performed hydrologic and hydraulic analysis for the Glenbrook Combined/Separated Trunk Sewer. The separated storm trunk sewer will convey both the minor and major system flows, and was therefore designed to accommodate the 1% annual exceedance probability (AEP) storm (100-year return period) event. A one-hour British Columbia (BC) coast Atmospheric Environment Service (AES) design storm distribution was used.

Intensity-Duration-Frequency (IDF) curves were updated as part of this project (see TM2). The closest rainfall measurement gauge is the Westburnco Reservoir Gauge (CW09), which is in homogeneous rainfall Zone 4. The case study area is near the eastern edge of Zone 4.

As indicated in TM2, the IDF curves generated in this project are dimensionless IDF curves which must be scaled by the index rain. The index rain is the mean annual maximum rainfall at the study area, which can be obtained from a rainfall monitoring location or from the index rain contour maps provided in Appendix D of TM2. The contour map is the preferred method of obtaining the index rain. The index rain (at-site mean) for the Westburnco Reservoir Gauge was compared to the index rain from the 1-hr contour map (Table 2.4). The Westburnco Reservoir is located near the edge of the study area, and was not representative of the index rain for the entire study area. Scaling by the index rain from the contour map was used for this location, as recommended in TM2. The dimensionless IDF curve quantiles in Appendix C were multiplied by the index rain.

Table 2.4 Comparison of One-Hour Means to Use for Scaling the Dimensionless IDF Curves for Case Study 1

	Westburnco Reservoir	Index Rain from 1-hr Contour Map
1-hr Index Rain (mm)	11.40	11.75

Future climate change IDF curves were developed in TM3. The scaled IDF quantiles were multiplied by the deltas in Appendix A of TM3. The 1-hr, 1% AEP rainfall depths for the current horizon and the four future horizon IDF curves are listed in Table 2.5. The 1-hr AES BC Coast design storm distribution was used in the modeling.

Table 2.5 Rainfall Depths for Current and Future IDF Curves for Case Study 1

	Current	2050		2100	
		Moderate Increase	High Increase	Moderate Increase	High Increase
1-hr, 1% AEP Rainfall Depth (mm)	23.0	28.6	35.2	34.7	44.2

2.2 Results

The Glenbrook combined trunk sewer consists of circular pipes ranging from 300 to 1,200 mm in diameter and horseshoe pipes along the 8th Avenue section. The City of Burnaby design guidelines for storm sewers require that the maximum hydraulic gradeline (HGL) is below the minimum building elevations (assumed to be ground level for this analysis). Gravity sewers larger than 300 mm should be designed to flow less than 70% full (by depth) when only the sewage flow is in the model. These criteria were used for Case Study 1.

McElhanney (2014) designed the sewer separation strategy, which involves reusing the existing combined trunk sewer as a stormwater-only sewer. McElhanney (2014) used a 1% AEP (100-year return period) 1-hr rainfall event. The first part of the analysis compared the McElhanney (2014) study results with the current results, followed by capacity analyses of the combined and separated trunk sewers.

A number of different scenarios were used in this analysis, with different sewer configurations, sanitary sewer flow, rainfall, and boundary condition. The scenarios that were run are listed in Table 2.6. Scenarios are referred to by their scenario names in the discussion.

Table 2.6 Scenarios for Case Study 1

Scenario Name	Configuration	Sanitary Sewer Flow	Rainfall	Boundary Condition at Fraser River Outfall
McElhanney Proposed	Separated	None	McElhanney rainfall	Free
Updated Proposed	Separated	None	Updated IDF Curve	Free
Updated Existing	Combined	2016	Updated IDF Curve	2016 sea level

Table 2.6 Scenarios for Case Study 1

Scenario Name	Configuration	Sanitary Sewer Flow	Rainfall	Boundary Condition at Fraser River Outfall
2050 Sea Level Rise Only	Combined	2050	Updated IDF Curve	2050 sea level
2050 Moderate	Combined	2050	2050 Moderate	2050 sea level
2050 High	Combined	2050	2050 High	2050 sea level
2100 Sea Level Rise Only	Separated	None	Updated IDF Curve	2100 sea level
2100 Moderate	Separated	None	2100 Moderate	2100 sea level
2100 High	Separated	None	2100 High	2100 sea level

2.2.1 Comparison to McElhanney (2014) Study

The proposed sewer separation strategy consists of reusing the existing Glenbrook combined trunk sewer as a storm sewer only. This option was modelled by McElhanney (2014) and it was found that most of the existing combined sewer had sufficient capacity to convey the 1% AEP (100-year return period) 1-hr storm event. However, McElhanney (2014) recommended that some pipes be upsized on the Cumberland branch. In the future separated trunk sewer model, the new manholes on the Cumberland branch were also sealed (allowed to surcharge) to prevent overflows.

The McElhanney (2014) 1% AEP (100-year return period) 1-hr storm was smaller than the storm used in this analysis (Figure 2.3), which used the updated IDF curves calculated in TM2. Using the larger storm(Updated Proposed scenario) resulted in flooding at five manholes, which indicates that the model was very sensitive to the amount of rainfall. There were no other changes to the model parameters (including subcatchment parameters and outfall boundary condition). To accommodate the larger storm event, it was necessary to increase the size of four more pipes (Table 2.7), but no additional manholes were sealed. Three of the extra upsized pipes were on the Colborne Street Branch, and one pipe was on the main line along Ovens Avenue.

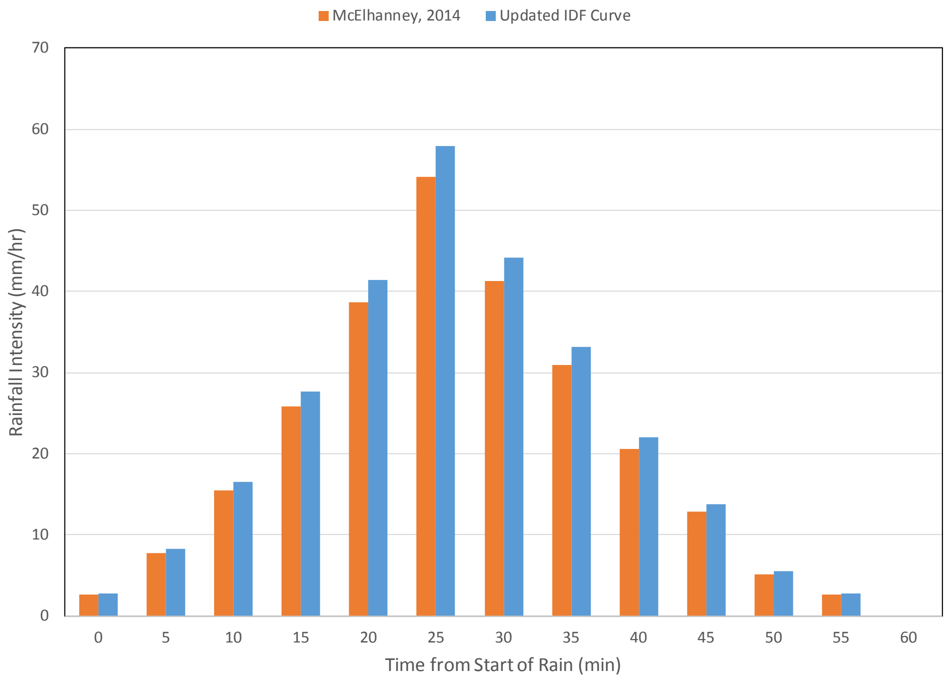

Figure 2.3 Comparison of McElhanney (2014) Rainfall Distribution and Updated IDF Curve Rainfall Distribution

Table 2.7 Comparison to McElhanney (2014) Study Rainfall and Pipe Upsizing for Case Study 1

Scenario	Total Rainfall Depth (mm)	Maximum Rainfall Intensity (mm/hour)	Number of Upsized Pipes	Comments
McElhanney Proposed	21.5	54.2	8 (+6 sealed manholes)	Pipe upsizing as specified by McElhanney, 2014
Updated Proposed	23.0	58.0	12 (+6 sealed manholes)	4 additional pipes
2100 Sea Level Rise Only	23.0	58.0	28 (+ 9 sealed manholes)	16 additional pipes, 3 additional manholes

McElhanney (2014) used a free outfall, which means that there was no backwater effect from the outfall. This study used sea level rise estimates as the downstream boundary condition. The amount of surface flooding due to the higher boundary condition is limited to the area of East Columbia Street. However, the sea level can cause a backwater effect in the storm sewer, and flooding in the upstream pipes. When the downstream boundary condition was changed to the 2100 sea level prediction (2100 Sea Level Rise Only Scenario), there was flooding at 18 manholes. These results indicate that higher sea level has a significant effect on the entire storm sewer system (even at higher elevations away from the outfall). To accommodate the higher sea level prediction, an additional 16 pipes needed to be upsized, and the final three manholes before the outfall location needed to be sealed. The manholes were sealed in the model to prevent overflow in the model. In actuality, the manholes would flood because of the high sea level boundary condition. The pipes that were upsized to accommodate the higher rainfall and sea level boundary condition in this study are shown in Figure 2.4.

2.2.2 Combined Trunk Sewer Scenarios

The combined trunk sewer configuration was used for the current and the 2050 time horizons. These scenarios included sanitary sewer flow in addition to the 1% AEP (100-year return period) 1-hr storm events. The depth of the sanitary sewer flow alone in the gravity sewers must be less than 70% of the diameter of the pipe. With the addition of the 1% AEP 1-hr storm, the criteria of no flooding applies.

With only the sanitary flow in the model, there was sufficient capacity in the gravity sewers (Table 2.8). There were no pipes that were more than 70% full by depth upstream of the diversion weir, and no flow was diverted to the outfall in the Fraser River. Therefore, no adjustments were required to accommodate the increase in sanitary flow due to population growth between 2016 and 2050.

Table 2.8 Sanitary Flow Capacity for Case Study 1

Scenario	Number of Gravity Pipes More Than 70% Full by Depth
Updated Existing (sanitary flow only)	0
2050 Moderate or High (sanitary flow only)	0

Source: Image ©2017 Google, Imagery date: 2017

0 150 300 450
Meters

Coordinate System:
NAD 1983 UTM Zone 10N

N

Legend

● Outfalls

● Manholes

▨ Subcatchments

Must Be Upsized

🟥 Yes

🟨 No

GHD

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PIPES THAT MUST BE UPSIZED FOR CURRENT RAINFALL FOR CASE STUDY 1
GLENBROOK COMBINED TRUNK SEWER AND SEWER SEPARATION

11140666-01
Dec 20, 2017

FIGURE 2.4

GIS File: Q:\GIS\PROJECTS\11140000s\11140666\Layouts\MEMO004\11140666-01(MEMO004)GIS-WA005.mxd

The 1% AEP, 1-hr storm was added to the current and 2050 time horizons. The current level of service was determined by using different storm events and determining the number of flooded manholes (Figure 2.5). The existing configuration was able to pass the Updated Existing 50% AEP (2-year return period) without flooding. The 2050 Sea Level Rise Only, 2050 Moderate, and 2050 High scenarios could not pass.

Climate change has a larger impact on the more frequent (higher AEP) events, and less of an impact on the less frequent (low AEP) events. The number of manholes with flooding increases substantially for climate change events from 50% to 4% AEP. For the 2% to 0.5% AEP events, there is relatively little increase in the number of flooded manholes, although the amount of flooding at each manhole does increase.

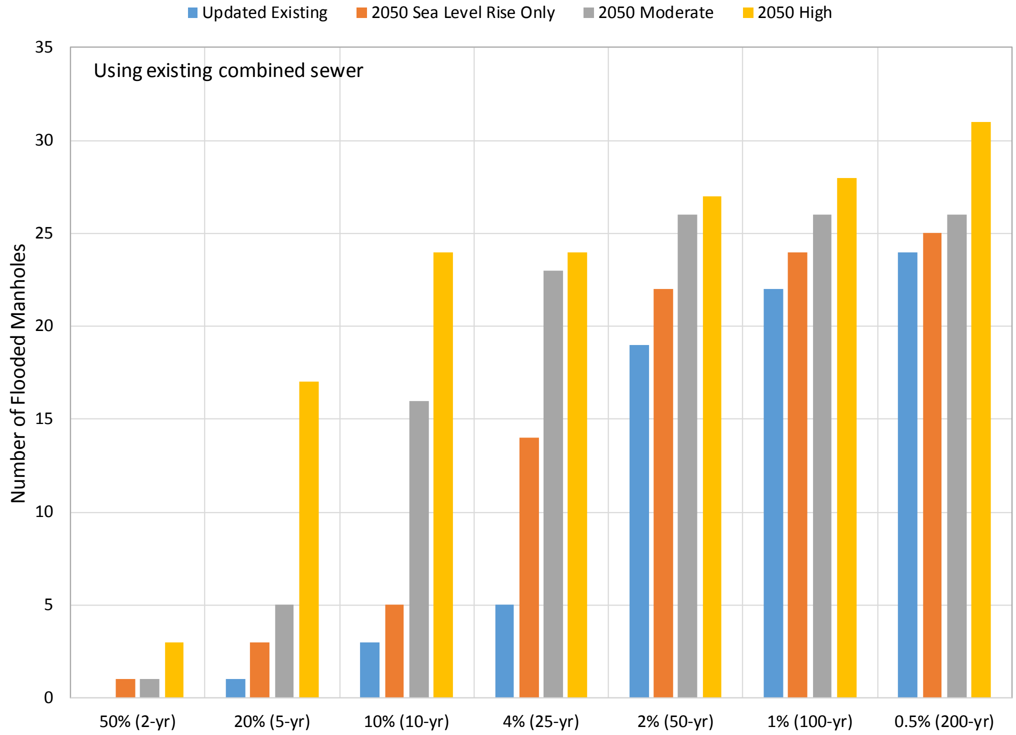

Figure 2.5 Number of Flooded Manholes for Different AEPs for Combined Trunk Configuration in 2050 for Case Study 1

There was surcharging and flooding at numerous gravity sewer manholes (surcharging is normal for the Glenbrook diversion extension) when the 1% AEP (100-year return period) 1-hr storm event was entered into the model (Table 2.9). In Section 2.2.1, the 1% AEP 1-hr storm caused flooding at 18 manholes: the addition of the sewage flow resulted in four additional flooded manholes. However, adding the sewage flow did not require a greater number of pipes to be upsized to address the flooding. Additional pipes must be upsized to accommodate the 2050 Moderate and 2050 High. The diversion weir and the outfall pipes become hydraulic constrictions for the 2050 Moderate and 2050 High rainfall events and must be upsized in order to prevent flooding upstream. Note that surcharging and backwater effects remain even with the upsized pipes (some pipes are running full). The system is running very close to its capacity (little capacity for additional flow). The pipes that were upsized are shown in Figure 2.6 and Figure 2.7.

Table 2.9 Summary of Surcharging and Flooding Results for Current and 2050 Rainfall for Case Study 1

Scenario	Number of Surcharged Manholes	Number of Flooded Manholes	Number of Upsized Pipes
Before Upsizing			
Updated Existing	54	22	N/A
2050 Current	56	25	N/A
2050 Moderate	57	26	N/A
2050 High	63	28	N/A
After Upsizing			
Updated Existing	30	0	28
2050 Current	31	0	42
2050 Moderate	32	0	44
2050 High	38	0	49

Source: Image ©2017 Google, Imagery date: 2017

0 150 300 450
Meters

Coordinate System:
NAD 1983 UTM Zone 10N

N

Legend

● Outfalls

● Manholes

▭ Subcatchments

Must Be Upsized

🟥 Yes

🟨 No

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PIPES THAT MUST BE UPSIZED FOR 2050 MODERATE CHANGE RAINFALL FOR CASE STUDY 1 GLENBROOK COMBINED TRUNK SEWER AND SEWER SEPARATION

11140666-01
Dec 20, 2017

FIGURE 2.6

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Source: Image ©2017 Google, Imagery date: 2017

0 150 300 450
Meters
Coordinate System:
NAD 1983 UTM Zone 10N

N

Legend

●	Outfalls
●	Manholes
▨	Subcatchments

Must Be Upsized

🟥	Yes
🟨	No

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PIPES THAT MUST BE UPSIZED FOR 2050 HIGH CHANGE RAINFALL FOR CASE STUDY 1
GLENBROOK COMBINED TRUNK SEWER AND SEWER SEPARATION

11140666-01
Dec 20, 2017

FIGURE 2.7

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2.2.3 Separated Trunk Sewer Scenarios

The ultimate use of the Glenbrook combined trunk sewer is storm sewer collection (after separation is complete). Figure 2.8 presents the summary of the level of service for the McElhanney configuration to pass different storm events with different AEPs. The separated sewer will pass the Current 10% AEP 1-hr event and the 2100 Moderate Change 50% AEP 1-hr event, but cannot pass any 2100 High Change events. The climate change scenarios have a large impact on flooding for the more frequent (higher AEP) events: there is a substantial increase in the number of flooded manholes for the 50% to 4% AEP events.

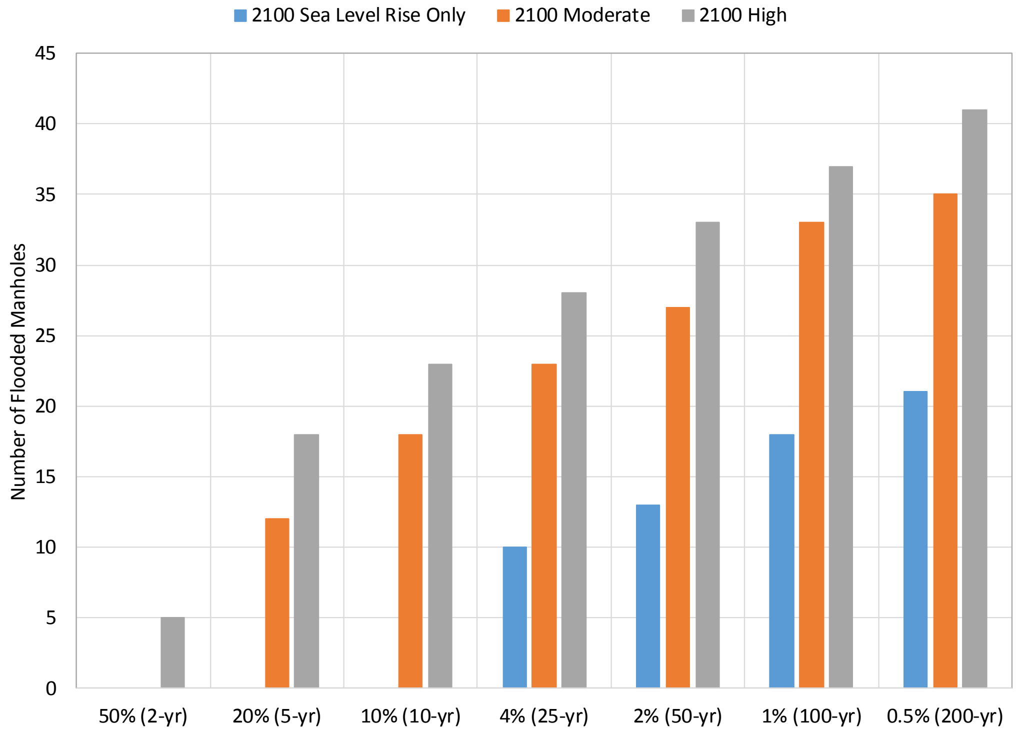

Figure 2.8 Number of Flooded Manholes for Different AEPs for Separated Trunk Configuration for Case Study 1

The results of applying the 2100 Moderate and High Change future rainfall to the future storm sewer configuration are summarized in Table 2.10. There was surcharging and flooding for both the 2100 Moderate and High Change rainfall events (when the storms were applied to the McElhanney setup). The pipes were upsized to enable the higher flow rates to pass without causing flooding. The number of upsized pipes for 2100 Moderate is the same as the 2050 Moderate scenario, except that some of the pipes are larger for the 2100 Moderate scenario. Note that surcharging and backwater effects remain even with the upsized pipes. The pipes that were upsized are shown in Figure 2.9 and Figure 2.10.

Table 2.10 Summary of Surcharging and Flooding Results for 2100 Rainfall for Case Study 1

Scenario	Number of Surcharged Manholes	Number of Flooded Manholes	Number of Upsized Pipes
Before Upsizing			
2100 Moderate	47	33	N/A
2100 High	54	39	N/A
After Upsizing			
2100 Moderate	17	0	44
2100 High	15	0	55

2.3 Costing

The costing summary for Case Study 1 is included in Table 2.11. The costs shown are for all changes from existing to the specified scenario. Incremental cost can be approximated by subtracting two scenarios. Note that there are scenarios where some pipes must be increased to accommodate a certain scenario, and then must be increased further to accommodate another scenario. Therefore, there can be some cost savings by selecting the final size and upgrading the pipes only once.

Preparing for climate change will cost an additional 20-30 million on top of upgrades currently needed to maintain levels of service. The incremental cost of choosing the more conservative high change climate scenario is only 17% and 12% for 2050 and 2100 respectively. Therefore, the majority of the cost is related to adaptation for climate change itself (which includes the combined effect of higher sea level and higher rainfall for this case study).

Table 2.11 Costing Summary for Case Study 1

Scenario	Number of Pipes with Increased Sizes	Estimated Cost ($)	Percent Increase in Cost from Updated Existing (%)	Percent Increase in Cost from Moderate to High (%)
McElhanney Proposed	6	0.9 million	N/A	N/A
Updated Existing	28	10.9 million	N/A	N/A
2050 Moderate	44	29.1 million	167	17
2050 High	49	34.0 million	212	
2100 Moderate	44	34.7 million	218	12
2100 High	55	38.8 million	256	

The costing provided in Table 2.11 is a class D costing estimate. It assumes open cut replacement, which includes asphalt removal, curb removal, removal of soils, removal and replacement of pipe, bedding and compaction, disposal of extra soil, and restoration. It does not include design costs (survey, layout, geotechnical, engineering) or other ancillary costs (insurance, mobilization/travel costs, traffic control, moving utilities, etc.). Unit costs for each size of pipe are provided in Appendix A.

Source: Image ©2017 Google, Imagery date: 2017

0 150 300 450
Meters
Coordinate System:
NAD 1983 UTM Zone 10N

Legend

		Must Be Upsized	
●	Outfalls	🟥	Yes
●	Manholes	🟨	No
▭	Subcatchments		

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Dec 20, 2017

PIPES THAT MUST BE UPSIZED FOR 2100 MODERATE CHANGE RAINFALL FOR CASE STUDY 1 GLENBROOK COMBINED TRUNK SEWER AND SEWER SEPARATION

FIGURE 2.9

GIS File : Q:\GIS\PROJECTS\11140000s\11140666\Layouts\MEMO004\11140666-01 (MEMO 004)GIS-WA008.mxd

Source: Image ©2017 Google, Imagery date: 2017

0 150 300 450
Meters
Coordinate System:
NAD 1983 UTM Zone 10N

N

Legend

● Outfalls
● Manholes
▭ Subcatchments

Must Be Upsized

🟥 Yes
🟨 No

GHD

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PIPES THAT MUST BE UPSIZED FOR 2100 HIGH CHANGE FOR CASE STUDY 1
GLENBROOK COMBINED TRUNK SEWER AND SEWER SEPARATION

11140666-01
Dec 20, 2017

FIGURE 2.10

GIS File : Q:\GIS\PROJECTS\11140000s\11140666\Layouts\MEMO004\11140666-01 (MEMO 004)GIS-WA009.mxd

2.4 Summary of Case Study 1

The Glenbrook combined trunk and separated sewers will be impacted primarily by increased flow due to increased rainfall from climate change. The 1% AEP, 1-hr rainfall depth for the 2100 High Change scenario is 1.9 times the 1% AEP, 1-hr rainfall depth for the current scenario. The flow rate for the 1% AEP is significantly higher in 2050 and 2100, and there were numerous locations along the trunk sewer where there were hydraulic constrictions at the higher flow rates. In order to pass the higher flow rates, a significant amount of upsizing of pipes is required.

The projected sea level rise is also a significant factor for this area. The increased sea level resulted in backwater and increased the number of pipes that must be upsized. The effect was significant at all time horizons: 2016, 2050, and 2100. Designing infrastructure to meet the Flood Construction Level (Kerr Wood Leidal, 2011) has a significant impact on cost.

Accommodating the combined effect of the increased rainfall and the increased sea level due to climate change will require the majority of the combined trunk sewer to be re-designed. The cost to upsize the pipes is significant. The incremental cost of upsizing pipes for the 2050 Scenarios was approximately $20-25 million. The incremental cost of upsizing pipes for the 2100 Scenarios was approximately $25-30 million. Upsizing the pipes to meet the 2050 Moderate or High Change rainfall plus sanitary sewage flow is insufficient to pass the 2100 Moderate or High Change rainfall. As a result, it may be preferable to accelerate sewer separation, and assume 2100 as the planning horizon. The incremental cost of upsizing pipes for the High Change scenarios instead of the Moderate Change scenarios is relatively low: 17% for 2050 and 12% for 2100. The design life cycle for the separated sewer must be used in determining the appropriate rainfall to use in the re-design to prevent the need to upsize pipes multiple times for multiple time horizons. In addition, selecting either moderate or high change rainfall will also affect how much pipe upsizing is required.

3. Case Study 2: Port Moody-Coquitlam Drainage Area

3.1 Model Setup

3.1.1 Model Description

The Port Moody-Coquitlam Drainage Area (PCMDA) is located in the Cities of Port Moody and Coquitlam. It is a stormwater collection system (no sanitary flow), covering 1,034 hectares. The PMCDA discharges into Burrard Inlet through five discharge pipes. The elevation ranges from sea level at the discharge locations to approximately 140 m at the headwaters of the system. The PMCDA is part of the Chines watershed, which also includes the Suter Brook and Pigeon Creek sub-watersheds. An Integrated Stormwater Management Plan (ISMP) for the Chines watershed was developed by Associated Engineering in 2016 (Associated, 2016), and this case study used the PCSWMM models developed as part of the ISMP.

The PMCDA is composed of natural channels and closed conduit sections. There are three main parts of the PMCDA. The upland/headwater area (located in Coquitlam) is largely residential. The central part of the

PMCDA is composed of steep wooded ravines, known as the Chines. The watercourses are largely unaltered, and flow through a mixed, mature deciduous and coniferous forest. The lowlands (located in Port Moody) are a combination of residential, commercial and industrial developments. The upland/headwater area and the lowlands are closed conduit channels, while the Chines are natural channels. Metro Vancouver is responsible for the main stems of the creeks and the major drainage trunks receiving creek flows below the escarpment (in Port Moody). The Cities are responsible for the local drainage system on top of and below the escarpment.

As part of the analysis performed by Associated (2016), two PCSWMM models (existing and future) were developed (Figure 3.1). In order to model the watershed correctly, some areas that were outside of the PMCDA drainage mandate area were included. In the existing model, there are 751 nodes, 757 conduits (564 closed conduits and 193 natural channels), and 759 subcatchments. The main differences between the existing and future models were in the pipe sizes and inverts of the inlets/outlets of the pipes (no changes to pipe location or connectivity). Four pipes were added, and 214 pipes had different sizes. The models were setup and calibrated by Associated (2016), and no recalibration or adjustments were performed in the current study. Both models were used for all time horizons in this analysis.

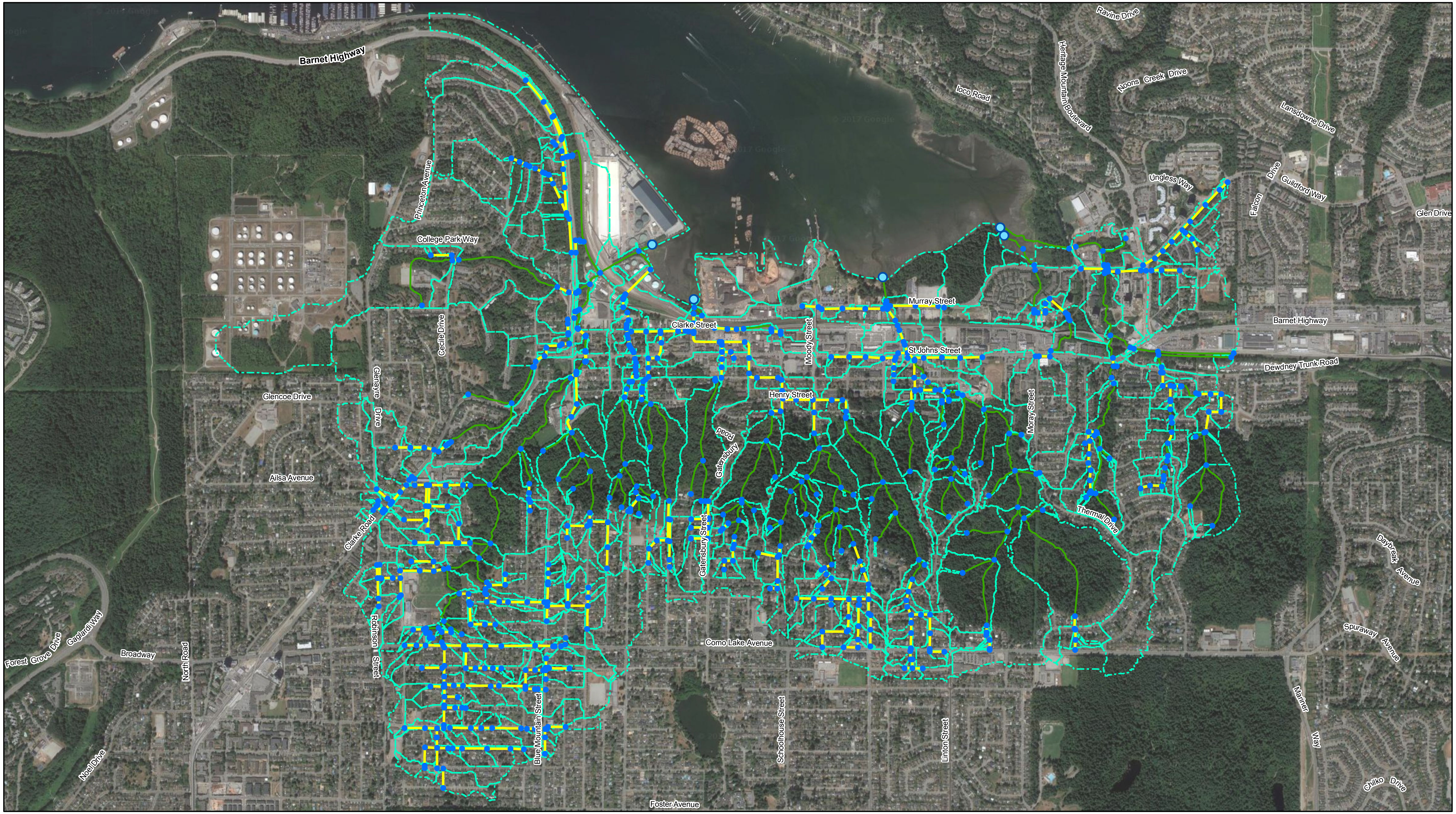
3.1.2 Downstream Boundary Condition

The five outfall locations for the PMCDA discharge into the Burrard Inlet. The downstream boundary conditions for the current, 2050, and 2100 horizons were selected based on potential sea level rise. The methodology for developing the Flood Construction Level (FCL) was taken from Kerr Wood Leidal (2011). The FCL for the current, 2050, and 2100 horizons are calculated in Table 3.1.

Table 3.1 Sea Level Rise Calculations for Case Study 2

Sea Level Component	Current (m)	2050 (m)	2100 (m)	Reference
Higher High Water at Large Tide	2.1[1]	2.1[1]	2.1[1]	Communication with Canadian Hydrographic Service
Sea Level Rise	0	0.5	1.0	Kerr Wood Leidal (2011)
Land Subsidence (2 mm/year)	0	0.07	0.17	Kerr Wood Leidal (2008)
500-year Storm Surge	1.3	1.3	1.3	Kerr Wood Leidal (2011)
Wave Setup	0.75	0.75	0.75	Calculated using Canadian Dam Association (2007) based on 500-year wind at Vancouver Intl A
Freeboard	0.6	0.6	0.6	Kerr Wood Leidal (2011)
Total	**4.75**	**5.32**	**5.92**	

Notes:
[1] HHWLT was 1.97 m for Port Moody (elevation expressed in Canadian Geodetic Vertical Datum 1928). Elevation was converted to Canadian Geodetic Vertical Datum 2013.



Source: Image ©2017 Google, Imagery date: 2017

0 150 300 450
Meters

Coordinate System:
NAD 1983 UTM Zone 10N

N

Legend

- ○ Outfalls
- ● Junctions
- Piped Sections
- Natural Channels
- Subcatchments

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BRITISH COLUMBIA, CANADA

MODEL SETUP FOR CASE STUDY #2:
PORT MOODY-COQUITLAM DRAINAGE AREA

11140666-01
Dec 20, 2017

FIGURE 3.1

GIS File: Q:\GIS\PROJECTS\11140000s\11140666\Layouts\MEMO004\11140666-01(MEMO004)GIS-WA002.mxd

3.1.3 Rainfall Estimates for Current and Future IDF Curves

Associated (2016) performed hydrologic and hydraulic analysis for the PMCDA. The required level of service for the main stems of the creeks and the storm trunk sewers in Port Moody was the 1% AEP storm event (100-year event). The required capacity for the remaining pipes (owned by the Cities) was the 10% AEP storm event (10-year event). Associated (2016) used a 24-hour storm. The distribution was a Chicago storm with r=0.5.

The PMCDA is located in homogeneous rainfall Zones 4 and 5 from TM2. The eastern part in located in Zone 5, while the western section is in Zone 4 (most of the PMCDA is in Zone 4). For simplicity in the case study, the analysis used the Zone 4 IDF curve for the entire PMCDA. However, both IDF curves should be considered for planning and design when a study area crosses a boundary between zones.

The closest rainfall measurement gauges are Port Moody Pump Station (PT11) and Rocky Point Park (PT32), which are both in Zone 5 and are both located in the northeastern part of the watershed. Burnaby Mountain (BU35), Coquitlam City Hall (QT10), Port Coquitlam City Yard (1106256) and Douglas College (QT77) are all located within approximately 3 km of the watershed (Zones 3, 4, 5, and 6). The index rains (at-site means) for each station are listed in Table 3.2. The average index rain for the stations was 83.0 mm. Alternatively, the average index rain can also be found on the contour map. From the contour map, the average 24-hour index rain is approximately 83 to 84 mm. In order to obtain the worst-case IDF curve, the dimensionless IDF curves were scaled by an index rain of 84 mm.

Table 3.2 Comparison of 24-Hour Means for Case Study 2

	Port Moody Pump Station	Rocky Point Park	Burnaby Mountain	Coquitlam City Hall	Port Coquitlam City Yard	Douglas College	Average	Index Rain from 24-hr Contour Map
24-hr Index Rain (mm)	83.9	84.5	83.9	69.8	80.7	95.0	83.0	83-84

The future climate change IDF curves were obtained from TM3. The 24-hr, 1% and 10% AEP rainfall depths for the current horizon and the four future horizon IDF curves are listed in Table 3.3. A 24-hr Chicago design storm distribution was used in the modeling, to match with Associated (2016).

Table 3.3 Design Storm Depths for Current and Future IDF Curves for Case Study 2

	Current	2050		2100	
		Moderate Increase	High Increase	Moderate Increase	High Increase
24-hr, 10% AEP Rainfall Depth (mm)	116.3	139.2	172.8	172.8	208.8
24-hr, 1% AEP Rainfall Depth (mm)	174.8	218.4	271.2	266.4	340.8

3.2 Results

The PMCDA is a drainage system that consists of natural channels and closed conduit sections. This analysis determined the impact of the increased rainfall due to climate change on the flood levels in the upper reaches of the watershed. In addition, the hydraulic capacity of the closed conduit sections of the network to carry the additional stormwater flow was also evaluated. Accordingly, the amount of surcharging and flooding and the elevation of the hydraulic grade line (HGL) were used as the level of service criteria

Associated (2016) developed the existing conditions model and a future mitigation model with larger pipe sizes as part of the Integrated Stormwater Management Plan. Both models were used to determine the impact of future rainfall. Planning and engineering approaches (such as source controls) were investigated to reduce flooding. A number of scenarios were used in the analysis (Table 3.4). The first six scenarios used both the existing and future models. The analyses for source controls and pipe upsizing were based on the future configuration model only.

Table 3.4 Scenarios for Case Study 2

Scenario Name	Configuration(s)	Outfall Boundary Condition	Description
Associated	Existing, Future	Free	Rainfall used by Associated (2016) with both the existing conditions and the future mitigation models
Current	Existing, Future	Sea Level Rise	Updated IDF curve rainfall with both the existing conditions and the future mitigation models
2050 Moderate	Existing, Future	Sea Level Rise	2050 Moderate Change rainfall with both the existing conditions and the future mitigation models
2050 High	Existing, Future	Sea Level Rise	2050 High Change rainfall with both the existing conditions and the future mitigation models
2100 Moderate	Existing, Future	Sea Level Rise	2100 Moderate Change rainfall with both the existing conditions and the future mitigation models
2100 High	Existing, Future	Sea Level Rise	2100 High Change rainfall with both the existing conditions and the future mitigation models
2050 Moderate with Source Controls	Future	Sea Level Rise	2050 Moderate Change rainfall with the future mitigation models and source controls
2050 High with Source Controls	Future	Sea Level Rise	2050 High Change rainfall with the future mitigation models and source controls
2100 Moderate with Source Controls	Future	Sea Level Rise	2100 Moderate Change rainfall with the future mitigation models and source controls
2100 High with Source Controls	Future	Sea Level Rise	2100 High Change rainfall with the future mitigation models and source controls

Table 3.4 Scenarios for Case Study 2

Scenario Name	Configuration(s)	Outfall Boundary Condition	Description
Upsized 2050 Moderate with Source Controls	Future with Source Controls	Sea Level Rise	2050 Moderate Change rainfall with the future mitigation models, source controls, and pipe upsizing
Upsized 2050 High with Source Controls	Future with Source Controls	Sea Level Rise	2050 High Change rainfall with the future mitigation models, source controls, and pipe upsizing
Upsized 2100 Moderate with Source Controls	Future with Source Controls	Sea Level Rise	2100 Moderate Change rainfall with the future mitigation models, source controls, and pipe upsizing
Upsized 2100 High with Source Controls	Future with Source Controls	Sea Level Rise	2100 High Change rainfall with the future mitigation models, source controls, and pipe upsizing

3.2.1 Comparison to Associated (2016) Results

The existing conditions model was compared with the future mitigation model using both the Associated rainfall and the updated IDF curve rainfall. The future mitigation model includes pipe size and invert changes developed by Associated (2016). The results of the comparison for the 10% AEP and 1% AEP models are shown in Table 3.5. There were a large number of manholes that surcharged or flooded in the existing conditions model for both the Associated (2016) rainfall and the current rainfall. Some of the surcharging and flooding were corrected in the future mitigation model with the larger pipe sizes, however, flooding remains even in the future mitigation model with the rainfall from Associated (2016). For the Current scenario with the updated IDF curve rainfall and higher sea level boundary condition, some of the flooding is due to the updated rainfall, and some of it is due to the higher sea level boundary condition. The average HGL has decreased from the existing conditions to the future mitigation scenario: larger pipes would cause fewer hydraulic constrictions, which would decrease the HGL. In addition, there are manholes that surcharge and flood due to the downstream boundary condition used in this study. There are differences in the IDF curve used by Associated (2016) and the IDF curve used in this study. As for Case Study 1, the differences in flooding observed in the existing conditions and future mitigation models is due to differences in the IDF curve and/or differences in the Chicago storm distribution parameters.

Table 3.5 Comparison Between Existing and Future Pipe Sizes with Current Rainfall for Case Study 2

Scenario Name	Rainfall Event	Existing Conditions			Future Mitigation		
		Number of Surcharged Manholes	Number of Flooded Manholes	Average HGL in Upper Reaches	Number of Surcharged Manholes	Number of Flooded Manholes	Average HGL in Upper Reaches
Associated	24-hr, 10% AEP	126	75	126.18	38	16	125.33
Associated	24-hr, 1% AEP	284	212	128.59	158	69	125.85
Current	24-hr, 10% AEP	139	93	128.6	78	56	125.35
Current	24-hr, 1% AEP	252	209	130.5	104	79	125.52

The pipe size changes that were included in the future mitigation scenario were priced by Associated (2016). These pipe changes were not priced as part of this study.

It should also be noted that there were runtime warnings and junctions with model instabilities in the Associated (2016) existing conditions and future mitigation models. These were related to possible data entry issues (e.g. pipes that have adverse slopes, junctions with connections that are greater than the ground level, subcatchments with very low area). Fixing these locations was outside of the scope for this project. No model adjustments were performed.

3.2.2 Future Climate Change Scenarios

The increase in rainfall due to climate change will result in higher flow rates in the watershed. A representative location was selected to compare the flow rates for the current, 2050, and 2100 horizons (Figure 3.2). This location is near one of the outfalls of the model, with a total drainage area of 444.1 ha. This location was selected because it has the largest upstream area of the five branches of the watershed and is representative of the behavior of the watershed. The Chicago storm distribution does not start at zero rainfall, and therefore there is flow in the watershed at the start of the simulation. As the amount of rainfall increases, both the initial rainfall and the peak of the Chicago storm distribution increase. The lowest flow rates were for the existing conditions, the 2050 Moderate and High Change scenarios were in the middle, and the highest flows were for the 2100 Moderate and High Change scenarios. The difference from Moderate to High for 2050 was less than the difference between 2100 and 2050.

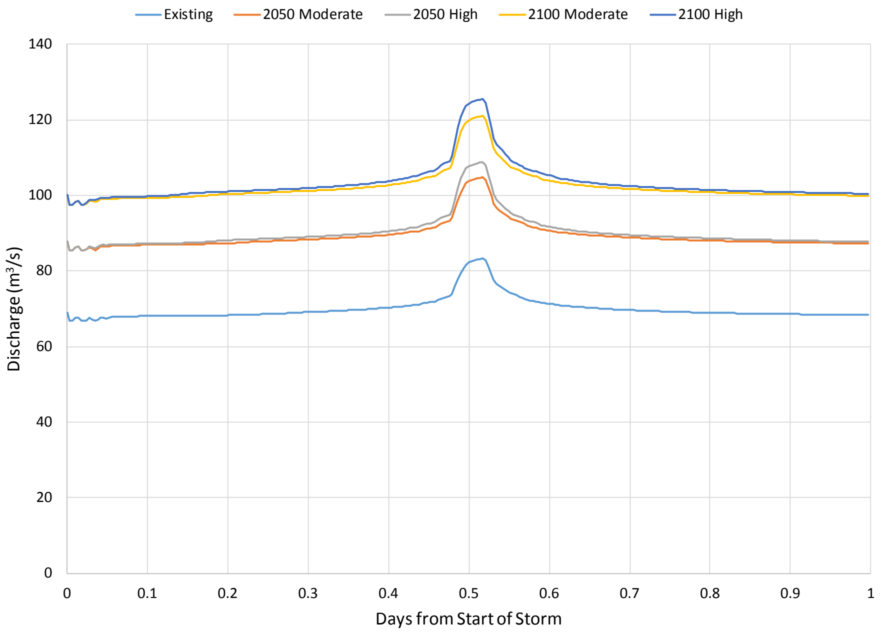


Figure 3.2 Comparison of Discharge at a Point near an Outfall (N-2520) for the Current and Future Climate Change Scenarios

The number of surcharged and flooded manholes, and the average HGL in the upper reaches of the watershed for the future climate change scenarios are summarized in Table 3.6. As the rainfall depth increases, the number of surcharged and flooded manholes increases. The average HGL also increases, indicating that the flood level has increased. This applies for both the existing conditions and the future mitigation models (the future mitigation model includes the pipe size increases recommended by Associated, 2016). The results indicate that the hydraulic capacity of the pipes is insufficient to accommodate the increases in rainfall due to climate change.

Table 3.6 Comparison Between Existing and Future Pipe Sizes with Future Rainfall for Case Study 2

	Existing Conditions			Future Mitigation		
	Number of Surcharged Manholes	Number of Flooded Manholes	Average HGL in Upper Reaches	Number of Surcharged Manholes	Number of Flooded Manholes	Average HGL in Upper Reaches
2050 Moderate Change						
24-hr, 10% AEP	205	159	127.25	85	71	125.41
24-hr, 1% AEP	362	307	130.80	196	148	125.96
2050 High Change						
24-hr, 10% AEP	285	239	128.77	126	102	125.62
24-hr, 1% AEP	444	408	134.24	306	269	127.12

Table 3.6 Comparison Between Existing and Future Pipe Sizes with Future Rainfall for Case Study 2

	Existing Conditions			Future Mitigation		
	Number of Surcharged Manholes	Number of Flooded Manholes	Average HGL in Upper Reaches	Number of Surcharged Manholes	Number of Flooded Manholes	Average HGL in Upper Reaches
2100 Moderate Change						
24-hr, 10% AEP	286	248	128.83	129	105	125.62
24-hr, 1% AEP	442	407	133.95	302	267	127.00
2100 High Change						
24-hr, 10% AEP	370	324	131.09	207	161	126.10
24-hr, 1% AEP	507	496	139.98	444	417	130.04

The preferred approach to reduce flooding in the watershed is through the application of source controls. The ability of the various source control measures to address the flooding observed in the watershed is discussed below.

3.2.3 Source Control Measures

The uplands and lowlands of the PMCDA are essentially fully developed. Changes to the watershed will take the form of redevelopment of existing lots. The redevelopment will result in increases in impervious area. Stormwater and rainwater management practices will be required to reduce the impact of the additional impervious coverage and prevent major flooding and erosion.

The Metro Vancouver Stormwater Source Control Design Guidelines (2012) provides a rainfall capture target of 72% of the 50% AEP (2-year return period) 24-hour event. For the PMCDA, the 50% AEP 24-hour event is 78.3 mm, and therefore the rainfall capture target is 56.4 mm. However, Associated (2016) stated that the low infiltration capacity of the uplands portion of the watershed may make this target unachievable. The City of Coquitlam has adopted a general rainfall capture target of half of the 50% AEP 24-hour storm event, which should be infiltrated or released slowly over a 24-hour period. Additionally, the 50% AEP post-development peak flow should be limited to half of the pre-development peak flow. Port Moody does not have a similar guideline or standard as of yet. Associated (2016) recommended that the City of Coquitlam post-development to pre-development peak flow limitation should be adopted.

A large variety of rainwater source controls are available (Table 3.7). These can be combined to achieve the flow reduction target. The flow limitation applies to new development, and if implemented, will result in a gradual decrease in stormwater flow in the watershed.

Table 3.7 Rainwater Source Controls

Source Control	Information
Infiltration trenches and bioswales	• Shallow grassed channel • Weir to hold back the stormwater and allow it to infiltrate • Maximum contributing drainage area: 2 hectares • Can be sized to retain 50-75% of 50% AEP 24-hour rainfall
Soakaway manhole	• Manhole that allows infiltration
Pervious paving with/ without subgrade storage and drain	• Maximum 2:1 ratio of impervious area to pervious area • Can receive flow from impervious areas • Subdrain can act as a flow restrictor • Can be sized to retain 50-75% of 50% AEP 24-hour rainfall
Absorbent growing medium	• Absorbent layer of soil with vegetation • 300 mm for lawns • 600 mm for shrubs and trees • 10 m^3 of soil per tree • Can receive flow from impervious areas • Maximum 2:1 ratio of impervious area to absorbent landscape • Can infiltrate the first 25-60 mm of rainfall
Rain gardens	• Vegetated area where surface runoff can pond and infiltrate • Generally include a subgrade drainage system • Can be sized to retain 50-75 % of the 50% AEP, 24-hour rainfall
Green roofs	• Waterproof membrane and layers of drainage and growing medium • Flat and shallow-sloped roofs • Rainwater removal varies between winter and summer • Can be sized to retain 50-75 % of the 50% AEP, 24-hour rainfall
Stormwater detention facilities	• Stormwater management ponds • Underground detention storage • Weirs/orifices restrict the outflow • Can incorporate infiltration • Can incorporate water treatment

It should be noted that the stormwater reduction achieved with the source controls will be counteracted by the increase in rainfall due to climate change. For each redevelopment, Table 3.8 provides the depth of stormwater available for runoff (assuming that the peak flow reduction is achieved by capturing half of the 50% AEP 24-hour event on-site as suggested by the City of Coquitlam). Due to the low infiltration capacity in the upland portions of the watershed (Associated, 2016), developers may select the source control options that capture the rainwater and release it slowly over a 24-hour period (e.g. stormwater detention ponds). If the source controls are not designed for potential increases in rainfall, they may become overwhelmed and not perform as designed (e.g. ponds could overflow and there would be no reduction in peak flow). In addition, even if the stormwater reduction amount increases as the rainfall increases, runoff will continue to increase and there will be a lower percentage reduction for the 1% AEP 24-hour storm events (for all four future scenarios). Therefore, without further stormwater controls, it is expected that flooding will increase as rainfall increases due to climate change. A similar effect would occur for the 10% AEP 24-hr event.

Table 3.8 Stormwater Runoff Comparison Assuming Stormwater Source Controls for Case Study 2

Scenario	50% AEP 24-hr Rainfall (mm)	Removal with Source Controls (mm)	1% AEP 24-hr Rainfall (mm)	Rainfall After Removal with Source Controls (mm)	Percent Reduction for 1% AEP 24-hr event (%)
Current	78.3	39.2	174.8	135.6	22
2050 Moderate With Source	88.8	44.4	218.4	174.0	20
2050 High With Source	105.6	52.8	271.2	218.4	19
2100 Moderate With Source	105.6	52.8	266.4	213.6	20
2100 High With Source	122.4	61.2	340.8	279.6	18

The stormwater source controls will be designed on a lot-by-lot basis, as existing lots are redeveloped. As such, it is not possible in a watershed model such as the PMCDA to model the detailed stormwater source controls because the model is not detailed enough for lot-by-lot analysis. For the purpose of modelling the effects on the watershed, the parameters of each subcatchment were modified to represent the overall impact of the stormwater source controls. A theoretical “subcatchment average” behavior was desired (i.e. how much impact would there be for the subcatchment if source controls were applied to some or all of the lots within the subcatchment). The following assumptions were applied:

- Approximately 25% of the subcatchment will be redeveloped by 2050, and 50% of the subcatchment will be redeveloped by 2100. These estimates are high, and would therefore provide a “best-case” degree of rainfall removal.
- Given the amount of redevelopment assumed above, the average decrease in the 50% AEP peak flow should be approximately 88% and 75% for 2050 and 2100, respectively (catchment average decrease).
- The amount of rainfall removal for the Current and 2050 time horizons is 40 mm (half of approximately 80 mm). The 40 mm removal applies to only one-quarter of the subcatchment, so 10 mm is the catchment average removal. The amount of removal for the 2100 horizon is 50 mm (half of approximately 100 mm), but it applies to only half of the subcatchment, so 25 mm is the catchment average removal.
- Approximately half of the rainwater removal will be accomplished with rainwater capture methods that do not allow runoff (e.g. permeable paving, absorbent growing medium, etc.); while the other half will

use methods that retain stormwater and release it slowly over a (minimum) 24-hour period (e.g. underground storage tanks, stormwater management ponds, etc.).

The parameters adjusted in this case study are illustrative only: detailed modelling (e.g. using the detailed design of the stormwater detention and release system) must be performed for each redevelopment. The analysis was performed to obtain a theoretical catchment-average response, according to the assumptions above.

The modelling parameters that were adjusted are listed in Table 3.9. Depression storage is the depth of rainfall that is captured in surface depressions. Many source controls act similarly to surface depressions (i.e. they capture rainwater). One-half of the expected removal at each time horizon was added to the depression storage. The percent zero impervious parameter describes how much of the impervious area is directly connected to the storm sewer system (e.g. roof leaders, parking lot drains). Directly connected stormwater flow bypasses the calculation of depression storage and infiltration in the model (i.e. 100% of the rainfall that falls on directly connected area runs off). It was assumed that direct connections to the storm sewer will be removed as redevelopment occurs (one-quarter by 2050, one-half by 2100). The Manning's n surface roughness parameter describes the surface roughness of the subcatchment. However, the stormwater detention options hold back the flow and release it slowly. This can be mimicked by increasing the surface roughness. The Manning's n was increased until the peak flow for subcatchments that are mainly impervious was decreased to 88% and 75% for 2050 and 2100, respectively (moderate change was used). The decrease was verified at numerous subcatchments in the upper reaches of the watershed. The decrease was approximate: some subcatchments decreased more or less than others.

Table 3.9 Modelling Parameters to Illustrate the Impacts of Stormwater Source Controls for Case Study 2

Parameter	Current Value	Value with Source Control	Notes
Depression Storage	Impervious: 1 mm Pervious: 5 mm to 20 mm	2050: Increase by 5 mm 2100: Increase by 12.5 mm	Half of stormwater removal assigned to depression storage
% Zero Impervious	25%	2050: 19% 2100: 12.5%	Removed zero impervious area as redevelopment occurs.
Manning's n Surface Roughness	Impervious: 0.016 Pervious: 0.3	2050: Impervious: 0.2 Pervious 0.35 2100: Impervious: 0.3 Pervious: 0.4	Increased Manning's n until peak flow for 2050 and 2100 was in the range of 88% and 75% (respectively) of the pre-development 50% AEP 24-hr peak flow

The outflow hydrographs for a sample subcatchment (S-26776) for a 50% AEP (2-year return period) 24-hr storm event with and without the source controls are shown in Figure 3.3. The outflow for the 2050 Moderate Change events is maintained at or below the current 50% AEP 24-hr flow. The outflow for the 2100 Moderate Change is slightly higher than the current 50% AEP 24-hr flow. However, the 2050 and 2100

High Change Events are greater than the current 50% AEP 24-hr flow. The modelling parameters used in this study are illustrative, and cannot be applied to any individual re-development. However, if the increase in rainfall is similar to the Moderate Change predictions, the current level of service for the 50% AEP can likely be maintained in subcatchments where a significant proportion of the subcatchment is redeveloped (using the current rainfall reduction standard for source control measures). If the increase in rainfall is similar to the High Change predictions, and/or if there are subcatchments with no redevelopment (no addition of source controls), the current level of service will not be maintained.

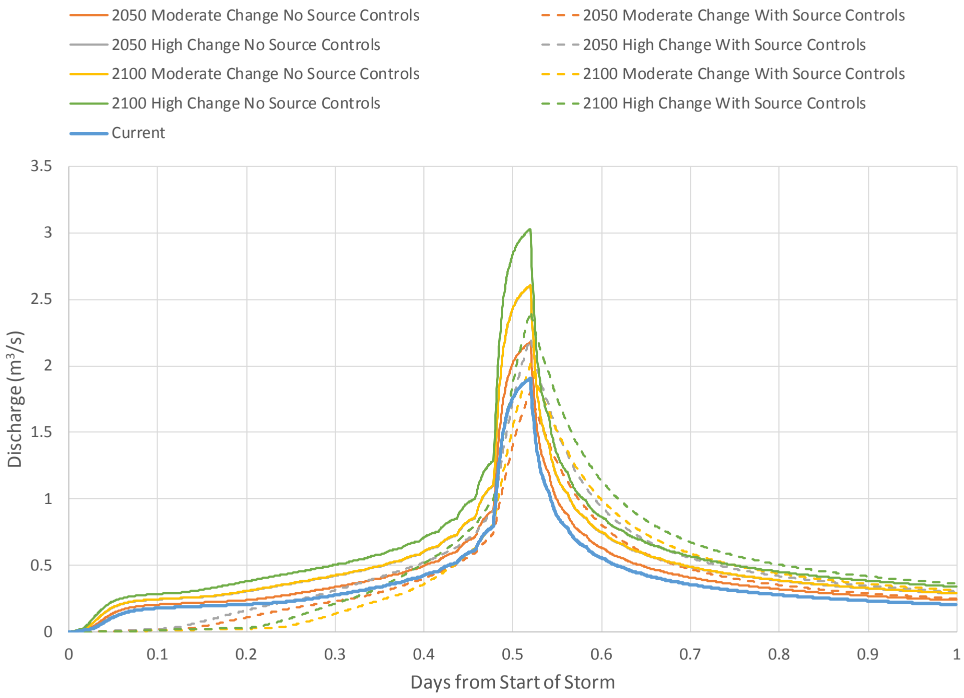


Figure 3.3 Comparison of Subcatchment Discharge With and Without Stormwater Source Controls for the 50% AEP Event for Case Study 2

The future mitigation model with the parameter changes to mimic the source controls was tested for lower AEP events for the future climate change scenarios. The 10% AEP and 1% AEP storm events are important for design. The required level of service for the main stems of the creeks and the storm trunk sewers in Port Moody was the 1% AEP storm event (100-year event). The required capacity for the remaining pipes (owned by the Cities) was the 10% AEP storm event (10-year event).The comparisons of the discharge for a 10% AEP (10-year return period) and 1% AEP (100-year return period) event for a representative subcatchment are shown in Figure 3.4 and Figure 3.5. The source controls decrease the peak flow of the 10% AEP event, but the peak is still higher than the peak flow of the current 10% AEP event. The 2050 Moderate Change event is nearly maintained at the current level by the source controls, but the 2050 High and 2100 events increase significantly. The source controls decrease the peak flow of the 1% AEP event slightly, but as for the 10% AEP, the peak is still higher than the peak flow of the current 1% AEP event. The use of the source controls is insufficient to maintain the peak flow at all AEP.

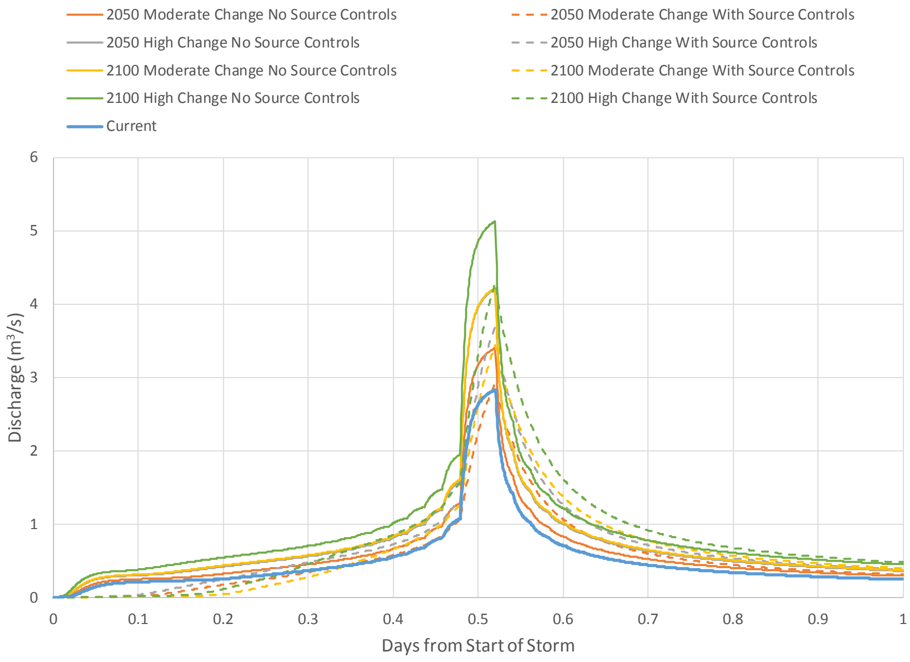


Figure 3.4 Comparison of Subcatchment Discharge With and Without Stormwater Source Controls for the 10% AEP Event for Case Study 2

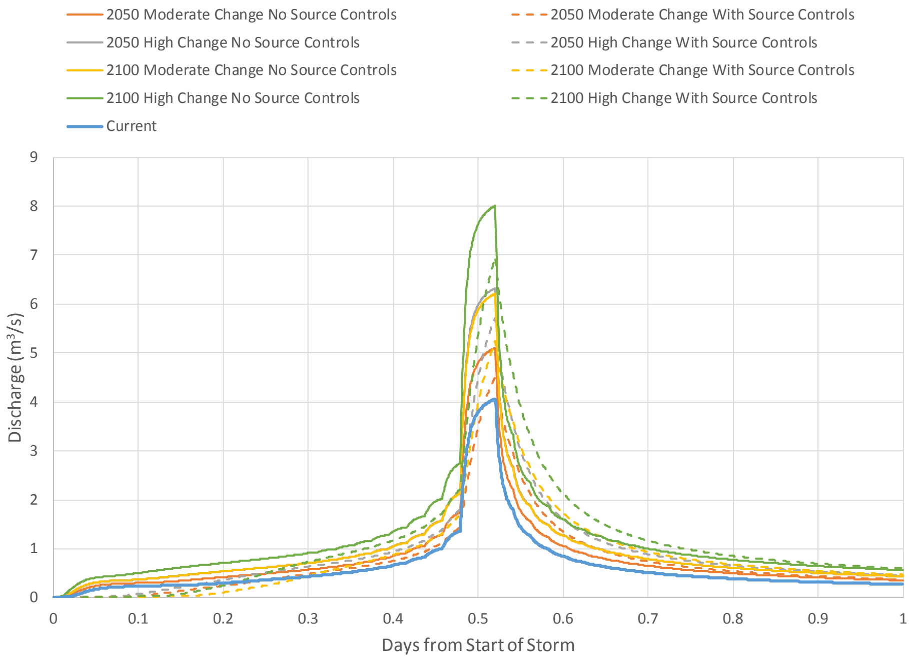


Figure 3.5 Comparison of Subcatchment Discharge With and Without Stormwater Source Controls for the 1% AEP Event for Case Study 2

The amount of surcharging, flooding, and the average HGL in the upper reaches of the watershed were compared to the model runs without source controls in Table 3.10. It was found that there was a decrease in surcharging, flooding, and flooding level with the source controls. However, the amount of surcharging, flooding and the average HGL in the upper reaches was still higher than when the current rainfall is used in the model. Therefore, the level of service would not be maintained for low-AEP events even when source controls are applied to a significant proportion of each subcatchment. The amount of flooding and erosion would increase in the future climate change scenarios even with source controls. These results imply that attaining a peak flow reduction for low AEP events must be addressed separately from attaining peak flow reductions for high AEP events.

Table 3.10 Comparison of Future Mitigation With and Without Source Controls for Case Study 2

	Future Mitigation			Future Mitigation with Source Controls		
	Number of Surcharged Manholes	Number of Flooded Manholes	Average HGL in Upper Reaches	Number of Surcharged Manholes	Number of Flooded Manholes	Average HGL in Upper Reaches
2050 Moderate Change Without or With Source Controls						
24-hr, 10% AEP	86	73	125.41	78	72	125.38
24-hr, 1% AEP	193	144	125.94	167	124	125.79
2050 High Change Without or With Source Controls						
24-hr, 10% AEP	118	101	125.61	107	92	125.53
24-hr, 1% AEP	301	270	127.12	278	230	126.72
2100 Moderate Change Without or With Source Controls						
24-hr, 10% AEP	129	105	125.62	102	95	125.51
24-hr, 1% AEP	302	267	127.00	256	197	126.44
2100 High Change Without or With Source Controls						
24-hr, 10% AEP	207	161	126.10	166	123	125.81
24-hr, 1% AEP	444	417	130.04	375	354	128.64

A stormwater reduction target that is based on the 50% AEP 24-hour storm event is insufficient to address the increase in flooding due to climate change for a lower AEP event. The source controls will fill before the peak of the 10% or 1% AEP storm events occur, and the reduction in the peak flow for the 10% or 1% AEP storm events will be minimal. These events will continue to cause major flooding and erosion, which will increase as rainfall increases due to climate change unless additional stormwater reduction targets are adopted.

In order to not exceed the current flooding state in the PMCDA, the stormwater reduction targets should be updated to account for climate change (compare current and future rainfall) over a range of AEP storm events. The goal should be (at a minimum) for the future post-development peak flow to not exceed the current pre-development peak flow for a range of AEPs. The current objective to decrease the current 50% AEP 24-hour flow by half can also be retained. It may also be advisable to include volume requirements. These are significant increases in the requirements for stormwater reduction and may not be achievable in all cases, but are required to maintain the current level of service. In addition, in areas where little or no redevelopment is planned, the current level of service will not be maintained unless source controls are retrofitted to the existing lots.

3.3 Costing

The costs to enact and enforce the rainfall detention criteria as discussed above would be shared between the municipalities and Metro Vancouver. In addition, an education and outreach program would also be required. The costs quoted below are for implementation of the program to develop and enforce the rainfall detention criteria. Depending on the level of redevelopment that is anticipated, the rainfall detention criteria can be adjusted to minimize the loss in level of service across the City.

Associated (2016) provided cost estimates for implementation and enforcement of rainfall detention criteria. Associated (2016) did not assign an education program to the City of Coquitlam since it already has rainfall detention criteria. However, this study is recommending a change to the City of Coquitlam's guidelines, and therefore an education program may be required. The cost estimates are shown in Table 3.11.

Table 3.11 Cost Estimates for Rainfall Detention Criteria for Case Study 2

Item	Approximate Cost	Primary Responsibility
Enact and enforce the rainfall detention criteria	< $50,000	City of Coquitlam
Develop and implement an education program	< $50,000	City of Coquitlam
Enact and enforce the rainfall detention criteria	< $50,000	City of Port Moody
Develop and implement an education program	< $50,000	City of Port Moody
Note: Costs from Associated (2016)		

Source controls alone cannot achieve the reductions in peak flow required (e.g. in areas where less redevelopment will occur). Metro Vancouver will need to upgrade the drainage system infrastructure. These costs are not included in the costs to implement the program, and must be priced separately. There are many end-of-pipe infrastructure improvement solutions that can be applied, which include (but are not limited to): stormwater detention ponds, subsurface stormwater storage, peak flow diversion, and pipe upsizing. The optimal end-of-pipe solutions vary with the amount of peak flow reduction that can be achieved through redevelopment with source controls, the downstream capacity, current level of service, and other factors. For instance, pipe upsizing may be selected in one location, but it may impact the level of service further downstream (i.e. the problem "moves downstream"). Stormwater detention ponds and subsurface stormwater storage solutions require sufficient storage volume to be effective (and therefore can only be applied in locations with sufficient space). The solutions must be selected as part of detailed study. For purposes of cost comparison for this project, the costing analysis was limited to upsizing the pipes.

It was found that the natural channels in Port Moody needed to be upsized in the model: this is due to the high sea levels used as the downstream boundary condition in addition to greater flow due to increased rainfall. The model does not allow water to overflow a channel: when a channel is full, the hydraulic grade line rises (the junctions flood) to provide increased pressure so that the flow rate can increase. In actuality, the waters would overflow the banks of the channels and there would be no increase in hydraulic grade line. Once the sizes of the natural channels in Port Moody were increased to prevent the increase in hydraulic grade line, piped sections were then increased. The costing included only the piped sections. The upsizing of the natural channels was performed to ensure that the hydraulic grade line did not increase (which is what would happen when the low-lying parts of Port Moody were flooded), and did not represent actual resizing of the natural channels.

Pipe upsizing should not be considered as the "preferred" method to address of level of service concerns. This cost analysis should only be used to compare costs between climate change scenarios and as a rough order of magnitude estimate. Preparing for climate change will cost an additional $4-11 million on top of upgrades currently needed to maintain levels of service. The incremental cost of choosing the more conservative high change climate scenario is only 9% and 19% for 2050 and 2100 respectively. Therefore, the majority of the cost is related to adaptation for climate change itself (which includes the combined effect of higher sea level and higher rainfall for this case study).

Table 3.12 Cost Estimates for Infrastructure Upgrades for Case Study 2

Scenario	Number of Pipes with Increased Sizes	Estimated Cost ($)	Percent Increase in Cost from Current (%)	Percent Increase in Cost from Moderate to High (%)
Current	30	4.2 million	N/A	N/A
Upsized 2050 Moderate with Source	32	8.2 million	95	9
Upsized 2050 High with Source	35	8.9 million	112	
Upsized 2100 Moderate with Source	37	12.7 million	202	19
Upsized 2100 High with Source	59	15.1 million	260	

The costing provided in Table 3.12 is a class D costing estimate. It assumes open cut replacement, which includes asphalt removal, curb removal, removal of soils, removal and replacement of pipe, bedding and compaction, disposal of extra soil, and restoration. It does not include design costs (survey, layout, geotechnical, engineering) or other ancillary costs (insurance, mobilization/travel costs, traffic control, moving utilities, etc.).

3.4 Summary of Case Study 2

The PMCDA will be heavily impacted by increased rainfall from climate change. The rainfall depth for the 2100 High Change scenario is 1.9 times the rainfall depth for the current scenario for the 1% AEP (100-year return period) event. The flow rate at each node is significantly increased in the future climate change scenarios. The amount of flooding and surcharging increases, as does the average HGL in the upper reaches of the watershed.

The guideline for the application of source controls is currently limited to the reduction of the peak flow for the 50% AEP (2-year return period) event. This technique, applied generally across each subcatchment, may be sufficient to maintain the current peak flows for high AEP events. However, it is insufficient to maintain the current peak flows for low AEP events. The amount of flooding and surcharging under the future climate change scenarios is increased above the current amount of flooding and surcharging for low AEP events (with and without source controls). Adding the source controls for the future climate change scenarios results in a minor decrease for low AEP events in the average HGL in the uplands portion of the watershed, compared to when no source controls are used.

Additional stormwater reduction targets would need to be implemented to maintain the current level of service as the amount of rainfall increases due to climate change. At a minimum, the targets should include a reduction of peak flow at a range of AEPs. For instance, the future post-development peak flow should not exceed the current pre-development peak flow. These stricter guidelines will only maintain the current level of service if a significant portion of the subcatchment will be redeveloped. The guidelines can be adjusted depending on the level of redevelopment that is anticipated.

Where little or no redevelopment is anticipated, the current level of service will not maintained under the future climate change scenarios unless source controls are retrofitted into the existing lots. Encouraging private land owners to add source controls may help to address high AEP events, but will likely have less impact on low AEP events. In addition, infrastructure changes in the drainage system (e.g. pipe size increases, redirecting flows) must be incorporated where source controls cannot maintain the current level of service.

There are many end-of-pipe infrastructure improvement solutions that can be applied, which include (but are not limited to): stormwater detention ponds, subsurface stormwater storage, peak flow diversion, and pipe upsizing. For this study, end-of-pipe infrastructure upgrades were limited to pipe upsizing. Upgrading the drainage infrastructure to accommodate climate change will cost an additional $4-11 million on top of upgrades currently needed to maintain levels of service. The incremental cost of choosing the more conservative high change climate scenario is only 9% and 19% for 2050 and 2100 respectively.

4. Case Study 3: Collingwood Sanitary Trunk Sewer

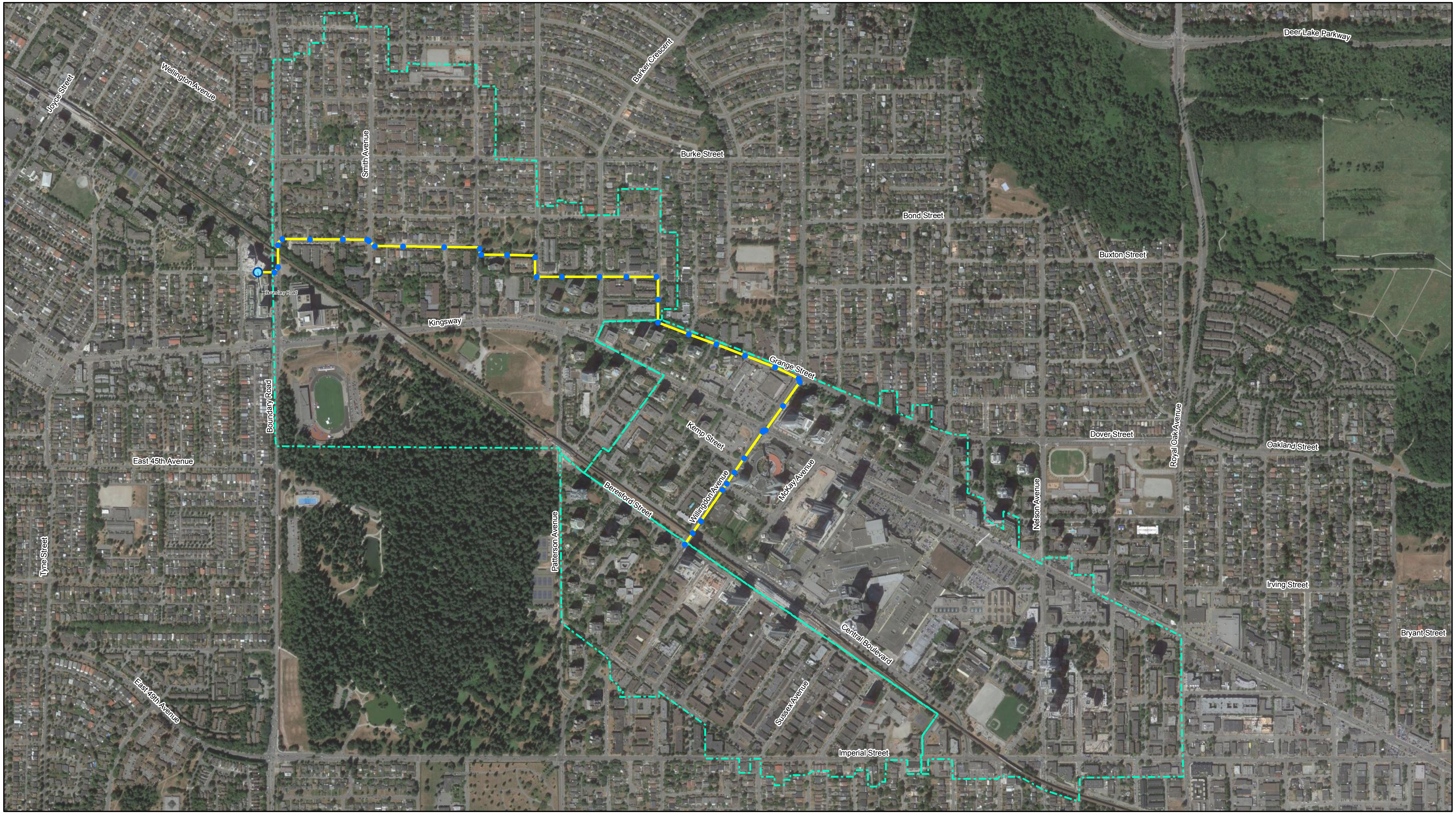
4.1 Model Setup

4.1.1 Model Description

The Collingwood Sanitary Trunk Sewer is located in the City of Burnaby. It is a sanitary collection system (no stormwater), which drains a total of 245.1 hectares. The level of rainfall derived inflow and infiltration (RDII) in the sewer, and its impact on the level of service for the trunk sewer as rainfall increases, was the focus of this case study. The Collingwood Sanitary Trunk Sewer starts at Willingdon Ave. and Beresford St., and proceeds north and west to Boundary Rd, near Vanness Ave. There is a sanitary flow measurement location at Boundary Road, which was selected as the downstream boundary for the model.

The GVS&DD provided the sewer catchment delineation, the locations of the manholes, and the sewer pipes. The GIS data included inverts, diameters, material, and other key information to include in the model. In addition, the City of Burnaby pipe network that discharges into the trunk sewer was provided. Land use data were also provided, so that the sewer flow could be allocated according to land use (i.e. residential, commercial, industrial, and institutional).

A PCSWMM model was developed and calibrated for this case study (Figure 4.1). PCSWMM was selected as the modelling software so that all three case studies would have the same modelling platform. There were three subcatchments, 40 conduits, and 40 junctions. The existing and future models were identical in setup (there are no planned changes to manhole or pipe location or connectivity). The sanitary flow and rainfall were different for different time horizons.



Source: Image ©2017 Google, Imagery date: 2017

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Meters

Coordinate System:
NAD 1983 UTM Zone 10N

N

Legend

- ◉ Outfalls
- ● Junctions
- — Pipes
- ▭ Subcatchments

METRO VANCOUVER
BRITISH COLUMBIA, CANADA

MODEL SETUP FOR CASE STUDY #3:
COLLINGWOOD SANITARY TRUNK SEWER

11140666-01
Dec 20, 2017

FIGURE 4.1

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4.1.2 Model Calibration and Validation

The calibration and validation used a two-stage methodology. The first stage of calibration was to setup the dry weather flow (DWF). The second stage of calibration was for the wet weather flow (WWF), which was also validated. The model calibration and validation used the sanitary flow monitoring data from the Boundary Road (CO1) gauge. The data were available at a temporal frequency of 5-minutes from 2007 to 2016. The period from April 2014 to the end of 2016 had numerous periods of missing data and data with unknown quality (e.g. sanitary flow was unusually high or unusually low), and therefore these data were not used. The rainfall data were taken from the Central Park Reservoir (BU29) rainfall monitoring gauge: data were available at a temporal frequency of 5-minutes for the period of 2007 to 2017.

The sanitary flow monitoring data and the rainfall monitoring data were loaded into PCSWMM, and the dry weather periods were delineated. The following patterns were generated: Hourly (Weekday), Hourly (Weekend), Daily, and Monthly. The average DWF for the sanitary flow monitoring data was portioned to the upstream manholes according to land use and population. The DWF calibration focused on the period from January 2013 to March 2014, which represents the most recent time period with suitable data. As an example of the fit of the DWF, the DWF for July 2013 is shown in Figure 4.2.The DWF calibration was successful: the model was able to reproduce the DWF patterns, but the low flows were overestimated. The low flows are not critical for this case study.

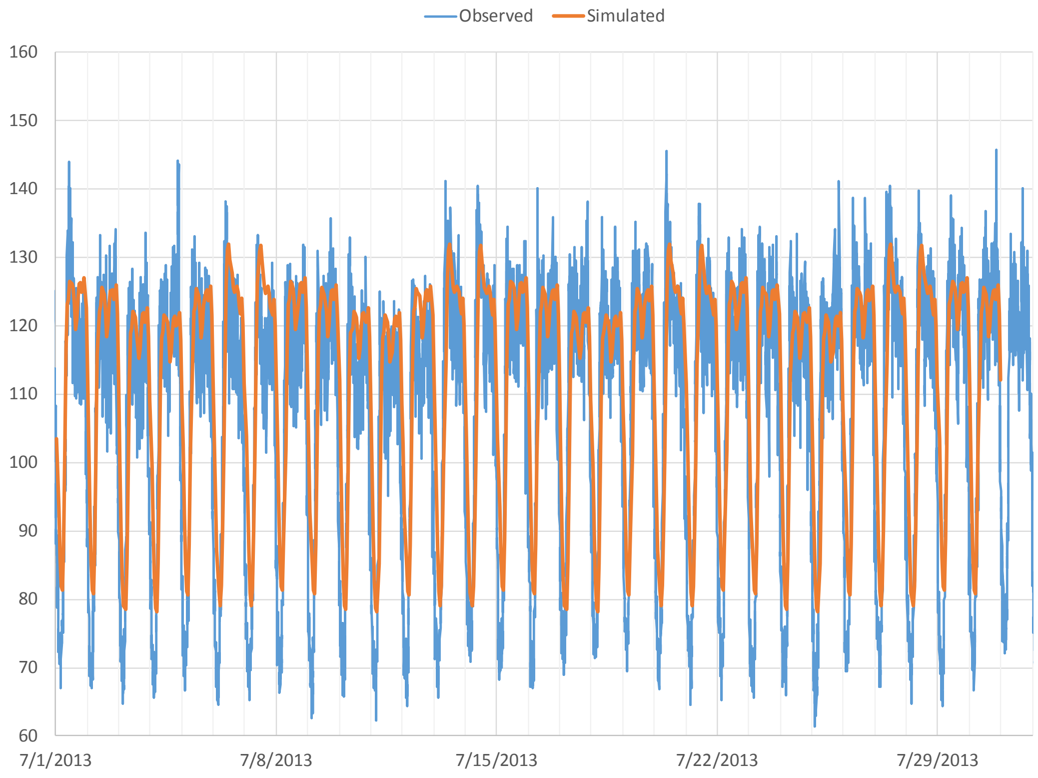


Figure 4.2 Dry Weather Flow Calibration Results for Case Study 3

The purpose of WWF calibration is to match the RDII response pattern in the sewershed. RDII is commonly modeled with the RTK method. The RTK method consists of a three-part unit hydrograph. The three unit hydrographs are known as short term, medium term, and long term, and are added together to develop the RDII response. Each unit hydrograph is a triangular unit hydrograph with three parameters (nine parameters in total). The “R” parameter controls the proportion of rain that enters the sewer for that unit hydrograph. The “T” parameter controls the time to peak, and the “K” parameter controls how long the response continues.

The calibration process involves adjusting the nine RTK parameters until the simulated flow matches the observed flow for a calibration event. Two WWF calibrations were performed, using different WWF events. The sanitary flow monitoring data at Boundary Road were reviewed to select suitable WWF events. The four largest WWF events from January 2013 to March 2014 were selected as the calibration and validation events.

The calibration and validation process considered the hydrograph shape, peak flow and timing, and total volume. The Wastewater Planning User’s Group (WaPUG, 2002) provided the following guidelines for calibration:

- Timing of the peaks and troughs should be similar
- The peak flow error should be in the range +25% to -15%
- The event volume error should be in the range +20% to -10%

The calibration and validation hydrographs are included in Figure 4.3 to Figure 4.6, and the peak flow and event volume errors are tabulated in Table 4.1. The RDII response in the Collingwood sanitary trunk sewer is generally rapid (low medium and long-term response). There were some parts of each event that were not modelled well (e.g. the second peak in the calibration event for Calibration 1) but these errors can be attributed to the fact that either more or less rain was recorded at the Central Park Reservoir rainfall monitoring location than was observed at the sanitary sewer flow measurement gauge at Boundary Road. However, the peak flow and event volume errors were within the guidelines provided by WaPUG (2002).

Table 4.1 Calibration and Validation Events for Case Study 3

Calibration Number	Calibration Event			Validation Event		
	Dates	Peak Flow Error (%)	Event Volume Error (%)	Dates	Peak Flow Error (%)	Event Volume Error (%)
Calibration 1	2013/02/27 – 2013/03/04	-3.89	6.26	2013/03/11 – 2013/03/18	-4.49	10.74
Calibration 2	2014/01/07 – 2014/01/14	3.13	3.61	2013/11/01 – 2013/11/04	-5.88	8.27

Note

A negative error indicates that the simulated flow underestimated the observed flow, while a positive error indicates that the simulated flow overestimated the observed flow.

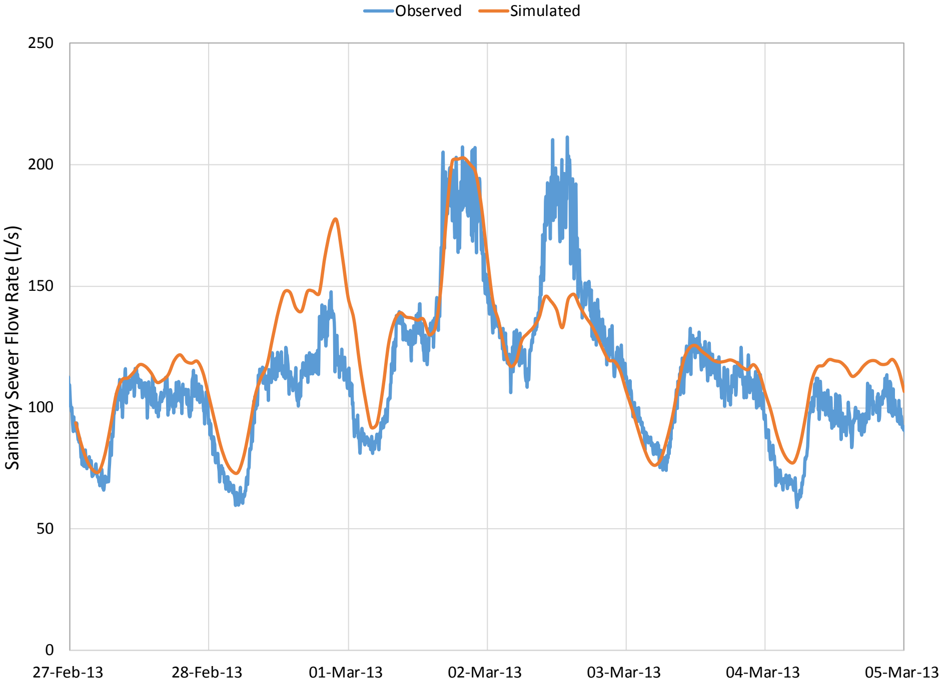


Figure 4.3 Observed and Simulated Sewer Flow at Boundary Road for Calibration Event (Calibration #1)

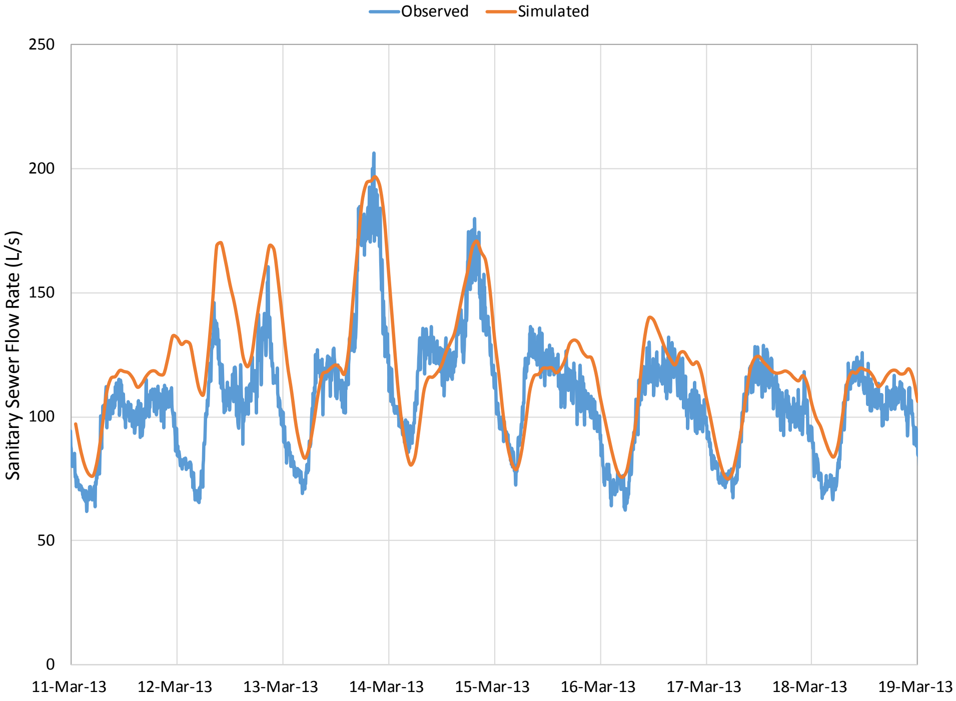


Figure 4.4 Observed and Simulated Sewer Flow at Boundary Road for Validation Event (Calibration #1)

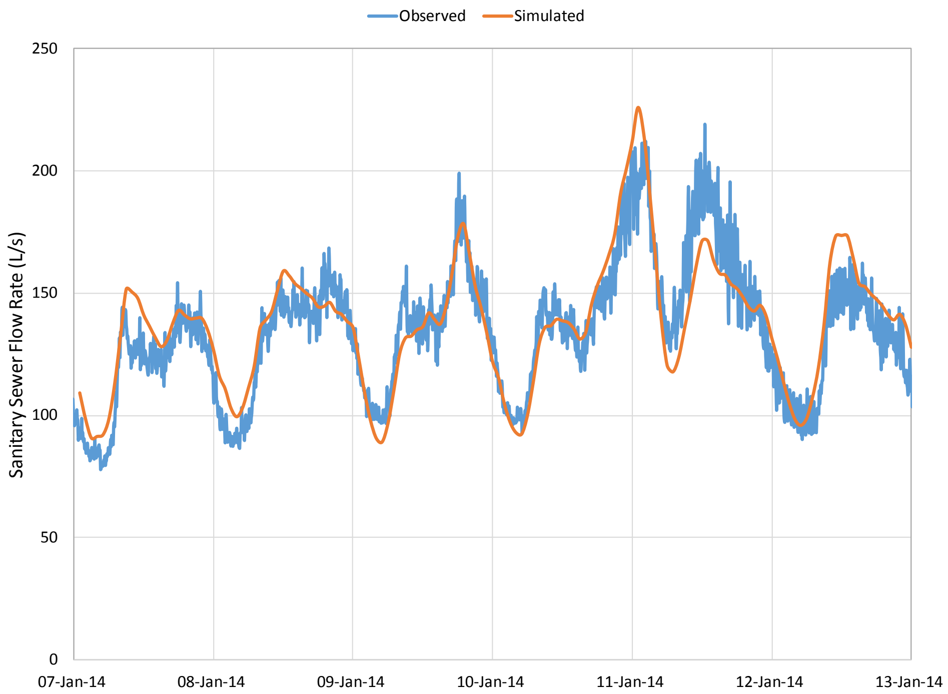


Figure 4.5 Observed and Simulated Sewer Flow at Boundary Road for Calibration Event (Calibration #2)

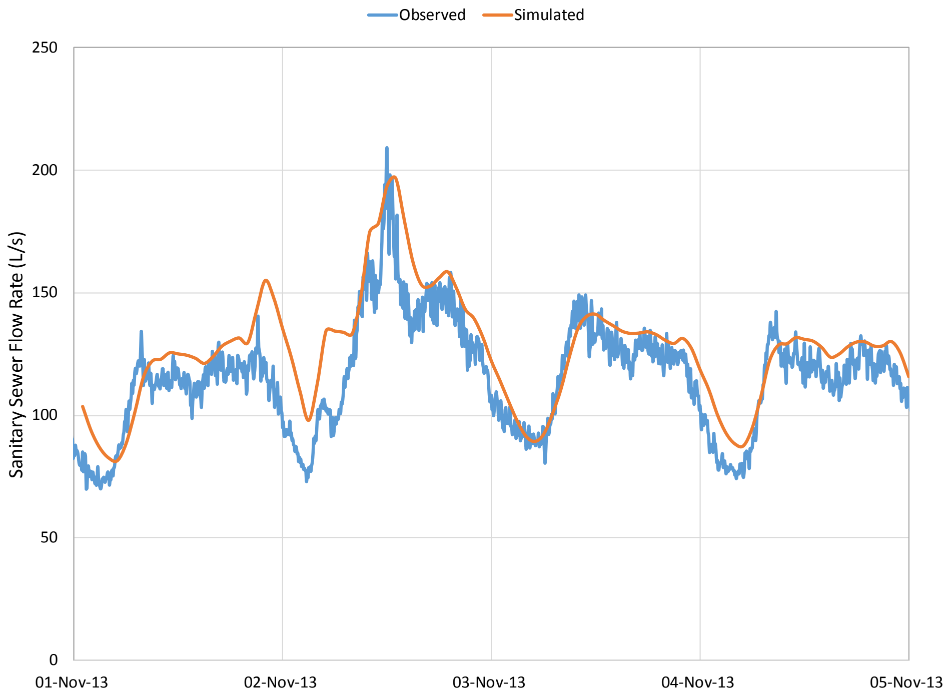


Figure 4.6 Observed and Simulated Sewer Flow at Boundary Road for Validation Event (Calibration #2)

The two calibrations were tested with a design storm event to determine which calibration provided the highest sanitary sewer flows. A 24-hour Soil Conservation Service Type IA design storm was utilized, with a total rainfall depth of 85.3 mm (20% AEP or 5-year return period rainfall depth). The total event volumes for both calibrations were similar, but the peak flow for Calibration 1 was higher than the peak flow for Calibration 2 (Table 4.2). Therefore, Calibration 1 was utilized for the analysis.

Table 4.2 Comparison of Calibration 1 and Calibration 2 for Case Study 3

Calibration Number	Peak Flow (L/s)	Total Event Volume (10^6 L)
Calibration 1	302	81.7
Calibration 2	290	80.2

4.1.3 Sewer Flow Calculations for the Current, 2050, and 2100 Horizons

The GVS&DD provided population and employment forecasts for each of the three subcatchments. The most upstream subcatchment (subcatchment ID 1190) drains to the most upstream manhole (J01) of the trunk sewer. The other two asubcatchments (subcatchment IDs 1192 and 1177) include multiple connection locations along the trunk sewer (as indicated in the GHD_CoB_San_Main shapefile). The total dry weather flow measured at Boundary Road (CO1) was portioned to each connection location.

The average sanitary sewer flow during dry weather was 140 L/s at the Boundary Road location. For 2016, the sanitary sewer flow was portioned to each of the three subcatchments according to their population and employment (e.g. subcatchment 1190 had 19% of the total population and employment, and it therefore produced 19% of the 140 L/s). The sewer flow was then scaled up according to population and employment for 2050 and 2100.

Table 4.3 Allocation of Sanitary Sewer Flow to Subcatchments for Case Study 3

Subcatchment ID	2016			2050			2100		
	Pop.	Emp.	Sewer Flow (L/s)	Pop.	Emp.	Sewer Flow (L/s)	Pop.	Emp.	Sewer Flow (L/s)
1190	9,340	652	27.0	14,554	974	41.9	18,012	1,221	51.9
1192	10,822	20,958	85.8	18,043	26,332	119.8	31,535	28,803	162.8
1177	6,721	3,389	27.3	19,586	4,283	64.4	26,272	4,709	83.6
Total	51,882		140.1	83,772		226.1	110,552		298.3

The sewer flow for subcatchments 1177 and 1192 was then subdivided to the locations where the City of Burnaby sewer mains connect into the trunk sewer. The amount of residential area serviced by each City of Burnaby sewer main was used to estimate the population serviced by each sewer main, and similarly, the total of commercial, industrial, and institutional area was used to estimate the employment population serviced by each sewer main. No wastewater loading was assigned to other types of area (e.g. roads, transit corridor, parks, open spaces). For instance, the area serviced by the J02 manhole consists of a transit corridor, and therefore the loading at this location was zero for all time horizons. The final sanitary sewer flow used in the model is listed in Table 4.4.

Table 4.4 Allocation of Sanitary Sewer Flow Within Subcatchments for Case Study 3

Model Junction ID	Subcatchment ID	2016 Sewer Flow (L/s)	2050 Sewer Flow (L/s)	2100 Sewer Flow (L/s)
J01	1190	27.0	41.9	51.9
J02	1192	0.0	0.0	0.0
J05	1192	7.5	11.8	19.0
J08	1192	27.6	37.0	46.4
J13	1192	45.7	64.2	88.3
J16	1192	3.1	4.5	6.5
J18	1192	1.9	2.3	2.6
J22	1177	1.4	3.9	5.3
J24	1177	1.0	3.0	4.0
J29	1177	1.8	2.9	3.5
J32	1177	1.9	3.7	4.6
J34	1177	13.8	37.0	49.0
J38	1177	1.1	3.2	4.3
J40	1177	6.4	10.7	12.9
Total		140.2	226.1	298.3

4.1.4 Downstream Boundary Condition

The downstream boundary for the model was the Boundary Road sanitary flow measurement gauge. The Boundary Road gauge measures depth, flow, and velocity. The average depth of flow at the Boundary Road sanitary flow measurement gauge was 0.19 m, and during DWF the depths range from 0.15 to 0.25 m. During WWF, the depth can rise to approximately 1.25 m. The downstream boundary condition for the 20% AEP event (5-year event) was set to a depth of 1.25 m (elevation of 93.31 m). The pipe that goes to the outfall is 0.375 m in diameter, and therefore, the pipe will be surcharged during the 20% AEP event.

4.1.5 Rainfall Estimates for Current and Future IDF Curves

The RDII allowance requirements in the City of Burnaby's design guidelines for sewers (Burnaby, 2014) state that if RDII measurements have not been taken, then pipes must have capacity to carry an RDII flow of 22,400 L/ha/day, which is based on a 20% AEP (5-year return period) 24-hour rainfall event. Metro Vancouver specifies an RDII allowance of 11,200 L/ha/day in the Rawn Criteria, which is less than the RDII allowance in the City of Burnaby's design guidelines. Metro Vancouver requested, however, that a 6-hr rainfall event be utilized for this study because of the area of the sewer catchment. Therefore, the RDII analysis used a 20% AEP 6-hour event as the required level of service for the Collingwood Sanitary Trunk Sewer.

The Collingwood Sanitary Trunk Sewer is located in the Homogeneous Rainfall Zone 4 from TM2. The 24-hr index rain (at-site mean) for Central Park Reservoir was compared to the index rain from the 6-hr contour maps (Table 4.5). An index rain of 34 mm was used for scaling.

Table 4.5 Comparison of 6-Hour Means to Use for Scaling the Dimensionless IDF Curves for Case Study 3

	Central Park Reservoir	Index Rain from 6-hr Contour Map
6-hr Index Rain (mm)	34.0	33-34

The future climate change IDF curves were obtained from TM3. The 6-hr, 20% AEP rainfall depths for the current horizon and the four future horizon IDF curves are listed in Table 4.6. The SCS 6-hr design storm distribution was used in the modeling.

Table 4.6 Rainfall Depths for Current and Future IDF Curves for Case Study 3

	Current	2050		2100	
		Moderate Increase	High Increase	Moderate Increase	High Increase
6-hr, 20% AEP Rainfall Depth (mm)	41.6	48.6	59.4	60.6	70.8

4.2 Results

The Collingwood sanitary trunk sewer ranges in size from 375 to 750 mm in diameter. The City of Burnaby design guidelines for sewers require that gravity sewers larger than 300 mm should be designed to flow less than 70% full (by depth). The downstream water level is higher than the obvert of the last pipe, and therefore it was not possible to ensure that the last pipe is less than 70% full. However, this criterion was used for all other pipes.

The future capacity of the Collingwood sanitary trunk sewer will be affected by a combination of population growth and increased RDII from higher rainfall due to climate change. In order to be able to separate these two factors and identify the capacity issues that are related to climate change, the analysis was performed in two parts: population growth only, and population growth with climate change. The scenarios analyzed for this case study are listed in Table 4.7.

Table 4.7 Scenarios for Case Study 3

Scenario Name	Sewer Flow	Rainfall	Adaptation
Current	2016	Current	As-built pipe sizes
2050 Population	2050	Current	Pipes upsized to accommodate population growth to 2050
2100 Population	2100	Current	Pipes upsized to accommodate population growth to 2100

Table 4.7 Scenarios for Case Study 3

Scenario Name	Sewer Flow	Rainfall	Adaptation
2050 Moderate Change	2050	2050 Moderate Change	Pipes upsized to accommodate population growth to 2050 plus increased RDII
2050 High Change	2050	2050 High Change	Pipes upsized to accommodate population growth to 2050 plus increased RDII
2100 Moderate Change	2100	2100 Moderate Change	Pipes upsized to accommodate population growth to 2100 plus increased RDII
2100 High Change	2100	2100 High Change	Pipes upsized to accommodate population growth to 2100 plus increased RDII

4.2.1 Scenarios with Population Growth Only

The scenarios with population growth only used the increased sewer flow at each time horizon with the current 20% AEP (5-year return period) 24-hour rainfall. As listed in Table 4.3, the combined population and equivalent population will more than double by 2100. Similarly, the sewer flow rate will also more than double. The flow rate at Boundary Road for each of the three time horizons is shown in Figure 4.7. The RDII response is identical between the three time horizons, but the sewage flow has increased.

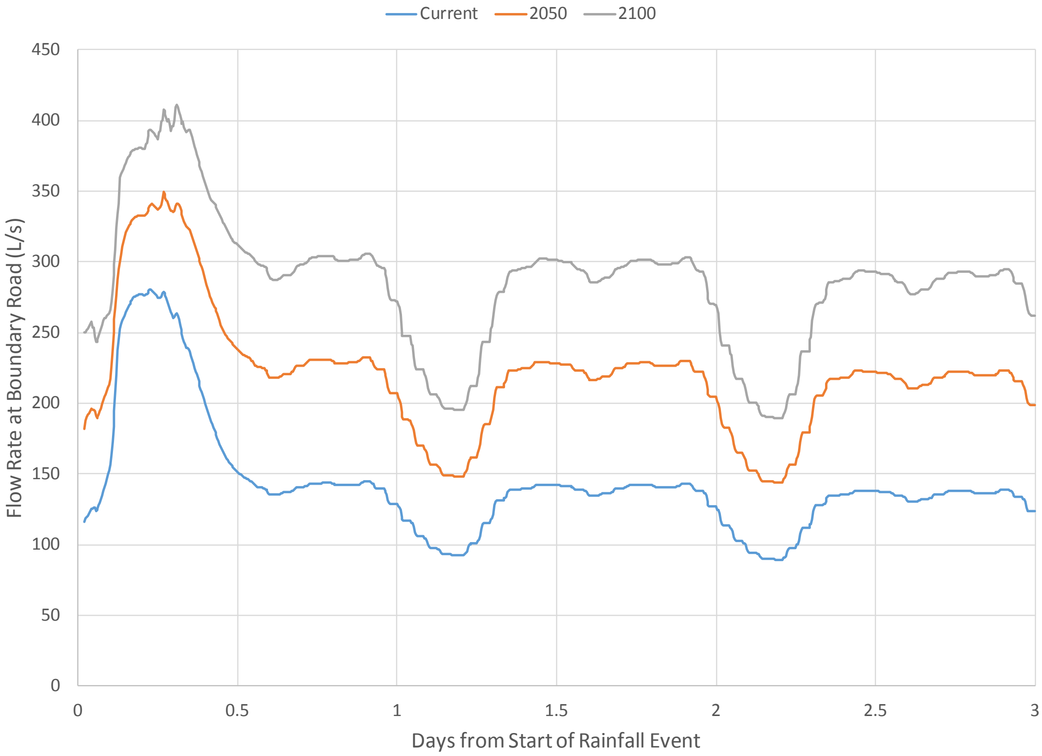


Figure 4.7 Comparison of Population Growth Only Scenarios for Current, 2050, and 2100 Time Horizons

The results for the three time horizons with a 20% AEP, 6-hour storm event are summarized in Table 4.8. There are five pipes in the current scenario that are exceeding the 70% full by depth criterion, and there is surcharging at two manholes as a result (surcharging occurs when a pipe is 100% full). In the 2050 and 2100 time horizons, these values increase. The average pipe depth ratio was greater than 0.7 for the 2100 time horizon. There was no flooding in any time horizon.

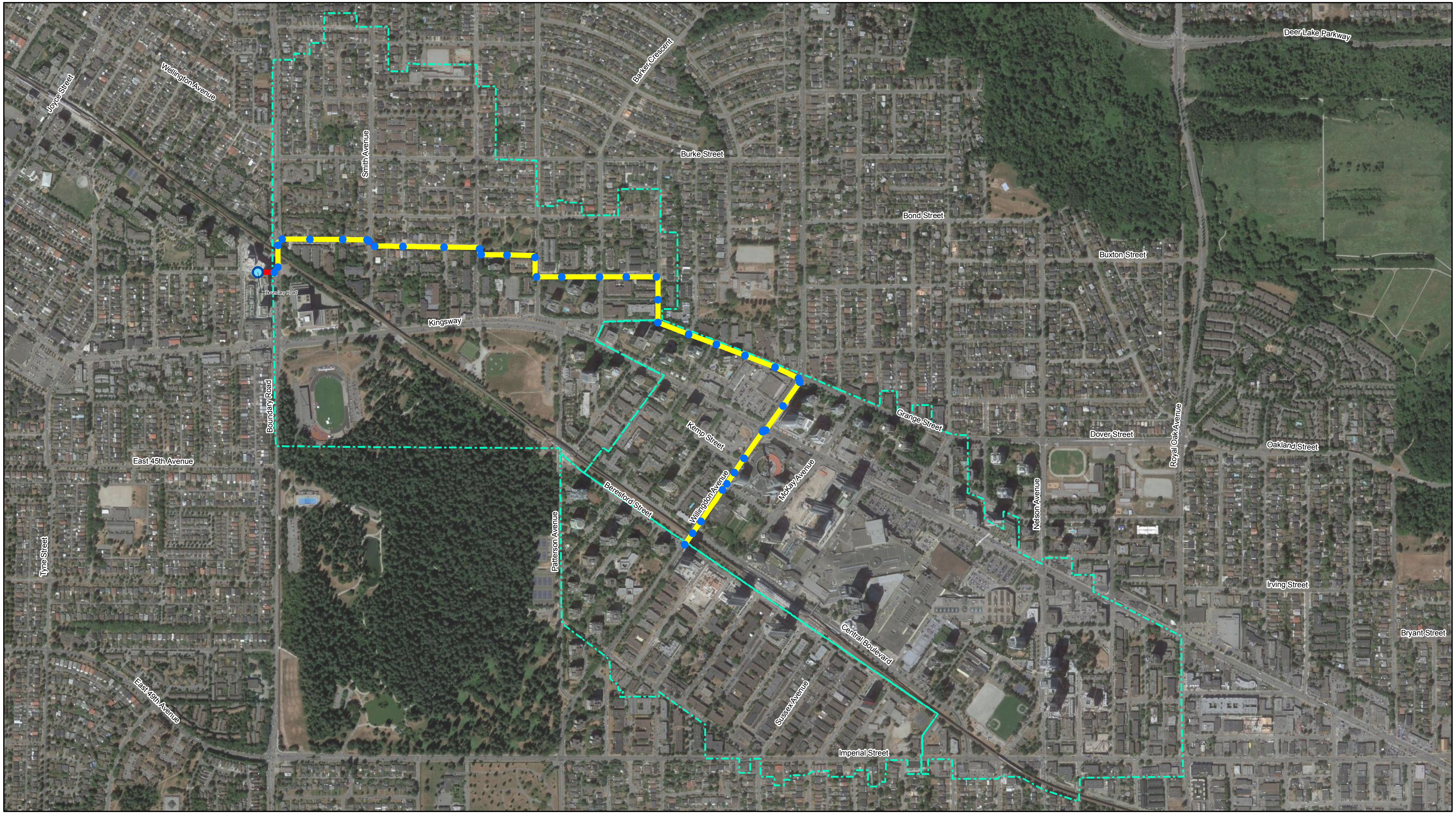
Table 4.8 Summary of Population Growth Only Scenarios for Case Study 3

Scenario	Number of Pipes > 70% Full by Depth	Number of Surcharged Manholes	Average Pipe Depth Ratio	Number of Upsized Pipes
Before Upsizing				
Current	5	2	0.50	N/A
2050 Population	10	6	0.59	N/A
2100 Population	28	17	0.83	N/A
After Upsizing				
2050 Population	1 (due to boundary condition)	0	0.51	4
2100 Population	1 (due to boundary condition)	0	0.55	6

Mitigation strategies were developed for the 2050 and 2100 time horizons to address the deficiencies identified in Table 4.8 (no mitigation was developed for the current time horizon). Selected pipes were increased in diameter until there was sufficient capacity in the trunk sewer system (less than 70% full by depth). The pipes that were upsized are shown in Figure 4.8 and Figure 4.9. There are a total of 40 pipes in the Collingwood sanitary trunk sewer system (to Boundary Road). Four pipes must be upsized to accommodate the population growth to 2050, and 15 must be upsized in order to provide the required level of service to accommodate the population growth to 2100 (less than 70% full by depth). Note that the pipe leading to Boundary Road (the most downstream pipe in the model) remains 100% full due to the downstream boundary condition adopted in this study.

4.2.2 Scenarios with Population Growth and Increased Rainfall due to Climate Change

The scenarios with population growth and increased rainfall due to climate change included the increased sewer flow at each time horizon with the increased rainfall events developed from the moderate and high change future climate IDF curves derived in TM3. The flow rate at Boundary Road for each of the scenarios is shown in Figure 4.10. The RDII response increases with increasing rainfall, and sewage flow has also increased. The RDII in the model is calculated using the RTK method. This method is an empirical method with parameters chosen to mimic the observed RDII response (see Section 4.1.2). The empirical parameters describe the proportion of rainfall that enters the sewer and how fast or slow it enters the sewer. As rainfall increases, the amount of RDII calculated in the model increases, however, the RDII response is assumed to be stationary (no change to the proportion or timing of rainfall that enters the sewer).



Source: Image ©2017 Google, Imagery date: 2017

0 100 200 300
Meters

Coordinate System:
NAD 1983 UTM Zone 10N

N

Legend

- ● Outfalls
- ● Junctions
- ▭ Subcatchments

Was Upsized

- 🟥 Yes
- 🟨 No

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PIPES THAT WERE UPSIZED FOR 2050 POPULATION GROWTH FOR CASE STUDY 3
COLLINGWOOD SANITARY TRUNK SEWER

11140666-01
Dec 20, 2017

FIGURE 4.8

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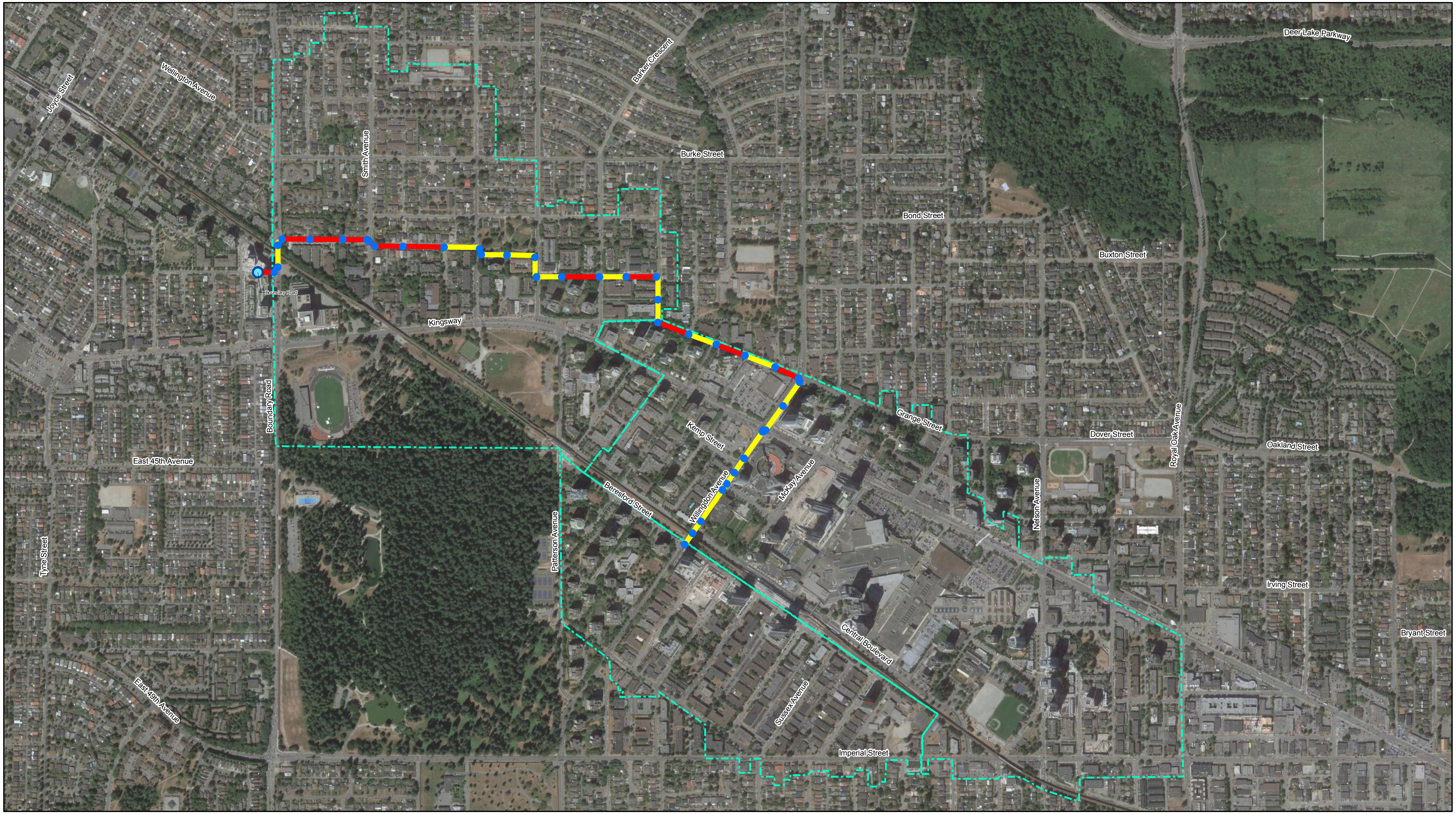

Source: Image ©2017 Google, Imagery date: 2017

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Meters

Coordinate System:
NAD 1983 UTM Zone 10N

N

Legend

- ● Outfalls
- ● Junctions
- ╌ Subcatchments

Was Upsized

- 🟥 Yes
- 🟨 No

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PIPES THAT WERE UPSIZED FOR 2100 POPULATION GROWTH FOR CASE STUDY 3
COLLINGWOOD SANITARY TRUNK SEWER

11140666-01
Dec 20, 2017

FIGURE 4.9

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For this area, the increase in flow from RDII is less than the increase in flow due to population growth. This indicates that population growth is a more significant factor for this location than increasing RDII in terms of flow volume. The peak flow increases due to increased RDII. Further pipe upsizing will be required to accommodate the higher peak flows and ensure that the pipes remain less than 70% full by depth.

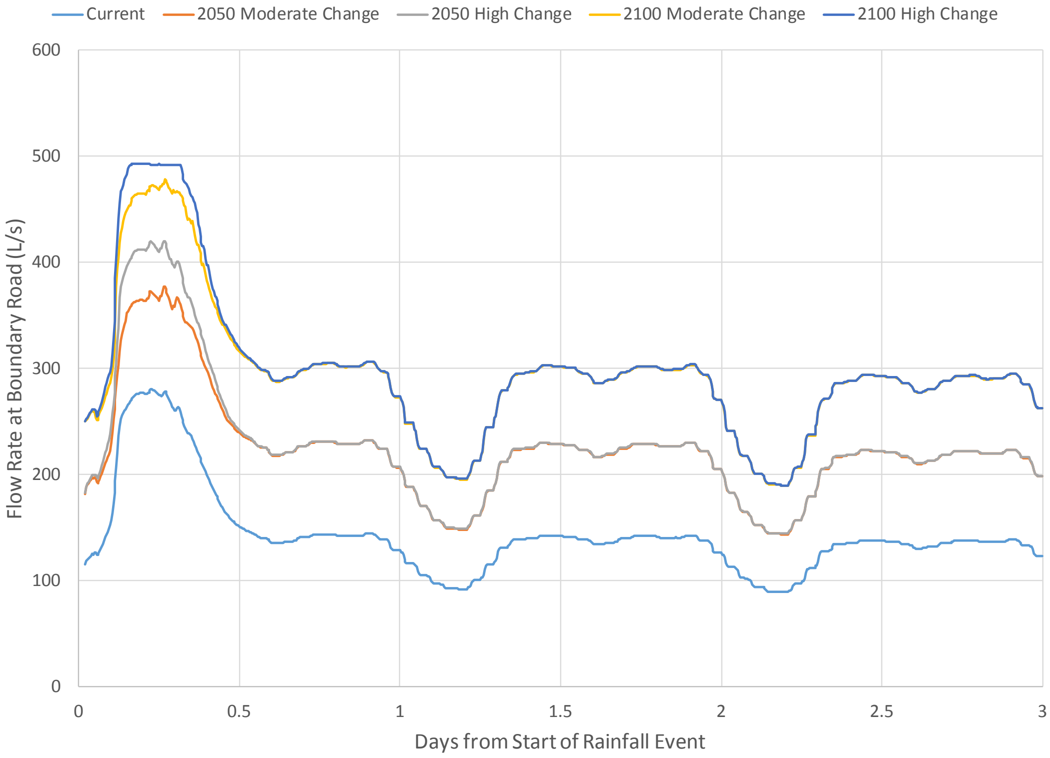


Figure 4.10 Comparison of Population Growth and Increasing Rainfall due to Climate Change Scenarios for Current, 2050, and 2100 Time Horizons

Flooded basements are of particular concern for sanitary sewer networks. For this analysis, manholes where the maximum hydraulic grade line rises is less than 1.8 m below the ground surface were considered to be potential manholes where basement flooding could occur. As the rain event increases in magnitude due to climate change, the flooded basements will increase. The number of manholes with freeboard (the distance between the maximum hydraulic grade line and the surface) less than 1.8 m for each AEP (return period) is presented in Figure 4.11 for the Current, 2050, and 2100 scenarios, with and without pipe upsizing for population growth. For the 2050 scenarios, basement flooding occurs at the 10% AEP (10-year return period) for the Moderate Change, and 20% AEP (5-year return period) for the High Change scenarios. For the 2100 scenarios, basement flooding occurs at the 50% AEP (2-year return period). When the pipes were upsized to account for population growth, the AEP when flooded manholes begin to occur ranges from 50% AEP (2-year return period) to 2% AEP (50-year return period), depending on the rainfall scenario.

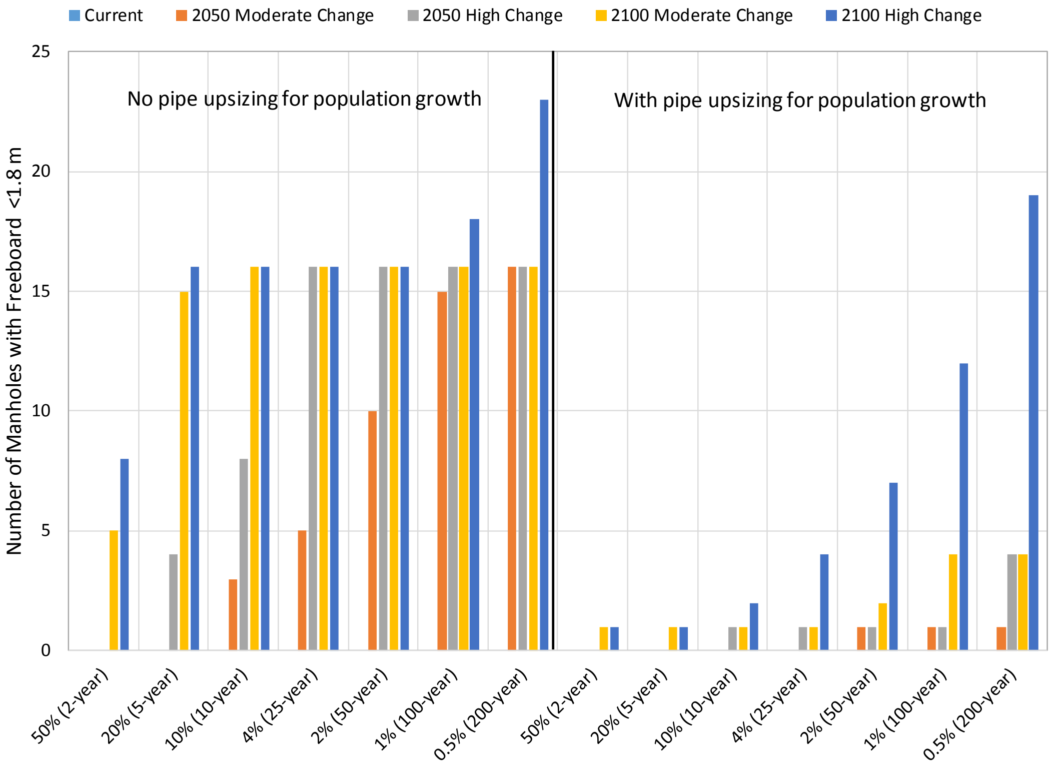


Figure 4.11 Number of Flooded Manholes for Different AEPs With and Without Pipe Upsizing for Population Growth for Case Study 3

The results for the three time horizons are summarized in Table 4.9. When the pipe sizes are increased so that they have capacity for population growth, there is no surcharging when the future rainfall is added to the model. RDIIThere are pipes that are greater than 70% full by depth for both the 2050 and 2100 scenarios, but the average pipe depth ratio remains below 0.7. Additional sewer capacity is required to accommodate the increasing RDII (e.g. a total of 14 pipes must be upsized to accommodate the 2100 Moderate Change and population growth, instead of the six pipes to accommodate the 2100 Population without climate change). The pipes that were upsized are shown in Figure 4.12 to Figure 4.15.

Table 4.9 Summary of Population Growth with Climate Change Scenarios for Case Study 3

Scenario	Number of Pipes > 70% Full by Depth	Number of Surcharged Manholes	Average Pipe Depth Ratio	Number of Upsized Pipes (Total)
Upsized for Population Only				
Current	5	2	0.50	N/A
2050 Moderate Change	2	0	0.53	N/A
2050 High Change	5	0	0.56	N/A

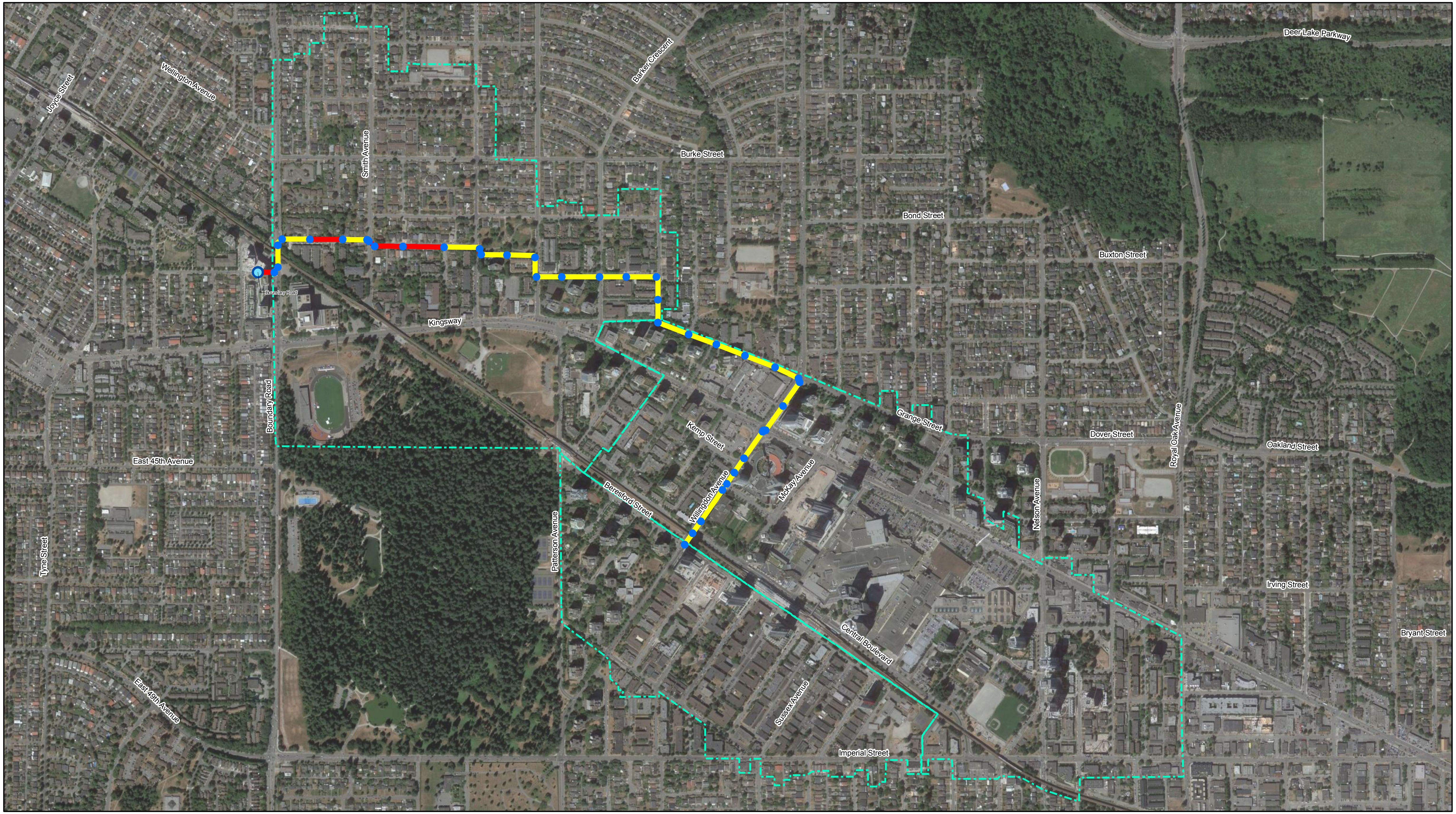
Table 4.9 Summary of Population Growth with Climate Change Scenarios for Case Study 3

Scenario	Number of Pipes > 70% Full by Depth	Number of Surcharged Manholes	Average Pipe Depth Ratio	Number of Upsized Pipes (Total)
Upsized for Population Only				
2100 Moderate Change	11	0	0.60	N/A
2100 High Change	17	0	0.64	N/A
Upsized for Population and Climate Change				
2050 Moderate Change	1 (due to boundary condition)	0	0.53	4
2050 High Change	1 (due to boundary condition)	0	0.55	4
2100 Moderate Change	1 (due to boundary condition)	0	0.58	14
2100 High Change	1 (due to boundary condition)	0	0.59	19

4.3 Costing

Pipe upsizing was performed for the population growth scenarios and the future climate change scenarios. A summary of how many pipes were upsized and the total cost of upsizing is provided in Table 4.10. Note that the summary provides the total number of pipes that were upsized and the total cost associated with upsizing them (not in addition to pipe upsizing for population growth). Some pipes that were upsized to accommodate population growth must be upsized further to accommodate the RDII from the increased rainfall due to climate change. The number of pipes that must be upsized and the total cost to ensure that the system remains less than 70% full by depth has increased relative to the scenarios with population increase only. Note that the pipe leading to Boundary Road (the most downstream pipe in the model) remains 100% full due to the downstream boundary condition adopted in this study.

Preparing for climate change will cost up to an additional $1.5 million on top of upgrades currently needed to maintain levels of service. The incremental cost of choosing the more conservative high change climate scenario is 47% and 42% for 2050 and 2100 respectively. The costs to accommodate the 2050 future climate change rainfall amounts are relatively low: the dry weather flow in the trunk sewer is not very close to the capacity of the trunk sewer. The costs to accommodate the 2100 future climate change rainfall amounts are much higher because the dry weather flow has increased and the trunk sewer is closer to its capacity.



Source: Image ©2017 Google, Imagery date: 2017

0 100 200 300
Meters

Coordinate System:
NAD 1983 UTM Zone 10N

N

Legend

● Outfalls
● Junctions
▭ Subcatchments

Pipe Upsized

🟥 Yes
🟨 No

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PIPES THAT WERE UPSIZED FOR 2050 MODERATE CHANGE RAINFALL FOR CASE STUDY 3
COLLINGWOOD SANITARY TRUNK SEWER

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Dec 20, 2017

FIGURE 4.12

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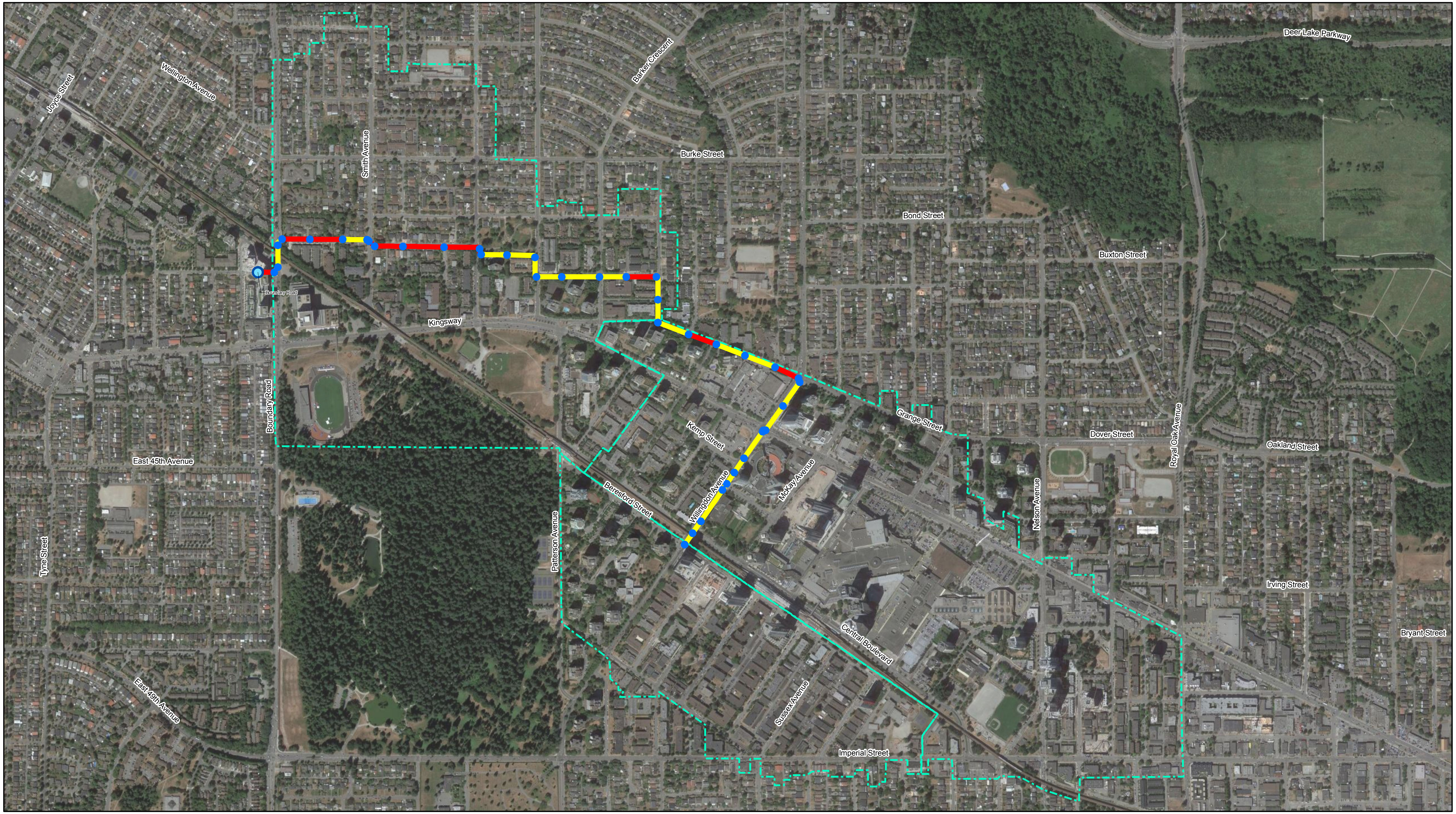

Source: Image ©2017 Google, Imagery date: 2017

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Meters

Coordinate System:
NAD 1983 UTM Zone 10N

Legend

● Outfalls
● Junctions
Subcatchments

Pipe Upsized
Yes
No

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PIPES THAT WERE UPSIZED FOR 2050 HIGH CHANGE RAINFALL FOR CASE STUDY 3
COLLINGWOOD SANITARY TRUNK SEWER

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Dec 20, 2017

FIGURE 4.13

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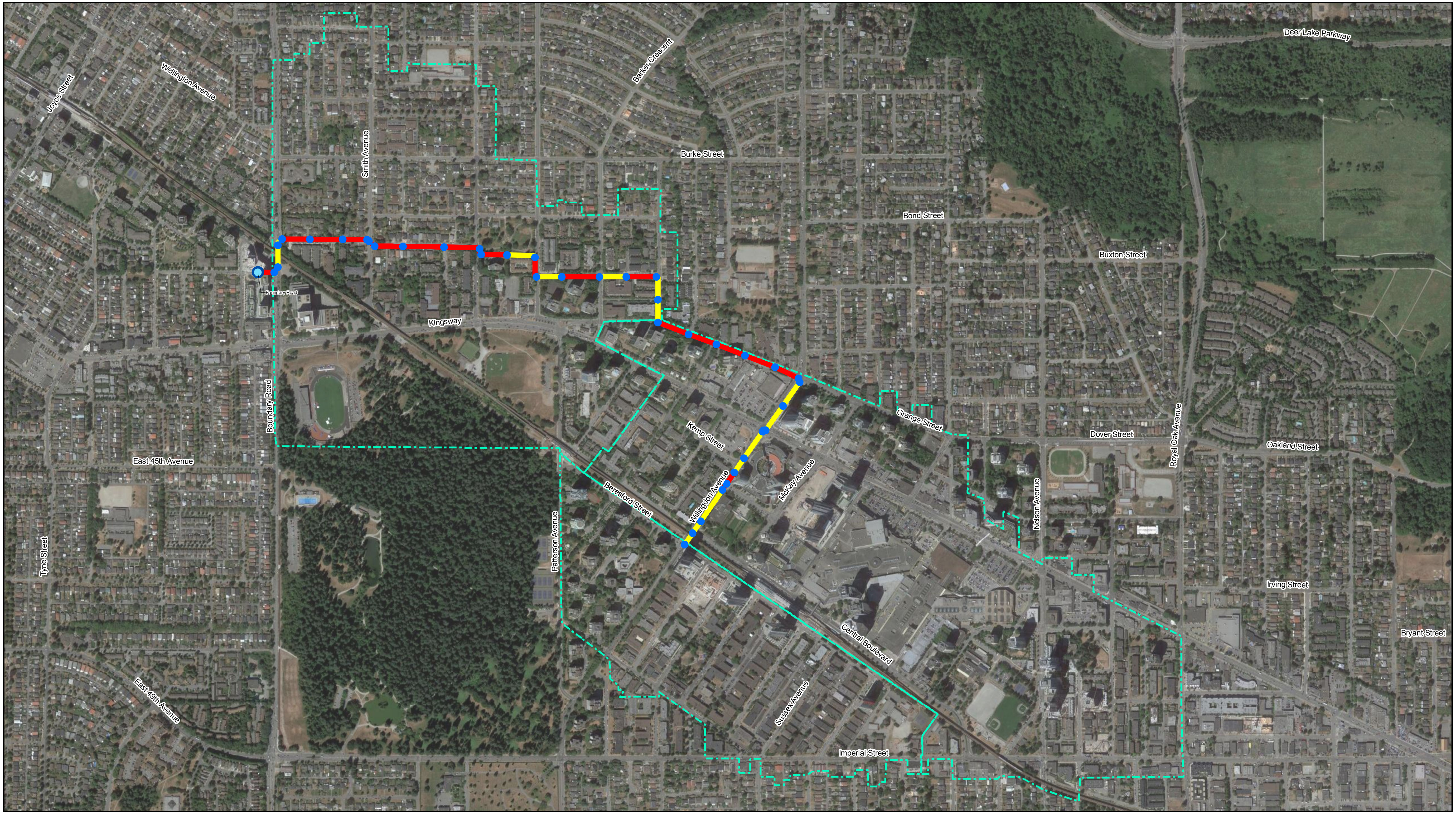

Source: Image ©2017 Google, Imagery date: 2017

0 100 200 300
Meters

Coordinate System:
NAD 1983 UTM Zone 10N

N

Legend

● Outfalls
● Junctions
▭ Subcatchments

Pipe Upsized

🟥 Yes
🟨 No

GHD

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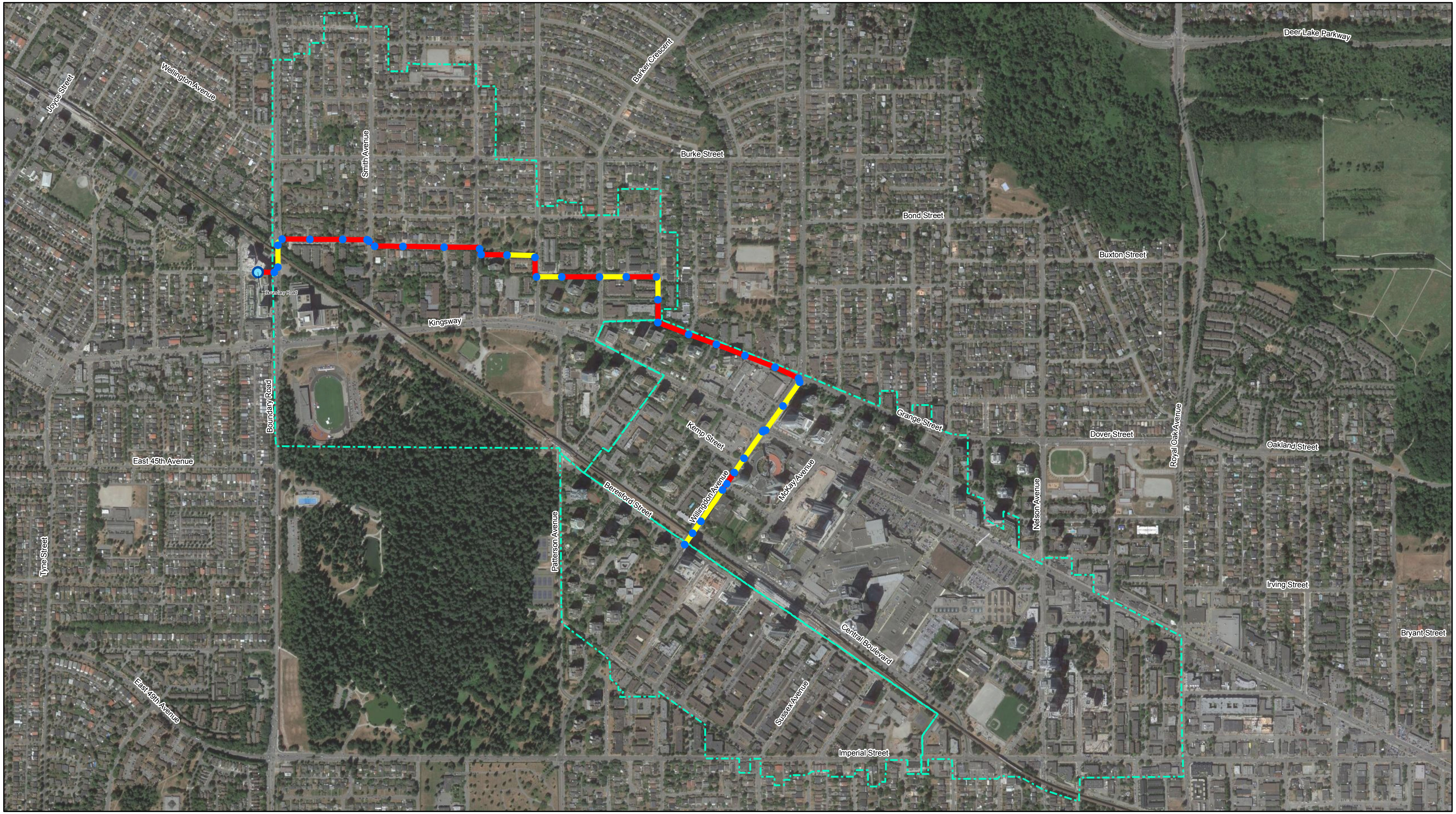
PIPES THAT WERE UPSIZED FOR 2100 MODERATE CHANGE RAINFALL FOR CASE STUDY 3
COLLINGWOOD SANITARY TRUNK SEWER

11140666-01
Dec 20, 2017

FIGURE 4.14

GIS File: Q:\GIS\PROJECTS\11140000s\11140666\Layouts\MEMO004\11140666-01(MEMO004)GIS-WA014.mxd



Source: Image ©2017 Google, Imagery date: 2017

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Meters

Coordinate System:
NAD 1983 UTM Zone 10N

N

Legend

● Outfalls
● Junctions
▨ Subcatchments

Pipe Upsized

🟥 Yes
🟨 No

METRO VANCOUVER
BRITISH COLUMBIA, CANADA

PIPES THAT WERE UPSIZED FOR 2100 HIGH CHANGE RAINFALL FOR CASE STUDY 3
COLLINGWOOD SANITARY TRUNK SEWER

11140666-01
Dec 20, 2017

FIGURE 4.15

GIS File: Q:\GIS\PROJECTS\11140000s\11140666\Layouts\MEMO004\11140666-01(MEMO004)GIS-WA015.mxd

Table 4.10 Summary of Costing for Case Study 3

Scenario	Number of Pipes with Increased Diameter	Estimated Cost ($)	Percent Increase in Cost from Current(%)	Percent Increase in Cost from Moderate to High (%)
2050 Population	4	0.1 Million	N/A	N/A
2050 Moderate Change	4	0.1 Million	1.7	47
2050 High Change	4	0.1 Million	2.5	
2100 Population	6	0.2 Million	N/A	N/A
2100 Moderate Change	14	1.2 Million	413	42
2100 High Change	19	1.7 Million	663	

The costing provided in Table 4.10 is a class D costing estimate. It assumes open cut replacement, which includes asphalt removal, curb removal, removal of soils, removal and replacement of pipe, bedding and compaction, disposal of extra soil, and restoration. It does not include design costs (survey, layout, geotechnical, engineering) or other ancillary costs (insurance, mobilization/travel costs, traffic control, moving utilities, etc.).

In addition to pipe replacement, RDII reduction strategies can also be implemented. Many of the existing pipes are made from concrete, which tends to develop cracks over time and significant RDII can occur. When the pipes are replaced, there will be a reduction in RDII. RDII reductions of 10% to 30% can be achieved by lining/replacing the main trunk sewer alone (Kunay, et al., 2014). In addition, other RDII identification and reduction strategies can also be incorporated (e.g. closed circuit television, smoke testing, dye testing) in the upstream area of the sewersheds to increase the level of RDII reduction.

For this analysis, a conservative RDII reduction was assumed (5% by 2050, 10% by 2100), since only 4 pipes and 15 pipes were upsized to accommodate the population growth to 2050 and 2100, respectively. If the RDII reduction targets are achieved, there would be a decrease in the number of pipes that are greater than 70% full and in the number of surcharged manholes. The maximum pipe depth ratio is between 0.7 and 0.8 (70% to 80% full by depth) for the 2050 scenarios and the 2100 moderate change scenario. These results indicate that with even minor RDII reduction, the trunk sewer only exceeds the design criteria by a small amount. A more detailed analysis should be performed to determine the level of RDII reduction that would be possible. If sufficient RDII reduction can be achieved, the trunk sewer would be able to meet the design criteria and additional pipe upsizing to accommodate the increased RDII due to climate change could be avoided.

Continued monitoring is recommended for the sanitary flow rates at Boundary Road, the effects of climate change on rainfall, and the degree of RDII reduction due to pipe replacement. Additional pipe upsizing may still be required (e.g. if the sanitary flow rates are increasing more than expected and/or the effect of climate change on rainfall is similar to the high change scenarios). Additional pipe upsizing to accommodate RDII is not recommended, as this will lead to oversized pipes for dry weather flow. An RDII reduction program could avoid costs associated with pipe upsizing, which can be used to cover the cost of the RDII reduction program. The RDII reduction program would also improve the functioning of the entire sanitary sewer network (e.g. less RDII flow is delivered to the wastewater treatment plant which would require fewer upgrades to handle the excess flow).

Table 4.11 Summary of Population Growth with Climate Change Scenarios and Inflow and Infiltration Reduction for Case Study 3

Time Horizon and Climate Change Scenario	Inflow and Infiltration Reduction Target[1]	Number of Pipes > 70% Full by Depth	Number of Surcharged Manholes	Number of Flooded Manholes	Average Pipe Depth Ratio	Maximum Pipe Depth Ratio[2]
2050 Moderate Change	5%	6	0	0	0.57	0.72
2050 High Change	5%	11	0	0	0.61	0.78
2100 Moderate Change	10%	10	0	0	0.61	0.76
2100 High Change	10%	13	2	0	0.65	1.00

Notes:

[1] Inflow and infiltration reduction to be performed in conjunction with pipe upsizing to accommodate population growth.

[2] Does not include the pipe leading to Boundary Road, which is surcharged due to the boundary condition adopted in this study.

4.4 Summary of Case Study 3 Results

The level of service for the Collingwood sanitary trunk sewer will be impacted by a combination of increased sewage flows due to population growth and increased RDII due to climate change impacts. For this location, the increased population has the larger impact. The sewage flow will more than double by 2100. The increase in RDII peak flow ranges from 8% to 24%, depending on the scenario (compared to the RDII peak flow for the current rainfall for each time horizon).

Preparing for climate change to 2050 will only result in minor increases in cost (less than $0.1 million). However, the cost increase for 2100 is significant (an additional $1 to $1.5 million). The cost increase for 2050 is minor because the sewage flow is lower and the trunk sewer has additional capacity to accommodate RDII. However, in 2100, the sewage flow is higher and the trunk sewer has very low additional capacity. The incremental cost of choosing the more conservative high change climate scenario is 47% and 42% for 2050 and 2100 respectively. The difference between moderate and high for 2050 is due to different sizes of pipes that are required for the future climate change scenarios. However, for 2100, the additional cost is due to the larger number of pipes that must be upsized.

Pipe upsizing to accommodate the future population growth is sufficient to eliminate flooding from the increased RDII due to climate change, but additional pipe upsizing is required to ensure that pipes are less than 70% full. Depending on the level of RDII, it may be possible to avoid upsizing pipes for RDII (only upsize pipes to accommodate population growth) if the requirement that pipes be less than 70% full by depth is relaxed. In addition, RDII reduction strategies can be applied during the mitigation to accommodate the future population growth. Removing RDII from the network can potentially eliminate the need for additional pipe upsizing. Further monitoring would be required to determine if additional pipe upsizing to accommodate the increased RDII due to climate change impacts would be necessary.

5. Conclusions and Recommendations

Three different types of case studies were evaluated in this TM. The case studies cover combined sewer collection systems, stormwater collection systems, and sanitary systems which are subject to RDII. The purpose of the case studies was to extrapolate from the case studies and develop overall conclusions that may be applied generally in the Metro Vancouver area.

All three case studies have illustrated that the level of climate change impact is case-dependent. For instance, climate change impact may be minor compared to other factors such as population increase. The level of impact may be minor in 2050 but major in 2100, or major upgrades to 2050 and fewer upgrades to 2100. There is no solution that applies to add locations, and detailed analysis will be required for each location.

The Glenbrook combined trunk sewer and separated sewer case study was selected to showcase vulnerabilities of combined sewers. Metro Vancouver is committed to eliminating combined sewer overflows and is in the process of separating all of their combined sewers (Kerr Wood Leidal, 2008). Prior to separation, the combined sewers will experience impacts from a combination of increased sewage flow due to population growth, higher sea level, and increased stormwater flow due to increased rainfall. Following separation, the sewers will experience the increased stormwater flow due to higher sea level and increased rainfall only. From the results of the Glenbrook combined trunk sewer, the following general recommendations can be developed:

- A vulnerability assessment should be used to prioritize the sewer separation. For instance, the combined sewers that are most at risk of capacity issues due to increased sewage flow and increased stormwater flow should be prioritized for separation.
- Population growth appears to be a relatively minor factor for impacting the combined sewer capacity. The projected increases in rainfall (both moderate and high increase) should be considered as the major factor during sewer separation design.
- Increasing the sewer capacity to accommodate the increased rainfall prior to sewer separation may also require increasing the capacity of the diversion weir, which separates the combined sewer flow into DWF and combined sewer overflows, and will be removed as part of sewer separation. Upgrading the diversion weir would be an inefficient use of resources and should be avoided. Upgrading the sewer to handle future flow rates should primarily consider the final (separated) use of the system. Accelerating sewer separation should be considered as an option.

- The separation strategy should account for the future rainfall estimates. The existing combined trunk sewer may not be sufficient to accommodate the increased flow rates due to the climate change. The separation strategy should examine the capacity of the existing combined sewer to handle future rainfall due to climate change.
- Risk analysis principles should be incorporated into the sewer separation strategy to determine whether to design the separated sewer for moderate increase or high increase.
- The selection of the 2050 or 2100 time horizon should be based on the design life. If the end of the design life is between 2050 and 2100, either the closer time horizon could be used or an interpolation between the 2050 and 2100 future rainfall events could be used.

The Port Moody-Coquitlam Drainage Area case study was selected to showcase the vulnerabilities of stormwater drainage systems. The PMCDA was heavily impacted by the increased rainfall and higher sea level associated with climate change. Source controls were investigated as a potential adaptation strategy for the PMCDA. From the results of the PMCDA analysis, the following general recommendations can be developed:

- The rainfall reduction strategy currently in use should be re-examined to include climate change and various AEPs (return periods). At a minimum, the rainfall reduction strategy should require that future peak flows should not exceed current peak flows at a range of AEPs.
- The rainfall reduction strategy should be established based on the characteristics of the area where it will be applied. Factors to be included are: amount of redevelopment expected, watershed characteristics (e.g. infiltration capacity, amount of impervious area, slope, etc.), and capacity of the current drainage system.
- Retrofitting existing lots and/or encouraging private land owners to add source controls on their property should also be considered. However, this will likely have less impact on low AEP events.
- In areas where rainfall reduction strategies cannot be implemented and/or low redevelopment is anticipated, drainage system infrastructure upgrades (e.g. pipe size increases, redirection of flow) should be considered.
- Where the existing drainage system is under-capacity, infrastructure upgrades should be incorporated to address the level of service deficiencies.
- Risk analysis principles should be incorporated when designing the rainfall reduction strategy and the infrastructure upgrades. For instance, the risk of flooding for a main trunk sewer may be greater than the risk of flooding for a collector sewer, and different strategies to address the flooding may be utilized.

The Collingwood sanitary trunk sewer was selected to showcase the vulnerabilities of sanitary sewers. Sanitary sewers will be impacted by a combination of increased sewage flows due to population growth and increased RDII due to climate change impacts. The relative level of impact of each factor will vary from location to location, depending on the projected population growth and the amount of RDII in the sewer.

From the results of the Collingwood sanitary trunk sewer, the following general recommendations can be developed:

- A vulnerability assessment should be used to prioritize the sewer upgrades to accommodate increased sewage due to population growth.
- The capacity of the existing sanitary sewer should be increased to accommodate population growth.
- RDII reduction strategies should be incorporated during sanitary sewer upgrades to accommodate population growth. RDII reduction may avoid the need for additional capacity increases to accommodate future RDII due to climate change (or at minimum, delay additional capacity increases).
- Continued monitoring of sewer flow, climate change, RDII reduction, and other factors is recommended so that planning for additional capacity increases can be performed.
- Risk analysis principles should be incorporated when increasing the capacity of the sanitary trunk sewer to accommodate the future rainfall. For example, there are different levels of risk to designing the sanitary trunk sewer for the moderate or the high increase in rainfall.

The next stage of the project is the development of good practice recommendations. The good practice recommendations will address the use of the different climate change scenarios and time horizons for infrastructure planning and design. They will provide Metro Vancouver with a framework to address climate change uncertainty and incorporate adaptation. Risk management and asset management principles will be incorporated to address the following key questions:

- Should infrastructure be designed for the moderate or the high increase in rainfall?
- What are the risks of designing infrastructure to the 2050 estimates or the 2100 estimates (given the high level of uncertainty)?
- How should be the design life cycle and/or infrastructure rehabilitation and re-use be incorporated into the design?

6. References

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Appendix A

Table Index

Table 1.1 Unit Costs for Pipe Upsizing

Pipe Size (mm)	Material	Unit Cost ($/m)
525 diameter	HPDE	1,241
600 diameter	HPDE	1,323
750 diameter	HPDE	1,480
900 diameter	HPDE	1,687
1050 diameter	HPDE	2,201
1200 diameter	HPDE	2,174
1500 diameter	HPDE	2,887
1800 diameter	Reinforced Concrete	4,220
2100 diameter	Reinforced Concrete	5,249
2400x2100 box	Reinforced Concrete	6,594
3000x2700 box	Reinforced Concrete	10,176
3600x1800 box	Reinforced Concrete	9,918
3600x2100 box	Reinforced Concrete	11,268
3600x2700 box	Reinforced Concrete	14,002
4200x2700 box	Reinforced Concrete	17,252

Notes and Assumptions:

1. The pricing is a Class D Estimate only.
2. Assumed Working Hours: 7am - 5pm, Mon-Fri.
3. Unit Cost Includes: asphalt removal, curb removal, removal of existing pipe, supply and installation of new pipe, bedding and compaction, excess soil disposal, curb and asphalt restoration.
4. No allowance made for Winter conditions in pricing.
5. Assumed that the Contractor will be local to Area.
6. Assumed work will be performed by Non-Union Labour.
7. General Requirements have not been included (insurance, bonding, Mob/Demob, Temporary Facilities, etc.)
8. By-pass pumping of stormwater has not been included in pricing.
9. Carried ADS Sanitite HP pipe for circular pipe 525mm - 1500mm in diameter.
10. Carried 100-D Reinforced Concrete Pipe for 1800mm and 2100mm dia. Pipe.
11. Carried Reinforced Concrete Box Culverts for Rectangular pipe.
12. No allowance to support or move any existing Utilities within the work area.
13. Assumed that native soils are capable of supporting the proposed features, no shoring, piles or over excavation have been carried.
14. No allowance to create haul roads for new work.
15. Density Conversion factor for Granular = 2.4 tonnes/m3.
16. Assumed Density Conversion factor for Existing Soil = 2 tonnes/m3.
17. Assumed all excess material, asphalt, concrete curb will have to be hauled off-site.
18. Assumed the excavated soil is clean and meets approval of clean fill site proposed.
19. No major dewatering carried in pricing.

20. Carried Standard Level D PPE for all works.
21. Pre & Post Surveying and Layout by Others.
22. Geotechnical and Engineering by Others.
23. All Permits, Approvals and Access Agreement by Others.
24. All sampling and testing by Others.
25. Priced in current Canadian Dollars.
26. All Taxes Extra

Technical Memorandum 5
Good Practice Recommendations

Memorandum

August 3, 2018

To:	Lillian Zaremba	Ref. No.:	11140666
From:	Juraj Cunderlik, Greg Munford, Aman Singh, Akeel Ali, Allyson Bingeman/jp/5	Tel:	519-884-0510

Subject: **Study of the Impacts of Climate Change on Precipitation and Stormwater Management Good Practice Recommendations**

1. Introduction

Increased rainfall is expected to result in additional loading to stormwater, sanitary sewer, and combined sewer infrastructure. This will impact the capacity and utilization of this infrastructure which will in turn necessitate adaptation measures to accommodate larger flow rates. The District provides stormwater drainage services to municipalities in two large areas (the Still Creek-Brunette River Drainage Area and the Port Moody-Coquitlam Drainage Area). The municipalities are responsible for the stormwater collection systems and developing stormwater management bylaws. The District is responsible for maintenance of the open channel areas and regional trunk sewers.

The capacity of the combined system is strongly impacted by increased rainfall due to climate change. The District plans to fully separate the combined sewer systems by 2075, however, the impact of the increased rainfall may necessitate earlier separation and/or other adaptation measures. Rain also enters the sanitary-only portion of the sewer network through inflow and infiltration (I&I). I&I will increase as rainfall increases, and affect the capacity of the sanitary-only portion of the sewer network. The decrease in capacity of the sanitary and combined sewer networks due to the increased rainfall has the potential to cause increased flooding, increased sewer backups, increased combined sewer overflows, and less effective wastewater treatment.

As a result, decision makers need better and more accessible climate change information to incorporate changing future conditions into their planning efforts. Project teams also may encounter several expected challenges in trying to find and apply relevant climatic information to planning efforts. New planning approaches and mindsets are needed to take action in the face of uncertainties.

Previous tasks under this Project described a temporal downscaling methodology using global climate model (GCM) data and updated Intensity-Duration-Frequency (IDF) curves. Four future climate change scenarios were derived: 2050 Moderate Change, 2050 High Change, 2100 Moderate Change, and 2100 High Change. Three case studies were used to determine how the projected increases in rainfall will impact sewerage and stormwater drainage in the Metro Vancouver area.

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The District's mandate requires demonstrating innovative, cost-effective, and integrated approaches to identifying, analyzing, and adapting to uncertainty in the future, including climate change, population growth, and land use and how these changes have the potential to affect the District's stormwater, sanitary sewer, and combined sewer infrastructure.

This Memorandum describes good practice recommendations for incorporating climate change data and projections into planning for adaption for storm and sewer infrastructure. The scope of work focuses on addressing the following two key objectives in relation to climate change adaptation:

- Providing a methodology to incorporate climate change data into planning for future climate projections and their associated uncertainty into planning for adaption for storm and sewer infrastructure.
- Providing a framework for strategic planning and decision-making to help the District understand and make decisions regarding the most cost effective asset management strategies to support reliable and efficient storm and sewer operation.

The District will be able to identify how good practice recommendations can be integrated into its maintenance, renewal and capital planning business processes using risk, adaptive planning and asset management approaches. These recommendations will be centered on the adaptive planning process to enable changing risks to the District's business. More importantly, the collection of all activities will help spearhead a climate change culture within Metro Vancouver which can be carried through to multiple areas of the organization.

The Technical Memorandum is organized as follows:

- Section 2 describes the overall framework for incorporating climate change into business processes.
- Sections 3 to 6 describe how good practices can be implemented in the planning, delivery, support services and performance management aspects of operations.
- Sections 7 and 8 provide conclusions and next steps to address uncertainty in climate change planning and decision making.

2. Business Process Framework

Climate change considerations were integrated into the components of a business process framework in order to create a systematic climate change process for GVS&DD. A literature review was conducted to compare other decision making and planning approaches made globally (Appendix A), which contributed to the development of the change process for GVS&DD. This process helps pioneer the improvement of climate change practices and helps spearhead a climate change culture. The framework is illustrated in Figure 2.1. There are four main components to the business process framework:

1. Planning
2. Delivery
3. Support services
4. Performance management

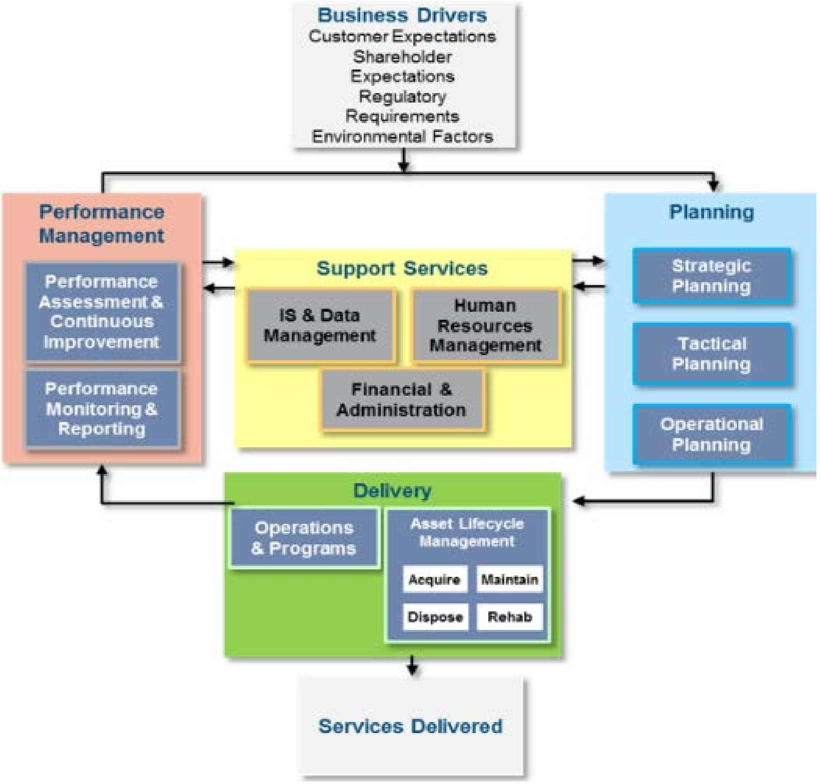


Figure 2.1 Business Process Framework

The recommendations for incorporating climate change considerations in each component of the framework are provided in the following sections.

3. Planning

The first component of planning is to develop a formal Climate Change Policy (CCP). A consistent and comprehensive approach to climate change adaptation will ensure that decision makers are doing the right things on the right assets, at the right cost, at the right time, and for the right reasons. A formal CCP will assist the GVS&DD to remain 'on track' and continue progressing over the long-term timeframe of climate adaptation.

The CCP should be consistent with Metro Vancouver's vision, strategic objectives/plans and other relevant policies. The CCP should also explain how these and other plans and policies apply to the practice of climate change adaptation. The CCP should be approved by senior staff decision makers and the Board. Both approvals are cohesive and needed – but it would be strategic to first gain approval from senior decision makers in order to influence board approval. It should be written in clear and concise language and should include:

- Adherence to relevant statutory requirements;
- Commitment to satisfy relevant strategic policies, objectives and plans;
- The context within which levels of service are set;
- Organization's risk tolerances for climate change
- Commitment to continuous improvement of the approach to climate change adaptation
- Asset management principles that have been adopted, for example: risk based, whole life value, sustainable, customer focused, socially inclusive and integrated

The CCP should be regularly reviewed regularly (every 2-3 years), as well as and after following significant changes to the operational context of the organization. Issues identified should be addressed and changes, where appropriate, should be implemented.

Once the CCP is in place, further planning will be required. A step-by-step framework to follow for planning is presented in Figure 3.1. There are seven main steps in this framework, which will be described in the following sub-sections.

3.1 Set Climate Change Objectives and Level of Service Targets

The first step of the planning and research framework is intended to provide guidance for ongoing development of consistent climate change adaptation practices for all municipalities. The overflow and capacity targets, as well as level of service targets for stormwater drainage and sewerage infrastructure for GVS&DD and its member municipalities are key to ensuring consistent climate change adaptation practices across the Metro Vancouver region. When determining and setting these objectives, it is important to consider the following:

- The relationship between strategic goals, shareholder expectations, and business level of service targets for each asset group are openly discussed and documented.
- Current and future levels of service are defined in measurable terms and are being tracked through specified performance measures.
- Costs for current and future levels of service options are recorded.
- Consultation on desired level of service/cost of service options have been undertaken and an action plan exists for implementing the agreed changes to level of service.

The targets can be both quantitative and qualitative. Information to consider and collect in order to set proposed level of service targets are listed in Figure 3.2.

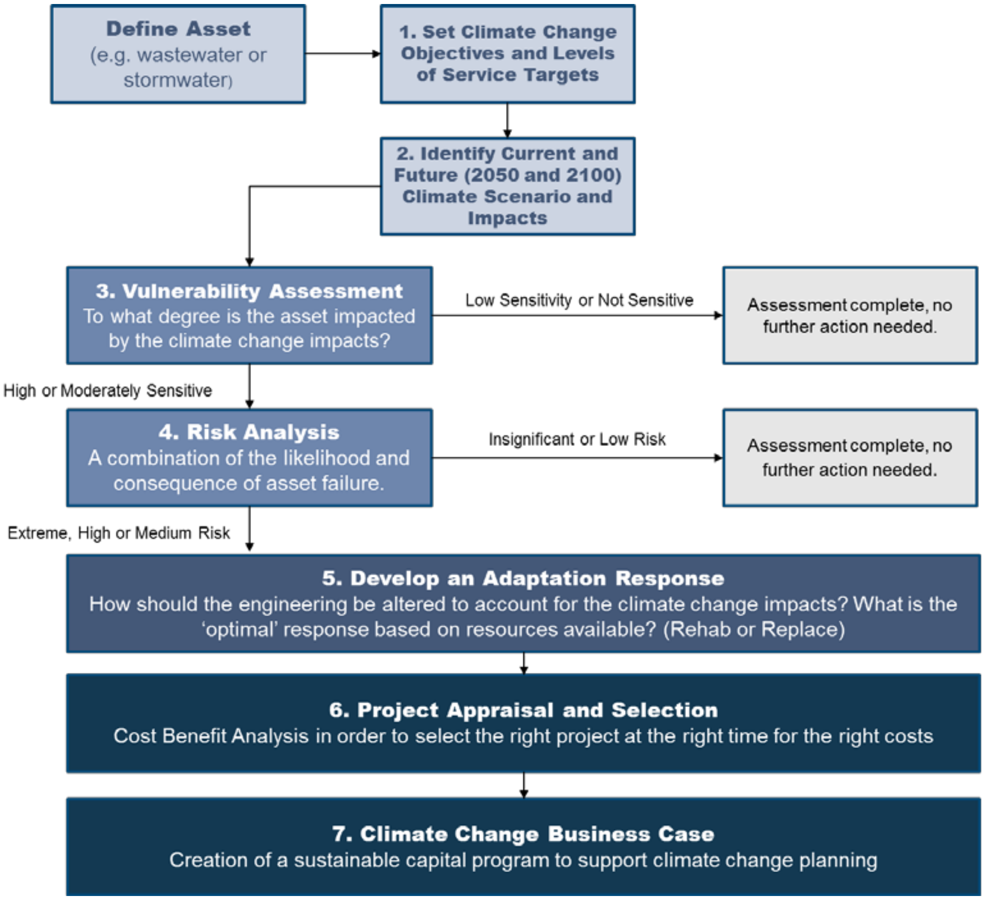


Figure 3.1 Planning Step-by-Step Framework

Storm Sewers

- Flow rates in drainage conveyance infrastructure (channels, storm sewers, culverts)
- Surface water flooding frequency and severity (velocity x depth)
- Property damage to drainage infrastructure, residences, and businesses
- Number and/or cost of insurance claims related to water incurred losses

Combined Sewers

- The number and volume of combined sewer overflows per annum
- The frequency and volume of surface flooding events from manholes
- Property damage to drainage infrastructure
- Number and/or cost of insurance claims related to water incurred losses

Sanitary Sewers

- Frequency of sewer backups
- Relative contribution of I&I in sewer systems
- Capacity of downstream infrastructure such as pumping stations and wastewater treatment plants
- Number and/or cost of insurance claims related to water incurred losses

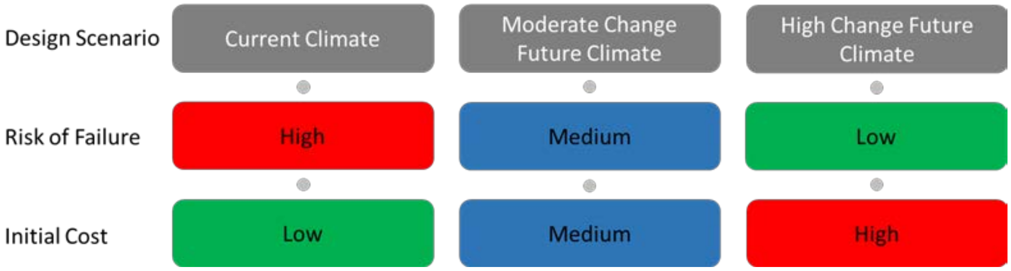
Figure 3.2 Level of Service Examples

3.2 Identify Current and Future (2050 and 2100) Climate Scenario and Impacts

Three approaches for climate change adaptation can be adopted for infrastructure planning and design under climate change uncertainties:

- **Do nothing/Business as usual** | This approach does not consider climate change, and continues to plan and design infrastructure for the current climate.
- **Middle of the road** | This approach uses the most likely future climate scenario, which is characterized by the moderate change future climate IDF curve developed in this project.
- **Worst-case** | This approach uses the extreme future climate scenario, which is characterized by the high change future climate IDF curve developed in this project.

Each approach has an associated risk of failure and adaptation cost (Figure 3.3). If the current climate is used for design, there is a high risk of failure of the infrastructure (insufficient level of service in the future), but the initial cost would be low (e.g., pipes would be smaller and less expensive). If the high future climate is used, there is a low risk that the infrastructure will fail, but it may be cost-prohibitive. The moderate future climate would result in a medium level of risk of failure, and the initial cost would be mid-range.



Design Scenario	Current Climate	Moderate Change Future Climate	High Change Future Climate
Risk of Failure	High	Medium	Low
Initial Cost	Low	Medium	High

Figure 3.3 Design Scenarios and Associated Risk of Failure and Cost

The three approaches are all suitable for different infrastructure planning and design applications. Four future climate scenarios have been developed (moderate and high change for both the 2050 and 2100 time horizons). The appropriate future climate scenario to use for a particular piece of infrastructure is shown schematically in Figure 3.4. The future climate scenario will vary depending on the level of risk due to failure and the planning horizon of the infrastructure.

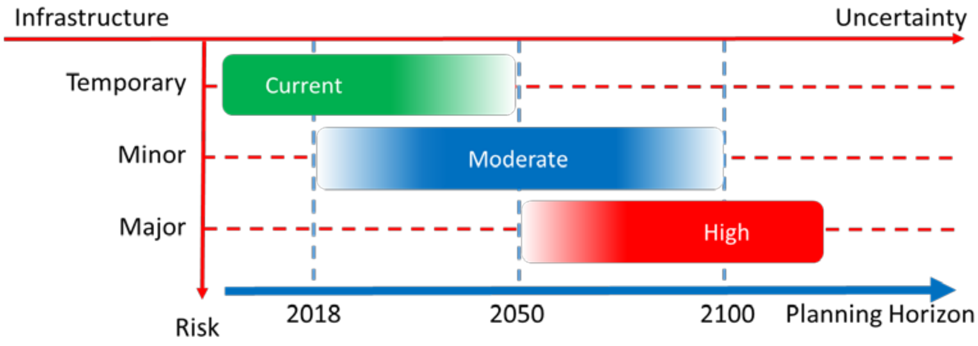


Figure 3.4 Selection of Future Climate Scenarios

The "Do nothing" approach (using the current IDF curve) is appropriate for temporary infrastructure (e.g., temporary water crossings), infrastructure near the end of its design life, or minor infrastructure repairs requiring immediate attention but with a major upgrade already scheduled in the near future. The design life for temporary infrastructure is approximately five years or less. As the planning horizon increases to 2050, the number of projects that use this approach will decrease.

The "Middle of the road" approach (using the moderate change IDF curves) is appropriate for infrastructure with a minor level of risk due to failure. For instance, if flooding were to occur, there would be some, but relatively minor, impacts on property, the environment, and/or human life. Infrastructure with a minor level of risk of failure will most likely have a planning horizon near the middle of the century. As the planning horizon increases, the usage of the moderate change IDF curves will decrease because infrastructure with a longer planning horizon is likely to be more major. However, the moderate change IDF curves can be used for all planning horizons.

The "Worst-case" approach (using the high change IDF curves) is appropriate for infrastructure where the consequences of failure/loss of service are catastrophic (i.e., major infrastructure). Major infrastructure tends to have a longer design life (planning horizon is closer to 2100). As a result, the high change IDF curves will likely be applied only for infrastructure with a planning horizon greater than 2050, and will be likely applied mainly for infrastructure with a planning horizon close to or greater than 2100.

A flowchart describing the selection process for the future climate IDF curve is provided in Figure 3.5. The flowchart provides step-by-step instructions to select the appropriate future climate IDF curve for an infrastructure planning or design project.

3.3 Vulnerability Assessment

Climatic vulnerability is the degree to which a system is affected, either adversely or beneficially, by climate stressors. Vulnerability can be measured in terms of the consequences associated with failure of an asset due to the increased rainfall.

Vulnerability can be measured in terms of the consequences associated with failure of an asset due to the increased rainfall. In some instances, the consequences can be very specific and defined for each sub-component of a large infrastructure system. There are several categories of consequences to consider:

- **Asset Damage:** Damage requiring minor restoration or repair may be considered minor while permanent damage or complete loss of an asset would be considered to be a significantly higher consequence.
- **Financial Loss:** Costs related to third party damages (e.g., basement back-ups), environmental clean-up or fines, and repair or rehabilitation of infrastructure.
- **Loss of Service:** Consequences associated with not meeting demand, conveyance and overflow targets.
- **Health and Safety:** A system serving a large number of people would be of major consequence compared to a system serving a smaller number. Casualties or other acute public health consequences would weigh more heavily.

- **Reputation:** Loss of service, health or environmental impacts may affect the reputation of the utility.

There are several categories of consequences to consider, and Table 3.1 provides examples of detailed criteria to consider for defining the consequence level in each category. These criteria can be adapted by GVS&DD to evaluate the impacts of climate change on their sewerage and stormwater collection infrastructure.

Hazard mapping is a valuable tool for understanding vulnerability to climate change. Hazard mapping integrates multiple types of information. Climate change data, hydrologic and hydraulic models, sewerage and stormwater collection capacity data, and operational data provide information regarding hazards (e.g., flooding, combined sewer overflows, etc.). The locations of sensitive areas (e.g., schools, ecologically sensitive areas) are also included in the hazard mapping, which then provides a visual summary of the interactions and interdependencies between infrastructure and facilities.

Table 3.1 provides a generic listing of detailed criteria to consider for defining the consequence level in each consequence category. These criteria can be adapted to suit the needs of GVS&DD when evaluating the impacts of climate change on their sewerage and stormwater collection infrastructure. Each organization will have a unique consequence table that focuses impacts and threshold limits that align with its risk threshold limits or appetite. Infrastructure with low vulnerability do not need to be examined further.

Table 3.1 Generic Consequence Table for Climate Change Impacts

Consequence Level	Asset Damage	Financial Loss	Loss of Service	Health and Safety	Reputation
Catastrophic	Permanent damage and/or loss of infrastructure	Above $10M	Disastrous service loss (for more than a day)	Potential for death(s) or probable permanent damage	Major ethics issue for multiple employees, major impacts to image
Major	Extensive infrastructure damage requiring repair	Up to $10M	Major service loss (less than a day)	Potential for serious injury(ies) with a possibility of loss of a life	Major accountability, minor ethics impacts to image
Moderate	Damage recoverable by maintenance and minor repair	Up to $5M	Service loss or major quality of service concern for critical users	Potential for serious injury or affects to health. disability	Minor accountability, minor impacts to image
Minor	No permanent damage, some minor restoration work required	Up to $625K	Reduced quality of service or service loss for critical users for less than an hour	Potential for minor injury to an individual. Full recovery is expected	Major communications issues impacting image

Table 3.1 Generic Consequence Table for Climate Change Impacts

Consequence Level	Asset Damage	Financial Loss	Loss of Service	Health and Safety	Reputation
Insignificant	No Infrastructure damage	Up to $125K	Reduced quality of service or service loss for few residents	No obvious potential for injury or affects to health	Minor communications issue impacting image

3.4 Risk Analysis

Formal risk analysis is used to combine the consequence of failure with the likelihood of failure of the asset. The risk analysis will categorize each infrastructure asset according to risk levels, as shown in Table 3.2.

Table 3.2 Risk Assessment - Likelihood and Consequence Matrix

	Consequence				
Likelihood	Insignificant	Minor	Moderate	Major	Catastrophic
Rare	Low	Low	Low	Low	Moderate
Unlikely	Low	Low	Moderate	Moderate	High
Possible	Low	Moderate	Moderate	High	Extreme
Likely	Low	Moderate	High	Extreme	Extreme
Almost certain	Moderate	High	Extreme	Extreme	Extreme

Risk based planning focuses on minimizing the risk associated with the asset through an appropriate intervention strategy, while ensuring that any risks are managed at the minimum cost. As seen in Figure 3.5, risk management is about finding the "sweet spot" between expected value and risk tolerance levels. For example, excessive risk taking would be choosing to upsize little or no pipes within the system to plan for surcharging, while insufficient risk taking would be deciding to upsize all pipes within the system.

Figure 3.5 Optimal Risk Taking Illustration

3.5 Prioritizing an Adaptation Response

The level of risk of an infrastructure asset will determine its priority for adaptation (Figure 3.6). For infrastructure that is categorized as an extreme risk, adaptation measures should be implemented immediately. As the level of risk decreases, the priority of the adaptation measures also decreases. Low risk infrastructure should be maintained by the current programs and strategies (i.e., the status quo).

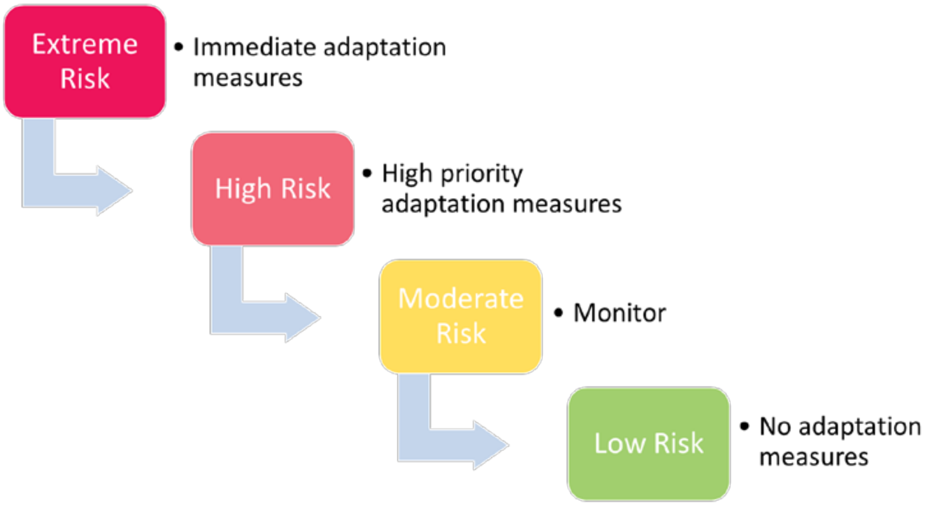


Figure 3.6 Prioritization of Adaptation Measures

A range of adaptation measures to mitigate risk of failure from increased rainfall should be investigated for each type of infrastructure. Selecting the right adaptation measures can be determined by the level of risk of the asset, a cost-benefit analysis, and/or by examining individual capabilities and resourcing. Table 3.3 highlights various adaptation measures that can be considered for stormwater and sewerage collection infrastructure.

Multiple strategic approaches for both current and new infrastructure assets should be considered in response to asset risk from increased rainfall in the future climate change scenarios (Table 3.4). Each approach is associated with certain risk levels and there are advantages and disadvantages for each method. However, the strategic approach for a particular infrastructure asset should be selected on a case-by-case basis.

Table 3.3 Stormwater and Sewerage Infrastructure Adaptation Measures

Asset Type	Adaptation Measures
Stormwater Infrastructure	• Conserve naturally functioning ecosystems to reduce stormwater runoff • Encourage Green Infrastructure/Low Impact Development (GI/LID) • Implement best stormwater practices • Add peak flow storage • Add an overland flow path and use the storm sewer for minor flows only • Maintain current level of service • Upsize pipes/culverts • Rehabilitate/upgrade part-way through the design life
Sewerage Infrastructure	• Reduce RDII • Add peak flow storage • Accept full pipes if hydraulic grade line is more than 1.8 m below ground • Allow surcharging (sealed manholes) • Upsize pipes • Private measures such as backwater valve requirements, pumps or other controls to prevent backflow into basements • Upgrade pump stations and wastewater treatment plants to increase resiliency

Table 3.4 **Strategic Approaches for Existing and New Infrastructure Assets**

Strategic Approach	Existing Infrastructure	New Infrastructure	Advantages	Disadvantages	Recommended Risk Level(s)
Harden and Protect	• Rehabilitate and reinforce • Add supportive or protective features • Incorporate redundancy	• Use more resilient materials, construction methods, or design standards • Design for greater capacity or service	• Easy to implement and justify • Demonstrates proactive adaptation	• More costly • Risk of overdesign of infrastructure	• Extreme • Very High
Accommodate and Maintain	• Extend, strengthen, repair or rehabilitate over time • Adjust Operation and Maintenance	• Design and build to allow for future upgrades, extensions or regular repairs	• Less costly • Flexible – can be adjusted over time	• Requires monitoring • May need frequent repairs	• Moderate
Accept or Decommission	• Keep as is, accepting diminishing level of service or performance	• Construct based on current climate, accepting possibly diminished levels of service of performance	• No upfront costs	• Lower level of service	• Low • Very Low

3.6 Project Appraisal and Selection

Once a range of possible adaptation options has been identified, the options should be prioritized to create a shortlist of the most appropriate options for implementation. A number of decision-making approaches are available:

- **Best Judgement:** Utilizes engineering judgement only and does not include detailed analysis and justification.
- **Cost-Benefit Analysis:** Quantifies and assesses intervention costs against economic benefits such as improved safety and reduced risk of service disruptions to enable selection of the "best" option to close a performance gap. This option is preferred when costs and benefits can be quantified.
- **Multi-Criteria Analysis:** Prioritizes competing adaptation options where benefits and costs are less tangible to define. A number of criteria are selected that align with climate change objectives. A weighting to demonstrate the relative importance of these factors is selected from an overall score. This option is preferred when costs and benefits cannot be quantified. The approach to develop a multi-criteria based decision-making process is based on a four-step process (see Table 3.5).

Table 3.5 Multi-Criteria Analysis Decision Making Process

Step	Description
1. Select the decision criteria or indicators for evaluating the business cases	Leverage triple bottom line criteria/indicators that are consistent with GVS&DD’s climate change adaptation goals. These criteria/indicators will reflect economic, social and environmental considerations.
2. Identify and assign a weighting to each indicator	Develop weighting factors for the multi-criteria criteria/indicators using established techniques such as single/multi-tier weighting criteria, the ‘pair wise’ method, etc.
3. Assess the indicator value for each business case	Test that the weightings are appropriate with sensitivity analysis. Run scenarios through the MCA multiple times, varying the score for one indicator from lowest to highest to identify how much variance this causes in the outcome score, and repeating this for each indicator.
4. Set minimum thresholds and calculate the overall results	It may be necessary to set minimum levels for some indicators, as poor performance in one indicator may be hidden by good performance in other indicators when combined in the multi-criteria analysis. Minimum thresholds can be utilized to correct this issue. An option that does not meet the minimum threshold requirement, irrespective of how well it scores in the other indicators, is not a recommended option. The multi-criteria decision-making process can then be used to select the preferred alternative.

3.7 Climate Change Business Case

After adaptation projects have been shortlisted, it is recommended to develop a business case for climate change adaptation funding. Once the business case is developed and accepted, Metro Vancouver should initiate a 10-year capital program for projects that address all risks associated with stormwater, sanitary and combined sewer systems. Initially, the highest risk infrastructure will have the highest priority for climate change adaptation. As climate change adaptation continues, the prioritization of climate change adaptation projects will shift towards lower risk infrastructure.

The capital program should consist of all climate change related projects identified for the next 10 years and be organized around the funding allocation categories. GVS&DD should demonstrate the impact of funding on risk reduction. This process will naturally prioritize the higher-risk infrastructure, and consider lower risk infrastructure as budgetary constraints allow.

4. Designing for Future Climate

As climate change progresses, rainfall intensity and frequency will increase, and design practices should be updated – it is imperative to consider climate change as part of design. The climate change adaptation design process is shown in Figure 4.1. The future climate IDF curve must be selected based on risk and design life. An additional climate change factor that must also be considered is the future sea level (e.g., for infrastructure discharging to the ocean or rivers affected by sea level rise). The climate change factors must then be considered with other factors that are typically included in infrastructure design (e.g., population growth, land use change, catchment area, etc.). Incorporating climate change explicitly in the design will enable GVS&DD to plan and build resilient infrastructure and facilities.

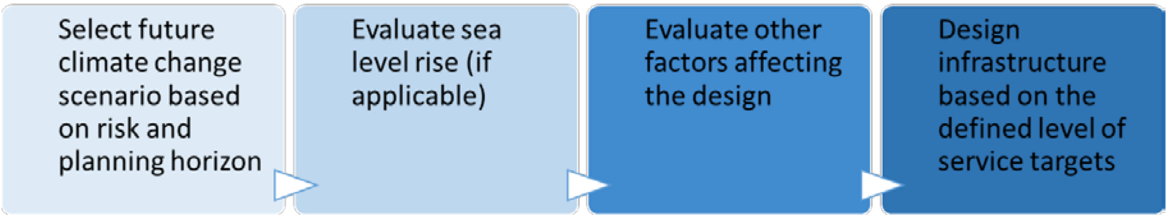


Figure 4.1 **Climate Change Adaptation Design Process**

It is important to consider that sewerage and stormwater collection infrastructure are part of a networked system. An integrated planning process should be utilized, which balances the needs of the infrastructure across the network and explicitly includes climate change with the other design factors. As part of the integrated planning process, it is also important to review the presence of people, businesses, schools, emergency services, environmentally sensitive areas, and other key features that are located in the area serviced by the infrastructure, which could be adversely impacted in the event of the loss of service of the infrastructure.

The performance of the network should be optimized. For example, increasing the capacity of a pipe to accommodate increased rainfall may be suitable at the current location, but upsizing the pipe may cause downstream capacity issues (e.g., flooding, insufficient capacity at pump stations, etc.). To optimize the level of service for the network, multiple adaptation measures should be considered (e.g., upsizing, stormwater detention pond, RDII reduction, increasing downstream capacity, etc.) to avoid downstream capacity issues. An optimized network approach considers all possible adaptation measures, and selects the option that minimizes adverse impact on the level of service of the entire network.

It is important to consider that the regulatory framework should be adapted to incorporate climate change impacts. By-laws, design standards and guidelines, and other regulations should be adjusted/modified to support climate change adaptation. Level of service targets used in the past may no longer be sufficient to accommodate adaptation to climate change. A stormwater example and two sewerage examples were identified in this project. A thorough review of the regulatory framework is recommended.

The current stormwater source control guidelines will need to be updated to support climate change adaptation. The guidelines are currently based on a rainfall reduction target for the 50% AEP, 24-hr design storm (Metro Vancouver Stormwater Source Control Guidelines, 2012). This will be insufficient to maintain the level of service, because the amount of runoff will increase with the future climate change rainfall. The stormwater reduction targets should be updated to account for both climate change and lower AEP storm events. The goal should be (at a minimum) for the proposed conditions peak flow to not exceed the current pre-development peak flow for a range of AEPs (e.g., 50% to 1% AEP). The proposed conditions should utilize the post-development conditions (future population, land use, etc. after development) and the future climate IDF curve. The existing conditions should utilize the pre-development conditions (existing population, land use, etc. before development) and the current IDF curve (Figure 4.2).

Existing	Proposed
• Pre-development conditions • Current rainfall • 50% AEP to 1% AEP	• Post-development conditions • 2050/2100 Moderate rainfall • 50% AEP to 1% AEP

Figure 4.2 Minimum Proposed Climate Change Stormwater Source Control Guideline

The proposed stormwater source control guideline represents a significant increase in the requirements for stormwater reduction. The proposed guideline may not be achievable in all cases but it should be noted that the level of service will degrade over time where it cannot be achieved. In addition, the target may need to be adjusted depending on watershed-specific characteristics, level of redevelopment, current level of service, and other factors. Further, the stormwater source control may be too stringent in that current flows may be restricted so that minimum flows are not achieved in the watercourses. Options to maintain water quantity and quality in the watercourses should be considered (e.g., plan to rehabilitate/upgrade part-way through the design life). Retrofitting source controls onto existing properties should also be encouraged, but the effectiveness of the retrofitted source controls will be limited by the existing conditions at the site.

The current wastewater design guidelines will also need to be updated to support climate change adaptation. The Rawn Criteria have been used historically in the design of sanitary sewers, which specify a constant RDII allowance. Some parts of the Metro Vancouver region have specified a higher RDII allowance or an allowance based on a 20% AEP event (e.g., City of Burnaby, 2014). However, there are areas in Metro Vancouver with RDII higher than the amount specified in the guidelines. In the future, it may be appropriate to consider adding a provision regarding a maximum RDII allowance based on proportion of the sewage flow. Where the existing sewers experience RDII greater than the maximum RDII allowance, RDII reduction should be mandated as part of the sewer system upgrades. This would result in an overall improvement of the condition of the sewerage collection network.

A second part of the wastewater design guideline that should be examined is the design criteria for the sanitary sewers. Some guidelines specify a maximum flow depth during wet weather in the sewer (e.g., City of Burnaby, 2014). As climate change progresses, the flow rate will increase, and pipe upsizing will be required to satisfy the design guideline. However, this could result in pipes that are oversized for the sanitary sewage flow. An alternate design guideline could specify that the maximum hydraulic gradeline in the sewer would be more than 1.8 m below the ground surface to reduce the risk of basement flooding. This could optimize climate adaptation resources.

5. Support Services

The necessary climate change skills and competencies (including proficiency levels) should be defined and a training program should be in place to deliver these skills to staff (together with refresher training as necessary). There should also be processes in place to manage and implement climate change adaptation related change throughout the business and to review whether the appropriate skills and staff numbers are available for implementing adaptation plans.

A knowledge management strategy should also be developed for the organization's knowledge on climate change adaptation. An effective knowledge management strategy should focus on the following questions:

- What knowledge needs to be captured? (e.g., rainfall data)
- Who is keeping up to date on climate change science?
- Who is tracking the innovations of adaptation practices locally, federally and globally?

- Who is keeping track of the financing of climate change adaptation projects?
- How will knowledge be organized and secured?
- How will the risks associated with ongoing knowledge gaps be addressed?

This initiative will provide organizational resiliency and long-term sustainability of the management of the sewerage and stormwater collection assets. The initiative also supports access to accurate and current asset knowledge and reduces the risk of knowledge loss to the organization.

Currently, climate change tasks are being done "ad hoc" at GVS&DD and are assumed within job descriptions of staff members. GVS&DD should formalize roles within job descriptions, organizational hierarchies (i.e., climate change champions) and identify specific responsibilities related to climate change. In addition, succession planning should be in place so climate change knowledge and initiatives do not diminish over time as staff roles shift and change.

A data and knowledge rich organization proactively uses and manages both hard performance data and broad knowledge of systems to create value for customers through decision-making. It is especially important to efficiently manage climate change data as it is constantly being updated and changed as uncertainties unfold.

There is a significant amount of data to collect as part of climate change adaptation (Figure 5.1), including both observed data (e.g., monitoring rainfall) and projected climate data (e.g., GCM predictions). It is especially important to efficiently manage climate change data. Continued monitoring of key climate variables (such as rainfall and sea level), the existing level of service of infrastructure, and climate change research is recommended.

Thresholds should be established to trigger changes to climate change adaptation. Thresholds to set may include the following:

- Changes to rainfall intensities (e.g., statistically significant increasing trends) could be used to trigger the development of new IDF curves.
- Changes to sea level and/or other climatic factors could be used to trigger changes to GVS&DD's approach to climate change adaptation.

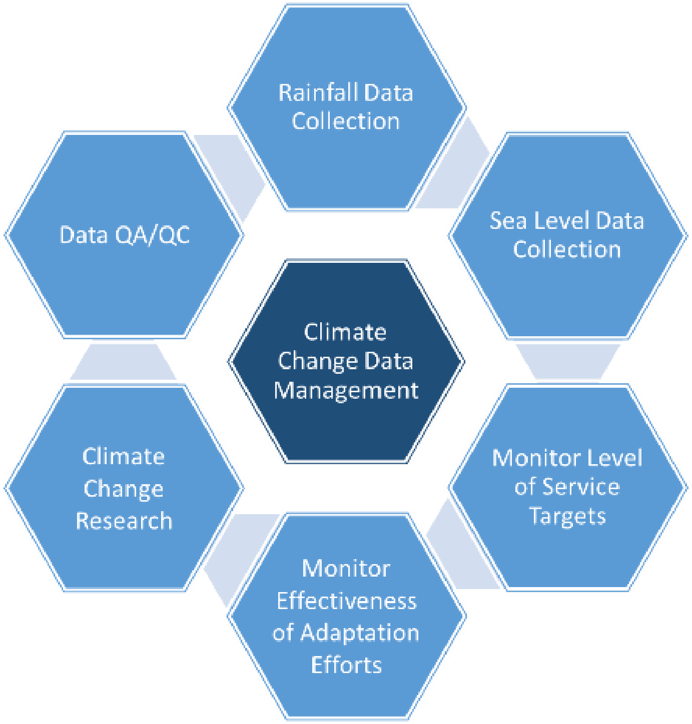


Figure 5.1 Data Collection for Climate Change Adaptation

- If the level of service of infrastructure is decreasing, it indicates that climate change adaptation efforts are not working effectively and/or that climate change is progressing more rapidly than anticipated. The reason(s) for the decrease in level of service should be discovered and the approaches to climate change adaptation should be altered (for instance, a greater level of climate change adaptation).
- As climate change science progresses, it may be necessary to generate new future climate IDF curves. For instance, when the sixth assessment report of the IPCC is published (due in 2021), it may contain new climate change scenarios with differences in climate change projections.
- Other external factors (e.g., changes in federal/provincial guidelines, the insurance sector or climate change legal liability) may also act as triggers to review and modify the GVS&DD's strategic approach to climate change adaptation.

6. Performance Management

GVS&DD should establish, implement, and maintain processes for identifying opportunities and assessing, prioritizing and implementing actions to continually improve their climate change adaptation practices. Continual improvement should be regarded as an iterative activity.

In order to track continual improvement, GVS&DD should consider conducting an annual audit that examines:

Seek and acquire new climate change adaptation practices

- A “snapshot” report of current performance
- Comparisons among parts of the network, identifying the strongest and weakest parts
- Trend analysis showing how performance has changed in different parts of the network
- Predictive analysis showing how condition and performance might change in the future

7. Conclusions and Recommendations

The conclusions and recommendations regarding incorporating climate change into the GVS&DD’s business planning framework are presented below.

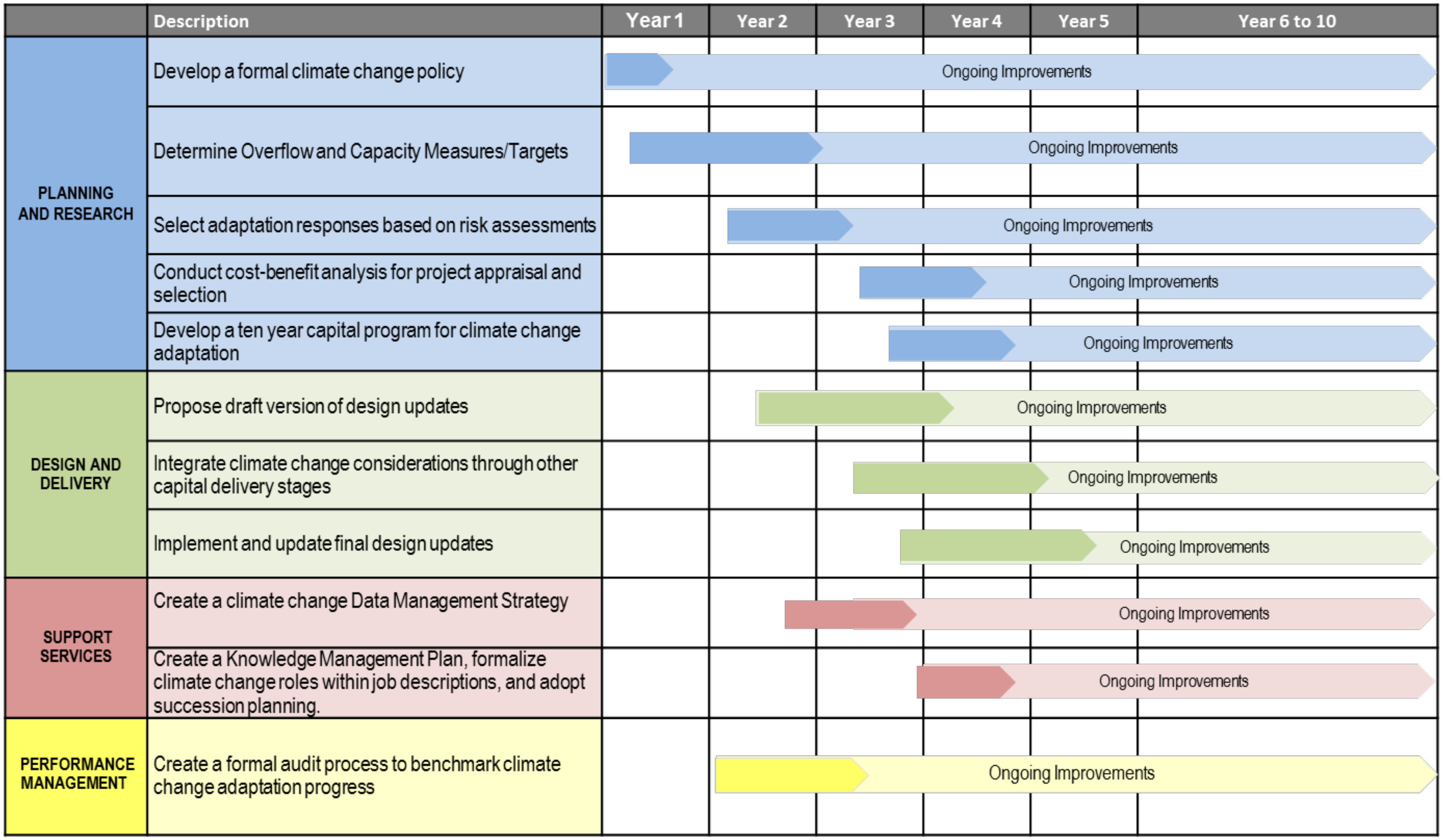
- Currently no 'gold standard' exists for climate change adaptation planning for sewerage and stormwater collection assets.
- It is important to aim and strive to create a climate change culture across all components of the organization’s business process.
- A formal CCP should be developed and adopted to guide the progress of climate change adaptation and ensure consistency and completeness. The CCP should incorporate climate change adaptation into the business process framework.
- Climate change objectives and level of service targets must be established. This is a basis for future climate change adaptation.

- The regulatory framework (by-laws, design standards and guidelines, and regulations) will need to be adjusted/modified to support climate change adaptation. The stormwater source control guidelines will need to be stricter to maintain current levels of service. The wastewater design guidelines will need to be updated to encourage or require RDII reduction and ensure that pipes are not oversized due to increased RDII. A thorough review of the regulatory framework is recommended.
- A vulnerability/risk assessment should be used to prioritize network upgrades. The assessment should include: current level of service, future level of service, and consequences of failure (e.g., financial/environmental/social impact of flooding). Higher risk areas should be upgraded earlier. It may be necessary to accept a lower level of service or maintain the current level of service for lower risk areas.
- There are three approaches for climate change adaptation: Do nothing (business as usual), Middle of the road, and Worst-case. There are applications for all three approaches.
- The moderate change scenario is considered "most likely", while the high change scenario is considered "worst-case". For most applications, the moderate change scenarios are acceptable, but for high-risk infrastructure the high change scenario should be used.
- The selection of the 2050 or 2100 time horizon should be based on the planning horizon. If the planning horizon is between 2050 and 2100, either the closer time horizon should be used or an interpolation between the 2050 and 2100 future rainfall events should be used.
- Design practices should be updated to explicitly incorporate climate change with an integrated planning approach. The following factors should be incorporated: future climate IDF curves, population growth, land development or redevelopment, sea level rise, level of service requirements, and other factors as appropriate. Explicitly incorporating climate change with the other design factors is necessary as part of planning and building resilient infrastructure.
- There are multiple types of infrastructure upgrades that can be used to address capacity concerns. There are also different ways to stage the infrastructure upgrades. An "optimized network approach" will consider multiple adaptation measures and select the option which minimizes adverse impact on the level of service of the entire network.
- Knowledge management gaps exist as climate change tasks are assumed within staff job descriptions. GVS&DD should formalize climate change adaptation tasks through training, succession planning, and formal roles with job descriptions.
- It is important to have a data management strategy in order ensure that climate change data are being recorded, used, and updated when appropriate. Threshold values should be set to trigger further climate change adaptation.
- The GVS&DD should continually track their climate change adaptation progress.

8. Next Steps

A number of recommendations have been provided for GVS&DD to develop adaptation practices and incorporate climate change into infrastructure planning and design. Current competencies exist within the organization, however multiple gaps must be filled to successfully plan for an uncertain future. As GVS&DD proactively addresses these gaps, adopting consistent approaches across the Metro Vancouver region would help create a regional climate change 'culture'."

Based on the good practice recommendations, a roadmap has been prepared to help GVS&DD achieve a well-executed climate change adaptation planning process (Figure 8.1). The roadmap has been set up as a ten-year plan. The first five years are instrumental in developing the plan, so that the plan can be implemented in years six to ten.



	Description	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6 to 10
PLANNING AND RESEARCH	Develop a formal climate change policy				Ongoing Improvements		
	Determine Overflow and Capacity Measures/Targets					Ongoing Improvements	
	Select adaptation responses based on risk assessments					Ongoing Improvements	
	Conduct cost-benefit analysis for project appraisal and selection						Ongoing Improvements
	Develop a ten year capital program for climate change adaptation						Ongoing Improvements
DESIGN AND DELIVERY	Propose draft version of design updates					Ongoing Improvements	
	Integrate climate change considerations through other capital delivery stages						Ongoing Improvements
	Implement and update final design updates						Ongoing Improvements
SUPPORT SERVICES	Create a climate change Data Management Strategy						Ongoing Improvements
	Create a Knowledge Management Plan, formalize climate change roles within job descriptions, and adopt succession planning.						Ongoing Improvements
PERFORMANCE MANAGEMENT	Create a formal audit process to benchmark climate change adaptation progress					Ongoing Improvements	

Figure 8.1 Data Collection for Climate Change Adaptation

9. References

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Appendix A

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1. Literature Review

1.1 Greater Vancouver Sewerage & Drainage District: Progress on Adaptive Planning

The Greater Vancouver Sewerage and Drainage District (GVS&DD) has undertaken a number of initiatives to prepare for and adapt to climate change. Metro Vancouver is currently in the process of releasing a climate change strategy that will provide a clear objective and vision of how it plans to tackle climate change from today to 2050. The major vulnerability for future liquid waste infrastructure planning has been identified as flooding – thus causing the need to achieve desired capacity metrics. Targeted impacts have been defined up to 2050. Extreme rainfall events are expected to intensify with 63% more rain projected for extremely wet days. This could lead to:

- Increased surface water flooding
- Sewer back-ups
- Combined sewer overflows

Metro Vancouver has been proactively taking measures to research and plan for adaptive measures for climate change. Within the past ten years, the following initiatives have stood out as Metro Vancouver is taking steps to assess tipping points:

- Vulnerability of Vancouver Sewerage Area Infrastructure to Climate Change (2008)
- Infrastructure Vulnerability to Climate Change – Fraser Sewerage Area (2009)
- Climate Change 2050 Adjusted IDF Curves, Metro Vancouver Climate Stations (2009)
- Regional IDF Curves, Metro Vancouver Climate Stations: Phase 1 (2009)
- Climate Change Adaptation Risk Management Study (2010)
- Climate Adaptation Environmental Scan and Gap Analysis (2015)
- Impacts of Climate Change on Precipitation and Stormwater Infrastructure (2018)

GVS&DD has a list of future projects to initiate related to adaptation of infrastructure due to climate change. They are currently using the International Council for Local Environmental Initiatives (ICLEI) Building Adaptive & Resilient Communities (BARC) process as a platform for strategic planning and decision making. A detailed illustration of the BARC process is provided in Figure 1.1 below.

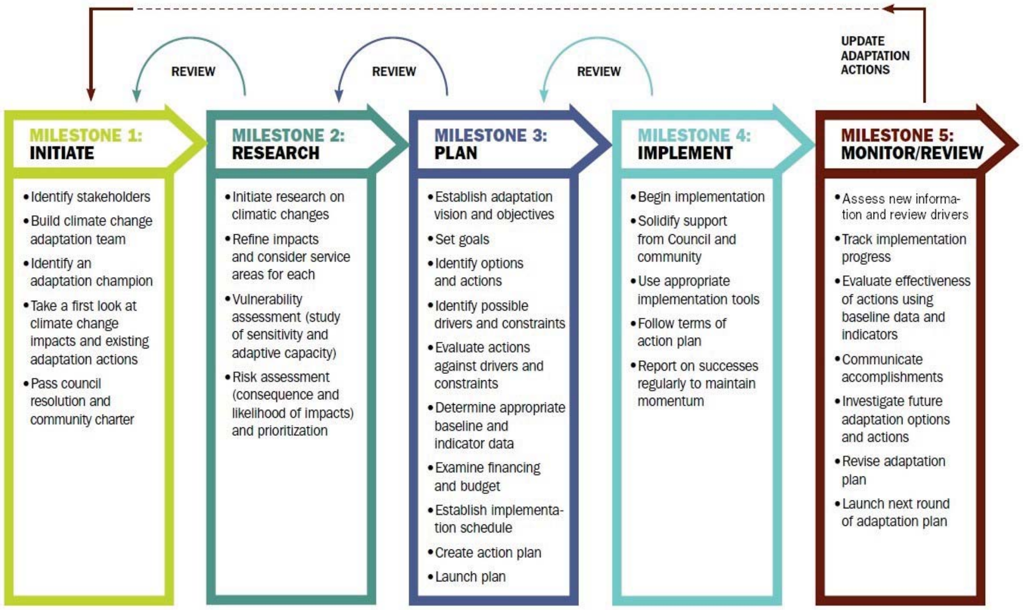


Figure 1.1 ICLEI BARC Framework (Murdock, 2012)

GVS&DD has been participating in ICLEI BARC since 2011, and completed the second milestone of the process in 2012. The BARC methodology provides a straightforward approach to adaptation planning using a five-milestone framework. Each milestone represents a fundamental step in the adaptation planning process, starting with the initiation of adaptation efforts (by building an adaptation team and identifying local stakeholders) and culminating with a monitoring and review process that analyzes the successes and reviews the challenges of the adaptation plan and its implementation. While each milestone builds off the findings of the one before, the methodology as a whole is meant to be iterative and creates opportunities to evaluate and review findings and decisions throughout the creation and implementation of a Local Adaptation Plan. Metro Vancouver is aiming to launch its Climate 2050 integrated climate action strategy in 2018, which is similar to milestone three of BARC. An adaptation plan specific to GVS&DD's liquid waste function may begin development in 2019. The next step in the BARC process which Metro Vancouver aims to achieve is milestone four, “Implement” - which aims to explore and select adaptation responses.

GVS&DD has not yet completed any substantial work in prioritizing projects yet. A list of projects have been compiled to address climate adaptation for infrastructure, however, no formal strategic plan or cost-benefit prioritization has been initiated. Understanding and accommodating stakeholder preferences can be demonstrated through the following initiatives:

- An engagement of multiple staff members (20) participating in the Climate Change Adaptation Risk Management Study for GVS & DD.
- A Survey for Climate Change Adaptation Environmental Scan and Gap Analysis which included 21 contacts from local government, 34 contacts from non-governmental organizations (NGOs) and 13 contacts from public authorities.

1.2 City of Vancouver: Climate Change Adaptation Strategy (2012)

The development of the City of Vancouver's (City) Climate Change Adaptation Strategy followed the ICLEI "Changing Climate, Changing Communities" guide loosely. The City worked with the Pacific Climate Impacts Consortium to acquire a detailed understanding of anticipated changes to the regional climate. Using these climate projections, impacts to the City were identified through interviews with general managers and working group meetings. Impacts were prioritized through a risk and vulnerability assessment, and adaptation actions were devised and evaluated through staff workshops. The purpose of the planning initiative was to ensure that Vancouver remains a live-able and resilient city, maintaining its values, character and charm in the face of climate change. The City of Vancouver defined their objectives for the planning horizon till 2050 to be:

- Increase the resilience of City infrastructure, programs and services to anticipated local climate change impacts.
- Promote and facilitate the incorporation of climate change information into City business.
- Improve awareness, knowledge, skills and resources of City staff.
- Enhance opportunities for coordination and cooperation through the development of networks and partnerships.

In order to measure Vancouver's adaptive capacity, impacts were assessed based on the cost and amount of staff intervention that would be needed to adapt. Engineering was most frequently identified as having low adaptive capacity; a direct reflection of how built infrastructure is generally unable to accommodate major changes in climate without additional costs and potentially significant disruptions. In order to explore different responses to climate change, Vancouver is joining a group of leading cities in Europe, Australia and the United States that have developed and implemented climate change adaptation strategies. Vancouver's Adaptation Strategy is a priority action in both the Greenest City Plan and the Corporate Strategic Business Plan. The City joined the ICLEI Climate Change Adaptation Initiative pilot in late 2010 along with a cohort of local and regional governments across Canada. The strategy for project selection for Vancouver included:

- A detailed matrix for primary and supporting actions which include accountability and priority.
- Evaluation based on their effectiveness; overlap with sustainability and mitigation goals; cost-benefit ratio; and time horizon for anticipated impacts.
- Prioritization into the categories of: 'must do', 'monitor' and 'investigate further'.
- Potential adaption indicators were also elaborated to inform decision making, For example, for the objective of 'minimizing rainfall-related flooding and associated consequences', the indicators were:
  - Number and/or cost of insurance claims related to water incurred losses
  - Number of combined sewer overflows
  - Percentage of permeable ground to total ground coverage

Vancouver has incorporated stakeholder preferences through workshops held with staff across the organization to brainstorm actions to prepare for, or reduce risks from, the prioritized impacts.

Workshop participants then reviewed a consolidated list of potential actions before the working group evaluated them.

1.3 Ontario – The Regional Municipality of York, Environmental Services Climate Change Risk Management Plan (2010)

The Region Municipality of York (York) identified the need to complete a high-level climate change risk and adaptation assessment of its water, wastewater, and solid waste infrastructure so that it can better understand and proactively manage these risks during project delivery. Overall, the practicality and effectiveness of the controls proposed for these risks are relatively easy to implement and are effective for addressing the respective risk scenarios.

The objective set by York was to develop a 'first pass' climate change risk and adaptation assessment tool proposed for use within the Capital Delivery Improvement Process (CDIP) to evaluate and account for climate change impacts on a project-by-project basis for the delivery of water, wastewater, and solid waste infrastructure projects. The Planning Horizon used was for 2010 and 2050. Adaptation tipping points were determined as the level of consequence and likelihood for twenty-eight (28) risks based on projected changes in climatic variables (i.e., increase rainfall, increased frequency of storm events, and increased mean average temperature) for 2010 and 2050 scenarios using York's Risk Management Framework. In order to explore responses, an evaluation framework was used for the York Region Climate Change Risk Assessment that was consistent with a Climate Change Impacts & Risk Management: A Guide for Business and Government risk management framework. This guide is suitable for this project because it provides a framework for managing climate change impacts, and it was developed for private, public and government organizations. Additionally, the risk assessment process aligned with the ISO 31000: Risk Management Principles and Guidelines. The Framework for this standard is illustrated in Figure 1.2.

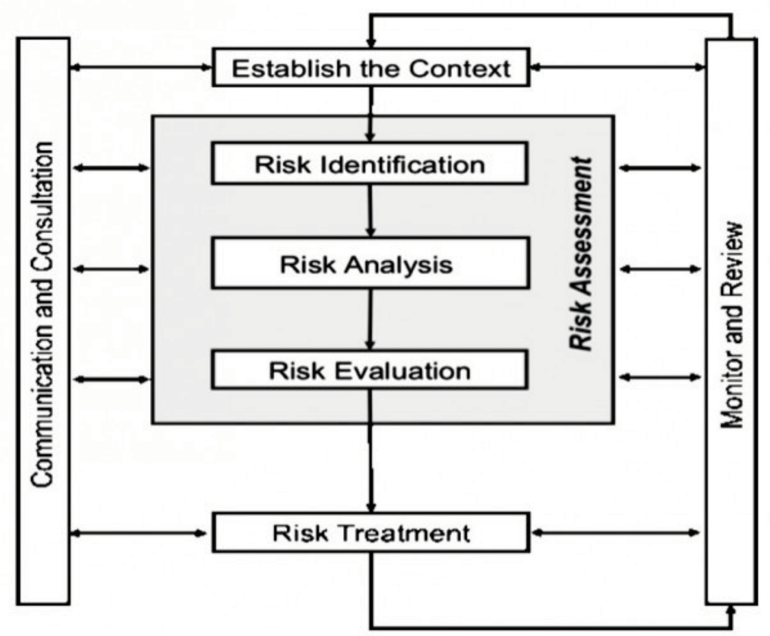


Figure 1.2 ISO 3100 Risk Management Framework

In order to select responses, a ‘first pass’ climate change assessment tool was used. This process was converted into a tool that was suitable for individual projects or assets. The tool has been customized for use by the Capital Delivery Group Project Managers to independently evaluate potential climate change risks and likely controls on a project-by-project basis for any infrastructure type. Stakeholder preferences were incorporated into the risk and adaptation assessments with stakeholder engagement workshops by the Environmental Services Department.

1.4 USA – Adaptation Framework, National Oceanic & Atmospheric Administration (NOAA) (2013)

Coastal areas across the U.S. are beginning to incorporate sea level rise adaptation into their community planning. However, many face the challenge of understanding the economic implications of future inundation risk. As a response, NOAA provided a four-step framework to perform a holistic assessment of costs and benefits of different adaptation approaches. The objective of the NOAA framework was to help communities begin to find answers to difficult questions regarding climate change. By understanding the costs and benefits of different adaptation strategies, decision-makers could make more fully informed decisions that are fiscally responsible in the short and long terms. More importantly, economically informed decision-making will lead to safer, more responsible, economically sound communities.

This framework, as seen in Figure 1.3, helped assess adaptation tipping points as it provided an overview of conducting either an impact assessment or a risk assessment. An impact assessment is done by assessing the impacts of just a few different water-level increases to develop a sense of the amount of damage to expect in certain scenarios compared to the financial cost of adaptation strategies. A risk assessment was done as a resource-intensive analysis that multiplied the probability of each water-level increase by the value of the impact to generate an apples-to-apples comparison of the expected costs and the expected benefits of implementing adaptation strategies against coastal flooding.

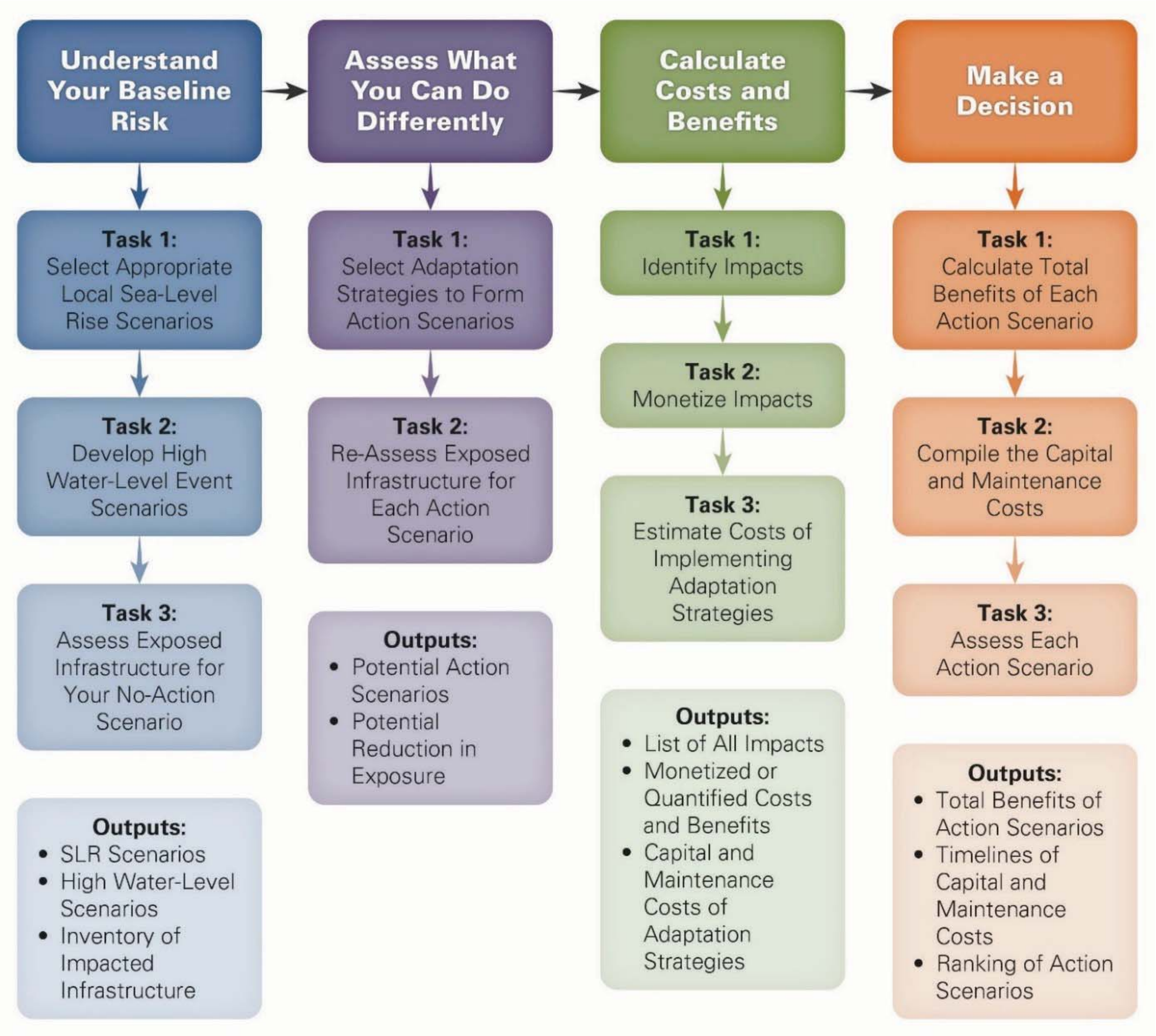


Figure 1.3 UKCIP Framework (Environmental Change Institute, 2013)

The framework helped explore responses by determining how each action scenario changed the flooding impacts for each water-level increase identified. Potential responses included:

- Moving the infrastructure to prevent flood damage
- Reducing the frequency of inundation and/or preventing flooding up to certain water levels
- Increasing the resiliency of infrastructure to against flooding

This framework helped select responses through calculating the cost and benefits of action scenarios. In addition, maintenance and capital costs were also examined. After all costing is completed, a decision is made based on the rankings of each option.

1.5 Great Britain – London, Thames Estuary 2100 Plan (2012)

The study was conducted to develop a plan to address sea level rise for flood protection in London. A key driver was considering how tidal flood risk could change over time. TE2100 is a flood risk management plan for London and the Thames Estuary. It was produced over 6 years and finalized in November 2012.

The planning approach considered a wide range of possible futures and resulted in the choice of options that were more robust and adaptable to uncertainties. The aim of the project was to develop a plan for actions to reduce flood risk. The objectives set by TE were to:

- Determine future work on flood warning, flood plain management and expenditure.
- Inform the work and expenditure of partners.
- Provide key information and actions for regional and local government.
- Raise awareness and improve the knowledge of tidal flooding.

A framework used to assess flooding from climate change was developed by TE as can be seen in Figure 1.4 and Figure 1.5.

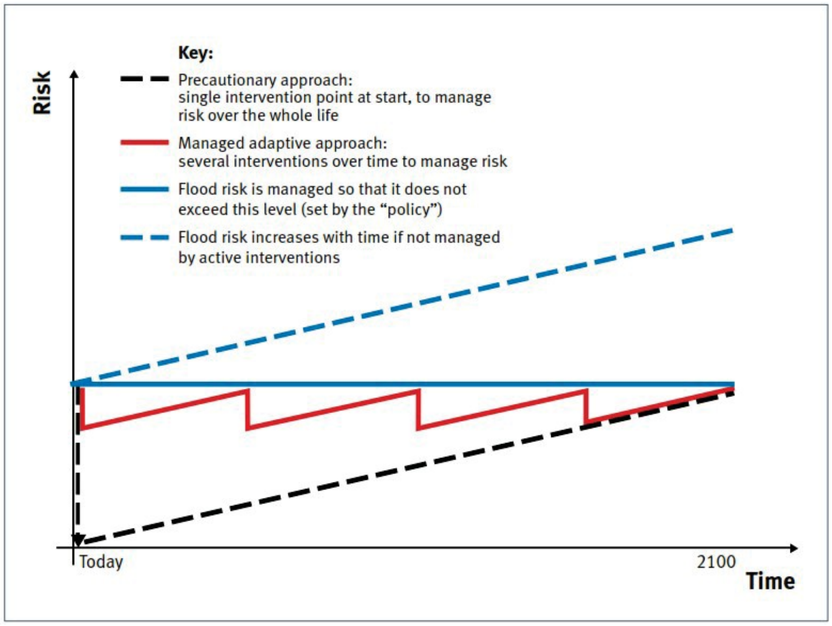
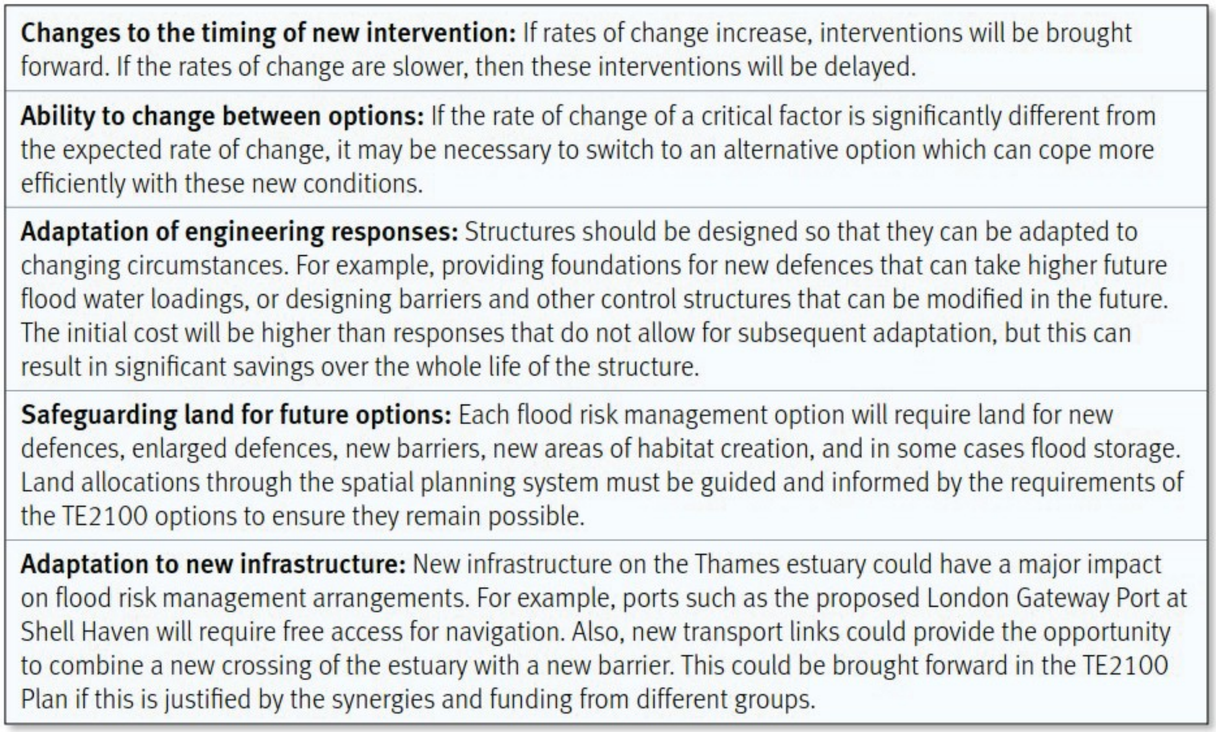


Figure 1.4 TE2100 Adaptive Approach Graph (Environment Agency, 2012)



Changes to the timing of new intervention: If rates of change increase, interventions will be brought forward. If the rates of change are slower, then these interventions will be delayed.

Ability to change between options: If the rate of change of a critical factor is significantly different from the expected rate of change, it may be necessary to switch to an alternative option which can cope more efficiently with these new conditions.

Adaptation of engineering responses: Structures should be designed so that they can be adapted to changing circumstances. For example, providing foundations for new defences that can take higher future flood water loadings, or designing barriers and other control structures that can be modified in the future. The initial cost will be higher than responses that do not allow for subsequent adaptation, but this can result in significant savings over the whole life of the structure.

Safeguarding land for future options: Each flood risk management option will require land for new defences, enlarged defences, new barriers, new areas of habitat creation, and in some cases flood storage. Land allocations through the spatial planning system must be guided and informed by the requirements of the TE2100 options to ensure they remain possible.

Adaptation to new infrastructure: New infrastructure on the Thames estuary could have a major impact on flood risk management arrangements. For example, ports such as the proposed London Gateway Port at Shell Haven will require free access for navigation. Also, new transport links could provide the opportunity to combine a new crossing of the estuary with a new barrier. This could be brought forward in the TE2100 Plan if this is justified by the synergies and funding from different groups.

Figure 1.5 TE2100 Adaptive Approach Elements (Environment Agency, 2012)

1.6 Great Britain – UK Climate Impacts Programme (UKCIP), Environmental Change Institute, University of Oxford (2013)

UKCIP is an online portal which provides a framework and resources to help generate information to inform adaptation strategies / planning. It provides users the tools to help in building adaptive capacity, decision-making and delivering adaptation actions. The objectives established by UKCIP were to:

- Raise awareness of climate change and adaptation
- Access information, tools and resources
- Assess vulnerability to climate change
- Make the case for adaptation in organizations
- Develop a climate-resilient project, Programme, policy or strategy
- Develop and implement a climate change adaptation strategy

Stages 1 and 2 of UKCIP's Risk framework, as seen in Figure 1.6, provide helpful guidance on objective setting, problem identification and on establishing decision-making criteria.

- What is the purpose of my evaluation?
- How can I maximise synergies or manage conflicting purposes?
- What are the learning objectives for the evaluation?

- What is being monitored or evaluated?
- Does the intervention involve building adaptive capacity, adaptation actions or both?

- What Theory of Change underpins the intervention?
- What assumptions have been made, are these valid?
- How have unexpected/ unintended impacts and outcomes been considered?

- Which 'Tricky Issues' are relevant to the evaluation, how can these be managed?
- What limitations influence the M&E approach?
- What trade-offs have been made, are these justified?

- Is efficient use made of existing data sources?
- Do indicators relate clearly to your purposes and objectives?
- Has qualitative data been used to complement metrics?

- Who needs to be engaged in the evaluation process, when and how?
- Whose voice will be heard?
- How should I communicate the findings?

Figure 1.6 UKCIP Framework (Environmental Change Institute, 2013)

UKCIP includes a risk, uncertainty and decision-making framework as a step-by-step process to help assess what adaptation measures are most appropriate for organisations or businesses. Stages 4 and 5 of UKCIP's Risk framework provide guidance on how to identify and appraise adaptation options. It includes a wizard to guide users to:

- Identify a range of adaptation options
- Select the most appropriate options
- Put together an implementation Programme

The tool guides users to consider the following criteria:

- Effectiveness – will the actions meet your objectives?
- Efficiency – do the benefits exceed the costs?
- Equity – the action should not adversely affect other areas or vulnerable groups
- Flexibility – is it flexible and will it allow for adjustments and incremental implementation?
- Sustainability – does it contribute to sustainability objectives, and are they themselves sustainable?
- Practical – can the action be implemented on relevant timescales?
- Legitimacy – is it politically and socially acceptable?
- Urgency – how soon could it be implemented?

- Costs – consider social and environmental costs, not just economic
- Robust – is the option able to cope with a range of future climate projections?
- Synergies / coherence with other strategic objectives – does it help to achieve other objectives?
- Any other important factors.

UKCIP identifies "windows of opportunity" for implementing adaptation. For example, ways of incorporating climate response strategies into mainstream activities in a way which works with other strategies and policies. The costs of adaptation can be minimized by incorporating adaptation in the following situations:

- The early steps of planning new developments;
- Planned infrastructure upgrades;
- Routine maintenance that is being conducted;
- Plans that come up naturally for review; and
- Your routine work plan rather than being dealt with as an emergency situation.

UKCIP's costings methodology can be used to convert significant risks – and opportunities – into financial costs. Technical and relatively simple versions of the methodology are available, depending on the importance of this information to the decision-making process.

1.7 Australia – Melbourne, Metropolitan Sewerage Strategy (2009)

The 2009 Melbourne Metropolitan Sewerage Strategy identified the challenges to and opportunities for Melbourne's sewerage system over the next 50 years to 2060. Using this information, strategic directions were established to guide Melbourne's water industry over this period and beyond. From these directions, short term actions were recommended. The strategy was initiated by the four metropolitan water authorities, in order to collaboratively develop a long term strategic direction for management of the sewerage system. Melbourne Sewerage identified their objectives for a 50 year planning horizon (2010-2060) to be:

- Identify the challenges and opportunities for sewage management
- Specify the strategic directions and near term actions to address these challenges and opportunities
- Prepare for future integrated water cycle planning options

Melbourne Sewerage assessed tipping points by examining four plausible futures for the year 2060, starting with a macro level description of Melbourne, the world and society, and then detailing the changes in the water cycle driven by environmental, social, economic, technological and cultural factors. It was a comprehensive visioning of possible futures. In order to aid with selecting appropriate responses, Melbourne Sewerage developed:

- An adaptive management framework
- A diverse portfolio of supply and demand options

These responses link together and support each other to create a dynamic pathway through the changing conditions ahead, as shown in Figure 1.7 below.

Figure 1.7 Melbourne Climate Change Response Framework (City of Melbourne, 2009)

Melbourne Sewerage also established an investment evaluation framework to support future investment, especially in adaptation projects. The framework provided a consistent set of guidelines as well as input assumptions developed in consultation with Melbourne Water and the Department of Environment, Land, and Planning.

1.8 Australia – Climate Change Adaptation for Settlement and Infrastructure – A Risk Based Approach (2013)

This Standard was prepared by Standards Australia Committee BD-103, Climate Change Adaptation. It provides a general and widely applicable approach and framework for decision-makers in all organizations that play a role in the commission, design, planning, approval, construction, maintenance, management, operation and decommission of settlements and infrastructure. The Standard provides guidance on managing climate change risks and includes implementation plans for suitable and effective adaptation. Objectives were set by considering:

- Inform legislation, policy review and development
- Understand future climate and adaptation responses for urban strategies, long term investment and development delivery
- Assess the impacts of future climates and adaptation responses through approval process
- Inform adaptation of existing development

In order to assess adaptation tipping points, the standard states that an organization should develop a risk management plan that describes how the management of each type of risk will be integrated in all of the organization's practices and processes. An overview of how risk is incorporated into an adaptation planning framework is shown in Figure 1.8 below.

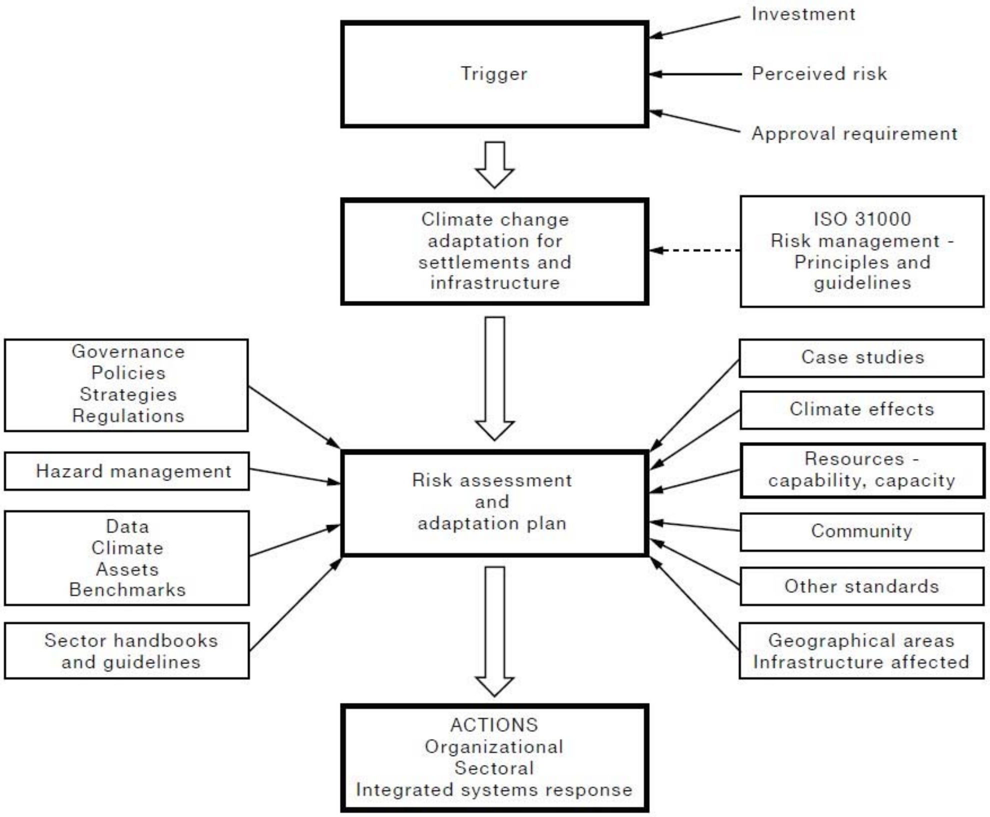


Figure 1.8 AS 5334-2013 Adaptation Planning Risk Framework (Standards Australia, 2013)

The responses should be examined based on:

- The organization's rationale for managing the risks from climate change to settlements and infrastructure.
- Links between the organization's corporate objectives, policies, climate-related policy and corporate risk management framework.
- Accountabilities and responsibilities for managing the risks from climate change to settlements and infrastructure and for adaptation.
- Commitment to make the necessary resources available to assist those accountable and responsible for managing the risks from climate change to settlements and infrastructure.
- The way in which performance against this policy will be measured and reported.

The net benefits of available options is an important part of decision making. Factors that could be considered in the selection of adaptation options include the following.

Effectiveness and robustness of the adaptation—over the life of the settlement or infrastructure including flexibility of the option in terms of its ability to respond to changing conditions of use and climate and the impacts from climate change.

- Practicability of implementation and ease of maintenance including technical capability, availability of human resources.
- Compatibility with existing systems within the settlement or infrastructure.
- Economic efficiency of operation and ongoing maintenance including funding options and their availability for adaptation and whether the adaptation can, itself, generate revenue
- Co-benefits over and above those that come from the direct treatment of the risks from climate change; or net benefits under a range of plausible future climates.
- Equity implications of the adaptation options for all potentially affected stakeholders.

The standard noted that high quality communication and consultation are required because the risks from climate change are uncertain, complex and may involve extreme weather events and slow onset consequences that are outside normal human experience. Plans for communication and consultation should be developed at an early stage.

about GHD

GHD is one of the world's leading professional services companies operating in the global markets of water, energy and resources, environment, property and buildings, and transportation. We provide engineering, environmental, and construction services to private and public sector clients.

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