ASSESSING THE IMPACTS OF CLIMATE CHANGE ON FLUVIAL PROCESSES:
USING A PHYSICALLY-BASED MODEL TO DETERMINE HYDROLOGIC RESPONSES OF THE SLATE RIVER

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ABSTRACT

Watershed models are an important tool in regional planning and conservation efforts. They can provide valuable insight into the potential impacts of different land use changes and future climate change scenarios on water resources, which can lead to better, more informed decision making. Climate impacts, in particular, add a new level of uncertainty with regard to freshwater supplies as the hydrological cycle is intimately linked with changes in atmospheric temperatures. The main objective of this study is to investigate the extent of long-term climate change on streamflow and stream temperature within an agriculturally defined watershed in Northern Ontario. For this purpose, the Soil and Water Assessment Tool (SWAT) model was utilized to provide a better understanding of how hydrological processes in the Slate River Watershed will alter in response to long-term climate change scenarios. The SWAT model is a distributed/semi-distributed physically-based continuous model, developed by the USDA for the management of agricultural watersheds, and is currently one of the most popular watershed-based models used in climate change analysis of snow-melt dominated watersheds. Historic flow data was compared to a discharge model that reflected four climate models driven by SRES A1B and A2 through the middle and end of the century. Hydrology modelling was enhanced with stream temperature analysis to gain a comprehensive understanding of the extent of changing climate regimes on the Slate River. A linear regression approach representing a positive relationship between stream temperature and air temperature was used to determine the thermal classification of the Slate River. Our results indicated that the Slate River was well within the warm-water character regime. Unusual high stream temperatures were recorded at mid-August; these were accompanied by low water levels and a lack of riparian vegetative cover at the recording site, providing a possible explanation for such temperature anomalies. The results of the flow discharge modelling supported our hypothesis that tributaries within our ecosystem would experience increasing water stress in a warming climate as the average total discharge from the Slate River decreased in both climate scenarios at the middle and end of the century. Although the lack of accurate subsurface soil data within the study region prevented our discharge model from quantifying the changes in stream discharge, the strong correlation between the observed and simulated flow data as reflected by a 0.92 r^2 statistic gave us confidence that discharge from the Slate River will continue to follow a decreasing trend as climate change persists into the future. This study aims to support the future endeavours of hydrologic modelling of watersheds in Northern Ontario by illustrating the current capabilities and limits of climate change analysis studies within this region.

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CHAPTER 1

INTRODUCTION

1.1 Background

Water resource management is a complex and multidisciplinary science that demands the integration of issues of values, equity, and social justice, and as such, requires a participatory approach to management (Cervoni et al., 2008). In the 21st century, Integrated Water Resources Management (IWRM) has become the recommended approach towards promoting the coordinated development and management of water, land, and related resources (Rahaman and Varis, 2005). Watershed-based management and IWRM are often used as interchangeable concepts. IWRM based on watershed units has been increasingly accepted as the most appropriate management unit for achieving sustainable water resource management (Blomquist and Schlager, 2005; Falkenmark, 2004; Lubell, 2004). Water resources within a watershed are interrelated, connected to all-natural resources, and thus influenced by the treatment of those resources (Plummer et al., 2005). Watersheds provide spatial boundaries for interdisciplinary work within IWRM and allows for management based on hydrological boundaries and a holistic view of the nature of issues concerning the competition for water resources, flooding, the management of water quality and environmental integrity, and maintaining natural flows and discharge (Cervoni et al., 2008).

Watersheds in the Canadian Boreal Shield belong to one of the largest ecozones in Canada, extending 3,800 km from Northern Saskatchewan to Newfoundland and Labrador, passing north of Lake Winnipeg, the Great lakes and the St. Lawrence River (Gautam, 2012). The boreal shield is characterized by predominantly coniferous forests rooted in very thin soils overtop Precambrian rock, with many bare rock outcrops as a result of glaciation during the last ice age. The effect of post-glacial rebound and the relatively young age of most catchments leaves this landscape covered in numerous lakes, rivers, marshes and wetlands (Fu et al., 2014). Although watersheds in the Canadian Boreal Shield region are under less pressure from population, agricultural and urbanization than southern regions, there are still pressures on Canadian Shield Watersheds from forestry, mining, hydro-electric development, and road and shoreline development (Fu et al., 2014). The impacts of climate change and future development further threatens water resources from streams to watersheds, and climate change alone is anticipated to have the greatest impact at the watershed scale compared to other anthropogenic forces such as land use change. In several studies in which climate change scenarios were compared to land use change scenarios, there were significantly more dramatic effects to hydrology and water quality from the climate change scenarios alone. For example, land use change scenarios may cause no significant changes to runoff and sediment loading in the long run (Fan and Shibata, 2015; Mehdi et al., 2015; Rahman et al., 2015; Li et al., 2009). As a consequence of the expected climate impacts, the reliability of current water management systems and water-related infrastructures may be compromised, thus posing a vital concern to water managers, water resource users, and policy makers (Rahman and Varis, 2005).

The impacts of climate change vary from region to region, however Canada as a whole has seen an increase of 1.6 °C from 1948 to 2010, while the mean annual temperature in the boreal region is projected to increase by 3.3° to 5.4°C compared with historic norms (1961–1990) by 2071–2100 (Gauthier et al., 2014). In some regions across the Eastern Boreal Shield, warming temperatures will increase the water holding capacity of the atmosphere and result in increases in the frequency and amount of precipitation (Bergeron et al., 2004). For example, based on high emission scenarios Thunder Bay, Ontario can expect a 3.9% annual increase in precipitation by 2020, 6.5% increase by 2050, and a 11% increase by 2080 (ICLEI Canada, 2013). Increased precipitation and basin hydrology is projected to shift from a combined rainfall/snowmelt regime to a more rainfall dominant one, affecting stream flow and sediment transportation and increaseing flood risk during the late winter and spring months. Such an event occurred in May 2012, where heavy rains and subsequent flooding caused a state of emergency for Thunder Bay, as some areas received as much as 108mm of rain in a two-day span. In June 2016, record precipitation amounts took place, reaching a total of 227mm, compared to a long-term average of 86mm. On June 25th, 2016, a severe rain event occurred in Thunder Bay and adjacent rural areas, where 84 mm, nearly the June monthly average in total rainfall, fell in about eight hours. Having a sound prediction of long-term basin hydrology shifts in future climate scenarios is imperative for estimating flood frequency in agriculturally dominated regions of Northern Ontario. Despite extensive research on specific impacts of climate change, research and information on the impacts of climate change to watershed systems remains in its infancy (Marshall and Randhir, 2008). Evaluation of climate change on the watershed system is important to develop alternative strategies and policies to mitigate the impacts of global warming.

1.2 Problem Definition

Quantifying the magnitudes and rates of future channel change is important for sustainable river channel management (Lotsari, et al., 2015). Climate change is expected to be an important driver for future rates of fluvial processes. The hydrological cycle is intimately linked with changes in atmospheric temperature and radiative fluxes, thus the economy and the livelihood of people will be effected by long-term climate change (Islam and Gan, 2012). Changes in the hydrological cycle caused by changes in global climate can impact processes such as precipitation, snowmelt, evaporation, soil moisture, and runoff. Such changes will affect agricultural productivity, flood control, municipal and industrial water supply, and fishery and wildlife management (Islam and Gan, 2012). The climate driven fluvial responses will also govern short and long-term morphological processes such as sediment fluxes as well as flow level patterns (Lotasri et al., 2015).

Modelling should play an important role in reducing the uncertainty associated with channel sensitivity and response to threshold conditions (Gregory, 2006). The widespread availability of hydrodynamic, morphodynamic and cellular models have led to the proliferation of studies investigating reach-scale modelling of environmental change impacts on channel form and process at contemporary or palaeo perspectives (Lotsari et al., 2015). Hydrologic models have yet to be routinely used in future-simulation applications. Nevertheless, physically-based models such as the popular Soil Water and Assessment Tool (SWAT) have successfully demonstrated long-term channel morphology modelling and water budget analysis under various climate change scenarios in multiple snow-melt dominated regions around the world (Abbaspour et al., 2014; Abbaspour et al., 2009; El-Khoury et al., 2015; Marshall and Randhir, 2008; Ficklin et al., 2014; Franczyk and Chang, 2009; Jha and Gassman, 2014).

Future changes in stream temperatures are important for ecological management and wildlife conservation as water temperatures influence the overall water quality of stream ecosystems as well as being determinant of the types of aquatic species that can survive within specified temperature thresholds. These temperature ranges classify tributaries as either warm-water, cool-water, or cold-water streams, capable of sustaining specific compositions of various aquatic species. Using the methodology developed by Stoneman and Jones (1996) it is possible to assess the thermal classification (coldwater, coolwater, or warmwater) of any site within a stream from single daily measurements of the maximum air and water temperatures at the timing of the daily maximum water temperature. This measurement thus provides a current thermal classification which can be compared with a simulated climate change scenario in which warmer air temperatures may result in a change in the thermal classification of the Slate River.

1.3 Research Objectives

Based on the preceding statements of problems, the objectives of this study are: (1) with reference to climate change scenarios projected by general circulation models (GCMs) forced by possible future emission scenarios developed by the IPCC, to investigate possible changes in the average discharge rate of the Slate River using the Soil Water and Assessment Extension of ArcGIS to model the hydrological changes; (2) to measure water temperature and air temperature to determine if a positive relation between air and water temperature exists without much deviation, thereby providing us with a thermal classification of the Slate River which can be forced with simulated climate model projections to determine if this thermal classification will be altered in various climate scenarios; (3) to determine the applicability and limitations of using hydrologic modelling techniques in climate change analysis studies in Northern Ontario.

The results of the research can provide practical information for water resource managers to better understand long-term climate change impacts on important ecological resources in our region. Current management efforts of the Slate River Valley watershed can be enhanced to incorporate more adaptive management practices that are sufficient in dealing with the possible ‘wicked’ issues that long-term climate change may impose on the region.

1.4 Methodology

For the first objective of this study, the SWAT extension of ArcGIS was used to conduct hydrological modeling of the Slate River. The input data required to run the model were Geographic Information System (GIS) data layers as well as historic and simulated meteorological data from a weather station and climate models respectively. The climate data acquired from our weather station and climate models included daily precipitation and maximum and minimum air temperature. Relative humidity, solar radiation, and wind speed are also required in the modelling process, however the SWAT model simulates these variables using estimations based on precipitation and air temperature data inputs. The GIS data included a digital elevation model (DEM) with burned-in streams and a land use/land cover (LULC) layer, which were both acquired from the provincial government database (Land Information Ontario). Streamflow data required to calibrate and validate the Slate River model was obtained from the federal government's Real-Time Hydrometric Database. The parameters that were used to calibrate and validate the model were based upon the common parameters used for calibration in previous studies conducted in snow-melt dominated regions within the Canadian Shield (list references to these studies).

The second objective of this study will be to attempt to provide a thermal classification of the Slate River using a linear regression approach between stream and air temperature. The positive relationship between warm air temperature (>24.5°C) and stream temperature has been exhibited in Stoneman and Jones (1996). In order to determine the appropriate water temperature sampling days, air temperature was recorded near the water temperature data collection site. Stream temperature was recorded from mid-August to mid-September when stream water temperatures are historically at their warmest in Thunder Bay. A nomogram was created depicting the positive relationship between the daily maximum air temperature (occurring at 1700 hours) and water temperature. The nomogram was used to approximate the thermal classification of the Slate River stream site during August and September using only data from at least 3 consecutive days having daily maximum air temperatures greater than 24.5°C, or no drastic change in weather. Simulated air temperature data from a future climate scenario was then derived from a GCM and used to approximate maximum water temperature and the thermal classification of the Slate River stream site in the new climate scenario.

The third objective of this study was to determine whether there was a trend in our results and if our confidence in the modelled outputs was sufficient to better inform local conservation authorities of the long-term effects of climate change at the watershed scale. Current watershed management strategies conducted by the Lakehead Region Conservation Authority are geared towards a reflexive approach in which continual monitoring is done and then any exceedances in nutrient levels or erosion are dealt with once they are detected. However, the long-term impacts of climate change require proactive and adaptive management strategies that preserve the ecological, economic, and social resilience of the Slate River valley for the generations to come.

Using the latest and most relevant modelling techniques to explore potential climatic influences on the hydrology of the Slate River allows us to project changes to our water resources and make inferences on the effectiveness of current water resource management strategies in preserving these natural resources. The Slate River Valley is an area of unique fertile topography that continues to support a legacy of agricultural lifestyles that are important to the economy and cultural heritage of the community. This study will therefore attempt to advance current knowledge on the ability of physically-based models to accurately simulate hydrologic responses to climate change on the Canadian Shield, as well as provide a case study that illustrates the potential long-term consequences of climate change on our water resources.

CHAPTER 2
LITERATURE REVIEW

2.1 Watershed Modelling

There is a growing need for geomorphologists and hydrologists to infer geomorphic and fluvial system response to predicted future climate change (IPCC, 2014). The primary tools applicable to the study of future geomorphic response are models (conceptual or physical for example) that can simulate earth surface processes as well as changes in processes and how they may alter the landscape (Lotsari et al., 2015). Such models are capable of simulating hydrological processes occurring at the reach-scale, while taking into consideration the river channel's interaction with the watershed as whole. This allows for an understanding of how the relationship between land, water, and atmosphere impact a river channel's response to future climate change.

Watershed models can be divided into three categories: (1) lumped models, (2) distributed models and (3) semi-distributed models (Gautam, 2012). Lumped models consider the entire watershed as a single unit, thereby averaging input values to represent the entire catchment. In this process, spatial variation is lost, and the averaging of parameters may lead to false representation of hydrological processes (Gautam, 2012). At the other end of the spectrum are distributed models, which consider spatial variations by delineating the watershed based on input variables and physical characteristics over a gridded surface. The public availability of digital data such as digital elevation models (DEM), soils, land use/land cover, and precipitation, along with advances in computing resources have all contributed toward the push to adopt distributed models (Pai et al., 2012). Semi-distributed models bridge the gap between lumped and distributed models by subdividing watersheds into several subbasins in which processes, input data, and physical characteristics are lumped within these subbasins to allow for faster processing times.

In addition to classifications based on space and time, hydrological models are also classified based on being either empirical, conceptual, or physically-based. Empirical models apply functional relationships between dependent and independent variables using mathematical equations derived from concurrent input and output time series at individual cross-sections and river reaches (Lotsari et al., 2015). Hence empirical models are said to be data driven in that they do not actually consider the physical processes of the hydrological system and are only valid within the boundaries of the data source (Devia et al., 2015). Conceptual models can only provide qualitative descriptions and predictions of landform and landscape evolution based on past or present data. Despite their qualitative nature, however, such models have occasionally been applied to future channel change analysis (Lotsari et al., 2015). Physically-based models, such as SWAT, are the mathematically idealized representation of the real phenomenon (Devia et al., 2015). Physical models can overcome the drawbacks of the previously mentioned models because they have parameters that can be physically interpreted and provide a large amount of information over a large region. To adequately describe the physical characteristics of the catchment, physical models require a large amount of input data and parameters that must be calibrated. This makes such models an inherently more complex modelling approach requiring expertise in computational modelling techniques and knowledge about naturally occurring processes within the watershed (Eckhardt and Arnold, 2001; Devia et al., 2015).

2.2 Soil Water & Assessment Tool

One of the most popular watershed models, SWAT (Soil Water and Assessment Tool) can be classified as either semi-distributed or distributed. The model can either simulate watershed processes at the subbasin level (semi-distributed) or it can delineate watersheds into the smallest of land units known as hydrological response units (HRUs) (distributed). SWAT's delineation criteria for HRUs is based on lumping land areas of homogenous land cover, soils, and topography. The homogenous HRU-based approach provides a more detailed analysis of the small variations of hydrological processes among different HRUs, and a better representation of smaller catchment areas (<200 km^2) (Pai et al., 2012).

SWAT can be further described as a continuous simulation model. Continuous simulation models are most appropriate for predicting long-term hydrologic changes as well as watershed management practices, as opposed to event models that are used to assess the effects of single intense storms that may cause floods and transport substantial loads of sediment and nutrients (Pai et al., 2012). SWAT's potential for long-term continuous simulation has been successfully demonstrated in many countries around the globe and is currently one of the most widely used watershed modelling systems for the continuous simulation of flow, prediction of sediment and nutrient transport from watersheds, water budget analysis, evaluating best management practices, and climate change impact studies (Abbaspour et al., 2009; Ficklin et al., 2012; Franczyk and Chang, 2009; Jha et al., 2004; Marshall and Randhir, 2008; Pai et al., 2012).

Although the SWAT model is characterized as being physically-based - as most distributed models tend to be, particularly because of their spatial detail - it still has a conceptual characterisitc that is common in most, if not all physcially-based models. Hydrology models are inherently complex, and considering the main processes in hydrological systems, as well as the factors that govern the relationships amongst these processes, there is always a level of conceptualization (Eckhardt and Arnold, 2001). For example, although the physical properties of a soil layer maybe be heterogeneous, the underlying soil-water content is averaged over the depth. Thus it is based on a conceptual description of the land-water-soil system functions even though it uses a physical processes scheme (Gautam, 2012). Technically, there is no simulation model based only on a pure physical description of the processes. Thus, under a physic-conceptual approach, SWAT computes the important hydrological processes such as evapotranspiration, surface storage, percolation, snowmelt, baseflow, and surface runoff by using simple mathematical equations, while incorporating different model calibration parameters that are representative of the hydrological/geomorphological processes occurring within the watershed, as determined by the modeller’s knowledge (with varying degrees of assumption) (Gautam, 2012).

2.3 Application of SWAT in Canada

SWAT was initially developed by the USDA in the 1990s as a large-scale watershed management model for agricultural regions in the U.S. (Lévesque et al., 2008). Since its development, however, the SWAT model has been adopted and used extensively around the world in varying environments from dry-arid regions to snow-melt dominated watersheds (Abbaspour et al., 2014; Abbaspour et al., 2009; Ficklin et al., 2009; Franczyk and Chang, 2009; Fu et al., 2014; Gautam, 2012; Jha et al., 2004; Lévesque et al., 2008; Marshall and Randhir, 2008; Watson et al., 2008). In Canada, SWAT is the primary hydrological model included in Agriculture and Agri-Foods Canada’s Watershed Evaluation of Beneficial Management Practices (WEBs) program

(Stuart et al., 2010), as well as its application in several agricultural catchments across the country (Fu et al., 2014).

To tailor SWAT's modelled hydrologic processes to reflect Canada's topography, several studies have developed specific calibration parameters (e.g., Lévesque et al., 2008; Watson et al., 2008; Fu et al., 2014). In Canada, the Canadian Shield covers over half of the nation and is characterized by very thin soils on top of Precambrian rock, with many bare bedrock outcrops and numerous rivers, lakes, marshes, and wetlands due to post-glacial rebound (Fu et al., 2014). Currently only a limited number of SWAT studies have been conducted on Canadian Shield catchments, including: Gautam (2012), whose study focused on two small scale watersheds; Chief Peter and Entwash, located 120 km northwest west of Thunder Bay; Troin and Caya (2014), that attempted the simulation of snow-melting-dominated streamflow in the Outardes Basin in Northern Quebec; and Fu et al. (2014), whose study developed their own specifically parametrized version of SWAT called SWAT-CS (Canadian Shield). SWAT-CS was expected to more accurately represent hydrological processes dominating Canadian Shield catchments following their test modelling of a catchment in south-central Ontario.

Prior to this, Watson et al. (2008) developed a modified version of the SWAT model called SWAT-BF (Boreal Forest) for the purpose of developing a hydrologic and water quality modelling tool that would be more reflective of the hydrologic processes occurring in the Boreal Plains in north central Alberta. The major modifications that were implemented in the SWAT-BF model include: incorporating a litter layer which the original SWAT model lacks, adjustments to the baseflow and percolation processes, as well as refining simulated wetland processes (Gautam, 2012). Watson et al. (2008) successfully tested SWAT-BF on the western Boreal Plain where the soil mantle is thick, so Gautam (2012) attempted to test the applicability of the SWAT-BF model to the eastern Boreal Shield watersheds where the soil layer is thin. Guatam (2012) excluded wetlands in his study, but otherwise could produce satisfactory results for daily (NSE > 0.5) and monthly (NSE > 0.73) runoff simulations for both catchments using SWAT-BF.

Troin and Caya (2014) tested SWAT's applicability to a large forested watershed (15,267 km^2) on the Canadian Shield in northern Quebec with glacial till soil characterizing the surficial geology. The daily NSE for streamflow resulted around 0.80 and proved SWAT's snowmelt module could accurately simulate streamflow. In one of the latest studies that uses the SWAT model for runoff simulations in the Canadian Shield, Fu et al. (2014) claimed to optimize the model in its ability to provide a reasonable and useful representation of the typical hydrology of Canadian Shield catchments. Fu et al. (2014) explains that the specific objectives of SWAT-CS was to modify the model's parameters to more accurately represent (1) overland flow; (2) macropore flow and the ability to generate interflow at the soil–bedrock interface; (3) snowmelt; and (4) the regulation of streamflow by wetlands and lakes.

2.4 Stream Temperature Analysis

Stream temperature is another hydrologic parameter expected to be influenced by potential changes in channel and floodplain morphology attributed to climate change. Although there has been a long-standing and continuing motivation to understand the impacts of human activities, such as forestry and agricultural practices on stream and river temperatures, it is the anthropogenic change in air temperature that has been identified to be the primary stimulus to changes in stream temperature and thermal habitat (Chu et al., 2009).

Temperature can vary depending on stream order, ground water discharge, depth and velocity of the stream, as well as the amount of shade by riparian vegetation. Northern streams that drain from the bedrock of the Canadian Shield are associated with cooler temperatures and are hydrologically connected to more lakes than southern streams (Chu et al., 2009). However, ground water discharge and stream order was found to have a weak relationship with air-water temperature in cool-cold streams (Chu et al., 2009; Tague et al., 2007; Webb et al., 2008).

The ability to predict stream temperature in response to climate change can be complex due to the thermal heterogeneity in streams and the influences of channel morphometry, inflows from tributaries, ground water flow, and surface runoff (Chu et al., 2009). Thus, models are complex and time consuming. However, Morrill et al., (2005) assumed that heating and cooling by heat exchange at the water/air interface was the most important influence on stream temperature, and subsequently developed a predictive relationship between air and stream temperature using a nonlinear equation. The main advantage of this method over linear regression (discussed below) is that it can better represent the tendency for warmer water bodies surrounded by high air temperature to exhibit strong evaporative cooling, causing stream temperature to level off at warm air temperatures (Chu et al., 2009; Morrill et al., 2005). Morrill et al., (2005) explains that, although air temperature is often used as a surrogate for the dominant controls on stream temperature, air temperature alone is unlikely to explain within-landscape stream temperature patterns caused by groundwater variability. Hence, before management plans are prepared to maintain temperature standards (i.e. restoring riparian vegetation and mitigating land-use changes) the geological factors that can strongly affect the variability of stream temperature should be analyzed (Tague et al., 2007).

For example, Tague et al. (2007) conducted a study that compared the hydrogeological influence of an area of high permeability and subsequent large groundwater storage contribution, to an area within the same subbasin that had a relatively impervious underlying geology. Their findings showed statistically significant differences in both maximum and mean summer stream temperatures between streams fed by deep groundwater versus shallow subsurface flow systems; the stream temperature variance as explained by air temperature for the groundwater fed streams had an r^2 statistic less than 0.1, while the stream temperature variance as explained by air temperature in shallow subsurface flow environments exhibited an r^2 statistic greater than 0.5, depending on the distance of groundwater-fed streams to shallow subsurface streams. In essence, sites dominated by groundwater inputs or extensive shading remain cold even on very hot days, whereas open sites with relatively little groundwater contribution can attain water temperatures approaching ambient air temperatures representing a positive linear relationship between stream and air (Stoneman and Jones, 1996). In reference to the Slate River, its overall low-permeability surficial geology and relatively large size is enough to dilute any small-scale ground-water effects, justifying the use of linear regression to link air and stream temperatures in this case study.

The simplest models predict water temperature by means of linear regressions with air temperature (Chu et al., 2009). Stoneman and Jones (1996) introduced a simple method for classifying the thermal regimes of streams by using single daily measurements of the maximum air temperature (limited to periods with at least three days of air temperature ≥24.5ºC) and water temperatures at 1600 hours (approximately the timing of the daily maximum water temperature) between July 1 and September 7 at several sites along the north shore of Lake Ontario with contrasting temperature conditions. Using this method, a positive linear relationship between daily maximum air temperature and water temperature at 1600 hours is established and can be plotted on a nomogram to allow the user to categorize streams as either being coldwater, coolwater, or warm water (Stoneman and Jones, 1996). This methodology has since been adopted by several agencies throughout Ontario for the purpose of thermally classifying streams

(Chu et al., 2009). Chu et al., (2009) revised the Stoneman and Jones (1996) methodology by adjusting the sampling days from July 1 to August 31, instead of July 1 to September 7, and using daily sampling periods between 1600 and 1800 hours, as opposed to 1600 hours, to capture the warmest temperatures at their test sites. This revision extended the applicability of Stoneman and Jones's (1996) methodology from outside the Lake Ontario region to other regions surrounding the Great Lakes such as the north shore of Lake Superior. Subsequently, Chu et al., (2009) created a revised nomogram that included five (cold, cold–cool, cool, cool–warm, and warm) rather than three (cold, cool, and warm) thermal classifications for sites in northern Ontario streams.

Of the four data logger sites on streams along the north shore of Lake Superior, the dates when water temperatures reached their maximum were from July 21 to August 9, while the timing of the daily maximum water temperature occurred primarily between 1400 and 1600 hours (Chu et al., 2009).

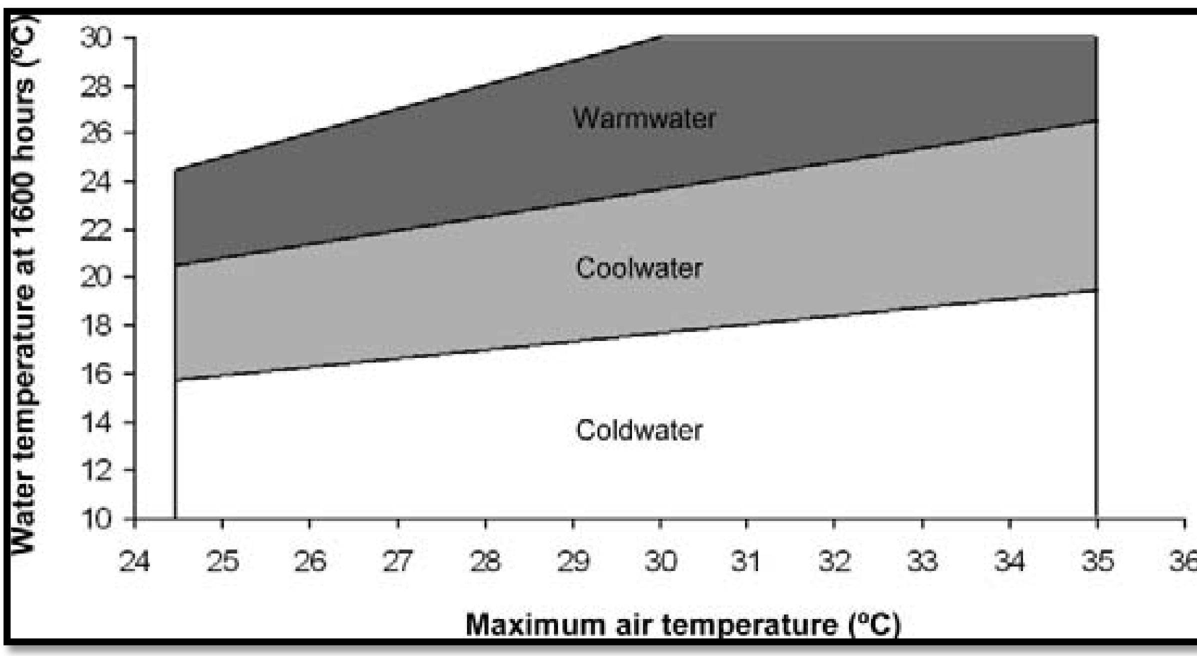

Figure 2.1: Re-print of Stoneman and Jone's (1996) nomogram of the maximum air and water temperatures at 1600 hours, used to estimate the thermal classification of stream sites from measurements of the daily maximum air temperature (≥24.58°C) and water temperature. (Source: Chu et al., 2009).

CHAPTER 3

DESCRIPTION OF STUDY AREA & CURRENT MANAGMENT OF THE SLATE RIVER VALLEY

3.1 Topography, Geology & Soils

A physical description of Northern Ontario is best understood by first examining the underlying bedrock geology that presents the surficial deposits and landforms typical of the Canadian Shield. The Shield consists primarily of Precambrian rock. In the Superior province, which covers Ontario north and west of the present city of Sudbury,

Figure 3.1: Slate River Valley (Photo Cred: Susan Dykstra)

this Precambrian rock can be dated as far back as the Archean eon - more than 2.5 billion years old (Baldwin et al., 2001). The Superior geologic province region can further be subdivided based on major rock types, from plutonic/volcanic granite to a range of sedimentary rock types. These sub-regions are separated by faults, or long narrow bands of volcanic granite-greenstone once part of ancient island arcs- similar to modern

Japan (Baldwin et al., 2001). These regions host world famous mines such as Gold Giant Mine in the Hemlo mining camp midway between Thunder Bay and Sault Ste. Marie, and the Kidd Mine, the world's deepest copper/zinc mine in the city of Timmins.

The topography of Ontario varies from flat plains, to low rolling hills, to dissected uplands with ridges, escarpments, and cuestas as high as 200 m above adjacent land (Baldwin et al., 2001). Carved by retreating ice sheets of the Quaternary glaciation, the most rugged and fragmented surfaces occur in a band extending from the north shore of Lake Superior, across the Algoma highlands, and through the Sudbury region (Baldwin et al., 2001). The rugged beauty of the northern shores of Superior can be attributed to the variety of resistant rocks in the region, including Archean granitic and metamorphic rocks and Proterozoic igneous rocks underlying the western Superior region (Pye, 1997). This contributes to the attractive shores in Canadian national and provincial parks such as Superior, Pukaskwa, Neyes, and Sibley. The Sibley Peninsula provides much of the lakeward view from the Thunder Bay area, which is dominated by the recumbent form of the Sleeping Giant, an imposing mass of Keweenawan diabase (Sutcliffe, 1991).

A contrasting topography unfolds towards the west of the city of Thunder Bay. The Slate River Valley, named for the river that runs through it, is characterized by farmlands amongst rolling hills and gentle slopes that are flanked by the Nor'westers towards the east (Fig. 3.1); a truly unique region that encompasses the topographic diversity of Ontario's landscapes. The Slate River itself extends 50.5 km from the range of mesa plateaus of the Nor'westers, which drops quickly more than 100 m into the valley, then flows through the valley's gorge to the Kaministiquia River (LRCA, 2008). The Slate River watershed (Fig. 3.2) is essentially comprised of all the surrounding land (183 km^2) that naturally drains into the Slate River.

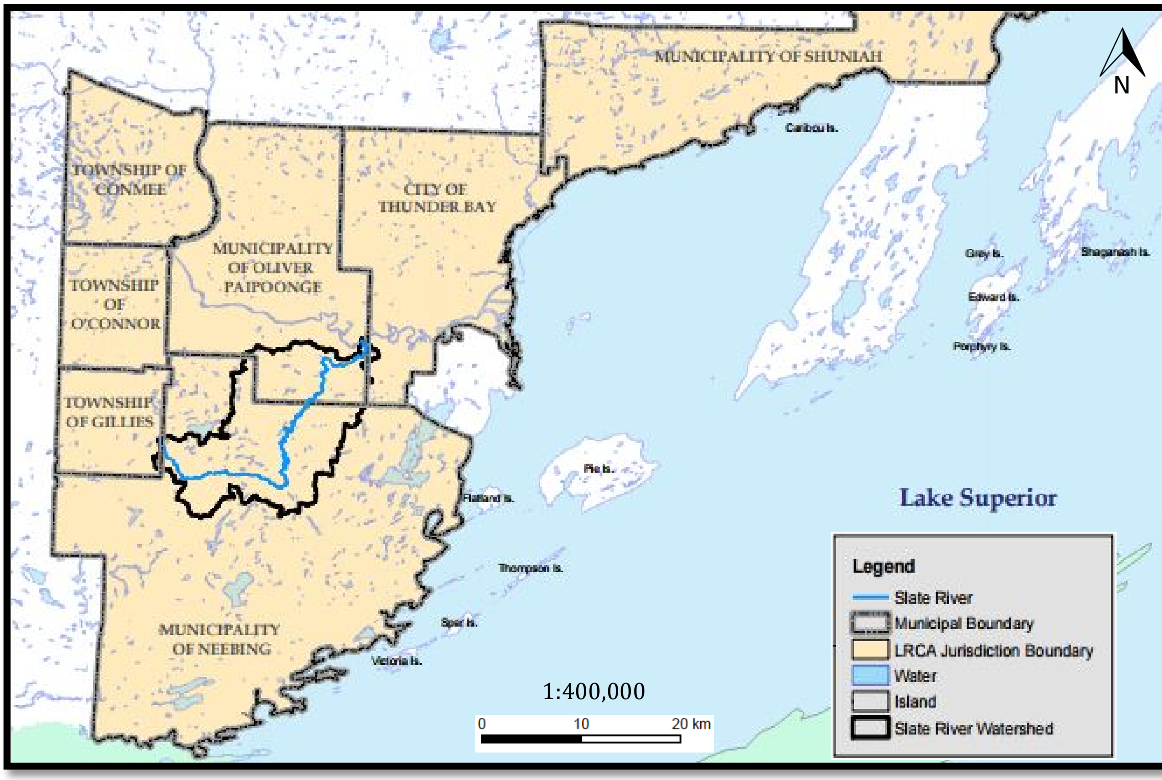

Figure 3.2: Slate River Valley Watershed outlined in black. LRCA jurisdiction boundary highlighted in yellow (Courtesy of Lakehead Region Conservation Authority).

Together, glaciation and postglacial deposition largely account for the present landscape and surficial geology found along the North Shore of Lake Superior, which is dominated by ground moraine and lacustrine deposits composed of varying combinations of silt, clay, fine sand, sandy till and clayey till (Sutcliffe, 1991). The Slate River geology and soils originate from the last glacial re-advancement in 11,000 B.P. The valley is the remnants of a breach in the Marks Moraine, causing very large quantities of sediment to spill into a large post-glacial lake, forming a delta (Pye, 1997). The shores of this ancient lake and all its sediments reside in the Slate River area. The bedrock of this watershed consists of diabase igneous rock, and a dark-coloured metamorphic rock that is an intermediate between shale and slate (hence the name of the river) which is derived from the outcropping of this bedrock near its mouth (LRCA, 2008).

The surficial geology of the Slate River watershed conforms with the rest of the region and is composed of lacustrine clay or silt deposits. However, moisture retention is much better in the Slate River watershed due to the presence of loamy soil compared to either the heavy clays (poor drainage) or light sands (high drainage) commonly found in the surrounding region (LRCA, 2008). According to the Canada Land Inventory performed in the 1960s the soils in the Slate River are Class 2 and 3 on a scale of soil classification ranging from 1 (no limitations in use for crop) to 7 (no capacity for arable culture or pasture) (Agriculture and Agri-Food Canada 1998).

3.2 Climate

Thunder Bay and the surrounding region's climate are modified by the lake effect of Lake Superior with prevailing westerly winds. The climate in the lower portion of the Slate River watershed is similar to Thunder Bay, while the upper portion exhibits minimal difference because of elevation and greater distance from Lake Superior. Although average monthly temperature and precipitation levels are recorded at the Thunder Bay airport, this study uses temperature and precipitation values recorded directly in the Slate Valley region (Tranquillo Ridge Climatological Station, 48.23N 89.52W).

Table 3.1a: Average monthly temperature for the Slate Valley region, 1970-2002. Data provided by Saunders G.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature - Daily Mean (°C)	-14.7	-11.2	-5.3	2.7	9.6	14.6	17.5	16.6	11.4	5.2	-2.8	-10.8

Table 3.1b: Average monthly precipitation for the Slate Valley region, 1991-2010. Data provided by Saunders G.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation - Daily Mean (mm)	57.1	28.8	43.4	61.6	76.2	81.1	89.3	63.3	75.8	82.3	65.3	64.2

3.3 Hydrology

The Slate River watershed basin consists of an area of 183 km^2, with an average gentle slope of 0.7 percent (LRCA, 2008). The water level of the Slate River is highly variable between seasons with high flow in the spring as a result of surface water runoff during the spring melt, to periods of low flow during the summer (Fig. 3.3). The Slate River historically exhibits high annual variations in water levels as well. For instance, from November 2006 to July 2007, the region received precipitation that was less than 60 percent of the monthly average (LRCA, 2008). The following year, on June 6, 2008, an extreme precipitation event was witnessed, as area gauges recorded between 56.5

mm and 105 mm of precipitation while discharge levels peaked around 57.1 m^3/s at the location of the streamflow gauge (LRCA, 2008). On average stream depth ranges from 0.3 to 1.5 m.

Figure 3.3: The Slate River running through a culvert during a low flow period (July 12, 2016).

3.4 Flora & Fauna

A 2008 assessment of the Slate River watershed performed by the Lakehead Region Conservation Authority (LRCA) took inventory of the common plant and animal species throughout several site locations along the river. Indicator species such as fresh water sponge and clams suggested healthy water quality. Fish populations lacked abundance and diversity, although physical water parameters were healthy enough to support fish populations; the natural variability in water level and flow, as well as the presence of multiple beaver dams that interfere with fish migrations, was thought to be the cause (LRCA, 2008).

Contrasting vegetative cover from riparian to farmland provides suitable habitat for species favouring both dense forest and open edges. The forest density along the riparian zone is low, providing less than 25 percent cover by shaded canopy (LRCA, 2008). Overall, the stream banks documented along the Slate River were stable. The gentle slope of the stream bank and its composition of silty clay soil gave the area low erosion potential (LRCA, 2008). According to Cullis et al. (1998), the Slate River watershed met most of the wildlife habitat targets identified in the Great Lakes Remedial Action Plans (RAPs) except for a lack of 30-metre-wide buffer zones along first to third order streams and a lack of wetlands in the watershed.

3.5 Land Use, Agricultural Practices, & Current Management

Agriculture is the predominant land use in the Slate River valley region. Dairy and beef cattle are the most significant farm types in the watershed with “pick-your-own” produce ventures becoming more popular amongst consumers (LRCA, 2008).Depending on the agricultural practices involved, agricultural development can have an alleviated or significant impact on the landscape. During the early 1980s – 1990s, the majority of farmers in the Slate River Valley practiced conventional tillage (LRCA, 2008). Conventional tillage incorporates or buries most of the crop residue into the soil. Since the method plows much of the crop stubble into the soil, it leaves the surface relatively bare and without cover protection (Hofmann, 2015). Conventional tillage has its advantages as the machinery is widely available, the techniques are well-known to farmers, and this practice is effective at loosening soil and increasing soil porosity. However, it also leaves the landscape vulnerable to wind and water erosion (Hofmann, 2015). According to the LRCA’s 2008 Watershed Assessment Report, during the spring snow melt, conventional tillage can be the main source of soil erosion contributing to sedimentation, nutrient loading, and bacterial contamination in the Slate River.

Apart from conventional tillage practices, it is also common for farmers to replace nutrients in the soil with fertilizers and manure which can build up in the soil and leach into the surrounding water. Allowing livestock to graze at the river’s edge, another common practice, further exacerbates stream bed erosion from trampling as well as the bacterial uptake of the river. In the particular case of dairy farms, the improper disposal or storage of manure and milkhouse wastewater is another source of nutrient loading and bacterial contamination. Tile drainage, which is the practice of digging and lining subsurface channels that collect excess water when precipitation levels exceed the saturation point of the soil, can also disrupt normal hydrology and increase the uptake of fertilizers and pesticides from farmland to nearby water.

There are options of conservative farming practices such as: conservation tillage and making use of cover crops to mitigate soil erosion as well as preventing weeds; using natural pest eliminators and biointensive integrated pest management techniques that emphasize pest prevention through biological rather than chemical measures; and managed grazing techniques that limit livestock impact on particularly vulnerable landscapes (FAO, 2015). However, best management practices require educative outreach programs and for farmers to take voluntary initiatives to switch from known agricultural practices to new ones that might incur high initial adjustment costs and 'a leap of faith' on the farmer's behalf, which many may be reluctant to make (FAO, 2015).

Concerns about the impacts of conventional agricultural practices in the Slate River Valley eventually prompted the Lake Superior Programs Office to produce the first Watershed Management Plan in 1998 (Table 3.3) (Cullis et al., 1998). The Lake Superior Programs Office was a joint initiative by Environment Canada, the Department of Fisheries and Oceans, the Ministry of Environment and Energy, and the Ministry of Natural Resources to deliver projects recommended by the Public Advisory Committees for the RAPs along the north shore of Lake Superior (LRCA, 2008). The Report brought to light evidence of surface water quality being significantly impacted throughout the region as levels of total phosphorus, suspended solids, total nitrogen and *Escherichia coli (E. coli)* exceeded 1994 Provincial Water Quality Objectives (PWQO) at the time of sampling (LRCA, 2008). It was indicated that the most significant factor in the poor water quality of the Slate River was the change of land use to agricultural, specifically dairy farming (LRCA, 2014).

LRCA Report	**Objective of Report**	**Year Published**
Slate River Watershed Management Plan	Address concerns of nutrient and E. coli exceeding 1994 Provincial Water Quality Objectives	1998
Watershed Assessment of the Slate River	Re-assess watershed health by comparing water quality to 1990 water quality results published in the 1998 Watershed Management Plan	2008
Slate River Watershed Report Card	Introduced by Conservation Ontario as a way for Conservation Authorities to assess and report on the health of surface and groundwater quality as well as forest conditions in watersheds across Ontario.	2013
Slate River Watershed Management Plan Review	Determine whether further implementation of the 'existing' Watershed Management Plan published in 1998 was warranted at the time.	2014

Table 3.3: Summary of LRCA Reports on the Slate River Watershed

In order to assist in the identification of watershed targets for rehabilitation, as well as determining management constraints and selecting preferred management options, the watershed management plan focused on creating stakeholder and technical committees to guide the process. However, the proposed committees were never formed and a full implementation of the Plan was never undertaken as the Lake Superior Programs Office closed in 1999 (LRCA, 2014). Even though the 1998 plan was never implemented, the LRCA states that the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) was capable of achieving the vision the original plan had in mind through their existing partnerships and programs. This was accomplished through on-going outreach programs which claim to have successfully created cooperative networks between farmers and the government, as well as the successful promotion of best management practices and funding opportunities being made available to farmers in the region (LRCA, 2014).

In partnership with the Ministry of the Environment under the Provincial Water Quality Monitoring Network (PWQMN) program, the LRCA conducted a Watershed Assessment of the Slate River in 2008 for the purposes of comparing the 1990 water quality results published in the 1998 Watershed Management Plan (Cullis et al., 1998). The 2008 results demonstrated improvements in total phosphorus, nitrate, ammonium, and *E. coli* levels using current PWQO guidelines. Most notable was the improvement of total phosphorus levels which were reduced by 29%. The 2008 report concluded that the improvement was due to the implementation of agricultural best management practices, such as the techniques mentioned previously, which farming communities in the region had eventually begun to adopt. The report declared the Slate River Watershed to be in good overall health at the time of the study and recommended a thorough assessment in ten years' time.

In 2013, the first Lakehead Region Watershed Report Card was developed by the LRCA. This was introduced by Conservation Ontario as a way for Conservation Authorities to assess and report on the health of surface and groundwater quality as well as forest conditions in watersheds across Ontario, including the Lakehead Region Watershed, which the Slate River is a part of. The 2013 report card gave the Slate River surface water quality a B (good) as although most nutrient and bacteria levels did not exceed PWQO limits, phosphorus levels were rising. A grade of B was also assigned as the overall surface water grade for the entire Lakehead Watershed (LRCA, 2013).

In February 2014, the LRCA published its Slate River Watershed Management Plan Review to determine whether further implementation of the ‘existing’ Watershed Management Plan published in 1998 was warranted at the time. The LRCA decided that based on the status of the Slate River watershed and current programs in place, the implementation of the Slate River Watershed Management Plan was unwarranted and that the majority of recommendations were being implemented through existing programs (LRCA, 2014). The LRCA concluded that the Slate River seemed to be improving since the Watershed Management Plan for the Slate River was developed in 1998, and recommended the continued monitoring and assessment of the Slate River Watershed.

Although the highlights of the 2008 Slate River Watershed Assessment report focused on water quality, it is worth mentioning that water quantity in the Slate River has been managed in partnership between the LRCA and Environment Canada since 2007. The 2014 review briefly mentions disruptions in flow having been observed within the Slate River watershed in recent years, although this has been correlated with low water conditions observed throughout the region, not just the Slate River area. From November 2006 until July 2007, the Slate River was confirmed as being a Level II Low Water Condition as precipitation was less than 60 percent of the monthly average. During this period the LRCA issued news releases asking the public to reduce water consumption by 20 percent, especially in rural areas where drinking water comes from wells (LRCA, 2008). Whether or not such conditions have or may eventually impact irrigation practices on farms in the region is still unclear as both the 2008 assessment and the 2014 review do not discuss such concerns; the bulk of the review focuses on water quality, erosion, and forested environments within the watershed.

Currently there are some known ‘Permit to Take Water’ holders on the Slate River as well as some low volume takers who collect water from the watershed for personal use (LRCA, 2014). A ‘Permit to Take Water’ (PTTW) is required by the Ontario Ministry of the Environment (MOE) when >50,000 litres per day (L/day) is taken from the water source.

3.6 Long-Term Concerns and Considerations: Adaptive Management in the Face of Climate Change

The concerns of the original 1998 Plan predominantly revolved around water quality, particularly on *E. coli* and phosphorus levels in the Slate River. *E. coli* and phosphorus levels have since reached PWQO standards although phosphorous levels have been increasing in recent years. The LRCA stated in its 2014 review that through the PWQMN program, the general water quality of Slate River will continue to be monitored, funding permitted (LRCA, 2014). The review also mentions sites of present erosion due to the natural meandering of the river, which will likely never be entirely eliminated. However, sites of greatest vulnerability could be inspected and prioritized for future remediation if warranted (LRCA, 2014). Besides the presupposition that water quality and erosion will continue to be monitored into the future, the 2014 review maintains that all other recommendations proposed in the 1998 review - including education on best management farming practices through the creation of voluntary programs such as the Environmental Farming Program and the Nutrient Management Strategy/Plan, as well as funding opportunities to promote best management practices - are being accomplished by programs administered by OMAFRA. The 2014 review thus concluded that, based on the current status of the Slate River Watershed and the current programs in place, the original concerns were adequately addressed.

In accordance with the 2014 review, watershed management in the Slate River region and most likely the Lakehead region as a whole seems to be predominantly reflexive. The key goals of the current watershed monitoring program in place by the LRCA are to record nutrient and *E. coli* levels, monitor potential high-risk sites of erosion, and occasionally record and report the flow level of the Slate River to the MOE. Considering that the monitoring of nutrients is most important for monitoring the overall health of the watershed according to the LRCA, the priority is then to report on any exceedances found in the following assessment report, followed by recommendations upon which OMAFRA adjusts their programs accordingly to mitigate these impacts.

The 1998 Watershed Assessment Plan was created after significant land use change of the watershed into dairy farming led to *E. coli* spikes in the surface waters of the region. Land use change in this case was an example of a long-term change that eventually caused unforeseen impacts to the Slate River Watershed and subsequently deteriorated surface water quality and posed a risk to the community and environment as a whole. The 1998 impact assessment that followed in response to concerns of surface water contamination confirmed the need for nutrient leaching mitigation and changes in conventional farming practices that had to be facilitated by government agencies such as OMAFRA. Fortunately, due to the successful cooperation between the farming community and the government, nutrient and bacteria levels were reduced to satisfactory levels under PWQO guidelines by the time the 2008 Slate River Watershed Assessment was released.

As with land-use change, the growing global awareness of climate change presents another long-term impact that may lead to unforeseen effects to the environment and community. Unlike the impacts caused by land-use change, climate impacts can create ‘wicked’ issues that are far more difficult to address in the aftermath. The anticipation of such impacts is why the adaptation to climate change has now become part of the contemporary discourse in its relation to food production, ecosystem health, and economic development. The focus of this discourse on climate change asks: how can adaptation to climate change be facilitated and enhanced, given that there are at least several generations in the twenty-first century that will experience progressively changing climates, including the societal, economic, and environmental consequences that follow? The future residents of the Slate River Valley may face very different issues from today’s residents; aside from water quality, changes in water quantity and fluctuations from seasonal norms in regard to temperature and precipitation may lead to unforeseen consequences that could affect living and economic standards of both farmers and residents in the region.

Although the LRCA is capable of monitoring changes in hydrology and environmental shifts, as well as proposing to OMAFRA recommendations for strategies to mitigate observed imbalances, there needs to be a more proactive approach in dealing with climate change related impacts. In order to minimize the damages and costs that might result from climate change scenarios, adaptive measures are needed for the Slate River region to resist or absorb impacts without threatening the long-term resilience of the community. The purpose of climate change adaptation research is to guide such adaptive measures through estimating the impacts of climate change. By examining various long-term climate change scenarios, we are essentially providing multiple windows, or views, showing various outcomes for which adaptive measures can be tailored. Using this information, conservation authorities may move forward with adaptation analyses which include: the evaluation of specified adaptation options; providing vulnerability indices that establish relative vulnerability scores for the region; and identifying adaptation strategies that are feasible and practical within the community. Climate change impacts can be considered together with other environmental and social stresses so that adaptation initiatives can be practically incorporated into other resource management, disaster preparedness, and sustainability programs within the Slate Rive Valley region.

Agriculture in its many different forms and locations remains highly sensitive to climate variations, which are the dominant source of the inter-annual variability of production in many regions. Climate impacts at the global scale can have regional repercussions, such as the El Nino Southern Oscillation phenomenon with its associated cycles of drought and flooding events, resulting in far reaching impacts that can be amplified by long term climate changes. This study will not only attempt to quantify the changes in climatic variables, such as temperature and precipitation at the regional scale, but also establish potential trends that reflect how the major tributaries in the Slate River Valley watershed might react to these changing climatic variables. It is the hope that such information leads to additional insights about future impacts and vulnerabilities that may guide long-term water management strategies.

3.7 Modelling Hydrologic Responses to Climate Change

The SWAT model is capable of simulating various hydrologic parameters including climate, hydrology, soil temperature, plant growth, land management practices and erosion (Arnold et al., 1998; Neitsch et al., 2005). SWAT partitions a watershed into subbasins, which can then be further subdivided into the aforementioned HRUs. Within each HRU, SWAT calculates a water balance equation that considers important hydrological processes such as precipitation, evapotranspiration, overland flow, lateral flow, baseflow, and soil water storage (Gautam, 2012). This equation calculates the contribution from each HRU to the overall streamflow in the watershed.

This study used historic and simulated climate model data, specifically precipitation and temperature data, as the meteorological inputs into SWAT. Other inputs included a DEM of the Slate River Valley region with a burned in streams layer, a surficial soil data layer, as well as a LULC map. Meteorological data was the driving variables affecting river hydrology and watershed geomorphology, as land-use was held constant. As mentioned previously, in relation to long term influences, climate change alone has significantly more dramatic effects to hydrology and water quality compared to studies that incorporated land-use change. To accurately estimate changes in flow level and discharge, historic hydrometric data for the Slate River was acquired from the Government of Canada's Real-Time Hydrometric Data and input into SWAT at the location of the measurement station. Discharge rates from the mouth of the Slate River (location of measurement station) was compared between the historic recordings and the simulated recordings produced by SWAT.

The second objective of this study intended to use the linear regression approach with stream and air temperature data from the Slate River Valley region to first determine if the positive relation between air and water temperature existed without much deviation. If a linear relationship could be established, using the criteria outlined by Stoneman and Jones (1996) and Chu et al. (2009) the Slate River could be given a thermal classification. Climate model data from various emission scenarios would then be used to substitute the observed air temperature data to get an idea of how much the water temperature may increase, and if this increase is enough to change the thermal classification of the Slate River. The first step in the process was to determine the best sampling time period for measuring maximum water temperature for the Slate River. This was done by examining historic air temperature to determine the longest time period that had most consecutive days warmer than 24.5 °C, followed by recording daily stream temperature to determine the time of day the Slate River was warmest.

3.8 Uncertainty Analysis & Calibration for Hydrologic Modelling of the Slate River Valley Watershed

It is important to understand several important issues that can beset calibration and uncertainty analysis of distributed watershed models. Firstly, correct parameter assignment and the number of model parameters to calibrate depends on the user's understanding of the physical processes and the heterogeneity of the landscape, as well as how well the user differentiates the various combinations of soil, slope, and LULC layers, although SWAT can mostly overcome this problem as the distributed model creates HRU's from each unique combination of soil, slope, and land cover. However, the spatial resolution of these data layers will affect the number of parameters to be calibrated and subsequently the parametrization results. Detailed information on soil parameters is essential for building a correct watershed model (Abbaspour, 2008). The process of parametrization and limitations in parameter assignment during the calibration of our model is discussed in more detail below.

The next issue pertains to when a watershed model can be said to be adequately calibrated. Whether a model is said to be calibrated using discharge data at the watershed outlet alone or whether discharge data from multiple stations inside the watershed all depends on what purpose the calibrated watershed model will be used for

(Abbaspour, 2008). If the primary purpose of this study was to produce the correct loads from various land uses in the watershed, then sediment loads would have to be included in the calibration process along with the need for multiple discharge data stations. Discharge data at the watershed outlet alone may be sufficient for a basic hydrology balance model; however, this means in terms of climate change analysis we are limited to predicting changes in water level and discharge at the outlet of our watershed and not changes in sediment loads.

Another issue with calibration of watershed models is that of uncertainty in the predictions. Watershed models, especially large-scale watersheds, can suffer from large model uncertainties, which may be divided into conceptual model uncertainty, input uncertainty, and parameter uncertainty (Abbaspour, 2008). Much of the uncertainty lays upon conceptual model uncertainty, which may be due to simplifications in the conceptual model, such as assumptions in calculating flow velocity in a river, or processes occurring in the watershed but not included by or not known to the modeller, which may include water withdrawal from irrigation, various forms of reservoirs, as well as the construction of roads, bridges, or culverts (such as the one the Slate River runs through shown in figure 3.3) (Abbaspour, 2008). In addition to model uncertainty, there are uncertainties that may lie in the input variables such as rainfall and temperature, depending on the point measurements of these variables. Although precipitation and temperature measurements were taken in close proximity to the Slate River, model outputs are very sensitive to input data, especially rainfall, and these should be considered carefully during the modelling process (Abbaspour, 2008).

Considering the large amount of uncertainty that essentially lies within any distributed conceptual watershed model, reporting the uncertainty in modeling is a necessity, as without uncertainty analysis, calibration is meaningless and misleading (Abbaspour, 2008). Therefore, the analysis of the calibrated model must include a level of uncertainty in the result. It is worth mentioning that another kind of uncertainty stems from that of “modeller uncertainty” as the experience of the modellers could potentially make a big difference in model calibration. However, applications such as SWAT-CUP offer semi-automated and automated calibration and sensitivity analysis, which can decrease modeller uncertainty as well as providing a variety of uncertainty analysis routes a modeller can utilize. Depending on the calibration uncertainty procedure chosen, the range of difficulty to implement a procedure varies depending on the types of uncertainties accounted for. Some procedures only account for parameter uncertainty while others account for all sources of uncertainty.

SUFI-2 (Sequential Uncertainty Fitting - Version 2) is one of the more popular calibration uncertainty procedures as it is relatively easy to implement and accounts for all sources of uncertainty, including driving variables, conceptual model parameters, and measured data (Abbaspour et al., 2014). SUFI-2 expresses uncertainty in parameters in uniformly distributed ranges, which are propagated as uncertainties in the model output variables, expressed as the 95% probability distributions (Abbaspour et al., 2014). This is refereed to as the 95% prediction uncertainty, or 95PPU (Arnold et al., 2012). The objective of using SUFI-2 is to have our model result (95PPU) envelop most of the observations, which we have measured in the natural system. To quantify the fit between simulation result, expressed as 95PPU, and observation, the p-factor and r-factor statistics are used. The p-factor represents the percentage of observed data enveloped by our modelling result, the 95PPU, and the r-factor is the thickness of the 95PPU envelop (Fig. 5.2). Ideally, the p-factor should have a value of 1, indicating 100% bracketing of the measured data, and an r-factor near zero, coinciding with the measured data (Arnold et al., 2012).

Prior to calibration, parameter assignment and the subsequent sensitivity analysis of the chosen parameters must be completed (Arnold et al., 2012). Correct parametrization is based on the analyst's knowledge of the physical processes and variability in soil, land use, slope, and location as defined by the specific subbasin of the watershed (Eckhardt and Arnold, 2001; Arnold et al., 2012). Although SWAT-CUP provides automatic calibration, according to Arnold et al. (2012) no automatic calibration procedure can substitute for actual physical knowledge of the watershed, which can translate into correct parameter ranges for different parts of the watershed. In the case of the SRV watershed, knowledge of the soil properties in the region was limited; accurate information was obtainable only for slope and land use. To determine which parameters were most pertinent to accurately simulate the hydrology balance of the SRV, the parameterization used by multiple SWAT modelling studies was reviewed (Arnold et al., 2012; Zhang et al., 2008; Levesque et al., 2008). Arnold et al. (2012) documented the calibration parameters used in 64 selected SWAT watershed studies. The parameters from SWAT studies located in snow-dominated watersheds within the Canadian Shield were also reviewed (Gautam, 2012; Fu et al., 2014; Troin and Kaya, 2014). Reviewing the most commonly calibrated parameters listed by Arnold et al.

(2012), Zhang et al. (2008), and Levesque et al. (2008) as well as the snowfall parameters used in Guatam (2012) and Fu et al. (2014) several parameters were chosen and tested to provide the best estimate for monthly flow, based on the aforementioned p- and r-factors, as well as the greatest r^2 coefficient. After each iteration, SWAT-CUP provides optimized minimum and maximum value ranges for each parameter, with each subsequent calibration producing more refined values, increasing the r^2 value and improving the p- and r-factors.

Regarding the length of data used in the calibration, the literature review performed by Guatam (2012) reported that there are no consistent recommendations given by researchers for the ideal temporal length of data required to calibrate a rainfall-runoff model. Considering the length of historical flow data available and the 'warm-up' period in which the model discards the first several years to eliminate anomalies in the simulation, our calibration and validation will consist of two years each. Several studies including Arabi et al. (2006) and Kang et al. (2006) have successfully calibrated and validated a rainfall-runoff model using two years of data each for the calibration and validation periods. In Guatam (2012) the Chief Peter Watershed located approximately 120 km west-northwest (WNW) of Thunder Bay was calibrated from 2006-2007 and validated from 2008-2009 using the measured streamflow data.

CHAPTER 4
MODELLING METHODOLOGY

4.1 SWAT Model Setup & Parameterization

4.1.1 Land-use and Land Type Data

In this study, the spatial geographic data for the Slate River Valley (SRV) watershed was obtained from the provincial geodatabase (Land Information Ontario). This data included a DEM with a burned-in stream network and a shapefile of the SRV watershed. After successful delineation of the SRV watershed, a stream outlet point was manually added to the mouth of the Slate River. This location was concurrent to the flow monitoring station from which the simulated flow output values would be later calibrated.

Following the watershed delineation and outlet definition, the SRV watershed was divided into sub-basins and then Hydrologic Response Units (HRUs) based on areas of similar soil, land use/land classification (LULC), and slope degree. Slope was derived from the DEM, while the LULC layer was obtained from the provincial Forest Resource Inventory (FRI) database. Regarding the soil layer, only surficial soil data was available for Northwestern Ontario from both provincial and federal government sources due to a general lack of soil classification studies in this region. Hence, to satisfy the measured sub-surface soil parameters required to run the SWAT model, a small-scale (1: 5,000,000) soil data layer provided by the FAO Harmonized World Soil Database was adopted. Thus, the soil data covering the SRV watershed was homogenous throughout. These data layers were then overlaid with the slope definitions to delineate the sub-basins and individual HRUs.

4.1.2 Climate Data

Meteorological variables required to run the simulation, including historic precipitation and temperature data from 2007-2015, was collected from the Tranquillo Ridge Climatological Station (48.23N 89.52W) located adjacent to the Slate River. The length of the simulation period was determined based on the availability of observed flow and discharge data for the Slate River. During the SWAT simulation, the first three years were used to “warm up” the simulation and eliminate the first few years which may be erratic, hence only simulated output data from 2010-2015 was used for calibration. Parameterization, calibration, and sensitivity analysis was performed on the model’s output using the semi-automated SWAT-CUP calibration application. Historical flow data was split between a model calibration period (2010-2012) and a model validation period (2013-2015). The parameters selected for calibration in this study include almost all those typically included in calibration in former studies of snow-melt dominated regions (eg. Lévesque et al., 2008; Fu et al., 2014; Guatam, 2012). The parameter ranges chosen were based on the ranges used in similar studies, particularly those performed on the Canadian Shield (Zhang et al., 2008; Fu et al., 2014). Soil parameters such as saturated hydraulic conductivity and moist bulk density were not included in calibration due to the lack of detailed soil information within our study area. The calibrated parameters are shown in Table 4.1.

4.2 ArcView Interface

The ArcView interface tool is designed to generate model inputs from ArcView 3.x GIS data layers and execute the SWAT model within the same framework (Gassman et al., 2007). SWAT requires topographic features, a land use layer, soil types, and other digital data that can be overlaid using the ArcView application. The SWAT interface that is compatible with ArcGIS 9.3 was used for this study. SWAT can be calibrated manually or automatically depending on the user’s preference. Applications such as SWAT-CUP (Calibration Uncertainty Program) offer semi-automated and automated calibration and sensitivity analysis that can decrease modeller uncertainty and provide a variety of uncertainty analysis routes. This study uses the autocalibration method supported by SWAT-CUP to refine parameter sensitivity analysis and reduce modelling uncertainty.

Table 4.1: Parameters used in calibration of the Slate River model. In this study, 14 parameters that govern the surface water response, subsurface water response, and basin response of the SWAT model were used in calibration.

Parameter	Description	Units
Parameters governing surface water response		
CN2	SCS runoff curve number	-
ESCO	Soil Evaporation Compensation Factor	-
GW_REVAP	Re-evaporation coefficients: controls the amount of water moving from the shallow aquifer to the root zone due to soil moisture depletion	-
REVAPMN	Threshold depth of water in shallow aquifer required to allow re-evaporation to occur	mmH2O
Parameters governing subsurface water response		
ALPHA_BF	Baseflow alpha factor	days
GW_DELAY	Groundwater delay time	days
GWQMN	Threshold depth of water required for return flow to occur	mmH2O
SURLAG	Surface runoff lag coefficient	days
RCHRG_DP	Deep aquifer percolation fraction	mmH2O
Parameters governing basin response		
SFTMP	Snowfall temperature	ºC
SMTMP	Snow melt base temperature	ºC
SMFMX	Maximum snowmelt factor for June 21	mm H2O/ºC-day
SMFMN	Maximum snowmelt factor for December 21	mm H2O/ºC-day
TIMP	Snow pack temperature lag factor	-

4.3 Climate Change Analysis

In this study, predicted climate data was obtained from four models of the Coupled Model Intercomparison Project (CMIP3). This included precipitation and temperature data projected from; the Coupled Global Climate Model Third Generation (CGCM3), the Geophysical Fluid Dynamics Laboratory Climate Model Version 2 (GFDL-CM2.0), Institut Pierre Simon Laplace Climate Model Version 4 (IPSL-CM4), and the Model for Interdisciplinary Research on Climate Version 3.2 (MIROC3.2). The climate models were driven by the Special Report on Emissions Scenarios (SRES) A1B and A2 storylines, over the periods 2049-2064 and 2084-2099, which were then compared to historical data. The SWAT model ran a total of 18 different simulations that reflected the differences in total discharge from the outlet of the Slate River amongst the various climate scenarios and time series.

4.4 Stream Temperature Analysis

Several data sets were needed to meet the stream temperature classification objective of this study. This included water and air temperature data as well as a summary of the landscape surrounding the temperature logger site (Fig 4.1). Stream temperature data was compiled from a singular logger (Hobo Pendant Temperature Logger) at a site that was adjacent to our climate station. The stream temperature data consisted of hourly recordings of the stream temperatures from August 13 to September 10, 2016, which was determined to be the period having the most consecutive days above 24.5ºC. The daily maximum air temperature from our climate station was used to represent the air temperature at the logger site. Daily maximum air and water temperature data were paired from August 13 to September 10, 2016 was compiled from our station. As in Stoneman and Jones (1996), the paired temperatures were filtered to periods with at least three consecutive days of air temperatures that were ≥24.5ºC, representing days with no major changes in weather. The paired temperatures that fit the criteria were then graphed using the nomogram created by Stoneman and Jones (1996) to estimate the thermal classification of the Slate River.

Figure 4.1: Location of the Hobo Pendant Temperature Logger in the Slate River. Tranquillo Ridge Climatological Station is located on the adjacent shore.

CHAPTER 5
RESULTS AND DISCUSSION

5.1 Stream Temperature Classification

Figure 5.1a illustrates stream temperatures recorded when there was at least three days of air temperatures ≥24.5ºC (or no drastic change in weather) from August 13 to September 26, 2016. As indicated by the high water temperatures exceeding 24ºC, the Slate River can be classified as a warm water river. Figure 5.1b shows the hourly air temperature and stream temperature recordings from August 13 to September 26. Figure 5.1c demonstrates the linear relationship that exists between recorded air and stream temperatures.

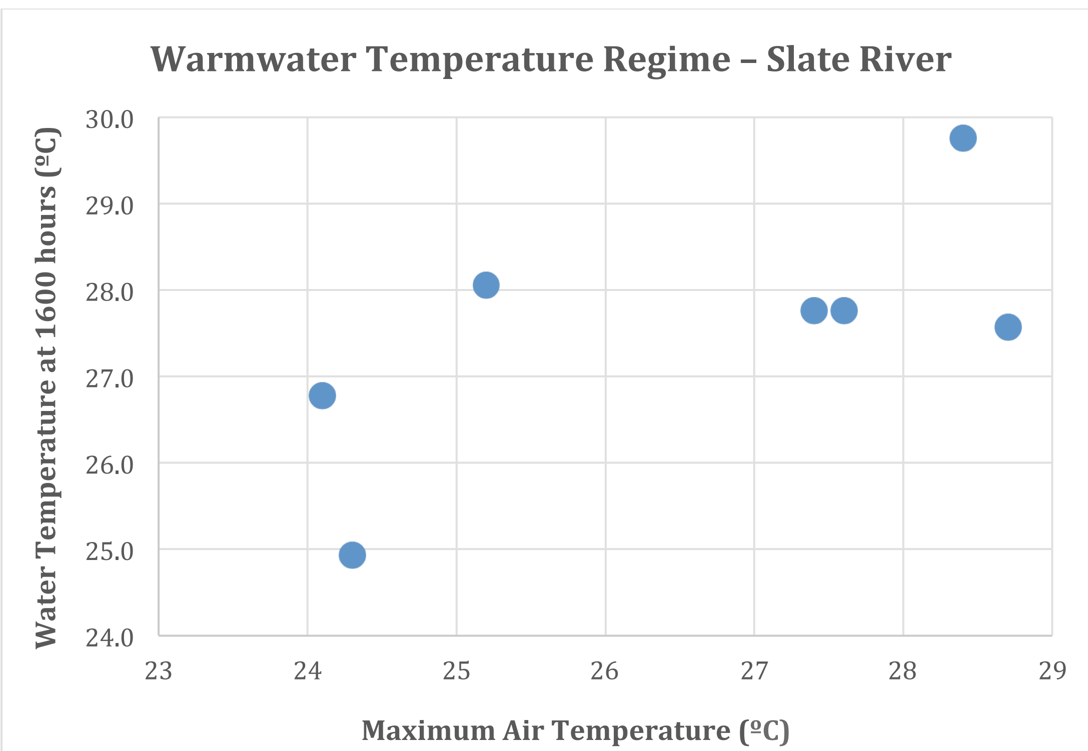

Figure 5.1a: Stream temperatures recorded when there was at least three consecutive days of air temperatures ≥24.5ºC. Referring to Stoneman and Jones' nomogram, the data suggests that the Slate River is clearly a warmwater classification as the lowest water temperature exceeds the warmwater classification threshold.

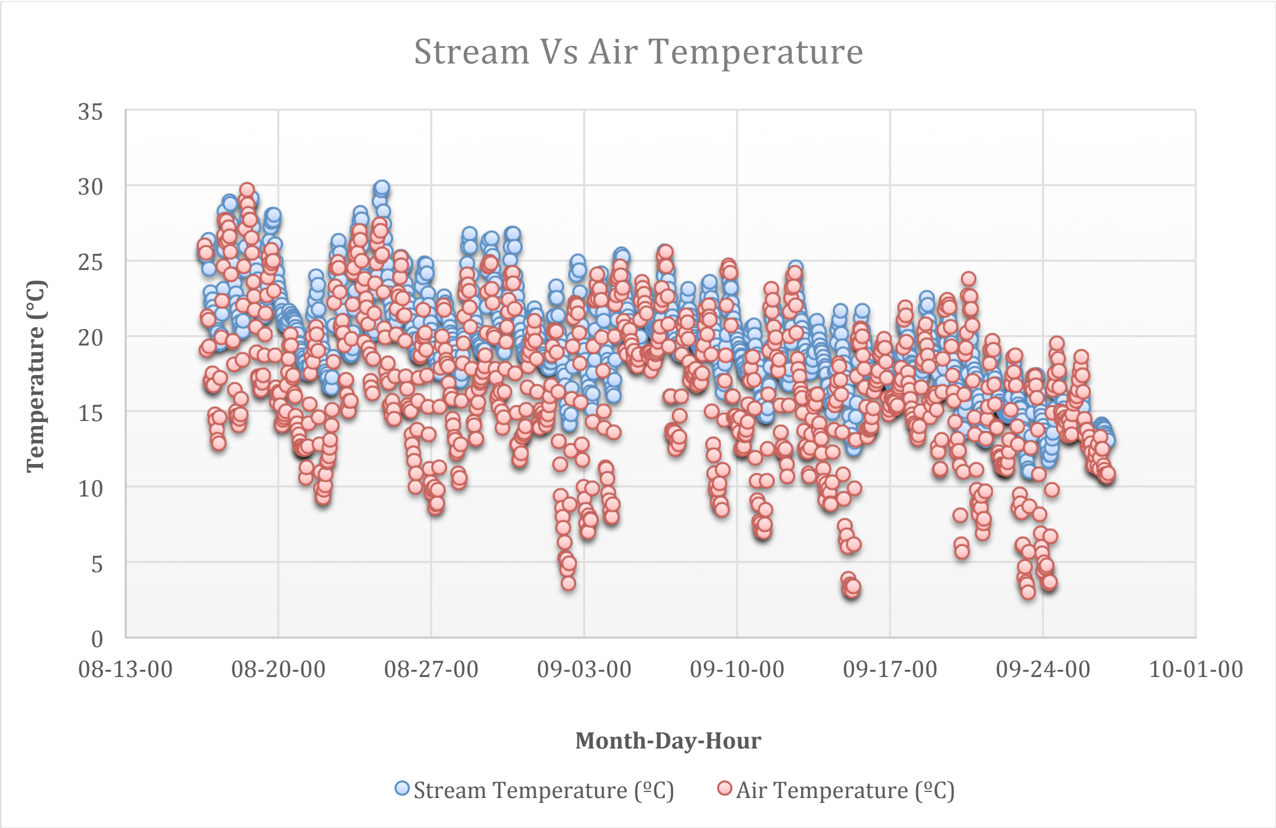

Figure 5.1b: Hourly stream temperature and air temperature recordings at our data collection site from August 13 to September 26, 2016.

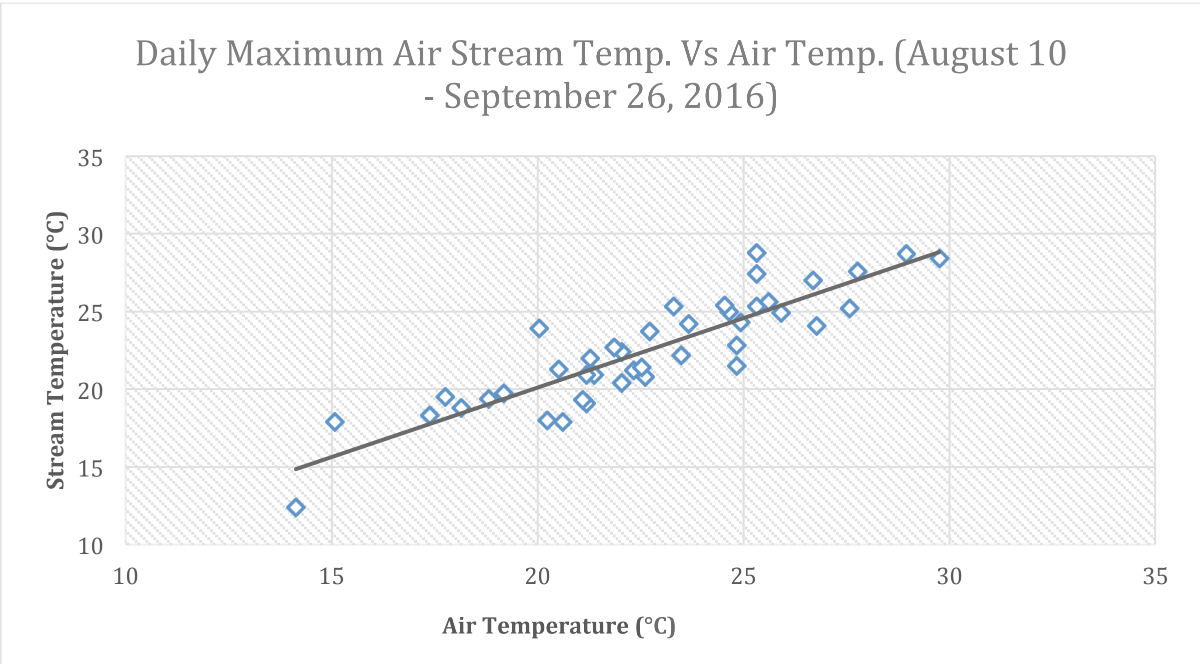

Figure 5.1c: Linear regression of stream temperature as a function of air temperature.

Unusually high stream temperatures were observed at mid-August, reaching the high 20s. There are several factors that could explain such temperature extremes, most of which pertain to stream morphology and riparian vegetation influences affecting the amount of exposure to solar radiation, the primary influence on stream temperature. Since the results of our stream temperature analysis provide evidence that the Slate River is in fact already a warm-water classification, exhibiting remarkably high temperatures as well as the localized spatial factors that may have strongly influenced these temperature recordings, the objective of using climate change analysis to determine a net change in the thermal regime of the Slate River was not relevant. Observations made at the site of data collection conclude that there were multiple ancillary factors that could influence stream temperature aside from air temperature, and that multiple data collection sites would be required in future studies to gain a more confident assessment of the thermal classification of the Slate River. These data collection sites would have to include a thorough recording of the morphological facets characterizing the site, because as discussed below, depending on such facets, air temperature alone may not be an accurate determinant of stream temperature in a particular location.

Multiple stream temperature related studies suggest that solar radiation and net-longwave radiation are among the most important factors responsible for the heat exchange processes that take place at the water surface (Cassie, 2006; Johnson, 2004; Poole and Berman, 2001; Webb 2008). Other components can also be considered, such as precipitation, wind speed, etc., although their contribution is generally small compared to the influence of solar radiation (Cassie, 2006). A study by Johnson (2004) used experimental shading of a second-order stream in Oregon to determine the consequences of solar inputs to stream. Using heat budget calculations, it was shown that net energy fluxes without shading were dominated by solar inputs. Maximum stream temperature immediately responded to the placement and the removal of shade, showing the importance of incoming radiation and, by extension, the shading provided by riparian vegetation in controlling daily maximum stream temperatures (Johnson, 2004). What Cassie (2006), Johnson (2004), Poole and Berman (2001), and Webb et al. (2008) demonstrate, contrary to other published accounts, is that the correlation between air and stream temperature exists because both are responding to the same temporal fluctuations in solar heat inputs.

Therefore, air temperature is a relatively weak determinant of stream temperature (Johnson, 2004). However, due to the correlation between stream temperature and air temperature, the use of regression and stochastic models which rely mainly on air temperature data for predicting river water temperatures are still widely popular amongst stream temperature analysis studies. It is important in such cases of stream temperature modelling, then, to record a summary of the landscape surrounding the data collection site, as shade provided by riparian vegetation blocks the solar radiation reaching the stream, subsequently reducing the total heat load added to the stream. The width of the river or the channel surface area across which heat is exchanged, is another ancillary influence affecting the amount of solar radiation received by the stream, as greater surface area allows for more rapid heat conduction and radiation (Poole and Berman, 2001). Under similar climatic conditions, narrower, deeper channels will not absorb as much incoming radiation. Observing the site of our data logger (Fig 4.1), which was located within a wider, shallower segment of the river, the increased surface area and minimal riparian vegetation cover would maximize the solar radiation input at this particular location. However, it seems characteristic of the Slate River to have low forest density along the riparian zone, as the LRCA documented that generally the riparian canopy along the river provides less than 25 percent cover. Another spatial influence that could partially explain the high water temperature recordings was the downstream distance of the study site from the source, which in this case, was closer to the outlet of the river. Water temperature is generally close to the groundwater temperature at the source and increases with distance/stream order (Cassie, 2006). The increase in water temperature is not linear, with greater rates of increases in smaller and intermediate size streams (Cassie, 2006; Zwieniecki and Newton, 1999).

To summarize it is the complex interaction between external drivers of stream temperature (i.e. solar radiation inputs) and the internal structure of integrated stream systems (e.g. stream morphology, riparian vegetation, etc.) that ultimately determines channel water temperature (Cassie, 2006; Johnson, 2004; Poole and Berman, 2001). To improve our stream classification study would require numerous stream temperature sampling locations along the Slate River, capturing a more holistic idea of the various internal influences affecting the temperatures at the locations of the data loggers. Then perhaps multiple linear regression analysis studies could be compared amongst the various locations and provide us with a better idea of the river's thermal classification. The observations made at our particular site of stream temperature recordings suggest that the high temperatures were due to the large surface area and shallow depth of the river, along with the lack of riparian vegetation shading, thus maximizing the solar heat input. However, if such observations are representative, there is a possibility that the Slate River may become intermittent in a future warming climate. Thus, the next question should not be whether climate change will modify the thermal regime of the Slate River, but should perhaps seek to answer whether climate change will lead to a further decease in the overall flow rate, which the following section of our study attempts to discover.

5.2 Stream Discharge Analysis

As previously mentioned, the parameters that were chosen for the calibration of Slate River were chosen based on the parameters calibrated in similar SWAT studies conducted on snow-melt dominated watersheds on the Canadian Shield. The parameters were then filtered after conducting parameter sensitivity analysis to determine which parameters were the most influential.

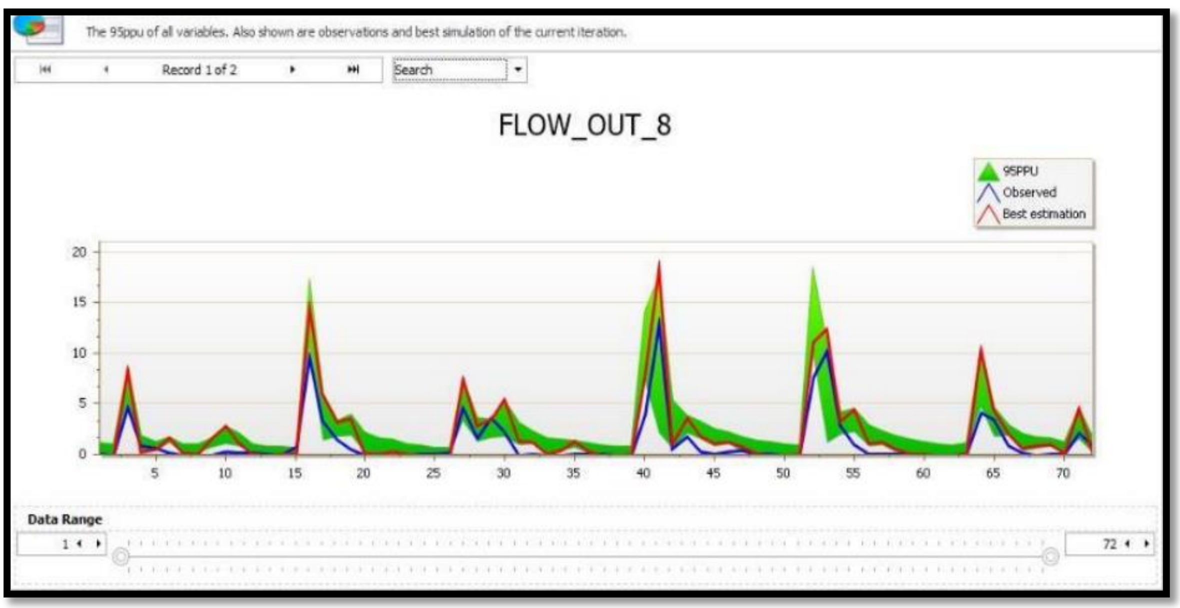

Figure 5.2: 95ppu plot. The green area contains the 95% of predictive uncertainty corresponding to the behavioural parameter sets. The blue line represents observed flow data, while the red line shows the best simulation of the current iteration.

To measure the fit quantitatively, the most widely used statistic for calibration of two signals is the r^2 coefficient. In this case an r^2 of 0.92 was achieved. However, when outputs are expressed as uncertainty bands, as in most uncertainty procedures, the traditional r^2 method should not be used to assume a good fit between observed and simulated data (Arnold et al., 2012). Instead, the aforementioned p- and r-factors are used together to indicate the strength of the model calibration. As mentioned in section 3.8, we chose to use SUFI-2 (Sequential Uncertainty Fitting - Version 2) for our calibration uncertainty procedure. SUFI-2 operates by performing several iterations, ideally less than 5, where in each iteration, the parameter ranges get smaller, thus producing better results in the next iteration. As the parameter ranges become narrower, the 95PPU envelop gets smaller, leading to a smaller p-factor and smaller r-factor. Initially, SUFI-2 begins by assuming a large parameter uncertainty, within a physically meaningful range as per the parameter ranges we adopted from similar studies. In this way, the initial iteration falls within the 95PPU, then with each following iteration, the previous parameter ranges are updated by calculating the sensitivity matrix, followed by the calculation of the covariance matrix, 95% confidence intervals of the parameters, and correlation matrix (Abbaspour, 2008). The parameter ranges are then updated so that the new ranges are smaller than the previous ranges so as to provide the best simulation (Abbaspour 2005, 2008). Due to the limitations in our data accuracy, the best iteration in our calibration achieved a p-factor and r-factor of 0.5 and 0.4 respectively, where a p-factor should ideally have a value of 1, indicating 100% bracketing of the measured data, and an r-factor near zero. However, as reflected by our high r^2 value illustrated by the visual representation of the calibration of our model (Fig 5.2), there is still a strong correlation between the observed and simulated signals. Hence, although our model cannot be used to quantitatively measure changes in discharge levels, the correlation that exists between the observed and the simulated discharge, as indicated by our high r^2 value, gives us confidence in predicting an overall trend in discharge in a changing climate. Similar to the linear regression approach used to determine stream temperature, the correlation that exists between the air and stream temperature is sufficient in providing researchers the confidence in determining an overall trend which is used to classify a streams temperature regime. Upon examining the results of our modelled discharge of the Slate River across the various climate scenarios over both time series, there was a slight decrease in average discharge at mid century (Fig. 5.3a) and a much more pronounced decrease at the end of the century (Fig. 5.3b).

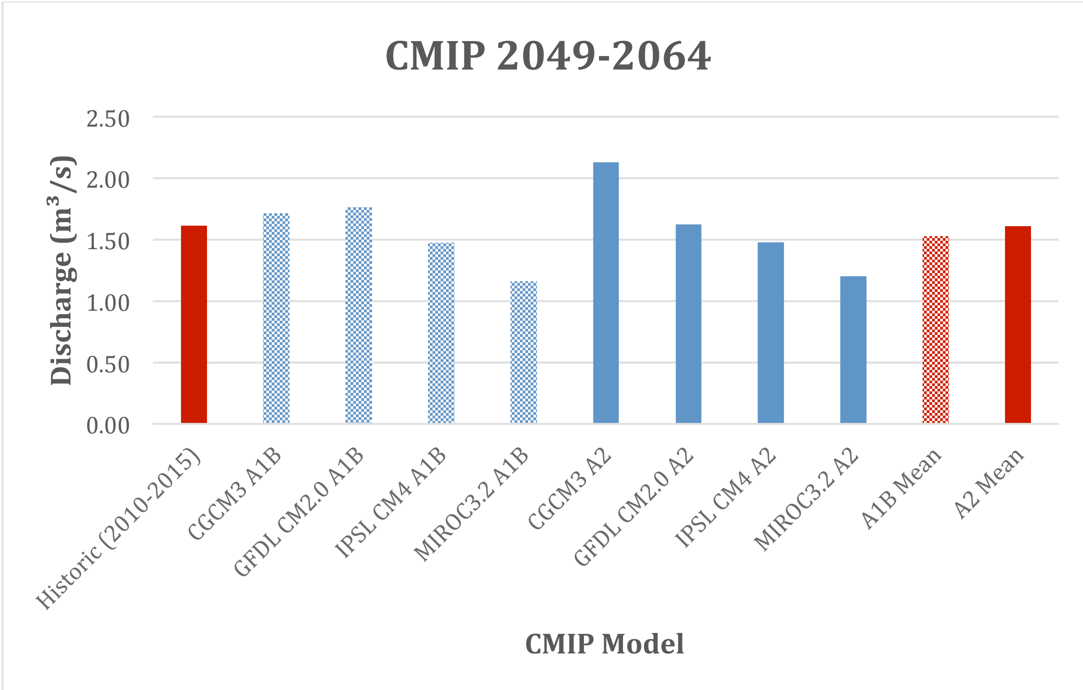

Figure 5.3a: Average discharge from the outlet of the Slate River in cubic metres/second projected at mid-century. The first bar represents the historic average discharge (2010-2015). The faded bars represent the average discharge for each A1B scenario. The following solid bars represents the average discharge for each A2 scenario. The last two bars show the mean discharge for all A1B and A2 scenarios respectively.

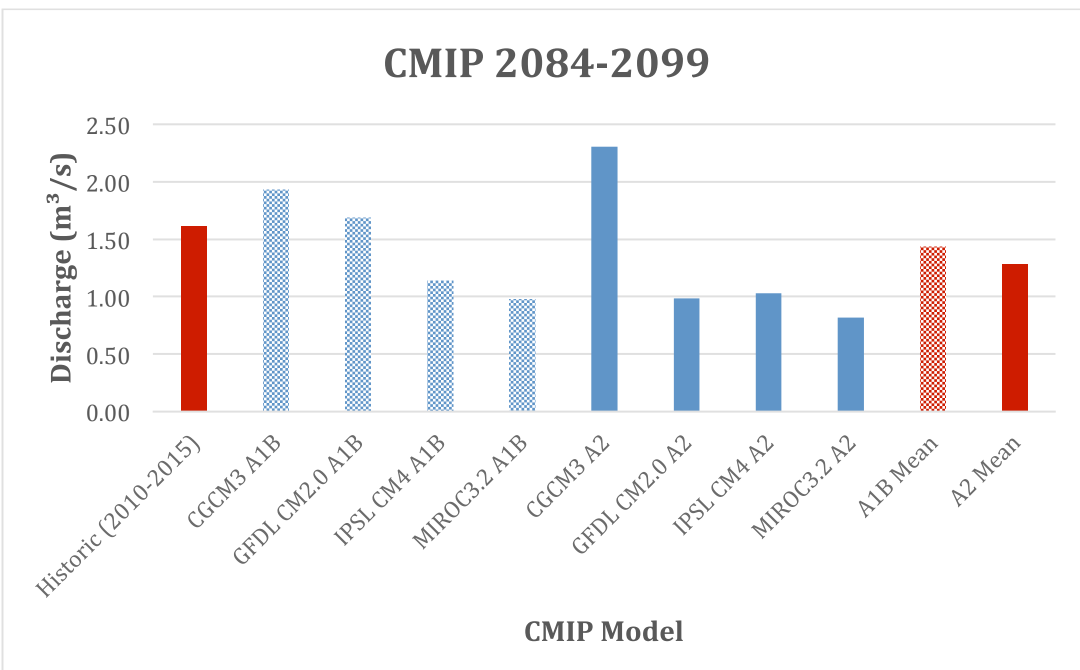

Figure 5.3b: Average discharge from the outlet of the Slate River in cubic metres/second projected at the end of the century. The first bar represents the historic average discharge (2010-2015). The faded bars represent the average discharge for each A1B scenario. The following solid bars represents the average discharge for each A2 scenario. The last two bars show the mean discharge for all A1B and A2 scenarios respectively.

5.3 Climate Model Analysis

To understand what driving variables are affecting the future discharge rates of the Slate River, the most influential model inputs (temperature and precipitation) should be examined. The climate models showed a clear increase in total precipitation in both climate scenarios at the mid-century (Fig. 5.4a) and at the end of the century (Fig. 5.4b). Yet our hydrologic model showed a decline in the average discharge of the Slate River, which means there must have been significant temperature increases projected at mid-century (Fig. 5.5a) and at the end of the century (Fig. 5.5b) as well. Such evidence suggests that the overall discharge from the outlet of the Slate River will likely continue to decrease in the future, despite the regional increase in total precipitation. Previous studies that utilized CMIP models to predict the impacts of climate change on natural phenomena within the Boreal Shield East region demonstrate, from modelled outputs, that increases in precipitation and relative humidity are generally outweighed by the drying effect of increasing temperatures (Baidoc and Cornwell, 2016; Wang et al., 2015; Bergeron et al., 2004). The regional climate model outputs suggest that an increase in average maximum temperatures without a proportionate increase in precipitation would increase the frequency and severity of drought in the Slate River Valley region due to increased evapotranspiration.

In addition to increased drying, the incidence of extreme weather events and variation in weather are expected to increase (IPCC 2014; Knapp et al., 2008; Colombo et al., 1998). The complexity, interactions, and scope of GCM models have made it difficult to predict changes in regional precipitation patterns as most GCMs agree on a modest rainfall increase on a global scale but disagree on the magnitude of change at regional or local scales (Knapp et al., 2008). However, CMIP projections within North America and Europe have been consistent for predicting intensified intra-annual precipitation regimes through larger individual precipitation events interspersed between infrequent precipitation events (IPCC, 2014; Ross et al., 2012; Knapp et al., 2008; Weltzin et al., 2003). This might explain the increase in total precipitation the Slate River Valley is expected to receive as projected by the CMIP models. This can have drastic impacts, especially on mesic environments that characterize most of Ontario, where ambient rainfall regimes characterized by numerous intermediate and small rain inputs are necessary to maintain natural hydrologic processes and keep soil water levels above drought stress levels (Knapp et al., 2008).

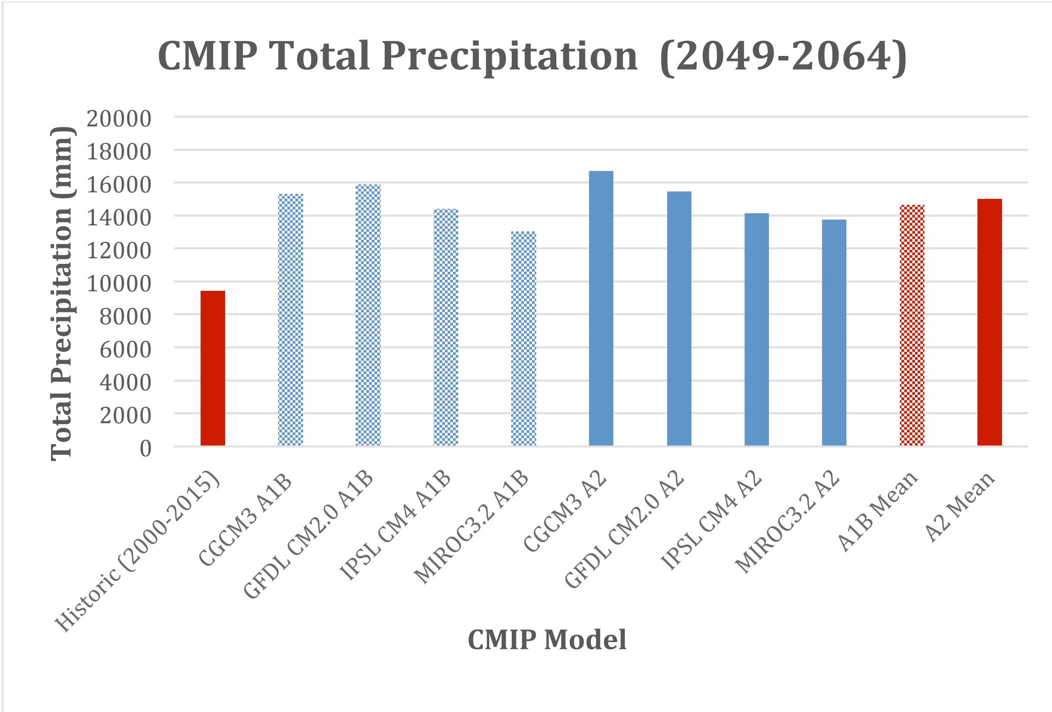

Figure 5.4a: Total precipitation received by the Slate River Valley watershed projected at mid-century. The first bar represents the historic total precipitation (2000-2015). The faded bars represent the total precipitation for each A1B scenario. The following solid bars represents the total precipitation for each A2 scenario. The last two bars show the mean total precipitation for all A1B and A2 scenarios respectively.

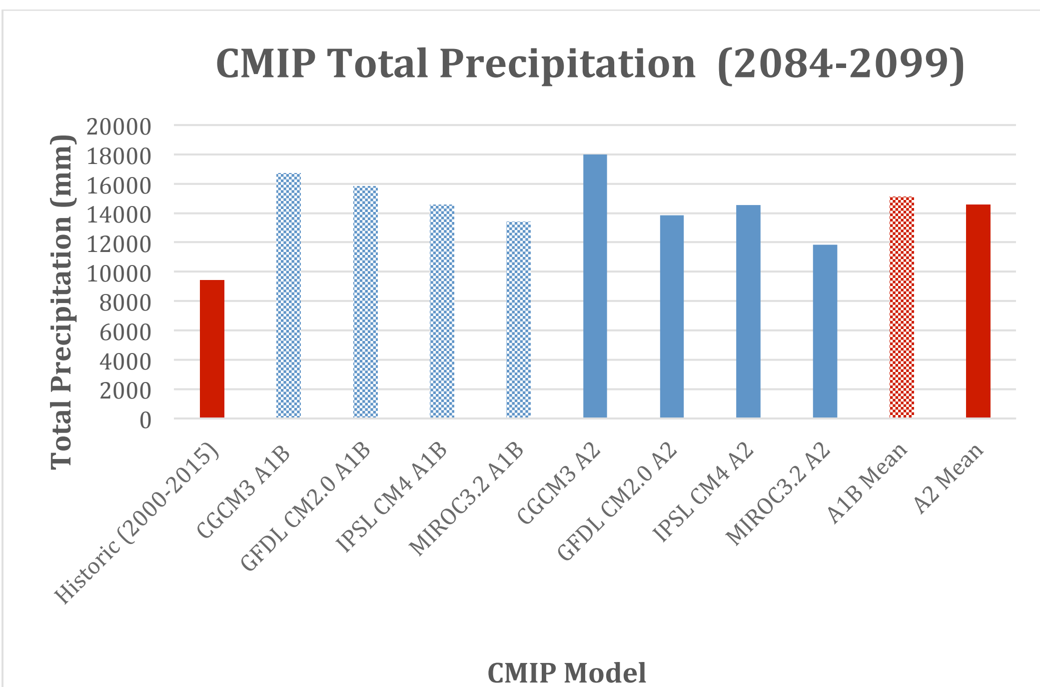

Figure 5.4b: Total precipitation received by the Slate River Valley watershed projected at the end of the century. The first bar represents the historic total precipitation (2000-2015). The faded bars represent the total precipitation for each A1B scenario. The following solid bars represents the total precipitation for each A2 scenario. The last two bars show the mean total precipitation for all A1B and A2 scenarios respectively.

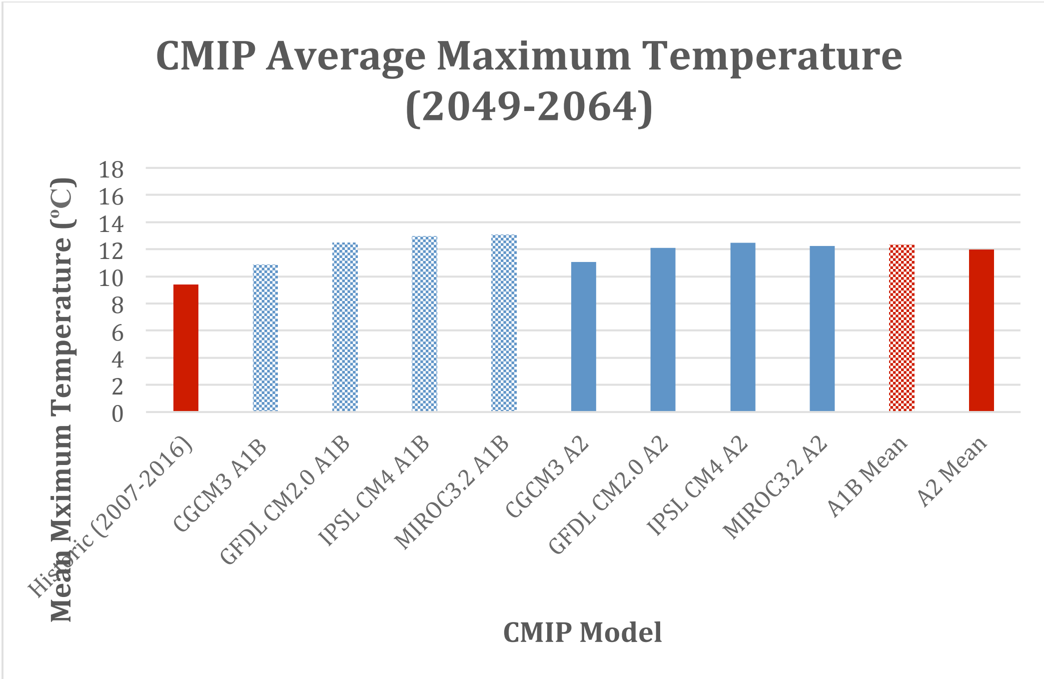

Figure 5.5a: Average maximum temperature for the Slate River Valley watershed projected at mid-century. The first bar represents the historic average maximum temperature (2007-2016). The faded bars represent the average maximum temperature for each A1B scenario. The following solid bars represents the average maximum temperature for each A2 scenario. The last two bars show the average maximum temperature for all A1B and A2 scenarios respectively.

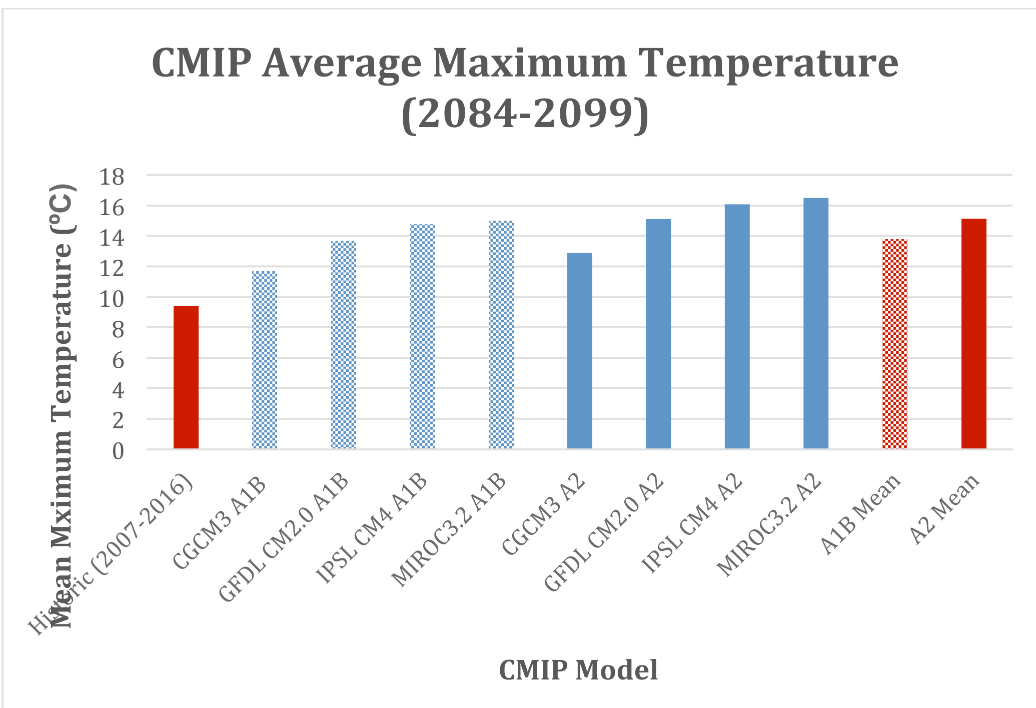

Figure 5.5b: Average maximum temperature for the Slate River Valley watershed projected at the end of the century. The first bar represents the historic average maximum temperature (2007-2016). The faded bars represent the average maximum temperature for each A1B scenario. The following solid bars represents the average maximum temperature for each A2 scenario. The last two bars show the average maximum temperature for all A1B and A2 scenarios respectively.

5.4 Ecological Consequences of Extreme Precipitation Patterns

Prolonged drought periods between precipitation events is expected to increase the length and occurrence of drought stress in the study region and uniquely modify hydrological and ecological processes that are dependent on ambient rainfall regimes (Zhang et al., 2013; Ross et al., 2012; Knapp et al., 2008). The severity of the consequences of changes in the temporal pattern of delivery of rainfall is dependent on soil water retention properties and ecosystem type, not just total annual rainfall amounts (Ross et al., 2012). If we are expecting longer drought periods, this will have a substantial effect on soil moisture levels during the summer, where evaporation and transpiration remove nearly all water from the shallow soil layers within days of rainfall. Hence, in the absence of rapid drainage through macropores, water does not infiltrate deeply into the soil profile where it may be stored (Weltzin et al., 2003). On the other hand, the infrequent occurrence of short-term heavy rain events will be unlikely to recover soil moisture deficits. For instance, soil drainage has a great influence on how the available moisture is distributed. For every 10 mm of rain, more than 50% infiltrates the soil (the rest is lost to runoff and evaporation) and if the amount of rain per rainfall increases, the proportion of infiltration increases (Colombo et al., 1998). Although the soil may be abundantly supplied with water, it may not have the capacity to retain it; this is especially the case in northwestern Ontario, where soils are shallow and stony, being more prone to water deficit (Colombo et al., 1998). Soil texture largely affects soil water regimes as coarse soils increase soil hydraulic conductivity (the rate of water movement in a soil).

Although organic matter significantly improves soil water retention by reducing hydraulic conductivity, the organic layer covering most soils in northwestern Ontario is typically thin (Colombo et al., 1998). Beneath the thin organic layer, the common surficial soil characteristics of the Slate River Valley are predominately lacustrine clay or silt deposits or a relatively thin layer of clay loam or sandy loam above heavy clay deposits, hence why most of the agricultural activity in the more productive parts of the region revolves around pasture land, having shallow root depths (LRCA, 2008). The relatively low water retention capabilities of the typical soil regimes in the Slate River Valley region, combined with prolonged drought periods, indicates the potential for future moisture deficit stress on the region. In context of the Slate River being surrounded by clay, silt, and stony glacial till, longer dry periods could potentially lead to hydrophobic surficial soil, further exacerbating the runoff load of already poorly drained soils during extreme rain events, subsequently increasing flood potential.

CHAPTER 6
SUMMARY AND RECOMMENDATIONS

6.1 Hydrologic Model Limitations and Steps for Improvement

Runoff models are essentially a set of equations that provide an estimation of runoff as a function of various parameters used for describing watershed characteristics. Hydrologic models may vary based on model input data, parameters, and the extent of physical principles applied in the model (Devia et al., 2015). The most popular hydrologic models currently used are characterized as either being conceptual or physically based. The predominant conceptual models include the HBV model and TOPMODEL. The HBV model is a semi-distributed conceptual model that is run on daily values of rainfall and temperature and monthly estimates of potential evapotranspiration (Zhang and Lindström, 1997). Although the structure of the HBV model is very robust and surprisingly applicable to a wide range of hydrologic modelling scenarios, the model has shown several physical inconsistencies such as a lack of an interception routine and the lack of an elevation correction of evapotranspiration, making this model questionable when being used for climate impact studies (Lindström et al., 1997).

The widespread availability of digital elevation models (DEM) and the integration of hydrologic modelling with geographic information software, have allowed for the creation of user-friendly models such as TOPMODEL and SWAT, which can derive the topographic index of a catchment from DEM data. TOPMODEL is not a single model structure, but more a set of conceptual tools that can be used to simulate hydrological processes in a relatively simple way (Beven, 1997). Because the TOPMODEL rainfall-runoff modeling at the catchment outlet is made based on the theory of hydrological similarity of points in a catchment, this model, as with most conceptual models, is restricted to modelling hydrologic fluxes (event-based) and cannot be used for long-term rainfall-runoff modelling (Nourani et al., 2011). In contrast, SWAT – a continuous physically-based model – is efficient in performing long-term simulations in predominantly agricultural watersheds. Unlike conceptual models, physically-based models such as SWAT do not consider the transfer of water in a catchment to occur in a few defined storage points; rather, physically-based models can simulate the complete runoff regime, providing multiple outputs (e.g. river discharge and evaporation loss) while conceptual (black box) models can offer only one output (Devia et al., 2015). As mentioned, the SWAT model can utilize features of geographic information systems, which allows the possibility of rapidly combining data of different types from different sources. The integration of GIS into SWAT allows for basin characteristics to be derived from a DEM and thus hydrology modelling of large-scale catchments is feasible.

Physically-based models such as SWAT offer a user-friendly application interface, as well as having the ability to rapidly capture idealized hydrologic processes that can produce relatively accurate catchment responses using physically based equations. However, the prediction accuracy of physically-based models depends on how well model input spatial parameters describe the characteristics of the watershed (Geza and McCray, 2008). For instance, soil data remains one of the key inputs for most hydrologic models, as the resolution and comprehensiveness of soil physiochemical information is crucial to accurately represent catchment responses to hydrologic processes (Chen et al., 2016). Varying soil types allows the model to consider high rates of water infiltration, producing less runoff, or, in the case of of poorly drained clay soils, a low infiltration rate that produces more runoff (Geza and McCray, 2008). The SWAT model expresses soil data as attribute layers in a GIS format, dividing each soil layer into varying percentages of clay, silt, sand, and rock, hence surficial soil data on its own cannot accurately capture underlying hydrological processes. The scale of mapped soil and topographic data is another concern. Detailed, high resolution soil maps are often costly and difficult to obtain; hence researchers often rely on small scale maps such as the FAO's Harmonized World Soil Database (1: 5,000,000) in data poor regions. Such soil maps attempt to dissect soil boundary units into regions of homogeneity, however at such a scale there remains a lot of heterogeneity within soil units, which may affect interpretation or modelling depending on the size of the modelled catchment (Geza and McCray, 2008).

Since the need to precisely describe the characteristics of a landscape is well-known in mathematical modeling, and the fact that the preparation of high-resolution soil data is especially difficult to obtain due to the numerous samplings and laboratory analysis required, several studies have investigated the extent to which the resolution of soil and terrain data can be reduced whilst quantifying the impacts related to data resolution (Chen et al., 2016). Although most studies acknowledge the importance of data input resolution on model predictions, the extent to which the effect of soil and terrain data resolutions impact stream flow predictions varies depending on specific soil and climate conditions, as well as the scale of modelling applications (Geza and McCray, 2008). Chaplot (2005) investigated the impact of DEM mesh size and soil map scale on SWAT runoff modelling. Their study focused on a watershed in central Iowa, using soil map scales of 1/25,000, 1/250,000, and 1/500,000, along with varying DEM mesh sizes from 20 to 500 m. The results indicated a threshold in DEM size of 50 m was optimal for accurately simulating watershed runoff and sediment loads, where finer resolutions beyond this threshold did not have a significant impact on the modelled results. Yet whatever mesh size DEM was considered, a detailed soil map was imperative to accurately estimate runoff loads. The finer resolution soil maps proved to be crucial in the modelling, as greater precision in soil variations and soil properties provided greater estimation in soil-affected processes, which is crucial in areas of lower relief, where DEM resolution is much less influential to the accuracy of the model (Chaplot, 2005). According to Chaplot (2014), the DEM is the most significant input parameter for runoff in watersheds that receive a mean annual precipitation of ≥1200 mm/yr. Climates that have a lower average annual precipitation, such as Thunder Bay (717 mm/yr), still produced accurate runoff estimates with a coarser DEM. Soil map resolution continued to be essential, especially in watersheds with smooth topography (<3% mean slope gradient), as in the case of the Slate River Valley. A greater sensitivity to soil map resolution in low relief environments is likely due to a greater proportion of water moving through the soil layer than under steep slopes (Chaplot, 2014). In regards to the land-use data layer, Chaplot (2005) showed that water and sediment load estimates in central Iowa were little affected by the resolution of the land-use map, as variations in crop-type or forest stands between low and high resolution were slight, but lower soil map resolution greatly degraded the prediction quality.

This confirmed our initial supposition that soil map resolution would be the bottleneck in terms of modelling accuracy. The fastest and most effective way to improve our model would be to acquire soil data that has more accurate estimates for the basic units for describing various soil properties; the percentages of sand, silt, and clay, and ideally, hydraulic conductivity as well as bulk density. Knowing the percentage of clay soils in relation to sand or silt loam, will produce much more accurate results when predicting runoff amounts, especially if hydraulic conductivity and bulk density is also known, the margin of error would be greatly improved. Aside from comprehensive and accurate soil map data, a DEM resolution of 30 m that is acquirable from provincial government data is more than adequate to accurately capture surface runoff processes in a relatively low relief area such as the Slate River Valley. Similarly, land use data resolution of 30 m that is again obtainable from provincial data sources such as FRI data, can accurately represent variations in crop-type or forest stands within the scale of our study.

6.2 Potential Implications of Climate Change on the Slate River Watershed

While global climate models provide realistic predictions of mean changes in climate over long periods of time, their skill in forecasting extreme events is low (Harrison et al., 2016). That is why any analyses using climate models should not rely solely on future climate scenarios forecasting changing means, but anticipate changes in inter-annual climate variability, which is important because agricultural systems in particular are exponentially sensitive to increasing frequencies of extreme climate events (Harrison et al., 2016; Mukundan et al., 2013).

As with any study, this present paper has limitations, in this case with regards to the lack of accurate subsurface soil data which hindered the accuracy of our hydrologic model. Yet given our knowledge of the surficial soil data of the region, we can still consider, to some degree, the potential implications of climate change impacts on the Slate River Watershed. Of particular concern are the effects on prolonged drought periods and more frequent extreme climate events. For instance, considering our environment and the general soil characteristics of the Slate River region, precipitation patterns should generally follow an ambient rainfall regime characterized by numerous intermediate and small rain inputs. This would maintain adequate moisture levels in the soils of mesic environments, thus maintaining natural ecological processes and hydrologic flow regimes, as well as preventing excessive erosion (Colombo et al., 1998). Considering the long-term effects of climate change on the Slate River, a decrease in total stream discharge due to longer dry periods, would decrease soil moisture within the soil profile and likely increase rates of erosion, subsequently increasing sediment yields in the Slate River (Harrison et al., 2016; Muku). Climate change impacts we are likely to see in the short-term because of extreme climate events include more frequent heavy down-pours; this will increase flooding risk as well as further exacerbating rates of erosion along the banks of the Slate River, subsequently increasing sediment loading into the river as well as elevating nutrient runoff loads in the summer (Falloon and Betts, 2010).

Besides the direct ecological consequences of increased rates of erosion on fluvial systems, soil erosion poses a serious issue on farming systems as well, as it is often blamed for the drastic reduction of soil fertility. Gradual erosion has substantially less of an effect on crop productivity than the sudden removal of a significant proportion of the top soil, which is commonly triggered by extreme climatic events (Valentin et al., 2005). A study by Harrison et al. (2016) on the effects of regional climate change on pasture-based dairy production systems showed that the combination of more extreme rainfall events, increased drought severity, and more intense heat-waves translated into lower soil water availability and higher evapotranspiration, which together reduced mean pasture growth rates and annual yields. There are generally fewer studies on the impact of changing climatic extremes on agriculture, especially concerning changes in extreme rainfall and flooding, yet studies that investigate impacts such as increases in heat waves and drought agree that increased yield variability and reduced yields are likely to be the consequences (Falloon and Betts, 2010; Harrison et al., 2016). Changing water management practices to adapt to increasing drought stress and improving riparian boundary management to create buffer zones that prevent nutrient losses to surface water and decrease rates of erosion, as well as increasing soil organic matter in agricultural soils to improve their water holding capacity, are potential mitigation and adaptation options to climate change (Falloon et al., 2004). According to the 2011 census, there are approximately 240 farms in Thunder Bay, and 41% of these farms are either in the dairy cattle, beef cattle, hog/pig, sheep/goat, or ‘other’ livestock farming industry. The Slate River Dairy is one example of many successful dairy farms in the Slate River Valley; dairy being the main commodity. Considering dairy and livestock production are the major industries in the Thunder Bay region, riparian boundary management as well as the management of grazing techniques that limit livestock impact on particularly vulnerable landscapes are essential for ensuring the integrity of the Slate River watershed.

As per the 2014 Slate River Watershed Management Plan Review conducted by the Lakehead Region Conservation Authority, the LRCA deemed that further efforts focused on reducing nutrient runoff concentrations into the Slate River were not warranted at the time of review, and that conservation efforts would be geared towards the monitoring of nutrient and *E. coli* levels, as well as assessing and monitoring potential high risk areas of erosion, under the assumption that adequate funding for monitoring programs is maintained. It is critical that the LRCA continues to take steps to ensure that nutrients levels and sites prone to erosion in the Slate River are routinely monitored, especially after extreme climatic events such as flooding of the river. However, there is also room for proactive steps to be taken towards mitigating climate impacts on our ecological resources. As previously mentioned, vegetative cover from riparian zones are effective at mitigating nutrient runoff into surface waters as well as stabilizing sloped banks from erosion, however, according to the Great Lakes Remedial Actions Plans (RAPs) there is a lack of 30-metre-wide riparian buffer zones along first to third order streams within the Slate River watershed. Increasing vegetative cover and widening riparian zones would be a good step forward for conservation efforts to maintain natural hydrological and ecological characteristics of the Slate River. Not only would riparian management mitigate exceedances in nutrient runoff, and sedimentation, increasing treed canopy for shading would decrease solar radiation inputs into the Slate River, the primary influence of increasing stream temperatures and evaporation. Since the current riparian canopy provides less than 25% shading along the Slate River, solar radiation continues to be a major determinant of future warming of the Slate River, subsequently influencing overall flow levels. The 2014 review of the Slate River Watershed mentions disruptions in the flow of the Slate River in recent years, which has been correlated with low water conditions observed throughout the region. Previous years in the region have documented water stress during unusually dry summer months, leading to news releases asking the public to reduce water consumption by 20 percent, especially in rural areas (LRCA, 2008). Considering the implications of changing climate regimes on future discharge levels of the Slate River, including the possibility of prolonged drought periods becoming more common during the summer months, we may expect more water stress events throughout the Slate River region, implicating residents and agricultural productions sites.

6.3 Conclusion

In this study, we attempted to apply a popular physically-based watershed modelling tool that was parametrized according to characteristics of the Canadian Shield, in the hopes of accurately simulating hydrologic flow processes within the Slate River Watershed of Thunder Bay, Ontario. The objectives of this study were to understand the capabilities and limitations of using the SWAT model in an agricultural catchment using the most accurate available data sources, including high resolution terrain and land use/land classification data, while settling for low resolution yet comprehensive soil data from the FAO's world soils database. We then selected four popular CMIP models from which we acquired climate projections that were forced into our hydrologic model to understand how flow hydrology would change in different climate emission scenarios. Results indicated an average decline in discharge amongst the various CMIP models in both climate scenarios at middle and end of the century. The high r^2 coefficient we achieved in the calibration of our model indicated a strong correlation between observed and simulated flow data, which gave us confidence in the overall trend projected by our model. However, the lack of accurate subsurface soil data prevented us from using the hydrology model to quantify changes in discharge levels with high confidence. The most effective way to improve our model would be to acquire essential subsurface soil data from each subbasin in the Slate River watershed including the percentages of sand, silt, and clay and, ideally, hydraulic conductivity as well as bulk density. Other model improvements, including addressing model uncertainties would be facilitated through more research geared towards SWAT applications in Canada, particularly on the Canadian Shield. Presently only a handful of studies (Fu et al., 2014; Troin and Caya, 2014; Gautam, 2012) have attempted the parametrization of SWAT to accurately reflect hydrologic and soil physiochemical characteristics of the Canadian Shield. Although physically-based hydrology models such as SWAT have become popular in recent years for climate change analysis studies, (Abbaspour et al., 2009; Marshall and Randhir, 2008; Ficklin et al., 2012; Franczyk and Chang, 2009; Jha et al., 2004; Pai et al., 2012), as general and regional climate models continue to become more refined the real issue is the availability of high resolution model input data, which is especially important in small and medium scale catchement modelling. In northern Ontario partiularly, there is a deficit of high resolution soil data, making it inherently more difficult to apply a physically-based model that can accurately quantify hydrologic responses to climate change. It is in the hopes that this current study, together with previous SWAT-related studies performed on the Canadian Shield, will motivate future research to address the lack of accurate subsurface soil data along with various modelling uncertainties (i.e. input, parameter, conceptual) which are more prevalent in the Canadian Shield region. Such studies are important in assisting watershed managment in northern communities such as Thunder Bay.

As the impacts of climate change in Canada become more apparent in the coming years, it is essential that research continues to attempt to predict and quantify climatic impacts so that water management and ecological conservation efforts can be pragmatic and directed towards the most at-risk areas in our region. The impacts associated with climate change will only increase in magnitude going into the future, hence proactive and adaptive management strategies collaborated through integrated catchment management is necessary to preserve the ecological, economic, and social resilience of northern communities in Ontario. Optimizing future catchment management practices requires an understanding of the potential consequences of climate change that can only be obtained by modelling climatic influences on ecological systems.

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