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MODELLING OF ENVIRONMENTAL FLOW TARGETS FOR THE LOVERS CREEK SUBWATERSHED

MODEL DEVELOPMENT, CALIBRATION, AND APPLICATION REPORT

Report Prepared for:
LAKE SIMCOE REGION CONSERVATION AUTHORITY

Prepared by:
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October 2015
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Report prepared for Lake Simcoe Region Conservation Authority, October 2015

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DISCLAIMER

We certify that this report is accurate and complete and reflects the information available during the study. Information obtained during the study or provided by Lake Simcoe Region Conservation Authority or third parties is believed to be accurate but is not guaranteed. We have exercised reasonable skill, care, and diligence in assessing the information obtained during the preparation of this report.

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EXECUTIVE SUMMARY

An integrated hydrologic model was developed in MIKE SHE for the project Study Area to facilitate environmental flow target determination for the Lovers Creek subwatershed. While the existing Barrie Tier Three MIKE SHE model was used as a guide for model construction, this model represents a new MIKE SHE model constructed for the area that was comprehensively updated relative to the previous model.

The model domain selected is 86 km^2 in extent (Figure 1) and was selected through assessment of regional groundwater heads from the Barrie Tier Three FEFLOW Model (AquaResource 2013). The model domain encompasses both Lovers Creek and Hewitt's Creek subwatersheds. A model resolution of 50 m was selected to balance the benefits of increased model resolution and computational burden.

A detailed hydraulic model of the river network was developed that represents lower order streams not previously modelled in the regional MIKE SHE model. This hydraulic model implements a fully dynamic wave approximation of channel flow providing a physically-based representation of flow that is valid for all forms of channel flow including backwater effects.

The land use of the Study Area was characterized in terms of vegetation and overland flow characteristics (surface roughness, depression storage, directly connected impervious surfaces, and vegetation) using detailed land use mapping provided by the Lake Simcoe Region Conservation Authority (LSRCA). Agricultural drains were integrated into the model based on the best available agricultural drainage mapping from Land information Ontario (LIO).

A detailed review of available climate data was conducted at the outset of modelling. This review determined the best available climate data representative of the Study Area. Various daily and hourly data sources were combined to create a climate data set featuring hourly precipitation (Section 2.2).

The geologic layer representation implemented in the MIKE SHE features all stratigraphic layers represented in the Barrie Tier Three FEFLOW model from surface to bedrock (AquaResource 2013).

The MIKE SHE model was calibrated to streamflow observations at the Lovers Creek at Tollendal Road Gauge. The most reliable streamflow and climate data for the Study Area were available from 2009 to 2013 and the calibration of the model primarily considered this period. The calibration of the model provided a good match to annual, mean, and median monthly flows. A very good ranked duration curve flow calibration was achieved, which was the focus of calibration efforts. This metric evaluates the representation of flows over the entire hydrologic regime and is therefore particularly important for environmental flow assessment.

The calibrated MIKE SHE model was used to conduct an evaluation of the effect of land use development on environmental flows. A set of two stressor states, which represent land use conditions in the Study Area during 1978 and pre-development were developed in MIKE SHE. The change in

environmental flows as a result of land use changes was evaluated at a set of key discharge locations identified by the LSRCA throughout the Study Area.

The calibrated MIKE SHE model was then used to conduct an evaluation of the effect of climate change on environmental flows within the Study Area. This comparison evaluated a set of ten future climates projections for the period of 2011 to 2040 for the Study Area and their effect on environmental flows. Detailed flow evaluations were completed for nine points throughout the watershed as illustrated in Appendices A through I.

ACKNOWLEDGMENTS

This project has received funding support from the Government of Ontario. Such support does not indicate endorsement by the Government of Ontario of the contents of this material.

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1 INTRODUCTION

1.1 Overview

The Lake Simcoe Protection Plan (LSPP; MOECC, LSRCA, and DMTI 2009) was passed by the Province of Ontario to protect, improve, and restore the ecological integrity of the watershed and its natural heritage features. Two objectives of the LSPP are to provide ongoing scientific research and monitoring related to the ecological health of the Lake Simcoe Watershed, as well as improving the Lake Simcoe Watersheds' capacity to adapt to change. In part, the plan states that to "protect aquatic ecosystems in the Lake Simcoe Watershed, an adequate portion of the available water supply must be reserved for the ecosystem and restricted from human consumption." Specifically, the LSPP supports research to estimate the reserve flows required to maintain healthy aquatic ecosystems in the watershed and to develop instream flow targets for water quantity-stressed subwatersheds.

In support of the LSPP, a framework (LSRCA and Bradford 2011) was developed to support the implementation of an ecological flow assessment process that can address multiple functions of aquatic ecosystems and consider a range of ecologically significant flows. The framework sets out a process for ecological flow assessment in the various subwatersheds in the Lake Simcoe Watershed. The framework is intended to provide consistency in approach, particularly in helping to match the level of analysis to the degree of sensitivity or vulnerability of the aquatic system. Lovers Creek subwatershed was selected to test and further develop this framework within the context of a pilot project.

1.2 Project Objectives and Scope

The primary objective of this study is to evaluate the hydrologic differences for selected development stressor states and climate change scenarios. This study will serve as a pilot project for developing a methodology for ecological flow targets in an effort to help meet the goals of the LSPP.

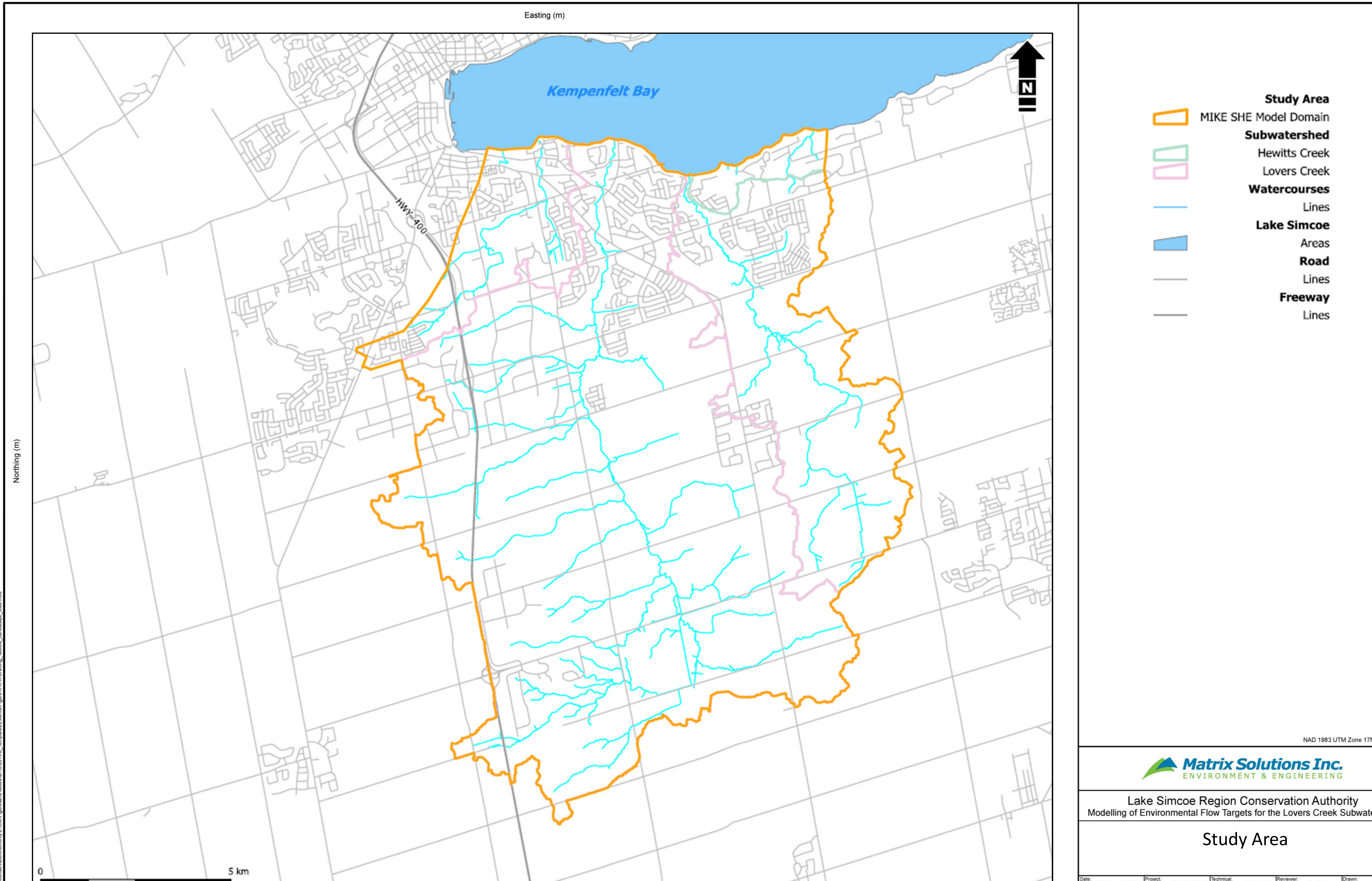
To accomplish this, an integrated hydrologic model was developed using MIKE SHE for the Lovers Creek and Hewitt's Creek subwatersheds (DHI 2014a). This model was developed using the MIKE SHE and FEFLOW (DHI 2014b) models developed for the City of Barrie Tier Three Water Budget and Local Area Risk Assessment as the basis. The potential hydrologic changes are evaluated for nine key discharge locations within the Lovers Creek subwatershed, by evaluating stressor state scenarios with the calibrated, integrated model.

1.3 Study Area

The Lovers Creek subwatershed covers 59.5 km², accounting for approximately 2% of Lake Simcoe Watershed's total area (Figure 1). Land use consists of urban and built-up areas (31%), agriculture (34%), and natural heritage areas (35%). The agricultural areas mostly consist of row crops and pastures and the wetlands are woody wetlands often surrounded by coniferous woodlands. Lovers Creek has a well vegetated riparian area with 70% natural heritage cover within a 30 m buffer from the creek and drains northwards to discharge into Kempenfelt Bay (Lake Simcoe). The subwatershed is partially located in the City of Barrie (26%) and the County of Simcoe (74%); as it borders the City of Barrie, it is subject to development and potential annexation.

The subwatershed has a gentle gradient with 70% of the area having slopes less than 5%. Steeper slopes of greater than 5% are mostly located in the west central area of the watershed. The physiography of the area is characterized by drumlinized till plains and surficial deposits of kame or sand and gravel outwash. The subwatershed contains a hydrogeologically significant groundwater recharge area called Lovers Creek Infiltration Area, which is considered to be a Key Natural Heritage Feature (KNHF) and Key Hydrologic Feature (KHF) under the LSPP. The population density within the subwatershed is between 83 and 300 persons/km^2 and expected to double by 2031 (LSRCA 2008).

The hydrogeology and groundwater resources in the Study Area have been delineated in detail within earlier studies, including the South Simcoe Groundwater Study report (Golder 2004), and more recently, the reports prepared for the Tier Three Risk Assessment for the City of Barrie (AquaResource 2013). The Quaternary deposits underlying the Study Area are part of a regionally extensive and complex system, within which a succession of five major aquifer units is identified. Four of these aquifers correspond to units found regionally and are referred to as the upper (Aquifer A1), intermediate (Aquifer A2), and lower (Aquifer A3 and A4) aquifers. The aquifers are separated by relatively continuous confining layers. The A3 and A4 aquifers are the deepest and form the source of the majority of the groundwater supply. The bedrock underlying the area consists of Ordovician shale and limestone of the Georgian Bay, Whitby, and/or Lindsay Formations. Previous studies have identified potential connections between the shallow and deeper groundwater strata, which have been incorporated into the available modelling tools.



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Study Area

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Figure 1

1.4 Review of Previous Modelling

In 2012, for the purposes of Source Water Protection Planning under the *Clean Water Act*, a Tier Three Risk Assessment (AquaResource 2013) was completed for the City of Barrie using a set of water budget tools, including a regional numerical groundwater flow model (FEFLOW) and an integrated groundwater-surface water model (MIKE SHE). The MIKE SHE model developed provided recharge estimates to the groundwater flow model, while the groundwater flow model provided the inter-basin transfers. Calibration effort for these models was focused within the immediate area of the City of Barrie, including the Lovers Creek subwatershed. Calibration to streamflow at the Lovers Creek gauge revealed an excellent match to data recorded before 2005, including high and low flow conditions. However, the gauge data appeared to contain an undocumented shift from 2005 to 2009.

Later in 2012, as part of a hydrogeological impact assessment, both the MIKE SHE model and the FEFLOW model were used to evaluate the impacts of land use changes to groundwater discharge. These land use changes reflect proposed future land use options within an area proposed for annexation to the City of Barrie (Blackport and Associates 2012), largely within the Lovers Creek Subwatershed. The results of this assessment indicated that the area was sensitive to land use development, and that perched aquifer conditions played a significant role in groundwater discharge to surface water features, particularly in the western headwaters of the subwatershed.

The MIKE SHE model used in these studies was applied in 2012 (Beaton 2012) in refining and testing the 2011 E-Flow Framework (LSRCA and Bradford 2011). In this work, a method for defining subwatershed objectives and identifying habitat specialists through expert input was proposed and tested. The natural regime of each streamflow and wetland site was characterized along with the hydrological alteration at the site. Potential ecological responses to the hydrologic alterations were then hypothesized for the different types of changes calculated at each site. The accuracy of the targets developed using the method was mainly limited by the accuracy of the hydrological model and quantified flow magnitudes; therefore, recommendations were made for improving these components. Among these recommendations were to include climate change scenarios within the future simulations and to explore the development of groundwater discharge regime targets.

1.5 Report Outline

This document describes the setup, calibration, and application of the integrated model for the Lovers Creek subwatershed. The remainder of the report is structured as follows:

- Section 2 presents the refinement and calibration of the MIKE SHE model, including the model processes, input parameters, and model performance.

- Section 3 presents the application of the model to evaluation of development stressor states and climate change, as well as their effects on environmental flows in the Study Area.

- Section 4 outlines elements within the water budget modelling process that are subject to uncertainty and data gaps.

- Section 5 provides a project summary and recommendations.

2 MIKE SHE MODEL

MIKE SHE is an integrated hydrologic modelling software package, which provides a fully dynamic, physically based representation of all major processes of the hydrologic cycle and their interaction. The major processes considered are as follows (DHI 2014a, 2014b):

- precipitation: water in the form of rainfall or snowfall that enters the watershed
- evapotranspiration: soil-water content, ponded water, and canopy -intercepted water that becomes water vapour and is returned to the atmosphere by evaporation and transpiration mechanisms
- surface runoff: water that does not infiltrate the Earth's surface and remains in the surface water regime as surface detention storage, surface runoff, or interflow
- groundwater recharge: water from rainfall or snowmelt, which infiltrates the Earth's surface and passes through the vadose zone to enter the groundwater or subsurface flow regime
- groundwater discharge: water that flows from the subsurface (i.e., groundwater) regime to the surface water regime (lakes and rivers)

The following sections describe the hydrologic process representation implemented in the MIKE SHE model.

2.1 Hydrologic Process Representation

MIKE SHE is able to simulate hydrologic processes using a variety of representations (e.g., 2D diffusive wave overland flow versus catchment-based overland routing). The following section describes which MIKE SHE representation was used for each major process.

2.1.1 Precipitation

Precipitation was characterized by hourly precipitation data from climate stations within the Study Area. Input precipitation is spatially distributed according to the Thiessen polygon regions created for the set of climate station locations.

2.1.2 Evapotranspiration

Daily potential evapotranspiration rates were computed for each climate station and spatially distributed according to the Thiessen polygons generated for the climate stations. Potential evapotranspiration rates were computed using a Penman-Monteith approach (Allen et al. 1998). Actual evapotranspiration is estimated using a two-layer water balance model that considers available water, vegetation parameters (rooting depth and leaf area index), and potential evapotranspiration. The model attempts to satisfy the potential evapotranspiration rate through consideration of water availability in the various phases of the hydrologic cycle in the following order:

- accumulated snow (if present, through evaporation or sublimation)
- canopy interception (through evaporation)
- ponded water (through evaporation)
- unsaturated zone (through transpiration and evaporation)
- saturated zone (through transpiration)

Once the water contained within one of these storage zones is depleted, no further evaporation or transpiration can occur from the storage zone until it is replenished through a precipitation event, overland runoff, or groundwater flow.

2.1.3 Snow Melt

Snow melt and accumulation is controlled using a degree-day process, which primarily relies on air temperature. The daily temperature variation of the subwatershed is provided using a temperature time series. Freezing or melting of water occurs when the temperature is above or below a threshold temperature (0°C). The rate at which snow melt occurs is controlled by a degree-day coefficient (units: mm snow/d/°C). This coefficient is often used as a calibration parameter to calibrate the snow melt volumes and timing to observed spring runoff. The wet and dry portions of the snow pack also regulate snow melt. Liquid water is released from the snow pack only when the fraction of wet snow within the snow pack exceeds a threshold value. As with the degree day coefficient, this parameter is adjusted to calibrate to observed snow melt runoff.

The spatial distribution of snow is also important in snow pack accumulation and depletion as snow tends to accumulate more in sheltered areas (e.g., forests) than open areas (e.g., fields). The non-uniform distribution of snow within a given area is considered by setting a minimum snow storage depth at which a model cell is considered entirely covered by snow. Snow depths below this threshold value linearly reduce the area of a model cell considered covered in snow. The melt rate of snow in partially snow-covered model cells is reduced in proportion to the fraction of the cell considered snow-covered.

2.1.4 Overland Flow

Overland flow is simulated though a diffusive wave approximation of the Saint-Venant equations (Chin 2006). Numerically, this method is implemented through a 2D finite difference method. Additional overland flow considerations represented within the model include the following:

- spatially variable surface roughness dictated by land use and characterized through a Manning's number

- spatially variable depression storage dictated by land use and characterized by a storage depth
- spatially variable directly connected impervious areas characterized by a fraction of overland flow directed immediately to nearby river systems

2.1.5 Channel Flow

Channel flow in MIKE SHE is simulated using a link to the MIKE 11 modelling system (DHI 2014a, 2014b). MIKE 11 is a fully featured 1D hydraulic model capable of complex hydrodynamic river simulations as well as flood forecasting, sediment transport, and water quality simulations. MIKE 11 is capable of simulating flow using the fully dynamic wave form of the 1D Saint-Venant equations and other simplified routing methods. In this application, the fully dynamic wave representation of channel flow was implemented. The fully dynamic wave representation of flow provides a comprehensive, physically based representation of flow that is appropriate for this study. This approach provides consideration for fast transient flows, flood waves, and rapidly changing backwater effects (DHI 2014c).

Channel locations and cross-sectional geometry are defined using a drainage network and topography from the high resolution (5 m) digital elevation model (DEM) supplied by the LSRCA.

2.1.6 Unsaturated Flow

1D (vertical) unsaturated flow is considered within MIKE SHE, using a two-layer water balance approach. This considers an upper layer of the unsaturated zone that extends from the ground surface to the top of the capillary fringe and a lower layer that extends from evapotranspiration extinction depth (the maximum root depth + capillary fringe thickness) to the water table. In areas where the water table is above the evapotranspiration extinction depth, there is only one layer (maximum root depth + capillary fringe).

Water that is accessible for evapotranspiration is defined by the amount of soil-water content contained within the rooting zone. The soils of the unsaturated zone are described with a spatial distribution, based on surficial geology, and are characterized by a hydraulic conductivity parameter, soil-water parameters (wilting point, field capacity, and saturation point) and suction head. Infiltration to the unsaturated zone is calculated using the Green and Ampt method. Limiting factors for infiltration are the soil hydraulic conductivity and the suction head. Soil-water content of the unsaturated zone is maintained on a mass balance basis. When the soil-water content of the unsaturated zone exceeds field capacity, water drains to the saturated zone (percolation or groundwater recharge). When soil-water content is below field capacity, percolation ceases with further reductions in soil-water content only occurring through evapotranspiration. The Green and Ampt infiltration equation modifies the infiltration rate to account for changes in soil moisture, and when net precipitation falls at a rate faster than the infiltration rate, overland runoff is generated.

2.1.7 Drainage

Subsurface drainage is simulated in MIKE SHE through a head-dependent boundary condition in the subsurface. The routing of drain flow is defined using detailed subwatershed delineation. Drain flow generated within each subwatershed is routed to the nearest stream segment in the subwatershed. Drain flow volume is calculated as the difference in head between the drain level and the water table, multiplied by the drain time constant. If the water table is below the drain level, no drain flow occurs. The drain time constant and depth are calibration parameters for drain flow and were adjusted to minimize the differences between the recession portion of the simulated and observed hydrographs. Drainage in MIKE SHE may be used to represent buried pipe drainage outflow (e.g., agricultural drainage). Alternatively, drainage may also be applied to simulate saturated zone drainage to ditches and other surface drainage features as well as interflow or subsurface storm flow.

2.1.8 Saturated Flow

3D saturated Darcy flow is simulated in MIKE SHE, using a finite difference approximation similar to that of a MODFLOW model (Harbaugh 2005).

2.1.9 Hydrologic Process Summary

Table 1 is a summary of all the major hydrologic processes and their representation within the model.

TABLE 1 Hydrologic Processes

Hydrologic Process	Process Approximation
Overland flow	2D - finite difference diffusive wave approximation of Saint-Venant equations of flow
Channel flow	1D – fully dynamic wave approximation of Saint-Venant equations of flow
Evapotranspiration	Two layer water balance model, which applies a simple mass balance approach to predicting ET
Unsaturated flow	1D, two layer water balance model. Infiltration based on soil-water content parameters as well as soil conductivity and suction head. Infiltration based on the Green and Ampt method
Saturated flow	3D finite difference implementation of Darcy's equation

2.2 Climate Data

Climate data for the study was obtained for a number of climate stations in close proximity to the Study Area (Figure 2). This climate data set includes data from the Ontario Ministry of Natural Resources and Forestry (MNRF)-infilled climate data set (LIO 2008), Environment Canada climate stations, and the LSRCA climate stations. For the purposes of model calibration, a continuous set of climate observations was assembled for the period of observed streamflow of the Lovers Creek at Tollendal streamflow gauge collected by the LSRCA (2001 to present).

The climate data observed at these stations and used in this study include rainfall, snowfall, precipitation, and temperature at various temporal intervals (daily to sub-hourly). The details of the climate stations and data sources used in this project are summarized in Table 2. Climate data was spatially distributed using a Thiessen polygon based on the locations of Barrie WPCC and Cookstown climate stations.

TABLE 2 Selected Climate Stations

Data Source	Station ID	Station Name	Elevation (m)	Easting (m)	Northing (m)	Data Precipitation Interval	Period of Records
MNR	6111859	Cookstown	243.8	604284	4895657	Hourly	1950 to 2005
MNR	6110557	Barrie WPCC	221	604385	4914452	Hourly	1950 to 2005
EC	611E001	Egbert CS	251	597162	4898509	Daily	2000 to 2015
EC	6117684	Shanty Bay	250	608876	4917150	Daily	1973 to 2015
LSRCA	LS0107	Keswick WTP	233	620848	4901364	15-minute	2007 to 2013
EC	6110556	Barrie Landfill	305	600673	4915443	Daily	2011 to 2015

MNRF – Ontario Ministry of Natural Resources and Forestry
EC – Environment Canada
LSRCA – Lake Simcoe Region Conservation Authority

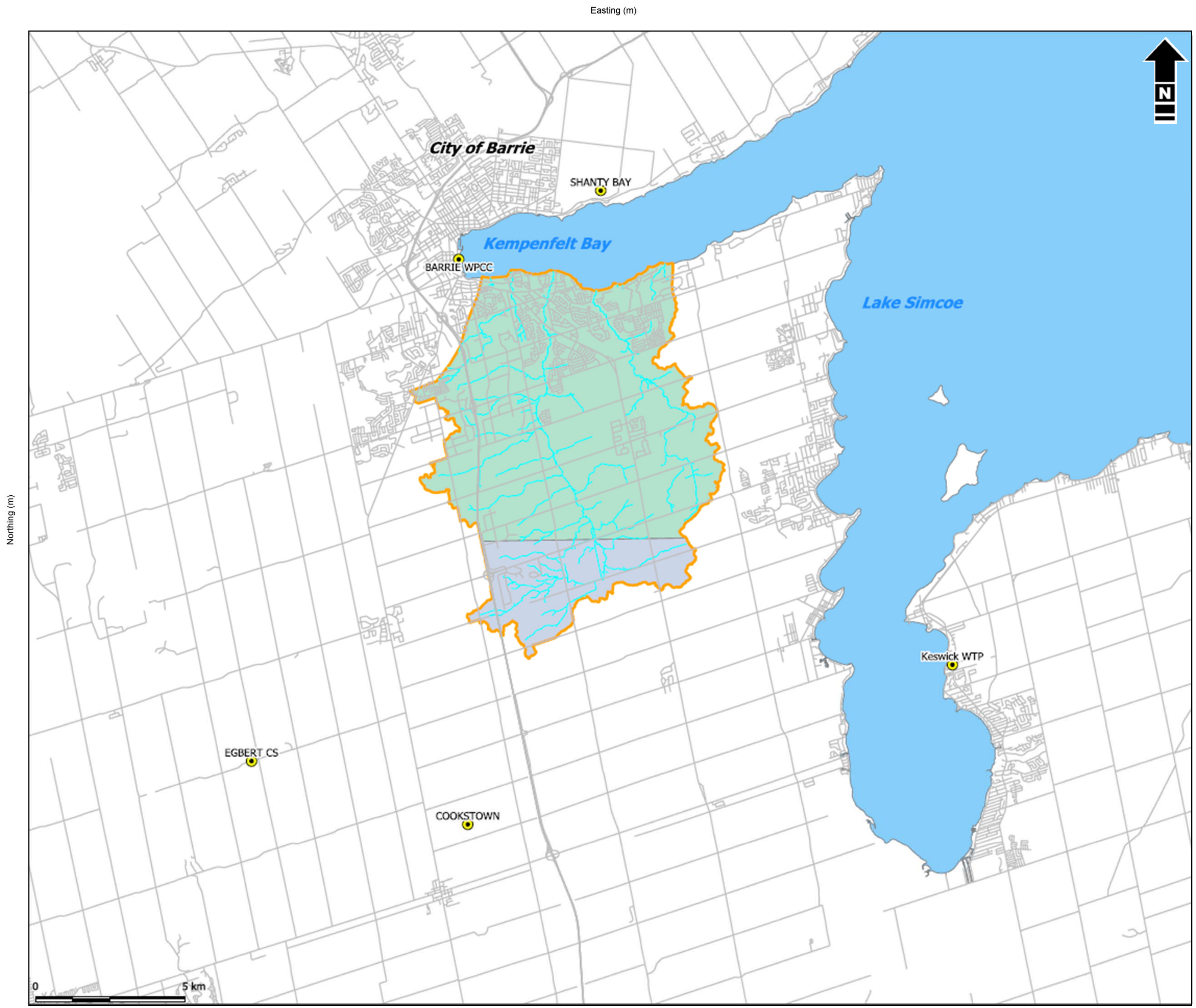
Climate data observations for Barrie WPCC were extended beyond 2005 to September 30, 2010, using methods similar to the one employed by Schroeter et al. (2000) to construct the MNRF-infilled climate data set (LIO 2008) by Matrix Solutions Inc. As Cookstown had insufficient data available during this period for the infill procedure to be appropriate, it was also infilled with the extended Barrie WPCC record until October 2010.

For the period of October 2010 to present, additional climate data was obtained. Shanty Bay and Egbert CS climate stations, maintained by Environment Canada, were selected as climate stations to provide observations for the remainder of the streamflow dataset (October 2010 to 2015). These stations were selected due to their relatively complete, daily observation dataset and proximity to the site. Additionally 15-minute and hourly precipitation observations for Keswick WTP climate station, maintained by the LSRCA, was also obtained for this period. In an effort to better replicate the duration and intensity of precipitation events in the area, the hourly precipitation observations at Keswick WTP were scaled to the daily volumes observed at Egbert CS and Shanty Bay.

Any gaps in the daily precipitation record for Shanty Bay and Egbert were first infilled with daily precipitation from Barrie Landfill. Remaining missing daily precipitation was infilled with Keswick daily precipitation. The climate data sets used during the period of streamflow observations at the Lovers Creek gauge are summarized in Table 3. The green-coloured cells in Table 3 indicate which datasets were used during the streamflow observation period.

TABLE 3 Climate Datasets

	Climate Station	Barrie WPCC	Cookstown	Keswick	Shanty Bay	Egbert CS
	Precipitation Temporal Resolution	Hourly	Hourly	Hourly	Daily	Daily
Model Simulation Period	2001					
	2002					
	2003					
	2004					
	2005					
	2006					
	2007					
	2008					
	2009					
	2010					
	2011					
	2012					
	2013					



MIKE SHE Domain
Areas
Road
Lines
Watercourse
Lines
Climate Stations
Points
Climate - Thiessen Polygon
Barrie WPCC
Cookstown

NAD 1983 UTM Zone 17N

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Climate Stations

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Figure 2

2.2.1 Precipitation

The MNRF-infilled climate data set reports daily rainfall, daily snowfall, daily total precipitation, and hourly rainfall. An hourly precipitation time series data set was derived by combining hourly rainfall estimates with daily snowfall estimates (LIO 2008) for these data. Daily snowfall estimates were converted to rainfall using a snow-water equivalency of 10% (i.e., 1 cm of snow equals 1 mm of rain). Daily snowfall rates were converted to hourly rates assuming a uniform distribution of snowfall over the day.

2.2.2 Temperature

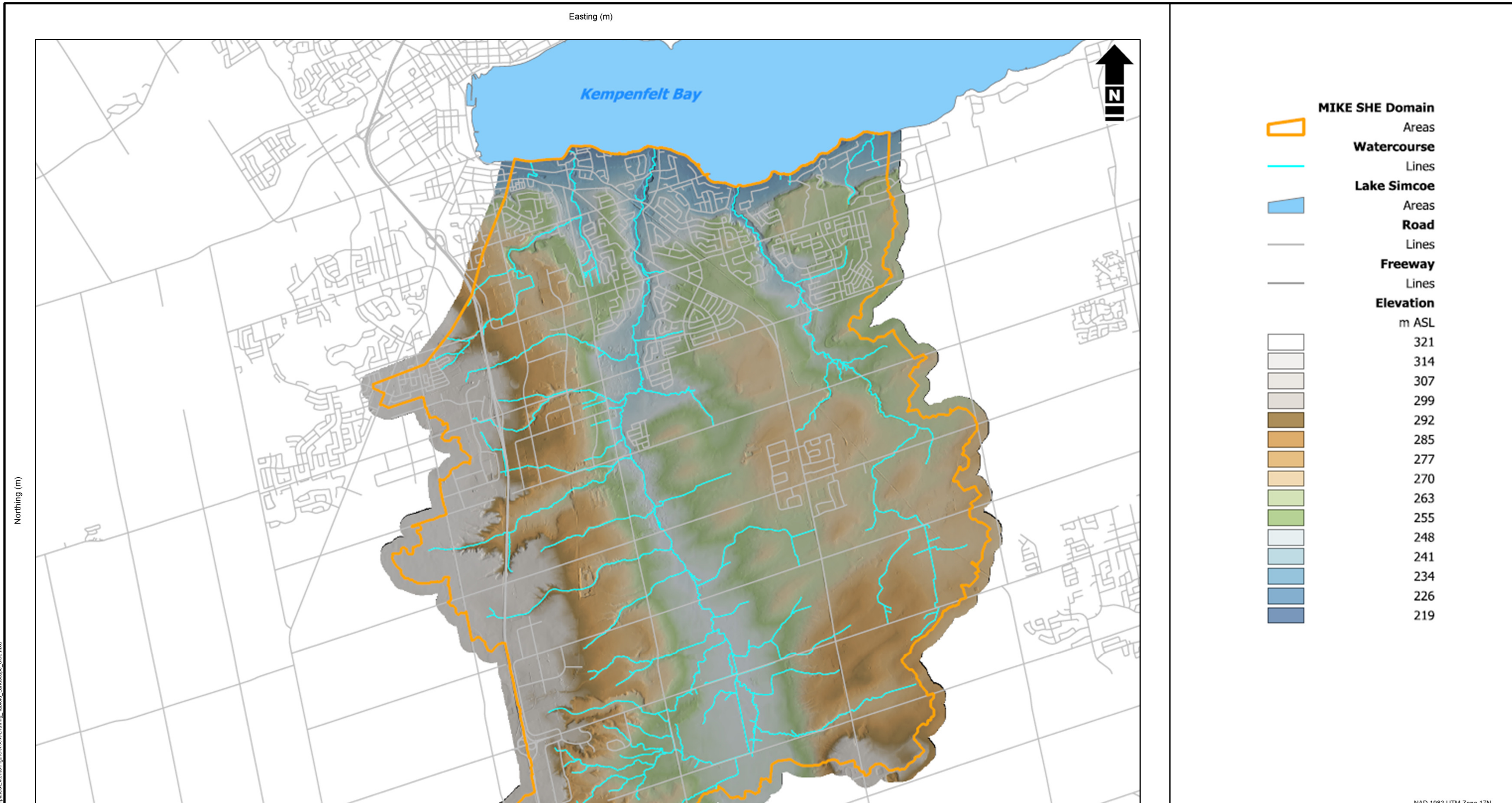
An hourly temperature time series was derived from daily maximum and minimum temperature values for each climate station. A daily sinusoidal temperature pattern was generated assuming that maximum and minimum temperatures occur at 3:00 p.m. and 3:00 a.m., respectively. This pattern is typical of temperature fluctuations within most days, but may not be representative of extremes experienced during a time in which a climatic frontal system moves into the area. This would primarily impact the timing of snowmelt events.

2.2.3 Evapotranspiration

Reference evapotranspiration rates were computed on a daily basis for the selected climate stations using the FAO 56 Penman-Monteith method (Allen et al. 1998).

2.3 Topography

A high resolution (5 m) DEM was supplied by the LSRCA to define topography within the Study Area. The topography of the Study Area is presented on Figure 3.



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Study Area Topography

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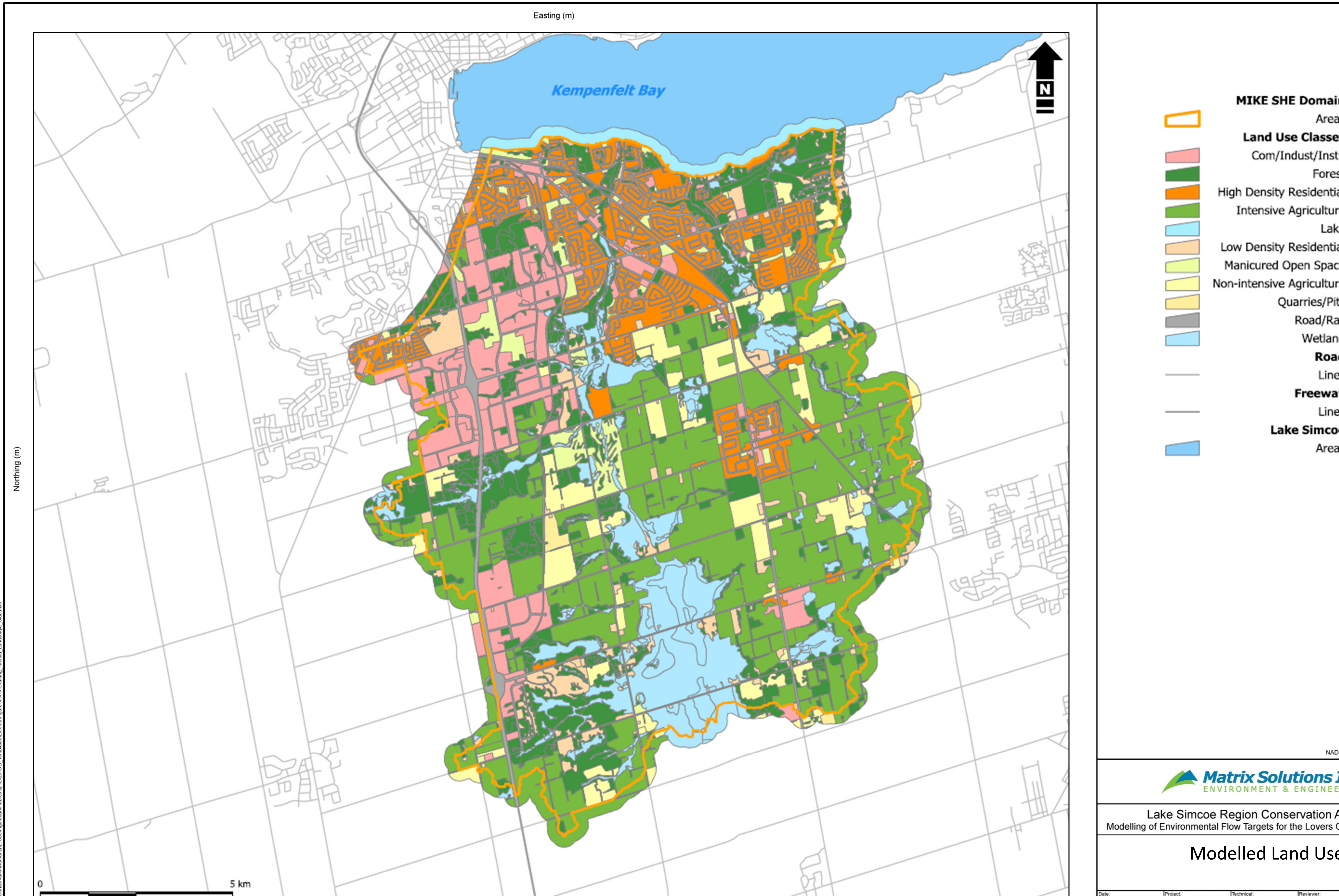
Figure 3

2.4 Land Use

A detailed land use dataset was provided for the Study Area by LSRCA. This land use is based on interpretation of 2008 orthophotography of the Study Area. Land use classes were aggregated into 11 generalized land use classes based on similar vegetation characteristics (Figure 4; Table 4).

Land use classes were assigned model parameters (e.g., leaf area indices and rooting depth) based on the vegetation characteristics of the land use class. The vegetation parameters assigned to the land use classes are varied temporally to represent the seasonal changes associated with vegetation growth, dormancy, and dieback, which occur between the spring and fall months. The initial values used for rooting depth and leaf area index for vegetation types was assigned based on literature values (Canadell et al. 1996; Scurlock et al. 2001) and adjusted during the calibration process where necessary.

The various land use classes are also defined in terms of their overland flow characteristics. The parameters used to describe these overland flow characteristics included surface roughness and depression storage. Values for these parameters were assigned based on scientific literature (Chin 2006; Watt 1989) and adjusted during the calibration process. The increased runoff associated with impervious and urbanized areas is represented in the model by assigning a directly connected impervious fraction to these regions. This fraction represents the portion of precipitation that is conveyed directly to receiving watercourses through storm sewers or other urban drainage systems. Values assigned for the paved runoff fraction parameter were set based on literature (Sullivan et al. 1978; Brabec et al. 2002) and adjusted during calibration. The final calibrated values used for vegetation, overland flow, and paved runoff parameters are listed in Table 4.



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Modelled Land Use

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Figure 4

TABLE 4 Vegetation and Overland Flow Parameters

Land Use Class	Leaf Area Index (minimum to maximum)	Rooting Depth (minimum to maximum; mm)	Surface Roughness (Manning's n)	Depression Storage (mm)	Paved Runoff Fraction
Commercial /Industrial/Institutional	0.8 to 2	200	0.025	1	50%
Forest	3 to 6	1,550 to 2,500	0.33	25	0
High Density Residential	0.8 to 2	100 to 600	0.033	2	25%
Intensive Agriculture	0.4 to 3.6	300 to 1,200	0.14	4	0
Lake	0	200	0.056	15	0
Low Density Residential	1.12 to 2.8	140 to 840	0.14	4	0
Manicured Open Space	1	200	0.14	5	0
Non-intensive Agriculture	0.4 to 3.6	300 to 1,200	0.17	5	0
Quarries/Pits	0	200		1	0
Road/Rail	0.8 to 2	100 to 600	0.20	5	35%*
Wetlands	3.2 to 6.4	200 to 600	0.40	30	0

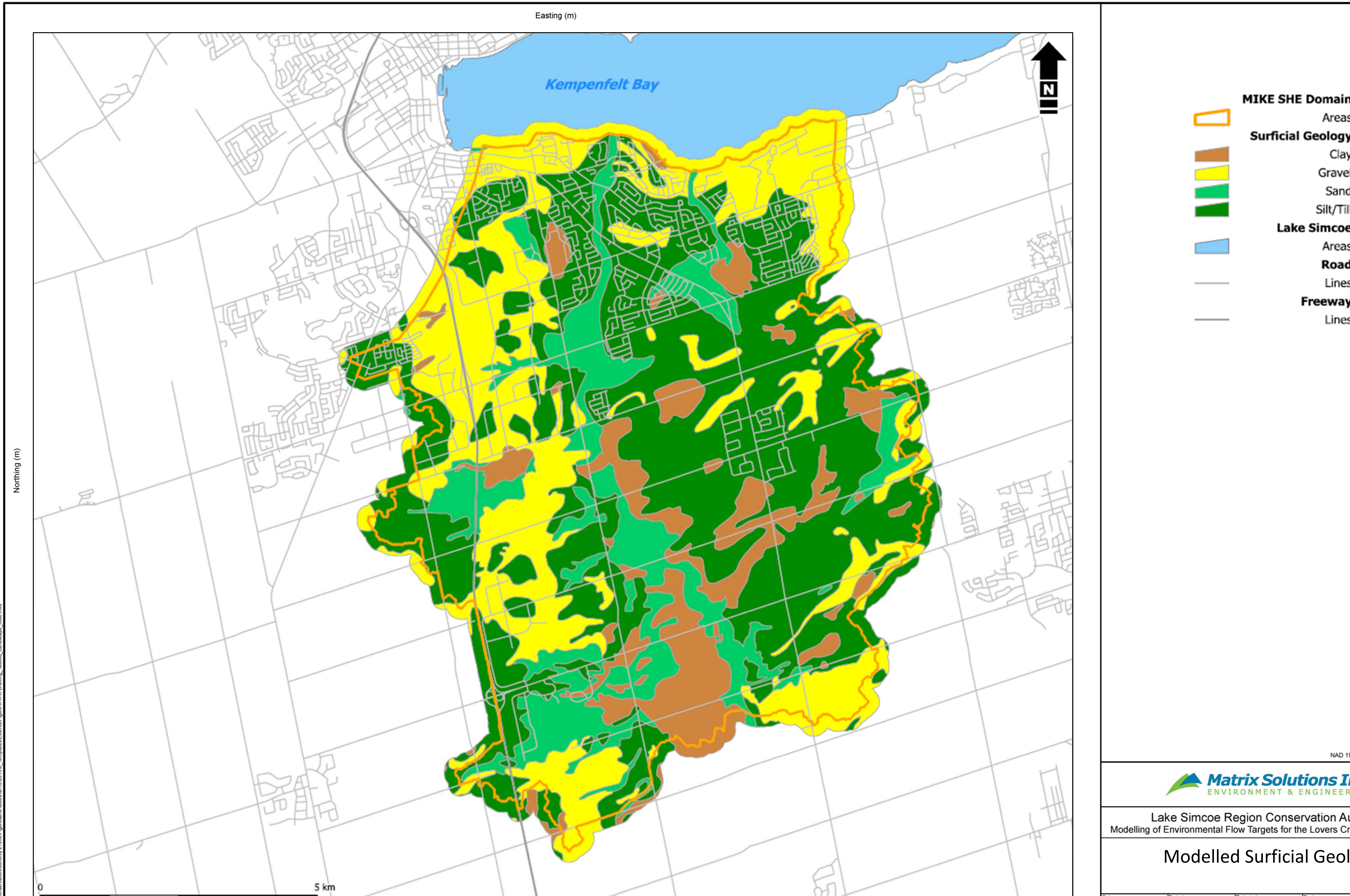
*defined in urban areas only

2.5 Surficial Geology

The surficial geology mapping of the Ontario Geological Survey (OGS 2003) for the region was used to define the variation of surficial materials throughout the model domain. Surficial geology classes were aggregated into four representative classes based on similar hydrologic properties as well as the following description elements from the OGS mapping:

- material description
- geologic material
- primary material
- single primary material

The four representative surficial geology classes are presented on Figure 5 and are summarized in Table 5.



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Modelled Surficial Geology

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Figure 5

These soil classes were parameterized in terms of their soil water content characteristics (saturation point, wilting point, and field capacity) and infiltration rate. The saturated conductivity represents the maximum rate at which water can travel through the unsaturated zone assuming storage is available and the groundwater gradient is not limiting (e.g., recharge is rejected in areas of upward gradients). Initial values for these parameters were sourced from literature (Watt 1989; Chin 2006) and professional experience, and adjusted during calibration. Final calibrated values are shown in Table 5.

TABLE 5 Surficial Geology Parameters

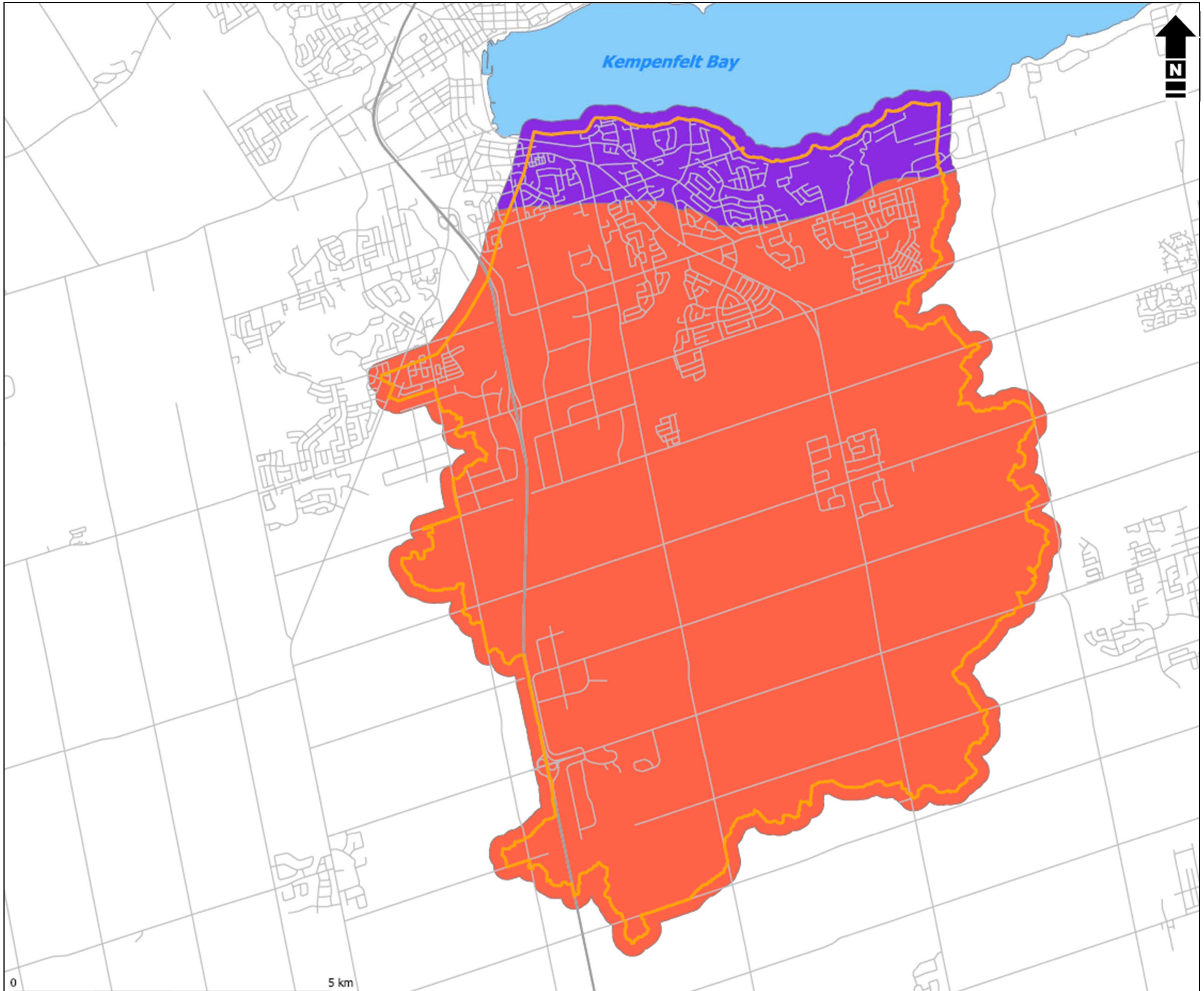
Generalized Soil Class	Vertical Saturated Conductivity (Ks; m/s)	Saturation Point (θs)	Field Capacity (θFC)	Wilting Point (θwp)	Suction Head (ψ, m)
Sand	5e-5	0.3	0.12	0.03	-0.05
Gravel	1e-4	0.25	0.12	0.02	-0.05
Silt/Till	8e-7	0.48	0.38	0.27	-0.2
Clay	2.5e-8	0.48	0.38	0.27	-0.3

2.6 Physiography

Physiographic mapping was obtained for the Study Area (Chapman and Putnam, 2007) and shown on Figure 6. The majority of the watershed is classified as Peterborough Drumlin and the area surrounding Kempenfelt Bay is classified as Simcoe Lowlands.

Easting (m)

Northing (m)



MIKE SHE Domain
Areas
Physiography
Peterborough Drumlin
Simcoe Lowlands
Lake Simcoe
Areas
Road
Lines
Freeway
Lines

NAD 1983 UTM Zone 17N

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Modelling of Environmental Flow Targets for the Lovers Creek Subwatershed

Physiography of Model Domain

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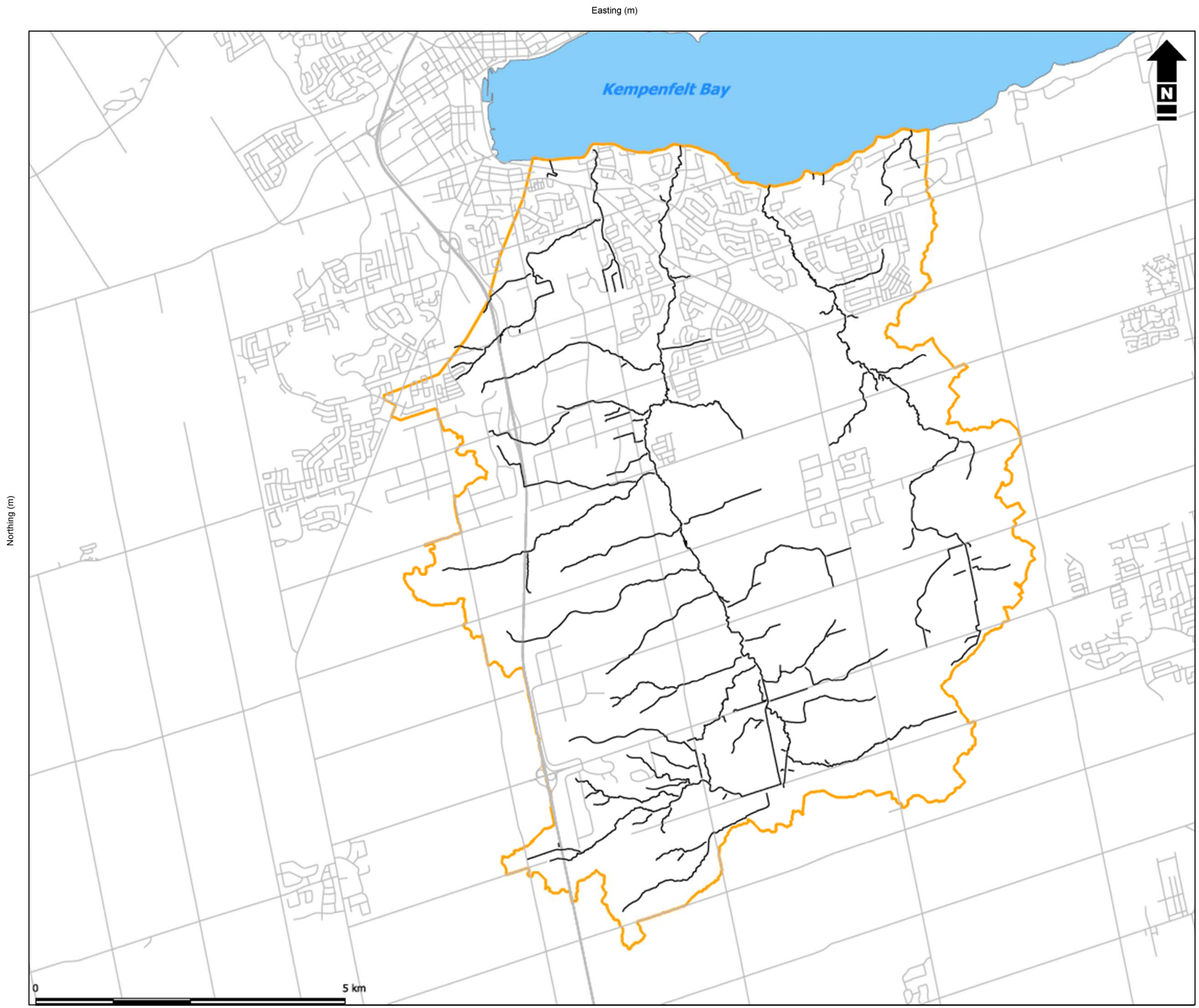
Figure 6

2.7 Watercourses

The following sections describe the representation of watercourses in MIKE SHE and the coupled MIKE 11 1D hydraulic model.

2.7.1 River Network

The watercourses represented in the MIKE SHE model (Figure 7) were based on a detailed drainage network and high resolution topographic data (DEM) supplied by the LSRCA for the Study Area. All watercourses identified by the LSRCA watercourse mapping were incorporated into the MIKE 11 model with the exception of a very limited number of small watercourses. In some cases, watercourses were not modelled in areas where development had occurred and the watercourses had been built over. In other cases, very small watercourses were not modelled as these features can be adequately represented through overland flow processes in the model.



MIKE SHE Model Domain
Areas
MIKE 11 Channel
Lines
Lake Simcoe
Areas
Road
Lines
Freeway
Lines

NAD 1983 UTM Zone 17N

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Lake Simcoe Region Conservation Authority
Modelling of Environmental Flow Targets for the Lovers Creek Subwatershed

Modelled Watercourses

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Figure 7

2.7.2 Watercourse Cross-sections

The watercourse channel cross-section geometry was defined for all watercourses represented in the model by sampling from the high resolution (5 m) DEM supplied by the LSRCA. Channel cross-sections were defined at 250 to 500 m intervals within the MIKE 11 model.

2.7.3 Watercourse Boundary Conditions

Downstream water level boundary conditions were set in the MIKE 11 hydraulic model for all watercourses, which outlet into Kempenfelt Bay. A transient water level boundary condition using monthly water level variation was set based on average observed water levels recorded in Lake Simcoe (Parks Canada 2015).

2.8 Subsurface Hydrogeology and Drainage

The saturated zone structure, properties, and boundary conditions within the MIKE SHE model are consistent with those used in the Barrie Tier Three groundwater model. Model layer elevations, hydraulic conductivity zones, porosity, and storage values were all imported from the FEFLOW model. In addition, hydraulic head values simulated within the FEFLOW model were used to establish boundary conditions for the saturated groundwater layers within the MIKE SHE model. Finally, water level calibration targets were also ported from the FEFLOW to the MIKE SHE model.

2.8.1 Hydrogeology

The hydrogeologic units in the Study Area were delineated in detail through earlier studies, including the South Simcoe Groundwater Study report (Golder 2004), and more recently, the reports prepared for the Tier Three Risk Assessment for the City of Barrie (AquaResource 2013). The Quaternary deposits underlying the Study Area are part of a regionally extensive and complex system, within which a succession of five major aquifer units is identified. Four of these aquifers correspond to units found regionally and are referred to as the upper (Aquifer A1), intermediate (Aquifer A2), and lower (Aquifer A3 and A4) aquifers. The aquifers are separated by relatively continuous confining layers. The A3 and A4 aquifers are the deepest and form the source of the majority of the groundwater supply. The bedrock underlying the area consists of Ordovician shale and limestone of the Georgian Bay, Whitby, and/or Lindsay Formations. Previous studies have identified potential connections between the shallow and deeper groundwater strata, which have been incorporated into the available modelling tools.

2.8.2 Drainage

In the MIKE SHE model, the drain depth establishes the elevation in the subsurface, above which the drain flow will occur. As the water table rises in response to groundwater recharge, it may reach the drain level, at which point, drain flow is generated. Drainage flow may be used to represent interflow (also referred to as subsurface storm flow) and it may be used to represent agricultural drainage.

Spatially drain flow is routed such that flow generated within a subwatershed is discharged at the closest river reach within that subwatershed. Drain flow generated during a given time step is routed to the nearby river reach within that time step.

Please note that drains do not abstract all water above the drainage level. Water can still transit downgradient and discharge to low-lying features such as wetlands. Drainage provides a preferential pathway in shallow subsurface flow, which will influence interflow but does not negate the potential for runoff and exfiltration processes that may influence features such as wetlands.

2.8.2.1 Storm Interflow

Drainage depths representing storm interflow were established and adjusted through model calibration. A drainage depth of 0.5 m below ground surface (bgs) was established as being appropriate through model calibration. Interflow was inactivated within a 50 m buffer zone around rivers to prevent constant interflow from occurring in these regions, where the water table is frequently at ground surface. The drainage time constant is a parameter that limits the rate at which interflow may occur. During calibration, adjustments were made to the drain levels (point at which interflow occurs) and time constants to replicate the recession components of the observed hydrograph associated with interflow.

2.8.2.2 Agricultural Drainage

Agricultural drainage areas were identified within the Study Area based on the Tile Drainage Area Mapping maintained by LIO (2015). Zones of agricultural drainage were represented using the drainage representation in the MIKE SHE model (as in Section 2.7.1). The drain depth in these agricultural drainage areas was set to 1 m bgs, which is consistent with typical agricultural drainage depth (U.S. EPA 2012). The drainage time constant in these areas was set to five times the drainage constant used for interflow in the model to represent the increased ease with which subsurface drainage occurs in tile-drained areas.

2.9 Water Takings

To represent the effects of water withdrawals on flows in Lovers Creek, all permitted water takings were incorporated into the model. The water takings simulated in the model are all groundwater takings and include both municipal water takings and other permitted water takings consistent with those represented in the Barrie Tier Three FEFLOW model (AquaResource 2013).

2.9.1 Municipal Water Takings

Municipal water withdrawals were simulated within the Study Area based on those documented in the Barrie Tier Three Report and are summarized in Table 6.

TABLE 6 Municipal Pumping Wells

Community	Well Name	Easting (m)	Northing (m)	Screen Depth (m)	Pumping Rate (m^3/day)
Stroud	Well 1	610360	4909456	105.8 to 111.8	166
Stroud	Well 2 Standby	610356	4909438	102.1 to 107.0	166
Stroud	Well 3	610386	4909474	104.0 to 109.7	166
Barrie	Well 10	606225	4912601	86.0 to 93.6	2,124
Innisfil Heights	Well 2	605518	4905031	68.3 to 77.4	170
Innisfil Heights	Well 3	605560	4904863	60.8 to 68.6	170

2.10 Model Calibration

Model calibration is the process of adjusting model parameters, variables, and other inputs to reduce the differences between simulated and observed conditions (typically streamflow and groundwater levels). As hydrologic models are simplifications of the real world, a margin of error between the simulated and observed conditions is expected. Precipitation events not captured by the climate monitoring network, or a condition that deviates from average (e.g., a midwinter melt) can cause differences between simulated and observed conditions. When evaluating a model's performance, the focus should be on how well the model fits the seasonal and annual trends.

If a reasonable replication of observed conditions can be achieved by the model, then this provides evidence that the underlying hydrologic processes of the watershed are being properly represented by the model and confidence that the model may be used as a predictive tool to inform decision-making.

The calibration of the model was focused initially on achieving a reasonable overall water budget for the Study Area. This ensures that precipitation is realistically partitioned into the various hydrologic components of evapotranspiration, overland flow, and recharge to groundwater. Subsequent to obtaining a reasonable water budget, the focus of calibration shifted to matching streamflow and groundwater levels. The calibration process focused on a suite of metrics to gauge the model's match to observed flows. This approach recognizes that the application of the model to understanding environmental flows necessitates matching flows over a broad range to provide meaningful insight.

2.10.1 Model Calibration Period

A model calibration period was selected for the MIKE SHE model considering streamflow observational data and climate data availability.

A review of the quality of streamflow observations recorded at the Lovers Creek at Tollendal gauge was conducted to identify which periods of observations should be included in the calibration period. The review of streamflow observations considered daily streamflow quality ratings provided by the LSRCA as well as a review of the gauge rating curves and observed streamflow hydrograph for the period of record (2001 to 2015). Streamflow observations recorded from 2009 to present were identified as suitable calibration targets through this process.

The availability of hourly precipitation observations was the primary consideration in terms of climate data and the period of model calibration. Review of the available climate data revealed that hourly precipitation data was available from 1950 to 2013.

Given the intersection of available climate data and streamflow observations, the period of 2002 to 2013 was selected as the model calibration period. Note that due to streamflow observation quality, the streamflow calibration is evaluated over the period of 2009 to 2013 only. The model water balance, groundwater levels, and groundwater recharge are evaluated over the full calibration period.

2.10.2 Water Budget

The average annual water budget for the Study Area is presented in Table 7. The water budget equation used is provided in Equation 1. Inflows to the model domain are represented by positive numbers (e.g., precipitation) and outflows from the domain are represented by negative numbers (e.g., pumping).

TABLE 7 Average Annual Water Budget (2002 to 2013)

Water Budget Component	mm/year
Precipitation	916
Evapotranspiration	-537
Total streamflow	**-341**
(Overland flow to streams)	-177
(Baseflow to streams)	-163
Pumping	-14
Overland boundary flow	-13
Subsurface boundary flow	-12
Storage change	-1

Equation 1 Water Budget Equation

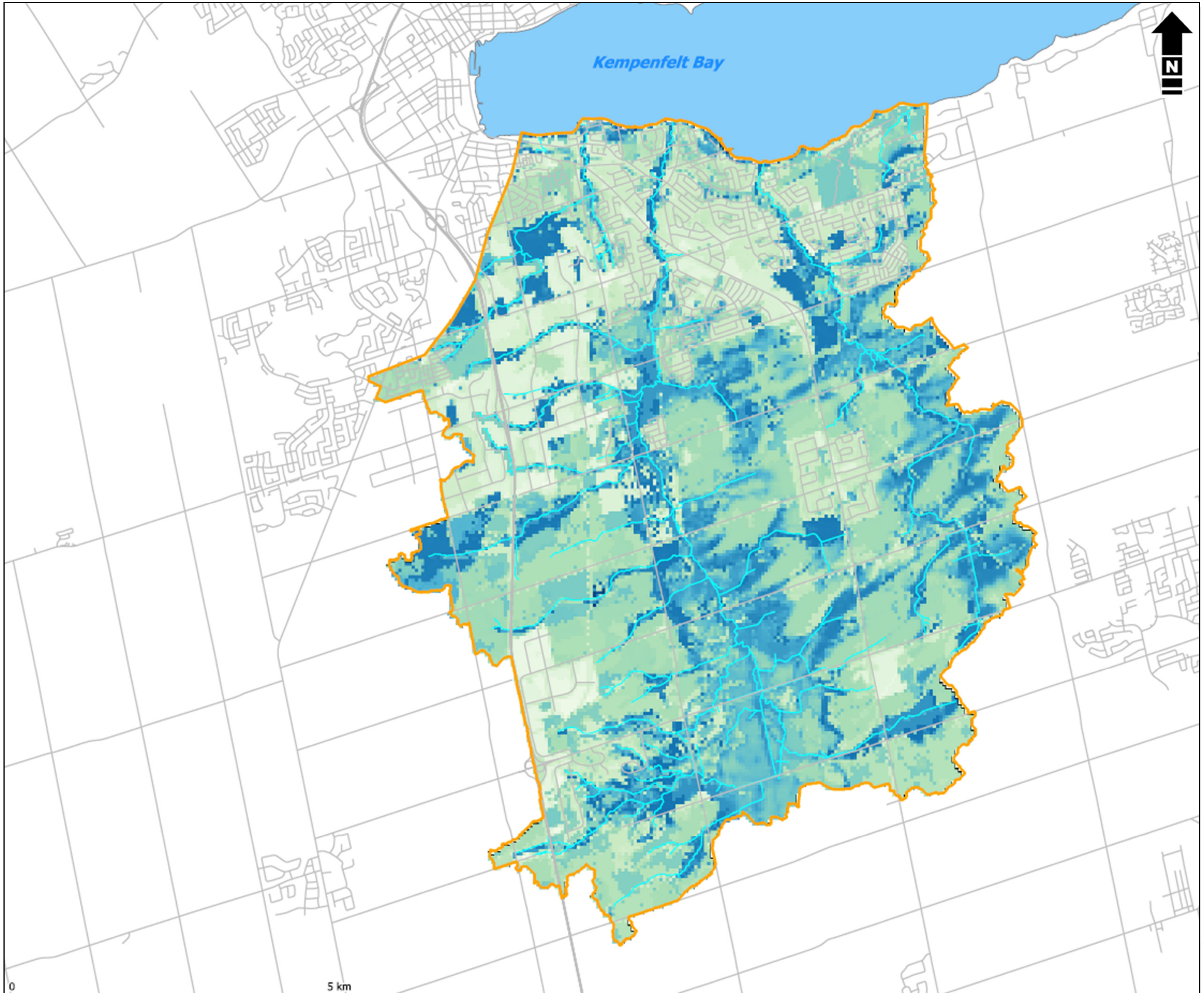
$$\Delta S = P + E + Q_{SO} + Q_{SB} + Q_P + Q_{BO} + Q_{BS}$$

Where:

ΔS - Storage change
P - Precipitation
E - Evapotranspiration
Q_{SO} - Overland flow to streams
Q_{SB} - Baseflow to streams (includes drain flow)
Q_P - Pumping
Q_{BO} - Overland boundary Flow
Q_{BS} - Subsurface boundary flow

Analysis of the long-term water budget indicates that a reasonable annual water balance has been achieved through calibration of the model. The average streamflow indicated by the water balance is considered reasonable for the region based on the available estimates of actual evapotranspiration, 500 to 600 mm/year on average for the region, as well as observed streamflow at the Water Survey of Canada (WSC) gauges within the watershed (MNR 1984).

Examination of the spatial distribution of evapotranspiration provides a valuable means of evaluating whether model predictions conform to theoretical understanding of the hydrology of the region. The spatial distribution of average annual evapotranspiration rates over the Study Area are shown on Figure 8. In areas with a shallow depth to water, such as along stream channels and in wetlands, increased rates of evapotranspiration occur as expected. The influence of surficial geology on evapotranspiration is also evident on Figure 8 as the fine-grained deposits of till and clay are distinguished from the sand and gravel regions by higher rates of evapotranspiration, due to their higher water content. Finally, urbanized areas in the region are distinguished by reduced evapotranspiration rates. The reduced evapotranspiration rate in urban areas is consistent with the lack of vegetation and reduced infiltration in these areas.



MIKE SHE Model Domain
Areas
Ontario_Roads
Lines
Ontario_Freeways
Lines
Watercourse
Lines
Lake Simcoe
Areas
Evapotranspiration Rate
mm/year
831
766
701
636
571
506
441
376
311

NAD 1983 UTM Zone 17N

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Modelling of Environmental Flow Targets for the Lovers Creek Subwatershed

Annual Average Evapotranspiration

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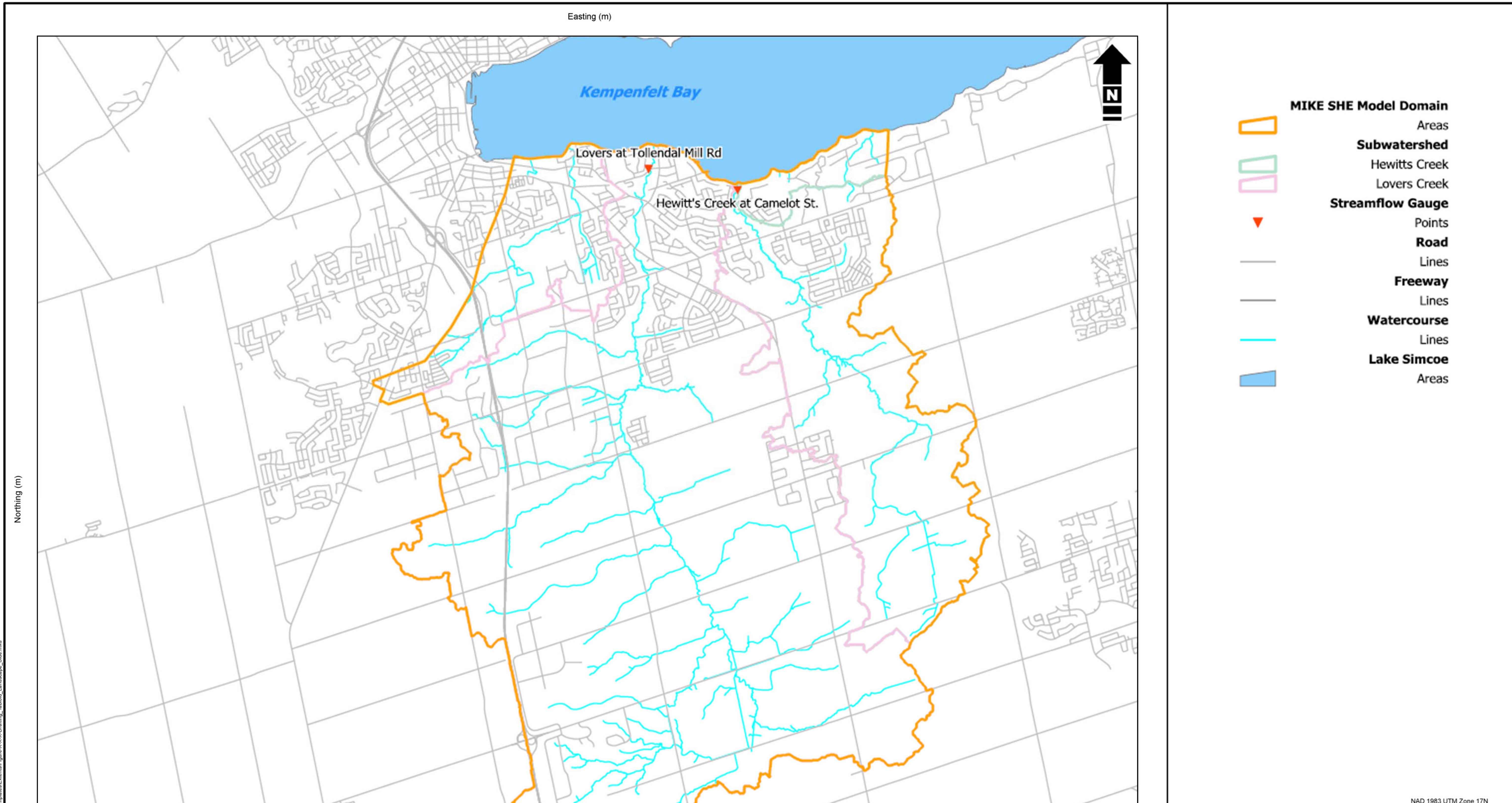
Figure 8

2.10.3 Streamflow Calibration

The streamflow representation within the model was evaluated on a variety of time scales at the Lovers Creek at Tollendal gauge as part of the calibration process. Initially, long-term average annual streamflow was evaluated to ensure a reasonable water balance. Annual flow analysis provides a good evaluation of whether precipitation is being appropriately partitioned into overland flow, evapotranspiration, and recharge to groundwater. Once a reasonable calibration to annual flows was achieved, the focus of streamflow calibration shifted towards the monthly representation of streamflow. Monthly representation of streamflow provides an evaluation of how well seasonal processes are being represented within the model (e.g., snow pack accumulation and melt). Finally, daily flows were evaluated to provide an analysis of streamflow representation in terms of event timing, magnitude, and post-event streamflow recession. As supplemental evidence of the model calibration, the average annual and monthly streamflow calibration of the model at Hewitt's Creek is included in this report. This watershed was included in the model domain but was not considered during the calibration process. The streamflow gauges are illustrated within the Study Area on Figure 9.

TABLE 8 Streamflow Observations

Station Name	Easting (m)	Northing (m)	Period of Record	Drainage Area (km^2)
Lovers Creek at Tollendal Mill Rd.	607431	4914120	2001 to 2015	60
Hewitt's Creek at Camelot St.	608946	4913761	2009 to 2015	18



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Streamflow Observation Locations

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Figure 9

The following sections summarize the evaluation of streamflow representation within the model.

2.10.3.1 Annual Flow

Streamflow calibration was initially focused on matching simulated and observed mean annual flow values. Annual streamflow values provide a long-term evaluation of the water balance of the model. Appropriate partitioning of precipitation to evapotranspiration, overland flow, and recharge to groundwater should produce mean annual flows that represent the observed streamflow values. The observed and simulated average annual streamflow are compared in Table 9.

TABLE 9 Average Annual Streamflow Calibration Statistics

	Lovers Creek at Tollendal Mill Road	Hewitt's Creek at Camelot Street
Mean Observed Flow (m^3/s)	0.65	0.16
Mean Simulated Flow (m^3/s)	0.68	0.17
Difference (%)	5	3
Mean Observed Flow (mm/y)	341	290
Mean Simulated Flow (mm/y)	359	299
Difference (mm/y)	19	9
Evaluation Period	2009 to 2013	2010 to 2013

The average annual flows for the evaluation periods in Lovers Creek and Hewitt's Creek are presented on Figure 10 and Figure 11, respectively.

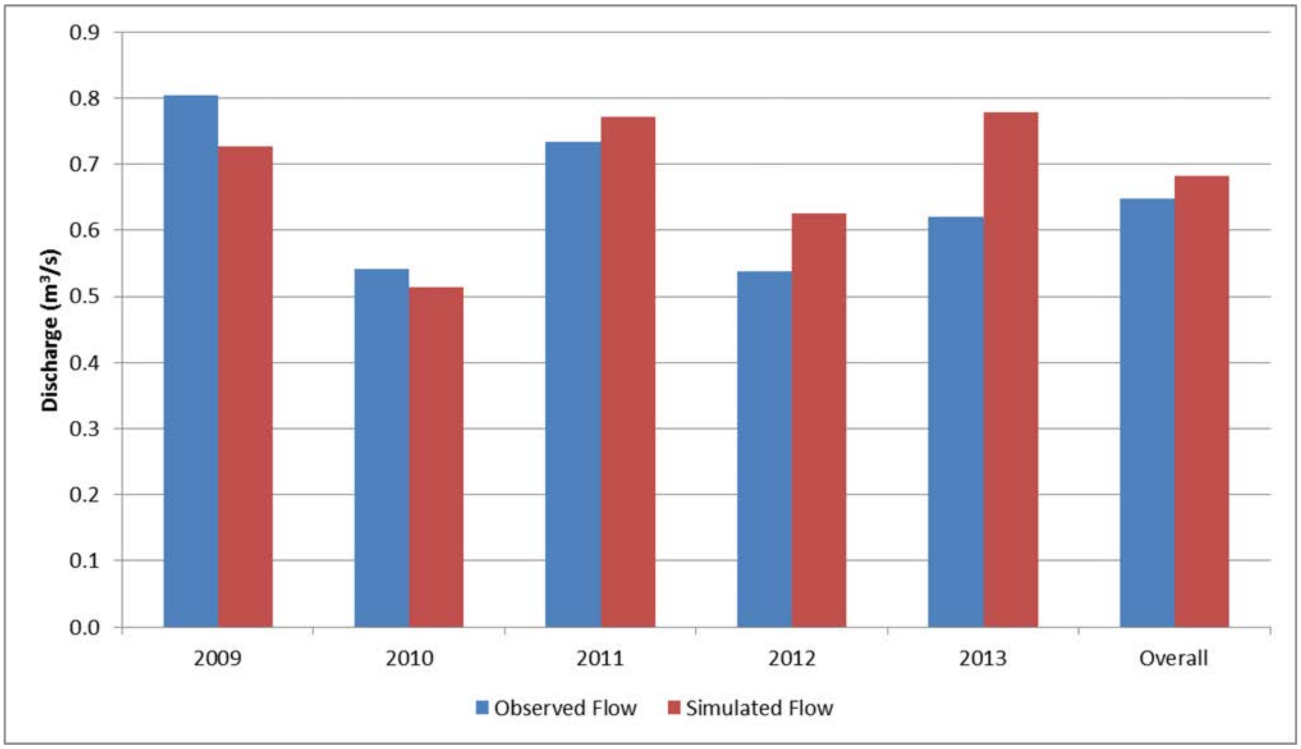


FIGURE 10 Lovers Creek - Average Annual Flow

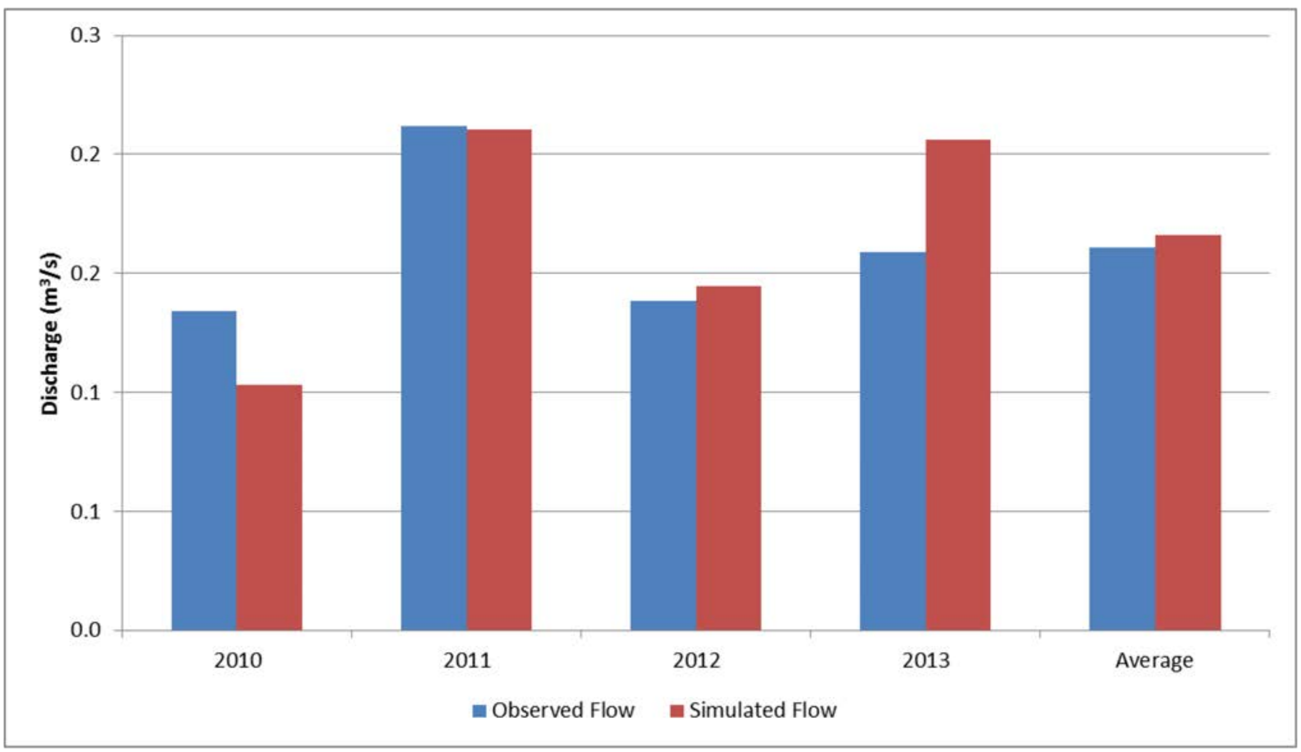


FIGURE 11 Hewitt's Creek - Average Annual Flow

The standard error in streamflow estimates is typically anywhere from 5% to 15% of the actual streamflow rate (Winter 1981). The difference between observed and simulated average annual flow is less than the accepted range of error for all gauges and as such the annual streamflow representation can be considered good.

2.10.3.2 Monthly Flow

Evaluation of mean and median monthly flows provides a good evaluation of how well the model represents seasonal behavior of the watershed. Mean monthly streamflow calibration statistics for Lovers Creek are presented in Table 10. A systematic quantitative evaluation of the accuracy of streamflow representation is conducted using Nash-Sutcliffe Efficiency (NSE). NSE indicates how well the simulated and observations fit a 1:1 line when plotted (Equation 2) and is a recommended quantitative statistic for measuring the accuracy of streamflow representation (Moriasi et al. 2007).

Equation 2 Nash-Sutcliffe Efficiency

$$= 1 - \left[\frac{\sum_{i=1}^{n}(Y_i^{Obs} - Y_i^{Sim})^2}{\sum_{i=1}^{n}(Y_i^{Obs} - Y^{mean})^2}\right]$$

Where: n is the total number of streamflow observations:

Y_i^{Obs} is the value of observed streamflow at time i
Y_i^{Sim} is the value of simulated streamflow at time i
Y^{mean} is the mean of the observed streamflow values

According to Chiew and McMahon (1993) and Nash and Sutcliffe (1970), NSE values may be related to calibration using the following guidelines:

- equal to 1 is a perfect fit
- greater than 0.8 is considered good
- greater than 0.6 is considered reasonable
- less than zero is when the observed mean is a better predictor than the model

While NSE is an accepted metric for reporting model fit, it is more sensitive to differences in observed and simulated flows at high flow rates than low flows due to the squaring of simulated and observed flows in the NSE equation. Calculation of NSE on the log transformation of streamflow values helps reduce NSE sensitivity towards fitting high flow rates and in turn, provides a streamflow representation metric, which considers high and low flow representation more equally. As such, the Log-NSE is presented in the mean monthly streamflow calibration metrics.

Overall, the calibration statistics provided in Table 10 indicate that a reasonable level of calibration was achieved in Lovers Creek.

TABLE 10 Mean Monthly Flow Calibration Statistics (2009 to 2013)

Mean Monthly Flow Calibration Statistics	Lovers Creek at Tollendal
Mean Observed Flow (m^3/s)	0.65
Mean Error(m^3/s)	0.04
R	0.66
Log-NSE	0.60

Charts that compare simulated and observed mean monthly flow and median monthly flow during the calibration period for Lovers Creek are presented on Figure 12 and Figure 13, respectively.

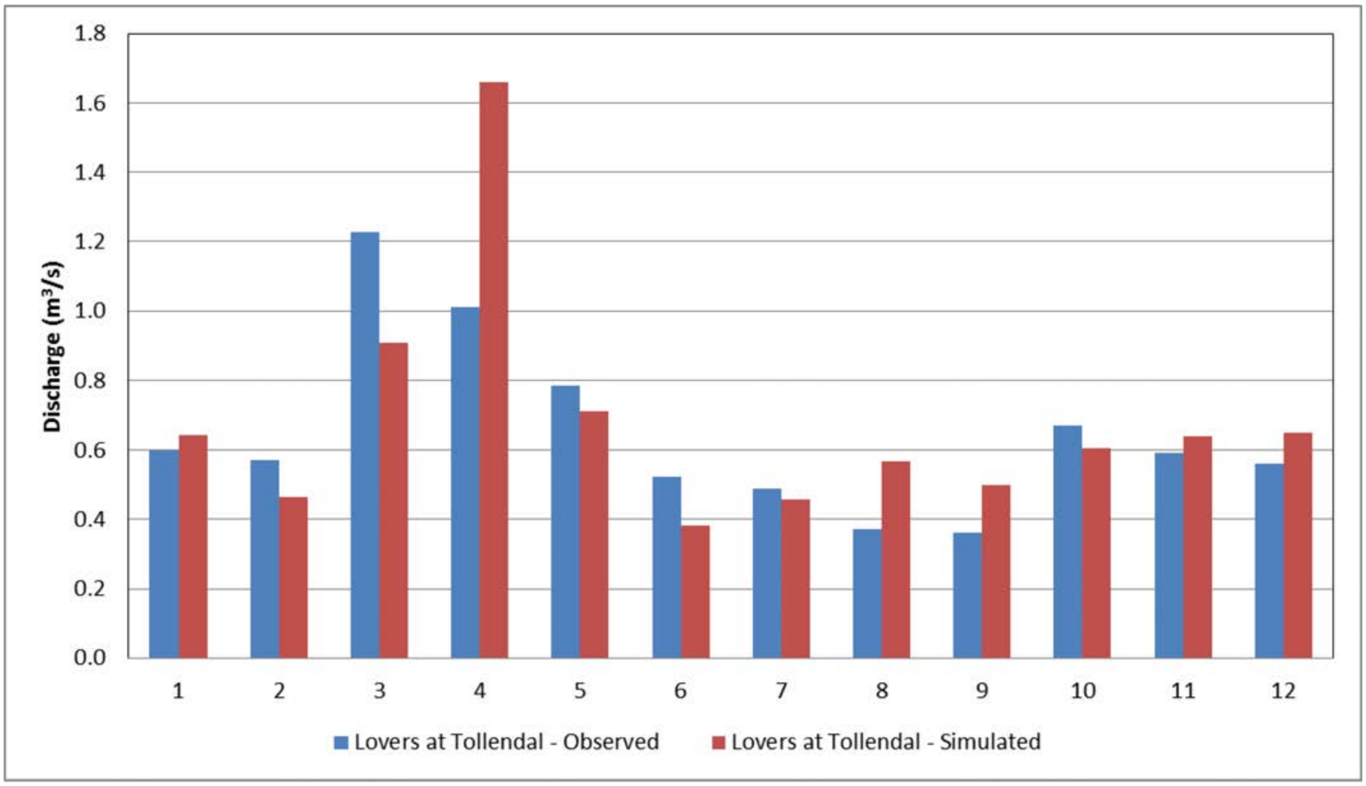


FIGURE 12 Lovers Creek Mean Monthly Flows (2009 to 2013)

In general, a good approximation of mean monthly flows was achieved in Lovers Creek. Spring flows associated with snow melt occur later than observed; however, all other periods of the year are reasonably represented.

Median monthly flows provide an alternative, frequency-based evaluation of monthly flows. This type of evaluation is useful as mean monthly flows may be skewed by a large single event. This is particularly relevant to the representation of summer precipitation events, which are typically localized convective storms and may or may not be captured by the local rain gauge and thus the climate data set used for model input. Rainfall observations obtained at the rain gauge are assumed to be representative of the conditions in their respective Thiessen polygon-derived areas; therefore, these events can easily be over- or under-estimated.

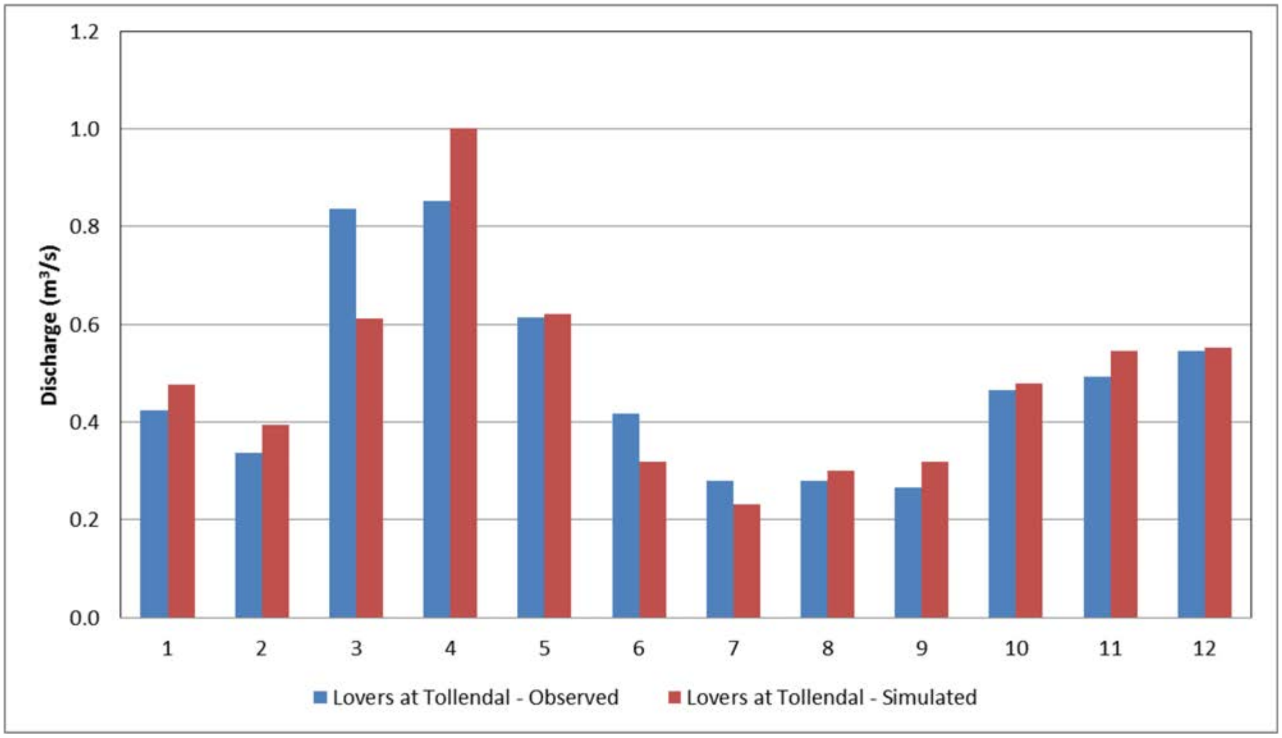


FIGURE 13 Lovers Creek Median Monthly Flows (2009 to 2013)

Examining the median monthly flow comparisons, it is evident that the model is representing median monthly flows well. Similar to mean monthly flows, simulated median monthly flow predicts spring melt flows slightly later than observed; however, other periods of the year are well represented.

2.10.3.3 Ranked Duration Curves

The comparison of the ranked duration curves for simulated and observed daily discharge provides an assessment of how well different magnitudes of streamflow are represented by the model. This calibration metric is particularly relevant to the application as the model must achieve a reasonable representation of a range of flows to provide meaningful insight into changes in environmental flows brought about by land use changes or climate changes.

The extreme high and low flows observed within the ranked duration curve are considered more uncertain because there are typically few streamflow measurements conducted during these flow regimes. Examination of the streamflow observation records confirms that observations greater than

2.0 m^3/s and below 0.2 m^3/s are relatively limited during the calibration period. As a result of this uncertainty fitting, the extreme high and low flows were not stressed during calibration.

Ranked duration curves were constructed using the simulated and observed daily discharge rates for Lovers Creek during the period of 2009 to 2013, and are presented on Figure 14.

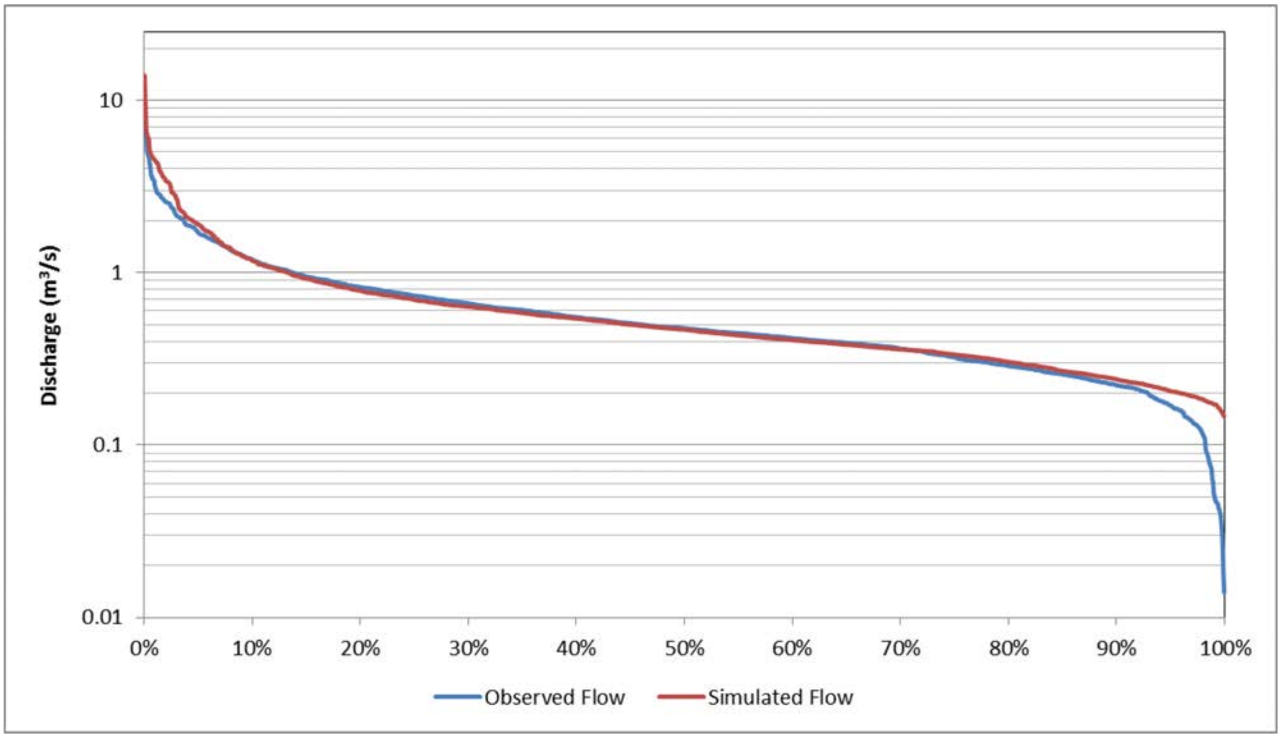


FIGURE 14 Lovers Creek - Ranked Duration Curve (2009 to 2013)

In general, a good representation of flow has been achieved throughout a wide range of flows for Lovers Creek.

2.10.3.4 Daily Flow

A daily streamflow hydrograph for 2012 is presented on Figure 15, as this year is characteristic of daily discharge representation for the model.

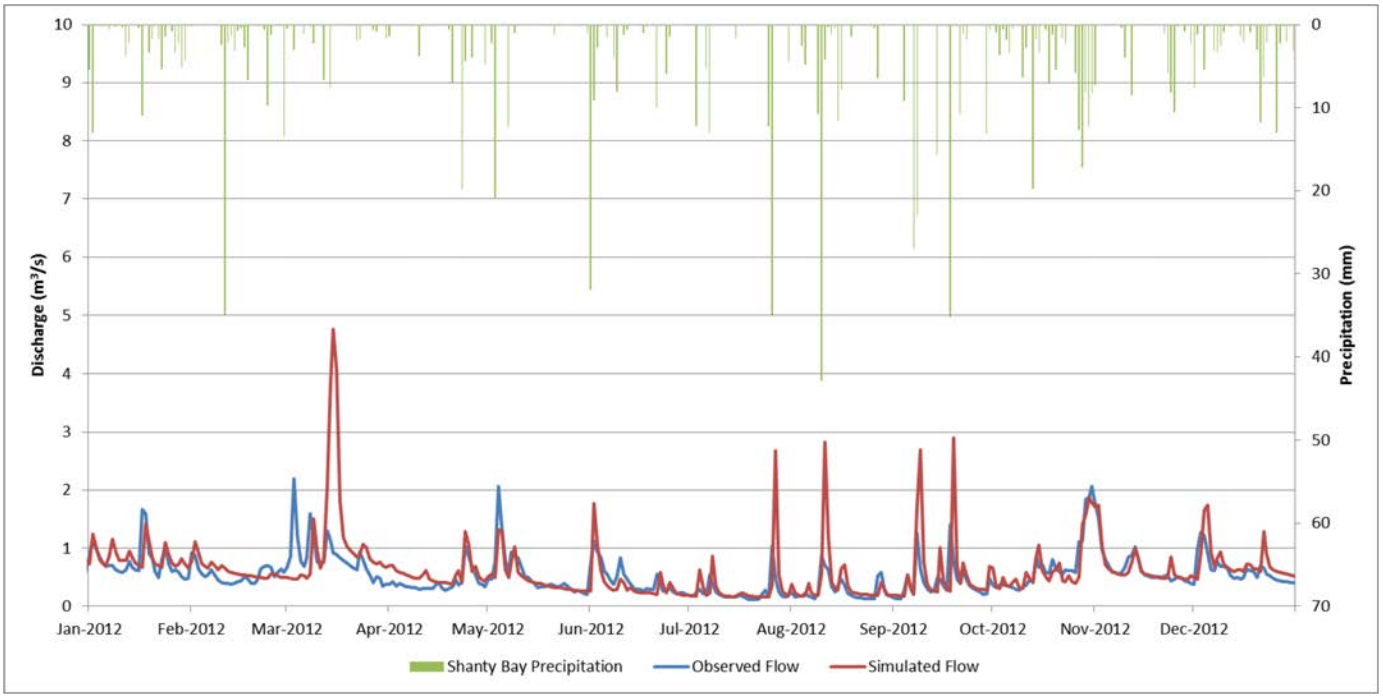


FIGURE 15 Lovers Creek Daily Streamflow 2012

In general, estimated streamflow events match the timing, magnitude, and duration of observed flows reasonably. In some instances, overestimation of streamflow events is occurring; however, this is often associated with significant events observed at the precipitation gauge (e.g., large events in August 2012) but not occurring over the watershed (i.e., as evident by the lack of streamflow gauge response).

2.10.4 Groundwater Calibration

To evaluate the groundwater flow representation of the model, simulated water levels were compared to observed water levels throughout the Study Area. The following section describes this evaluation.

2.10.4.1 Groundwater Water Levels

The evaluation of the groundwater flow portion of the model is conducted against static water level observations at wells in the Study Area. The observation dataset is taken from the water level observation dataset used in the Barrie Tier Three FEFLOW model (AquaResource 2013). The observation data set consist of water levels from the Ministry of the Environment and Climate Change Water Well Information System (MOECC WWIS) and high quality water level observations (City of Barrie Monitoring Well Network and Equipotential Surface Review Wells). These observations were compared against the average simulated water levels at the observation locations during the calibration period. The calibration statistics for 189 wells are summarized in Table 11.

TABLE 11 Groundwater Water Level Calibration Statistics (2002 to 2013)

Groundwater Level Calibration Statistics	
Number of Observations	189
Mean Error (m)	1.1
Mean Absolute Error (m)	5.8
Root Mean Squared (RMS) Error (m)	7.1
Normalized RMS Error (%)	9.5
Maximum Observed Head (m ASL)	292.4
Minimum Observed Head (m ASL)	218.0

RMS – root mean square

A review of spatially distributed, observed groundwater levels illustrated that there is a relatively large degree of scatter associated with local groundwater observations (Figure 16). This scatter may be due to the long time period represented by observation data. The spatial review was used to ensure that simulated values were representative of average conditions; the appropriateness of the fit is reflected in the mean error statistic in Table 11. The degree of scatter results in a higher than desirable (although acceptable) normalized root mean square (NRMS) statistic.

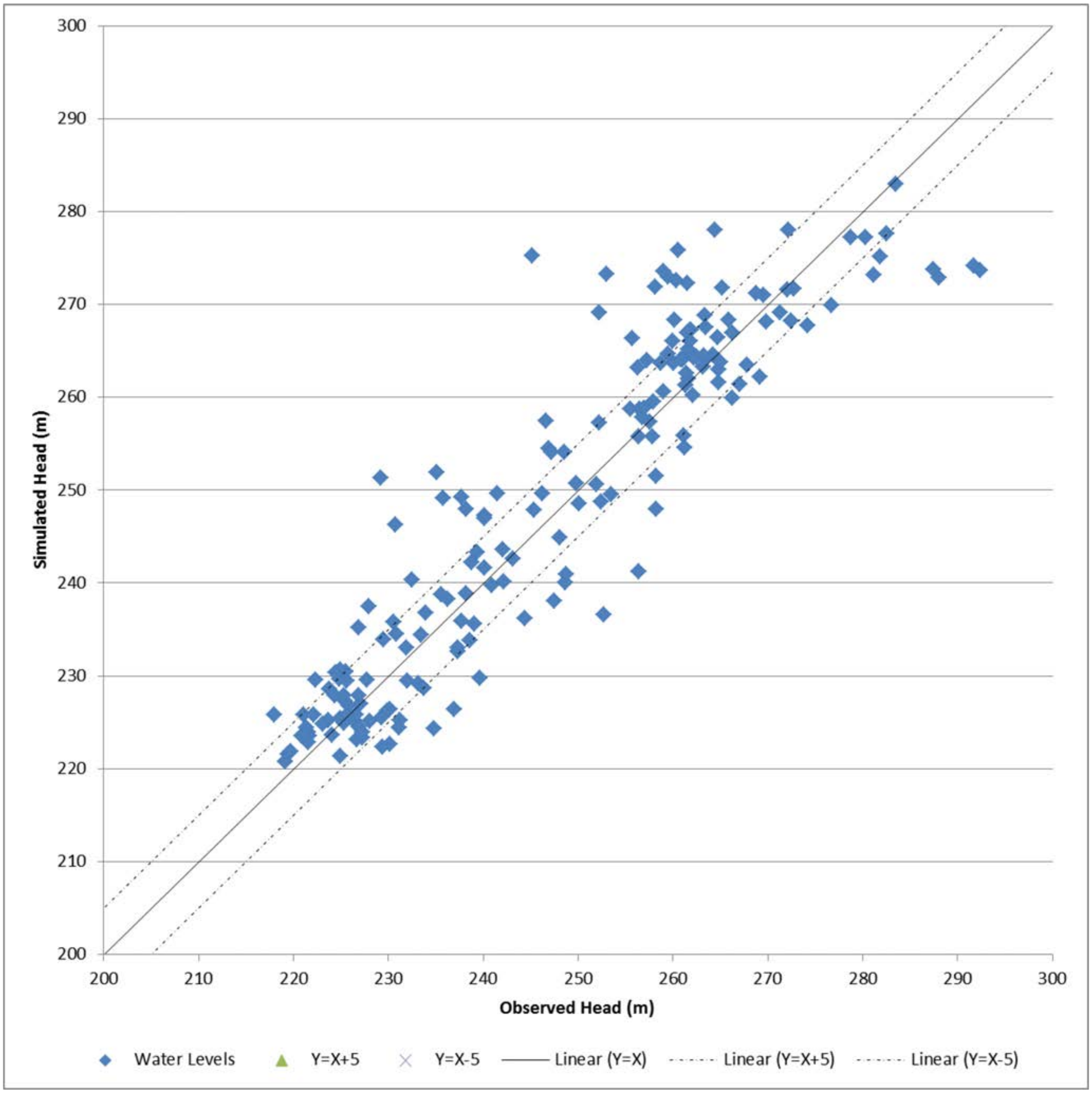
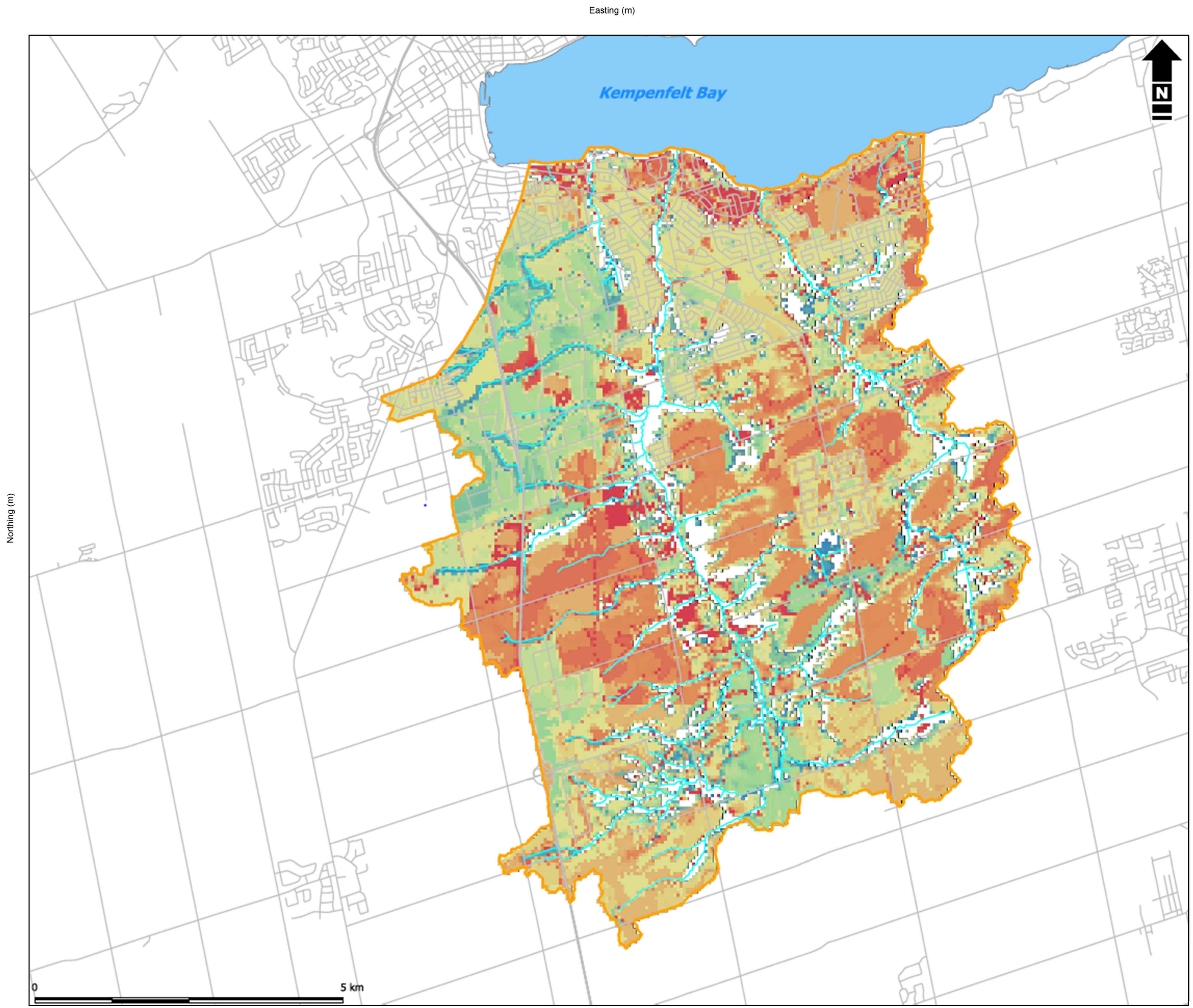


FIGURE 16 Simulated Vs. Observed Water Levels - Scatter Plot

2.10.4.2 Groundwater Recharge

Groundwater recharge was evaluated as during the model calibration process. The calibrated Barrie Tier Three FEFLOW model was calibrated to have an average annual recharge rate of 307 mm/year over the Study Area (AquaResource 2013). The calibrated Lovers Creek MIKE SHE model had a very similar groundwater recharge rate of 291 mm/year (Figure 17). As such, the groundwater recharge rates simulated by the FEFLOW and MIKE SHE models are considered consistent.



MIKE SHE Model Domain
Areas
Road
Lines
Freeway
Lines
Watercourse
Lines
Lake Simcoe
Areas
Groundwater Recharge
mm/year
500
400
300
200
100
0

NAD 1983 UTM Zone 17N

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Modelling of Environmental Flow Targets for the Lovers Creek Subwatershed

Annual Average Groundwater Recharge (2002-2013)

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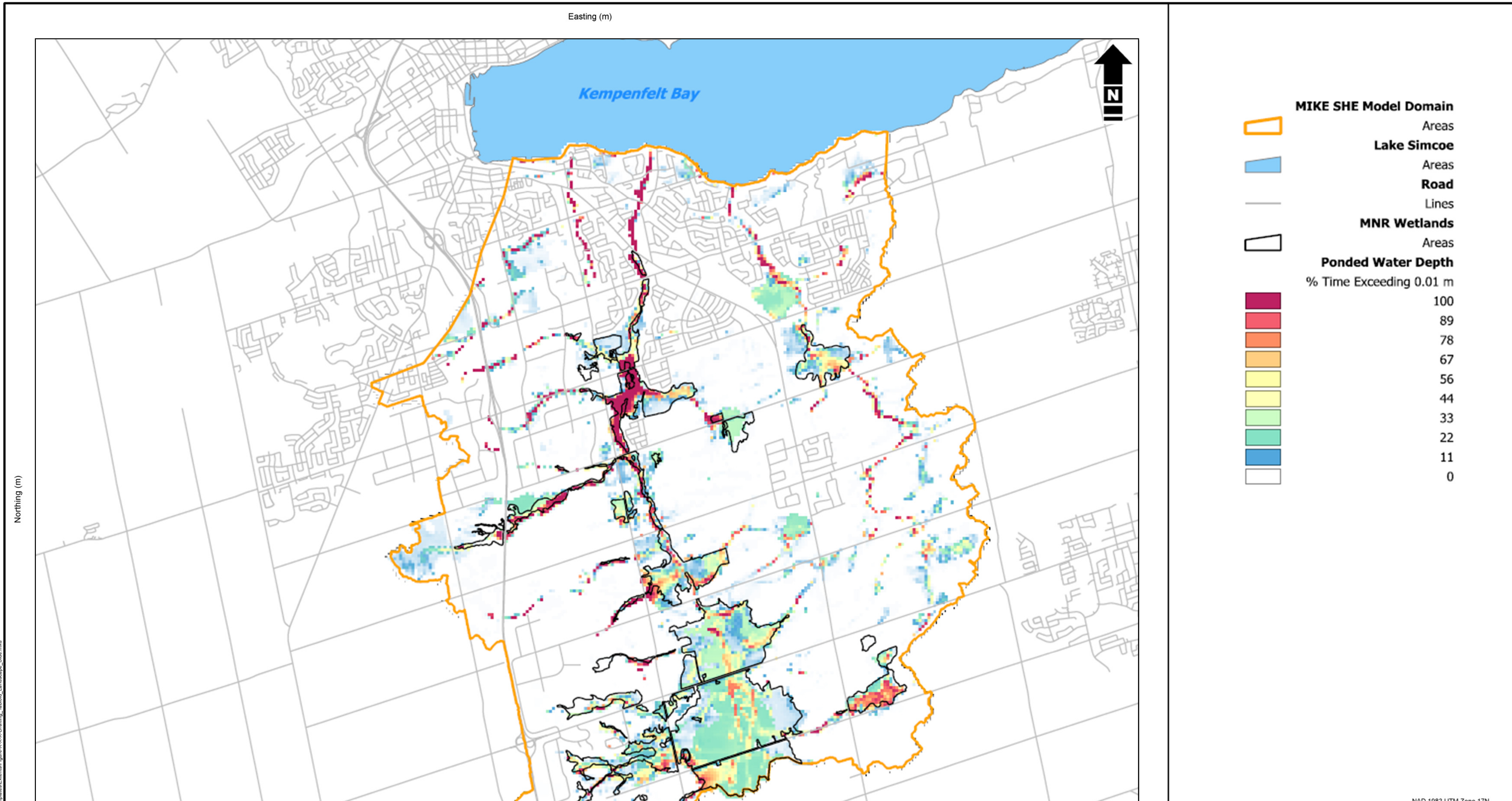
Figure 17

2.11 Model Verification

As a model verification, check the depth of ponded water predicted by the model that was evaluated throughout the calibration period to determine the level of agreement that exists between identified wetlands and simulated wetlands.

A frequency analysis of ponded water simulated by the model is presented on Figure 18.



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Modelling of Environmental Flow Targets for the Lovers Creek Subwatershed

Frequency of Ponded Water Exceeding 0.01 m vs MNR Wetlands

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Figure 18

This map illustrates the frequency with which ponded water exceeded a reference depth of 0.01 m during the calibration period. The areas which frequently exceed this threshold are simulated to be probable wetland areas. In general, a good agreement between the MNRF mapped wetlands and those simulated with the model is observed. This type of analysis also provides critical insight into the transient nature of wetlands in the area as lower percentage wetland areas may be considered ephemeral and high percentage areas may be considered perennial.

3 E-FLOW EVALUATION

The evaluation of development stressor states and future climate scenarios was conducted using the calibrated MIKE SHE model. All evaluations were conducted using climate data from the period from 1980 to 2000; this period is assumed representative of future conditions, neglecting potential climate change effects. Climate observations from the Cookstown Environment Canada climate station were assumed representative of the entire Lovers Creek watershed for the stressor state comparisons.

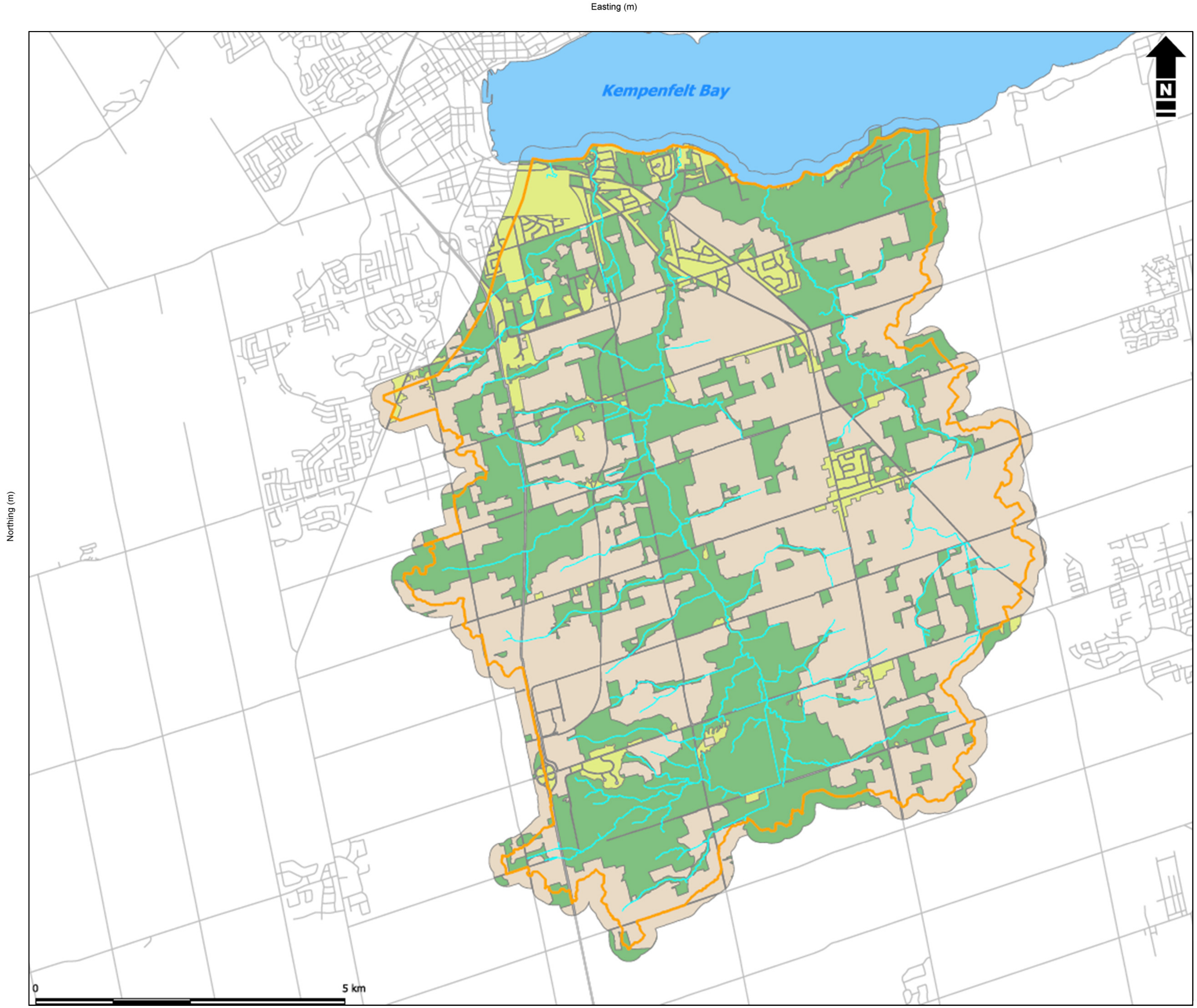
Section 3.1 describes the stressor state scenarios; Section 3.2 describes the evaluation locations throughout the watershed. The results are summarized in Sections 3.3 and 3.4; Appendices A through I present detailed results.

3.1 Stressor States

The effect of land development within the watershed on environmental flows was examined through the evaluation of differing levels of development for three "stressor states." These stressor states represent the development of the Study Area under current conditions, 1978 conditions, and pre-development conditions.

To represent each stressor state, the land use within the MIKE SHE model was updated to be consistent with the stressor state land use. A revised land use representation was created for the 1978 and pre-development scenarios within the MIKE SHE model. The changes in land use results in changes the spatial distribution of vegetation, surface roughness, depression storage, and directly connected impervious surfaces. Agricultural drainage was included in the 1978 Stressor State and assumed to be identical to agricultural drainage as represented in the current conditions model.

A 1978 land use mapping was provided to Matrix based on historic aerial photograph interpretation from this period conducted by the LSRCA and is presented on Figure 19.



MIKE SHE Domain
Areas
Road
Lines
Freeway
Lines
Watercourse
Lines
Lake Simcoe
Areas
Land Use 1978
Agriculture
Natural Heritage
Rail
Road
Urban
Urban_Road
Water

NAD 1983 UTM Zone 17N

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Historical Land Use (1978)

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Figure 19

Land use within the MIKE SHE model was updated to represent this historic land use state. This process involved revising land use within the model and updating the vegetation, depression storage, surface roughness, and directly connected impervious areas to be consistent with this land use distribution.

3.1.1 Pre-development Stressor State

Land use within the MIKE SHE model for the pre-development stressor state was represented as a continuous coverage of forest. The land use within the MIKE SHE model was updated to represent this pre-development land use state. Land use was revised to represent appropriate vegetation, depression storage, and surface roughness. All directly connected impervious areas were removed in this development state. Additionally, all agricultural drainage was removed from the model as well as all pumping.

3.1.2 Future Climate Scenarios

An assessment of the effects of climate change on environmental flows within the Study Area was developed consistently with the methods outlined in the *Guide for Assessment of Hydrologic Effects of Climate Change in Ontario* (EBNFLO and AquaResource 2010). The Percentile Approach articulated in this guidance document has been adopted here to select which Global Climate Models (GCMs) and which Greenhouse Gas (GHG) emission scenarios to select. Ten future climate projections were selected, from a range, produced by GCMs and respective GHG emission scenarios, for the Environment Canada Cookstown climate station for the period from 2011 to 2040. Climate projections were selected in terms of both change in mean annual precipitation and change in mean annual temperature relative to the reference period of 1971 to 2000. Climate projections, which represented the 5th, 25th, 50th, 75th, and 95th percentile climate change scenarios in terms of change in mean annual precipitation and change in mean annual temperature were selected. The selected climate change model projections are summarized on Figure 20 and listed in Table 12. The subset of climate projections selected by the percentile approach represent the full range of predicted future climates and are therefore appropriate for examining the central tendency among projected future climate conditions as well as more extreme conditions projected (i.e., 5th and 95th percentile).

A "change field" approach is employed to represent the projected future climate conditions. Monthly factors for temperature and precipitation are generated through a comparison of the mean monthly temperature and mean monthly precipitation in the baseline and future climate conditions. These monthly factors are then applied to the existing climate dataset at the Cookstown climate station. Thus, the daily temperature observations and hourly precipitation observations at Cookstown are perturbed by monthly factors for each of the ten selected climate change projections. This process generated ten sets of climate data, including daily temperature, daily evapotranspiration, and hourly precipitation, which serve to represent the conditions for ten unique future climate scenarios.

To evaluate the impacts of the selected climate scenarios, the model was run from 1971 to 2000 for each of the climate scenarios. The assessment of the climate change scenarios focused on the period from 1980 to 2000. This period was chosen after examination of the generated climate data, which resulted in non-natural conditions that affected flows during a period of the 1970s. The period from 1980 to 2000 was selected to ensure the climate change analysis was unaffected by this issue.

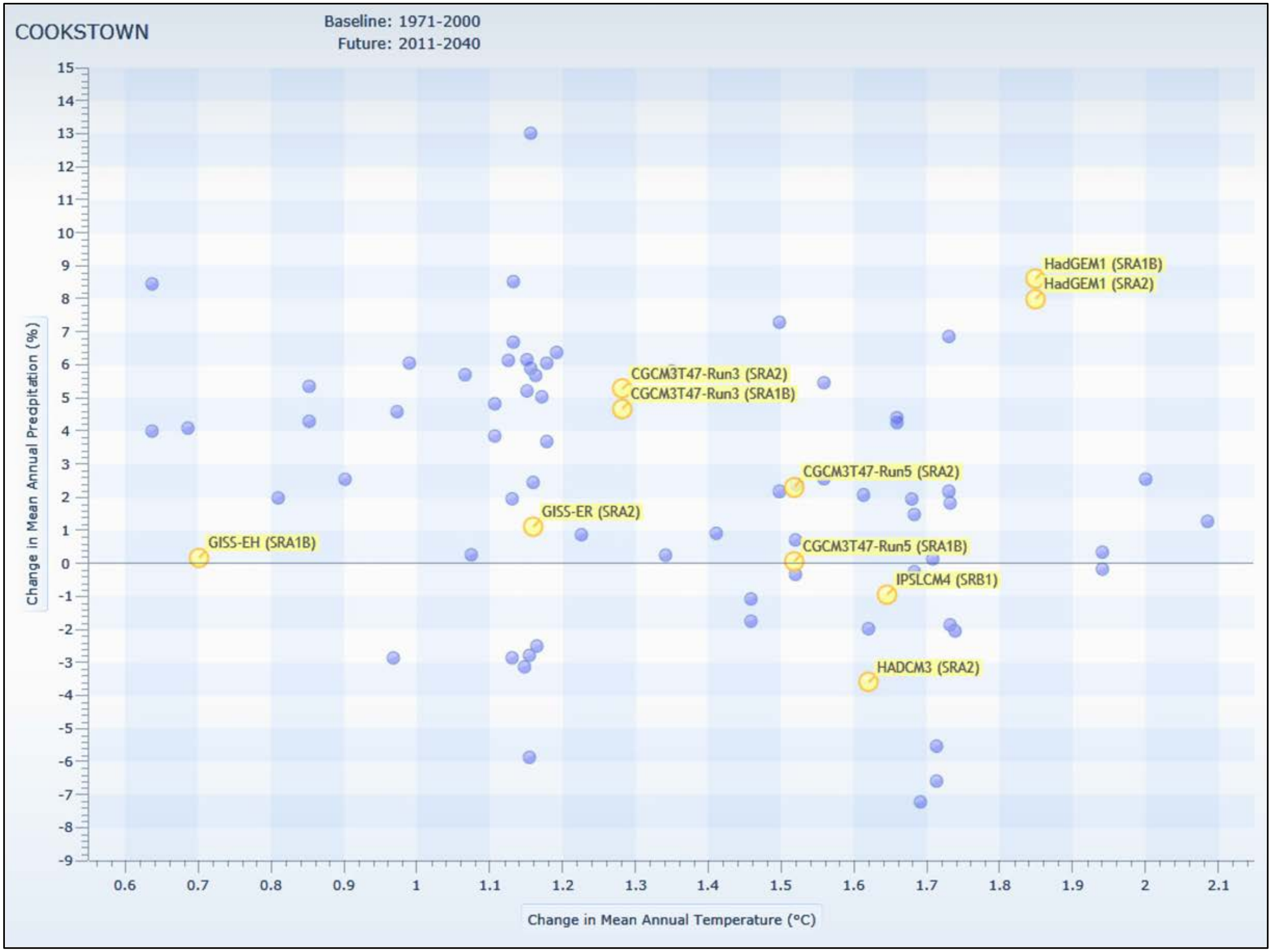


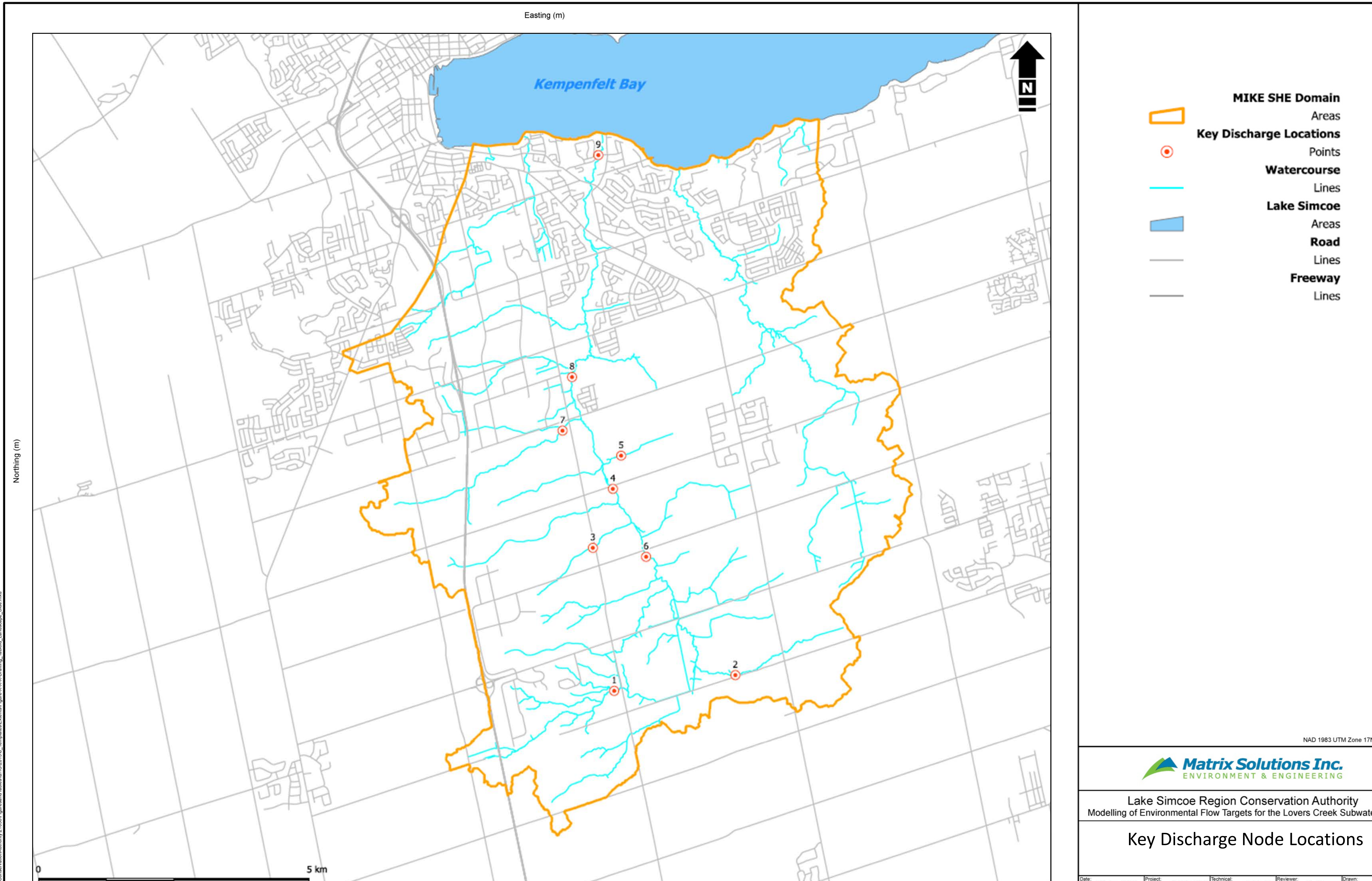
FIGURE 20 Climate Change Scenarios for Cookstown Climate Station

TABLE 12 Climate Change Scenarios for Cookstown Climate Station

Climate Scenario	Global Climate Model
CLM1	CGCM3T47-Run3 (SRA1B)
CLM2	CGCM3T47-Run3 (SRA2)
CLM3	CGCM3T47-Run5 (SRA1B)
CLM4	CGCM3T47-Run5 (SRA2)
CLM5	GISS-ER (SRA1B)
CLM6	GISS-ER (SRA2)
CLM7	HADCM3 (SRA2)
CLM8	HADGEM1 (SRA1B)
CLM9	HADGEM1 (SRA2)
CLM10	IPSLCM4 (SRB1)

3.2 Key Discharge Locations

The LSRCA identified nine key locations in Lovers Creek to assess environmental flows. The locations of these key discharge nodes are shown on Figure 21. These locations were selected by LSRCA to represent various land use conditions, and other variables throughout the watershed.



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Key Discharge Node Locations

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Figure 21

3.3 Summary

Changes in streamflow under land use stressor states and climate change scenarios were assessed at the pre-determined key locations in the Study Area (see Section 3.2) through a variety of graphic and statistical analyses. Evaluation of streamflow changes included the following:

- ranked duration curves
- Indicators of hydrologic alteration (IHA) statistical evaluation to characterize flow changes throughout the entire hydrologic regime

These results are presented in Appendix A (Key Location 1), Appendix B (Key Location 2), Appendix C (Key Location 3), Appendix D (Key Location 4), Appendix E (Key Location 5), Appendix F (Key Location 6), Appendix G (Key Location 7), Appendix H (Key Location 8), and Appendix I (Key Location 9).

The selected IHA metrics presented include peak magnitude, timing, duration, and annual frequency for extreme low flow events, high flow events, small flood events (2-year), and large flood events (10-year). The rise and fall rates are also presented for high flow events, small flood events (2-year), and large flood events (10-year). Flows exceeding 75% of the daily flows were defined as high flows and flows less than 75% were defined as low flows. Extreme low flows were defined as an initial low flow below 10% of the daily flows over the period of record. To compare climate scenarios, the predictions for each metric were ranked among the ten climate scenarios. For brevity, only the minimum, median, and maximum value predicted by a climate scenario for each metric are presented and discussed.

To characterize seasonal changes, the monthly 10^{th}, 50^{th}, and 90^{th} percentile flows were assessed and compared graphically between scenarios. To compare climate scenarios, monthly discharges were ranked among each climate scenario and the median value predicted by a climate scenario for that month was denoted as a red marker (see appended materials). The range bars display the highest and lowest monthly discharge value predicted within a climate scenario (i.e., a shorter bar indicates agreement in predictions among climate scenarios).

A summary of changes identified in the metrics under development and future climate projections are highlighted in Table 14. These changes are identified for each key location, along with a description of these locations and a characterization of their contributing drainage area.

Within the land use stressor states, it was identified that, for a number of locations, baseflow had decreased under pre-development conditions relative to the historic (1978) and current development stressor states. The decrease in baseflow is primarily related to increases in vegetative cover in pre-development conditions. The average rooting depth of vegetation is increased throughout most of the study area in the pre-development stressor state. As a result of this, evapotranspiration rates are increased in the pre-development state. The average annual evapotranspiration rates for each of the land use stressor states are presented in Table 13.

TABLE 13 Land Use Stressor State Average Annual Evapotranspiration Rate (1971 to 2000)

Land Use Stressor State	Evapotranspiration (mm/year)
Predevelopment	622
Historic (1978)	574
Current	526

A reduction in evapotranspiration with deforestation is consistent with current scientific understanding (Sahin and Hall 1996; Bala et al. 2007; Woodward et al. 2014).

TABLE 14 Environmental Flows Evaluation Summary

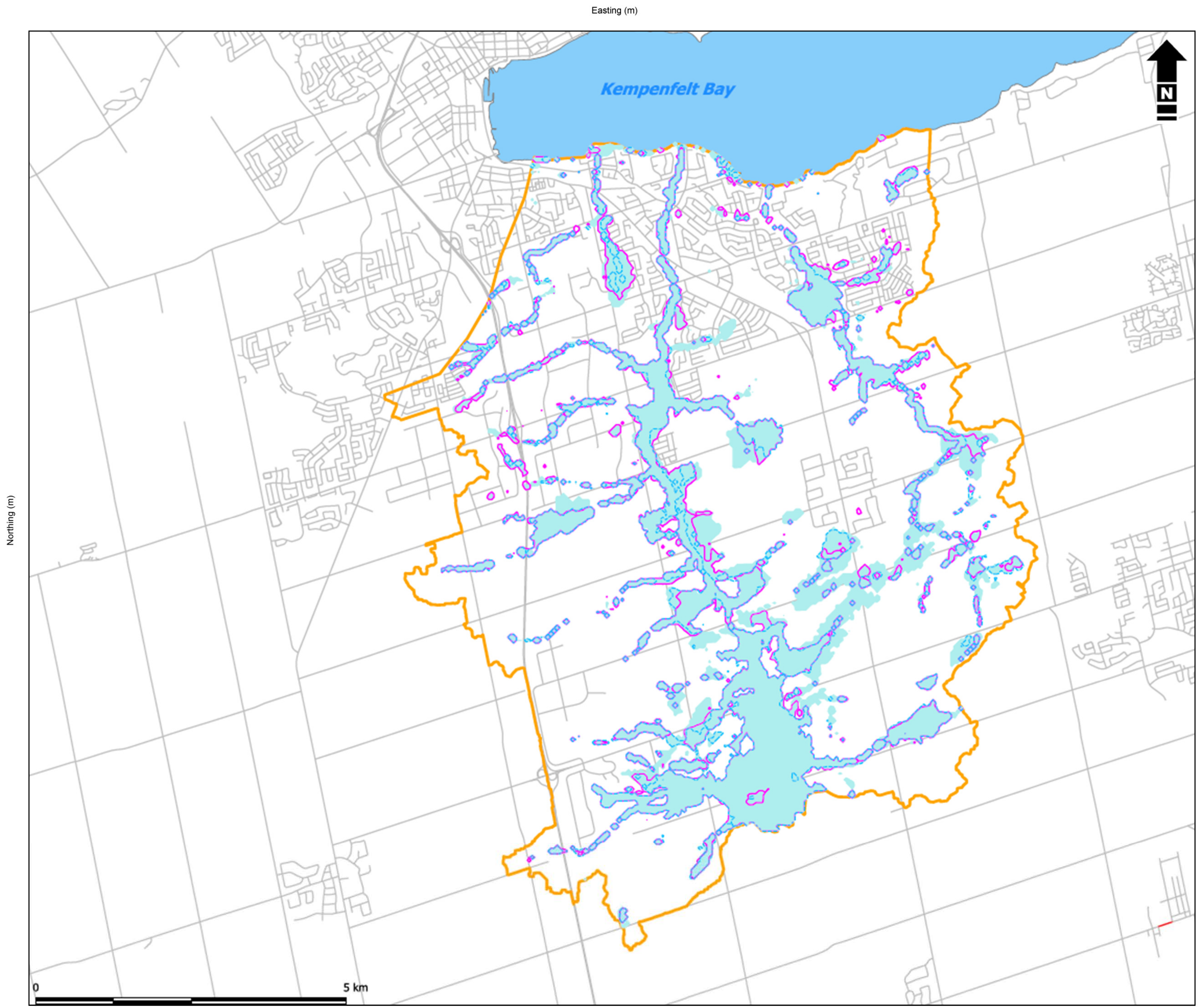
	Key Discharge Location and Characteristics	Response to Changes in Land Use	Response to Climate Change
Key Location 1	***Location:*** Upstream of Centennial Park at 10th Sideroad (tributary). ***Surficial Geology:*** Catchment is largely sand with silt/till, gravel, and clay. ***Land Use:*** Located on upstream edge of wetland. Catchment is largely forest, with some residential and commercial/industrial development at the headwaters. ***Physiography:*** Peterborough Drumlin.	***Ranked Duration:*** All flows increased with the level of development, deviation in lower flows most noticeable between land use scenarios. ***Extreme Low Flow Event:*** Increase in peak flows and in frequency with development. Decrease in duration with development. ***High Flow Event:*** Increase in peak flows, rise and fall rates, and frequency with development. ***Small Flood (2-year):*** Increase in peak flows, rise and fall rates with development. Decrease in duration with development. Events occur later under development. ***Large Flood (10-year):*** Increase in peak flows, rise and fall rates with development. Decrease in duration with development. ***Seasonal Flows:*** Slightly higher flows in the spring under the 1978 Land Use compared to predevelopment. Increase in Spring, Summer, and Fall monthly flows under Current Land Use.	***Ranked Duration:*** Nearly all climate change scenarios are in agreement that the large and mid-ranged flows will increase with climate change. Most models also predict an increase in low flows. ***Extreme Low Flow Event:*** Minimal change. ***High Flow Event:*** Occurring later. ***Small Flood (2-year):*** Increasing in duration and occurring between 2 weeks and 2 months earlier. ***Large Flood (10-year):*** The rise rate and magnitude of peak flows are predicted to increase. ***Monthly Flows:*** Low flows are increasing in the winter and early spring months (December to April). Median monthly flows are increasing in November to April. High flows are increasing from December to March. The shift in the 90th percentile flows from peaking in March in the baseline scenario to April in the climate change scenarios indicates a shift towards an earlier snowmelt.
Key Location 2	***Location:*** Downstream of Yonge street near 7th Line (tributary). ***Surficial Geology:*** Catchment is mainly silt/till and gravel, with some clay and sand deposits. ***Land Use:*** Mainly agriculture with some wetland and forest. ***Physiography:*** Peterborough Drumlin.	***Ranked Duration:*** All ranges of flows increased in 1978 Land Use from pre-development. Current land use flows are very similar to 1978, with slight differences in low flows. ***Extreme Low Flow Event:*** Increase in peak flows, frequency, and decrease in duration. ***High Flow Event:*** Increase in peak flows, and event frequency and earlier event timing with 1978 land use. Similar results between 1978 and current land use. ***Small Flood (2-year):*** Increase in peak flows. Similar results between 1978 and current land use. ***Large Flood (10-year):*** Increase in peak flows, with later event timing, and shorter event duration. Similar results between 1978 and current land use. ***Seasonal Flows:*** Increase in all months for all levels of flow (10th, 50th, and 90th) with 1978 land use. Further increase with current land use evident only in spring and summer.	***Ranked Duration:*** The majority of the climate change scenarios are in agreement that the large and mid-ranged flows will increase with climate change while the magnitude of low flows will decrease. ***Extreme Low Flow Event:*** Minimal change. ***High Flow Event:*** Large spread in event timing. ***Small Flood (2-year):*** Rise rate for small flood is increasing in all scenarios. Large variance on duration and timing of a small flood. Generally they are shorter in duration. ***Large Flood (10-year):*** Duration of Large floods is increasing, and generally peak events are getting larger ***Seasonal Flows:*** Low flows are increasing in winter months, particularly in march, while summer low flows are similar to baseline. Median flows are increasing in Winter. The 90th percentile flows indicate a shift to an earlier snowmelt.
Key Location 3	***Location:*** 10th Sideroad downstream of 9th Line (tributary). ***Surficial Geology:*** Gravel, silt/till with some sand. ***Land Use:*** Mainly agriculture, some commercial/industrial development at upstream location. ***Physiography:*** Peterborough Drumlin.	***Ranked Duration:*** With 1978 land use, rating curve appears to have shifted upwards. Very high flows (exceedances <25%) are much higher in current land use, while mid-ranged to low flows are unchanged from 1978 land use. ***Extreme Low Flow Event:*** Increase in frequency and decrease in duration with development. ***High Flow Event:*** Increase in peak flow, rate and fall rates, frequency, and later timing with development. ***Small Flood (2-year):*** Increase in peak flow, rate and fall rates, decrease in duration, and later timing with development. ***Large Flood (10-year):*** Increase in peak flow, rate, and fall rates, decrease in duration, and later timing with development. ***Seasonal Flows:*** 1978 land use sees even increase in 10th, 50th, and 90th monthly flows for all months. Current land use is similar to 1978 in 10th percentile, with slightly higher spring and fall peaks in 50th percentile, with much higher spring melt in 90th percentile and higher August and fall flows.	***Ranked Duration:*** Climate change scenarios are in disagreement as to whether flows with exceedance percentages less than 25% will increase or decrease. With the exception of one scenario, the models consistently predict similar or increased flows between the 25th and 100th percent exceedance threshold. ***Extreme Low Flow Event:*** Occurring later in the summer. ***High Flow Event:*** Large spread in event timing ***Small Flood (2-year):*** Becoming shorter in duration, generally occur later, more frequent, and increase up to 10x in peak magnitude with a higher rise rate. ***Large Flood (10-year):*** Increase in peak flows and rise rate. ***Seasonal Flows:*** Low flows are higher in most months, especially in the winter and early spring. Median Monthly flows increase November through June with the exception of April the peak flow month. 90th percentile flows increase November through March, while decreasing in April. This suggests a more gradual less peaky snowmelt.

	Key Discharge Location and Characteristics	Response to Changes in Land Use	Response to Climate Change
Key Location 4	***Location:*** Just upstream of 10th Line (main branch). ***Surficial Geology:*** Catchment is a mixture of sand, clay, silt/till, and gravel. ***Land Use:*** Mainly wetland and agriculture, with some forest and development. ***Physiography:*** Peterborough Drumlin.	***Ranked Duration:*** Shift increase for all ranges of flows from predevelopment to 1978 land use and again to current land use. ***Extreme Low Flow Event:*** Increase in frequency and decrease in event duration with development. ***High Flow Event:*** Increase in peak flow, rise and fall rates and event frequency; decrease in duration, and earlier event timing with development. ***Small Flood (2-year):*** Increase in peak flow, rise and fall rates and earlier event timing with development. ***Large Flood (10-year):*** Increase in peak flow, and rise and fall rates with development. Later event timing under current development. ***Seasonal Flows:*** Increase in all months from predevelopment to 1978 and again to current land use. Largest increase observed in the spring.	***Ranked Duration:*** Under future climate conditions, medium to high flows are likely to increase. ***Extreme Low Flow Event:*** Minimal change. ***High Flow Event:*** Large spread in event timing, increase in median peak flow. ***Small Flood (2-year):*** Median results show decrease in peak flow. Most small floods occur in spring during the freshet, while other models predict these to occur as late as November. ***Large Flood (10-year):*** Magnitude of large flood increasing. ***Seasonal Flows:*** Increased 10th and 50th percentile flows in January, February, and March. Minimal change in high flows.
Key Location 5	***Location:*** Upstream of National Pines Golf Club, east of main branch (tributary). ***Surficial Geology:*** Mainly silt till. ***Land Use:*** Mainly agricultural. ***Physiography:*** Peterborough Drumlin.	***Ranked Duration:*** Flows increase with development, particularly in lower flows (flows >50% exceedance) where the curves diverge. ***Extreme Low Flow Event:*** Increase in frequency and decrease in duration with development. ***High Flow Event:*** Magnitude of peak event highest under 1978 land use. Increase in rise and fall rate and event frequency with development. Decrease in duration and later timing of events with development. ***Small Flood (2-year):*** Increase in peak flows, and rise and fall rate with development. Later event timing with development. ***Large Flood (10-year):*** Increase peak flows and rise and fall rates with development. ***Seasonal Flows:*** Increased spring flows with development. The 50th and 90th fall flows reduced with development.	***Ranked Duration:*** Most models are predicting higher flows for flows with an exceedance probability less than 50%. ***Extreme Low Flow Event:*** Occurring later in summer. ***High Flow Event:*** Occurring earlier. ***Small Flood (2-year):*** Occurring earlier. Median peak flow increasing. ***Large Flood (10-year):*** Peak discharge for large flood events are more attenuated, generally decreasing and lasting much longer, with a lower rise and fall rates. The timing of the large flood occurs at a similar time. ***Seasonal Flows:*** Flows from January to April increase for low, median, and high flows. Flows predicted from June to October are fairly consistent with the baseline and between climate scenarios.
Key Location 6	***Location:*** Upstream of 9th Line (main branch). ***Surficial Geology:*** Catchment is a mixture of sand, clay, silt/till, and gravel. ***Land Use:*** Downstream of large wetland. Mainly wetland and agriculture, with some forest and development. ***Physiography:*** Peterborough Drumlin.	***Ranked Duration:*** Shift increase for all ranges of flows from predevelopment to 1978 and again to current land use. ***Extreme Low Flow Event:*** Increase in peak flows and frequency, and decrease in duration with development. ***High Flow Event:*** Increase in peak flows, magnitude of fall rate, and event frequency, decrease in duration and earlier timing of events with development. ***Small Flood (2-year):*** Increase in peak flow and rise rate with development. ***Large Flood (10-year):*** Increase in fall rate with development. Events occur later and longer under the current land use. ***Seasonal Flows:*** Increase in all months from predevelopment to 1978 and again to current land use. Largest increase observed in the spring.	***Ranked Duration:*** Most models are predicting higher flows for flows with an exceedance probability less than 60%. ***Extreme Low Flow Event:*** Minimal change. ***High Flow Event:*** Large spread in event timing, increase in median peak flow. ***Small Flood (2-year):*** Large spread in event timing. ***Large Flood (10-year):*** Increase in Large flood peak with decrease in duration and variable timing. Increase in large flood rate of rise and fall. ***Seasonal Flows:*** Higher winter flows observed in 10th, 50th, and 90th percentile. 90th percentile flows are decreasing in April, May, and October.
Key Location 7	***Location:*** In Innisbrook Golf Course (tributary). ***Surficial Geology:*** Catchment is a mixture of sand, gravel, clay, and silt/till. ***Land Use:*** Located in a golf course. Watershed is mainly forest, some agriculture, wetlands, and urban development. ***Physiography:*** Peterborough Drumlin.	***Ranked Duration:*** Shift increase for nearly all range of flows from predevelopment to 1978 and again to a lesser extent from 1978 to current land use. ***Extreme Low Flow Event:*** Increase in peak flows, frequency and decrease in duration with development. ***High Flow Event:*** Increase in peak flows, rise and fall rates, frequency, and decrease in duration with development. ***Small Flood (2-year):*** Increase in peak flows, fall rates, and decrease in duration with development. ***Large Flood (10-year):*** Increase in peak flows, rise, and fall rate, and decrease in duration and later event timing with development. ***Seasonal Flows:*** Increase in all months from predevelopment to 1978. Current land use has similar flows to 1978 with increased spring flows for 10th and 50th percentile. Minimal change in 90th percentile between 1978 and current land use.	***Ranked Duration:*** Most climate scenarios project increased flows for all ranges (2 scenarios project decreases). ***Extreme Low Flow Event:*** Occurring slightly earlier. ***High Flow Event:*** In most cases occurring later. ***Small Flood (2-year):*** Large spread in event timing, increase in median peak flow. ***Large Flood (10-year):*** Most of the large events under climate scenarios have very short durations. ***Seasonal Flows:*** Flows increase for December – March for 10th, 50th, and 90th. Decreasing flows in May for 50th and 90th. Increasing November flows in 50th.

	Key Discharge Location and Characteristics	Response to Changes in Land Use	Response to Climate Change
Key Location 8	***Location:*** Between Lockhart and Maple View (main branch). ***Surficial Geology:*** Catchment is a mixture of sand, clay, silt/till, and gravel. ***Land Use:*** Located in a wetland, near residential area, and some commercial development. The drainage area is comprised mainly of agriculture, forest, and wetlands. ***Physiography:*** Peterborough Drumlin.	***Ranked Duration:*** Shift increase for all ranges of flows from predevelopment to 1978 and again to current land use. ***Extreme Low Flow Event:*** increase in peak flows, frequency, and decrease in duration with development. ***High Flow Event:*** increase in peak flows, rise and fall rates, frequency, and decrease in duration with development. ***Small Flood (2-year):*** Increase in peak flows, rise and fall rates, and decrease in duration with development. ***Large Flood (10-year):*** Increase in peak flows, and rise and fall rates with development ***Seasonal Flows:*** Higher flows in 1978 particularly in the spring. Current land use higher flows in all months (but minimal in winter).	***Ranked Duration:*** Most of the climate change scenarios are in agreement that the large and mid-ranged flows (exceedance probability less than 60%) will increase with climate change. ***Extreme Low Flow Event:*** minimal change. ***High Flow Event:*** large spread in event timing with more scenarios occurring later, increase in median peak flow. ***Small Flood (2-year):*** Occurring earlier in most scenarios. ***Large Flood (10-year):*** Magnitude of Large flood events increasing with climate change with more often a shorter duration. ***Seasonal Flows:*** Median and 10^{th} percentile monthly flows increase from December to March and decrease in April. 90^{th} percentile has increased winter flows with decreased flows in May. The 90^{th} percentile November flows are highly variable depending on the climate model.
Key Location 9	***Location:*** Lovers Creek at Tollendal Mill Road gauge (main branch), near outlet to Kempenfelt Bay. ***Surficial Geology:*** Catchment is a mixture of sand, clay, silt/till, and gravel. ***Land Use:*** Located in urbanized area, drains entire watershed. ***Physiography:*** Simcoe Lowlands.	***Ranked Duration:*** Shift increase for all ranges of flows from predevelopment to 1978 and again to current land use. ***Extreme Low Flow Event:*** Increase in peak flows and decrease in duration with development. ***High Flow Event:*** Increase in peak flows, rise and fall rates, frequency, and decrease in duration with development. ***Small Flood (2-year):*** Increase in peak flows, rise and fall rates, and decrease in duration and later event timing with development. ***Large Flood (10-year):*** Increase in peak flows, rise and fall rates with development, and later event timing under current land use. ***Seasonal Flows:*** Higher flows in 1978 particularly in the spring. Current land use higher flows in all months (but minimal in winter).	***Ranked Duration:*** Most of the climate change scenarios are in agreement that the large and mid-ranged flows (exceedance probability less than 70%) will increase with climate change. ***Extreme Low Flow Event:*** Minimal change. ***High Flow Event:*** Large spread in event timing, with more scenarios occurring later. ***Small Flood (2-year):*** Small floods occur earlier in all climate scenarios with smaller peak flows, consistent with an earlier snowmelt. ***Large Flood (10-year):*** Peak magnitudes are increasing. ***Seasonal Flows:*** Median monthly flows increase from January to March and decrease in April. 10^{th} percentile flows decrease December through March with decreasing flows in April. 90^{th} percentile has increased winter flows with decreased flows in May.

3.4 Wetland Contours

Area of inundation mapping for wetlands was created for the different land use conditions (pre-development, 1978 land use, and current land use) to assess how the nature of wetlands has changed as a result of changes in development. Specifically, contours of the area inundated by 1 cm of overland water for 10%, 50%, and 90% of the simulated time period are presented on Figure 22 through Figure 24, respectively.



MIKE SHE Model Domain
Areas
Lake Simcoe
Areas
Road
Lines
Extend of Wetland Ponded Area
Current Land Use
Lines
Historic Land Use
Lines
Pre-Development
Areas

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Contours of ponded water exceeding 0.01 m 10% of the time under different Land Use Stressor States

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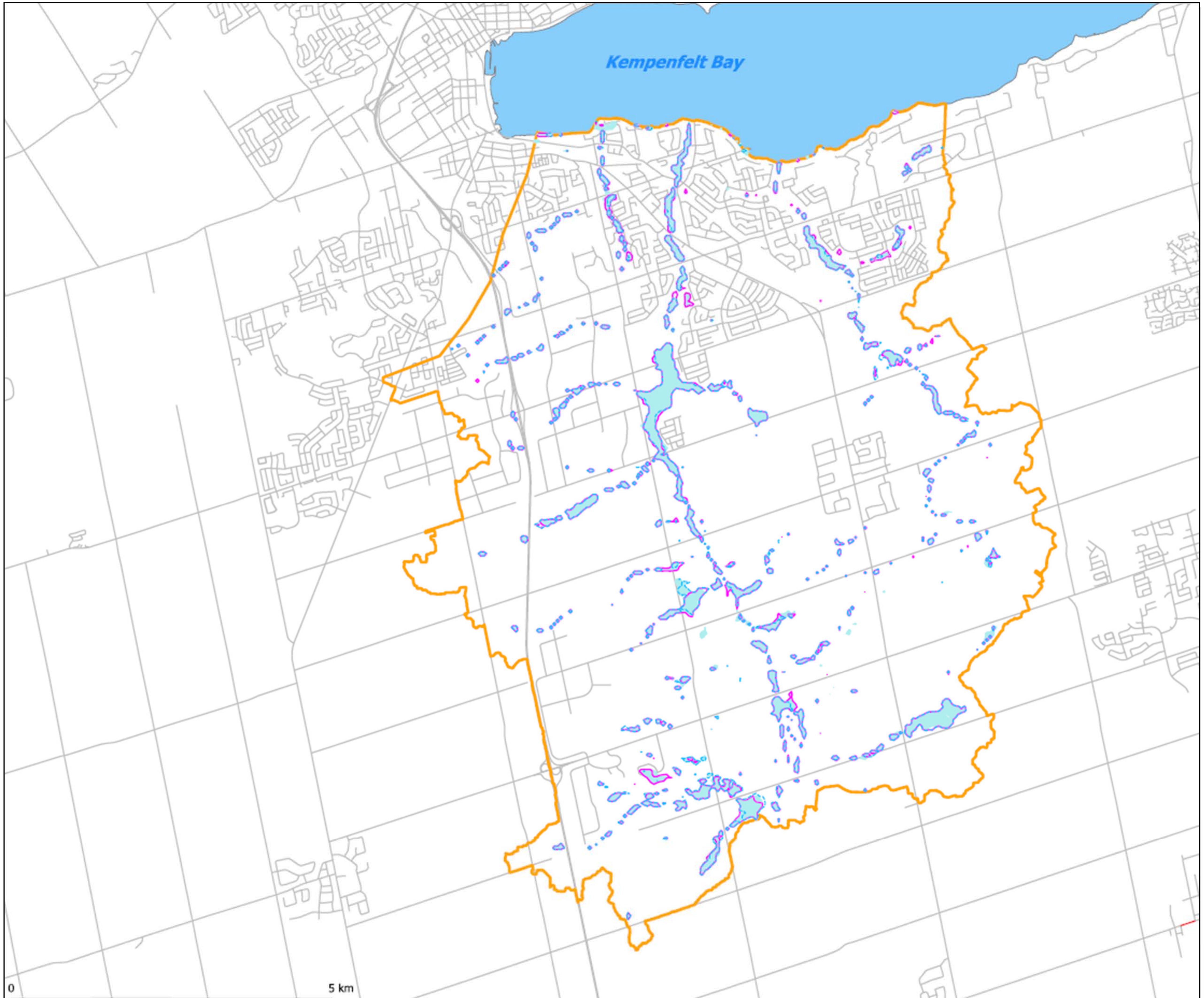
Figure 22

Easting (m)

Northing (m)



MIKE SHE Model Domain
Areas
Lake Simcoe
Areas
Road
Lines
Extend of Wetland Ponded Area
Current Land Use
Lines
Historic Land Use
Lines
Pre-Development
Areas

NAD 1983 UTM Zone 17N

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Contours of ponded water exceeding 0.01 m 50% of the time under different Land Use Stressor States

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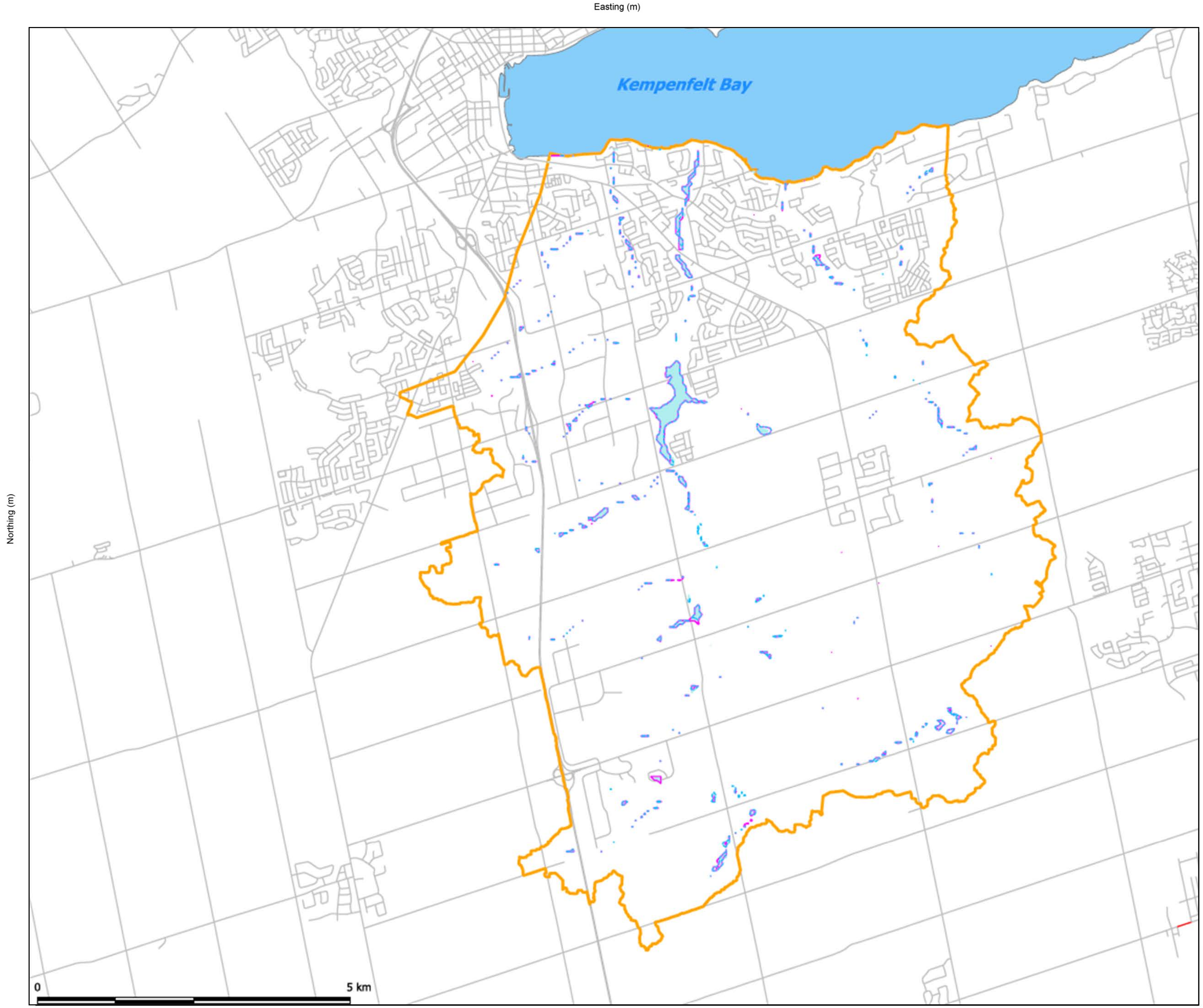
30 Jun 2015	21036-528	P. Martin	S. Murray	C. Curry

Figure 23



MIKE SHE Model Domain
Areas
Lake Simcoe
Areas
Road
Lines
Extend of Wetland Ponded Area
Current Land Use
Lines
Historic Land Use
Lines
Pre-Development
Areas

NAD 1983 UTM Zone 17N

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Contours of ponded water exceeding 0.01 m 90% of the time under different Land Use Stressor States

Date:	Project:	Technical:	Reviewer:	Drawn:
30 Jun 2015	21036-528	P. Martin	S. Murray	C. Curry

Figure 24

Most of the wetland areas are ephemeral in nature as indicated by the large extent of the wetlands shown to exist only 10% of the time on Figure 22, compared to 50% of the time on Figure 23. Under the three frequencies, the area of wetland shrinks with development. This is particularly evident in the reduced area for ephemeral wetlands, where ponded water exceeding 1 cm 10% of the time from pre-development to 1978 land use.

4 UNCERTAINTIES AND DATA GAPS

A variety of elements within the hydrologic and hydraulic modelling process are subject to uncertainty. Although the model calibration process is performed to reduce uncertainty, the model results and water budgets reflect uncertainty within the input parameters. A useful by-product of the process of model calibration and uncertainty reduction is the identification of data gaps, which contribute to uncertainty within the model.

The following section summarizes some of the uncertainties associated with the current modelling process, discusses some of the potential impacts of this uncertainty, and identifies significant data gaps that may be addressed to help reduce some of these uncertainties.

4.1 Noted Elements of Uncertainty

4.1.1 Watershed Characterization

The hydrologic response of the watershed is determined in part by land use, vegetation, and surficial geology, which have been simplified into aggregated groups (e.g., “bog” and “wetland” regions classified as simply wetland regions). This allows variability in regional conditions across the Study Area to be represented in the model. This simplification accounts for larger scale differences in land cover, but may not precisely reflect the heterogeneity that exists at the local scale. Therefore, model estimates of hydrologic processes evaluated at scales smaller scales than the watershed characterization scale are subject to increased uncertainty.

4.1.2 Climate Data

The MIKE SHE model relies on climate data collected at discrete locations (climate stations) that are assumed to be representative of conditions over a specified geographic area. The density of climate stations with long-term datasets is not sufficient to fully reflect the expected spatial variability; particularly during the summer months where extremely localized rainfall events are common (thunderstorms). Further uncertainty is introduced by measurement error in climate observations themselves. Uncertainty with the precipitation measurement has been estimated by Cumming Cockburn Limited (2001) to be approximately ±10%, with uncertainty during winter months reaching ±20%. Precipitation measurement in winter months has a higher uncertainty due to the difficulty of measuring snowfall, which can be highly affected by wind. These levels of uncertainty must be considered, particularly when comparing modelled conditions to short-term rainfall events.

4.1.3 Streamflow Data

Streamflow measurements have varying degrees of uncertainty that must be considered when calibrating a model. Manual flow measurements, which are used to generate rating curves (allowing the translation of river stage to river flow), may contain errors of approximately ±5% to 15% (Winter 1981). Measurement error for extreme events (very low or very high flow) may be significantly higher. In addition to uncertainty in measurements used to generate a rating curve, changes in river channel geometry may alter the accuracy of the rating curve with time. Changes in river channel geometry may be over the long-term (riverbed erosion) or the short-term (aquatic plant growth or river ice conditions causing backwater). Malfunctions in gauge station equipment may also lead to loss of, or distortion of, streamflow calculations. Such challenges are reported to exist at the Lovers Creek gauge location.

4.1.4 Water Use

Water usage has been incorporated into the MIKE SHE model without complete knowledge of actual water taking practices within the Study Area. This has introduced an element of uncertainty into the models.

4.1.5 Snow Processes

Snow accumulation, evaporation/sublimation, redistribution, and melt are significant hydrologic processes in Canadian watersheds. The rates of these processes are determined by the inter-relation of many factors, including land cover, albedo, solar radiation, wind speed/direction, cloud cover, temperature fluctuations, rainfall amount/temperature, and new snow density. While the snow processes representation in MIKE SHE are relatively good and consistent with other models commonly applied in southern Ontario (e.g., GAWSER and HSP-F, SWAT), the simulated processes still represent a simplification of reality. The state of science with respect to the impact of these factors, and their effect on snow processes introduces a level of uncertainty into hydrologic modelling.

Review of the model calibration indicates that snow melt is typically estimated to occur later than it is occurring, as indicated by streamflow observations. The late timing of snow melt may be a result of one or more of the following:

- changes in snow pack melt rates occurring due to changes in the albedo of the snow pack
- changes in the structure of the snow pack
- road salt accumulation within the snowpack due to urban snow management, which would decrease the temperature at which snow can melt in urbanized areas and highways

4.1.6 Urban Systems

Urban systems, and their associated stormwater management infrastructure (stormwater ponds, infiltration galleries, etc.), are not explicitly modelled within the MIKE SHE model. Urban areas are represented within the model as having directly connected runoff systems where a portion of incident precipitation is routed directly to nearby rivers to replicate the effects of stormwater conveyance systems. The parameterization of the urban areas is adjusted during model calibration to ensure the effects of urban stormwater systems are reasonably characterized. This approach provides a good representation of the larger scale response of stormwater systems but may not capture more localized effects of stormwater infrastructure (e.g., retention ponds and overflow thresholds).

4.1.7 Limitations of the Modelling Approach

In addition to the characterization and calibration uncertainty, the numerical representation and simulation of surface water and groundwater flow systems also contains limitations. Model simulation uncertainty comes from both the approximate solution of the equations defining surface water and groundwater flow using finite difference methods (MIKE SHE), as well as the limitations surrounding finite discretization.

Practically, the solution of the equations is limited to calculating groundwater head or overland flow at a finite number of points; the higher the number of points (smaller the elements or node spacing), the more computer power and time needed. More precision is achieved when using a higher number of calculation points, particularly in areas of larger water level changes or more dynamic flow conditions exist. With any scale of model, there is a balance between the level discretization (distance between calculation points) and the required computer power to efficiently run and calibrate the model (also financial budget). Therefore, the practical limitation of discretization presents some uncertainty in the hydrologic and hydraulic modelling results. This limitation is especially important because it affects the majority of both the adjustable model parameters, as well as the trends in observations (e.g., where many monitoring wells could be contained within one model cell). In models of this scale, balance needs to be struck among the level of detail needed, the data available, and the computational effort that is still needed to be practical for the project goals.

As noted above, there are a number of limitations in the numerical modelling process that lead to uncertainty in model predictions. However, the uncertainty due to the modelling process is considered to be relatively minor compared to the uncertainty in the physical characterization.

4.1.8 Uncertainty Summary

The uncertainties identified in this section are important considerations in the application of the model; however, overall, the discussed model limitations and uncertainty do not detract from using the MIKE SHE model developed for the project objectives.

4.2 Data Gaps

4.2.1 Climate Data

Climate data gaps have been identified in terms of observation locations. The available climate data is observed at a variety of stations, which are proximate to but not contained within the Study Area. Given the significant changes in the topography within the Study Area as well as the presence of a significant water body at the northern boundary, it would be beneficial to obtain climate at multiple points within the Study Area. Observations collected within the Study Area would reduce the uncertainty associated with using climate observations from more distant climate stations and should serve to improve model calibration.

4.2.2 Streamflow Observations

The streamflow observations available within the Study Area are relatively limited in terms of temporal extent of data collected. Review of the streamflow data for Lovers Creek at Tollendal gauge indicated quality issues with a large proportion of the observational dataset. After review of the data, only the period of 2009 to 2015 was considered suitable for use as calibration targets in the development of the model. The continuing collection of additional high quality observations at this gauge and the Hewitt's Creek at Camelot Street gauge, as well as regular updates to the stage-discharge curves used at these gauges, will provide valuable calibration data for extension of this and other hydrologic and hydraulic modelling conducted in the Study Area.

5 SUMMARY AND RECOMMENDATIONS

The following sections provide a summary of the project and recommendations for future work.

5.1 Project Summary

A detailed integrated hydrologic model was developed for the Lovers Creek subwatershed to facilitate environmental flow characterization. The model was subsequently calibrated to observed flows and water levels within the subwatershed. Following calibration, the model was applied to identify environmental flow characteristics at key discharge location in the subwatershed under current development, 1978 development, and pre-development conditions, during the period of 1971 to 2000. A further application of the model was conducted to assess the effects of climate change on environmental flows in the Lovers Creek subwatershed. Ten future climate scenarios were simulated, which capture the range of future climate projections for the subwatershed.

Changes in environmental flows as a result of development and climate change were identified through statistical and graphical analysis of flows under the various development and climate conditions. The characterization of environmental flows under various development and climate change conditions will serve to support the development of an environmental flow target methodology in support of the

LSPP. Further, the changes identified within the Lovers Creek subwatershed under development and climate change conditions will support the development of environmental flow targets in the Lovers Creek subwatershed.

5.2 Recommendations

This section identifies a number of different tasks that could be completed to provide further insight into the changes in environmental flow identified in this project. These tasks serve to enhance understanding of environmental flows in the Study Area, reduce model uncertainties, and evaluate the impacts of changes in environmental flows on fish habitat within the Study Area.

5.2.1 Water Budget Analysis for Key Discharge Locations

Additional insight into the changes in environmental flows observed at the key discharge locations may be gained by conducting a water budget analysis on the contributing drainage area to the key discharge locations. This analysis would compare the baseline water balance of the drainage area to the water balance under stressor states. This differential analysis would provide insight into the changes in precipitation, evaporation, and streamflow composition (proportion of overland, interflow, and baseflow) occurring in the drainage area to the key discharge location and how these changes correspond to changes in environmental flows.

5.2.2 Areal Inundation in Wetlands in Climate Change

The effects of changes in the hydro-period of wetlands in the Study Area as a result of climate change could be assessed in the same manner as the assessment provided for land use stressor states in this report. This would provide insight into the potential changes in wetland inundation extent and frequency brought about by climate change.

5.2.3 Future Improvements and Modelling Extension

5.2.3.1 Hydraulic Structure Representation

A number of hydraulic structures, culverts, and bridges, which exist within the Study Area are not currently represented within the MIKE SHE model. Evaluation of the existing LSRCA HEC-RAS models of Lovers Creek and Hewitt's Creek identified 29 hydraulic structures in Lovers Creek and 8 structures in Hewitt's Creek. These structures generate hydraulic effects such as backwater, which alter environmental flows within the watershed. Incorporation of the hydraulic structures found within the Study Area would serve to improve the representation of flow regimes within the model. As the structures are already researched and represented within HEC-RAS models a field survey of the structures is not necessary and the structure locations and dimensions could be readily incorporated into the existing model.

5.2.3.2 Future Development Scenario

The development stressor states considered in this project consider only current and previous states of development within the Study Area. The understanding of environmental flows within the Study Area could be added by evaluating a future land use stressor state. This future stressor state would provide insight into the effect of future development (e.g. continuing urbanization) on environmental flows throughout the Study Area and could be used to inform development of the Study Area.

5.2.3.3 Extended Climate Change Analysis

The climate change assessment used a “change-field” approach to representing the effects of climate change. This approach incorporated a change in precipitation volume as well as temperature by modifying existing climate data using monthly factors. This approach does not consider the changes forecast in precipitation inter-event duration or precipitation intensity. Regional climate change model data is available, which provides consideration for changes in the precipitation frequency and duration. The model could be used to consider future climate scenarios that consider these forecast changes in frequency and duration; this more detailed approach may provide a more comprehensive understanding of the climate change effects on environmental flows within the Study Area.

5.2.3.4 Ecologic Impact of Changes in Environmental Flows

This project has provided an evaluation of changes in environmental flows at key locations within the Study Area. A natural extension of this work is to evaluate the ecological impacts of the forecast changes in environmental flows. The evaluation of ecological impacts could involve assessment of the impacts of changes in environmental flows on the Brook Trout habitats within the Study Area. The impact assessment with respect to Brook Trout could be evaluated in the following manner.

1. Identify stream reaches significant to Brook Trout for detailed evaluation.
2. Conduct a detailed channel survey to characterize the channel geometry and bed materials.
3. Develop a detailed numerical representation of the channel in a 2D flow model (e.g. River 2D) based on the channel survey (U of A 2010).
4. Develop a habitat suitability index for the Brook Trout considering water depth, velocity, and substrate.
5. Evaluate the change in habitat suitability from baseline conditions to those of the stressor states using River 2D and an integrated habitat suitability index.

6 REFERENCES

Allen, R.G. et al. 1998. *Crop evapotranspiration – Guidelines for computing crop water requirements*. FAO Irrigation and Drainage Paper No.°56. Food and Agriculture Organization for the United Nations, Natural Resources Management and Environment Department. Rome, Italy.

AquaResource, a Division of Matrix Solutions Inc. (AquaResource). 2013. *City of Barrie Tier Three Water Budget and Local Area Risk Assessment*. Report submitted to the Lake Simcoe Region Conservation Authority.

Bala et al. 2007. *"Combined Climate and Carbon-Cycle Effects of Large-Scale Deforestation". Proceedings of the National Academy of Sciences of the United States of America.104 (16)*: 6550-6555.

Beaton, A.D. 2012. T*esting and Refining a Unique Approach for Setting Environmental Flow and Water Level Targets for a Southern Ontario Subwatershed*. Master's Thesis. University of Guelph.

Beaton, A.D. and A. Bradford. 2013. "Demonstration of a methodology for setting ecological flow and water level targets." *Canadian Water Resources Journal 38 (4)*: 296-310.

Blackport and Associates. 2012. Draft Hydrogeology Framework Technical Memorandum #2 for the City of Barrie Secondary Plan, Background Studies and Infrastructure Master Plan: Intensification and Annexed Lands.

Brabec E., Shulte S. and P.L. Richards. 2002. "Impervious surfaces and water quality: a review of current literature and its implications for watershed planning." *Journal of Planning Literature 16 (4)*: 499-514.

Canadell, J. et al. 1996. "Maximum rooting depth of vegetation types at the global scale." *Oecologia 108 (4)*: 583-595.

Chapman, L.J. and Putnam, D.F. 2007. Physiography of Southern Ontario; Ontario Geological Survey, Miscellaneous Release--Data 228 ISBN 978-1-4249-5158-1

Chiew, F.H.S. and McMahon, T.A. 1993. "Assessing the adequacy of catchment streamflow yield estimates." *Australian Journal of Soil Research 31*: 665-680.

Chin, D.A. 2006. *Water-Resource Engineering*. Second Edition. Pearson PLC, Prentice Hall. Upper Saddle River, New Jersey.

Cumming Cockburn Limited. 2001. *Water Budget Analysis on a Watershed Basis*. Prepared for the Watershed Management Committee. May 2001.

DHI Water & Environment (DHI). 2014a. *MIKE SHE.* DHI Software. Accessed in July 2015.

DHI Water & Environment (DHI). 2014b. *FEFLOW*. Version 6.2. DHI-WASY Software. Accessed in July 2015.

EBNFLO Environmental and AquaResource Inc. (EBNFLO and AquaResource). 2010. *Guide for Assessment of Hydrologic Effects of Climate Change in Ontario.* Prepared for The Ontario Ministry of Natural Resources and the Ontario Ministry of the Environment. June 2010.

Golder Associates Inc. (Golder). 2004. *South Simcoe Groundwater Study*. Report completed using the Province of Ontario's Groundwater Protection Fund.

Harbaugh A.W. 2005. *MODFLOW-2005, the U.S. Geological Survey Modular Ground-water Model-the Ground-water Flow Process*. U.S. Geological Survey Techniques and Methods 6-A16. U.S. Department of the Interior, U.S. Geological Survey. Reston, Virginia. http://pubs.usgs.gov/tm/2005/tm6A16/PDF/TM6A16.pdf

Kristensen K.J. and S.E. Jensen. 1975. "A model for estimating actual evapotranspiration from potential evapotranspiration." *Nordic Hydrology 6(3)*: 170-188.

Land Information Ontario (LIO). 2008. *Ontario In-Filled Climate Data*. Land Information Ontario. Ontario Ministry of Natural Resources.

Lake Simcoe Region Conservation Authority (LSRCA). 2008. *Integrated Watershed Management Plan*.

Lake Simcoe Region Conservation Authority (LSRCA) and Bradford, A. 2011. *Towards a Framework for Determining Ecological Flows in the Lake Simcoe Watershed – A Guidance Document*. Prepared for the Ontario Ministry of the Environment. 29p

Moriasi D.N. et al. 2007. "Model evaluation guidelines for systematic quantification of accuracy in watershed simulations." *Transactions of the ASABE 50(3)*: 885-900.

Nash J.E. and J.V. Sutcliffe. 1970. "River flow forecasting through conceptual models part I - a discussion of principles." *Journal of Hydrology 10(3)*: 282–290.

Ontario Geological Survey (OGS). 2003. *Surficial Geology of Southern Ontario.* Ontario Geological Survey, Miscellaneous Release-Data 128. CD-ROM dataset.

Ontario Ministry of Environment, Ministry of Natural Resources, Lake Simcoe Region Conservation Authority, and DMTI Spatial, Inc. (MOE, LSRCA, and DMTI). 2009. *Lake Simcoe Protection Plan (LSPP)*.

Ontario Ministry of Natural Resources (MNR). 1984. *Water Quantity Resources of Ontario*. Fort Erie, Ontario. June 1984.

Parks Canada. 2012. Trent-Severn Waterway National Historic Site of Canada. Lake Simcoe Water Levels. Retrieved from http://www.pc.gc.ca/lhn-nhs/on/trentsevern/visit/ne-wl/trent_e.asp

Sahin V. and M. Hall. 1996. "The effects of Afforestation and Deforestation on Water Yields." *Journal of Hydrology 178(1)*: 239-309.

Schroeter H.O., Boyd D.K. and H.R. Whiteley. 2000. "Filling in Gaps in Meteorological Data Sets Used for Long-Term Watershed Modelling." *Ontario Water Conference*. Richmond, Ontario. April 26 to 27, 2000.

Scurlock J.M.O., Asner G.P. and S.T. Gower. 2001. *Worldwide Historical Estimates of Leaf Area Index, 1932–2000*. ORNL/TM- 2001/268. Prepared by the Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the Department of Energy. December 2001.

Sullivan R.H. et al. 1978. E*valuation of the Magnitude and Significance of Pollution from Urban Stormwater Runoff in Ontario*. Research Report No. 81, Canada-Ontario Agreement, Environment Canada. Ottawa, Ontario.

University of Alberta (U of A). 2010. *River2D – Two Dimensional Hydrodynamic model software*. http://www.river2d.ualberta.ca/

United States Environmental Protection Agency (U.S. EPA). 2012. *Ag 101. Drainage*. Last updated on June 27, 2012. Retrieved from http://www.epa.gov/agriculture/ag101/cropdrainage.html

Watt W. E. 1989. *Hydrology of Floods in Canada - A Guide to Planning and Design*. National Research Council of Canada. Ottawa, Ontario.

Woodward et al. 2014. "The Hydrological Legacy of Deforestation on Global Wetlands." *Science 346(6221)*: 844-847.

Winter T.C. 1981. "Uncertainties in estimating the water balance of lakes." *Water Resources Bulletin 17(1)*: 82-115.

APPENDIX A
Key Location 1

APPENDIX A

KEY LOCATION 1

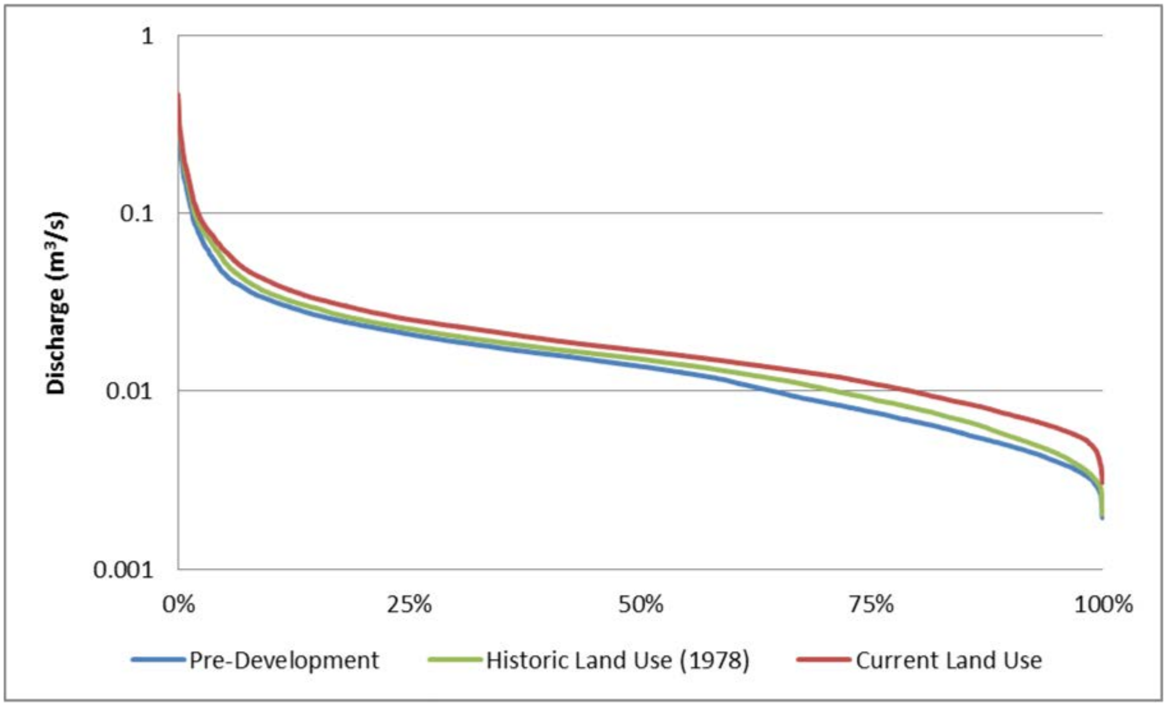

Figure A-1 Ranked Duration Curves for Key Location 1 under Land Use Scenarios

Table A-1 IHA Statistics for Key Location 1 under Land Use Stressor States

Flow Category	Flow Metric	Land Use		
		Pre-development	Historic (1978)	Current (2015)
Extreme Low Flow Event	Peak (m^3/s)	0.0042	0.0047	0.0065
	Duration (days)	8	4	3
	Timing (date)	230	228	233
	Frequency (# of events)	3	6	7
High Flow Event	Peak (m^3/s)	0.030	0.035	0.043
	Duration (days)	2	2	2
	Timing (date)	32	253	215
	Frequency (# of events)	7	14	19
	Rise Rate (m^3/day)	0.010	0.015	0.022
	Fall Rate (m^3/day)	-0.0049	-0.010	-0.015
Small Flood Event (2-year)	Peak (m^3/s)	0.29	0.34	0.38
	Duration (days)	36	32	29
	Timing (date)	98	114	121
	Frequency (# of events)	0	0	0
	Rise Rate (m^3/day)	0.027	0.049	0.073
	Fall Rate (m^3/day)	-0.014	-0.019	-0.022
Large Flood Event (10-year)	Peak (m^3/s)	0.37	0.41	0.44
	Duration (days)	46	32	20
	Timing (date)	91	91	96
	Frequency (# of events)	0	0	0
	Rise Rate (m^3/day)	0.059	0.066	0.11
	Fall Rate (m^3/day)	-0.012	-0.015	-0.025

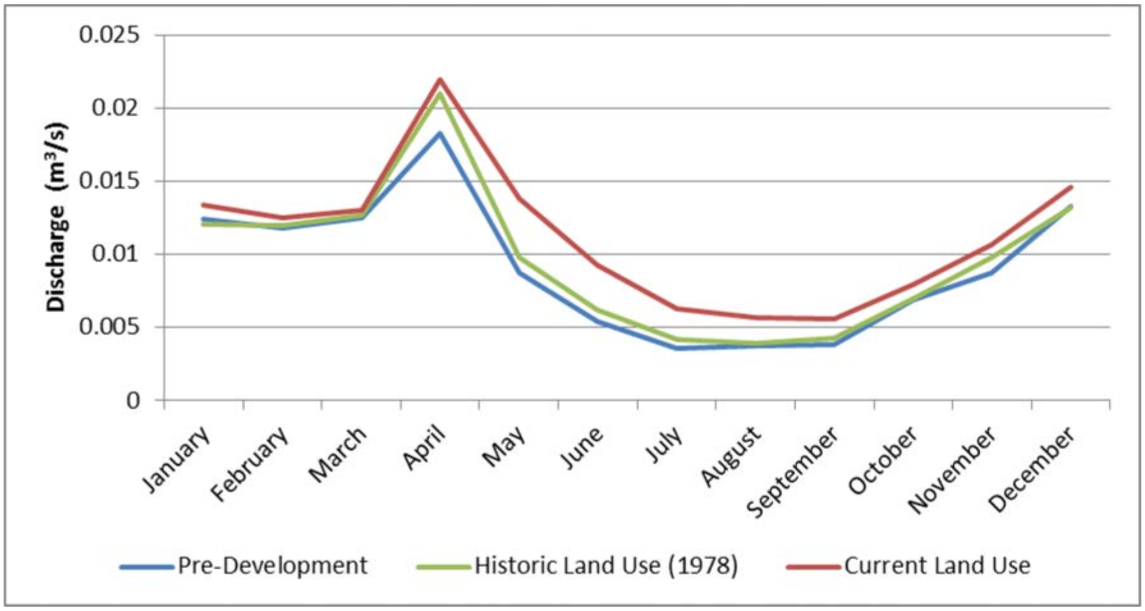

Figure A-2 **Tenth percentile monthly discharge for land use scenarios at Key Location 1**

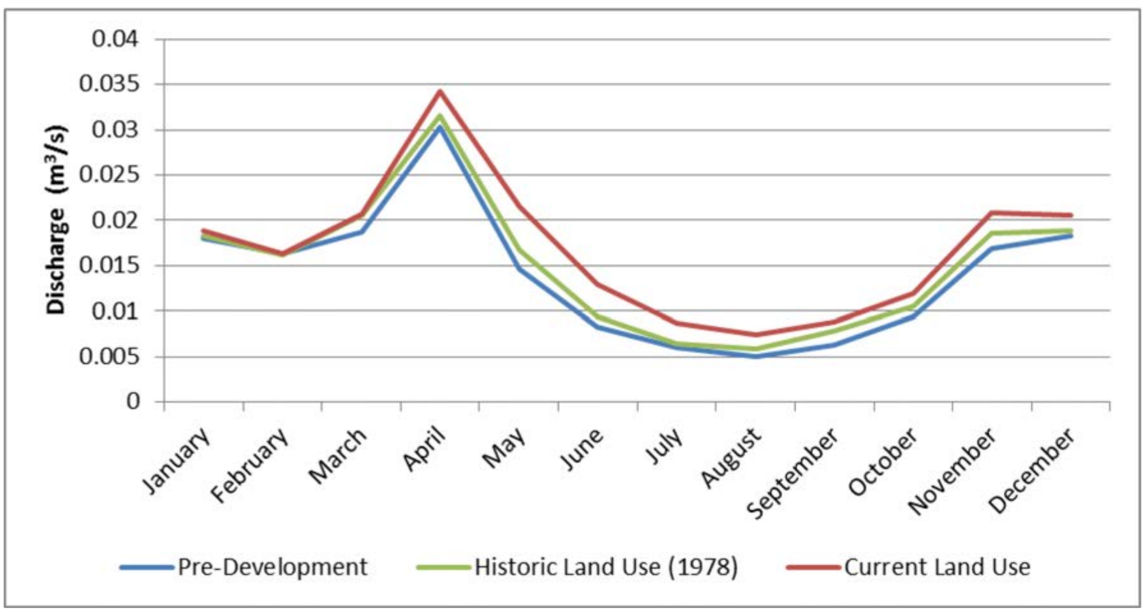

Figure A-3 **Median monthly discharge for land use scenarios at Key Location 1**

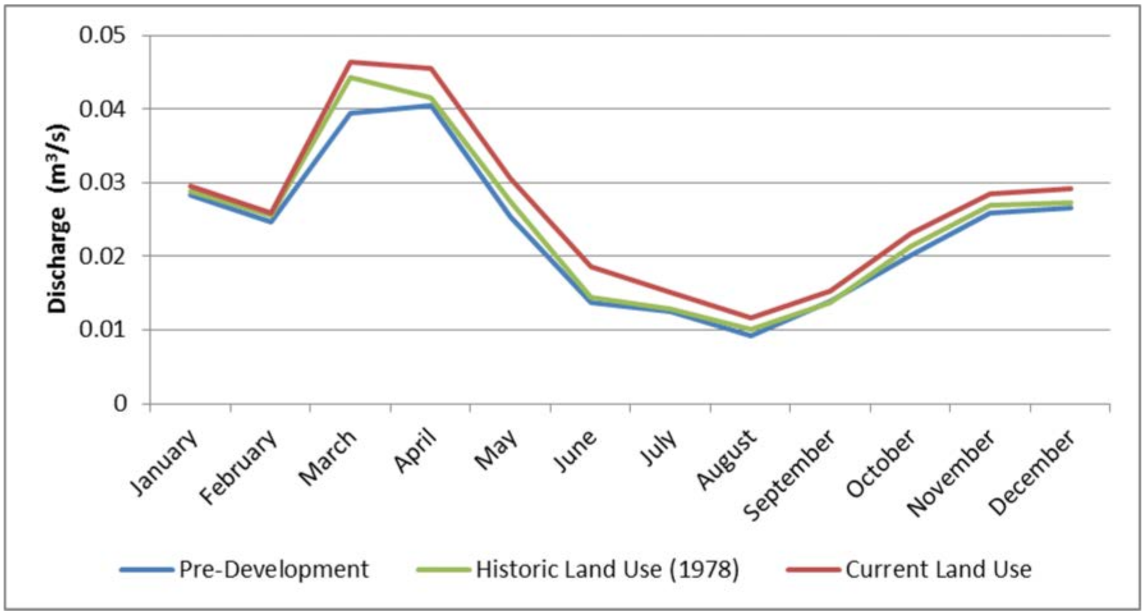

Figure A-4 **Ninetieth percentile monthly flow for land use scenarios at Key Location 1**

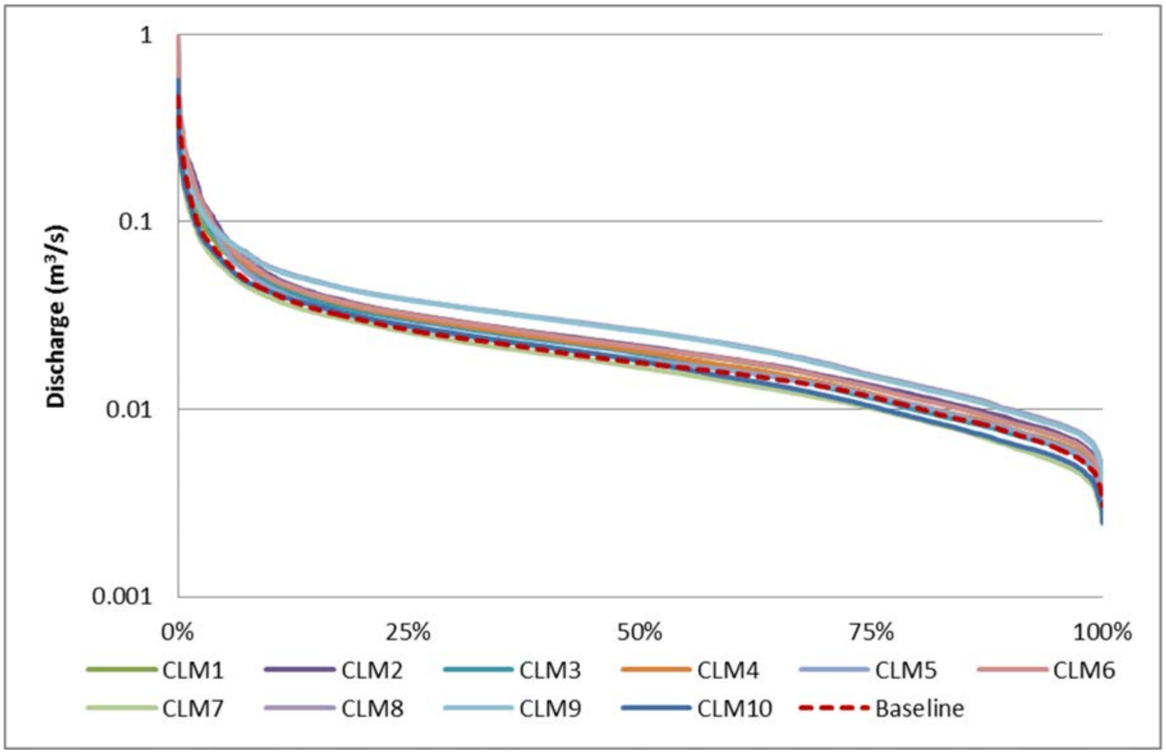

Figure A-5 **Ranked Duration Curves for Key Location 1 under Climate Change Scenarios**

Table A-2 IHA Statistics for Key Location 1 under Climate Change Stressor States

Flow Category	Flow Metric	Baseline (1980-2000)	Climate Change Future (2020-2040) Minimum	Median	Maximum
Extreme Low Flow Event	Peak (m^3/s)	0.0065	0.0054	0.0072	0.0089
	Duration (days)	3	3	3	4
	Timing (Julian date)	230	223	230	237
	Frequency (# of events)	7	4	7	9
High Flow Event	Peak (m^3/s)	0.044	0.040	0.055	0.066
	Duration (days)	2	1	1	2
	Timing (Julian date)	210	211	247	287
	Frequency (# of events)	22	20	23	24
	Rise Rate (m^3/day)	0.022	0.018	0.029	0.033
	Fall Rate (m^3/day)	-0.016	-0.026	-0.020	-0.013
Small Flood Event (2-year)	Peak (m^3/s)	0.38	0.24	0.35	0.48
	Duration (days)	17	18	25	38
	Timing (Julian date)	114	55	91	102
	Frequency (# of events)	0	0	0	1
	Rise Rate (m^3/day)	0.11	0.038	0.060	0.15
	Fall Rate (m^3/day)	-0.024	-0.028	-0.021	-0.011
Large Flood Event (10-year)	Peak (m^3/s)	0.45	0.45	0.55	0.84
	Duration (days)	17	4	17	28
	Timing (Julian date)	147	8	138	236
	Frequency (# of events)	0	0	0	0
	Rise Rate (m^3/day)	0.26	0.28	0.43	0.53
	Fall Rate (m^3/day)	-0.23	-0.48	-0.30	-0.02

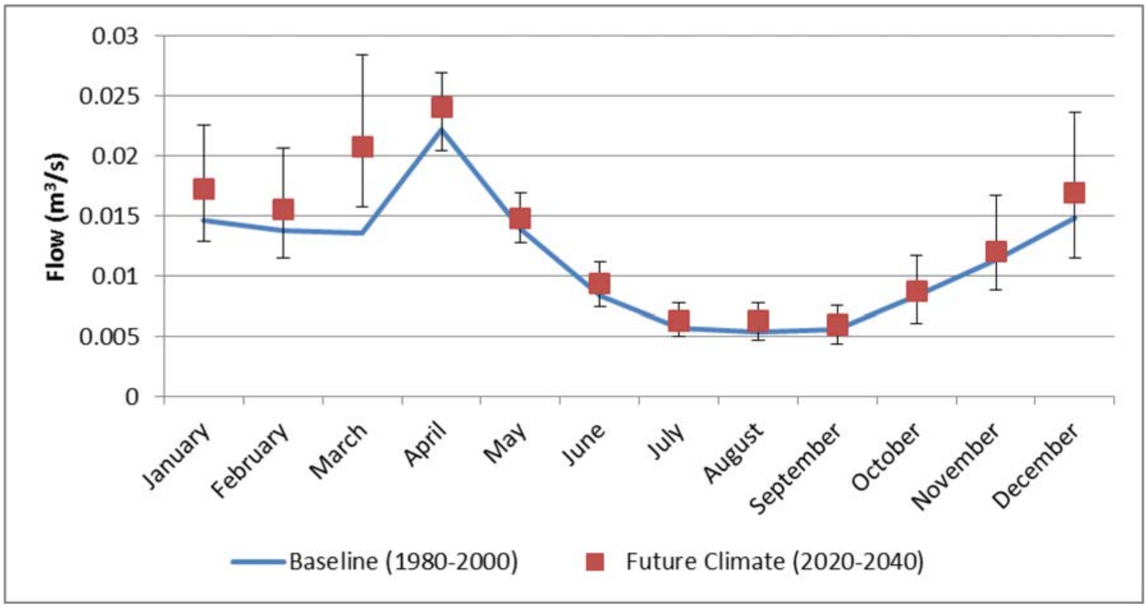

Figure A-6 **Tenth percentile monthly discharge for climate change scenarios at Key Location 1**

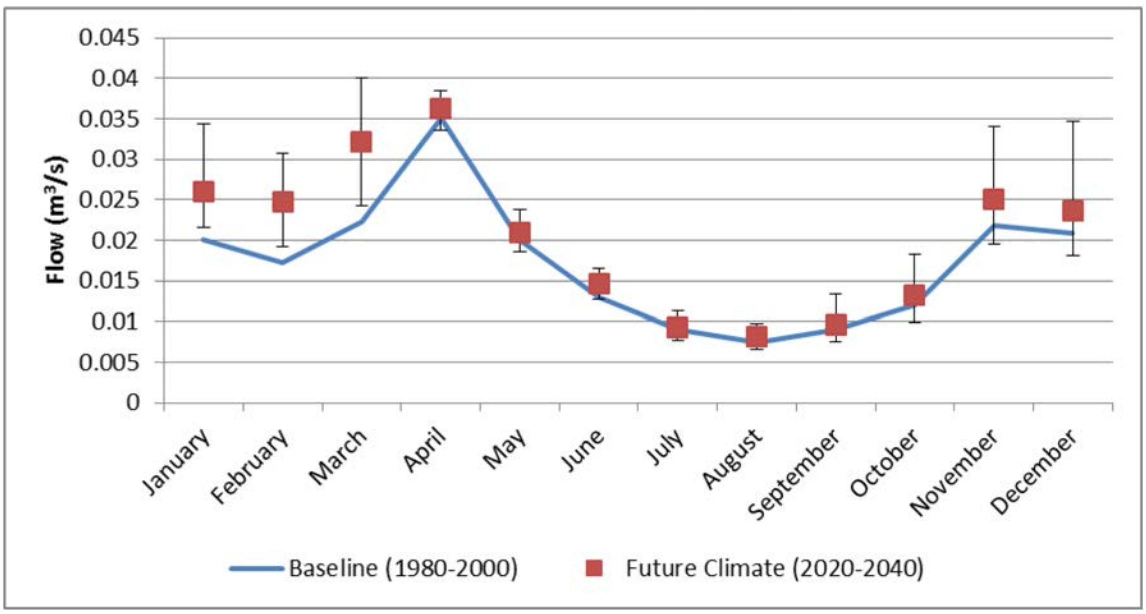

Figure A-7 **Median Monthly discharge for climate change scenarios at Key Location 1**

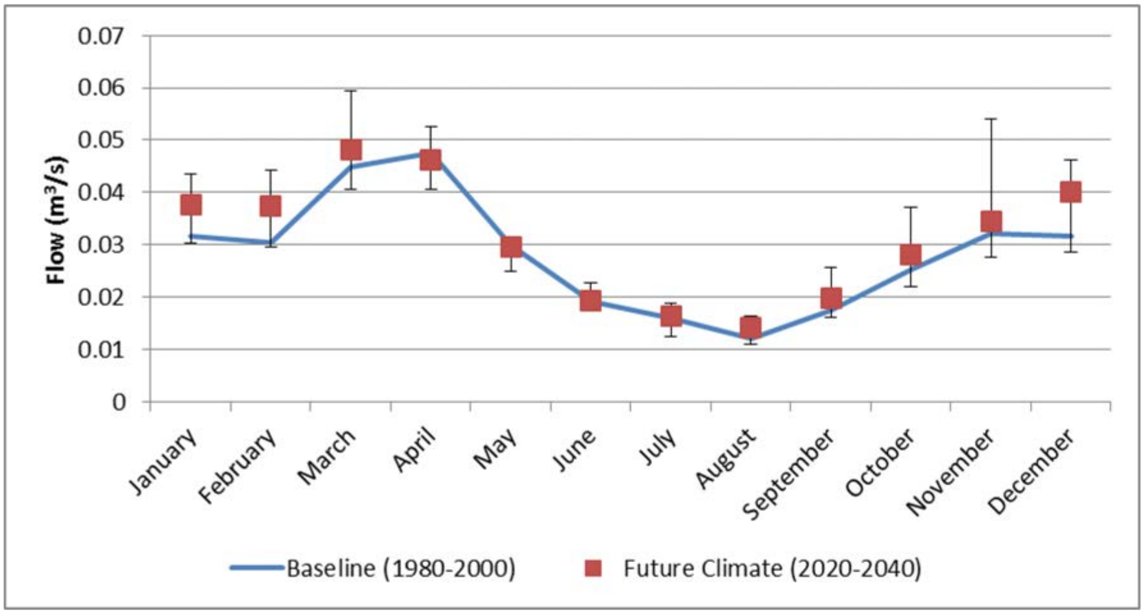

Figure A-8 **Ninetieth percentile monthly discharge for climate change scenarios at Key Location 1**

APPENDIX B
Key Location 2

APPENDIX B

KEY LOCATION 2

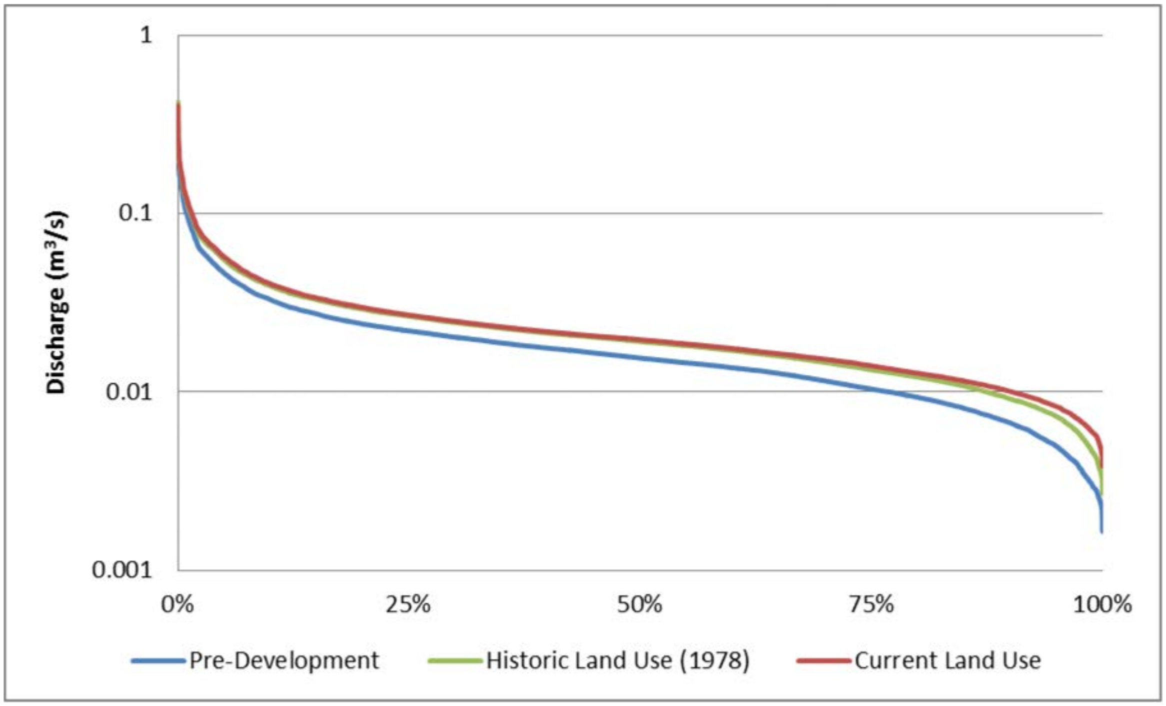

Figure B-1 **Ranked Duration Curves for Key Location 2 under Land Use Scenarios**

Table B-1 IHA Statistics for Key Location 2 under Land Use Stressor States

Flow Category	Flow Metric	Land Use		
		Pre-development	Historic (1978)	Current (2015)
Extreme Low Flow Event	Peak (m3/s)	0.00523	0.0076	0.0088
	Duration (days)	10	7	4
	Timing (date)	219	221	226
	Frequency (# of events)	2	3	3
High Flow Event	Peak (m3/s)	0.036	0.043	0.044
	Duration (days)	3	2	2
	Timing (date)	333	292	291
	Frequency (# of events)	14	16	17
	Rise Rate (m3/day)	0.011	0.016	0.016
	Fall Rate (m3/day)	-0.007	-0.010	-0.010
Small Flood Event (2-year)	Peak (m3/s)	0.19	0.23	0.24
	Duration (days)	24	19	26
	Timing (date)	100	101	109
	Frequency (# of events)	0	0	0
	Rise Rate (m3/day)	0.043	0.044	0.040
	Fall Rate (m3/day)	-0.010	-0.014	-0.014
Large Flood Event (10-year)	Peak (m3/s)	0.23	0.33	0.32
	Duration (days)	24	2	2
	Timing (date)	91	201	201
	Frequency (# of events)	0	0	0
	Rise Rate (m3/day)	0.035	0.32	0.30
	Fall Rate (m3/day)	-0.011	-0.16	-0.15

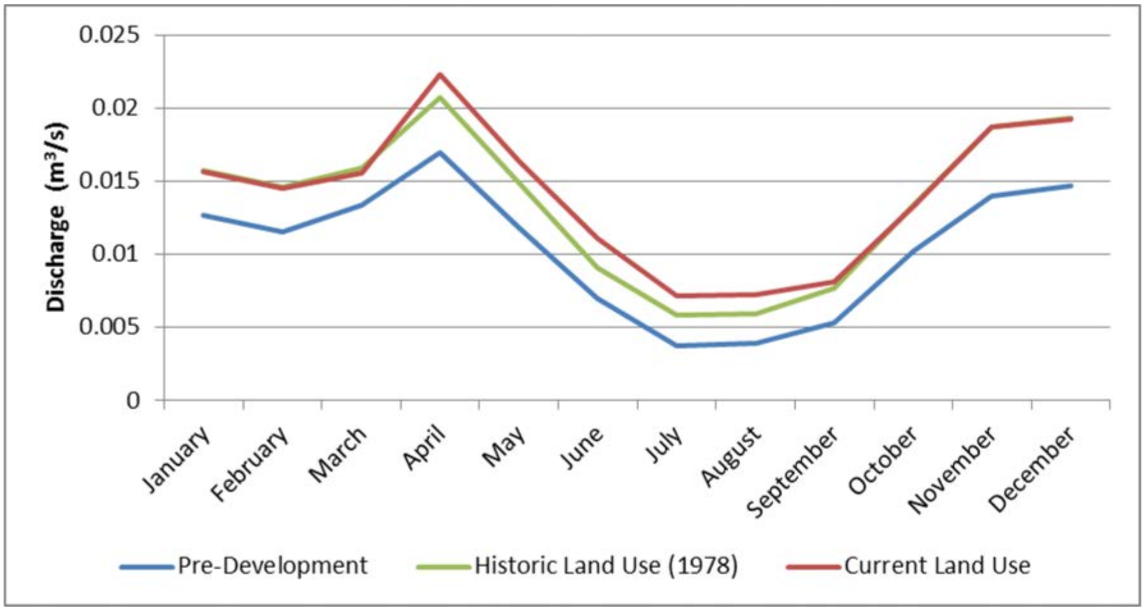

Figure B-2 **Tenth percentile monthly discharge for land use scenarios at Key Location 2**

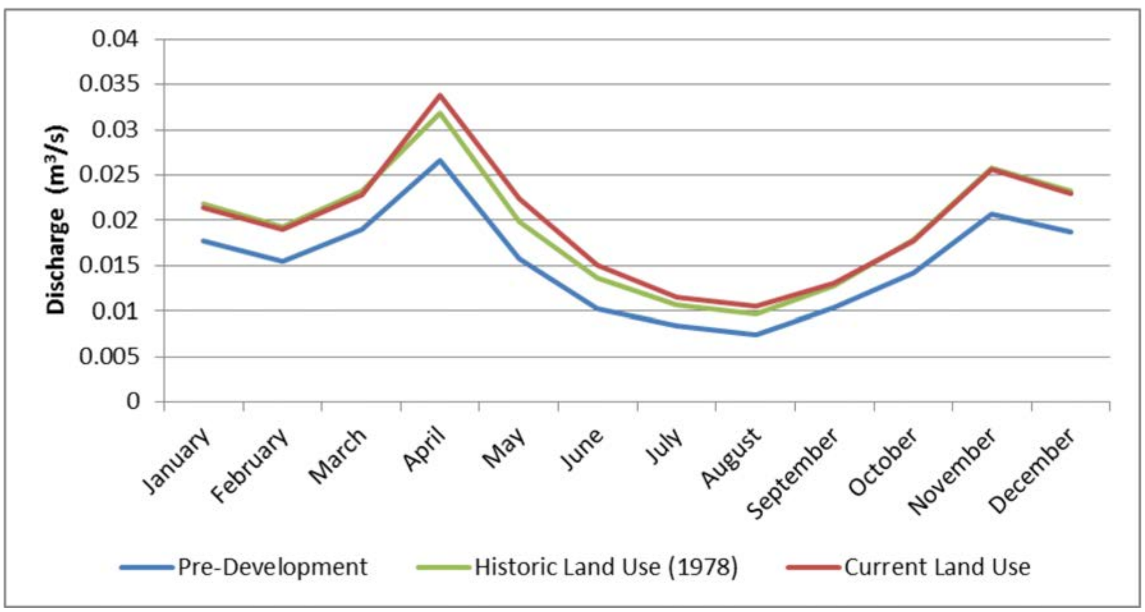

Figure B-3 **Median monthly discharge for land use scenarios at Key Location 2**

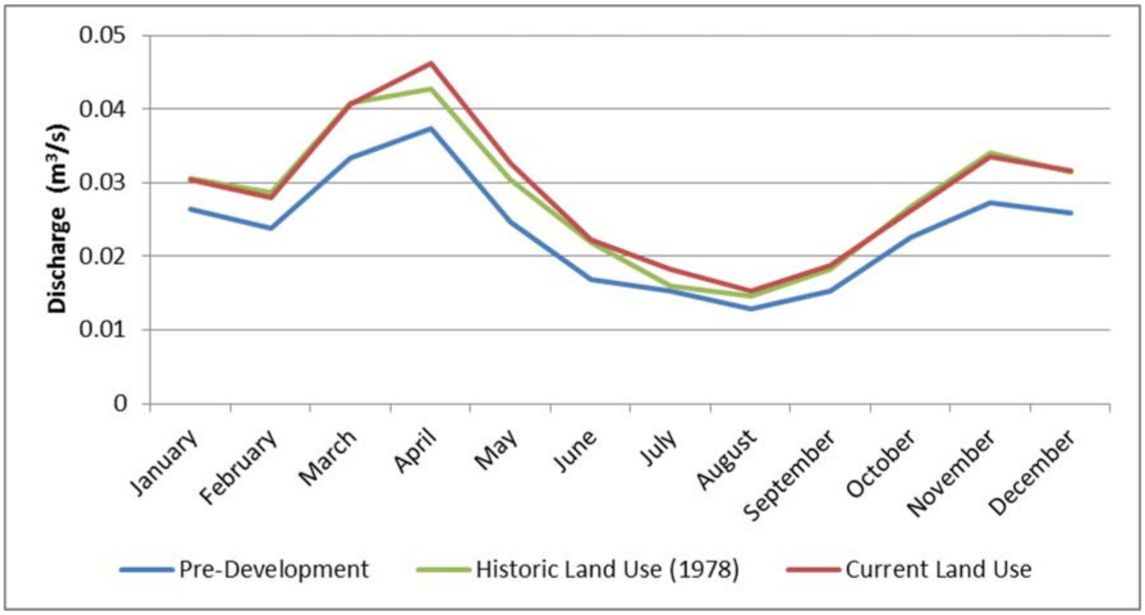

Figure B-4 **Ninetieth percentile monthly flow for land use scenarios at Key Location 2**

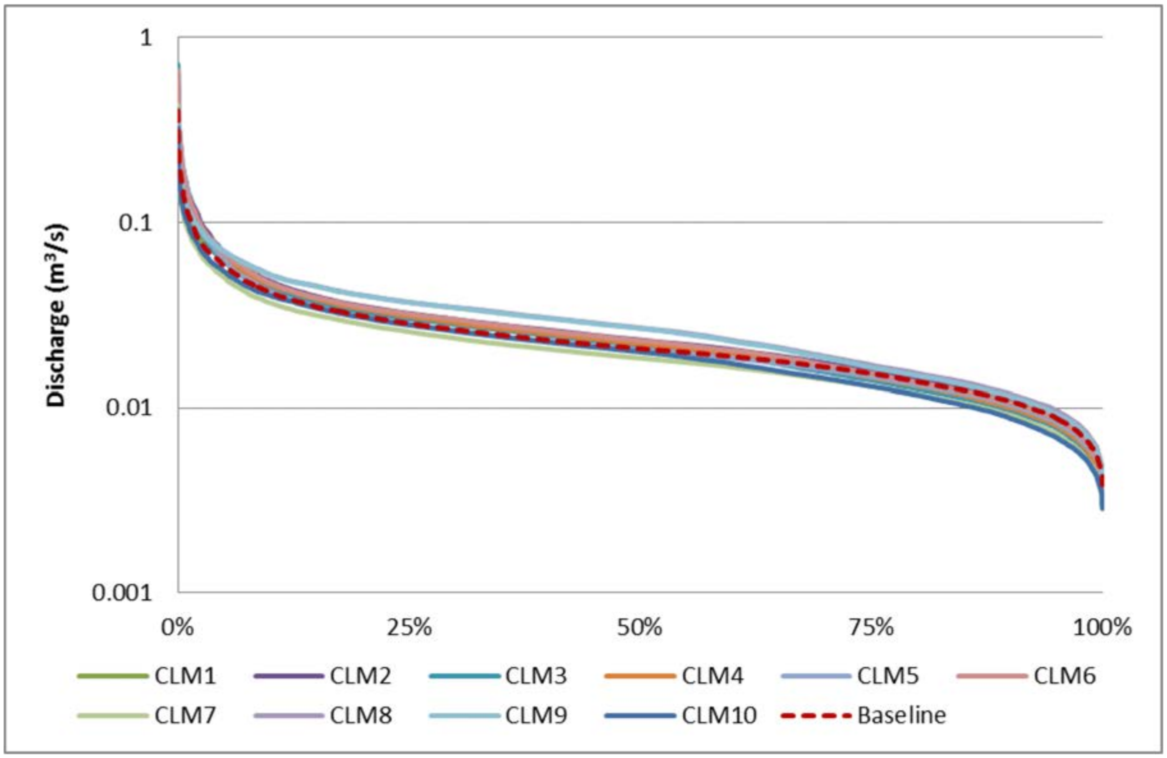

Figure B-5 **Ranked Duration Curves for Key Location 2 under Climate Change Scenarios**

Table B-2 **IHA Statistics for Key Location 2 under Climate Change Stressor States**

Flow Category	Flow Metric	Baseline (1980-2000)	Climate Change Future (2020-2040)		
			Minimum	Median	Maximum
Extreme Low Flow Event	Peak (m^3/s)	0.0095	0.0075	0.0093	0.010
	Duration (days)	5	3	4	5
	Timing (Julian date)	217	215	219	223
	Frequency (# of events)	4	3	4	5
High Flow Event	Peak (m^3/s)	0.047	0.040	0.052	0.060
	Duration (days)	2	2	2	2
	Timing (Julian date)	278	181	292	308
	Frequency (# of events)	18	17	22	24
	Rise Rate (m^3/day)	0.017	0.013	0.020	0.023
	Fall Rate (m^3/day)	-0.010	-0.015	-0.013	-0.0076
Small Flood Event (2-year)	Peak (m^3/s)	0.24	0.17	0.25	0.33
	Duration (days)	23	2	15	28
	Timing (Julian date)	100	55	104	113
	Frequency (# of events)	0	0	0	0
	Rise Rate (m^3/day)	0.042	0.045	0.081	0.13
	Fall Rate (m^3/day)	-0.013	-0.13	-0.020	-0.0059
Large Flood Event (10-year)	Peak (m^3/s)	0.36	0.31	0.43	0.61
	Duration (days)	2	2	16	26
	Timing (Julian date)	202	125	203	211
	Frequency (# of events)	0	0	0	0
	Rise Rate (m^3/day)	0.35	0.19	0.35	0.38
	Fall Rate (m^3/day)	-0.17	-0.19	-0.16	-0.023

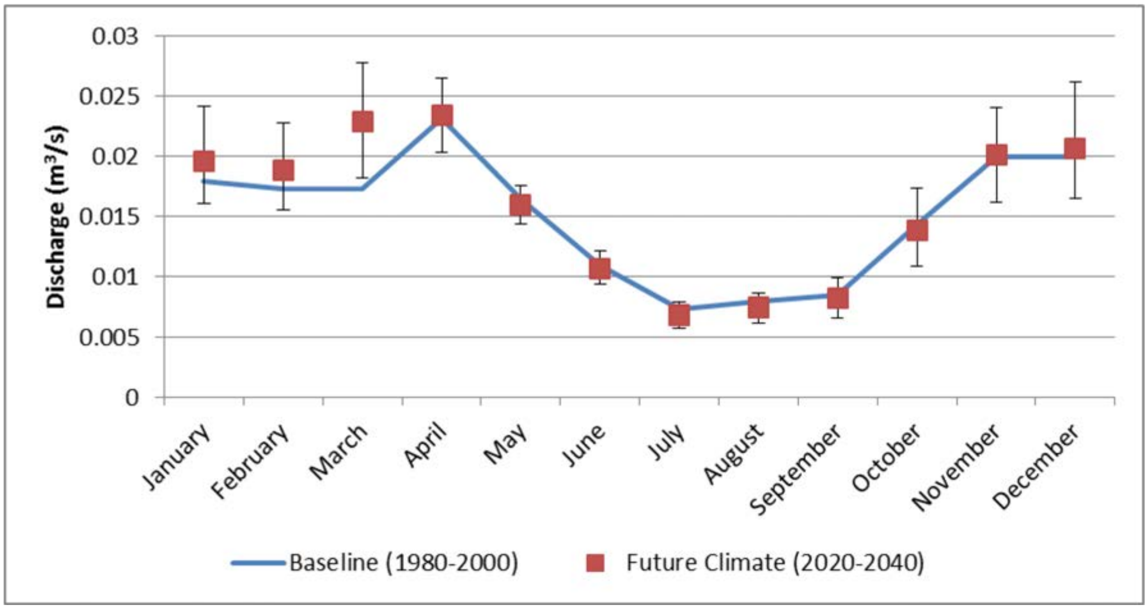

Figure B-6 **Tenth percentile monthly discharge for climate change scenarios at Key Location 2**

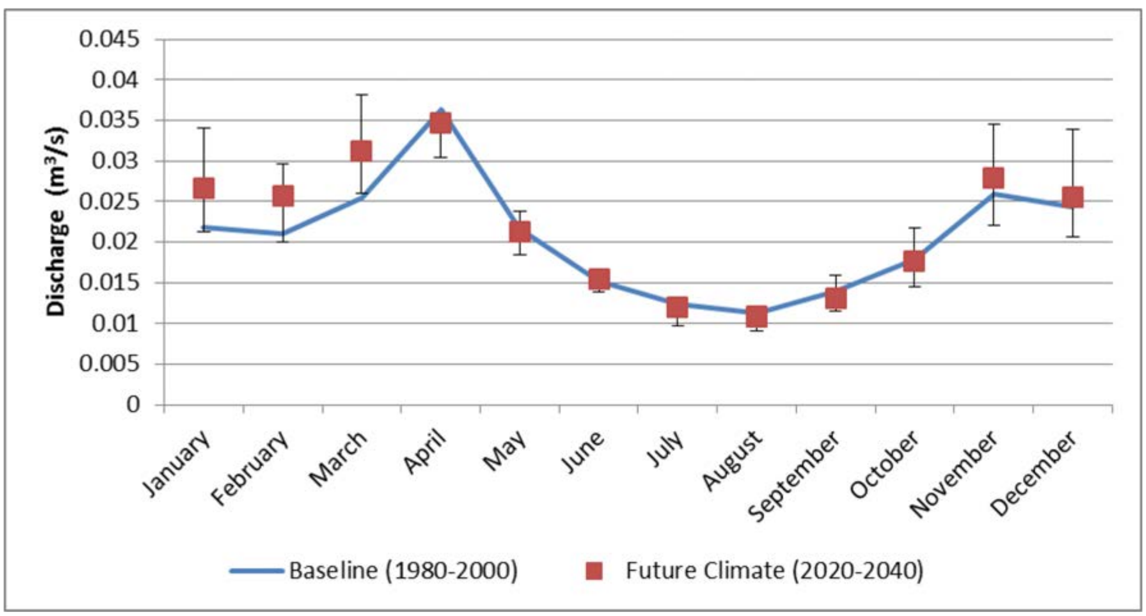

Figure B-7 **Median Monthly discharge for climate change scenarios at Key Location 2**

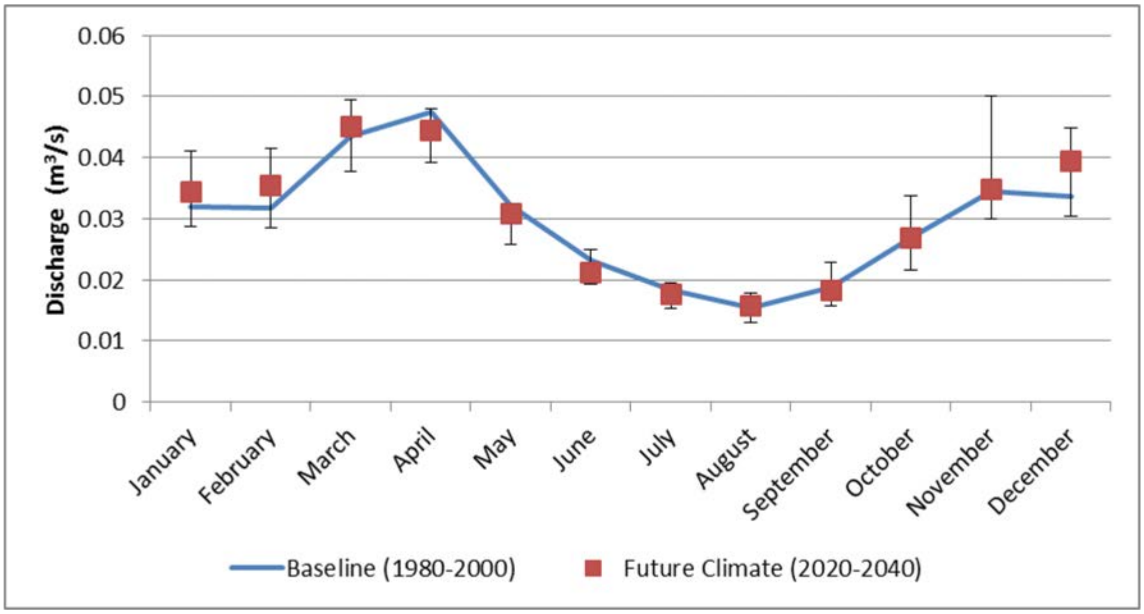

Figure B-8 **Ninetieth percentile monthly discharge for climate change scenarios at Key Location 2**

APPENDIX C
Key Location 3

APPENDIX C

KEY LOCATION 3

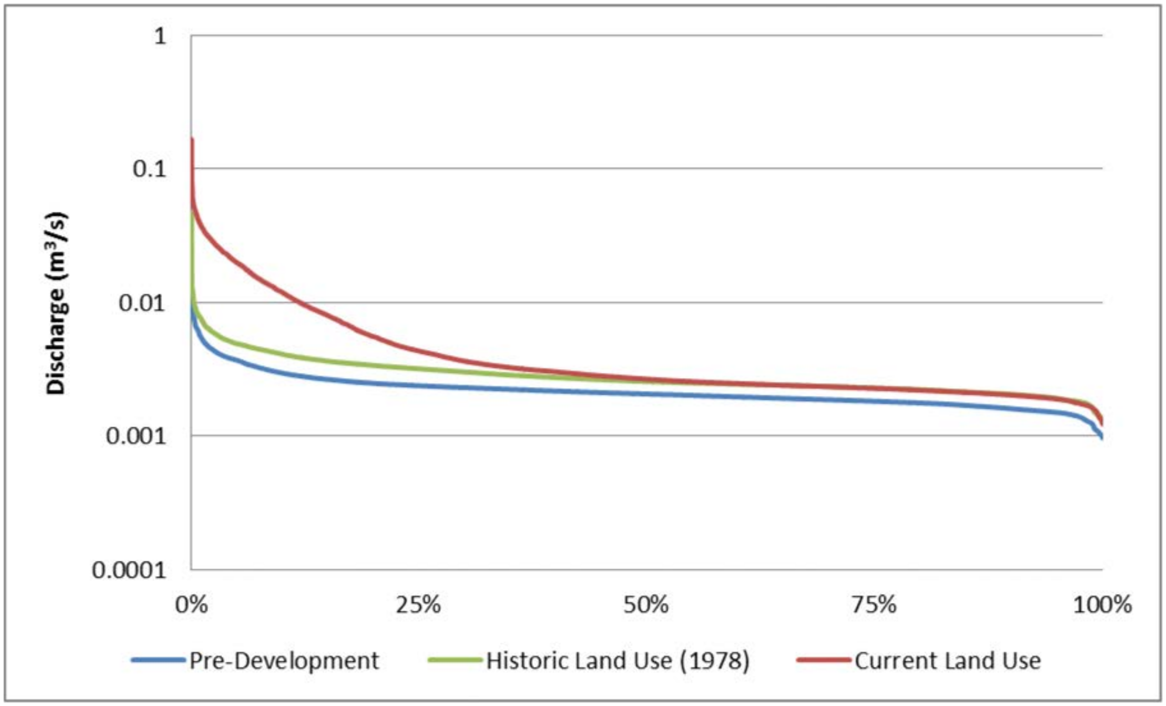

Figure C-1 **Ranked Duration Curves for Key Location 3 under Land Use Scenarios**

Table C-1 IHA Statistics for Key Location 3 under Land Use Stressor States

Flow Category	Flow Metric	Land Use		
		Pre-development	Historic (1978)	Current (2015)
Extreme Low Flow Event	Peak (m3/s)	0.0015	0.0021	0.0019
	Duration (days)	10	6	3
	Timing (date)	222	227	225
	Frequency (# of events)	0	4	5
High Flow Event	Peak (m3/s)	0.0027	0.0042	0.012
	Duration (days)	1	1	1
	Timing (date)	75	177	208
	Frequency (# of events)	12	16	41
	Rise Rate (m3/day)	0.00050	0.0011	0.0067
	Fall Rate (m3/day)	-0.00041	-0.00092	-0.0064
Small Flood Event (2-year)	Peak (m3/s)	0.0089	0.012	0.066
	Duration (days)	48	37	5
	Timing (date)	110	115	146
	Frequency (# of events)	0	0	0
	Rise Rate (m3/day)	0.00066	0.0018	0.024
	Fall Rate (m3/day)	-0.00019	-0.00040	-0.028
Large Flood Event (10-year)	Peak (m3/s)	0.013	0.036	0.13
	Duration (days)	69	2	1
	Timing (date)	130	201	201
	Frequency (# of events)	0	0	0
	Rise Rate (m3/day)	0.00060	0.024	0.10
	Fall Rate (m3/day)	-0.00018	-0.033	-0.13

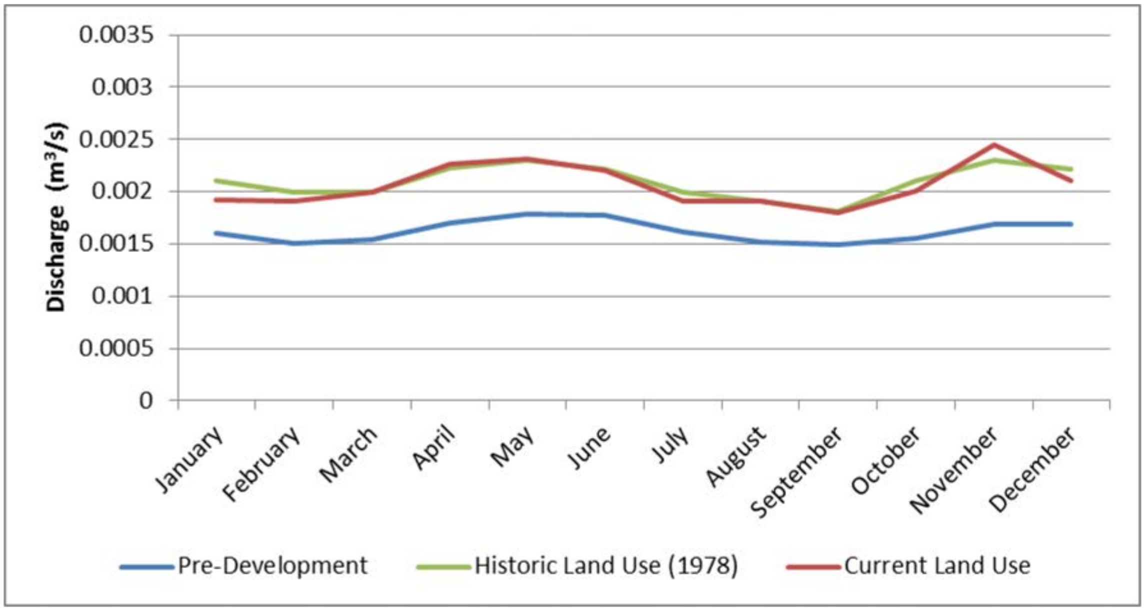

Figure C-2 **Tenth percentile monthly discharge for land use scenarios at Key Location 3**

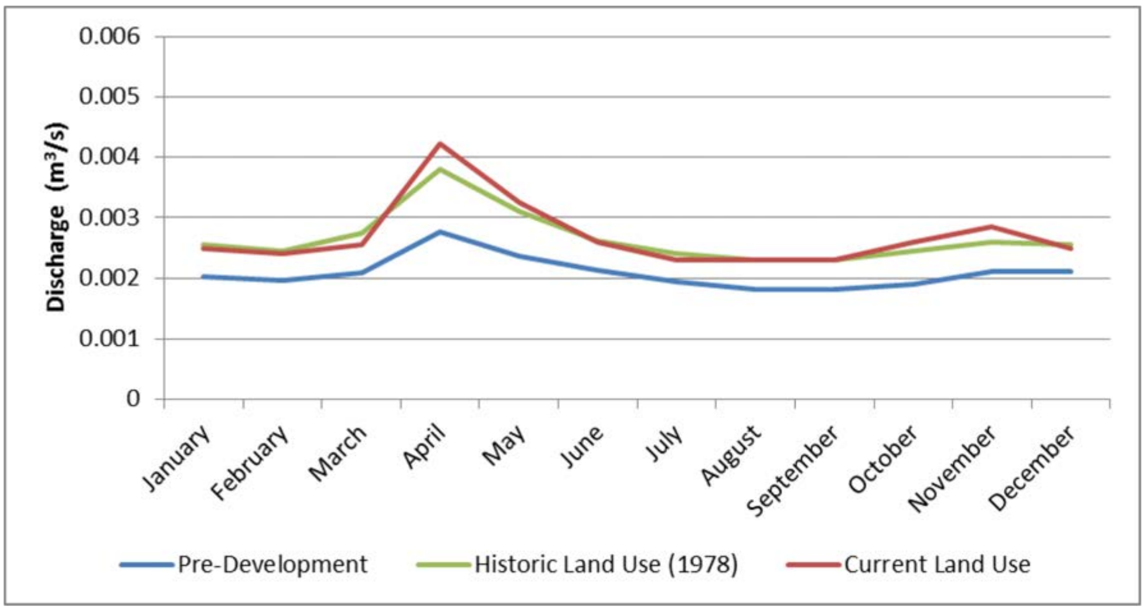

Figure C-3 **Median monthly discharge for land use scenarios at Key Location 3**

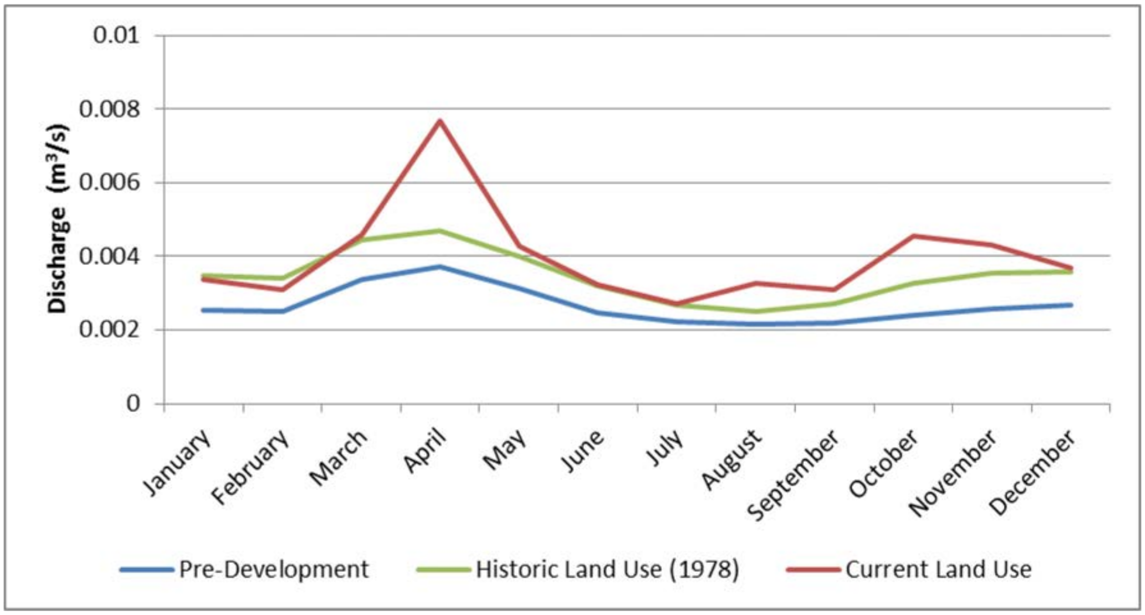

Figure C-4 **Ninetieth percentile monthly flow for land use scenarios at Key Location 3**

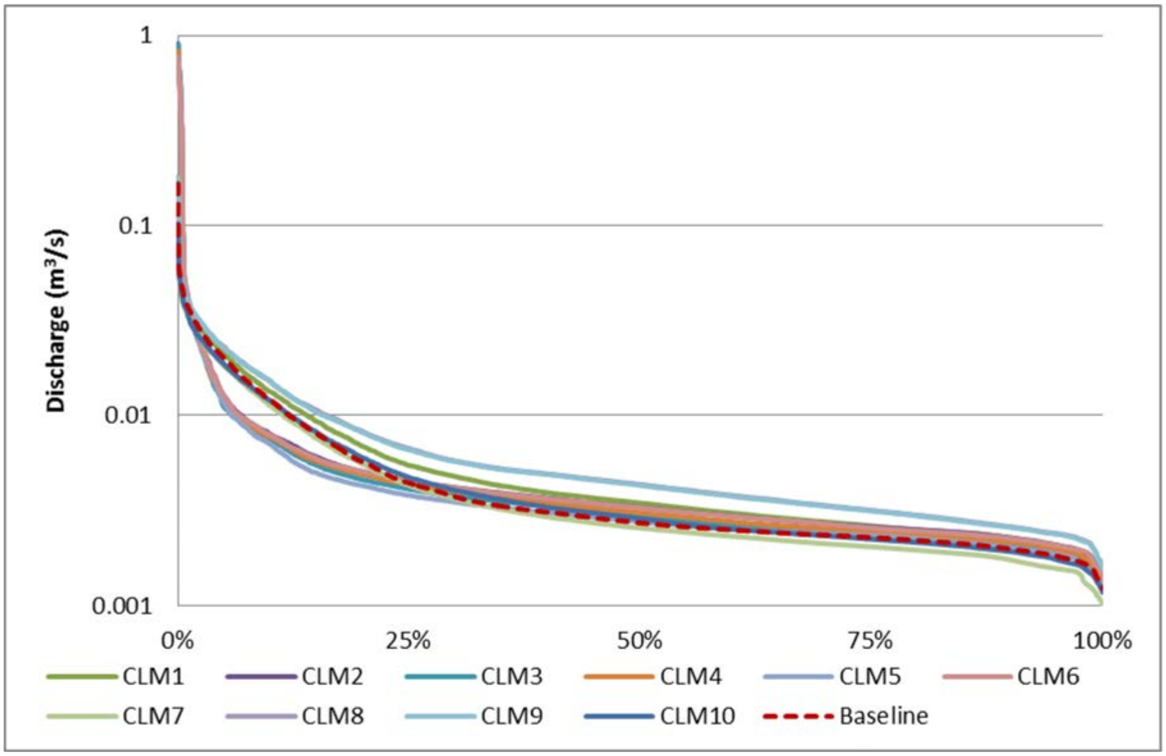

Figure C-5 **Ranked Duration Curves for Key Location 3 under Climate Change Scenarios**

Table C-2 IHA Statistics for Key Location 3 under Climate Change Stressor States

Flow Category	Flow Metric	Baseline (1980-2000)	Climate Change Future (2020-2040) Minimum	Median	Maximum
Extreme Low Flow Event	Peak (m^3/s)	0.0019	0.0016	0.0022	0.0025
	Duration (days)	3	3	3	4
	Timing (Julian date)	228	236	239	259
	Frequency (# of events)	5	0	3	7
High Flow Event	Peak (m^3/s)	0.013	0.0078	0.010	0.015
	Duration (days)	1	1	1	2
	Timing (Julian date)	204	193	269	304
	Frequency (# of events)	42	30	39	47
	Rise Rate (m^3/day)	0.0068	0.0051	0.0061	0.0087
	Fall Rate (m^3/day)	-0.0064	-0.0079	-0.0054	-0.0035
Small Flood Event (2-year)	Peak (m^3/s)	0.060	0.055	0.32	0.69
	Duration (days)	5	1	2	4
	Timing (Julian date)	121	72	229	236
	Frequency (# of events)	0	0	1	1
	Rise Rate (m^3/day)	0.022	0.03	0.31	0.69
	Fall Rate (m^3/day)	-0.027	-0.69	-0.31	-0.024
Large Flood Event (10-year)	Peak (m^3/s)	0.15	0.10	0.45	0.89
	Duration (days)	2	2	2	3
	Timing (Julian date)	202	190	221	244
	Frequency (# of events)	0	0	0	0
	Rise Rate (m^3/day)	0.11	0.10	0.33	0.66
	Fall Rate (m^3/day)	-0.14	-0.58	-0.32	-0.07

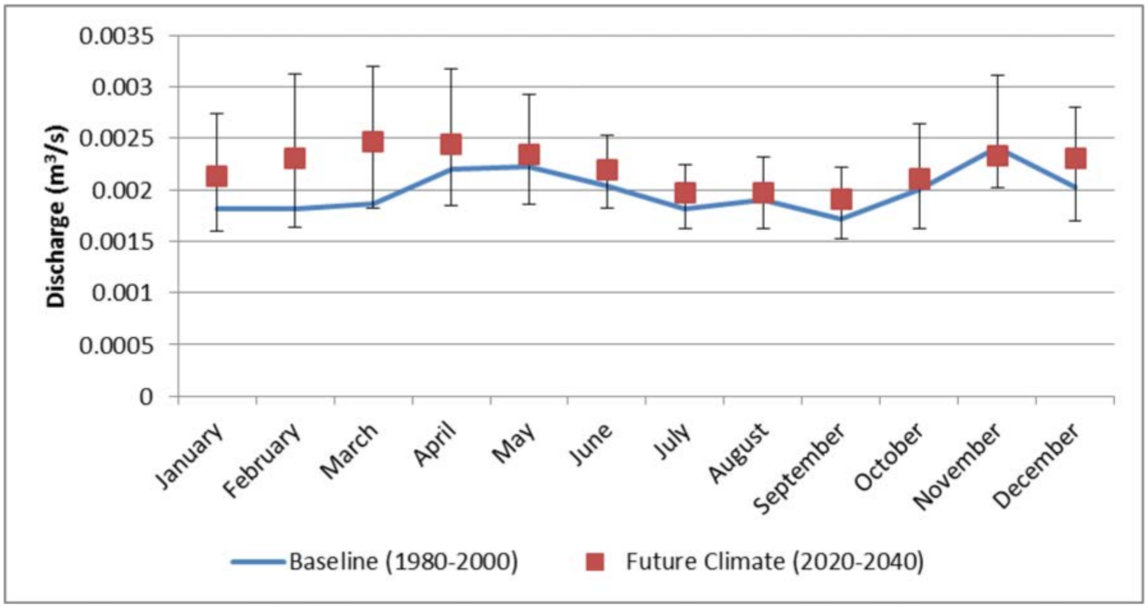

Figure C-6 **Tenth percentile monthly discharge for climate change scenarios at Key Location 3**

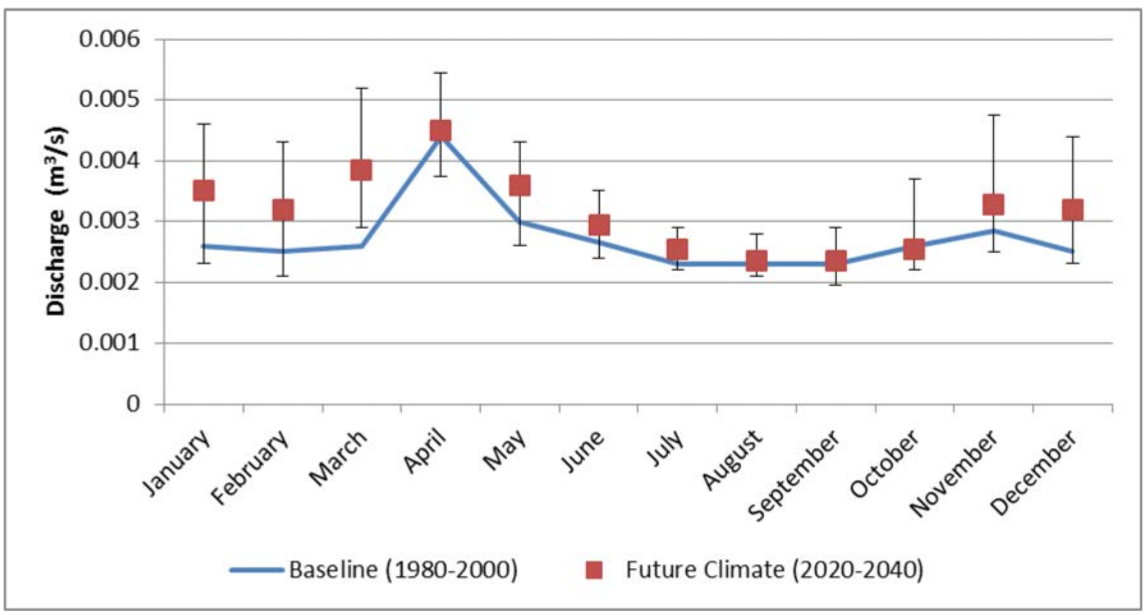

Figure C-7 **Median Monthly discharge for climate change scenarios at Key Location 3**

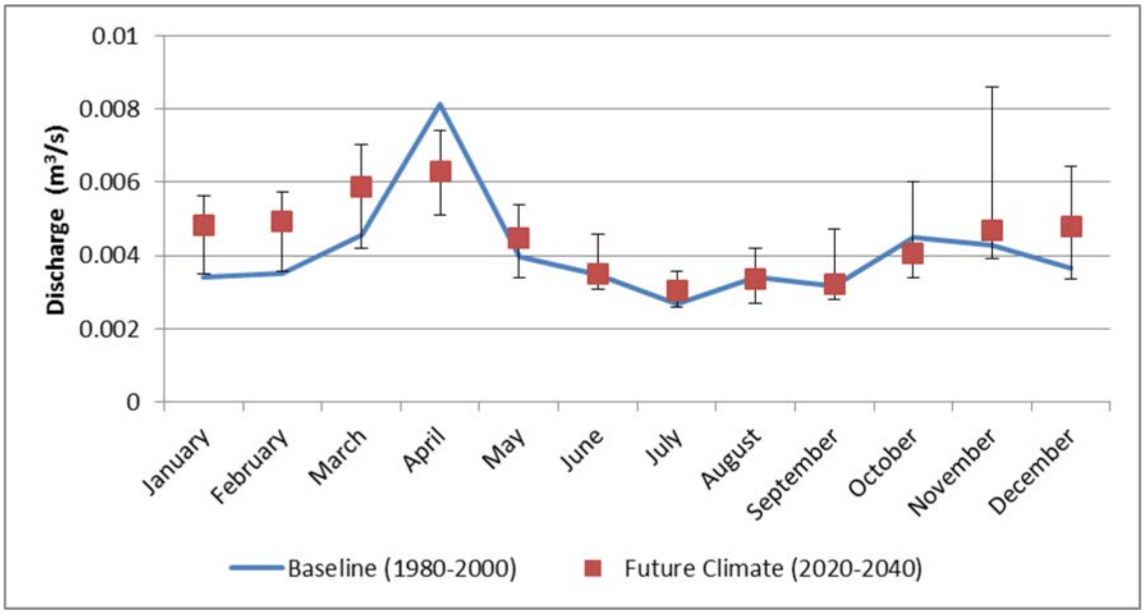

Figure C-8 **Ninetieth percentile monthly discharge for climate change scenarios at Key Location 3**

APPENDIX D
Key Location 4

APPENDIX D

KEY LOCATION 4

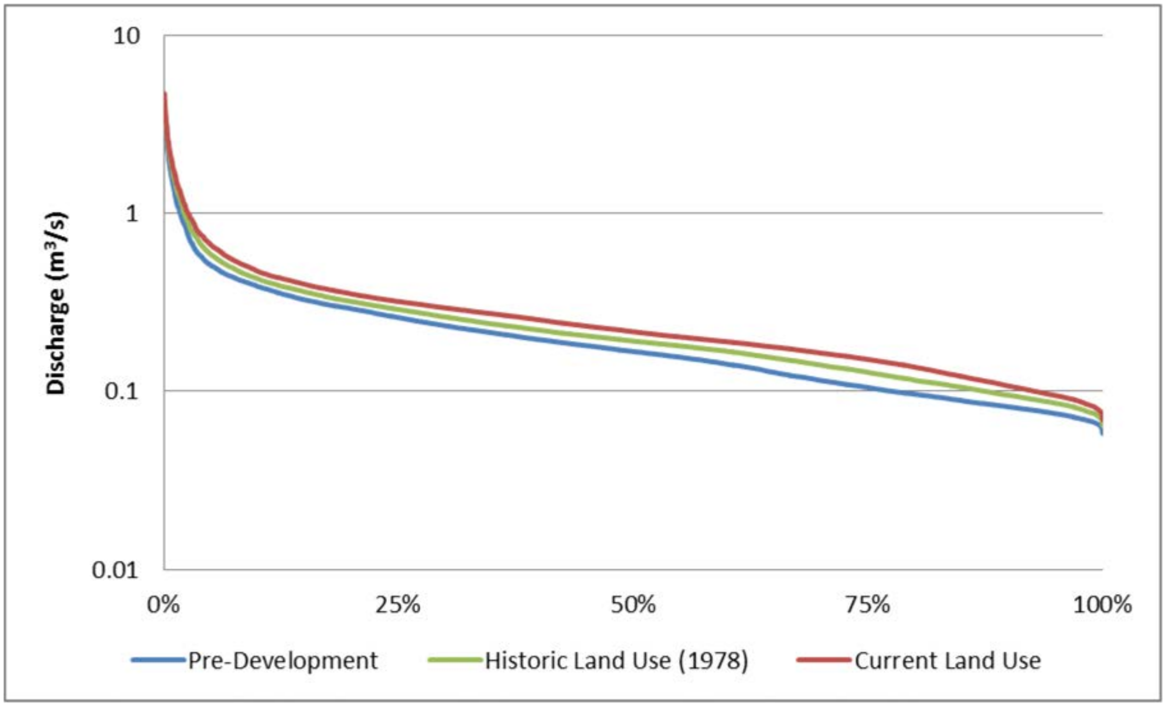

Figure D-1 **Ranked Duration Curves for Key Location 4 under Land Use Scenarios**

Table D-1 IHA Statistics for Key Location 4 under Land Use Stressor States

Flow Category	Flow Metric	Land Use		
		Pre-development	Historic (1978)	Current (2015)
Extreme Low Flow Event	Peak (m3/s)	0.075	0.088	0.098
	Duration (days)	13	5	4
	Timing (date)	231	234	230
	Frequency (# of events)	2	3	7
High Flow Event	Peak (m3/s)	0.41	0.45	0.49
	Duration (days)	4	3	2
	Timing (date)	335	269	255
	Frequency (# of events)	5	8	14
	Rise Rate (m3/day)	0.083	0.14	0.16
	Fall Rate (m3/day)	-0.032	-0.064	-0.11
Small Flood Event (2-year)	Peak (m3/s)	2.8	3.3	3.6
	Duration (days)	39	32	34
	Timing (date)	107	106	103
	Frequency (# of events)	0	0	0
	Rise Rate (m3/day)	0.21	0.32	0.65
	Fall Rate (m3/day)	-0.11	-0.13	-0.13
Large Flood Event (10-year)	Peak (m3/s)	4.0	4.2	4.4
	Duration (days)	45	40	41
	Timing (date)	91	91	130
	Frequency (# of events)	0	0	0
	Rise Rate (m3/day)	0.75	0.79	0.84
	Fall Rate (m3/day)	-0.12	-0.14	-0.20

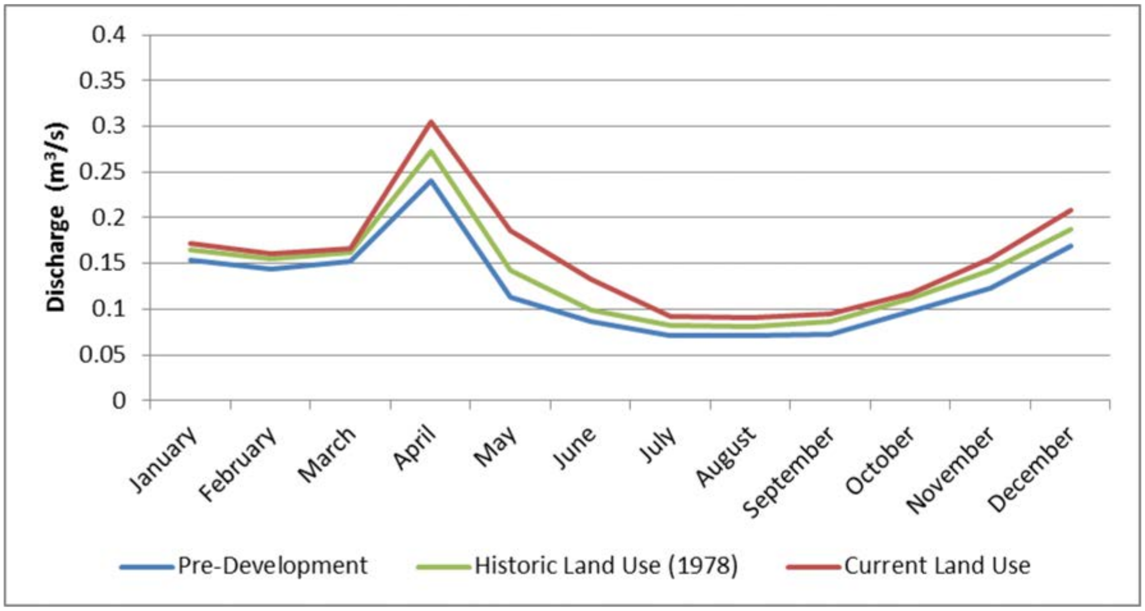

Figure D-2 **Tenth percentile monthly discharge for land use scenarios at Key Location 4**

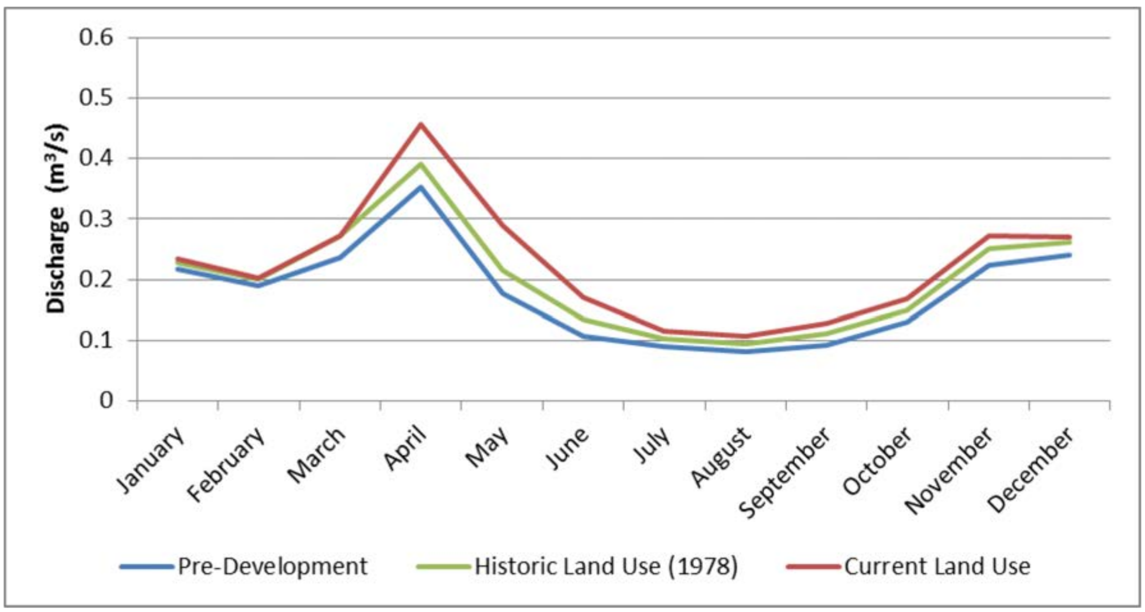

Figure D-3 **Median monthly discharge for land use scenarios at Key Location 4**

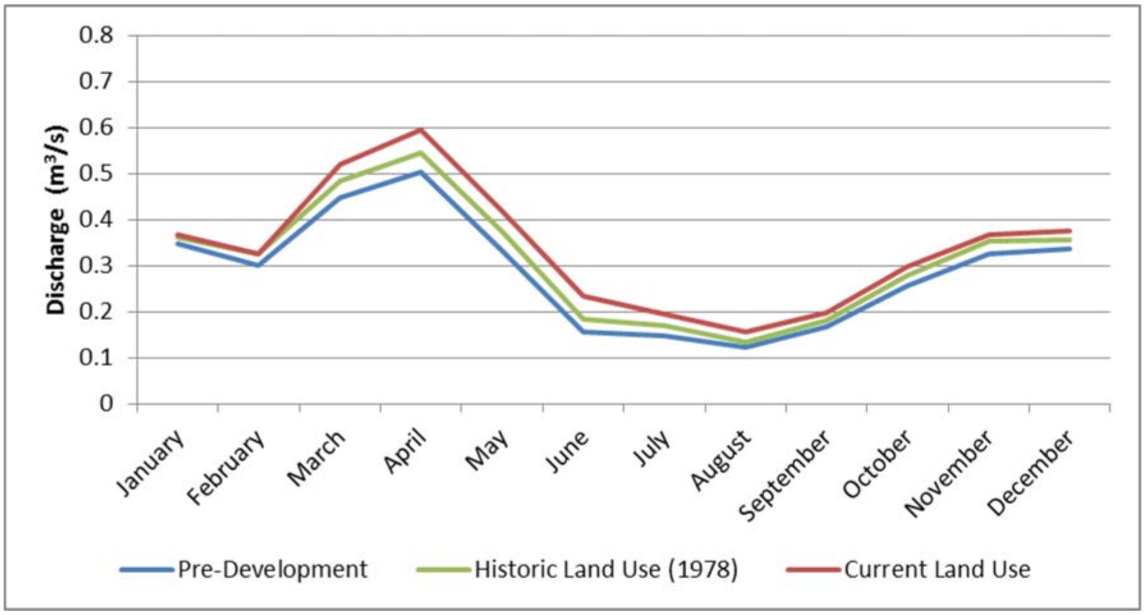

Figure D-4 **Ninetieth percentile monthly flow for land use scenarios at Key Location 4**

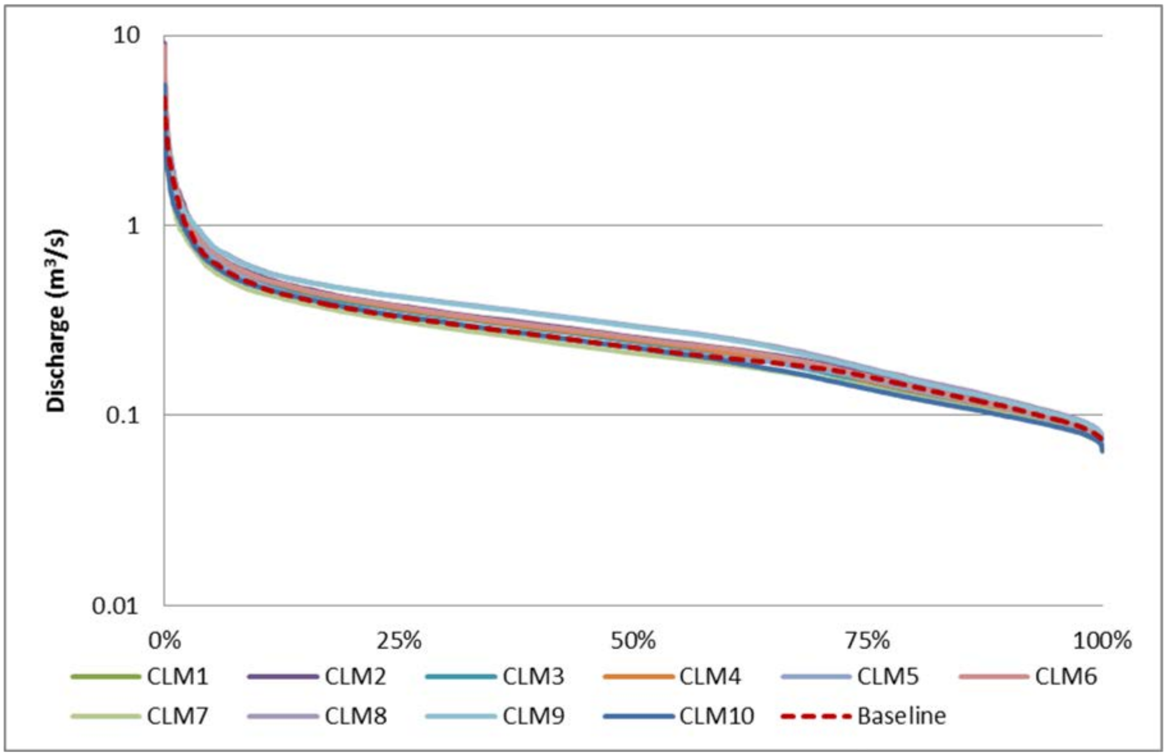

Figure D-5 Ranked Duration Curves for Key Location 4 under Climate Change Scenarios

Table D-2 IHA Statistics for Key Location 4 under Climate Change Stressor States

Flow Category	Flow Metric	Baseline (1980-2000)	Climate Change Future (2020-2040)		
			Minimum	Median	Maximum
Extreme Low Flow Event	Peak (m^3/s)	0.099	0.090	0.10	0.11
	Duration (days)	4	3	4	4
	Timing (Julian date)	223	217	223	229
	Frequency (# of events)	6	5	7	7
High Flow Event	Peak (m^3/s)	0.48	0.45	0.56	0.64
	Duration (days)	2	2	2	2
	Timing (Julian date)	228	157	239	300
	Frequency (# of events)	15	13	16	18
	Rise Rate (m^3/day)	0.15	0.14	0.22	0.27
	Fall Rate (m^3/day)	-0.10	-0.15	-0.12	-0.089
Small Flood Event (2-year)	Peak (m^3/s)	3.7	2.4	3.4	5.5
	Duration (days)	32	24	30	36
	Timing (Julian date)	102	82	101	317
	Frequency (# of events)	0	0	0	1
	Rise Rate (m^3/day)	0.63	0.41	0.75	2.1
	Fall Rate (m^3/day)	-0.13	-0.31	-0.19	-0.084
Large Flood Event (10-year)	Peak (m^3/s)	4.5	4.5	5.4	8.7
	Duration (days)	25	3	24	32
	Timing (Julian date)	140	16	139	202
	Frequency (# of events)	0	0	0	0
	Rise Rate (m^3/day)	2.7	2.3	3.4	8.5
	Fall Rate (m^3/day)	-0.78	-3.5	-1.0	-0.20

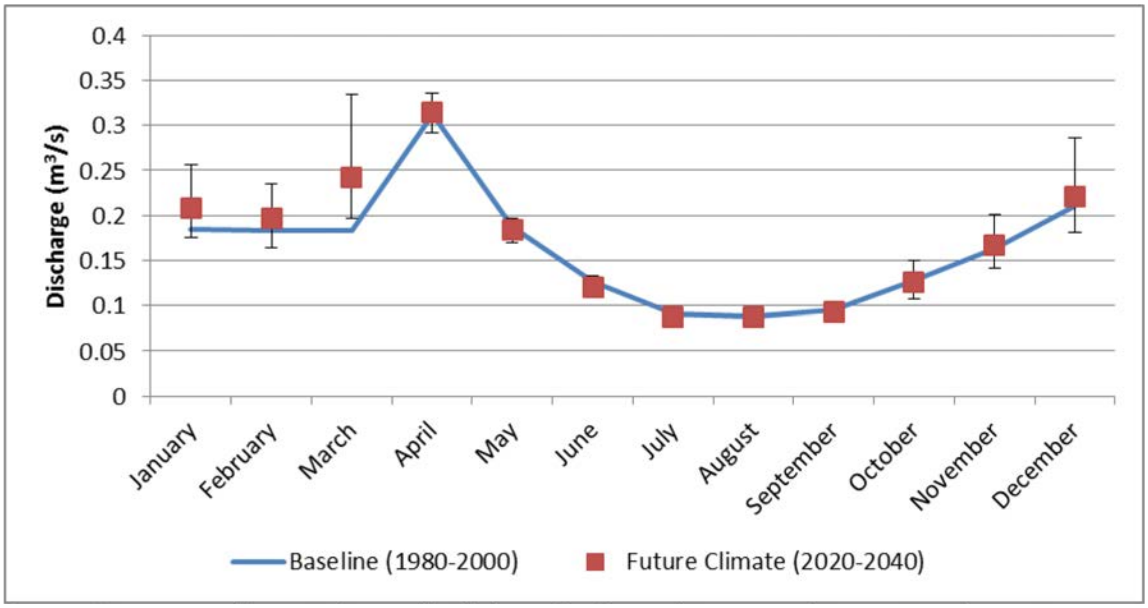

Figure D-6 **Tenth percentile monthly discharge for climate change scenarios at Key Location 4**

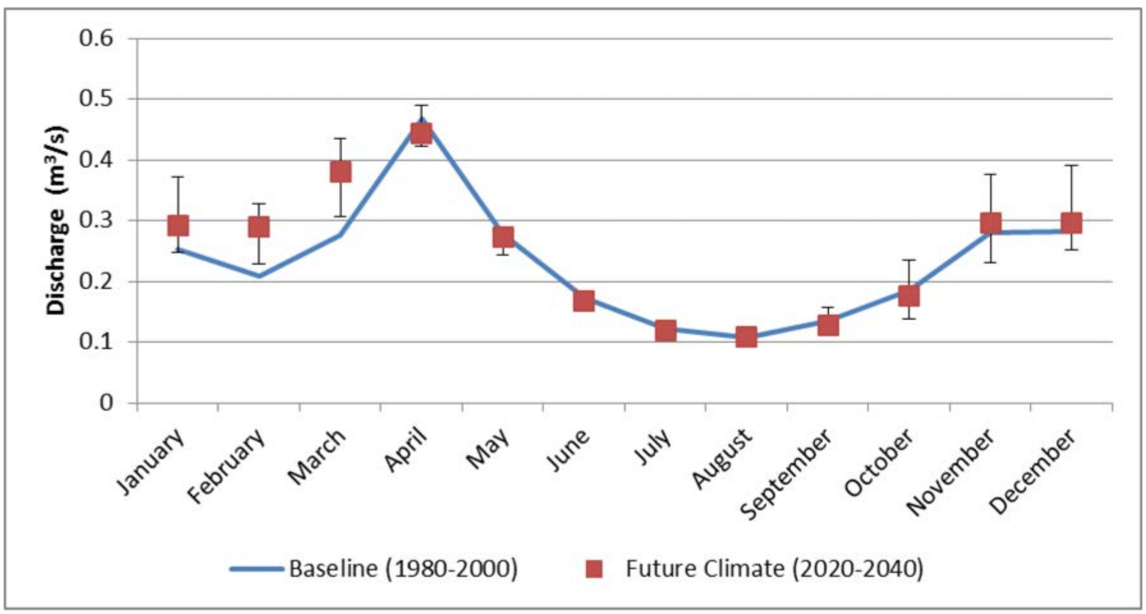

Figure D-7 **Median Monthly discharge for climate change scenarios at Key Location 4**

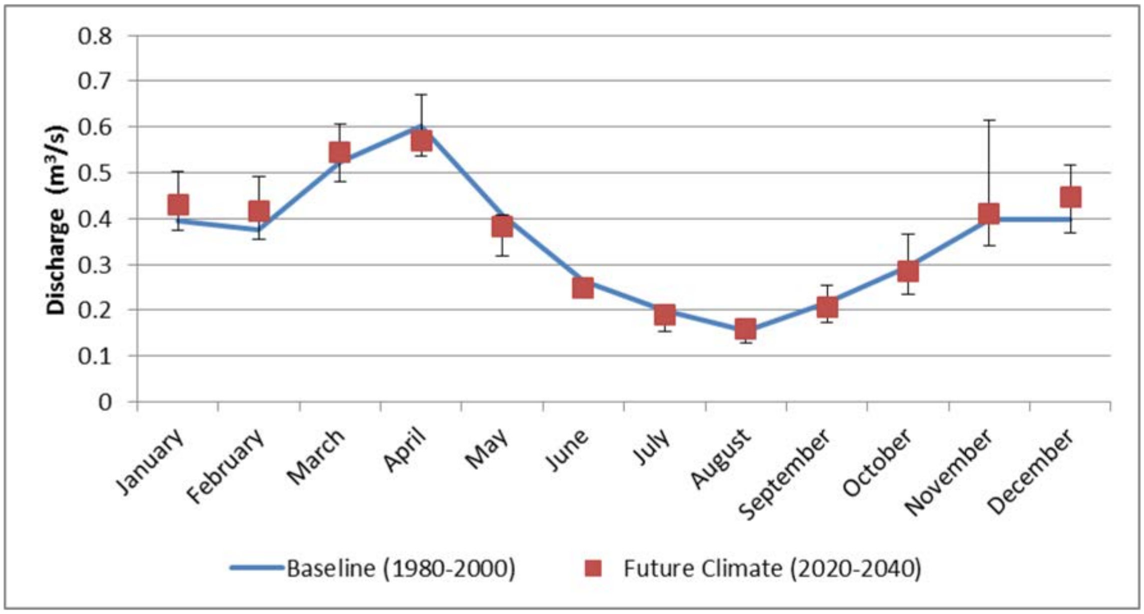

Figure D-8 **Ninetieth percentile monthly discharge for climate change scenarios at Key Location 4**

APPENDIX E
Key Location 5

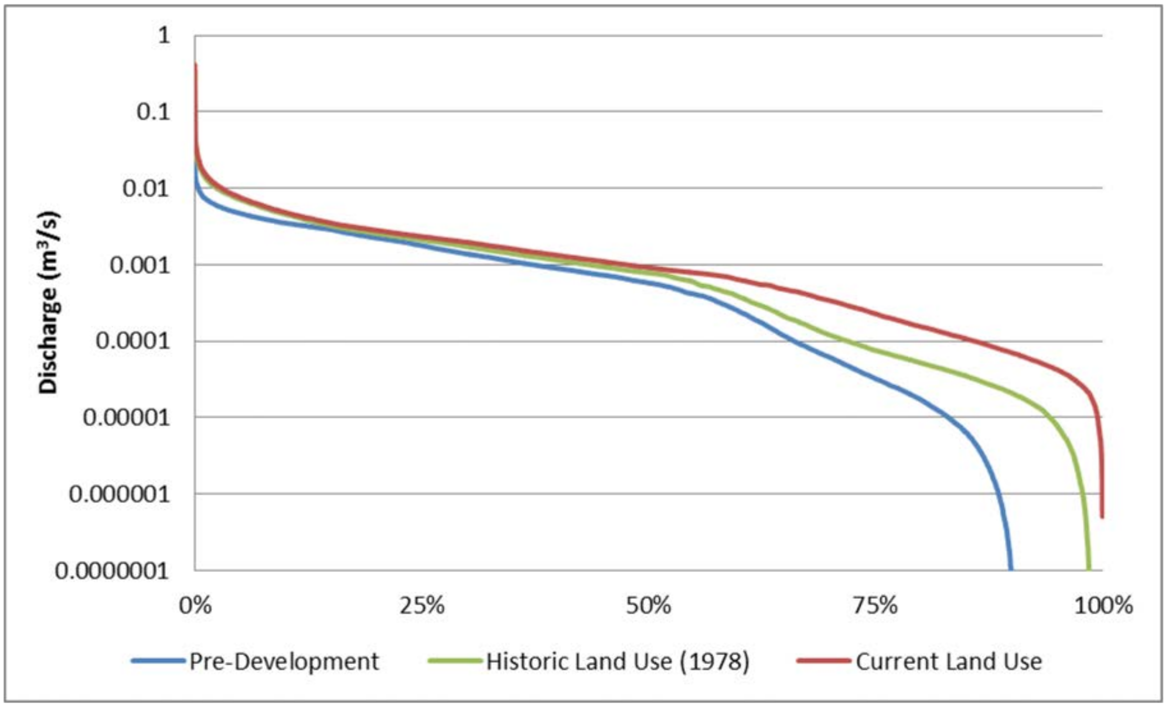

Figure E-1 **Ranked Duration Curves for Key Location 5 under Land Use Scenarios**

Table E-1 IHA Statistics for Key Location 5 under Land Use Stressor States

Flow Category	Flow Metric	Land Use		
		Pre-development	Historic (1978)	Current (2015)
Extreme Low Flow Event	Peak (m3/s)	0	0	0.0001
	Duration (days)	35	15	5
	Timing (date)	270	231	242
	Frequency (# of events)	1	3	11
High Flow Event	Peak (m3/s)	0.0029	0.0045	0.0036
	Duration (days)	23	14	2
	Timing (date)	38	124	225
	Frequency (# of events)	2	3	9
	Rise Rate (m3/day)	0.00022	0.00063	0.0019
	Fall Rate (m3/day)	-0.00012	-0.00019	-0.0011
Small Flood Event (2-year)	Peak (m3/s)	0.013	0.031	0.039
	Duration (days)	53	53	43
	Timing (date)	103	114	118
	Frequency (# of events)	0	0	0
	Rise Rate (m3/day)	0.00048	0.0018	0.0032
	Fall Rate (m3/day)	-0.00043	-0.00080	-0.0018
Large Flood Event (10-year)	Peak (m3/s)	0.025	0.21	0.28
	Duration (days)	2	2	2
	Timing (date)	201	201	201
	Frequency (# of events)	0	0	0
	Rise Rate (m3/day)	0.025	0.21	0.28
	Fall Rate (m3/day)	-0.012	-0.11	-0.14

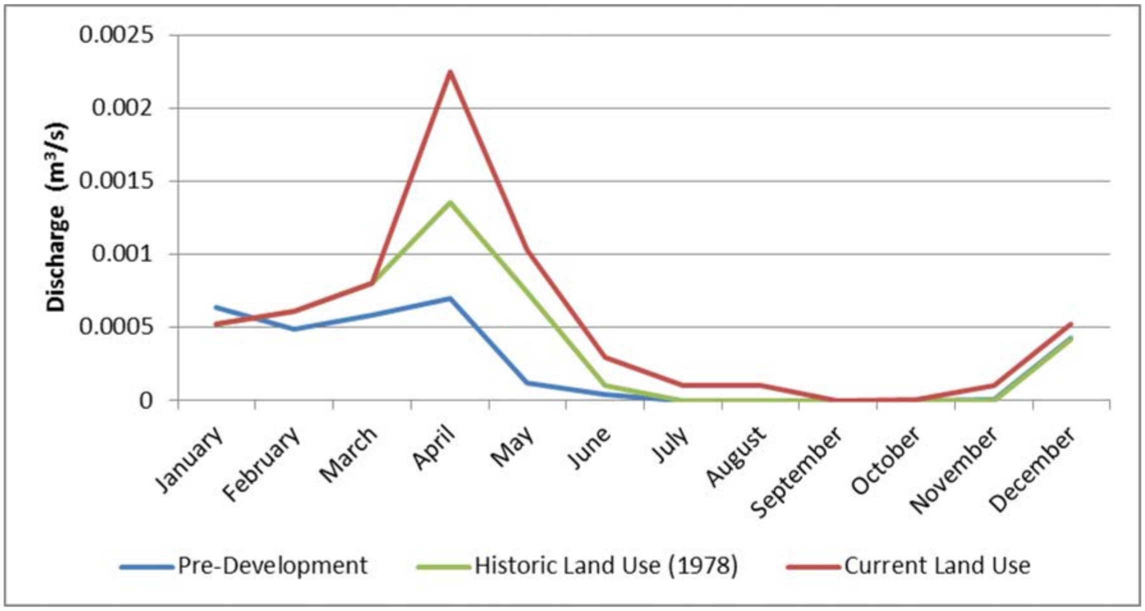

Figure E-2 **Tenth percentile monthly discharge for land use scenarios at Key Location 5**

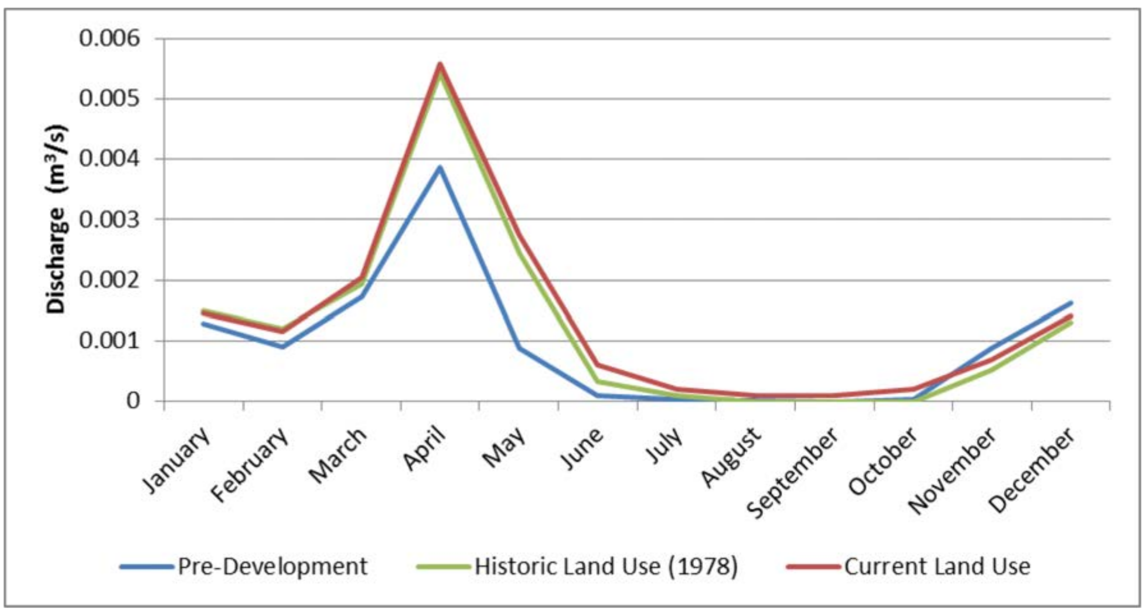

Figure E-3 **Median monthly discharge for land use scenarios at Key Location 5**

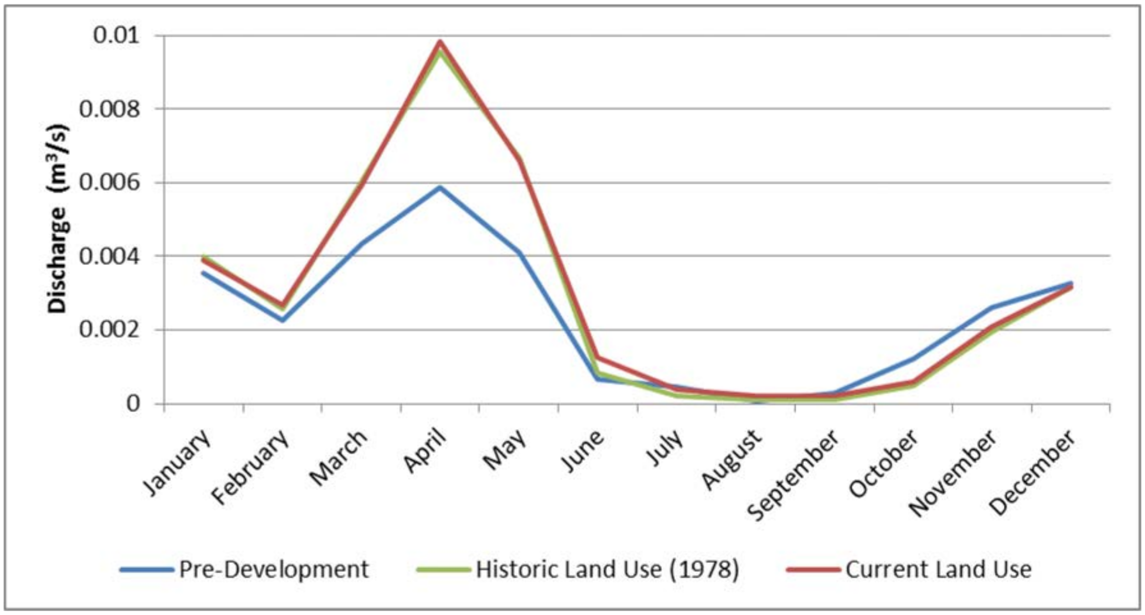

Figure E-4 **Ninetieth percentile monthly flow for land use scenarios at Key Location 5**

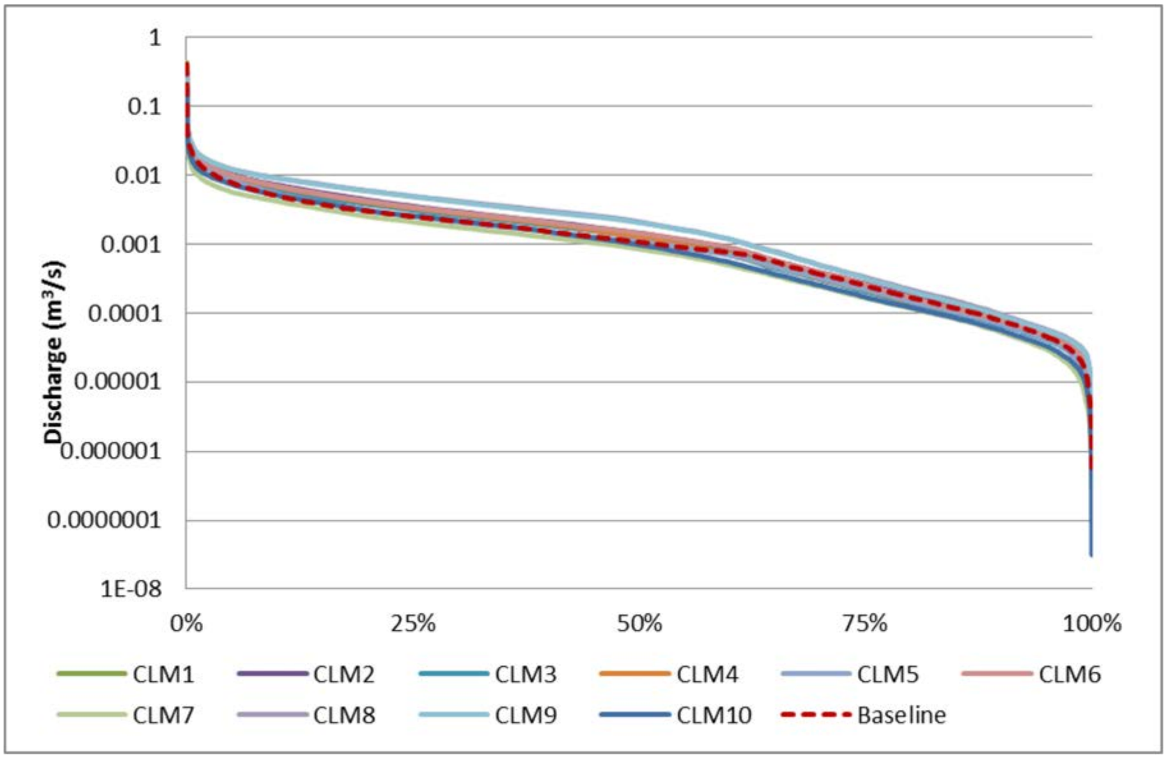

Figure E-5 Ranked Duration Curves for Key Location 5 under Climate Change Scenarios

Table E-2 **IHA Statistics for Key Location 5 under Climate Change Stressor States**

Flow Category	Flow Metric	Baseline (1980-2000)	Climate Change Future (2020-2040)		
			Minimum	Median	Maximum
Extreme Low Flow Event	Peak (m^3/s)	0.0001	0.0001	0.0001	0.0001
	Duration (days)	5	4	5	6
	Timing (Julian date)	234	236	240	245
	Frequency (# of events)	10	9	11	12
High Flow Event	Peak (m^3/s)	0.0041	0.0035	0.0053	0.0093
	Duration (days)	2	1	1	4
	Timing (Julian date)	206	45	166	196
	Frequency (# of events)	9	5	9	11
	Rise Rate (m^3/day)	0.0018	0.0016	0.0030	0.0041
	Fall Rate (m^3/day)	-0.0012	-0.0028	-0.0014	-0.00085
Small Flood Event (2-year)	Peak (m^3/s)	0.038	0.033	0.041	0.059
	Duration (days)	41	16	51	66
	Timing (Julian date)	113	89	100	114
	Frequency (# of events)	0	0	0	0
	Rise Rate (m^3/day)	0.0037	0.0025	0.0042	0.018
	Fall Rate (m^3/day)	-0.0015	-0.0036	-0.0015	-0.00086
Large Flood Event (10-year)	Peak (m^3/s)	0.35	0.11	0.20	0.37
	Duration (days)	2	1	16	42
	Timing (Julian date)	202	190	206	211
	Frequency (# of events)	0	0	0	0
	Rise Rate (m^3/day)	0.34	0.051	0.16	0.37
	Fall Rate (m^3/day)	-0.17	-0.33	-0.13	-0.050

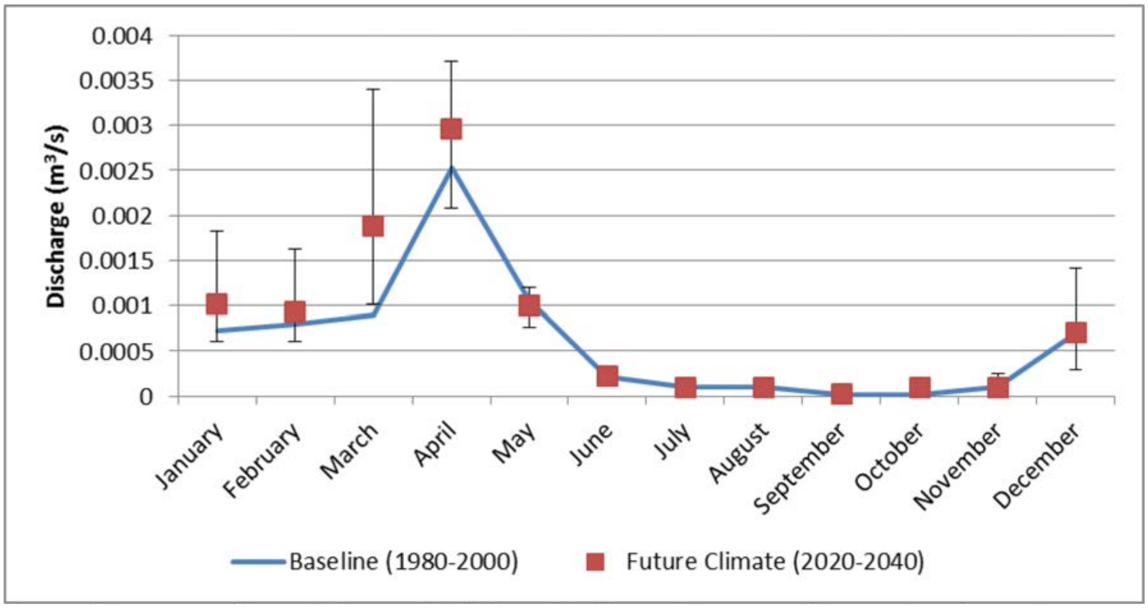

Figure E-6 **Tenth percentile monthly discharge for climate change scenarios at Key Location 5**

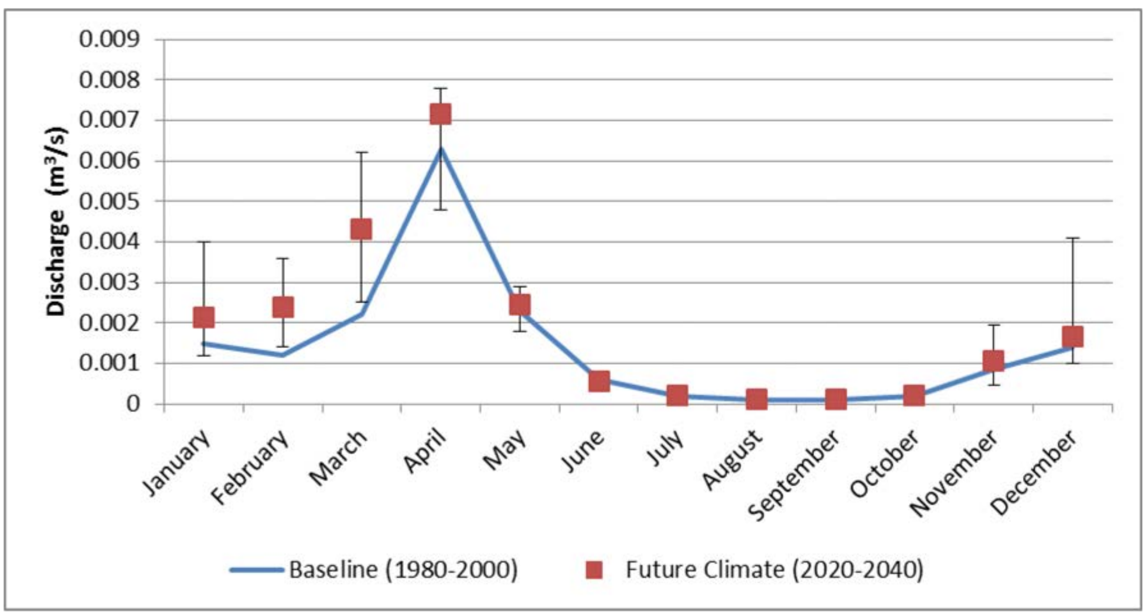

Figure E-7 **Median Monthly discharge for climate change scenarios at Key Location 5**

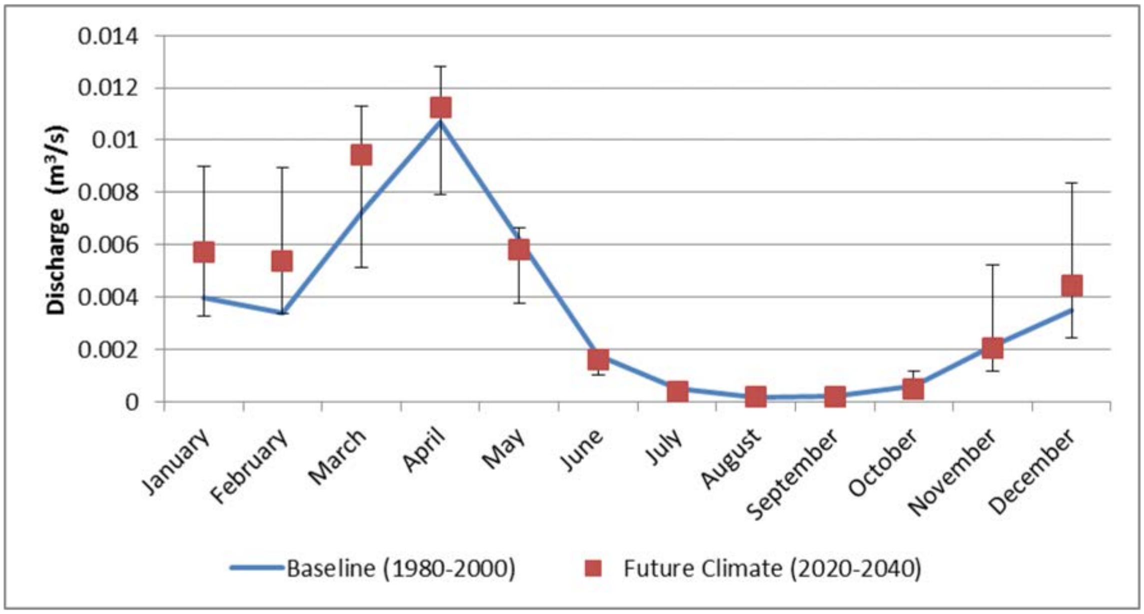

Figure E-8 **Ninetieth percentile monthly discharge for climate change scenarios at Key Location 5**

APPENDIX F
Key Location 6

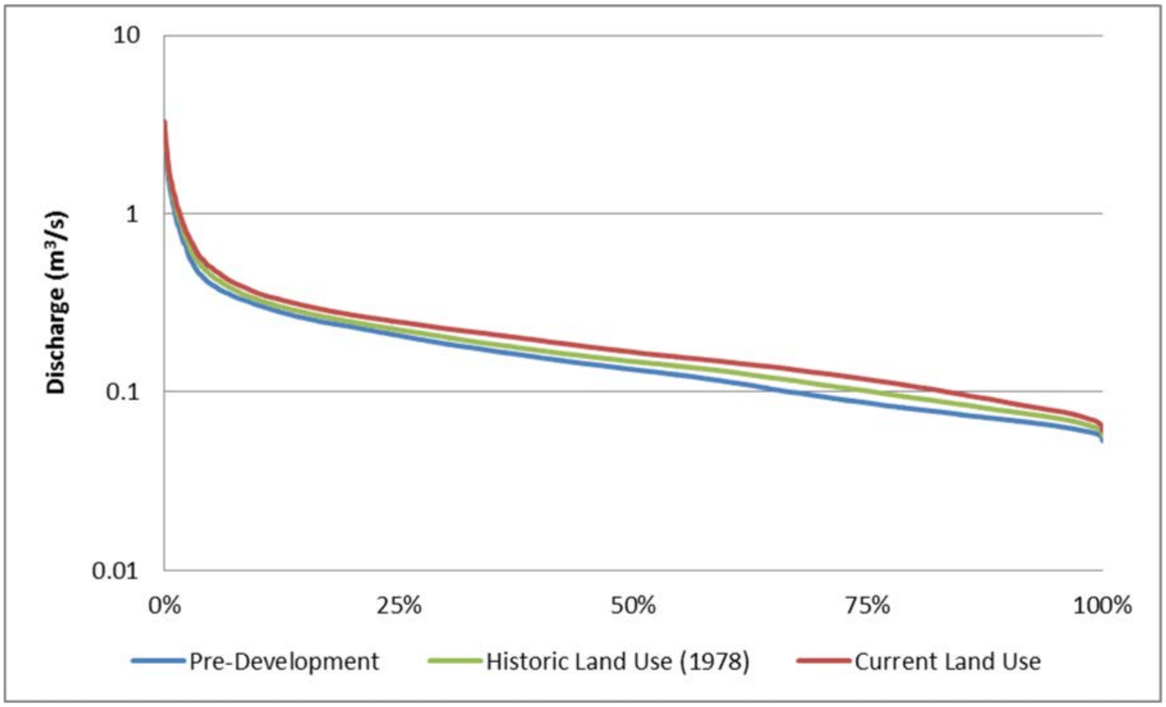

Figure F-1 **Ranked Duration Curves for Key Location 6 under Land Use Scenarios**

Table F-1 IHA Statistics for Key Location 6 under Land Use Stressor States

Flow Category	Flow Metric	Land Use		
		Pre-development	Historic (1978)	Current (2015)
Extreme Low Flow Event	Peak (m3/s)	0.065	0.072	0.080
	Duration (days)	12	8	4
	Timing (date)	229	229	230
	Frequency (# of events)	2	3	6
High Flow Event	Peak (m3/s)	0.33	0.34	0.37
	Duration (days)	4	3	2
	Timing (date)	317	284	257
	Frequency (# of events)	5	8	12
	Rise Rate (m3/day)	0.075	0.13	0.12
	Fall Rate (m3/day)	-0.029	-0.045	-0.079
Small Flood Event (2-year)	Peak (m3/s)	2.1	2.3	2.6
	Duration (days)	36	37	33
	Timing (date)	102	108	103
	Frequency (# of events)	0	0	0
	Rise Rate (m3/day)	0.18	0.22	0.45
	Fall Rate (m3/day)	-0.085	-0.11	-0.092
Large Flood Event (10-year)	Peak (m3/s)	3.0	3.2	3.2
	Duration (days)	34	33	42
	Timing (date)	91	91	124
	Frequency (# of events)	0	0	0
	Rise Rate (m3/day)	0.57	0.60	0.59
	Fall Rate (m3/day)	-0.093	-0.10	-0.14

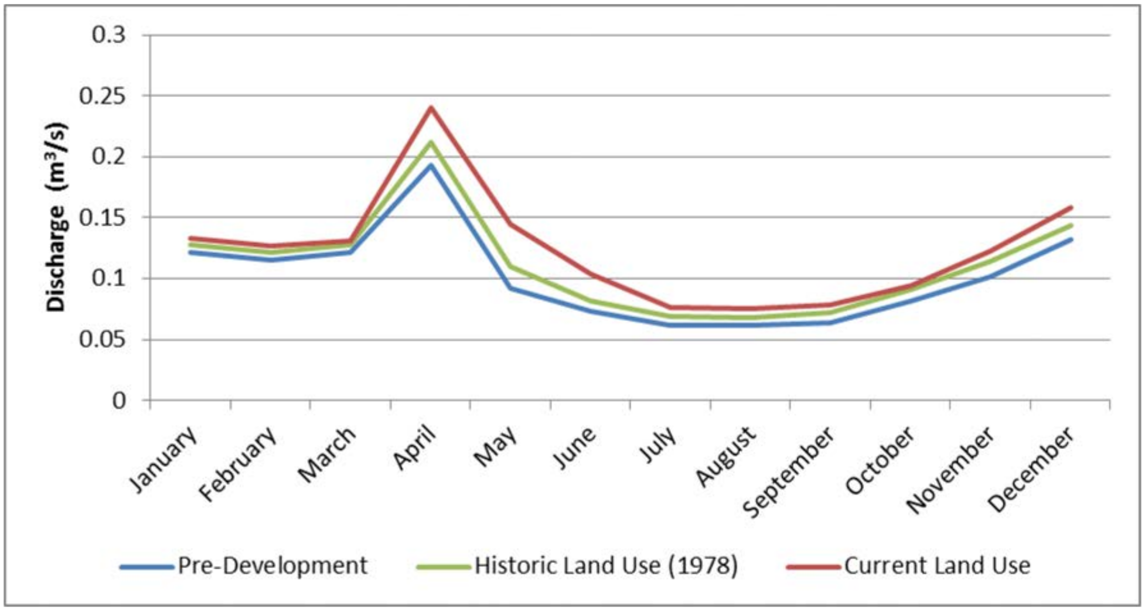

Figure F-2 **Tenth percentile monthly discharge for land use scenarios at Key Location 6**

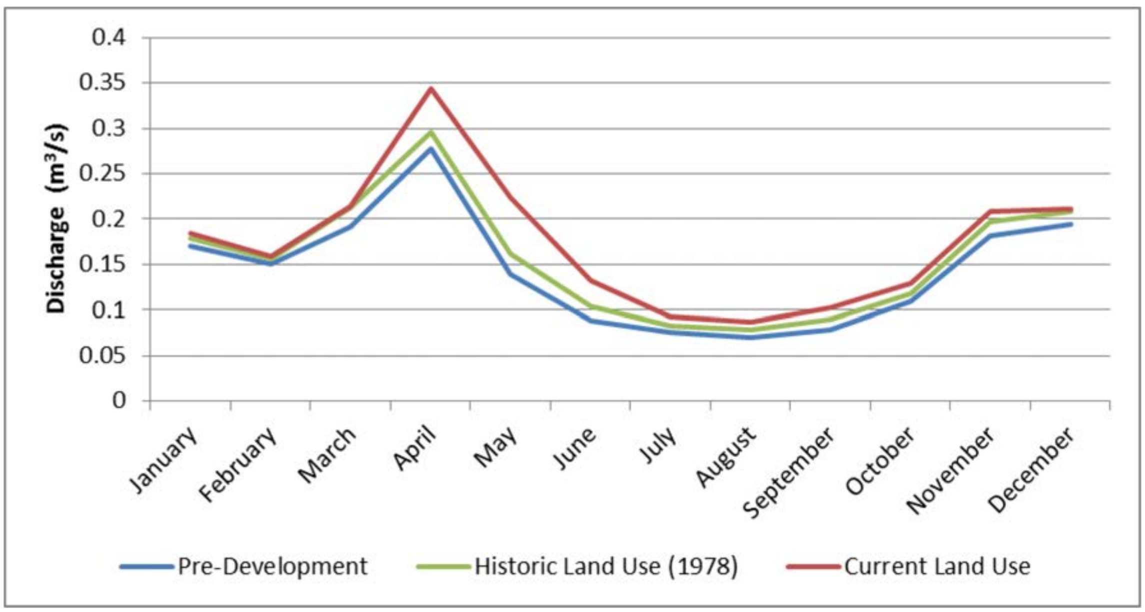

Figure F-3 **Median monthly discharge for land use scenarios at Key Location 6**

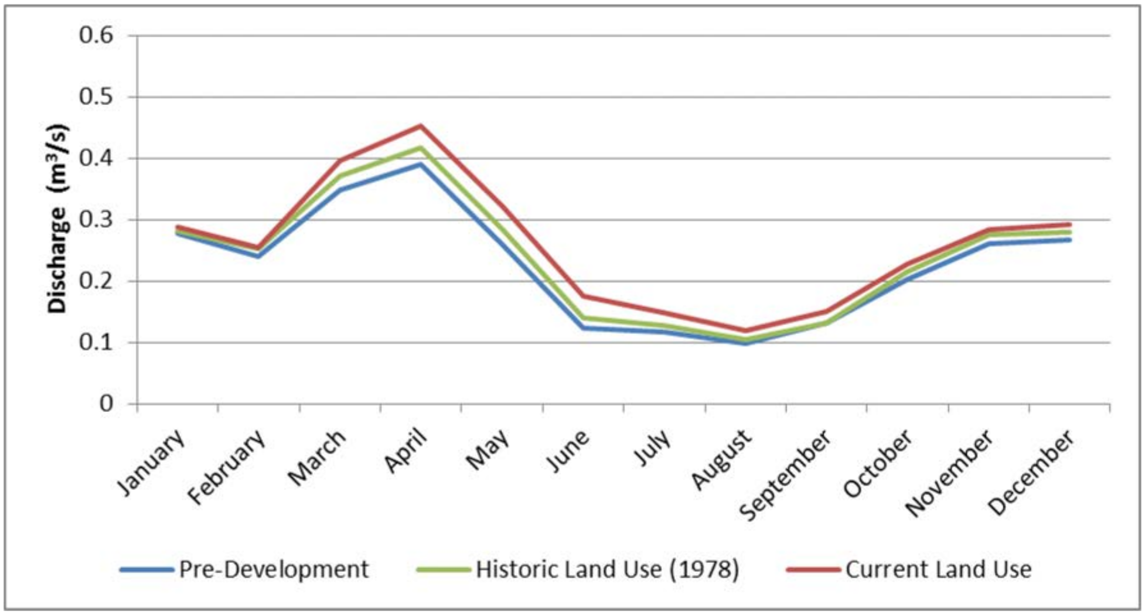

Figure F-4 **Ninetieth percentile monthly flow for land use scenarios at Key Location 6**

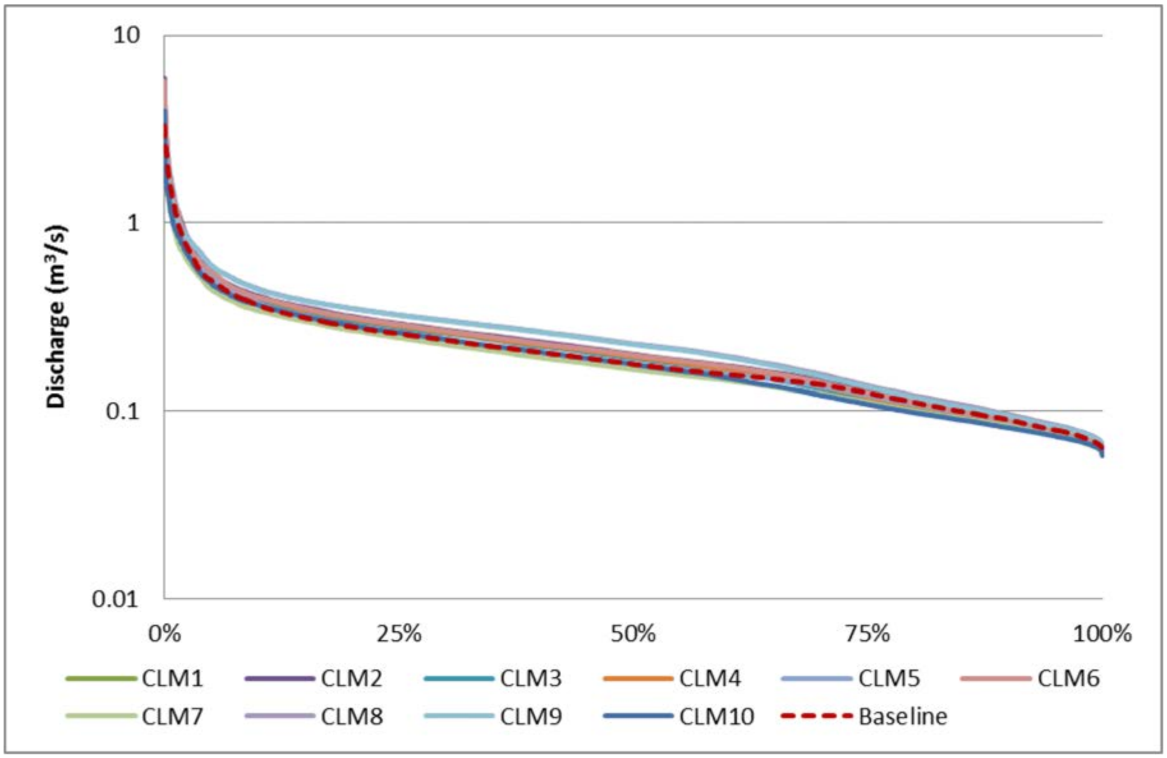

Figure F-5 **Ranked Duration Curves for Key Location 6 under Climate Change Scenarios**

Table F-2 **IHA Statistics for Key Location 6 under Climate Change Stressor States**

Flow Category	Flow Metric	Baseline (1980-2000)	Climate Change Future (2020-2040) Minimum	Median	Maximum
Extreme Low Flow Event	Peak (m^3/s)	0.082	0.075	0.082	0.087
	Duration (days)	4	3	4	4
	Timing (Julian date)	223	219	223	230
	Frequency (# of events)	6	5	6	7
High Flow Event	Peak (m^3/s)	0.37	0.33	0.42	0.50
	Duration (days)	2	2	2	3
	Timing (Julian date)	228	52	272	311
	Frequency (# of events)	13	12	14	18
	Rise Rate (m^3/day)	0.12	0.10	0.15	0.19
	Fall Rate (m^3/day)	-0.074	-0.10	-0.090	-0.060
Small Flood Event (2-year)	Peak (m^3/s)	2.6	1.7	2.5	4.1
	Duration (days)	32	23	31	46
	Timing (Julian date)	107	82	101	313
	Frequency (# of events)	0	0	0	1
	Rise Rate (m^3/day)	0.47	0.22	0.55	1.1
	Fall Rate (m^3/day)	-0.094	-0.23	-0.13	-0.063
Large Flood Event (10-year)	Peak (m^3/s)	3.2	3.1	3.7	5.5
	Duration (days)	40	3	24	44
	Timing (Julian date)	84	8	139	202
	Frequency (# of events)	0	0	0	0
	Rise Rate (m^3/day)	0.60	0.78	2.1	5.3
	Fall Rate (m^3/day)	-0.08	-2.2	-0.66	-0.13

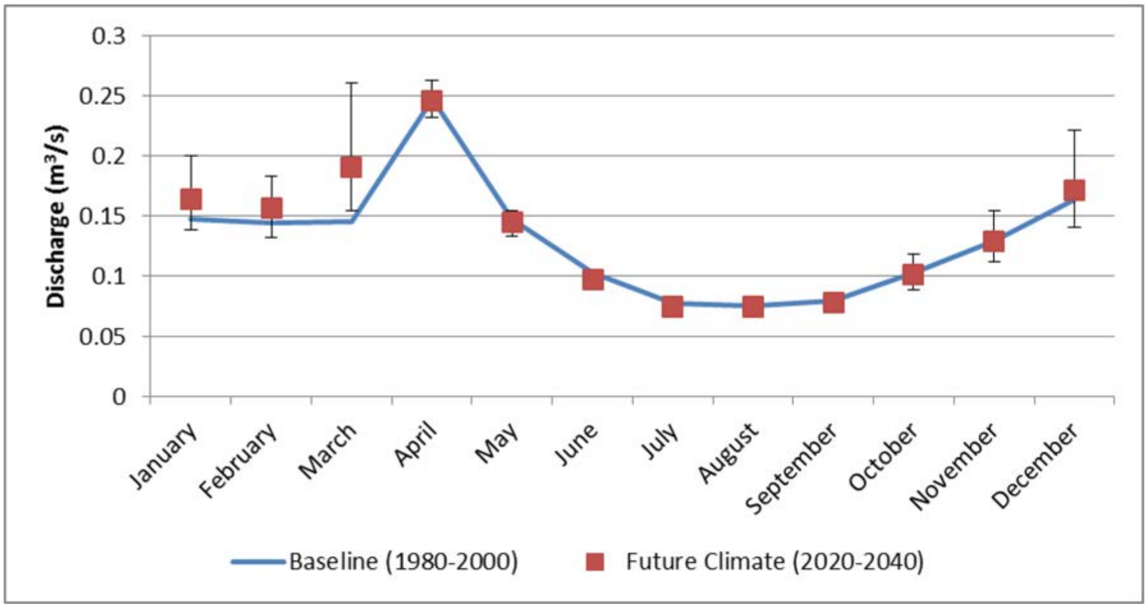

Figure F-6 **Tenth percentile monthly discharge for climate change scenarios at Key Location 6**

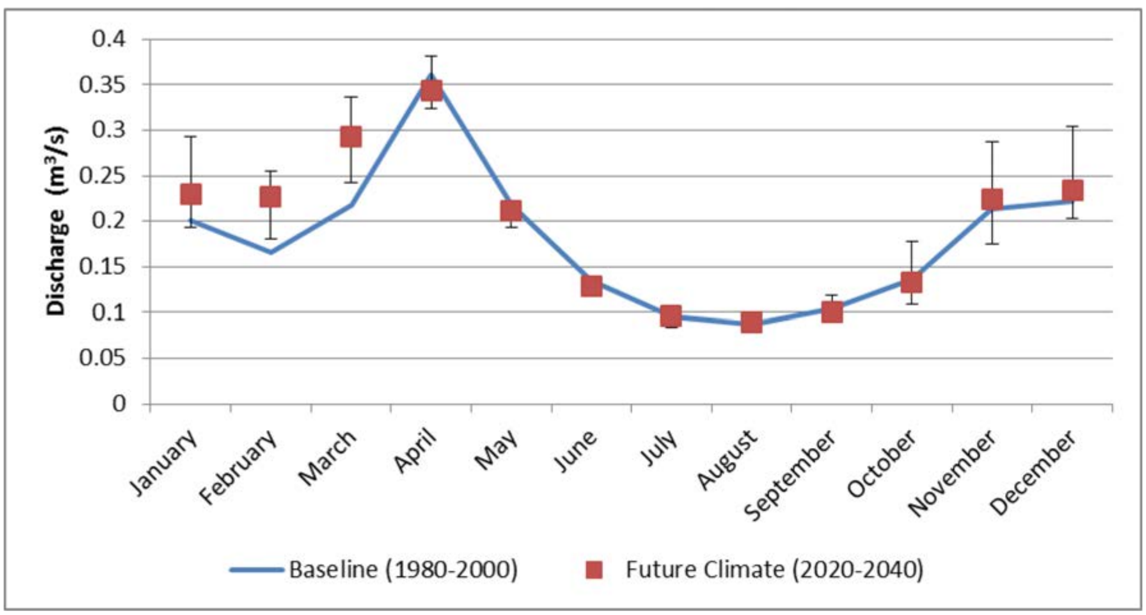

Figure F-7 **Median Monthly discharge for climate change scenarios at Key Location 6**

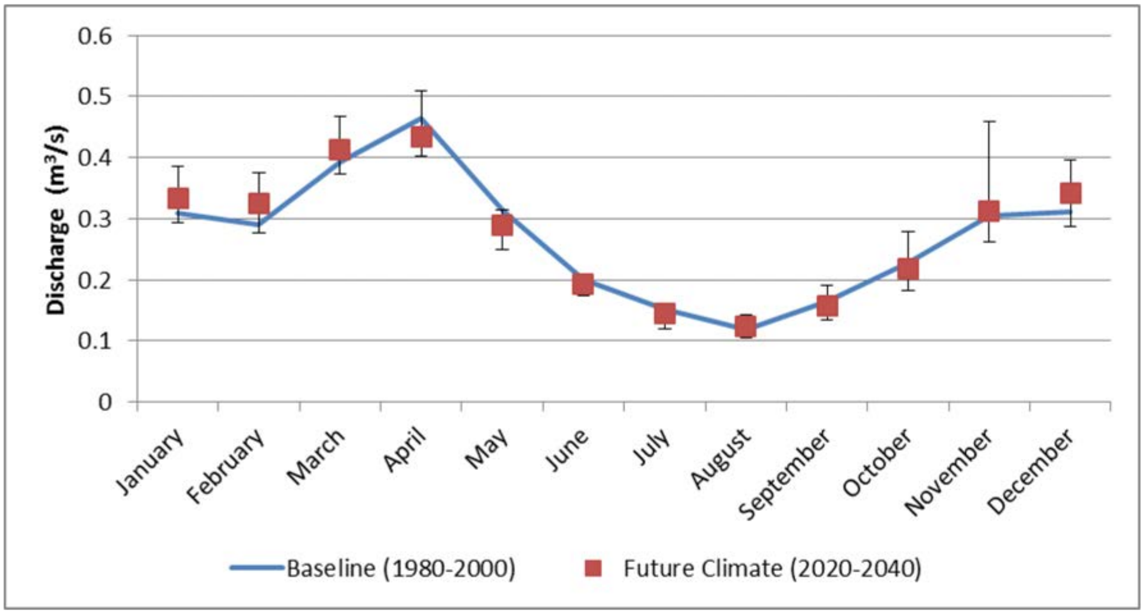

Figure F-8 **Ninetieth percentile monthly discharge for climate change scenarios at Key Location 6**

APPENDIX G
Key Location 7

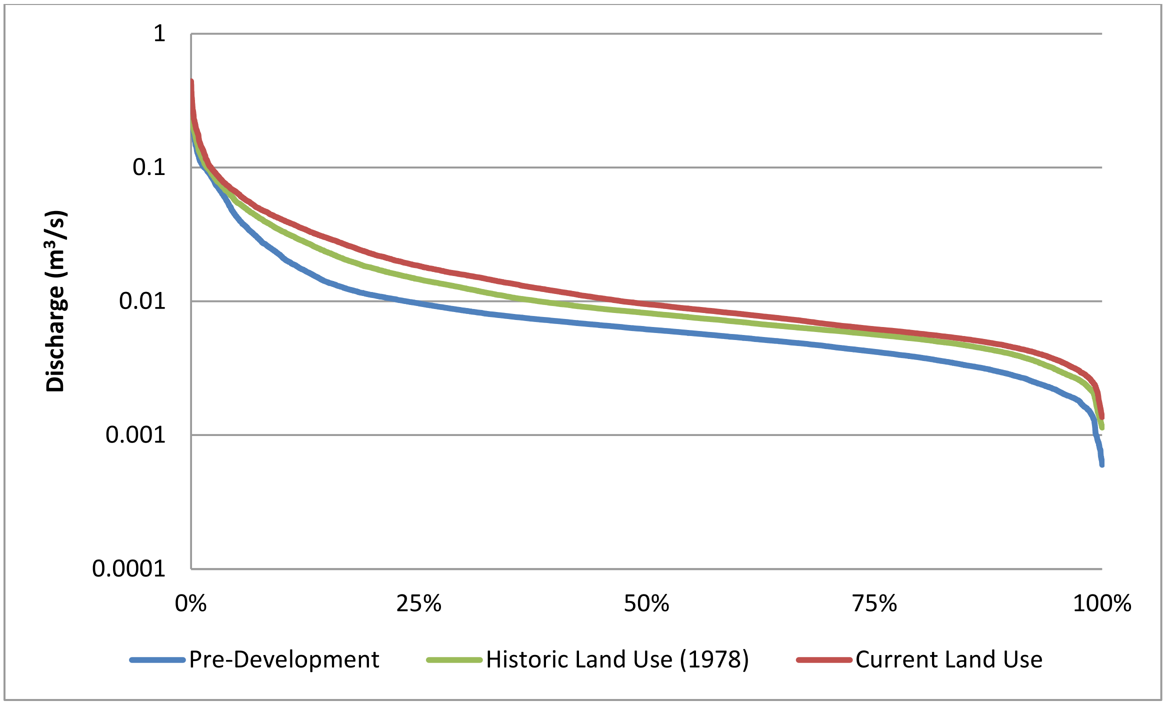

Figure G-1 **Ranked Duration Curves for Key Location 7 under Land Use Scenarios**

Table G-1 IHA Statistics for Key Location 7 under Land Use Stressor States

Flow Category	Flow Metric	Land Use		
		Pre-development	Historic (1978)	Current (2015)
Extreme Low Flow Event	Peak (m3/s)	0.0025	0.0036	0.0040
	Duration (days)	5	4	3
	Timing (date)	229	227	230
	Frequency (# of events)	4	5	6
High Flow Event	Peak (m3/s)	0.013	0.025	0.035
	Duration (days)	2	2	1
	Timing (date)	187	241	207
	Frequency (# of events)	14	14	21
	Rise Rate (m3/day)	0.0063	0.013	0.019
	Fall Rate (m3/day)	-0.0044	-0.0087	-0.015
Small Flood Event (2-year)	Peak (m3/s)	0.21	0.23	0.30
	Duration (days)	43	44	33
	Timing (date)	111	107	118
	Frequency (# of events)	0	0	0
	Rise Rate (m3/day)	0.023	0.017	0.062
	Fall Rate (m3/day)	-0.0079	-0.0081	-0.013
Large Flood Event (10-year)	Peak (m3/s)	0.32	0.35	0.44
	Duration (days)	64	53	40
	Timing (date)	109	109	130
	Frequency (# of events)	0	0	0
	Rise Rate (m3/day)	0.013	0.016	0.053
	Fall Rate (m3/day)	-0.0066	-0.011	-0.017

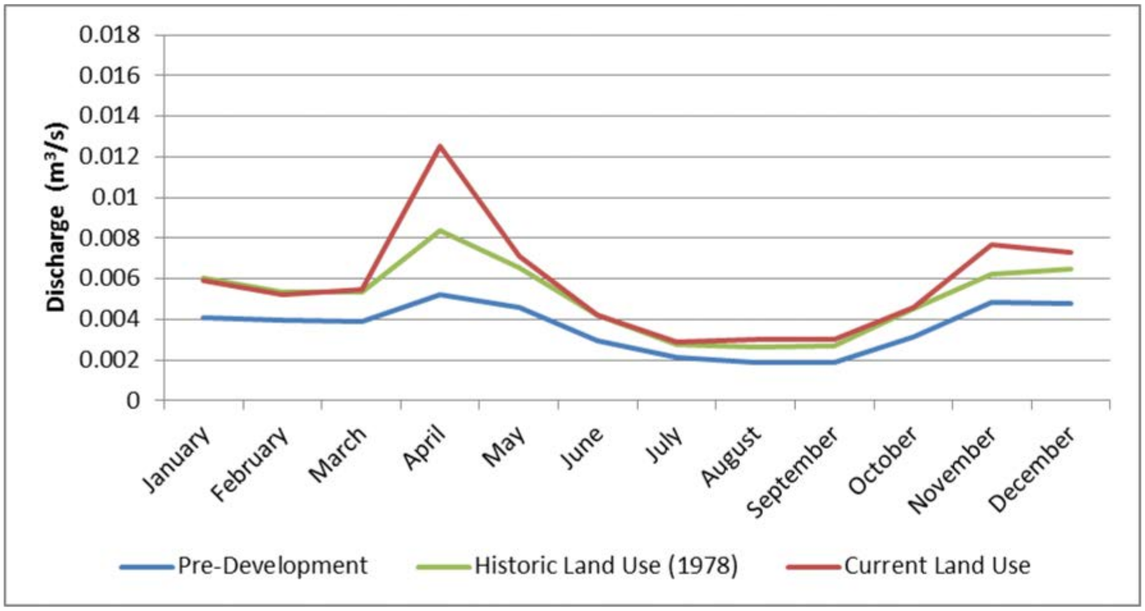

Figure G-2 **Tenth percentile monthly discharge for land use scenarios at Key Location 7**

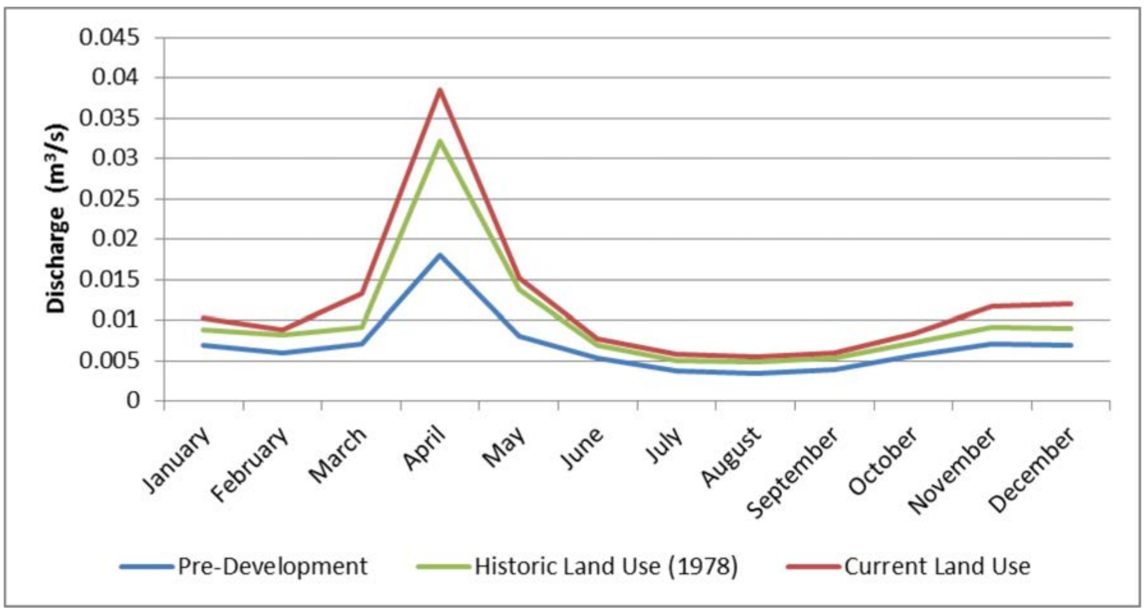

Figure G-3 **Median monthly discharge for land use scenarios at Key Location 7**

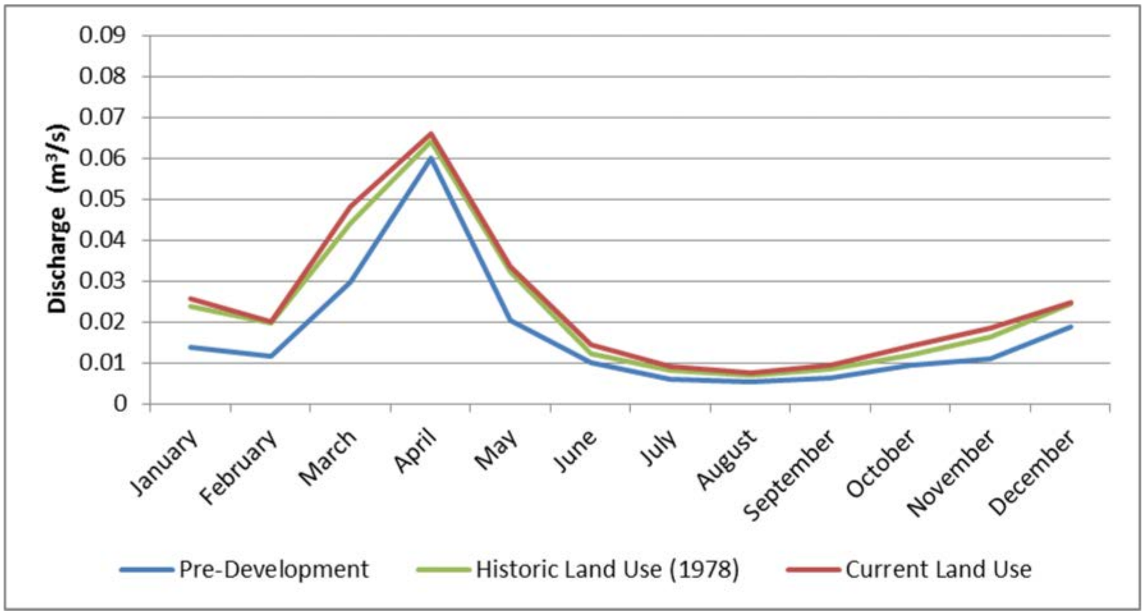

Figure G-4 **Ninetieth percentile monthly flow for land use scenarios at Key Location 7**

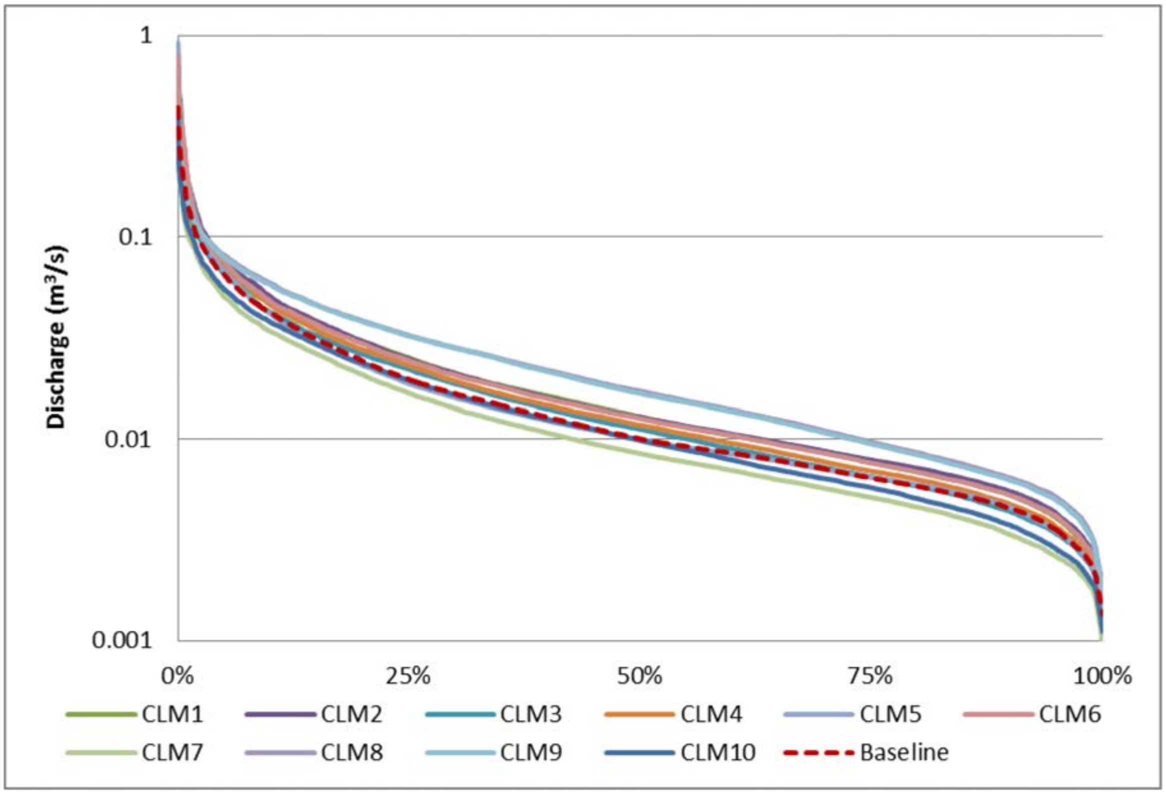

Figure G-5 **Ranked Duration Curves for Key Location 7 under Climate Change Scenarios**

Table G-2 **IHA Statistics for Key Location 7 under Climate Change Stressor States**

Flow Category	Flow Metric	Baseline (1980-2000)	Climate Change Future (2020-2040) Minimum	Median	Maximum
Extreme Low Flow Event	Peak (m^3/s)	0.0038	0.0030	0.0044	0.0057
	Duration (days)	3	2	3	4
	Timing (Julian date)	233	221	226	230
	Frequency (# of events)	7	5	7	8
High Flow Event	Peak (m^3/s)	0.037	0.032	0.042	0.053
	Duration (days)	1	1	1	1
	Timing (Julian date)	213	202	307	337
	Frequency (# of events)	21	19	20	23
	Rise Rate (m^3/day)	0.021	0.017	0.024	0.031
	Fall Rate (m^3/day)	-0.015	-0.022	-0.019	-0.015
Small Flood Event (2-year)	Peak (m^3/s)	0.30	0.21	0.40	0.53
	Duration (days)	32	1	23	46
	Timing (Julian date)	107	60	140	226
	Frequency (# of events)	0	0	0	1
	Rise Rate (m^3/day)	0.065	0.049	0.16	0.50
	Fall Rate (m^3/day)	-0.010	-0.50	-0.13	-0.0090
Large Flood Event (10-year)	Peak (m^3/s)	0.43	0.34	0.53	0.85
	Duration (days)	20	1	2	37
	Timing (Julian date)	147	125	220	275
	Frequency (# of events)	0	0	0	0
	Rise Rate (m^3/day)	0.24	0.20	0.37	0.73
	Fall Rate (m^3/day)	-0.20	-0.62	-0.38	-0.014

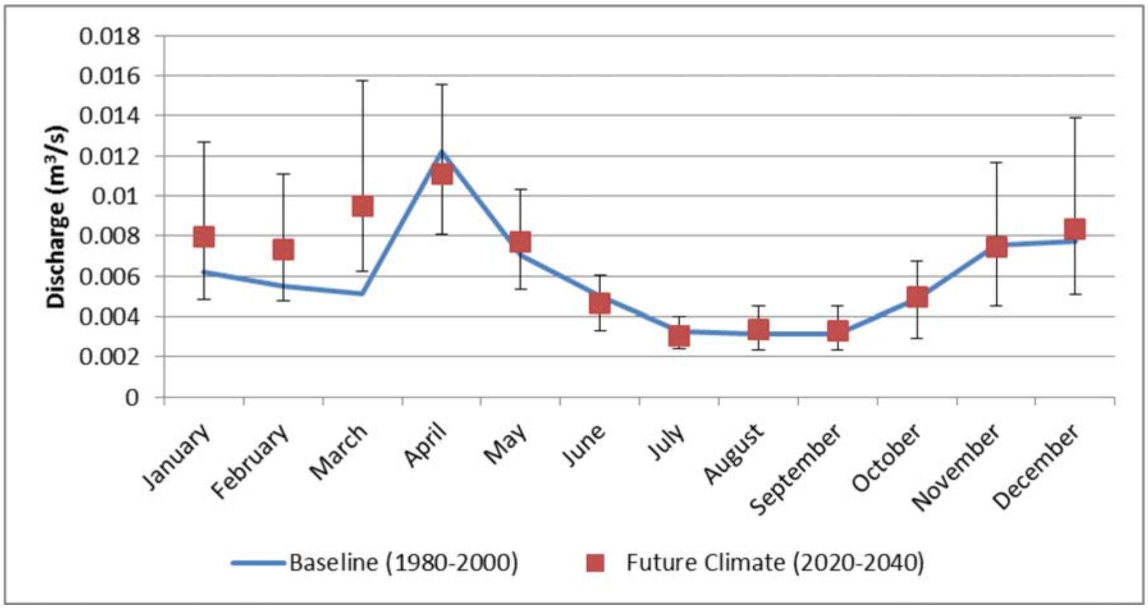

Figure G-6 **Tenth percentile monthly discharge for climate change scenarios at Key Location 7**

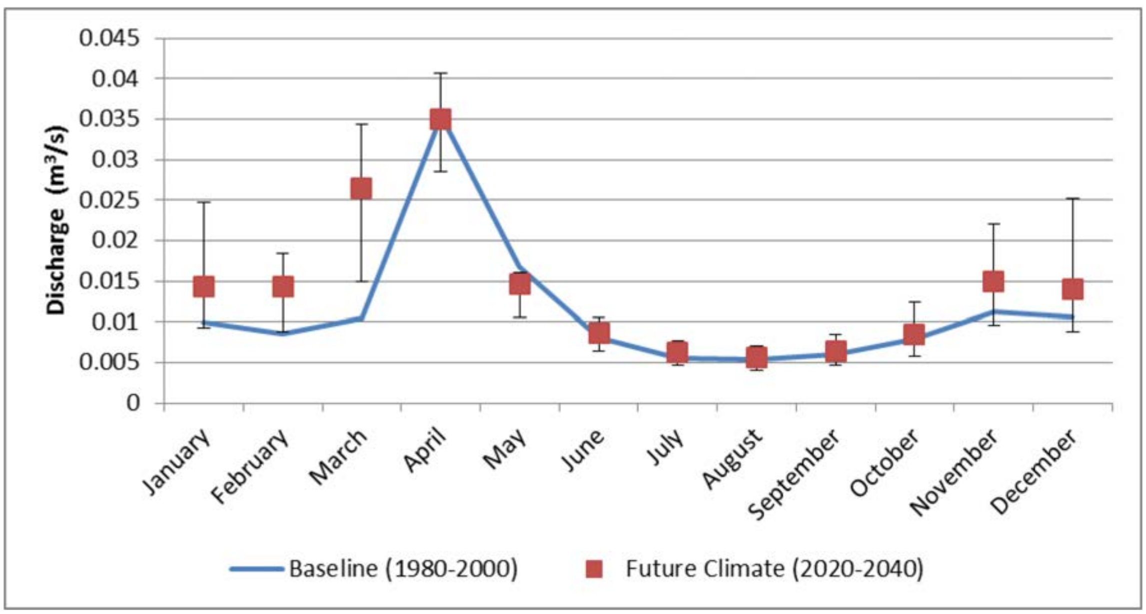

Figure G-7 **Median Monthly discharge for climate change scenarios at Key Location 7**

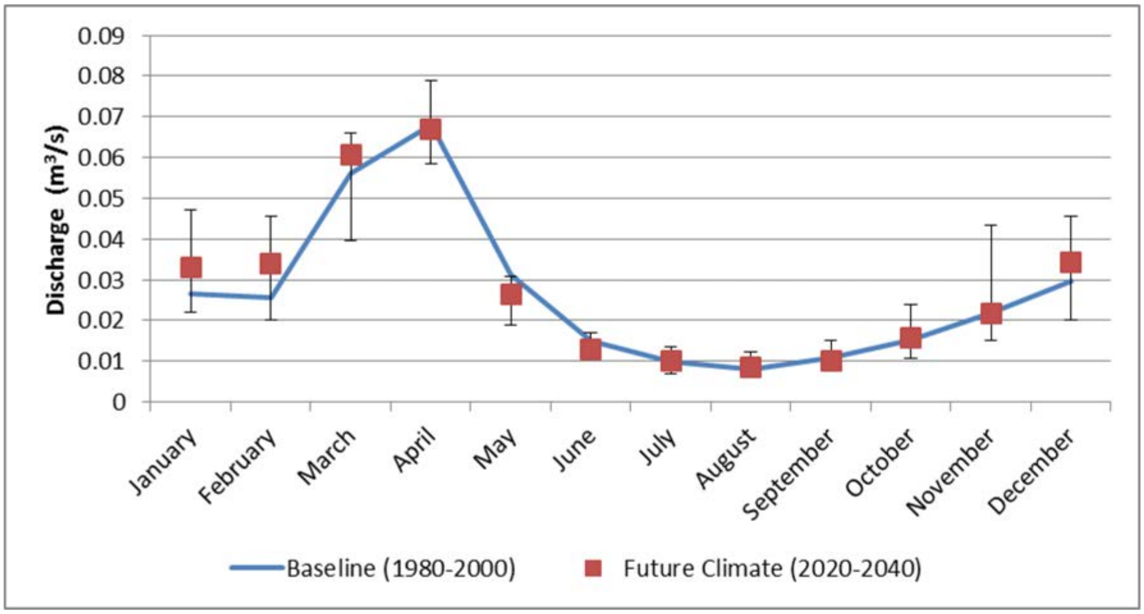

Figure G-8 **Ninetieth percentile monthly discharge for climate change scenarios at Key Location 7**

APPENDIX H
Key Location 8

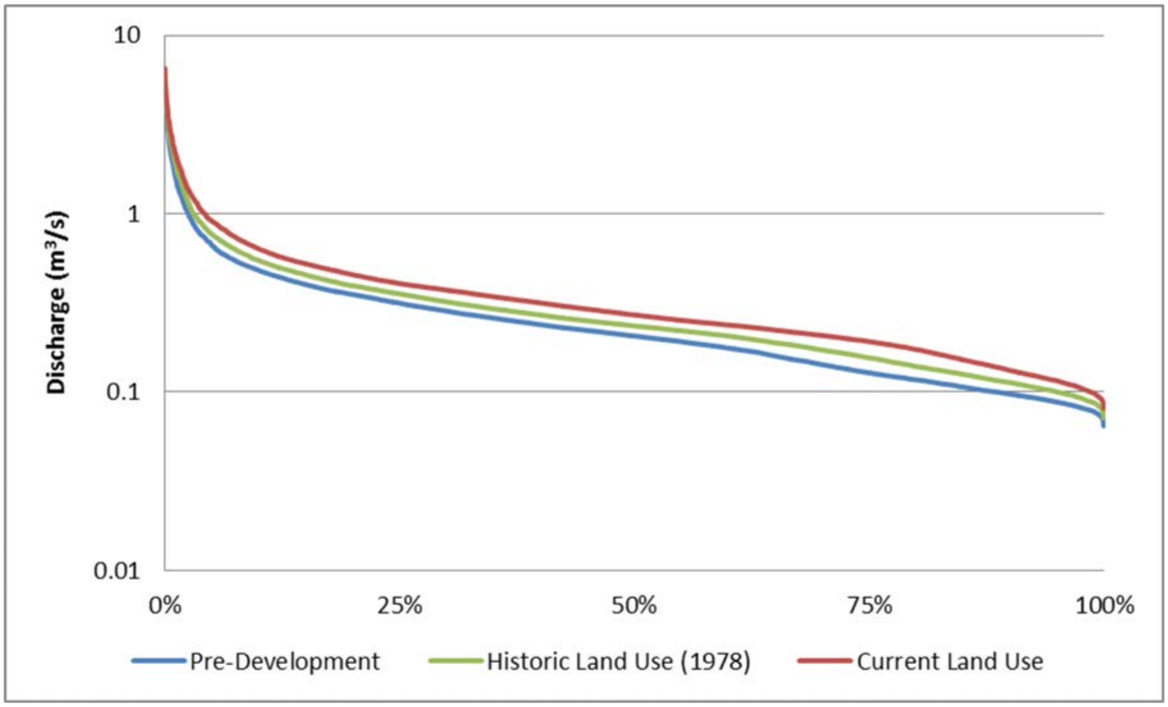

Figure H-1 **Ranked Duration Curves for Key Location 8 under Land Use Scenarios**

Table H-1 **IHA Statistics for Key Location 8 under Land Use Stressor States**

Flow Category	Flow Metric	Land Use		
		Pre-development	Historic (1978)	Current (2015)
Extreme Low Flow Event	Peak (m3/s)	0.090	0.10	0.12
	Duration (days)	8	6	3
	Timing (date)	227	229	228
	Frequency (# of events)	2	4	6
High Flow Event	Peak (m3/s)	0.53	0.55	0.62
	Duration (days)	5	3	2
	Timing (date)	319	319	236
	Frequency (# of events)	5	8	16
	Rise Rate (m3/day)	0.10	0.16	0.23
	Fall Rate (m3/day)	-0.043	-0.076	-0.15
Small Flood Event (2-year)	Peak (m3/s)	3.5	4.0	4.8
	Duration (days)	39	37	33
	Timing (date)	102	107	107
	Frequency (# of events)	0	0	0
	Rise Rate (m3/day)	0.29	0.37	0.87
	Fall Rate (m3/day)	-0.15	-0.15	-0.16
Large Flood Event (10-year)	Peak (m3/s)	4.8	5.2	5.9
	Duration (days)	45	40	45
	Timing (date)	91	91	130
	Frequency (# of events)	0	0	0
	Rise Rate (m3/day)	0.20	0.95	1.1
	Fall Rate (m3/day)	-0.16	-0.17	-0.27

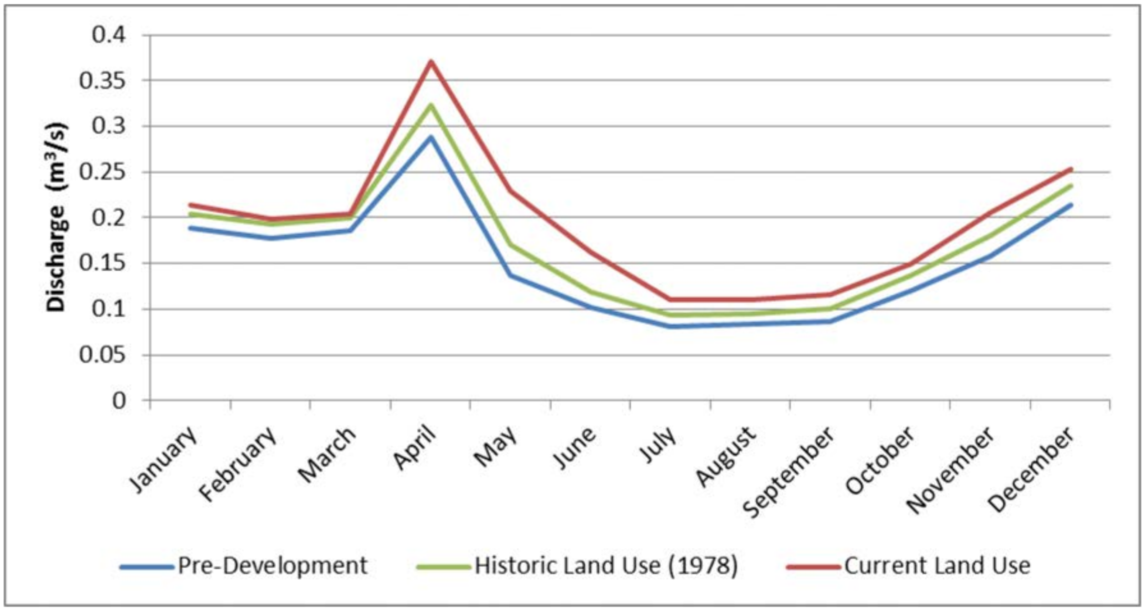

Figure H-2 **Tenth percentile monthly discharge for land use scenarios at Key Location 8**

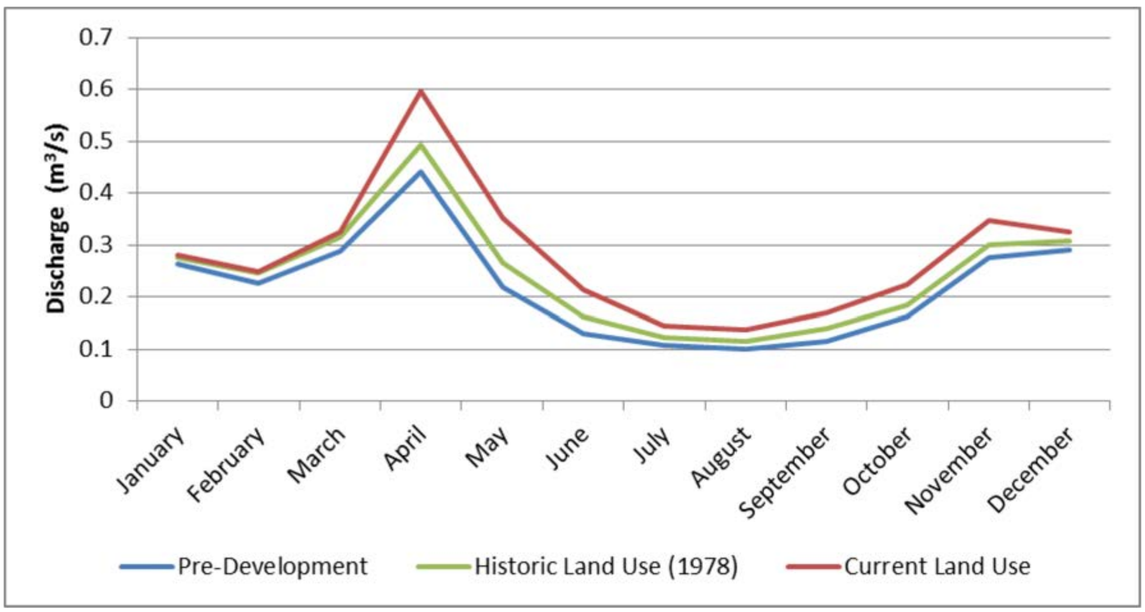

Figure H-3 **Median monthly discharge for land use scenarios at Key Location 8**

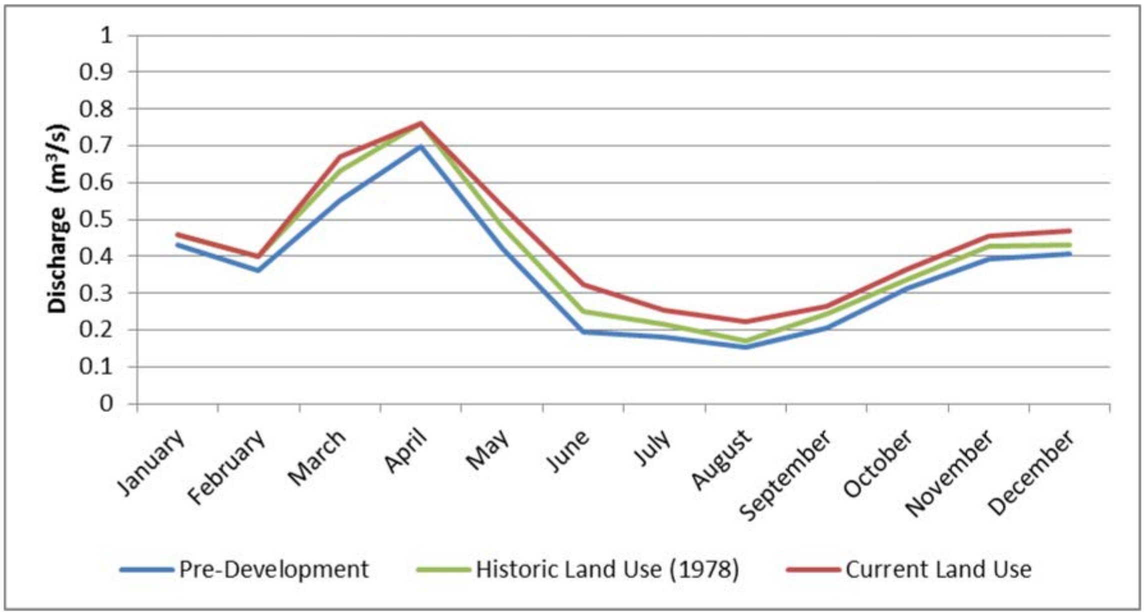

Figure H-4 **Ninetieth percentile monthly flow for land use scenarios at Key Location 8**

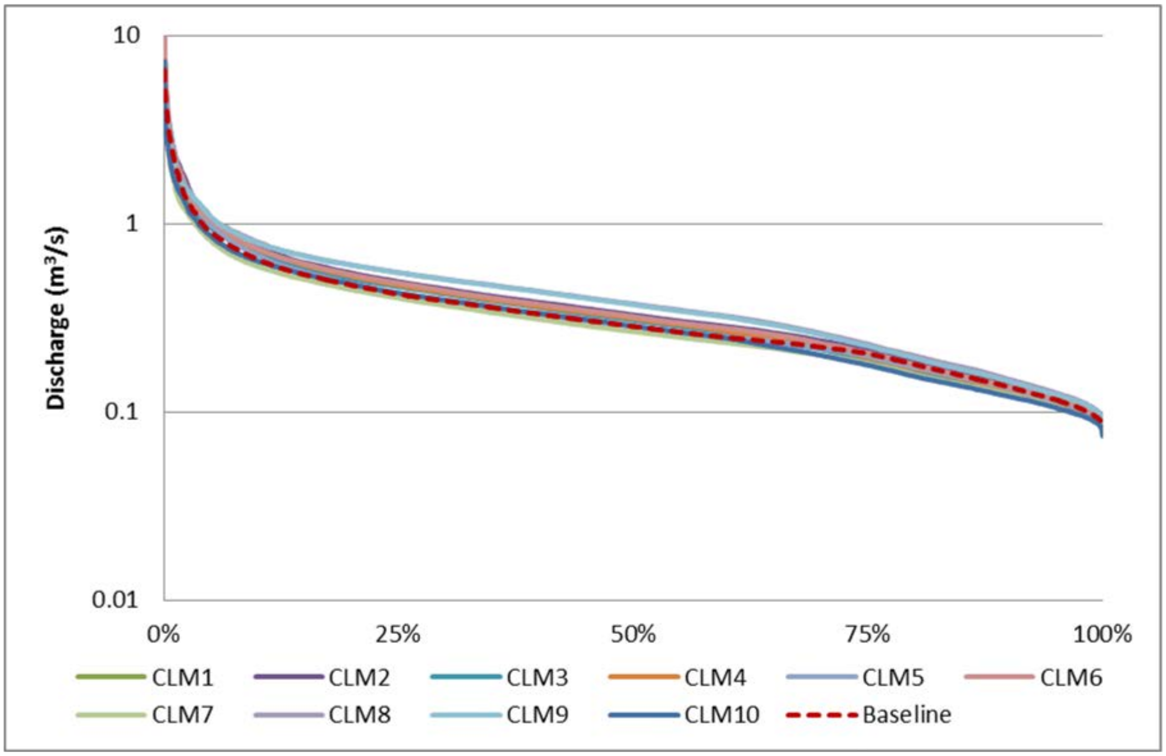

Figure H-5 **Ranked Duration Curves for Key Location 8 under Climate Change Scenarios**

Table H-2 IHA Statistics for Key Location 8 under Climate Change Stressor States

Flow Category	Flow Metric	Baseline (1980-2000)	Climate Change Future (2020-2040)		
			Minimum	Median	Maximum
Extreme Low Flow Event	Peak (m^3/s)	0.12	0.11	0.12	0.13
	Duration (days)	4	4	4	4
	Timing (Julian date)	217	216	223	223
	Frequency (# of events)	7	6	7	8
High Flow Event	Peak (m^3/s)	0.62	0.58	0.75	0.85
	Duration (days)	2	1	2	2
	Timing (Julian date)	242	218	316	337
	Frequency (# of events)	17	16	20	22
	Rise Rate (m^3/day)	0.22	0.20	0.33	0.41
	Fall Rate (m^3/day)	-0.15	-0.24	-0.21	-0.15
Small Flood Event (2-year)	Peak (m^3/s)	4.7	3.1	4.6	6.9
	Duration (days)	32	20	28	41
	Timing (Julian date)	107	55	89	108
	Frequency (# of events)	0	0	0	1
	Rise Rate (m^3/day)	0.72	0.60	0.92	1.8
	Fall Rate (m^3/day)	-0.21	-0.30	-0.23	-0.096
Large Flood Event (10-year)	Peak (m^3/s)	6.1	6.1	7.2	11.4
	Duration (days)	25	3	16	30
	Timing (Julian date)	140	125	165	256
	Frequency (# of events)	0	0	0	0
	Rise Rate (m^3/day)	3.8	3.4	5.5	11.1
	Fall Rate (m^3/day)	-1.1	-4.5	-1.6	-0.27

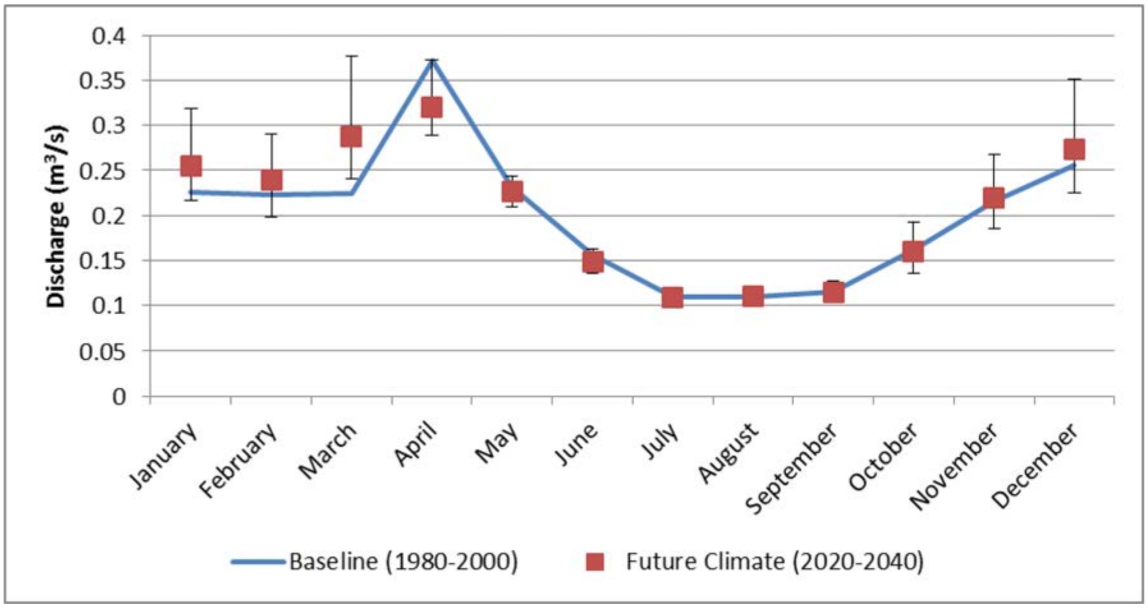

Figure H-6 **Tenth percentile monthly discharge for climate change scenarios at Key Location 8**

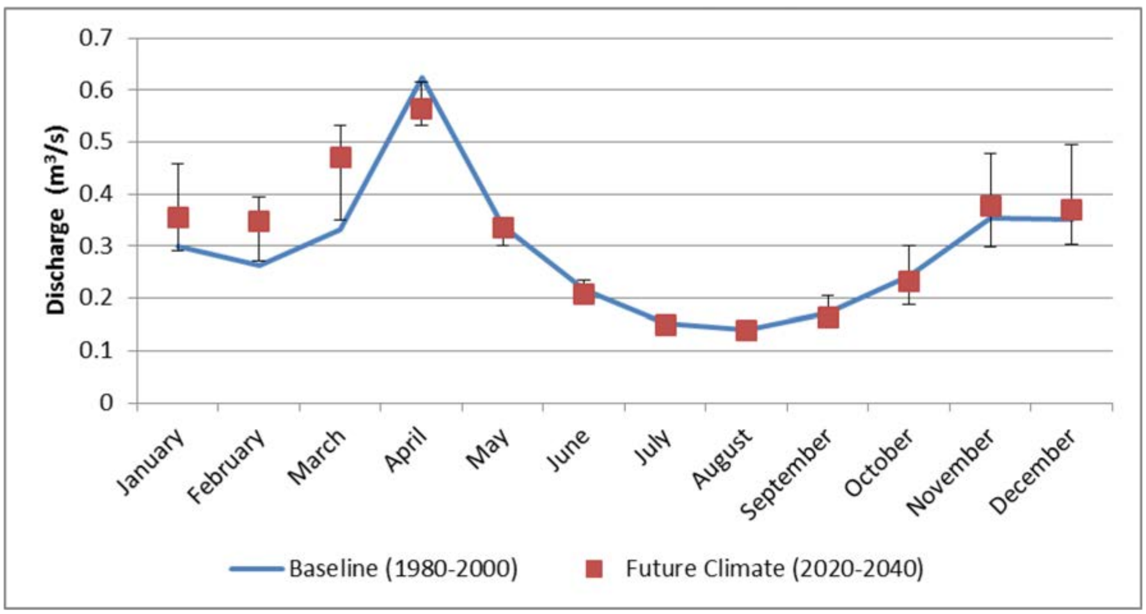

Figure H-7 **Median Monthly discharge for climate change scenarios at Key Location 8**

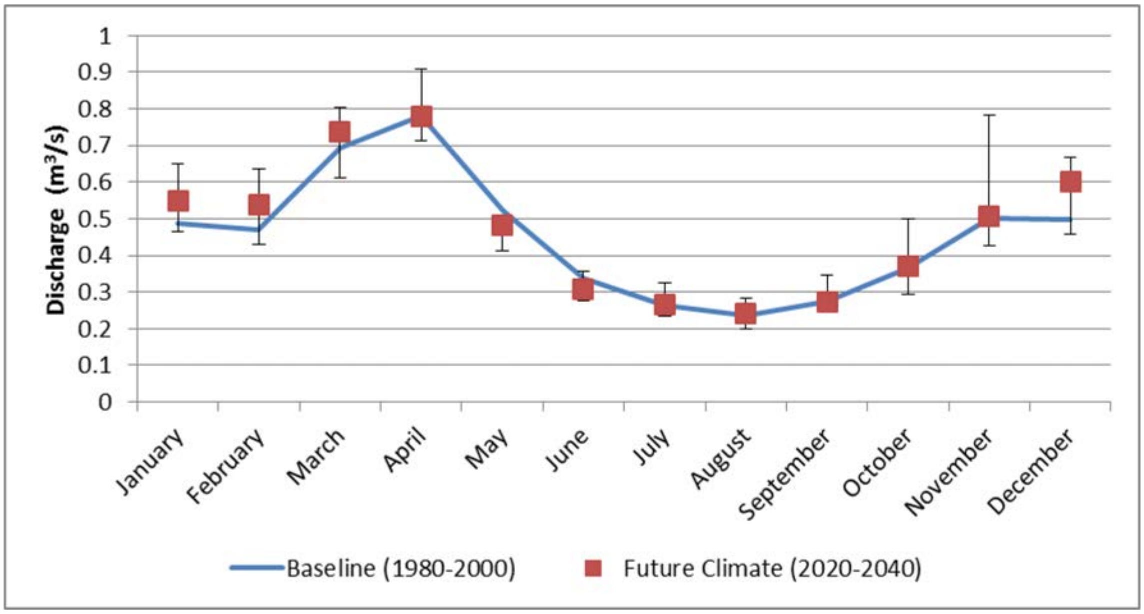

Figure H-8 **Ninetieth percentile monthly discharge for climate change scenarios at Key Location 8**

APPENDIX I
Key Location 9

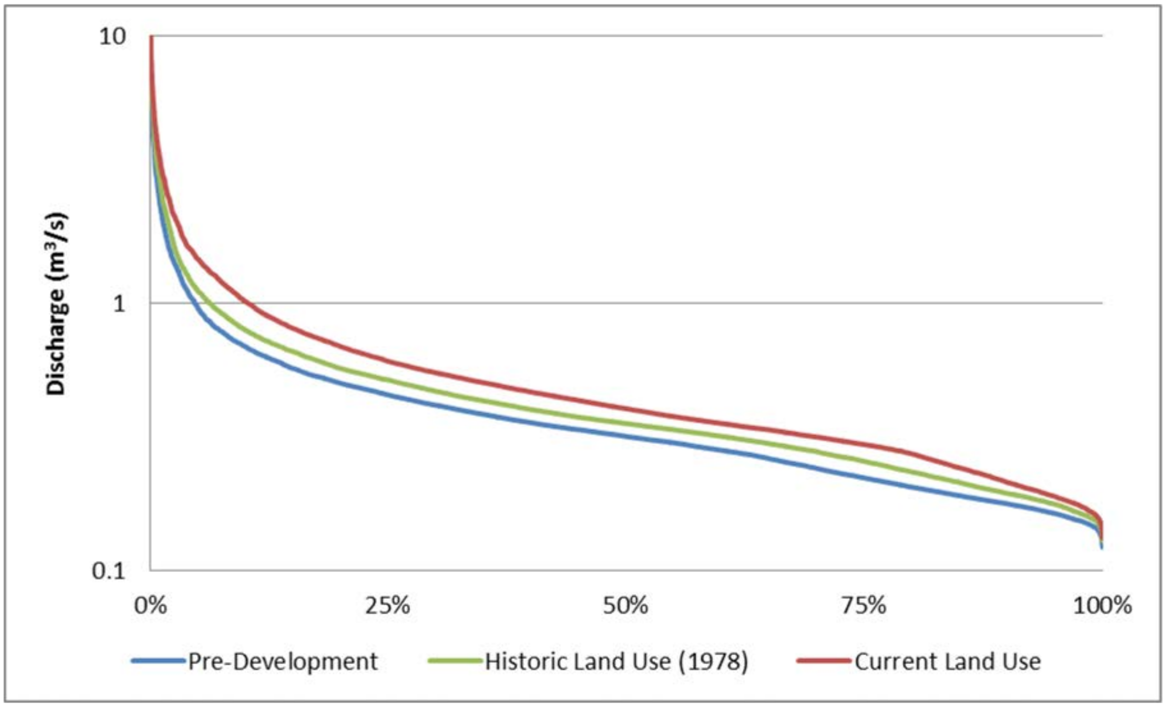

Figure I-1 **Ranked Duration Curves for Key Location 9 under Land Use Scenarios**

Table I-1 **IHA Statistics for Key Location 9 under Land Use Stressor States**

Flow Category	Flow Metric	Land Use		
		Pre-development	Historic (1978)	Current (2015)
Extreme Low Flow Event	Peak (m3/s)	0.17	0.18	0.19
	Duration (days)	4	4	3
	Timing (date)	225	227	225
	Frequency (# of events)	6	6	8
High Flow Event	Peak (m3/s)	0.64	0.72	0.99
	Duration (days)	4	3	2
	Timing (date)	334	61	221
	Frequency (# of events)	6	8	20
	Rise Rate (m3/day)	0.11	0.19	0.45
	Fall Rate (m3/day)	-0.046	-0.11	-0.31
Small Flood Event (2-year)	Peak (m3/s)	4.7	5.6	6.7
	Duration (days)	41	32	29
	Timing (date)	102	107	118
	Frequency (# of events)	0	0	0
	Rise Rate (m3/day)	0.36	0.56	1.3
	Fall Rate (m3/day)	-0.21	-0.22	-0.35
Large Flood Event (10-year)	Peak (m3/s)	6.6	7.3	8.6
	Duration (days)	46	40	45
	Timing (date)	91	91	130
	Frequency (# of events)	0	0	0
	Rise Rate (m3/day)	0.30	1.0	1.6
	Fall Rate (m3/day)	-0.22	-0.22	-0.42

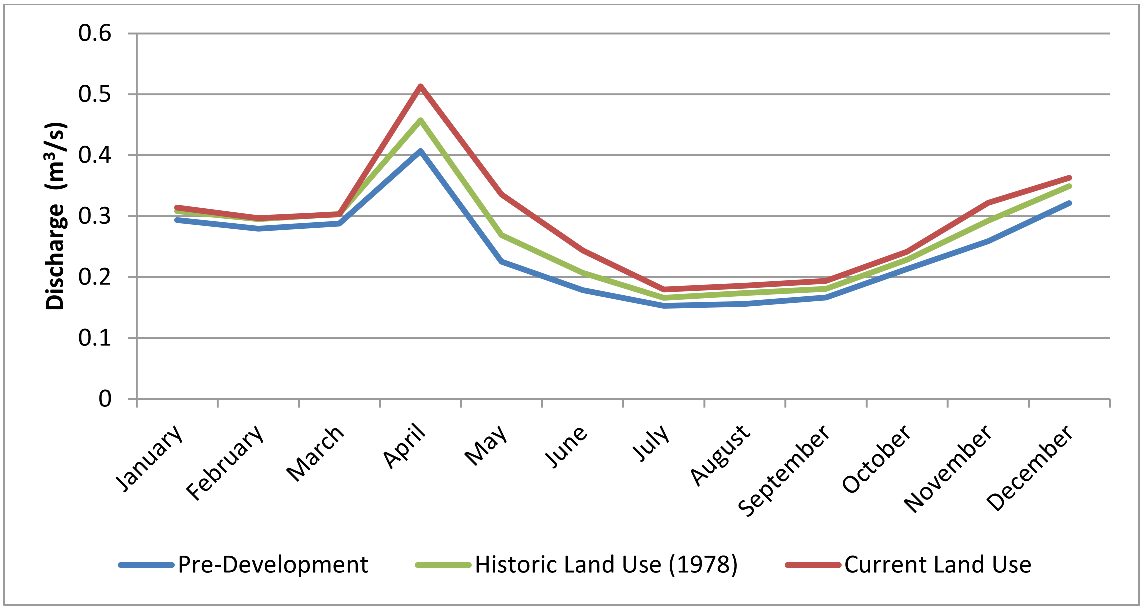

Figure I-2 **Tenth percentile monthly discharge for land use scenarios at Key Location 9**

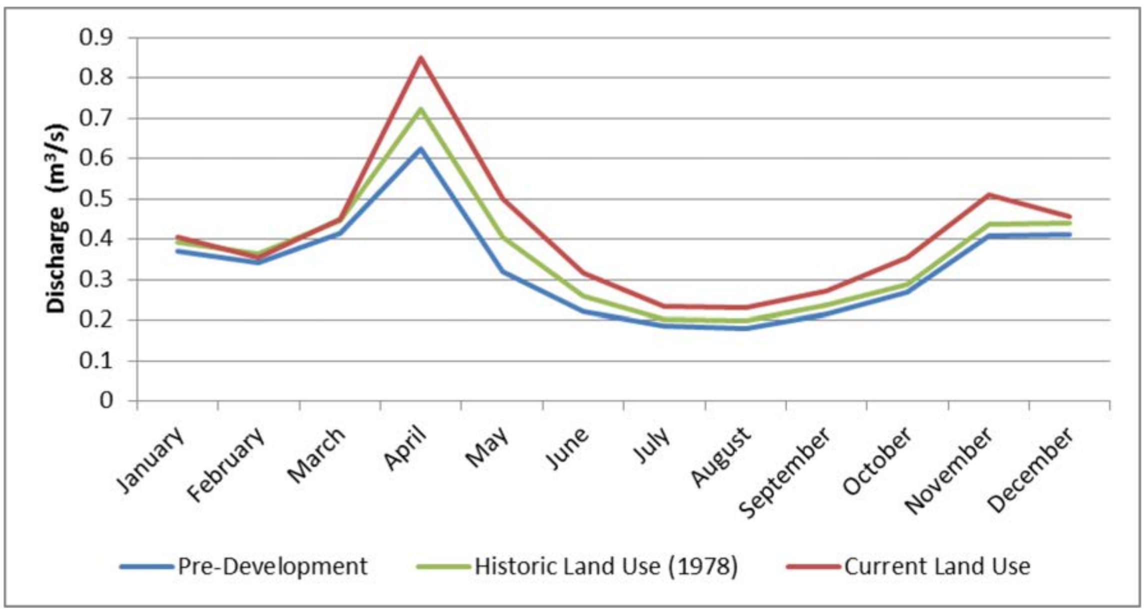

Figure I-3 **Median monthly discharge for land use scenarios at Key Location 9**

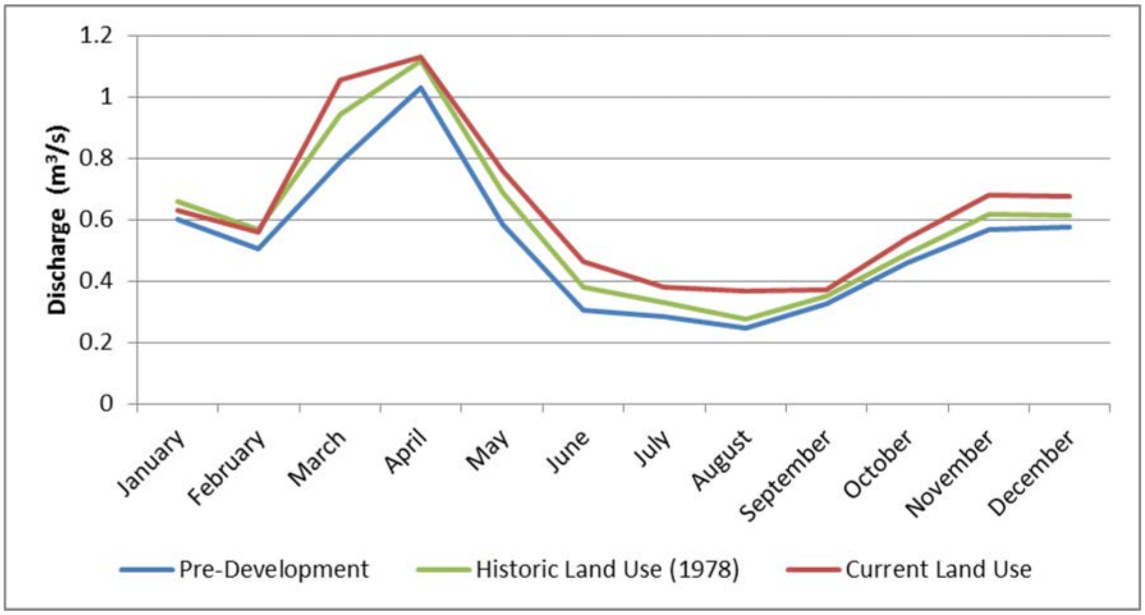

Figure I-4 **Ninetieth percentile monthly flow for land use scenarios at Key Location 9**

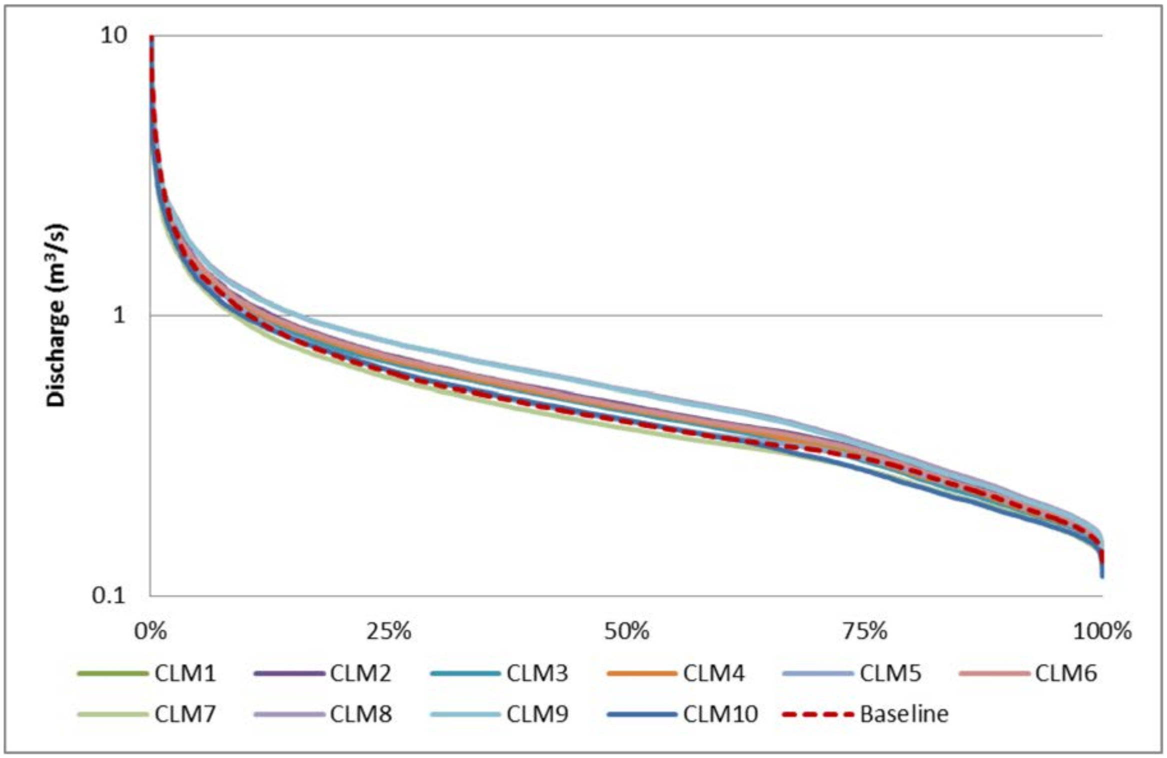

Figure I-5 **Ranked Duration Curves for Key Location 9 under Climate Change Scenarios**

Table I-2 IHA Statistics for Key Location 9 under Climate Change Stressor States

Flow Category	Flow Metric	Baseline (1980-2000)	Climate Change Future (2020-2040)		
			Minimum	Median	Maximum
Extreme Low Flow Event	Peak (m^3/s)	0.20	0.18	0.20	0.21
	Duration (days)	3	3	3	4
	Timing (Julian date)	218	214	221	225
	Frequency (# of events)	8	7	7	8
High Flow Event	Peak (m^3/s)	1.0	0.95	1.1	1.3
	Duration (days)	2	2	2	2
	Timing (Julian date)	239	230	318	342
	Frequency (# of events)	23	22	23	24
	Rise Rate (m^3/day)	0.44	0.40	0.48	0.57
	Fall Rate (m^3/day)	-0.32	-0.38	-0.32	-0.30
Small Flood Event (2-year)	Peak (m^3/s)	7.0	4.6	5.8	6.6
	Duration (days)	27	19	26	30
	Timing (Julian date)	107	61	94	106
	Frequency (# of events)	0	0	0	0
	Rise Rate (m^3/day)	1.0	1.0	1.4	1.7
	Fall Rate (m^3/day)	-0.37	-0.59	-0.30	-0.17
Large Flood Event (10-year)	Peak (m^3/s)	9.4	9.4	10	12
	Duration (days)	24	4	13	36
	Timing (Julian date)	140	86	165	202
	Frequency (# of events)	0	0	0	0
	Rise Rate (m^3/day)	6.0	2.1	7.1	11
	Fall Rate (m^3/day)	-1.8	-3.1	-2.0	-0.3

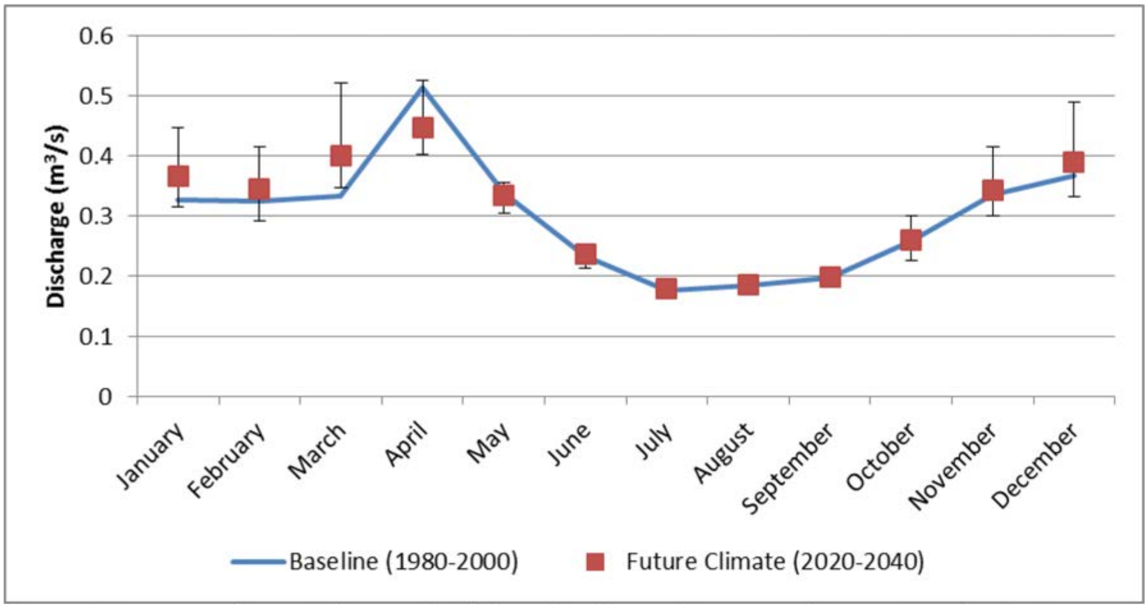

Figure I-6 **Tenth percentile monthly discharge for climate change scenarios at Key Location 9**

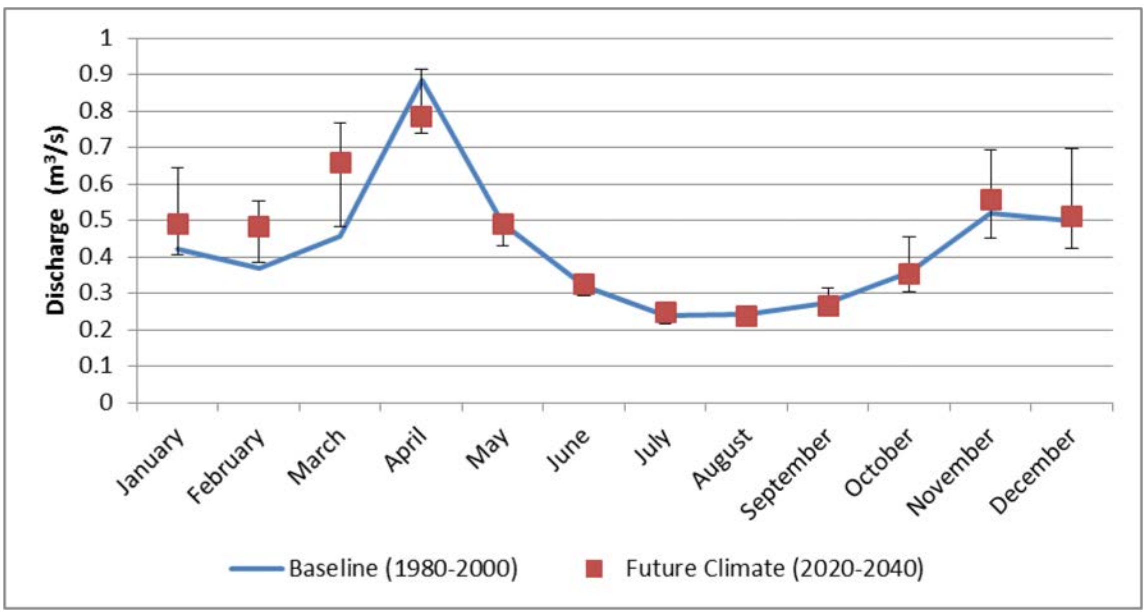

Figure I-7 **Median Monthly discharge for climate change scenarios at Key Location 9**

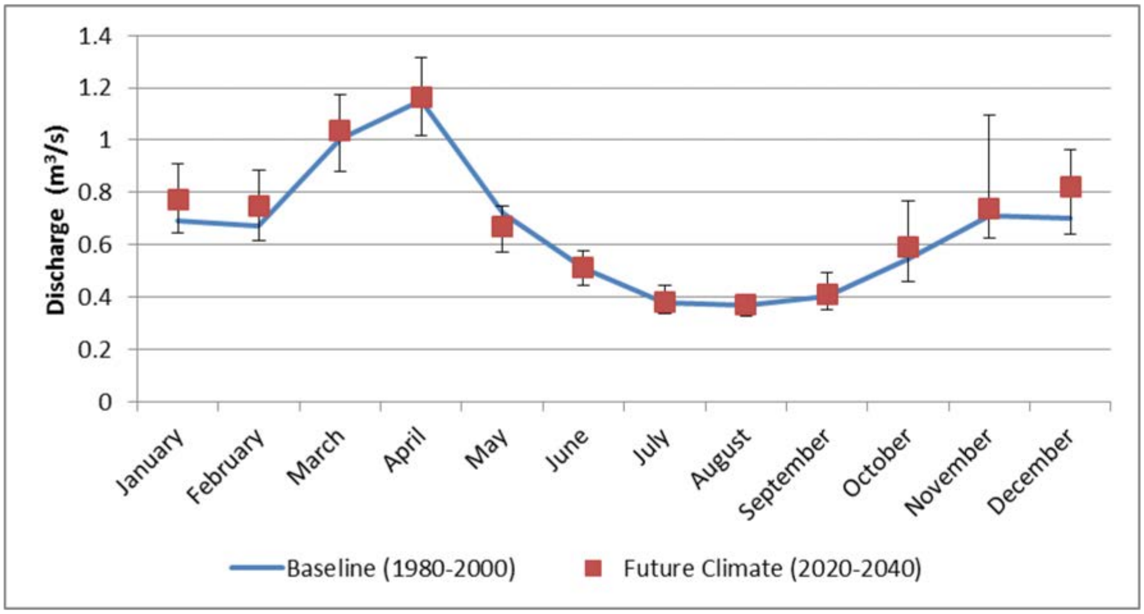

Figure I-8 **Ninetieth percentile monthly discharge for climate change scenarios at Key Location 9**