GRAND RIVER WATERSHED
Water Management Plan

Grand River Watershed Water Management Plan

Climate Change Scenario Modeling

Prepared by Stephanie Shifflett

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Acronyms and Abbreviations

ET	Evapotranspiration
GAWSER	Guelph All-Weather Sequential-Events Runoff model
GCM	Global Circulation Model
GW	Groundwater
GRCA	Grand River Conservation Authority
IPCC	Intergovernmental Panel on Climate Change
MNRF	Ministry of Natural Resources and Forestry
RCM	Regional Climate Model
ZUMS	Zones of Uniform Meteorology
DWSP	Drinking Water Source Protection Program

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Preface

The Climate Change Modeling Project was initiated in 2011 under both the Water Budget Program and as part of the Water Management Plan Update. Within the Water Management Plan Update the results of climate change modeling are being used to provide guidance on building resiliency in the watershed to deal with climate change by detailing possible hydrologic effects of climate change in the Grand River Watershed.

Climate change is an evolving science with many knowledge gaps. A significant limitation for hydrologic modeling is that climate models are at too large of a scale to model local weather patterns including storm events. In this study, model output was adapted to analyse average climate conditions with existing weather patterns. Research continues on methods to adapt model output for storm events, but these methods were not available for this study. As such, this study is focused on average conditions, water budgets and low flow augmentation. The effect of climate change on flooding, intense storm events or the frequency and severity of drought are not included in this study and are recommended for future studies regarding climate change.

Executive Summary

The Climate Change Modeling Project was initiated in 2011 under the Water Budget Program and as part of the Water Management Plan Update. Within the Water Management Plan Update, the results of climate change modeling are being used to provide guidance on building resiliency in the watershed to deal with a changing climate by detailing possible hydrologic effects of climate change in the Grand River watershed.

The Climate Change Modeling Project focused on using future climate data sets with established watershed models to study the effects of a changing climate on different aspects of water management within the Grand River watershed. This project built on past work completed under the Source Water Protection Program, earlier climate change modeling completed by the Grand River Conservation Authority (GRCA) in 2000 and reservoir yield modeling completed as part of the Water Management Plan update.

Limitations and Uncertainty

Climate change is an evolving science with many knowledge gaps. An understanding of the limitations of climate model output is needed to understand the uncertainty involved in its use. A significant limitation for hydrologic modeling is that climate models are at too large of a scale to model local weather patterns including storm events. In this study, model output was adapted to analyse average climate conditions with existing weather patterns. Research continues on methods to adapt model output for storm events, but these methods were not available for this study.

With little information available on changes to intensity and frequency of storm events, this study is focused on changes to water budget parameters, seasonal low flows and general watershed processes. Based on the information available, changes to flood events, intense storms and frequency of drought were not included.

Climate Data Sets

The Ministry of Natural Resources and Forestry provided future climate data for 76 different climate change scenarios based on 28 global climate models (GCM) and 3 emission scenarios. The data sets were made using the change field approach, where monthly relative changes for precipitation and temperature are calculated from the global climate models and applied to existing climate data (baseline data). The 1960 to 1990 baseline data set was chosen to include both periods of drought (1960s) and high precipitation (1970s) while the 2050s was chosen for the future period to coincide with the planning horizon of the water management plan.

The original 10 scenarios were chosen using the percentile method as described in EBNFLOW & AquaResource (2010). The percentile method chooses scenarios based on the average annual change field values for precipitation and temperature separately. Further analysis of the scenarios, by categorising scenarios on a seasonal basis, showed that two additional scenarios should be included to ensure the majority of seasonal effects were accounted for. With these additional scenarios close to 80% of the 76 future climate scenarios were covered, although a few extreme scenarios were still not represented.

The seasonal analysis categorized scenarios by looking at the relative change in both precipitation and temperature over a three month period. The category characterised as having a small increase in precipitation with a moderate increase in temperature represented the most scenarios across all seasons. This category dominated the winter season. The other three seasons also have a large number of scenarios classified as no increase in precipitation with a moderate increase in temperature. The summer season has almost 20% of scenarios with a small decrease in precipitation with a moderate increase in temperature.

Models

Two coupled numerical models were used to estimate hydrologic response and stream flow. The Grand River Tier 3 surface water model was used to estimate runoff, recharge, evapotranspiration and stream flow. A Linacre ET routine and a frozen ground infiltration routine were incorporated into the model to allow for changes to ET and infiltration rates based on temperature. The Tier 2 groundwater flow model was run in steady state using average annual recharge from the surface water model. The groundwater flow model is used to estimate groundwater discharge to surface water, groundwater flow between sub-basins and groundwater flow into and out of the watershed or model boundaries. Additional transient groundwater modeling is planned for this project, but has not been completed to date.

The Grand River Reservoir Yield model was used to simulate reservoir operations in a changed climate. The reservoir yield model includes the three largest watershed reservoirs: Shand Dam, Conestogo Dam and Guelph Dam. Operational flow targets are assigned to reservoir discharges and four downstream target locations. RY modelling used the current operating procedures with future estimated stream flows by using output from the GAWSER model to modify stream flow inputs. The model is primarily a tool for investigating flow augmentation reliability and not for determining flood storage requirements.

General Results

Annual changes to precipitation and temperature had an impact on water budget parameters at the extreme end of the range, but monthly or seasonal climate changes effected parameters regardless of the overall annual changes. The majority of changes to hydrologic parameters were within 15% of baseline values on an average annual basis.

Winter was most affected by changes in temperature and all available scenarios predict an increase in winter temperature. There was also a strong trend to higher winter precipitation. The combination of increased temperature and precipitation will lead to more winter runoff and stream flow. Recharge will also increase during the winter because of a greater availability of water and a decrease in frozen ground. Higher temperatures will also decrease the stability of the snow pack with a higher number of melt events and more precipitation falling as rain rather than snow.

The spring season was affected by changes to the winter season with a shift in spring runoff and recharge moving to the winter season because of increased winter temperatures. This shift could result in the traditional spring freshet being less significant because of a reduced snowpack. Trends show an increase in precipitation in the early spring with a drop by late spring resulting in the summer low stream flow season shifting into the spring.

Summer was affected by changes to precipitation more than temperature changes. Decreased or little change in precipitation resulted in decreased summer stream flow, while large increases in summer precipitation resulted in increased stream flow. Summer scenarios are split with about 40% predicting a decrease, 30% predicting an increase and 30% predicting little change to precipitation. This results in 70% of scenarios with decreased stream flow. Evapotranspiration dropped in the summer in many cases because of a lack of water available with decreased precipitation. The summer low flow season was extended with an earlier start and later end.

The fall period was variable. There was a weak trend towards the low flow season extending into October. There was an increase in evapotranspiration in the fall months and a decrease in runoff and recharge. December results were variable, but showed an increase in runoff and recharge. Two additional scenarios were run to cover higher fall rainfall scenarios. Results from the additional scenarios were mixed. For the fall period, monthly changes seem more important than seasonal changes. Generally, the fall period has a wide range of variability both in the future climates predicted and in the hydrologic response to these changes.

Water Budget and Stress Assessment

An annual water budget was calculated for each scenario similar to the Tier 2 Integrated Water Budget (AquaResource Inc. 2009a). Most of the parameters were close to those in the baseline water budget. Recharge was the most affected groundwater parameter, while runoff was affected the most out of surface water parameters. Results showed an almost direct correlation between change in parameters and the change in precipitation.

A Tier 2 Stress Assessment for current water demand was also calculated for each scenario using water demand values from the Tier 2 Stress Assessment (AquaResource Inc. 2009b). Drought conditions were not evaluated. The groundwater stress assessment did not change with climate change scenarios, except for one scenario for the most southern sub-basin. Changes to the surface water stress assessment included five sub-basins with higher potential stress levels for three to nine scenarios. No additional municipal systems were flagged as requiring more study because of the climate change scenarios.

Reservoir Operations

These results show that there will most likely be a greater need for summer and fall flow augmentation in the future. This will be especially important with raising temperatures that can further affect water quality and increase evaporative loses. It will be important that the reservoirs are filled during the spring period so that they can continue to provide augmentation. With more mid-winter melts, there is a greater need to capture and store melt-water as it becomes available, but this needs to be balanced with maintaining required flood storage for protection of downstream communities. Current climate models are predicting more intense storm events which could lead to localized flooding, but the data is not available to analyze how that might affect flood storage needs within the Grand River watershed.

With the great uncertainty in climate change predictions and a lack of information on potential changes to flood storage needed, it is recommended that some flexibility is built into reservoir operations supported by a high degree of monitoring so that operators can react to increasingly variable conditions expected with climate change. The reservoirs will be operated more often and to the more extreme ends of past conditions. The number of flow violations may increase, but the reliability of meeting flow targets will most likely stay at or above 95% reliability based on the climate change scenarios run in this study.

Regional Climate Model Scenario

There are limitations with using GCM output for watershed scale hydrologic modeling, with the biggest limitation being the lack of influence of the Great Lakes. Weather patterns in southern Ontario are greatly affected by the influence of the Great Lakes, but the scale of GCMs excludes them. So changes to weather patterns including lake effect snow, convective storms and lake breeze effects are not included in output from GCMs. Regional Climate Models (RCMs) have the potential to overcome the short falls of GCMs on a local scale. RCMs are localized models that take GCM model output and run it through a more localised model of a smaller area. The RCM models have a finer grid size and can include local landforms and therefore better simulate local weather patterns.

As part of climate change studies in the Grand River watershed the GRCA teamed up with government and University researchers, who provided output from one RCM run. Output was provided in three forms: cleaned up raw 3-hourly, corrected 3-hourly and change fields. Each data set was run through the GAWSER model and the output evaluated. The main result is that the RCM data cannot be used in its raw or corrected form for hydrologic modeling since it does not model current conditions close enough for key hydrologic processes in the watershed. The change field method data set showed the most promising results, but lacks changes to the intensity and frequency of storm events. Change field results were very close the GCM change fields for the same model run.

Summary

There is a lot of uncertainty and variability expected as the climate changes. This study found strong trends for warmer winters, more mid-winter melts and a smaller snow pack. These changes to winter hydrology have already been observed over the past couple of decades. Changes to winter hydrology will affect reservoir filling cycles, seasonal recharge and flood events. Summer trends are a bit weaker, and include similar to less precipitation, lower stream flows and hotter temperatures. The low flow season will start earlier and last longer. The spring and fall seasons have the weakest trends and the most uncertainty.

Climate change is an evolving science. There is no single answer to what the effects will be with a changing climate. A proper understanding of the uncertainty and how it pertains to the questions asked is important in decision making. In light of uncertainty, water managers can prepare for the challenges of a changing climate by building resiliency in the watershed. A healthy, well-managed watershed will be better able to adapt to changing conditions in the future.

1. Introduction

The Grand River Conservation Authority (GRCA) is working with municipalities, the federal and provincial governments, First Nations and others to update the Grand River Water Management Plan. One of the goals of the updated plan is to build resiliency in the watershed to deal with climate change. This report describes methods used to help develop a better understanding of some of the potential impacts of climate change to hydrological parameters. A better understanding of the potential impacts of climate change will help focus plans for building resiliency within the watershed.

1.1. Limitations and Uncertainty in Climate Change Analysis

Climate change is an evolving science with many knowledge gaps. There is confidence in many general predictions including predictions regarding temperature changes, but there is relatively low confidence in specific predictions such as future storm intensity, local weather patterns and frequency of precipitation events. For example, it is very likely that heavy precipitation events will become more frequent along with an increased risk of drought in the future (Bates et. al. 2008), but the exact frequency or intensity of these events is highly uncertain. Likewise, there is uncertainty in how local land forms may affect future weather patterns, since they are too small to include in Global Climate Models. For the Grand River Watershed these include the proximately to the Great Lakes and the Niagara Escarpment, which can affect lake effect snow fall, convective storm events and general storm pathways.

Interpretation of climate model output is another area of uncertainty. Climate models are global scale models that are calibrated to average conditions over an extended time period. The scale of the models makes it difficult to calibrate to local conditions or short time periods. Output from climate models is likewise at a scale and time step much too large for hydrologic modeling. The output from the models must be adapted to be used for watershed scale modeling.

Two methods were used to adapt global climate model output for use at the watershed scale. The main method, the change field method, used in this study relies on using historic weather patterns and projecting them into the future by modifying temperature and the amount of precipitation. This method helps to adapt climate model output to local weather patterns, but it limits analysis of extreme events especially changes to frequency and intensity. The second method used output from a Regional Climate Model in an effort to determine changes to frequency and intensity of precipitation events. The output proved problematic to use resulting in even greater uncertainty and is discussed in detail in Section 5. Some other methods are available to help answer the intensity and frequency question, such as weather generators. These methods have not been used in this study, but it is recommended that they are included in future studies.

With little information available on changes to intensity and frequency of storm events, this study is focused on changes to water budget, low flows and general watershed processes. Based on the information available, changes to flood events, intense storms and frequency of drought were not included.

1.2. Watershed Models

Two coupled numerical models were used to model hydrologic processes in the watershed. The Grand River Tier 3 surface water model has been developed and refined over the last few decades. The model is built using the GAWSER (Guelph All-Weather Sequential-Events Runoff) code and was originally developed for flood forecasting. The current version of the Grand River surface water model was from the Tier 3 water budget program. Improvements in the model from the Tier 2 version include additional climate stations, redefined sub-catchments and a refinement to estimates of impervious surfaces in some of the larger urban areas of the watershed (AquaResource 2009c). The Linacre ET routine and a Frozen Ground Infiltration routine were incorporated for modeling climate change scenarios. These sub-routines were not used in the Tier 2 water budget and allow for changes to ET and infiltration rates based on temperature. The surface water model simulates runoff, recharge, evapotranspiration (ET) and stream flow.

The groundwater flow model used in this study was developed for the Tier 2 water budget (AquaResource 2009a). The Grand River watershed regional groundwater model is a FEFLOW model. The groundwater model was run in steady state using average annual recharge from the surface water model. The groundwater flow model was used to estimate groundwater discharge to surface water, groundwater flow between sub-basins and groundwater flow into and out of the watershed or model boundaries. Further groundwater modeling using transient recharge is planned for the climate change study.

1.3. Climate Change Scenarios

The MNRF provided climate data for 76 different climate change scenarios on their web application (AquaResource and EBNFLOW 2011). The future climate data is based on 28 global climate models and 3 emission scenarios from the Intergovernmental Panel on Climate Change fourth assessment report. Not all global climate models ran all three emissions scenarios. The data sets were made using the change field approach. Monthly relative changes for precipitation and temperature were taken from the global climate models and applied to existing climate data (baseline data). Two sets of baseline data and three future periods were available from the MNRF. For this project, the 1960 to 1990 baseline data set was chosen to include both periods of drought (1960s) and high precipitation (1970s), while the 2050s was chosen for the future period to coincide with the planning horizon of the Water Management Plan. Figure 1–1 shows the range of annual changes to temperature and precipitation for all 76 scenarios.

The percentile method, using annual average change field values, as recommended in the *Guide for the Assessment of Hydrologic Effects of Climate Change in Ontario* (EBNFLOW & AquaResource 2010) was used to select ten scenarios for watershed modeling. The surface water model uses 21 different climate stations for 26 Zones of Uniform Meteorology (ZUMS) as shown on Figure 1–2. A central climate station was chosen to represent the watershed and simplify scenario selection. The Waterloo-Wellington station was selected as the central station since it is central to the watershed and has similar change fields with many of the other climate stations within the Grand River watershed. The percentile method resulted in nine scenarios being selected since Scenario 65 was chosen for both the 75th percentile for temperature and 5th percentile for precipitation. An additional Scenario (58) was included to complete the set of ten modeling scenarios. This scenario balances average temperature increases with a large drop in annual precipitation.

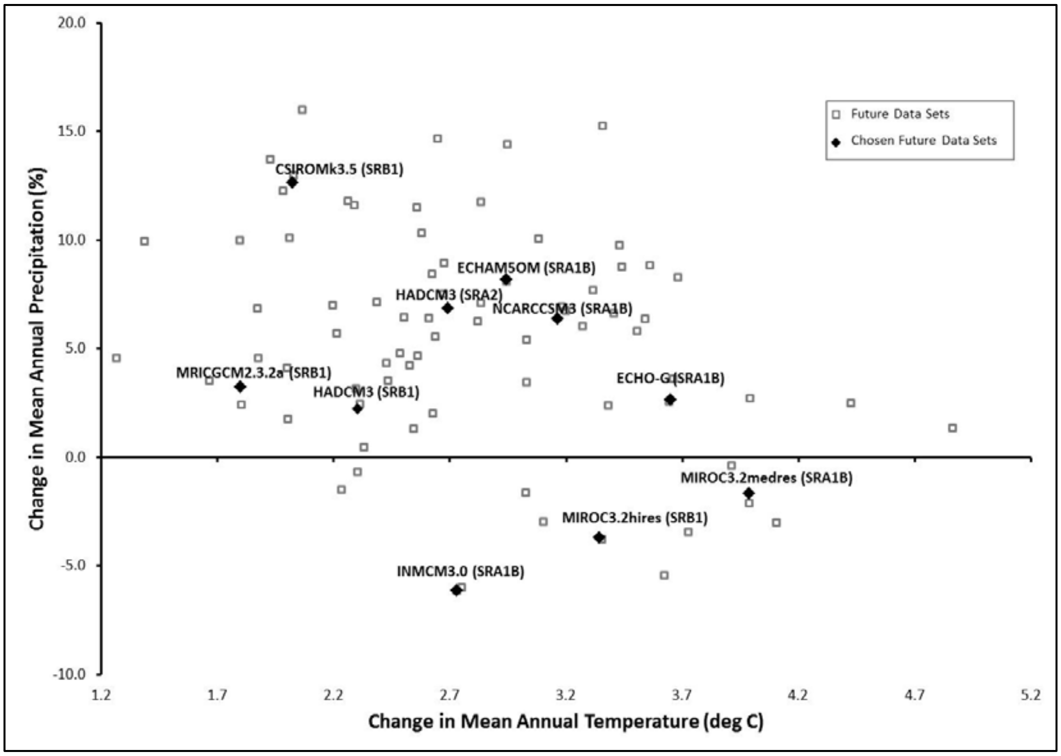


Figure 1–1: Annual change fields for temperature and precipitation for future climate data sets

Table 1-1 Chosen climate change scenarios based on the percentile method

Percentile	Temperature	Precipitation
5th	71 (MRICGCM2.3.2a SRB1)	65 (MIROC3.2hires_SRB1)
25th	53 (HADCM3 SRB1)	34 (ECHO-G SRA1B)
50th	52 (HADCM3 SRA2)	72 (NCARCCSM3M3 SRA1B)
75th	65 (MIROC3.2hires_SRB1)	31 (ECHAM5OM SRA1B)
95th	66 (MIROC3.2medres SRA1B)	30 (CSIROMk3.5 SRB1)

** added Scenario 58 (INMNM3.0 SRA1B) to show precipitation extreme

All of the scenarios had an increase in average annual and average monthly temperatures from baseline. Precipitation increased on an average annual basis for six scenarios, was close to baseline for two scenarios and decreased for two scenarios although there was additional variation for individual climate stations. There was variability on a monthly basis with all scenarios having some months with increased and some months with decreased precipitation. Further descriptions of each scenario is included in the following section and shown in figures in Appendix A.

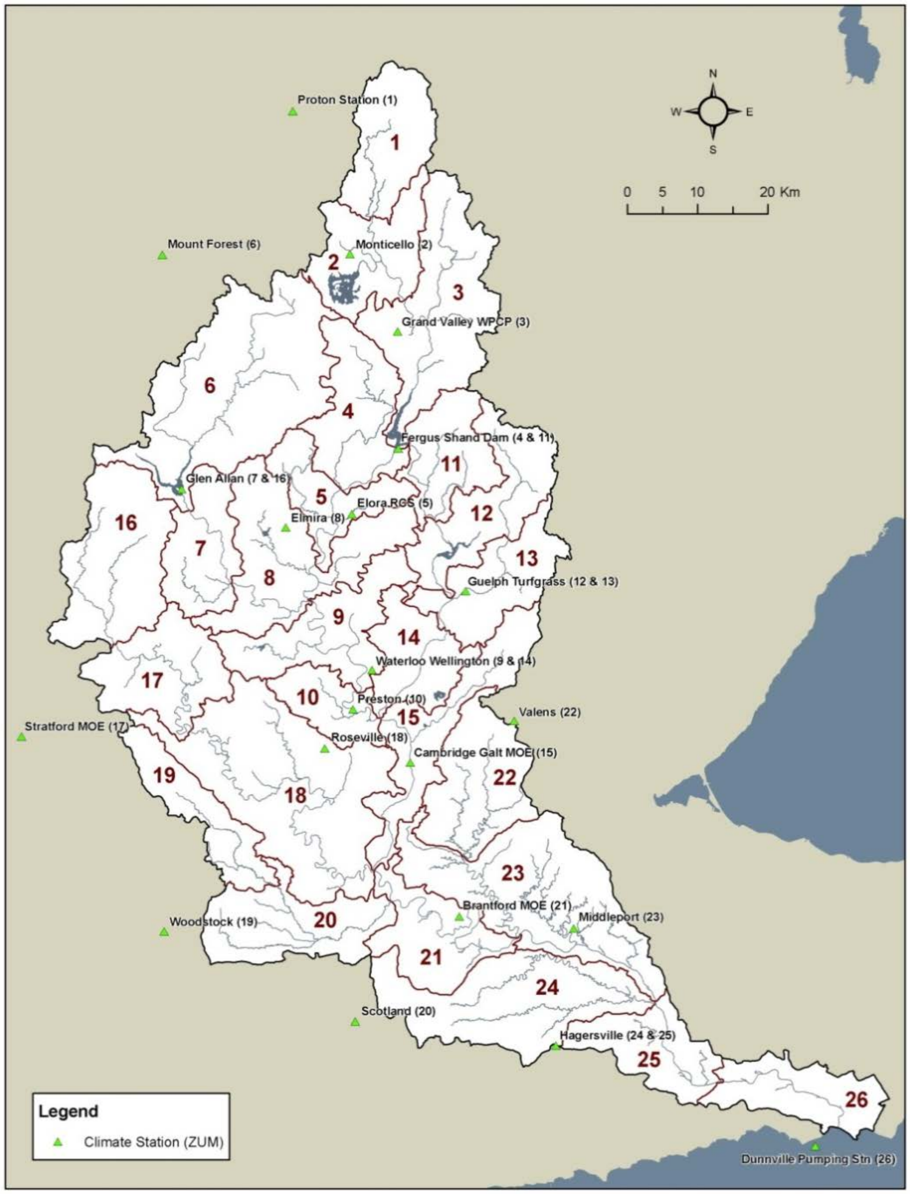


Figure 1–2: Tier 3 surface water model Zones of Uniform Meteorology (ZUMS) and climate stations

1.3.1. Scenario Descriptions

Each of the ten modeling scenarios are described below including a brief description of both annual and monthly changes to temperature and precipitation. Each scenario description includes a description of differences across watershed climate stations. Charts of monthly and mean annual change fields for each scenario are included in Appendix A.

Scenario 30 (CSIROMk3.5 SRB1)

This scenario had the highest precipitation increase of all of the chosen scenarios, 115mm higher annual precipitation than baseline for the watershed average. Precipitation was near or slightly lower than baseline in the late fall and early winter period, and higher than baseline in the rest of the year. Temperature increases were moderate with an average increase of 2 degrees. Temperature increased the most in the summer and early fall, but was fairly balanced throughout the year. Change fields were the same for all of the climate stations except for the extreme southern station, which had similar changes in temperature and a smaller increase in precipitation compared to the other stations.

Scenario 31 (ECHAM5OM SRA1B)

This scenario had the second highest precipitation increase with an average increase of 84mm watershed wide. Precipitation was near normal or lower for the spring months and higher than baseline for the rest of the year. The highest increases were in the summer and fall period. Temperature increased by close to 3 degrees on an annual basis. Temperature increases were less in March and June, but fairly close to average throughout the rest of the year. Climate stations had the same change field applied except for the extreme southern station. The Dunnville station had slightly higher temperature and precipitation increases than the other climate stations.

Scenario 34 (ECHO-G SRA1B)

Precipitation increased by a moderate amount with an average increase of 37mm across the watershed. Changes to precipitation were different on a monthly basis with higher precipitation in the winter and early spring and less or near baseline precipitation in the late spring, summer and early fall. This scenario had the second highest average temperature increase of 3.7 degrees. Temperature increases were highest through the winter and less in the spring. There were 2 sets of change fields for this scenario. The most western climate stations had a higher precipitation increase than the rest of the watershed, but similar temperature changes.

Scenario 52 (HADCM3 SRA2)

This scenario is considered one of the moderate scenarios run in this project based on annual values. It also had greater variability across the watershed with four sets of change fields used for different climate stations and throughout the year. Precipitation increased by about 64mm watershed wide. The northern and western climate stations had a greater increase in precipitation compared to the central climate stations. Monthly precipitation decreased or was near normal in the winter, spring and summer and increased in the fall. September had a monthly increase in precipitation of over 40% from baseline. Temperature increased by an average of 2.7 degrees watershed wide. Temperature changes were similar for most of the climate stations except for the Mount Forest station, which had the smallest increase in temperature. Based on the central climate stations the largest temperature increase was in the summer and fall with a much smaller increase in the winter period.

Scenario 53 (HADCM3 SRB1)

This scenario was close to the 25th percentile for both temperature and precipitation. Like Scenario 52 it also had a great deal of variability both seasonally and across the watershed. On an average basis precipitation was close to baseline across the entire watershed, but on a monthly basis February, May, November and December had increased precipitation and the summer months had less precipitation than baseline for the central climate stations. The northern climate stations had a lower increase in precipitation and the western stations had a decrease in annual precipitation. Temperature increased by 2.3 degrees, with only a small increase in the winter of less than 1 degree and a near average increase through the rest of the year. The annual temperature increase was much less for the Mount Forest climate station.

Scenario 58 (INMCM3.0 SRA1B)

This is the extra scenario that was chosen outside of the percentile method to make up 10 scenarios. All of the climate stations had the same changes to both temperature and precipitation. Precipitation decreased by the largest amount of any scenario available with an average decrease of 55mm. Precipitation decreased from baseline for the spring, summer and fall. Precipitation slightly increased in the winter period. Temperature increases were moderate (2.7 degrees) with a bit of monthly variation. The lowest increase was in May and the highest in December.

Scenario 65 (MIROC3.2hires SRB1)

This scenario was chosen both as the 5th percentile for precipitation and the 75th percentile for temperature. It had the second greatest decrease in precipitation of the ten scenarios modeled with an average decrease in precipitation of 26mm across the watershed. Precipitation was lower through the late spring, summer and early fall and higher or close to baseline in the winter. Precipitation changes varied throughout the watershed. The northern climate stations had increased precipitation, the western climate stations had decreased precipitation and the rest of the watershed was near to baseline. Temperature increased by 3.3 degrees on an average annual watershed basis. March and October were peak months for temperature increases, but generally the temperature increase was near average for most months.

Scenario 66 (MICROC3.2medres SRA1B)

On an annual basis this scenario had precipitation similar to the baseline scenario, but precipitation varied on a seasonal basis. Precipitation was lower through the summer and early fall period and higher or close to baseline in the winter and spring. Temperature increased by the largest amount of any of the scenarios with an average increase of approximately 4 degrees. Temperature increases varied monthly with the biggest predicted increase in March of approximately 6 degrees. Regionally the most southern climate stations had slightly different change fields applied than the rest of the watershed.

Scenario 71 (MRICGCM2.3.2a SRB1)

Scenario 71 is a moderate scenario with an increase in precipitation of 17mm on an average basis from the baseline. Precipitation changes varied throughout the year with higher winter and lower early summer precipitation. Precipitation was much higher for the southern climate stations than for the rest of the watershed. Scenario 71 had the lowest temperature increase of any of the chosen scenarios with an average increase of 1.8 degrees. Temperature increases were fairly stable throughout the year with the largest increases in January and October.

Scenario 72 (NCARCCSM3 SRA1B)

Precipitation was higher than baseline on an average basis by approximately 72mm. Seasonally precipitation was higher in the summer and November, lower in May and close to baseline for the rest of the year. Different climate stations had different seasonal patterns of precipitation although the average changes were similar for most climate stations. Temperature increased by approximately 3.2 degrees on an average annual basis.

1.4. Seasonal Analysis of Future Climate Scenarios

Seasonal analysis on all of the 76 scenarios was completed to determine the breadth of scenarios covered by the ten modeling scenarios chosen using the percentile method. Categories where used for each season to simplify the analysis and allow for comparison with the modeling scenarios. Two climate stations were used; one in the north (Proton Station) and a central station (Waterloo Wellington), to cover most of the key watershed processes.

Seasons are defined by:

- Winter (January to March);
- Spring (April to June);
- Summer (July to September); and
- Fall (October to December).

1.4.1. Methodology and Reasoning

Monthly change fields were averaged for each seasonal period for temperature and precipitation separately. Temperature categories were grouped into 2 degree Celsius blocks while precipitation was categorized into 10% ranges (see Table 1-2). Each scenario had eight variables, four for precipitation and four for temperature, as opposed to 24 (monthly change fields). The groupings were then combined for a total of 21 different combinations for each season. For example: Station 1 Scenario 19 was categorized as: Winter P3T3, Spring P0T2, Summer P0T2 and Fall P1T2.

Table 1-2: Climate change scenario categories

Precipitation Categories			Temperature Categories		
P-2	Moderate Decrease	-25% to -15%	T1	Small Increase	0 to 2 degrees
P-1	Small Decrease	-15% to -5%	T2	Moderate Increase	2 to 4 degrees
P0	No change	-5% to +5%	T3	Large Increase	4 to 6 degrees
P1	Small Increase	5% to 15%			
P2	Moderate Increase	15% to 25%			
P3	Large Increase	Over 25%			

Scenarios with like seasons were grouped and compared with the original modeling scenarios. The preponderance of each temperature/precipitation category as in Table 1-2 was compared for each season. A comparison of combinations of seasonal categories (e.g., P0T3 winter followed by a P2T1 spring) was not carried out because of the complexity and number of combinations when multiple seasons were taken into consideration.

1.4.2. Preponderance of Scenarios

Figure 1–3 shows the number of scenarios for each category and season for the central climate station. For each season, a moderate increase in temperature occurs most often with 72% of all scenarios across all seasons in the T2 category. A large increase is temperature occurs rarely except for the winter season when it accounts for 13% of scenarios at the central climate station and 18% of scenarios for the northern climate station. About 20% of all scenarios are in the T1 or small increase in temperature category.

Precipitation trends are more seasonally based than temperature trends. For the winter season, just under 50% of the scenarios fall into the small increase in precipitation (P1) category. The spring period is split between no change (P0) and a small increase in precipitation (P1) categories. The summer months are almost split three ways with small decrease (P-1), no change (P0) and a small increase in precipitation (P1). The summer period also has the most scenarios (40%) with decreases in precipitation. Finally, the fall period is split between no change in precipitation and a small increase with more scenarios in the P1 category than the P0 category.

The most numerous combined category across all months is the P1T2 category (small increase in precipitation with a moderate increase in temperature). This category is dominant for the winter season (33%). The other seasons also have almost 25% of scenarios in the no increase in precipitation with a moderate increase in temperature category (P0T2). Finally, the summer season has almost 20% of scenarios in the P-1T2 category (small decrease in precipitation with a moderate increase in temperature).

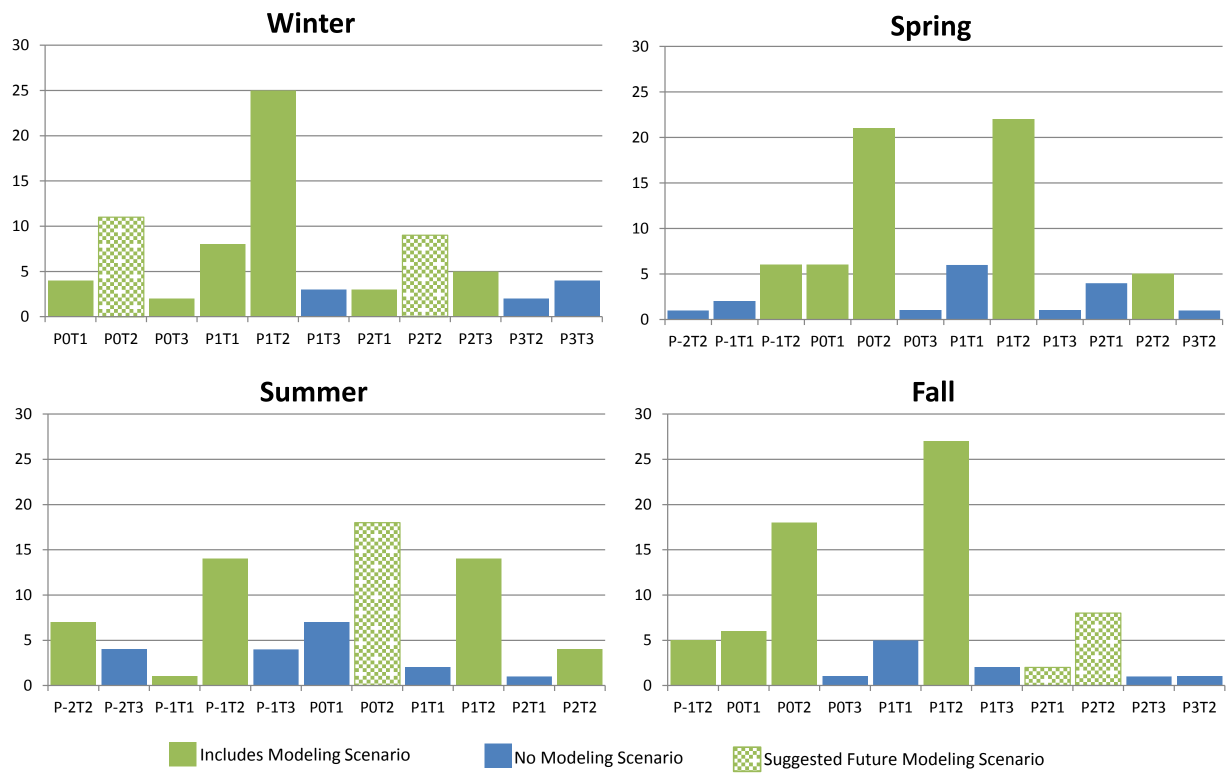


Figure 1–3: Number of scenarios by category and season for the central climate station

1.4.3. Coverage of the Modeling Scenarios

Table 1-3 shows the category placements for the ten modeling scenarios for each season. Except for the summer season, approximately half of the scenarios fell into a single category. This category mostly corresponded with the category with the greatest or second greatest number of scenarios as well and can be considered to be a fairly good representative sample of the scenarios available.

Table 1-3: Categories for the original modelling scenarios (number of scenarios given in brackets)

Northern Station				Central Station			
Winter	**Spring**	**Summer**	**Fall**	**Winter**	**Spring**	**Summer**	**Fall**
P0T1 (1)	P0T1 (1)	P-1T1 (1)	P0T1 (2)	P0T1 (1)	P0T1 (1)	P-1T1 (1)	P0T1 (2)
P0T3 (1)	P0T2 (5)	P1T2 (3)	P0T2 (2)	P0T3 (1)	P0T2 (6)	P1T2 (2)	P0T2 (2)
P1T2 (5)	P1T2 (1)	P-1T2 (2)	P1T2 (5)	P1T1 (1)	P1T2 (1)	P-1T2 (2)	P1T2 (5)
P2T1 (2)	P-1T2 (2)	P2T2 (1)	P-1T2 (1)	P1T2 (4)	P-1T2 (1)	P2T2 (2)	P-1T2 (1)
P2T3 (1)	P2T2 (1)	P-2T2 (3)		P2T1 (2)	P2T2 (1)	P-2T2 (3)	
				P2T3 (1)			

Winter

The ten modeling scenarios covered 49% of all scenarios in the northern part of the watershed and 62% of all scenarios in the central part of the watershed.

The scenarios not represented by the modeling scenarios were mostly similar for both the northern and central climate stations. For both stations, the main scenarios that were not run include: no change in precipitation with a moderate increase in temperature (P0T2); moderate increase in both temperature and precipitation (P2T2); and any scenario with a large increase in precipitation (P3T2 & P3T3). The northern climate station also did not have any scenarios in the small increase in precipitation with moderate increase in temperature (P1T1) category.

It is recommended that additional scenarios are run to capture some of the non-represented categories, especially the P0T2 and P2T2 categories since they represent approximately 35% of all scenarios. Only one scenario for one location showed a decrease in precipitation and as such it is not necessary to run a scenario with a decrease in precipitation.

Spring

The spring season had good representation with the modeling scenarios representing approximately 80% of the 76 scenarios analyzed. The only category with a number of scenarios that was not represented was a small increase in both precipitation and temperature (P1T1), but since this is a moderate scenario, it is not anticipated that modeling results will be very different from the historic record or the other moderate scenarios that were included in the analysis. Therefore, no additional scenarios are recommended based on the spring season results.

Summer

The modeling scenarios for the summer season represented approximately half of the total scenarios. The scenario with no change in precipitation and a moderate increase in temperature (P0T2) was the largest category but was not represented by the original modeling scenarios. It is recommended that at least one scenario from this category is run, although this category does fall in the middle of all of the modelling scenarios run.

Fall

The fall season is similar to the spring season with good representation. The original modeling scenarios represent approximately 75% of the total scenarios available. However, there are no scenarios in the modeling scenarios that have a moderate increase in precipitation. Therefore, it is recommended that a scenario with a moderate increase in precipitation in the fall months be modeled to complete the range of possible scenarios.

1.5. Additional Scenarios

Based on recommendations made in Section 1.4.3 a list of additional scenarios that should be included was made. From that list the scenarios that were represented in more than one category (e.g. P0T2 for summer and P2T2 for winter) were grouped together to narrow down the list of recommended additional scenarios. This identified two additional scenarios to be run to ensure a large percentage of all of the available scenarios are represented. These scenarios are listed in Table 1-4.

Table 1-4: Additional Suggested Scenarios

Scenario	Chosen for	Season	Category
	Winter P0T2	Winter	(P0T2)
6	Summer P0T2	Spring	(P1T2)
		Summer	(P0T2)
		Fall	(P2T1)
	Winter P2T2	Winter	(P2T2)
10	Summer P0T2	Spring	(P1T2)
	Fall P2T2	Summer	(P0T2)
		Fall	(P2T2)

Addition of these two additional scenarios would increase the coverage of the entire suite of scenarios to approximately 88% of winter, 76% of summer and 84% of fall scenarios. Coverage of spring scenarios would be the same at approximately 80%.

Scenario 6 (CGCM3T47-Run1 SRB1)

This scenario was chosen to represent both winters and summers with no change in precipitation and a moderate increase in temperature. On an annual basis this scenario is moderate for both temperature and precipitation with an increase in precipitation of 6.4mm and temperature of 2.6 degrees. The fall period of this scenario is wet and cool with an increase in December rainfall of about 43mm. The summer period is fairly dry and extended from June through to October. Change fields were similar throughout the watershed, but the northwestern climate stations had a slightly drier September and a slightly cooler winter period than the rest of the watershed.

Scenario 10 (CGCM3T47-Run3 SRA1B)

This scenario was chosen to represent a moderate increase in both temperature and precipitation during the winter and fall periods. On an annual basis this scenario has one of the highest precipitation increases with an average increase of 116mm from baseline but it was moderate for temperature with an average increase of 2.9 degrees. The summer season was dry and extended from July through to September. The fall and winter periods were wet. The northwestern climate stations were slightly different from the other climate stations with a drier summer period.

1.5.1. Inclusion of Additional Scenarios

The analysis of scenarios on a seasonal basis occurred after the original ten modeling scenarios were used in the watershed models and the results analysed, therefore the results are not included in Section 2 and are separated from many of the results in Section 3. Results from the hydrologic model for Scenarios 6 and 10 are included in Section 3.4. A discussion of results from the additional scenarios and their implications to the original ten modeling scenarios is provided in Section 3.4.5.

2. Water Budget

The following is a discussion of the annual results from the original ten modeling scenarios run through the watershed models on a sub-basin basis (Figure 2–1). This discussion includes the effects of the scenarios on hydrologic processes (climate, evapotranspiration, runoff, recharge, discharge from groundwater, and groundwater interbasin flow), a description of the resulting water budget and stress assessment and a summary of the results including some recommended next steps.

2.1. Hydrology

The Grand River watershed was divided into 18 sub-basins for the hydrology discussion and consolidated water budget. These basins are shown in Figure 2–1.

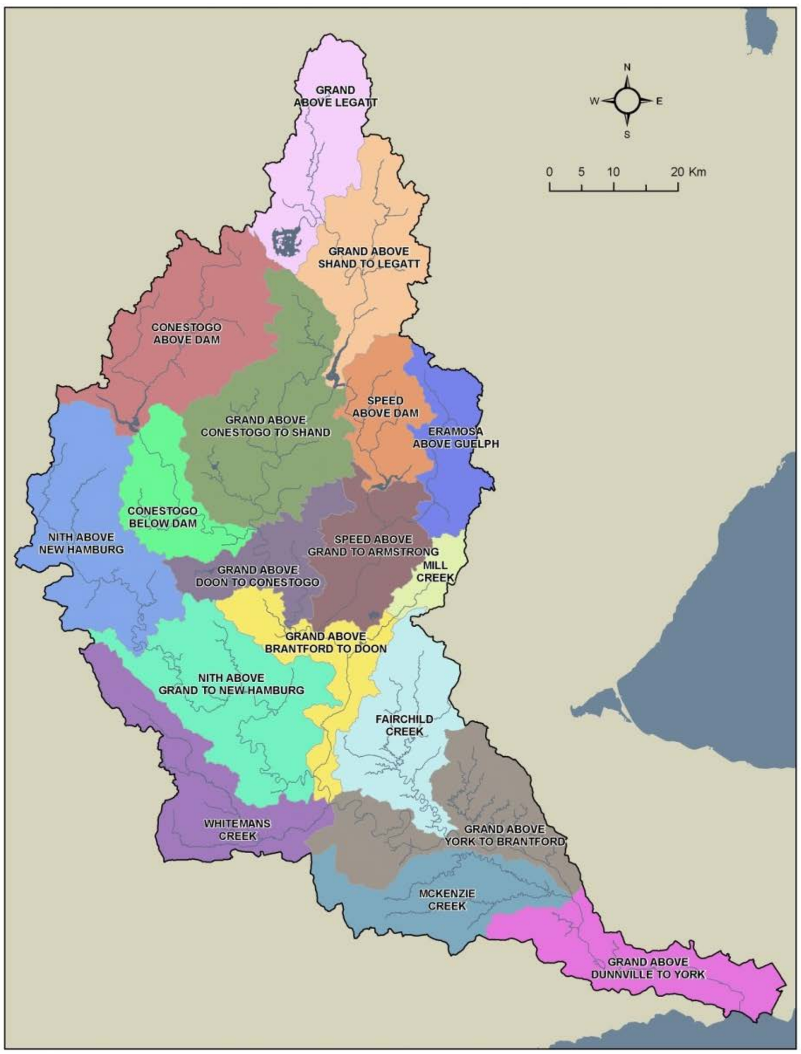


Figure 2–1: Sub-basins of the Grand River watershed

2.1.1. Hydrologic Processes

For each hydrologic process discussed, scenarios were placed into one of three categories: Greater than Baseline, Similar to Baseline and Less than Baseline. The Greater than Baseline category included scenarios where the average annual result was more than 2.5% greater than the baseline data for that sub-basin. Similar to Baseline included scenarios where the average annual result was within ±2.5% of the baseline data for that sub-basin. Finally, Less than Baseline scenarios were where the average annual result was greater than 2.5% smaller than the baseline data for that sub-basin. To simplify representation of the results the Similar to Baseline category has not been included on charts and is the difference between the total number of scenarios (ten) and the number of scenarios in the other two categories.

Climate

Annual precipitation was greater than baseline for five of the ten scenarios for all basins except Fairchild Creek, which had six greater than baseline scenarios (Figure 2–2). The northern sub-basins had only one scenario less than baseline, while the rest of the watershed had two scenarios less than baseline. There were between two and four scenarios similar to baseline depending on sub-basin. All of the scenarios for all sub-basins and months had higher temperature than the baseline climate. The effects of changes in precipitation and temperature affected the sub-basins differently, but seasonal and monthly differences in temperature and precipitation often had a greater effect on the hydrologic response than the annual average changes which is discussed in more detail in Section 3.

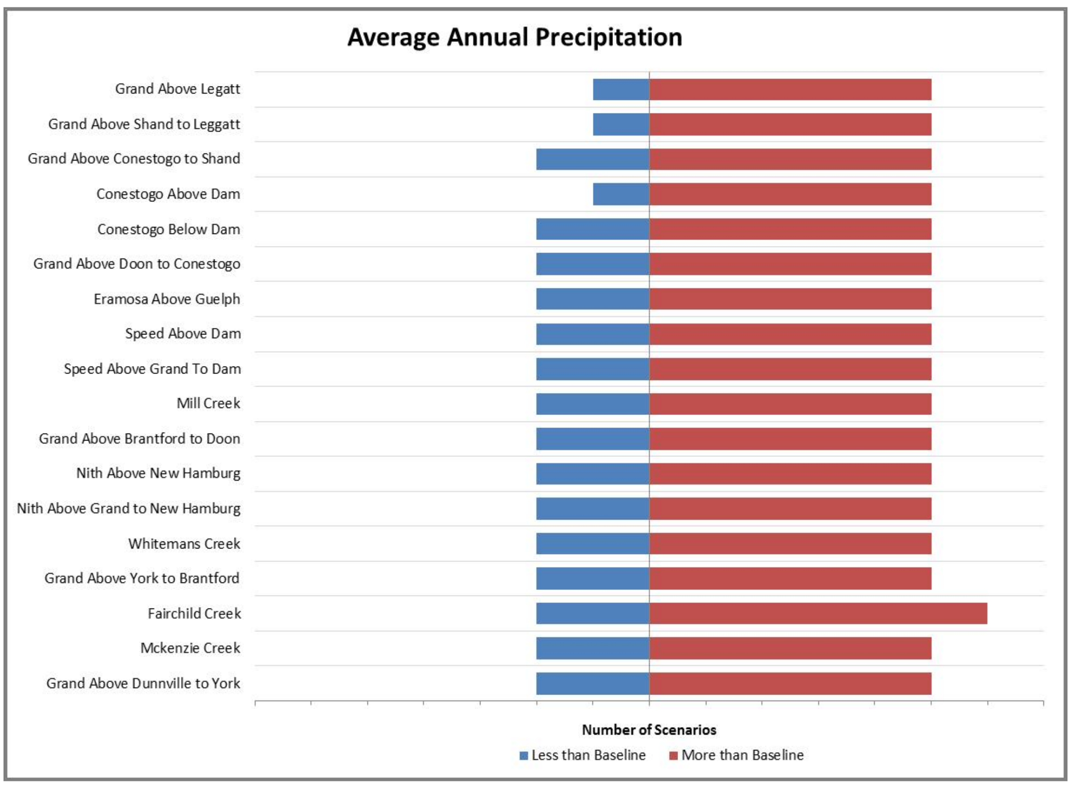


Figure 2–2: Number of scenarios less than or greater than baseline for precipitation by sub-basin

Evapotranspiration (ET)

Higher temperatures resulted in higher annual ET for many scenarios and across most sub-basins as shown in Figure 2–3. Scenario 58 was the only scenario to have a decrease in ET across most of the watershed, which was the result of lower precipitation during the growing season rather than temperature changes. In general, ET was most tied to temperature increase with the highest increases resulting in large increases in ET except where water availability was low from extreme low precipitation. When additional water is lost to ET it is not available for runoff, recharge or stream flow.

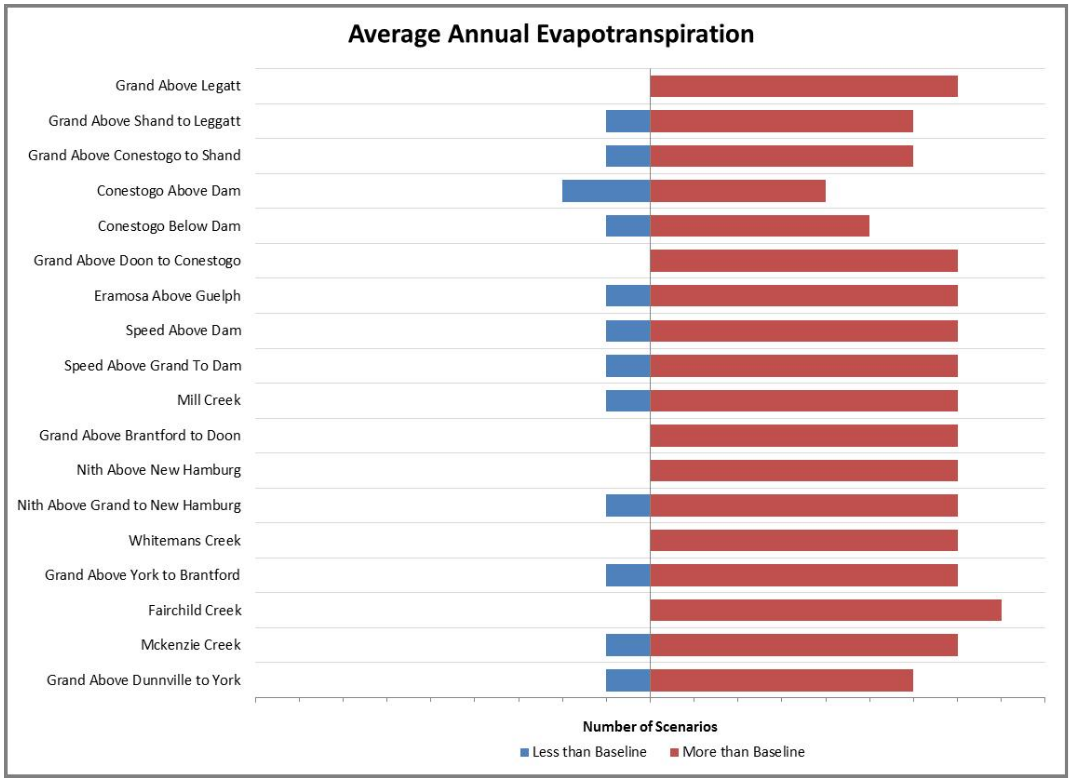


Figure 2–3: Number of scenarios less than or greater than baseline for evapotranspiration by sub-basin

There was some variability in ET for different sub-basins. For some of the scenarios this was a result of different climate change fields for different climate stations. The Mount Forest climate station which is used for climate input into the Conestogo Above Dam sub-basin often had very different change fields compared to the rest of the watershed resulting in more scenarios with ET close to or lower than baseline than any other sub-basin. There did not seem to be any strong trends to changes to ET based on land use, soil type or hydrologic response unit.

Runoff

There were some sub-basin trends for runoff with different climate change scenarios, but results were not consistent across the watershed as shown in Figure 2–4. Some notable trends included scenarios with very high increased precipitation resulting in increased runoff and scenarios with decreased precipitation resulting in decreased runoff across the watershed. Scenarios with moderate increased precipitation or with precipitation close to baseline had different results for different sub-basins with some results tied to the seasonality of precipitation, some tied to the climate station and some tied to the response of the sub-basin.

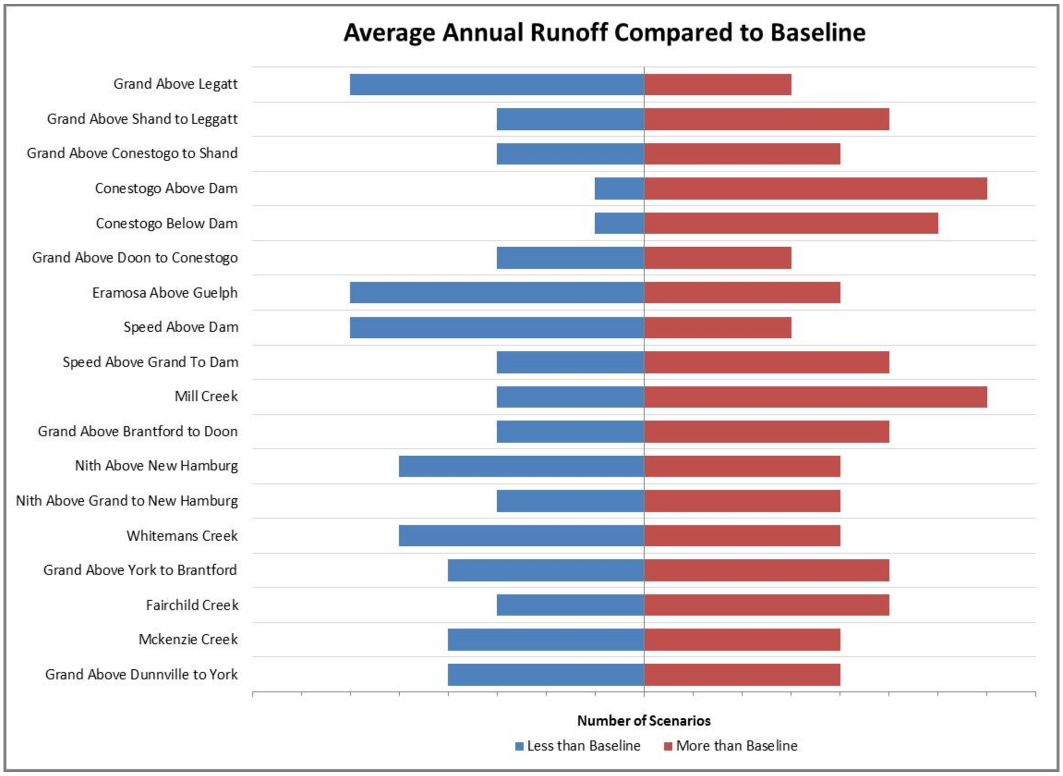


Figure 2–4: Number of scenarios less than or greater than baseline for runoff by sub-basin

Eight sub-basins had five or more scenarios with increased runoff. These sub-basins include some highly responsive areas that are more prone to runoff such as the Conestogo River and Fairchild Creek, but this trend was not true for other highly responsive basins such as the Upper Nith River. Mill Creek also had a large number of scenarios with increased runoff, but this is more of a result of scale than of hydrologic response (Mill Creek is the smallest sub-basin with the smallest runoff therefore all increases in runoff were greater than 2.5% of baseline so no results fell into the similar category).

Some sub-basins with traditionally lower levels of runoff such as Whitemans Creek and the Eramosa River had more scenarios with decreased runoff. While the southern parts of the watershed, Grand Above Dunnville to York and McKenzie Creek, showed no trend at all.

Recharge

There is a weak trend toward more recharge when the watershed is looked at as a whole, but there is a definite regional trend for recharge as seen in Figure 2–5. The northern sub-basins have more scenarios with increased recharge and fewer scenarios with decreased recharge, than the rest of the watershed. This may be due, in part, to more precipitation predicted for the climate stations, but may also be due to a reduction in the number of days with frozen ground allowing for more recharge during the winter period. All of the scenarios had more days with above freezing temperatures than the baseline. The northern most climate station had between 18 and 45 more days above freezing than the baseline depending on scenarios.

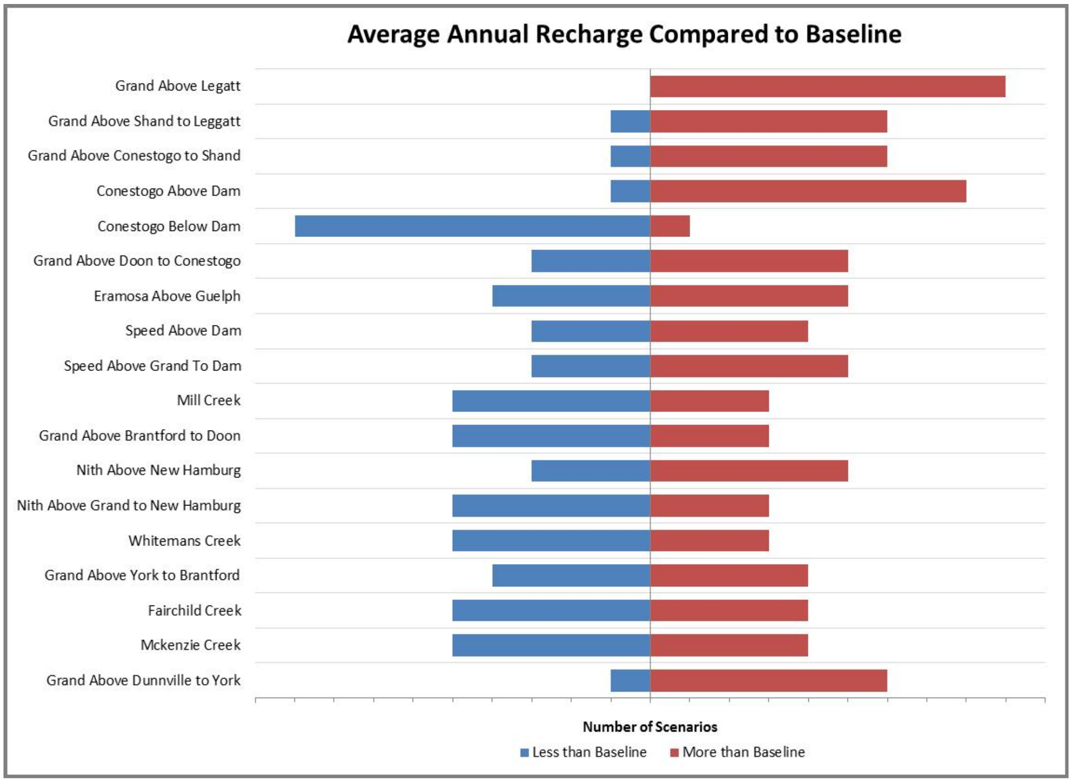


Figure 2–5: Number of scenarios less than, similar to or greater than baseline for recharge by sub-basin

Nine sub-basins had five or more scenarios with increased recharge and seven scenarios had five or more scenarios with less recharge than baseline. Some surprising results that do not follow other trends are for the Conestogo Below Dam sub-basin that had nine scenarios with less recharge and the Grand Above Dunnville to York sub-basin that had six scenarios with higher recharge. A more detailed discussion of sub-basin trends is located in Appendix B.

Discharge from Groundwater

There were no modifications of the surface water model made to take into account changes in groundwater discharges for each scenario. Groundwater discharge to surface water was investigated using the groundwater model only. Average annual recharge from each scenario was input into the groundwater model and then the model was run in steady state. Groundwater discharge to surface water was calculated for each basin and includes discharge to streams, rivers and reservoirs for features included in the model. Small watercourses, wetlands and ponds were not included in the model and therefore are not included in this analysis.

There are some very definite regional trends for groundwater discharge as shown in Figure 2–6. Discharge was greater than baseline for most scenarios in the northern basins, whereas the rest of the watershed had more scenarios less than Baseline. As you move downstream in the watershed, there is an increase in scenarios in the Less than Baseline category with Grand Above Dunnville to York which has seven scenarios with groundwater discharge less than baseline and none greater than baseline. Only the Grand above Shand to Leggatt increased for all scenarios. This sub-basin includes the Shand Dam reservoir which has high modeled groundwater discharge. Some of the key discharge reaches, Grand Above Brantford to Doon, Eramosa River and Whitemans Creek, had a greater number of scenarios within the Less than Baseline category.

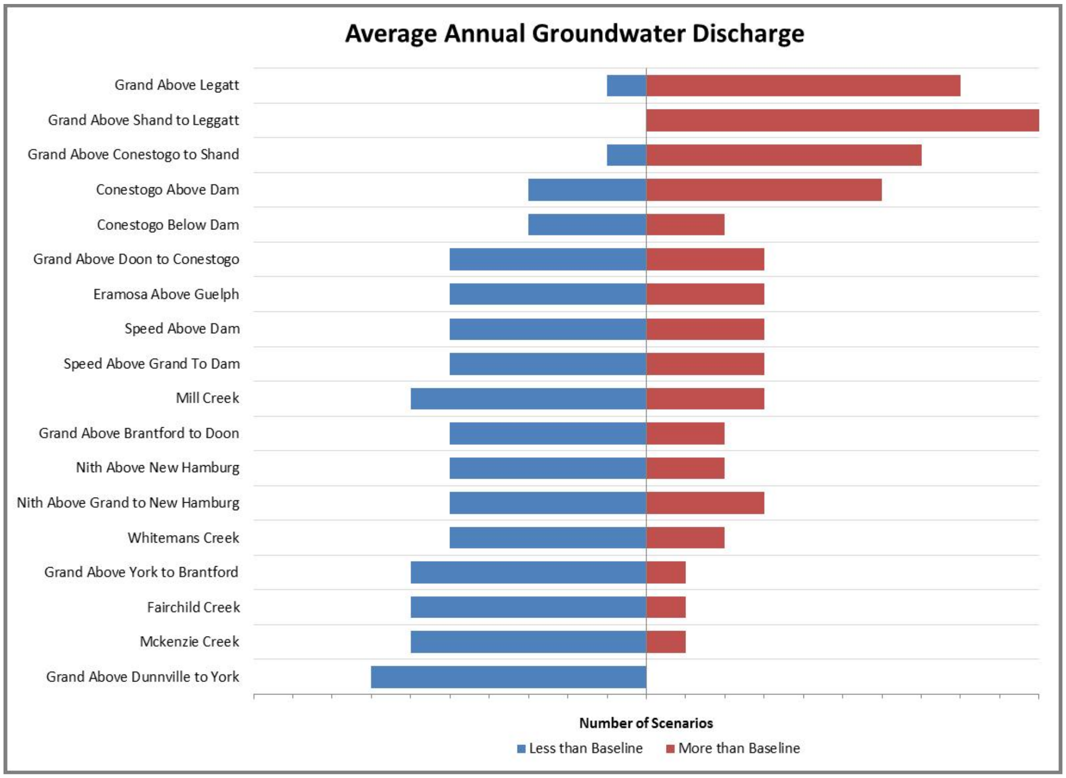


Figure 2–6: Number of scenarios less than or greater than baseline for groundwater discharge by sub-basin

Groundwater Inter-basin and External Flow

Inter-basin groundwater flow and groundwater flow into and out of the groundwater model did not change by significant amounts for any of the scenarios. This could be a function of running the model in steady state or it could be that changes to recharge were not significant compared to other hydrogeological factors. Confidence in the model decreases as recharge values move away from the values used to calibrate the model during the Tier 2 water budget study. It is recommended that additional runs of the model in transient mode and an investigation in the boundary conditions of the model be completed to ensure that these findings are reasonable.

2.1.2. Change in Hydrologic Parameters

The preceding descriptions of changes to parameters categorised the change as greater, less or similar to baseline and did not include the amount of the change from baseline values. Figure 2–7 shows the percent change from baseline for recharge, runoff, ET and groundwater discharge.

The largest change from baseline and the most variability is for runoff. Generally, runoff values are within 15% of baseline, but can be as high as 39% greater than baseline for one scenario and one sub-basin. Values that fall within the 90th percentile are fairly equally distributed above and below baseline. Recharge has the second largest change from baseline. Most values fall within about 12% of baseline, with an equal spread above and below baseline values. Groundwater discharge had a similar change from baseline as recharge at about 10 to 12%. ET was the only parameter to have most of the 90th percentile above baseline, but the changes were smaller with about 10% change above baseline, but only 2% change below baseline.

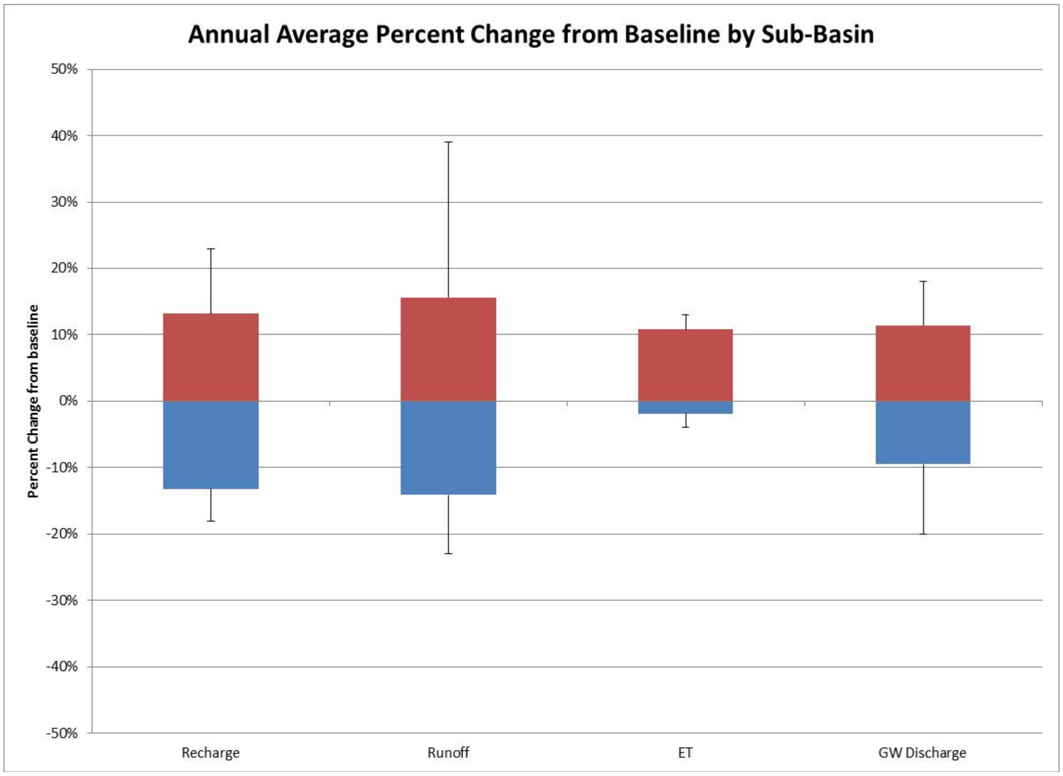


Figure 2–7: Average annual percent change in recharge, runoff, ET and groundwater discharge showing the 90th percentile with error bars to the largest change for a sub-basin

2.1.3. Stream Flow

The climate change scenarios in this study used the same frequency of weather related events as the baseline data, therefore it is not possible to investigate changes to the frequency of events. The intensity of events will only change by the factor applied to the baseline data, so changes to the intensity of events cannot be investigated either. However, generated flow data can be used to investigate changes to seasonal trends and overall watershed flow values. These findings can be important when planning for reservoir operations, drought contingency planning and to focus on areas to build resiliency in the watershed. Two sub-basins are discussed in this section, Whitemans Creek and Conestogo Above Dam, as an example of results of changes to stream flow. Daily stream flow was generated for all of the sub-basin outlets and are provided in Appendix C.

Annual Flow Changes

Annual changes to flow are closely tied to changes in precipitation and loosely tied to changes in temperature. Increased precipitation increases water in the water budget, but this water can be lost to ET or be tied up in the deeper groundwater system through recharge and become unavailable for stream flow. Figure 2–8 shows the change from baseline for average annual flow and precipitation for two sub-basins, Whitemans Creek and Conestogo Above Dam, for all ten climate change scenarios. The Upper Conestogo sub-basin had increased flow for five scenarios, decreased for three and two similar to baseline, while Whitemans Creek had only two scenarios with increased flow, six scenarios with decreased flow, and two similar to baseline.

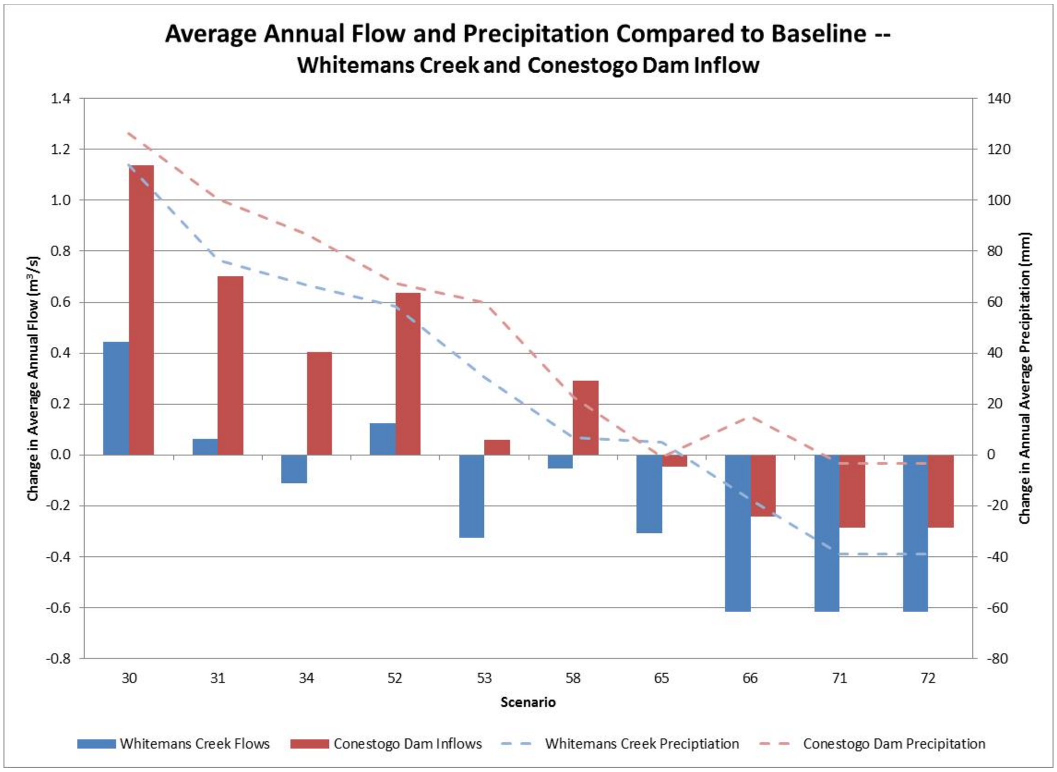


Figure 2–8: Difference from baseline for average annual flow and precipitation for Whitemans Creek and Inflows to Conestogo Dam

Figure 2–8 also illustrates different reactions to climate inputs between the two sub-basins. For instance, Scenario 34 had the largest increase in temperature and although precipitation increased for both sub-basins, stream flow decreased in the Whitemans Creek sub-basin due to increased ET, while flows in the Conestogo Above Dam sub-basin remained similar. There are similar results for Scenarios 71 and 72. Scenario 65 had similar precipitation to baseline for both basins, but flows decreased due to more water lost to ET.

The sub-basins also reacted differently to different scenarios. The Upper Conestogo River is a highly reactive watershed with high runoff and low baseflow. It reacted more with increased precipitation than Whitemans Creek, which tends to react slowly and has high recharge and baseflow. Except for Scenario 66, the Upper Conestogo had increased flows with increased precipitation. On the other hand, Whitemans Creek had increased flows with increased precipitation for only three scenarios.

Runoff and Baseflow

Although the amount of runoff and groundwater discharge changed for each scenario, their relative values were very similar. Looking at baseline data the Upper Conestogo River annual flow is comprised of approximately 81% runoff and 19% groundwater discharge (including Conestogo Lake), while in Whitemans Creek annual flow is comprised of approximately 56% runoff and 44% groundwater discharge. Under scenarios of climate change in the upper Conestogo sub-basin runoff comprises between 80 and 82% of average annual flow, while groundwater discharge accounts for between 18 to 20% of flow. For Whitemans Creek under scenarios of climate change runoff accounts for between 41 and 44% of average annual flow, while groundwater discharge accounts for between 56 and 59%.

It is important to note that these relationships may vary on a seasonal basis and will vary from year to year. Groundwater discharge is based on a steady state groundwater flow model while the runoff values are from a daily simulation. It is recommended that the ratios of runoff to baseflow be re-evaluated after transient groundwater modeling is completed.

2.2. Water Budget and Stress Assessment

Part of the Drinking Water Source Protection Program (DWSP) was to develop a water budget and water quantity risk assessment for the Grand River watershed. The GRCA has completed the Tier 2 version of the water budget, which included developing watershed wide numerical models for both surface and groundwater systems, evaluating water budget parameters, and completing a water quantity stress assessment using current climate conditions. Additional work is underway in the Tier 3 phase to determine and quantify risks to drinking water quantity in certain areas of the watershed. Part of the DWSP program is also to include the effects of climate change. This study is part of that process by investigating the effects of climate change on both the water budget and the water quantity stress assessment.

A water budget and water quantity stress assessment was completed for each sub-basin and each scenario. This section presents the average annual results for the water budget and summarizes the sub-basin stress assessment results. More detailed sub-basin results for the water budget are included in Appendix B.

2.2.1. Watershed Water Budget

The average annual water budget for the entire Grand River watershed for both the baseline data and the climate change scenarios is given in Table 2-1. Details of changes to hydrologic processes are included in Section 2.1 and are described in Appendix B for each sub-basin.

General trends include:

- Higher precipitation and temperature;
- Higher ET;
- Higher recharge and groundwater discharge in the northern part of the watershed;
- Lower groundwater discharge in the southern part of the watershed;
- Hydrologic response changes based on both precipitation and temperature changes; and
- Seasonality of changing climate conditions is as or more important than annual changes.

Seasonal trends to water budget parameters are included in Section 3 in more detail. An earlier study (Appendix D) included only four scenarios and focused on three sub-basins. In this study changes to ET, runoff and recharge were investigated on a seasonal basis. All three basins, Upper Conestogo, Eramosa and Whitemans Creek, had similar seasonal trends but with different magnitudes. ET increased in the spring and fall and decreased in the summer. Recharge increased in the winter and decreased for the rest of the year. Runoff increased in the winter, decreased by a large amount in the spring and decreased by a smaller amount in the summer and fall. These results tie very closely with increased temperatures that result in an earlier melt, more recharge in the winter and an earlier and extended growing season.

Table 2-1: Grand River watershed water budget under scenarios of climate change given annual average values over a thirty year time period in mm/yr

Scenario	Precipitation	ET	Runoff	Recharge	External GW Flow	GW Discharge
Baseline	874	519	200	155	-4	-130
30	986	572	237	177	-5	-140
31	955	569	218	168	-5	-141
72	942	573	206	163	-4	-137
52	938	550	220	168	-5	-141
34	907	556	197	155	-3	-131
71	892	518	213	161	-4	-135
53	886	536	199	151	-3	-128
66	869	540	180	149	-3	-127
65	844	519	179	146	-2	-124
58	819	505	174	139	-2	-120
Baseline	--	--	--	--	--	--
30	up	up	up	up	up	up
31	up	up	up	up	up	up
72	up	up	up	up	--	up
52	up	up	up	up	up	up
34	up	up	--	--	down	--
71	up	--	up	up	--	up
53	--	up	--	--	down	--
66	--	up	down	down	down	down
65	down	--	down	down	down	down
58	down	down	down	down	down	down

Notes:

"up" represents values greater than baseline by at least 2%
"down" represents values less than baseline by at least 2%
"--" represents values similar to baseline

There were a few regional trends as discussed in Section 2.1. The most noted trends were increased recharge and discharge in the northern basins and decreased groundwater discharge in most of the rest of the watershed. Increased recharge in the northern basins is most likely from a combination of increased precipitation and more days without frozen ground therefore allowing for more recharge during the winter period. The groundwater discharge results have a bit of uncertainty to them as the groundwater model was only run in steady state. This result should be investigated further with transient runs of the groundwater model.

2.2.2. Stress Assessment

The stress assessment differed from the Tier 2 Stress Assessment under the DWSP program in that the surface sub-basins were used for both the surface water and groundwater assessments and 30 instead of 20 years of data was used to calculate average annual values. Other changes from the Tier 2 water budget are most likely due to using the Tier 3 surface water model, which has more climate stations and a change to hydrologic response units in some of the urban areas. The Linacre ET and frozen ground infiltration sub-routines were also used in this study but not for the Tier 2 assessment. No changes were made to water use values which were taken directly from the Tier 2 Water Budget (AquaResource 2009a&b).

The groundwater stress assessment did not change under climate change scenarios, except for Grand Above Dunnville to York which increased to a moderate potential for stress in Scenario 58. The groundwater stress assessment results are a little uncertain as changes to recharge resulted in little change to inter-basin flow and subsequently water available for the groundwater assessment. The model should be run in transient mode with changing recharge to see the full effects of the climate change scenarios. The groundwater stress assessment results were slightly different from the Tier 2 assessment because of different baseline climate data, surface water model and sub-basin boundaries.

The surface water stress assessment changed under scenarios of climate change as shown in Table 2-2. There were five sub-basins with changes to the surface water stress assessment. Eramosa Above Guelph, Whitemans Creek and Mckenzie Creek all increased from a moderate potential for stress under the baseline to a significant potential for stress under scenarios of climate change. The Eramosa sub-basin only increased to significant for three scenarios while Whitemans Creek and Mckenzie Creek increased for nine scenarios.

Two sub-basins increased from low potential for stress under baseline conditions to moderate potential for stress. The Speed Above Dam sub-basin increased to moderate for five scenarios. Mostly the change occurred for the month of September where a longer and more severe low flow season was predicted. The Nith Above Grand to New Hamburg sub-basin increased to a moderate potential for stress for three scenarios. Only the month of September in each scenario was classified as moderate. Precipitation for September and the summer months were predicted to be lower than baseline for these scenarios.

None of the sub-basins with predicted increased levels of potential stress contain municipal water supply systems that would be affected. The Eramosa River sub-basin has a surface water intake in it, but the Tier 2 stress assessment already determined a moderate potential for stress and a Tier 3 risk assessment is underway. The other surface water sub-basins with increased potential for stress do not have surface water intakes. The Grand Above Dunnville to York groundwater sub-basin also does not have a groundwater municipal drinking water system.

Although additional Tier 3 assessments are not required because of this assessment, it is important to note the affected sub-basins for other water use and water availability programs such as the Permit to Take Water Program and the Ontario Low Water Response program. Water demand planning, drought contingency planning and sub-watershed studies should also make note of the affected sub-basins when considering future work.

Table 2-2: Summarized results of the water quantity stress assessment under scenarios of climate change (L – Low, M – Moderate, S – Significant potential for stress)

	Surface Water Stress Assessment											GW
Basin	Base	30	31	34	52	53	58	65	66	71	72	Stress*
Grand Above Legatt	L	L	L	L	L	L	L	L	L	L	L	L
Grand Shand to Leggatt	L	L	L	L	L	L	L	L	L	L	L	L
Grand Conestogo to Shand	L	L	L	L	L	L	L	L	L	L	L	M
Conestogo Above Dam	L	L	L	L	L	L	L	L	L	L	L	L
Conestogo Below Dam	L	L	L	L	L	L	L	L	L	L	L	L
Grand Doon to Conestogo	L	L	L	L	L	L	L	L	L	L	L	S
Eramosa Above Guelph	M	L	M	M	M	M	S	S	S	M	M	M
Speed Above Dam	L	L	L	M	L	M	M	M	M	L	L	L
Speed Grand To Dam	L	L	L	L	L	L	L	L	L	L	L	S
Mill Creek	L	L	L	L	L	L	L	L	L	L	L	M
Grand Brantford to Doon	L	L	L	L	L	L	L	L	L	L	L	S
Nith Above New Hamburg	L	L	L	L	L	L	L	L	L	L	L	L
Nith Grand to New Hamburg	L	L	L	L	L	L	M	M	M	L	L	L
Whitemans Creek	M	M	S	S	S	S	S	S	S	S	S	L
Grand York to Brantford	L	L	L	L	L	L	L	L	L	L	L	M
Fairchild Creek	L	L	L	L	L	L	L	L	L	L	L	L
Mckenzie Creek	M	M	S	S	S	S	S	S	S	S	S	L
Grand Dunnville to York	L	L	L	L	L	L	L	L	L	L	L	L*

GW - Groundwater
* all scenarios had the same results for groundwater as the baseline case, except for *Grand Above Dunnville to York* for Scenario 58 which had a stress assessment of moderate

2.3. Summary

The main results of the water budget analysis based on the original ten modeling scenarios include:

- Annual changes to precipitation and temperature had an impact to water budget parameters at the extreme end of the range:
- ET increased for all scenarios except in water limited situations (i.e., extreme low precipitation);
- Recharge increased for more scenarios in the northern basins than in the rest of the basins, similarly groundwater discharge increased in the northern basins and decreased in the southern basins for more scenarios;
- Runoff did not have any clear trends and seemed to be basin and scenario dependant;
- Majority of changes to hydrologic parameters were within 15% of baseline values on an average annual basis;
- Increased precipitation did not always lead to increased stream flow with the relationship being very basin and timing dependant and somewhat temperature dependant;
- Based on steady state conditions, the groundwater stress assessment did not change with climate change scenarios, except for one scenario for the most southern sub-basin; and

- Changes to the surface water stress assessment included five sub-basins with higher potential stress levels for three to nine scenarios.

3. Seasonal Climate Change Modelling Results

The results of hydrologic modeling were first analysed on an annual basis (Section 2), but it was found that the annual effects of most hydrologic parameters were not appropriate for decision making in regards to climate change and resiliency planning. Instead, seasonal or monthly changes to hydrologic parameters were needed. This section starts with a monthly analysis for climate (Section 3.1) and hydrologic parameters including stream flow (Section 3.2), while Section 3.3 contains a discussion of key hydrologic processes on a seasonal basis. The Sections 3.1 to 3.3 focus on the original ten modeling scenarios. Section 3.4 contains the results of the additional two climate scenarios chosen to extend the range of future climate possibilities. Finally, the summary at the end of Section 3 includes discussion about seasonal results versus multiple seasons and trends in seasonal results.

3.1. Climate Parameters

The future climate data sets were created using monthly change fields for precipitation and temperature. Although the surface water model runs on an hourly time step and uses both hourly and daily data, climate data was modified on a monthly basis making monthly analysis appropriate. Analysis of climate parameters is first based on applied change fields and includes all 76 scenarios. Further analysis on precipitation is from the modeling output aggregated to a monthly basis.

3.1.1. Temperature

There were a total of 76 scenarios available for analysis (full suite of scenarios). None of the scenarios predicted a decrease in temperature for any months. The average monthly increase in temperature for all of the scenarios is 2.8 degrees with a range of 0.2 to 6.9 degrees monthly. The highest average monthly increase is for January with an average increase of 3.1 degrees, while the lowest monthly increase is for November with an average increase of only 2.4 degrees. The largest variability is in the winter and late summer months where the range of future scenarios is over 5 degrees.

The ten modeling scenarios cover the range of future temperatures well, as shown in Figure 3–1. The average change in temperature for the modeling scenarios is 2.9 degrees which is slightly higher than the entire suite of scenarios. The average monthly temperatures for the modeling scenarios are similar to the entire suite although the modeling scenarios tended to be a bit warmer in the late summer and early fall period. March has the highest single increase with 6.0 degrees for Scenario 66, but it also had the lowest consistent change in temperature with a median increase of 2.1 degrees for all ten modelling scenarios.

The increase in average temperatures in the winter for the modeling scenarios resulted in fewer days with daily temperatures below freezing compared to baseline data. For example the most northern climate station, Proton, had an average of 128 days per year with daily temperatures below freezing from 1961 to 1990, but for Scenario 34 there was only 89 days per year with average daily temperatures below freezing. A reduction in the number of days with temperatures below freezing will affect winter hydrologic processes such as accumulation of the snowpack, river ice processes and an increase in winter infiltration.

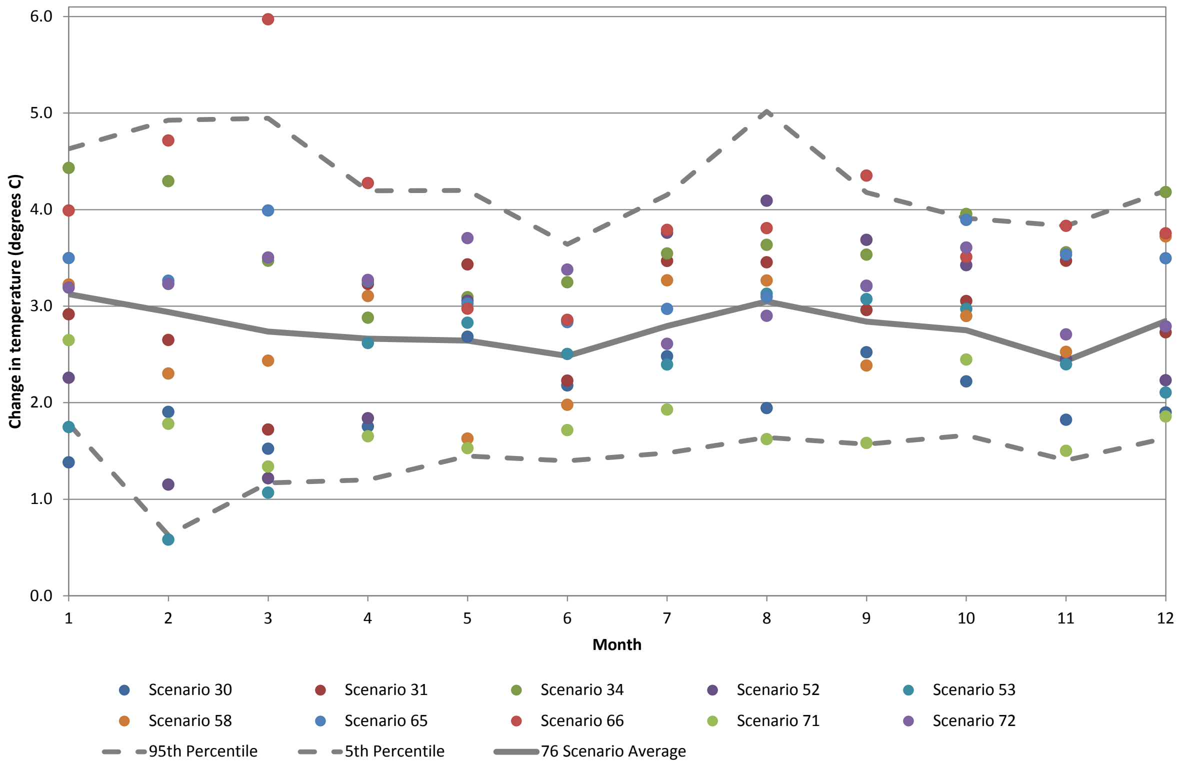


Figure 3–1: Average monthly change in temperature from baseline for modeling scenarios

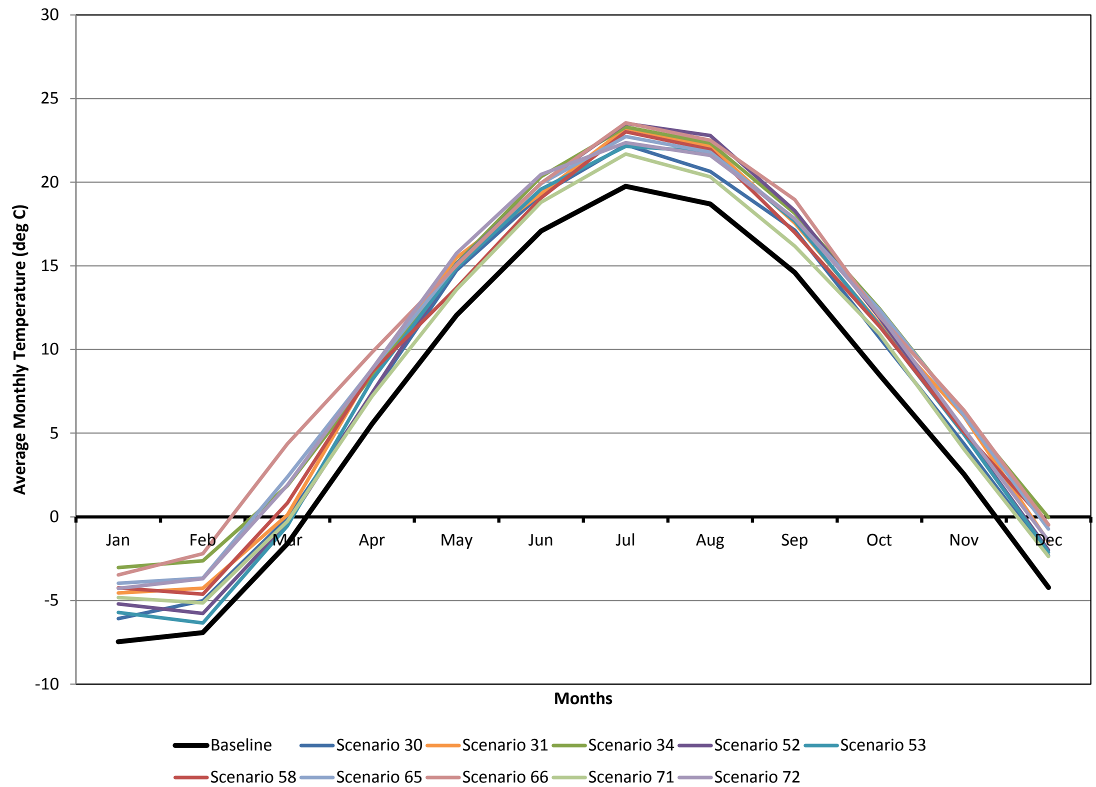


Figure 3–2: Average monthly temperature for modeled climate change scenarios and baseline

Although overall changes in temperature were similar throughout the watershed, there were some differences in the overall effects of these changes based on baseline data for the climate stations. The average monthly temperatures for the winter months stayed below freezing for all scenarios in the north, but in the southern parts of the watershed December monthly temperatures were above freezing for all ten scenarios. January and February average monthly temperatures stayed below freezing for all scenarios throughout the watershed. The watershed average monthly temperature for all ten scenarios plus baseline is presented in Figure 3–2.

3.1.2. Precipitation

The full suite of scenarios showed a strong trend towards more precipitation for the first five and last two months of the year with higher than 80% of the scenarios with increased precipitation. From June through to October the scenarios were split between an increase or decrease in precipitation. There was a high degree of variation throughout the scenarios with a maximum increase of 53% and a maximum decrease of 38%. The average range of monthly precipitation changes was between -21% and +39%.

The ten modeling scenarios covered the range of future scenarios fairly well (Figure 3–3), although the modeling scenarios trended to lower precipitation increases in April, November and December than the full suite of scenarios. The winter months of January, February and December had all ten scenarios above or close to the baseline. There was more uncertainty in the summer months (July and August) with three scenarios with greater precipitation and five with less precipitation than baseline. September and October had an equal number of scenarios with more and less precipitation than baseline resulting in a median close to zero. April and May trended to slightly more precipitation.

For the modeling scenarios, the month with the largest consistent decrease was July with an average decrease of 4%. August had the largest single scenario decrease with a decrease of 28% for Scenario 65, which resulted in a decrease of 26mm across the watershed. September had some of the largest changes in precipitation of any of the months with an increase of 42% (35mm) for Scenario 52 to a decrease of 23% (19mm) for Scenario 66. The month with the highest consistent increase was February with an average monthly increase of 14% or 10mm.

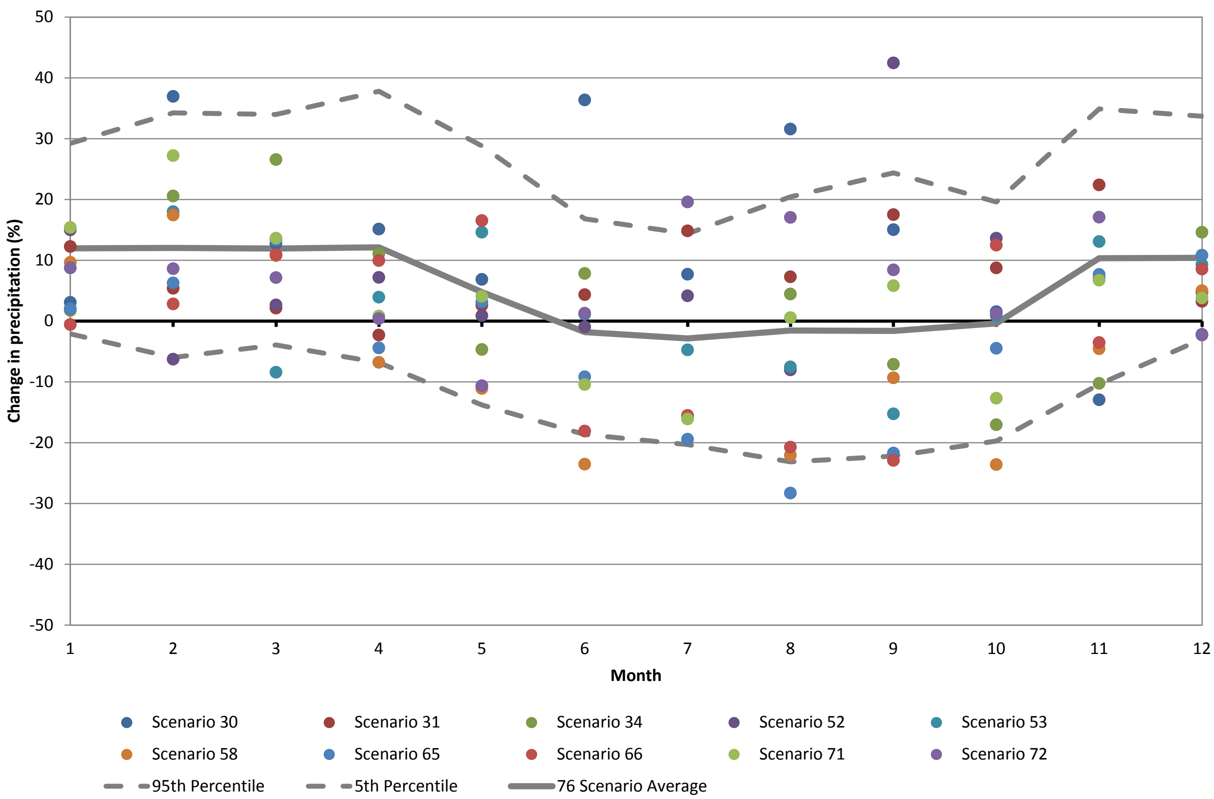


Figure 3–3: Monthly change in precipitation from baseline for modeling scenarios

3.2. Hydrologic Processes

This section gives a brief discussion of monthly changes to hydrologic processes based on modeling results for the ten modeling scenarios. Processes include evapotranspiration, runoff, recharge and stream flow. How seasonal changes to hydrologic processes affect some of the key hydrologic functions in the watershed is included in Section 3.3.

3.2.1. Evapotranspiration

Evapotranspiration is the largest component of the water budget on an annual basis. It increased for all scenarios across most months as shown in Figure 3–4. Only in water limited months (i.e., during very dry summer months) was there a decrease in evapotranspiration. In these cases, there was no additional water available for evapotranspiration.

July had the largest average monthly decrease (7.3mm) with only two scenarios showing an increase. August was similar with seven scenarios with a decrease and September had four scenarios with a decrease in evapotranspiration. The spring and fall months had increases in evapotranspiration, while changes in winter evapotranspiration were minimal because of a combination of low temperatures and assumptions of no plant growth. April had the largest average increase in evapotranspiration (8.2mm) due to a combination of higher temperatures and abundance of water available.

Generally, changes in evapotranspiration were small in comparison to total amount of evapotranspiration. The largest changes occurred when there was an increase in temperature during the regular growing season and water was available. Changes to the length or timing of the growing season were not taken into account in the model, which has upper limits of potential evapotranspiration rates for each month. An earlier start to the growing season could result in even higher spring evapotranspiration rates and may lead to more summer water limited situations.

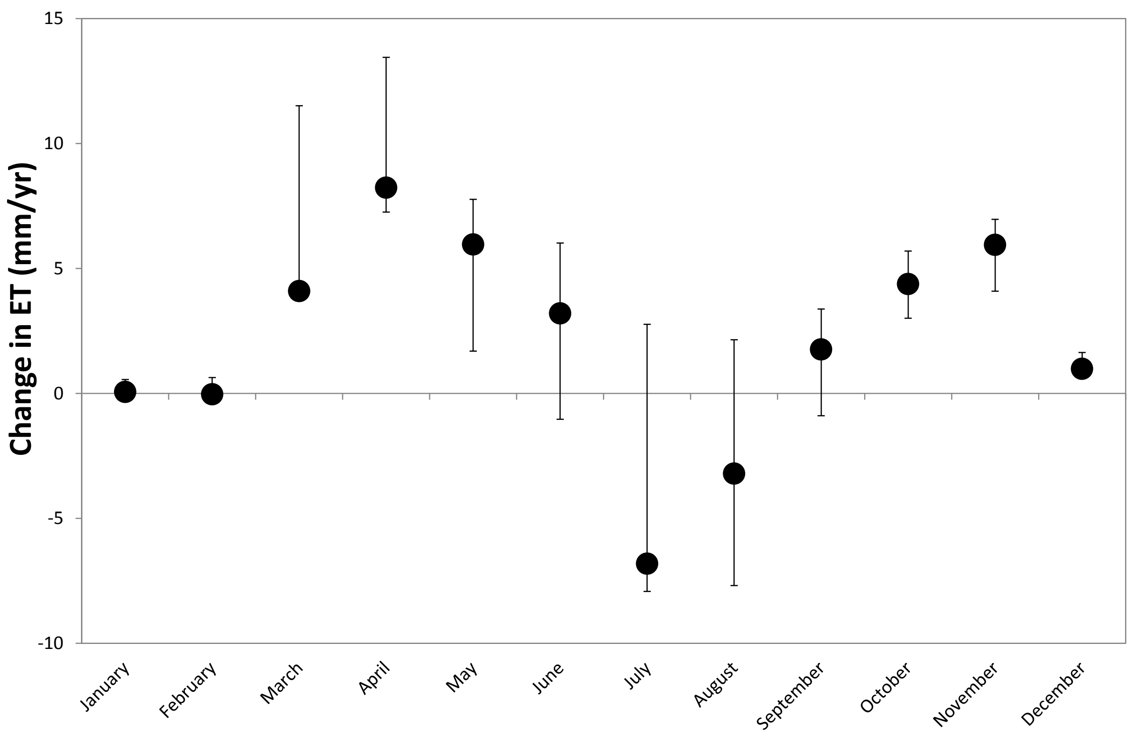


Figure 3–4: Monthly change in evapotranspiration from baseline for modeled climate change scenarios

3.2.2. Runoff

Runoff increased in the winter months and generally decreased throughout the rest of the year as shown in Figure 3–5. The largest average decrease was for April (8mm). April also had the most variability although a majority of the scenarios predicted a decrease in runoff. All scenarios had increased runoff for the winter months (January, February and December) with February having the highest average increase with 6.9mm. The increase in winter runoff and decrease in spring runoff is most likely due to changes to the winter snowpack from more mid-winter melts. Traditionally the winter snowpack built throughout the winter and melted in early spring (March or April) resulting in high spring runoff. With higher winter temperatures there will be more mid-winter melts, resulting in higher winter runoff and a smaller snowpack come spring. Additional precipitation predicted during the winter season will most likely contribute to winter runoff as it is expected to be in the form of rain rather than snow.

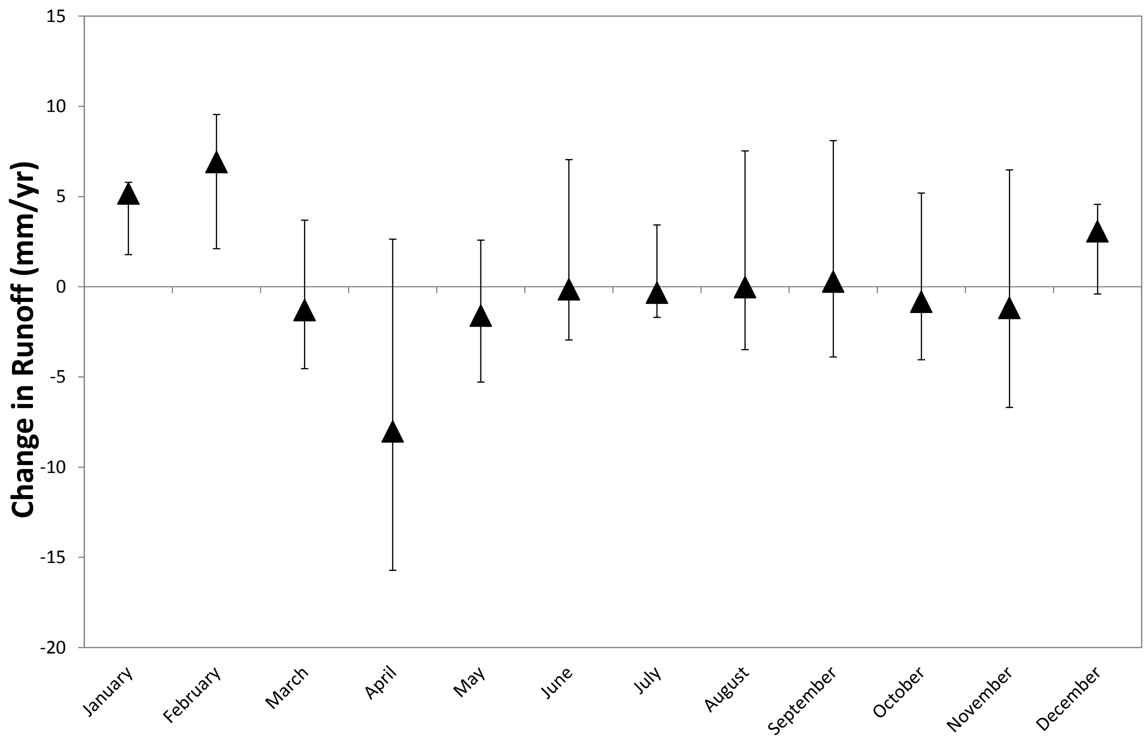


Figure 3–5: Monthly change in runoff from baseline for modeled climate change scenarios

Although more scenarios predicted less runoff in the summer, runoff is usually very low during the summer months (approximately 10mm/month on a watershed basis) so the change is not significant. During the summer months the runoff component of stream flow is low with most of the water in the watercourses coming from groundwater or reservoir and wetland discharges.

Winter and spring monthly change patterns are similar throughout the watershed. The summer and fall months vary by sub-basin with different numbers of scenarios below or above baseline runoff, but most values are very close to baseline. The largest changes in runoff values occur in the northern sub-basins. The Grand River Above Leggatt sub-basin had a decrease of 45mm in April for Scenario 66, while the median decrease for the watershed in April for all scenarios was 8.6mm. Increases in runoff were also greater in the northern basins. The central sub-basins had much smaller changes in runoff, but these basins have low runoff to begin with. The southern sub-basins were less than the watershed average, but generally greater than the central sub-basins. The most urban sub-basins had changes in runoff that were close to the watershed average on a monthly basis.

3.2.3. Recharge

Recharge, similar to runoff, increased in the winter and decreased in the spring as shown in Figure 3–6. Spring will still be a key time of year for recharge, but there will be a shift in months from April and May to March and April. December will also become an important month for recharge instead of the mid-fall period. Winter recharge is expected to increase because of an increase in precipitation and a decrease in the amount of frozen ground which will result in an increase in the rate of infiltration. There is more uncertainty with respect to changes in fall recharge, but the trend is for less recharge in the traditional fall months and an increase in recharge in December. The scenarios run had high variability for precipitation in the fall and as such, there is high variability as to the amount of recharge in this key recharge period.

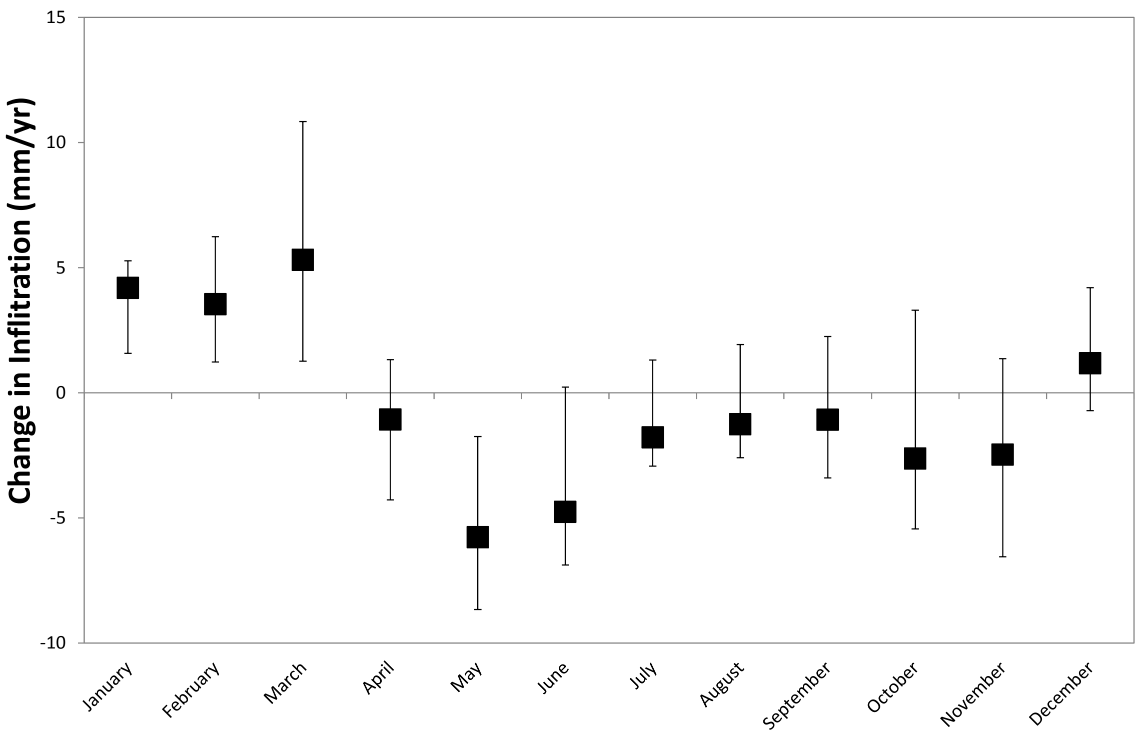


Figure 3–6: Monthly change in recharge from baseline for modeled climate change scenarios

March had the greatest increase in recharge with an average increase of 6.1mm and a maximum increase for Scenario 66 of 10.8mm. May had the greatest decrease in recharge with an average decrease of 5.0mm across all ten modeling scenarios. Scenario 72 had the largest decrease with a decrease of 7.9mm for May. Increases in the winter and decreases in the spring are part of a shift in recharge from mid-spring to early spring. Overall, the scenarios are predicting a slight decrease in recharge mainly from the late spring through the fall period.

Generally, the sub-basins followed the watershed wide patterns for seasonal recharge, but the amounts of change varied greatly from basin to basin. For the most part, the change in recharge was proportional to the amount of recharge in that basin. Sub-basins with high recharge had larger changes in recharge than sub-basins with low recharge. The Grand Above Leggatt and Upper Conestogo River sub-basins seemed to have a larger change in recharge than other basins with similar recharge levels. Some basins had some slight variations to the general trends such as Mill Creek that had a very large reduction in recharge in April as well as May.

3.2.4. Stream Flow

Winter flows were higher across the watershed. This was true for all sub-basins and all scenarios for January and February, but December flows had more variability for some sub-basins. December median flows in the Speed River, Whitemans, Fairchild and McKenzie Creeks had the most variability across the scenarios. Monthly median flows are given for two sub-basins, Conestogo Inflows and Whitemans Creek, in Figure 3–7 and Figure 3–8. Charts for additional gauges are provided in Appendix D.

There is a trend for the highest median monthly flow to occur about a month earlier in most sub-basins, often in March instead of April; the exception is McKenzie Creek where all 10 modeling scenarios predicted the highest monthly median to be the same month as the baseline. Whitemans Creek, with similar climate and hydrology, had the opposite with nine scenarios with an earlier max median monthly flow. There was less of a trend for the magnitude of the highest monthly median flows. Some sub-basins trended towards higher max monthly median flows (Upper Conestogo, Eramosa, Lower Speed) while others trended towards lower max monthly median flows (Upper Grand River, Nith River and McKenzie Creek).

The May-June period saw lower flows for all scenarios, except for the high precipitation scenario, and all sub-basins. This resulted in the low flow season starting one or two months earlier than baseline. Summer flows were also less throughout the watershed, with the exception of the high precipitation scenario. About half of the scenarios also had the low flow season extended by one month into October. Fall flows were also smaller than the baseline for about half of the modeling scenarios.

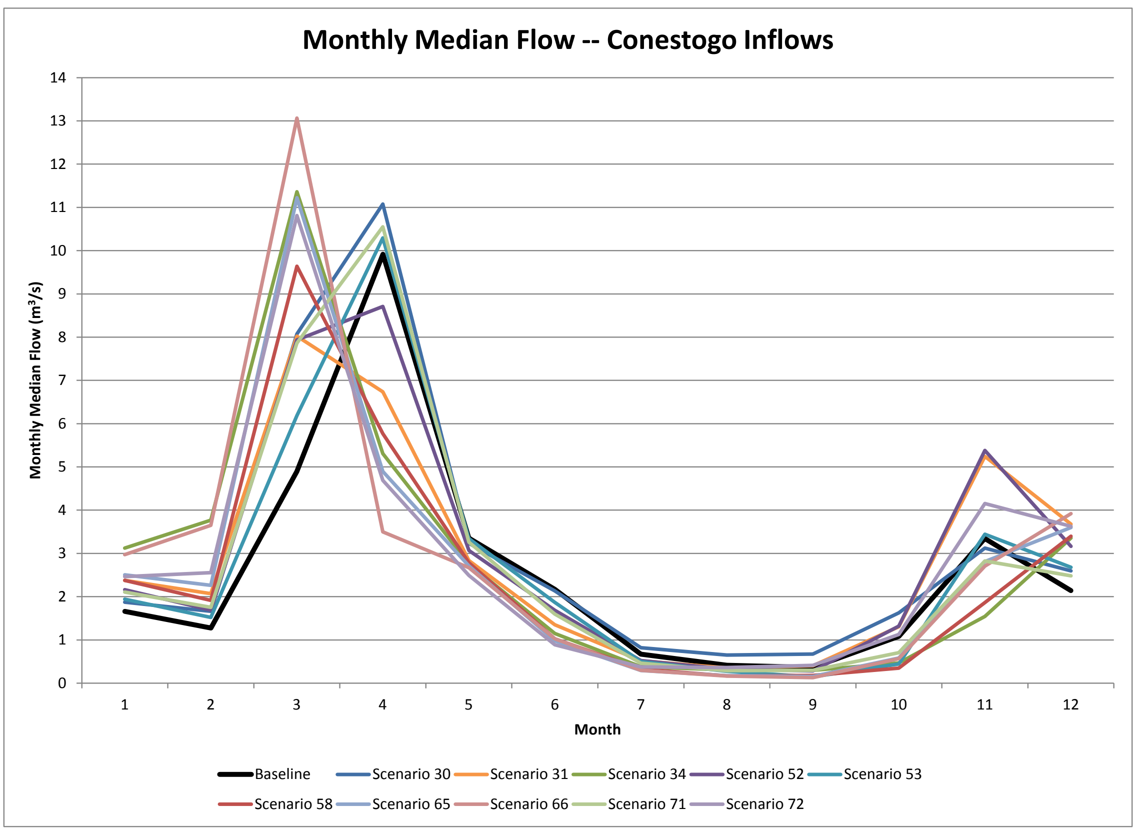


Figure 3–7: Monthly median flows for the inflows to the Conestogo Reservoir

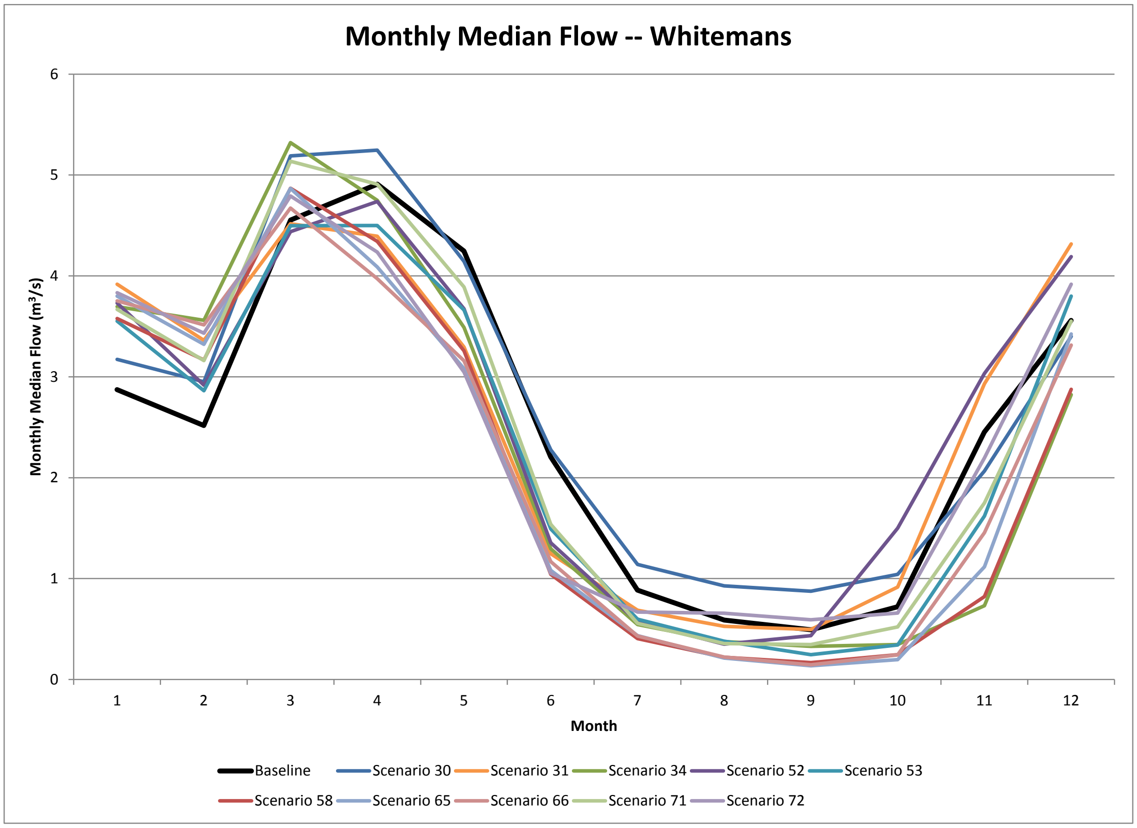


Figure 3–8: Monthly median flows for Whitemans Creek at Mt. Vernon

3.3. Key Hydrologic Processes

This section gives a brief discussion of changes to some key watershed processes based on modeling results for the 10 modeling scenarios. Key processes include stream flow to reservoirs, stream flow in high water use watersheds, recharge to high recharge sub-basins, and groundwater discharge to high baseflow watercourses. Groundwater discharge is discussed on an annual basis only, while the other parameters are discussed seasonally. Seasons are categorized as given in Table 1-2 in Section 1.4.1.

3.3.1. Flows

Flow increased in the winter and decreased in the spring compared to baseline data. Increases in winter flows appear more dependent on increases in temperature rather than increases in precipitation with the largest increases in flow corresponding to the largest increases in temperature. Decreased flow in the spring is most likely due to early melting of the snowpack (i.e., in the winter months). Generally, there is good confidence in temperature predictions with climate change modeling and therefore there is also good confidence in these results.

Summer flows generally decreased for most scenarios and appear to be more dependent on changes to precipitation rather than temperature. Generally, there is low confidence in precipitation predictions with climate change modeling making results from the summer period highly uncertain.

The results in the fall were variable. There was a trend with a decrease in precipitation resulting in decreased stream flow regardless of temperature, but an increase in precipitation did not always lead to an increase in stream flow. There were five modeling scenarios in the P1T2 (small increase in precipitation and moderate increase in temperature) category. Flow results for these five scenarios were not similar. There may be more variability on a monthly basis and/or the last three months of the year may not react hydrologically in a similar manner. As a result, the fall period will need to be re-examined in the future.

In Flow to Reservoirs

Changes to flow into the large reservoirs (Shand, Conestogo and Guelph) can affect reservoir operations including flood storage and low flow augmentation. The reservoirs are operated using rule curves with target levels for both the filling cycle and drawdown cycle based on calendar date. Additional information on reservoir operations is included in Section 4.

General trends to reservoir inflows, shown in Figure 3–9 for Shand Dam, include an increase in winter flows and a decrease in spring and summer flows. The fall period was variable between scenarios with no consistent trends for reservoir inflow. High spring flows are being shifted to the winter period because of earlier snow pack melting and more mid-winter melts. Total volumes of winter/spring flows have not changed significantly, but they have shifted seasonally with the traditional spring melt occurring in the winter months.

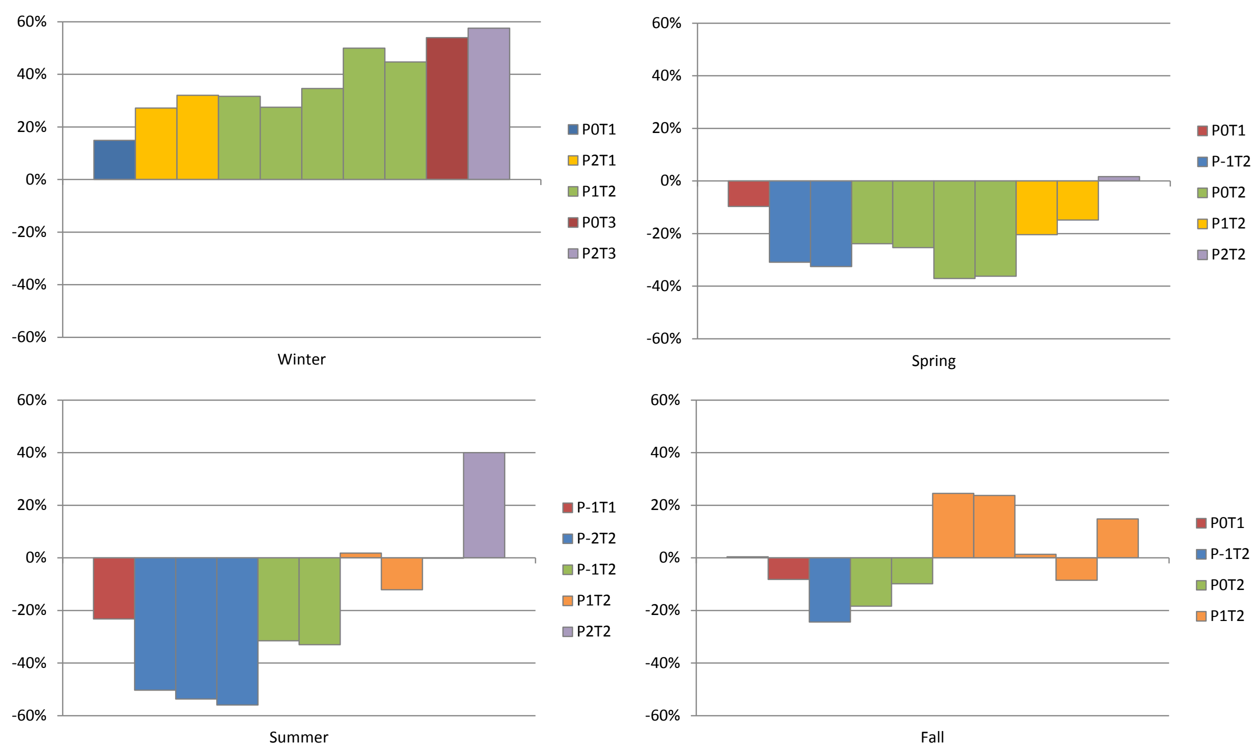


Figure 3–9: Percent Change to Seasonal inflows to Shand Dam grouped by category (as described in Section 1.4.1 and Table 1-2)

Increases in winter flows appear more dependent on increases in temperature rather than increases in precipitation. The scenario with the largest increase in winter flow (58% Shand, 67% Conestogo and 30% Guelph) had a large increase in temperature with a moderate increase in precipitation (P2T3). The second highest increase in winter inflows had no change in precipitation with a large increase in winter temperature (P0T3). Even a small increase in temperature with no increase in precipitation (P0T1) resulted in higher flows. There is more certainty with temperature predictions than precipitation predictions and with higher winter temperatures forecasted (all 76 scenarios), there is higher certainty that winter flows will increase in the future.

Most of the original ten modelling scenarios predicted a drop in summer inflows to the reservoirs. Lower summer inflows will increase the need for summer low flow augmentation. Changes in summer reservoir inflow appears to be more influenced by precipitation changes rather than temperature changes, but the combination of an increase in temperature with a decrease in precipitation resulted in the largest drop in inflows (approximately 52% for P-2T2 category). This category represents about 10% of all the scenarios, but approximately 30% of all summer scenarios predict a drop in precipitation. A small increase in precipitation during the summer with a moderate increase in temperature (P1T2) results in inflows very similar to the baseline (or historic) case. This category represents about 20% of all of the scenarios.

Subwatershed Flows

Changes to flow for high water use watersheds, ecologically sensitive streams and at municipal drinking water intakes are important to consider when planning for climate change within water management.

Three gauges were chosen to investigate seasonal changes to flows based on climate change scenario runs. The Eramosa River is a natural system that supports cold and cool water fisheries, has a municipal drinking water intake and is considered under stress from current water use. Whitemans Creek is a cold water fishery and is under stress from high seasonal water use for agricultural irrigation. Finally, the Lower Nith River is a high water use area with high groundwater discharge and is under pressure with increasing water use. None of these gauges are affected by reservoir operations. Other points of interest downstream of the major reservoirs are included in Section 4.

Figure 3–10 shows the results for Whitemans Creek on a seasonal basis. Winter flows increased in the watershed, with the highest increases observed in the northern parts of the watershed, which may be the result of a smaller snowpack. The summer period is most important in the Whitemans Creek watershed as this is when most of the water use occurs. Each of the six scenarios that showed a decrease in summer flows also had a decrease in summer precipitation. In total, about 40% of all scenarios have a decrease in summer precipitation. The biggest decrease in summer flows were observed in the P-2T2 scenarios with a greater than 50% flow decrease. The P-2T2 scenarios account for about 10% of all scenarios. Increases in precipitation resulted in increased stream flow. Increased summer precipitation is predicted by about 30% of scenarios. No scenarios were run with similar summer precipitation, which leaves 30% of scenarios with unknown results.

The Eramosa watershed and the lower Nith River had similar results to Whitemans Creek, but winter flows increased a bit more and summer flows decreased a bit less. For both of these watersheds summer decreases for the P-2T2 scenarios were approximately 35% instead of over 55% in the Whitemans Creek watershed. Winter flow increases were in the range of 20% or greater compared to the less than 15% in Whitemans Creek. Water use in these watersheds is balanced a bit more throughout the year and tends to be more groundwater than surface water based. Groundwater recharge is as important or more importation than surface water flow in these sub-basins.

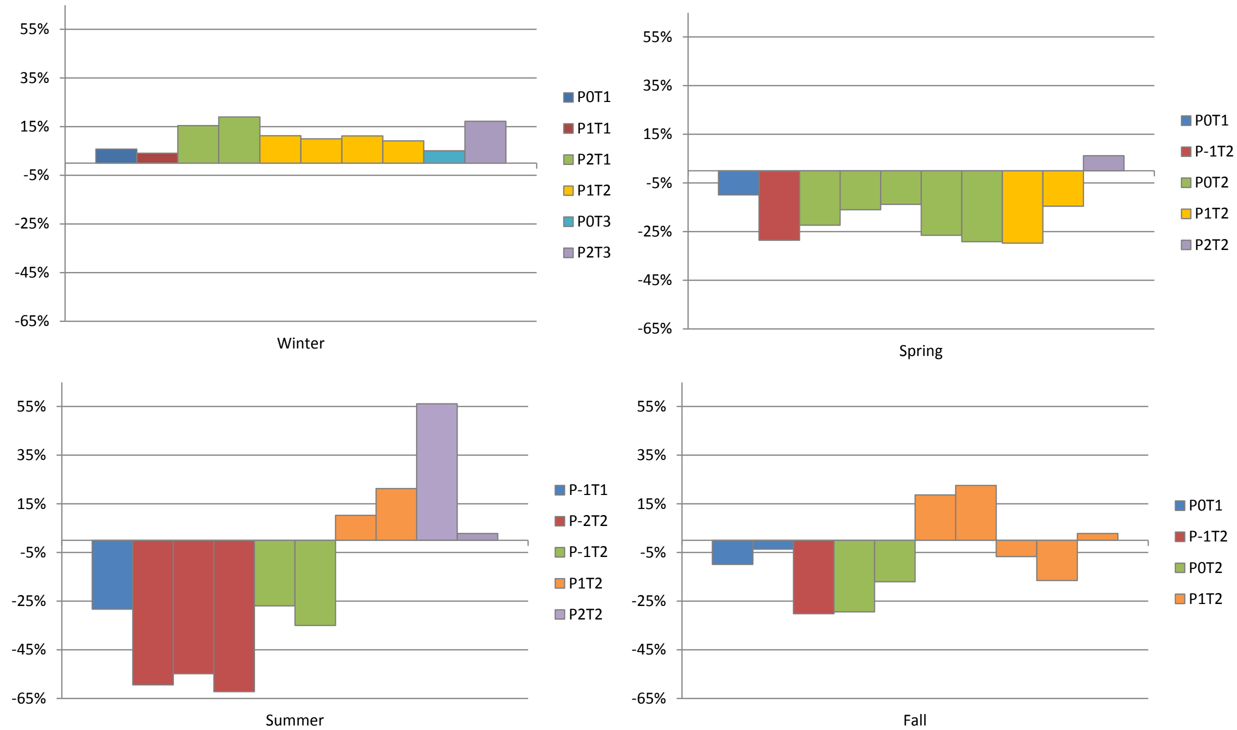


Figure 3–10: Percent Change to Seasonal Flows on Whitemans Creek grouped by category (as described in Section 1.4.1 and Table 1-2)

3.3.2. Recharge

Recharge in the Grand River watershed had historically been highest in the spring period with an estimated watershed average of approximately 40% of the annual recharge occurring during the spring months. The fall and winter months account for about 25% recharge each with the fall period contributing a bit more recharge than the winter period. The remainder of the recharge, approximately 10%, occurs during the summer months.

There are a number of high recharge areas within the watershed that support municipal drinking water supplies and groundwater fed baseflow. One of these key areas is the lower Nith River, which contains portions of the Waterloo Moraine and contributes to the large groundwater discharge zone on the Grand River between Cambridge and Paris. Groundwater discharge in this reach is important for improving river water quality, maintaining habitat and supporting municipal drinking water intakes downstream.

Figure 3–11 shows the seasonal recharge in the lower Nith subwatershed for the 10 modeling scenarios relative to baseline. The biggest changes occurred in the winter and spring periods. The winter period saw an increase in recharge, while the spring period saw a decrease. Part of these results is from a shifting of the highest runoff period of the year from the spring to the winter months. Scenarios in the higher temperature categories had the largest increase in winter recharge. Additionally more winter precipitation and less frozen ground contributed to greater recharge during the winter period. The spring period had the largest decreases for the higher increase in temperature with no increase in precipitation.

Recharge in the north increased a greater amount in the winter with some scenarios more than doubling the amount of winter recharge relative to baseline. The spring period decreased more as well, but not to the same extent. On an annual basis, recharge increased for more scenarios than decreased in the North, but was the opposite in the central part of the watershed with more scenarios with decreased recharge. For more than half of the scenarios annual changes to recharge were below 10%.

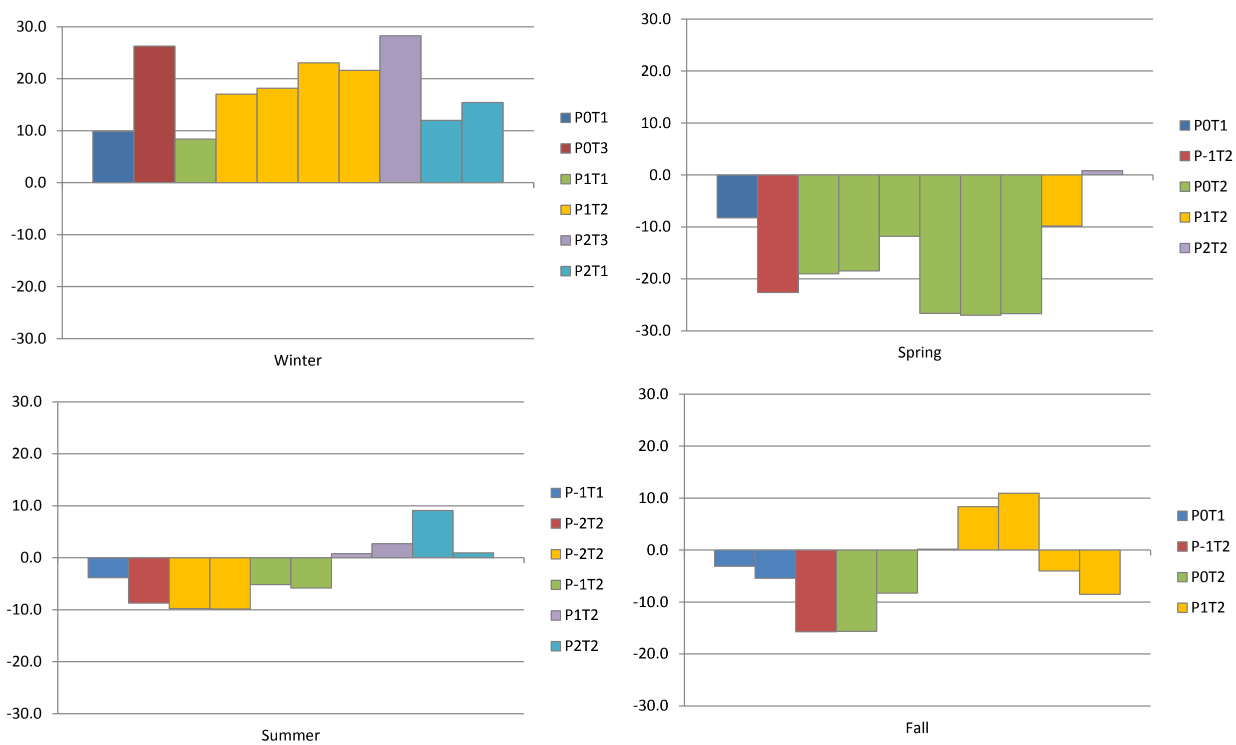


Figure 3–11: Change to seasonal recharge in the Lower Nith Subwatershed grouped by category (as described in Section 1.4.1 and Table 1-2)

3.3.3. Groundwater Discharge

Groundwater discharge to surface water is calculated using output from the groundwater model. As of the date of this report only steady state groundwater model runs using average annual recharge have been completed. This means that only average annual discharge rates are available for analysis and no discussion on the seasonality of discharge can be included.

Groundwater discharge to surface water is tied directly to recharge, but is also dependant on water table, geology and water takings. Changes in recharge can affect the amount and timing of groundwater discharge. With only average annual values available, the timing of groundwater discharge cannot be included in the discussion. Discharges from groundwater are very important for the Grand River below Cambridge through to Paris. This reach of the river is often called the ‘recovery reach’ because groundwater discharges increase stream flow and improve water quality. Groundwater discharge to this reach is important year round. In the summer, groundwater discharge improves water quality by dilution and temperature modification and helps to ensure flow targets at Brantford are met. In the winter, discharge along this reach help to modify temperature and keep some areas free of ice cover so volatilization of ammonia compounds is possible and provides habitat for some species.

Discharge to the middle Grand decreased for six of the modelling scenarios, increased for three scenarios and was the same for one. The largest decrease was 11% and corresponded to a scenario that had a 15% decrease in recharge for a nearby sub-basin. The largest increase in groundwater discharge was 7% and corresponded to an increase in recharge at a nearby sub-basin of 10%. There is a relationship between groundwater discharge and recharge, but it is not direct. The seasonal shift in recharge from spring to winter may also affect the timing of groundwater discharge. More information on the seasonality of groundwater discharge is needed to expand further discussion on groundwater discharge.

3.4. Additional Scenarios

Two additional climate scenarios, Scenario 6 and Scenario 10, were chosen to cover a wider range of future seasonal climates (described in Section 1.5). These scenarios were run through the surface water model after the original ten modeling scenarios were run and results analysed, so their results were not included in earlier sections. The additional scenario modeling results are described in this section including evapotranspiration, runoff, recharge and stream flow. Results are compared with the original ten modeling scenarios to provide a wider coverage of possible future conditions. The groundwater model was not run with these additional scenarios and as such, there are no groundwater discharge results available.

3.4.1. Evapotranspiration

Results for evapotranspiration were very similar to the original ten modeling scenarios as Figure 3–12 shows. Monthly average change in evapotranspiration was very close to the average of the original scenarios with a few exceptions. In June, Scenario 10 was slightly higher than the maximum June average of the ten modeling scenarios with a value of 8.6mm. Scenario 6 evapotranspiration in October and December were slightly below the ten modeling scenario range with values of 1.7mm and -0.4mm respectively.

3.4.2. Recharge

Recharge was high during the winter for both of the scenarios. Winter recharge is dependent on both temperature and precipitation. Increased temperature results in more melt events and less frozen ground allowing for more winter recharge. Scenario 6, which had high temperature, but not high precipitation still had higher recharge than the original ten scenario average. This is most likely the result of really high precipitation in December contributing to an early winter snowpack and saturated ground conditions leading into the winter season. Scenario 10 had moderate increases in both winter precipitation and temperature leading to more water available for recharge and less frozen ground. Recharge in the fall was also high for both scenarios due to increased fall precipitation. Figure 3–13 shows how the new scenarios fit with the original modeling scenarios on a watershed basis.

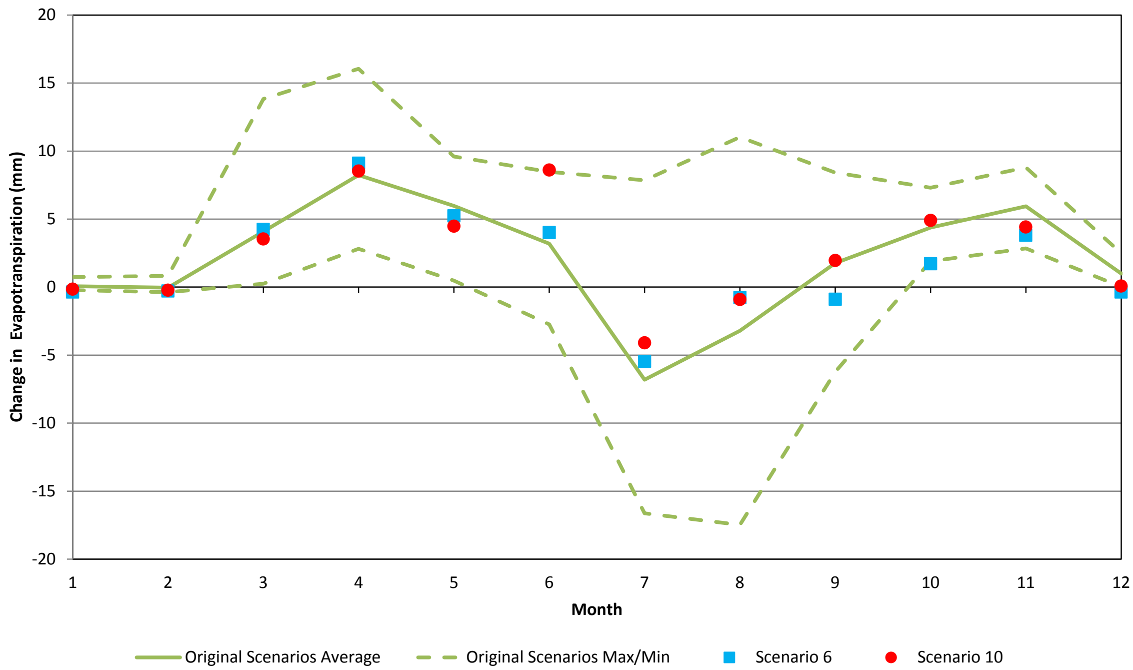


Figure 3–12: Modeling results for average monthly change in evapotranspiration for additional scenarios

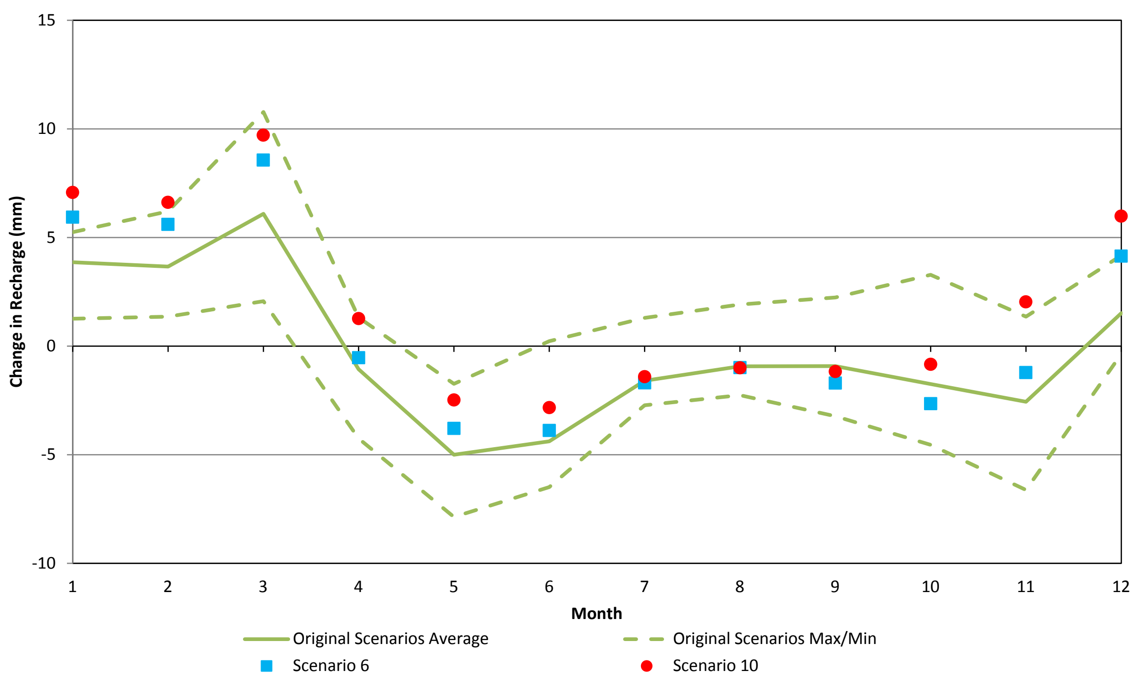


Figure 3–13: Modeling results for average monthly change in recharge for additional scenarios

3.4.3. Runoff

Runoff increased with higher precipitation months and was near the other modeling scenarios during the drier months. The winter and fall periods had higher runoff than the original modeling scenarios. For Scenario 10 this is a result of higher precipitation, coupled with more melt events during the winter. For Scenario 6 the high winter runoff is likely from melt events with a winter snowpack started in December and wet conditions leading into the winter season.

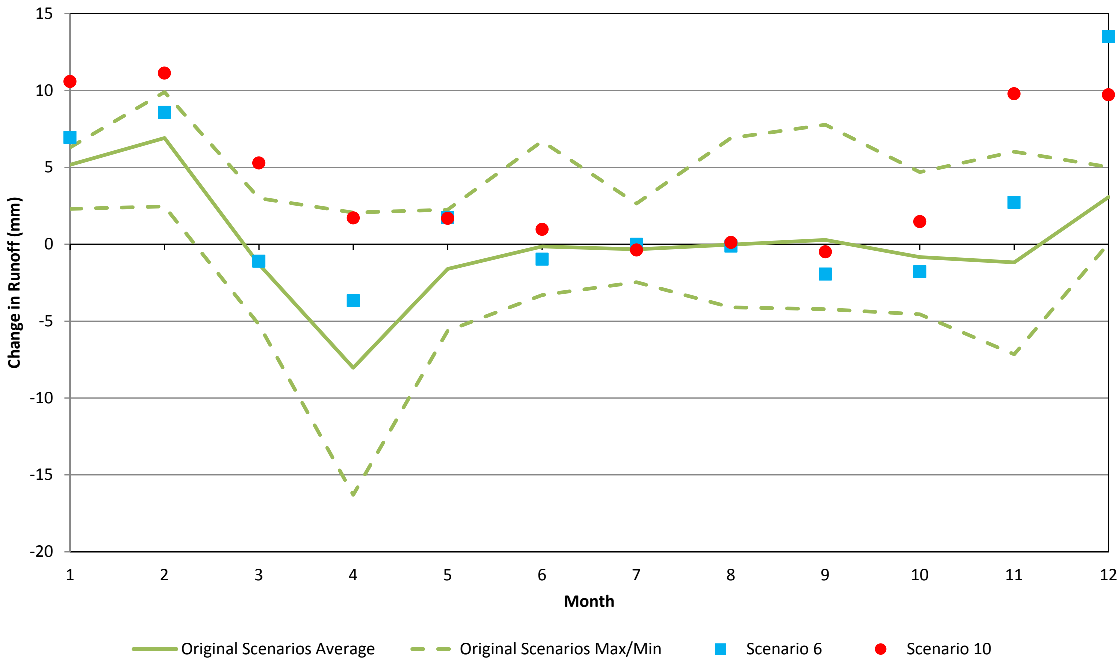


Figure 3–14: Modeling results for average monthly change in runoff for additional scenarios

3.4.4. Stream Flow

The two additional scenarios had similar seasonal stream flow results to the original ten modeling scenarios. Flows were higher than baseline in the winter including December. Spring shifted earlier, along with the low flow season. The low flow season was longer with lower average flows. All of these results strengthen trends from the original modeling scenarios. Figure 3–15 gives an example for one location, Whitemans Creek at the Mt. Vernon stream gauge.

The original modeling scenarios had both strong and weak seasonal trends. Strong trends occur when results are similar for all of the scenarios, while weaker trends occur when a large number, but not all of the scenarios have similar results. Strong trends include higher winter flows, earlier spring melt and higher December flows. Weak trends include earlier low flow season, lower summer flows and longer low flow season.

The fall season was very variable in the original modeling scenarios and the additional scenarios were similar. Results have been so variable in the fall that there have not been any clear trends.

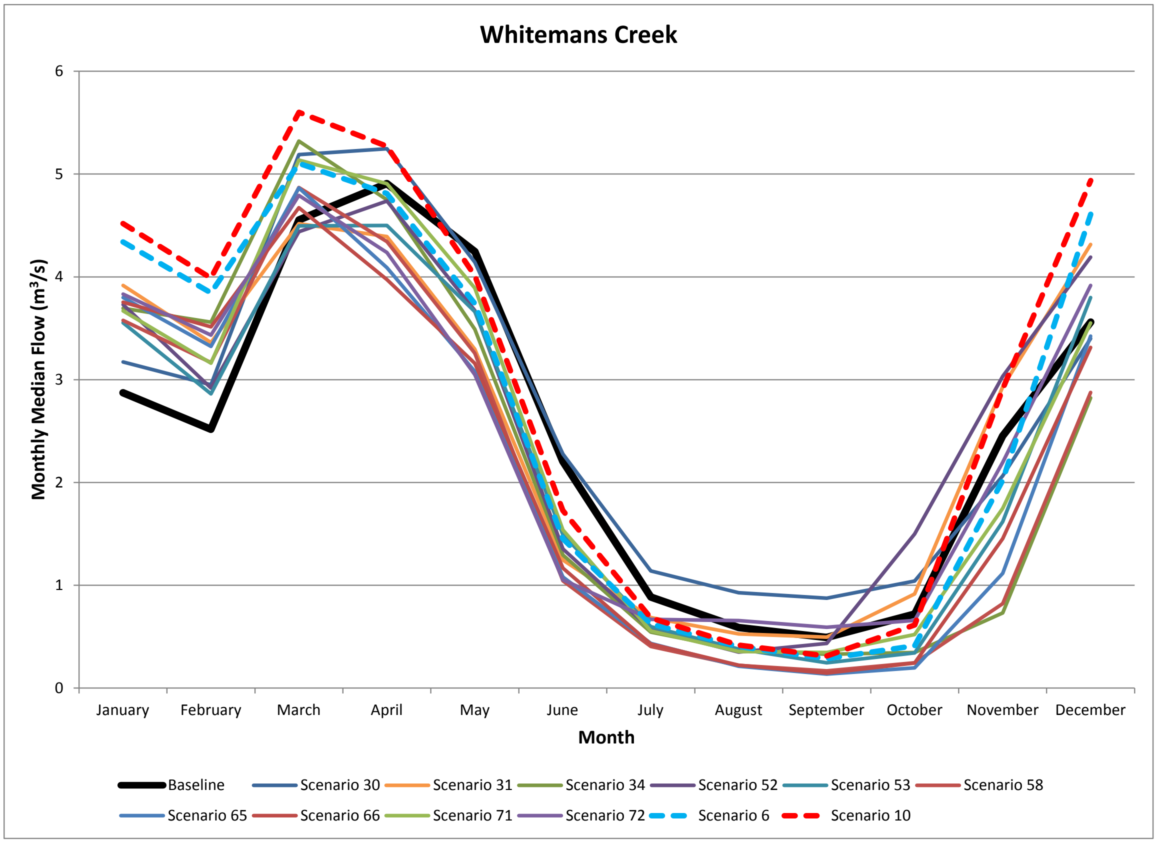


Figure 3–15: Flow results for 12 modeling scenarios for Whitemans Creek at Mt. Vernon.

3.4.5. Summary

The additional scenarios filled in some seasonal gaps in the future climates that were missing in the ten original modeling scenarios. There is still a gap in analysing combinations of scenarios such as a wet winter followed by a dry and hot spring. The additional scenarios strengthen some of the trends found with the original scenarios and increased the range to other trends but generally, the new scenarios were within or close to the results of the original modeling scenarios.

The additional scenarios increased the coverage of winter scenarios from approximately 50% to 90% of all 76 scenarios. The additional scenarios were both for a moderate increase in temperature, but different increases in precipitation. For all 12 scenarios there was an increase in both winter precipitation and temperature, which resulted in an increase in stream flow, recharge and runoff.

The additional scenarios did not change the coverage of scenarios for the spring with the original ten modeling scenarios covering approximately 80% of all scenarios available. Spring trends included a decrease in both runoff and recharge, which was balanced with an increase during the winter. As well, there was a shift to an earlier spring freshet. With the shift to an earlier spring and key runoff period being earlier, flows also dropped to summer low flow levels earlier.

The additional scenarios increased the coverage of summer scenarios from approximately 50% to 75%. Summer trends were a bit weaker than the spring trends with a weak trend to lower summer flows, but a strong trend of similar or lower summer flows. Only a moderate increase in summer precipitation lead to increased summer flows and only 7% of scenarios had increases in summer precipitation in that category.

The additional scenarios for the fall period were both for a moderate increase in precipitation. None of the original ten scenarios had a moderate or large increase in precipitation. The additional scenarios increased the coverage of fall scenarios to over 86% of the 76 scenarios. With the increase in precipitation in the additional scenarios, there was an increase in stream flow, runoff and recharge. Some of these increases were outside of the range of the original ten modeling scenarios. The fall period still shows a wide range of variability both in the future climates predicted and in the hydrologic response to these changes.

There are still some categories that are not covered by these scenarios. For the winter, there are no 'large increase in precipitation' (P3) scenarios included and the summer does not have a 'large increase in temperature' (T3) scenario. Both of these scenarios are rare and show extreme conditions, but consideration should be given to adding more scenarios depending on the resources available.

3.5. Summary

Winter

The winter season was highly affected by the increase in temperature and mildly affected by increased precipitation. Resulting in more mid-season snow melt events and more rain rather than snow, this in turn resulted in more runoff and higher stream flows. Recharge also increased as a result of cover crops, less frozen ground conditions and more available water. All 76 scenarios predicted increased winter temperatures, with approximately 80% with more than a 2 degree average winter increase and 18% with more than a 4 degree average increase. In addition, 80% of scenarios predicted increased precipitation. There is low uncertainty in winter results.

Spring

The spring season is affected by the changes to the winter and summer seasons. The winter is predicted to have a less stable snowpack and warmer temperatures, resulting in spring like conditions approximately one month earlier than the baseline observed data. The reduced snowpack will also lessen the spring freshet resulting in lower flows, runoff and recharge in the normal spring months. Summer low flow conditions are predicted to start earlier by about a month. The result will be a shift in the typical spring months from April, May and June to March, April and May. There is high certainty in the winter predictions, but less certainty in the summer predictions so the earlier spring predictions have more certainty than the later spring predictions.

Summer

The summer low flow season may see lower flows. The summer season is more affected by the changes in precipitation rather than changes in temperature. For scenarios with less summer precipitation and scenarios with similar summer precipitation, stream flow decreased along with a decrease in runoff and recharge. Only scenarios with much higher precipitation had higher summer stream flows. Summer scenarios are split with about 40% predicting a decrease, 30% predicting little change and 30% predicting an increase to precipitation. There were very few scenarios (less than 10%) with a high increase in precipitation during the summer. Precipitation predictions based on current climate models are fairly uncertain and variable, increasing the uncertainty in summer results.

Fall

Fall results were variable and highly uncertain. There was uncertainty in climate predictions for the fall months and variability in how changes in climate affected hydrologic processes in the fall. There was a weak trend to the low flow season extending into October. This would result in a much longer low flow season since there was also a trend for it to start earlier by a month. December was the most variable month and should be re-examined as part of winter, instead of fall, in the future.

Multiple Seasons

To date there has been little analysis of multiple seasons (e.g. a dry winter followed by a hot summer). Even an analysis on the most common multi-seasonal patterns has not been done because of the complexity and the number of combinations when multiple seasons are taken into consideration.

A focus on the key hydrologic functions and connections to seasonality can help to reduce the number of combinations of seasons by focusing on situations that have the potential to cause conditions different from the historical record. For example, results show that a warm winter shifts the spring runoff period into the winter months and a low precipitation summer increases the need for flow augmentation. Before focusing on the question; what would happen if a warm winter were followed by a dry summer, an investigation into whether that type of scenario exists and the number of those scenarios, is needed.

Another important consideration is regarding key functions that bridge multiple seasons and changes to these functions that cannot be assessed by looking at seasons in isolation. For example, the connection between seasonal changes in recharge and seasonal changes to groundwater discharge cannot be analysed separately because the groundwater system may take months or years to react to changes. However, the effects of an increase in winter melt events on spring runoff can be assessed by looking at the seasons separately, because of the direct relationship between spring runoff and the size of the snowpack.

The two key hydrologic processes in the watershed that are most effected by multiple seasonal changes are recharge/discharge and reservoir operations. Reservoir operations are investigated more closely in Section 4 and transient groundwater modeling will be included in future studies.

4. Reservoir Yield Modeling

Current reservoir operations and low flow targets have been set based on past flow and climate conditions. In order to ensure that the GRCA can continue to meet low flow targets in the future a review of reservoir operations taking into account climate change was needed using the Grand River Reservoir Yield model. The surface water model simulates reservoir operations at a sufficient level to simulate watershed processes, but it does not include a decision making routine that would mimic operation of the reservoirs to meet low flow targets along the river system. The reservoir yield model is a simulation model that simulates reservoir operations based on observed daily inflows and downstream local contributions between the reservoirs and flow target locations. In terms of reservoir operations, the reservoir yield model is a better predictor of flow rates downstream of the large reservoirs than the surface water model alone.

4.1. Methods

4.1.1. Reservoir Yield Model

The reservoir yield model includes the three largest watershed reservoirs: Shand Dam, Conestogo Dam and Guelph Dam. Operational flow targets are assigned to reservoir discharges and four downstream target locations. The model assumes May 1st storage targets are achieved for each year. This is a source of error when using this model to determine reservoir operations with future climate scenarios. A discussion on how this affects the results of the analysis is included in Section 4.2.2. Reservoir yield modelling as part of this study only uses the current operating procedures. The model is primarily a tool for investigating flow augmentation reliability and not for determining flood storage requirements. A separate study was conducted for the Luther Reservoir and has been included in Appendix F.

The reservoir yield model does not have foresight. It assesses discharge requirements at each reservoir and available storage to supply the required discharge to the downstream flow target locations on a day by day basis. In real operating situations, reservoir managers have foresight and weather forecasts and can adapt operations to anticipated conditions. Therefore it should be kept in mind; the reservoir yield model provides only an approximation of how the reservoir would be operated and the flow reliability that would result.

4.1.2. Data Preparation

Output from the surface water model cannot be used directly as input into the reservoir yield model because the surface water model over estimates low flows and flows during the late spring season (May and June). These are key times for reservoir operations and the errors in flow estimation although small on a watershed scale are significant enough to give misleading results. The surface water model uses a simplified routine to model groundwater fed baseflow, which is the predominant source of flow during low precipitation conditions in the watershed. Recent calibration of the model has improved low flow estimation, but there are limitations with the GAWSER model code that has limited additional calibration in this area. More information on these issues and modifications are included in Appendix E.

To solve the overestimation of low flows issue, surface water modeled data was used to adjust existing observed data to mimic the results of flow changes from the climate change scenarios. The reservoir yield model can then be used to analyse effects of climate change on reservoir operations particularly during the low flow season. By using observed data and a relative change approach, the results of the future climate data sets can be compared against observed data model runs.

Flow output from the climate change scenarios surface water model runs was summarized on a monthly basis and the percent change from baseline output data was calculated. The percent change values were then applied to observed data from the baseline period (1961-1990) to make reservoir yield input data sets. Appendix E contains additional information on the difference between using flow data directly from surface water compared to adjusted observed data.

4.2. Results

The results from the reservoir yield model runs have been divided into three sections. The first section (4.2.1) presents the overall results in comprehensive tables. The second section (4.2.2) presents a discussion of the results in terms of reservoir operating seasons and the last section (4.2.3) presents a discussion of the results in terms of different climate change scenarios.

Low flow targets were set as part of the 1982 Basin Study based on a 95% reliability of the reservoirs having enough water in storage to meet or exceed the targets. Evaluation of reliability is based on whether a reliability of 95% by time can be achieved (Boyd and Shifflett, 2013).

4.2.1. General Results

Reliability results for the ten climate change scenarios and the observed baseline period are given in Table 4-1, while the number of years in which the flow target was not reached for 2 or more days is given in Table 4-2. Table 4-3 gives the number of years that the reservoirs did not reach 90% of May 1st levels for each of the climate change scenarios. The total model simulation covers 30 years.

Table 4-1: Reliability of meeting low flow targets under climate change

Scenario	Jan-Apr			May-Sep			Oct-Dec		
	Doon	Brantford	Hanlon	Doon	Brantford	Hanlon	Doon	Brantford	Hanlon
Observed*	100%	99%	100%	99%	100%	98%	96%	96%	99%
30	100%	98%	100%	100%	100%	99%	99%	98%	100%
31	100%	100%	100%	100%	100%	96%	99%	97%	99%
34	100%	100%	100%	98%	97%	**93%**	**90%**	**86%**	98%
52	100%	100%	100%	100%	100%	97%	99%	97%	99%
53	100%	99%	100%	99%	99%	96%	96%	**93%**	98%
58	100%	99%	100%	100%	98%	**90%**	**90%**	**82%**	98%
65	100%	100%	100%	**93%**	**90%**	**88%**	**89%**	**79%**	98%
66	100%	100%	100%	**94%**	**90%**	**88%**	**90%**	**84%**	98%
71	100%	100%	100%	99%	99%	96%	95%	**93%**	99%
72	100%	100%	100%	100%	100%	**93%**	98%	95%	99%

*Model results using observed flow data

Table 4-2: Number of years with flow target violations under climate change scenarios (N= 30 years)

Scenario	Jan-Apr			May-Sep			Oct-Dec		
	Doon	Brantford	Hanlon	Doon	Brantford	Hanlon	Doon	Brantford	Hanlon
Observed*	0	3	0	2	1	4	3	4	1
30	0	3	0	0	0	3	1	1	1
31	0	0	0	1	1	5	2	3	2
34	0	2	0	7	9	9	9	16	3
52	0	2	0	1	2	5	1	4	2
53	0	3	0	3	4	5	7	8	2
58	0	6	0	5	8	13	14	18	5
65	0	2	0	17	18	12	15	22	5
66	0	1	0	17	16	12	12	17	3
71	0	2	0	2	5	6	6	9	2
72	0	1	0	2	2	7	3	8	2

*Model results using observed flow data

Table 4-3: Number of years reservoirs did not reach 90% of May 1st level (N = 30 years)

	Shand	Conestogo	Guelph
Observed*	0	1	0
30	1	0	0
31	5	5	0
34	5	4	0
52	3	5	0
53	3	2	0
58	2	3	0
65	6	6	0
66	8	8	0
71	2	2	0
72	7	6	0

*Model results using observed flow data

4.2.2. Operating Season

The large reservoirs are operated based on three seasons. The winter/spring (January to April) season includes some winter flow augmentation but is more focused on the filling cycle of the reservoirs and flood storage. The late spring and summer season (May to September) is the primary augmentation season with the highest target flows throughout the watershed to support wastewater assimilation, supply municipal water and support ecological functions. The fall season (October to December) has lower augmentation needs as flow targets are lower since the river has a greater capacity to assimilate wastewater outflows due to cooler temperatures and less aquatic vegetation growth.

January to April

The climate change scenario reservoir yield results showed that winter flow augmentation reliability would not change from current conditions, but there was a greater chance of not filling the reservoirs to the May 1st filling target, especially at the Shand and Conestogo reservoirs.

Although winter flows were higher under scenarios of climate change, the reservoir filling cycle has been designed to allow for flood storage so excess water throughout the winter is released to maintain needed flood storage. An earlier spring melt or more frequent winter melt events under climate change scenarios therefore resulted in a loss of water for storage under current operating procedures. In order to capture water that was traditionally in the snowpack an adjustment may be needed to the winter rule curves to allow for more flexibility in winter operating levels. Any changes to the rule curves must account for flood storage needs, and at this point, there is limited information on how climate change will affect storm patterns and intense precipitation events. Changes to winter processes and the winter rule curve will result in more active management of the reservoirs during the winter season to balance available flood storage needs with storage for low flow augmentation needs in the summer period.

There was no change in the reliability of meeting the May 1st filling target at Guelph Dam.

May to September

The primary augmentation season of May to September has the highest flow targets on the river system. For the Grand River targets, the number of times the flow target was not met increased with the climate change scenarios compared to baseline, but the overall reliability dropped below 95% for only two climate change scenarios. These two scenarios had the lowest summer precipitation levels with a decrease in precipitation by approximately 20%. These scenarios also had the most instances of not meeting May 1st targets, which would result in an even lower reliability than the reservoir yield model results show with the current rule curves.

For the Speed River target, there were five climate change scenarios with flow reliability lower than 95%. Four of these scenarios had a decrease in summer precipitation of between 7% and 20%. The other scenario had an increase in precipitation, but also a high increase in summer temperatures. Decrease in summer precipitation or a large increase in summer temperatures may result in increased difficulty in meeting summer flow targets on the Speed River. Instances of not meeting target increased, with the highest increases for the low precipitation years.

October to December

In the fall season flow targets are reduced from the summer targets recognizing that generally water quality improves and the aquatic community is under less stress with cooler temperatures. Even with lower flow targets, the climate change scenarios resulted in a large number of target violations and resulting reliabilities below 95%. For the Grand River, there were four scenarios at Doon and six scenarios at Brantford where flow targets did not meet the 95% reliability level. Meeting the flow target at Brantford in the fall season had fairly low reliability. The Brantford flow target is not lowered for the fall period and remains at $17m^3/s$ year round. Flow at Brantford can be highly affected by groundwater discharges between the reservoirs and the flow target location. More study on the effects of future climate on the groundwater system is needed to confirm these findings.

The flow target on the Speed River was met with similar reliability to the observed data for all climate change scenarios, but there were more instances of flows dropping below the target for short periods of time.

4.2.3. Climate Change Scenarios

The climate change scenarios with the most flow target violations were Scenario 65 and 66. Scenario 65 was the second lowest for annual precipitation, while Scenario 66 annual precipitation was close to the baseline. These scenarios predicted a 20% drop in summer precipitation and represented the driest 9% of all 76 scenarios available for analysis. Temperature increases were moderate for Scenario 65, while Scenario 66 had the largest increase out of all 10 scenarios, causing more mid-winter melts and a reduced spring runoff. Low summer precipitation coupled with low runoff to fill the reservoirs appears to be the primary drivers resulting in high instances of flow target violations for these two scenarios.

Some of the other scenarios that had annual decreases in total precipitation, but had summer precipitation close to or higher than baseline did not have the same results as the really low summer precipitation scenarios. Scenario 58 had the biggest decrease in annual precipitation of all of the scenarios studied, but in the summer season precipitation was only slightly below baseline. This scenario resulted in many flow target violations, but was not as severe as the scenarios with very dry summers. This shows the importance of precipitation during the summer to maintain flows in the river regardless of reservoir operations. Flow targets in the river system were set based on historic local inflows remaining at similar levels into the future. Reductions in summer precipitation will lower local inflows and put stress on the reservoir system to maintain flow targets.

4.3. Reservoir Operations Recommendations

These results show that there will most likely be a greater need for summer and fall flow augmentation in the future. This will be especially important with raising temperatures which can further affect water quality. It will be important that the reservoirs be filled during the spring period. With more mid-winter melts there is a greater need to capture and store melt-water as it becomes available, but this needs to be balanced with maintaining required flood storage for protection of downstream communities. Current climate models are predicting more intense storm events which could lead to localized flooding, however the data is not available to analyze how this might affect flood storage needs within the Grand River watershed.

With the great uncertainty in climate change predictions and a lack of information on potential changes to flood storage needs, it is recommended that flexibility is built into the reservoir operations and that operations are supported by a high degree of monitoring so that operators can react to increasingly variable conditions expected with climate change. This study showed that the future may be within the past range of variability, but changes to average conditions can mean that the reservoirs will be operated to the extreme ends of past conditions more often. The number of flow violations may increase, but the reliability of meeting flow targets will most likely stay at or above 95% reliability based on the climate change scenarios run in this study.

5. Regional Climate Model Scenario

The previous sections of this report were based on future climates predicted using Global Circulation Models (GCMs). There are some limitations with using GCMs because of the large scale of the output and lack of regional land forms that can affect local weather patterns (see Section 1.1). Weather patterns in Southern Ontario are greatly affected by the influence of the Great Lakes, but GCMs grid sizes are too big to include them. So weather patterns including lake effect snow, convective storms and lake breeze effect are not included in output from GCMs. These weather patterns are important in the Grand River watershed for winter hydrology and storm events that can result in flooding.

Regional Climate Models (RCMs) have the potential to overcome the short falls of GCMs on a local scale. RCMs are localized models that take GCM model output and run it through a more localised model of a smaller area. The RCM models have a finer grid size and can include local landforms and therefore better simulate local weather patterns. RCMs are not without some problems. There is a limited number of RCMs and they have been driven with a small number of GCMs so there are not as many data sets compared to using GCM model output. To date access to data from RCMs has been limited and consequently there are few studies that look at the effectiveness of RCMs in modeling localized weather patterns that are important to water resource management in Southern Ontario.

As part of climate change studies in the Grand River watershed the GRCA teamed up with a group from Environment Canada and the University of Waterloo. One aspect of the partnership was to collaborate on RCM data. The team from the University of Waterloo accessed RCM data and studied ways of correcting the data to remove some known modeling bias. The data was then provided to the GRCA to use in the Grand River watershed models to analyses the differences between GCM and RCM data and the effectiveness of the bias correction techniques. Work on the RCM data sets occurred after the work on the GCM change field scenarios described in early sections.

5.1. Future Climate Data Sets

Only one scenario was available with RCM output. The scenario was from the CRCM_CGCM3 model run using baseline data from the 1971 to 2000 period. The future time period was the 2050's. The RCM data was provided to the GRCA in both raw and corrected forms. Data sets that were used in this study include the observed baseline period, RCM model output for the baseline period, RCM model output for the future period, RCM change fields and GCM change fields. Each data set is described in the following sections including how they were used or adapted for the hydrologic model.

5.1.1. Scenario Description

The description of the scenario is based on GCM change fields to put it into context with the other scenarios described in Section 1. This scenario had a high increase in annual precipitation with an increase of 10% and is near the 85th percentile for precipitation. The scenario was closer to the middle for temperature, at about the 70th percentile, with an annual increase of approximately 3 degrees. Increases in temperature were fairly moderate year round. The winter and spring periods had a small overall increase in precipitation, but high monthly increases in January, March and December. There was no change for summer precipitation and a moderate increase in fall precipitation.

5.1.2. Climate Data Sets

RCM future climate data was provided to the GRCA in raw and corrected formats and covered the entire area of the watershed in 12 square grids of 45 km x 45 km. The majority of the watershed was contained in seven grids which were used to build the modeling data sets. Precipitation data was provided in 3 hourly time steps and temperature data in daily maximum and minimum values. A set of monthly change fields were provided that were calculated based on uncorrected data. RCM output for the baseline period was also available for comparison.

There were eight different scenarios that were run through the hydrologic model. Analysis of the scenarios varies with some only analysed on a limited basis and other analysed extensively. The data sets are given in Table 5-1.

Table 5-1: Climate Data Sets

Data Set	Type	Period	Correction
Baseline	Observed	Baseline (1971-2000)	None
RCMBase-Raw	RCM Output	Baseline (1971-2000)	None
RCMBase-Corr	RCM Output	Baseline (1971-2000)	Corrected for drizzle effect
GCM-CF	GCM Change Field	Future (2050's)	None
RCM-CF	RCM Change Field	Future (2050's)	None
RCM-Raw	RCM Output	Future (2050's)	None
RCM-P125	RCM Output	Future (2050's)	Corrected for temperature bias and 0.125mm drizzle effect
RCM-P221	RCM Output	Future (2050's)	Corrected for temperature bias and 0.221mm drizzle effect

Some adjustments were needed to the RCM data sets in order to use them in the hydrologic model. The model uses 21 different climate stations applied to 26 zones of uniform meteorology (ZUMS). Climate stations are not always within the ZUM they represent and it is important to apply the RCM gridded data to the appropriate ZUM as well as climate station for comparison with other model runs.

RCM Change Field

The RCM grids were mapped on top of the ZUMs and climate stations (Figure 5–1). If 80% of the ZUM fell into a single grid than the change field for that grid was applied to baseline data for that ZUM's climate station. Half of the ZUMs were assigned change fields in this way. In areas where the ZUM was in two or more grids, the change fields were inspected to compare differences in values. If the change fields were similar between the grids, 60% or more of the ZUM was within one grid, and the area covered by that grid contained the landscape that controlled the major hydrologic process (i.e. sand plain in lower Whitemans Creek) then that grid change field was applied to the baseline climate data for the ZUM. The remaining four ZUMs were split fairly equally between two grids. For these ZUMs an average of the change fields on a monthly basis for the two grids were used. Generally the change fields for the seven girds used were fairly similar with only minor differences.

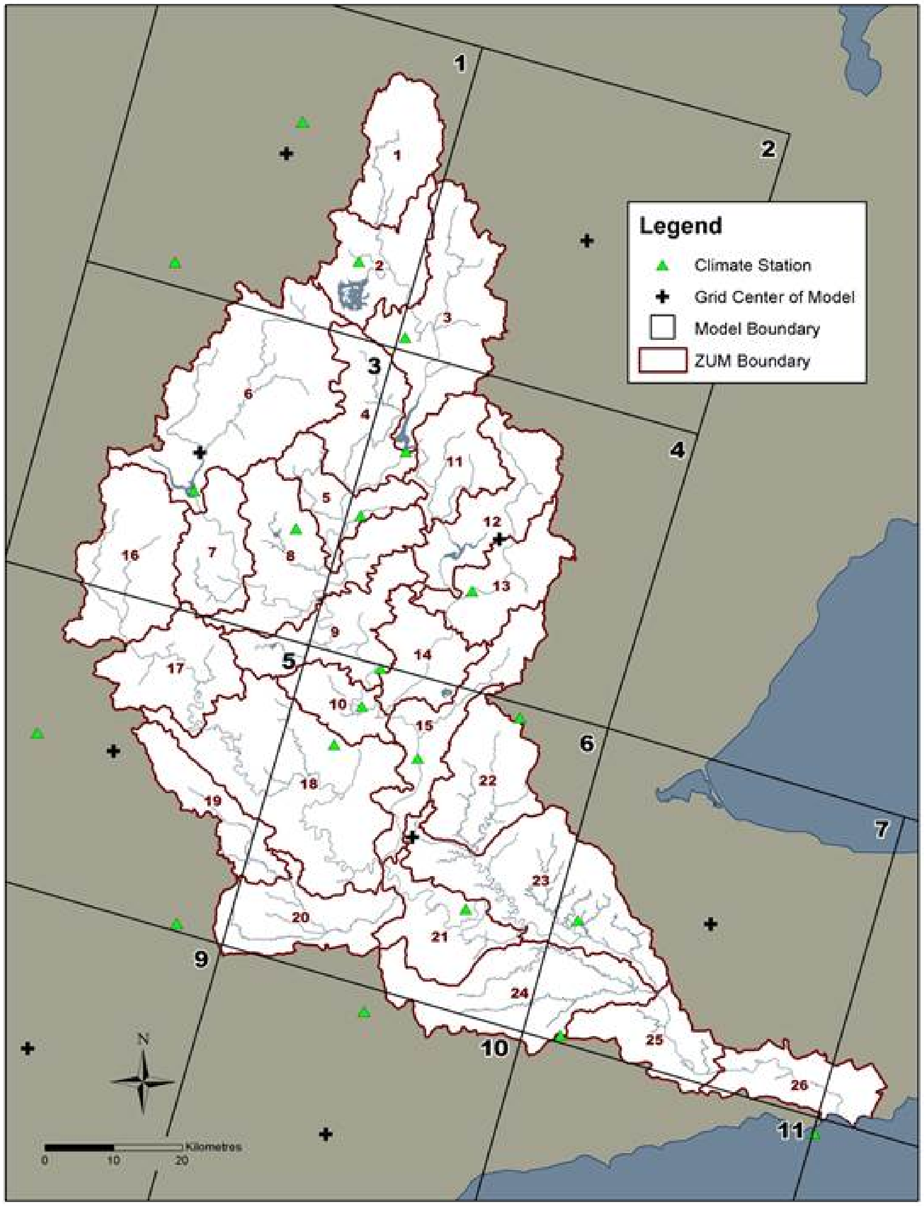


Figure 5–1: Map of RCM grids, model ZUMS and climate stations

Change fields were then applied to the baseline observed data set for each climate station. Temperature change fields were added to the maximum and minimum day observed temperatures and used as is. Precipitation change fields are given as a percentage so they are multiplied with the observed data to create the future climate data set. For hourly precipitation, change fields were applied to the observed baseline data and used as is. For daily data, change fields were applied for both rain and snow in the observed data set. These values were added for the total daily precipitation. Daily precipitation was then partitioned between rain and snow based on average daily temperature. If the average of the maximum and minimum daily temperature was greater than zero then all of the daily precipitation was recorded as rain and if it was below zero all of the daily precipitation was recorded as snow. This method over simplifies when precipitation may be snow or rain, but it was used in the absence of better information.

RCM Output

With the RCM output it was not possible to split up ZUMs between grids so each ZUM was applied to a single grid using the same criteria used to assign change fields. For the four ZUMs that were split fairly equally between two grids, the upstream grid was applied to the entire ZUM.

Daily maximum and minimum temperature data from the seven grids was used as provided. Precipitation data was provided in 3-hourly time steps. This data was summed on a daily basis for the daily data set and then assigned to either snow or rain based on daily temperature. If the average of the maximum and minimum temperature for a day was below freezing then all precipitation for that day was assumed to be snow. If temperatures were above freezing then all precipitation was assumed to be rain.

The hydrologic model runs on an hourly time-step so the 3-houly precipitation data had to be converted to hourly data. The 3-hour data was split equally between each hour so that each hour received 1/3 of the total 3 hourly rain. This resulted in periods of low intensity rainfall with consistent wetted ground. This method introduces a bias in the results that needs to be accounted for when analysing modeling results.

5.1.3. Analysis of Future Climate Data Sets

Temperature

Baseline output from the RCM (RCMBase-Raw) had much lower average monthly temperatures for the winter and spring period compared to the observed baseline, Figure 5–2. The summer period was similar between the RCMBase-Raw and the observed baseline and the fall period had slightly lower temperatures for the RCM temperature data. These discrepancies also show up in the future RCM data for both the raw and corrected temperature data.

The change field method accounts for the discrepancy in the baseline data and provides future temperatures that are relative to the observed baseline. Analysis of the change field data sets, show there is not much difference between the GCM-CF and the RCM-CF for future temperatures, except that the RCM-CF predicts a bit higher temperature in the summer period. Therefore there is little new insight gained with the RCM output for future temperatures when differences in modeling of the baseline period are taken into account.

By assuming that the RCM-CF future temperatures are the best representation of future conditions, Figure 5–2 shows that the temperature corrected RCM data (RCM-P125/P225) is still under predicting future temperatures in the winter and early spring period, while over predicting them in the summer period. Temperature bias correction was done on an average monthly basis, while the University of Waterloo team that supplied the RCM data noted there were differences in the daily maximum and minimum temperatures between the observed baseline and RCM Base Raw data sets, such that corrections on an average basis only would not address. The University of Waterloo team recommended additional work on temperature bias correction to match the observed baseline temperatures (Disch et. al 2012).

Temperature affects winter processes more so than summer processes (Section 3), therefore under predicting future winter temperatures may have a big effect on modeled hydrologic response including stream flow.

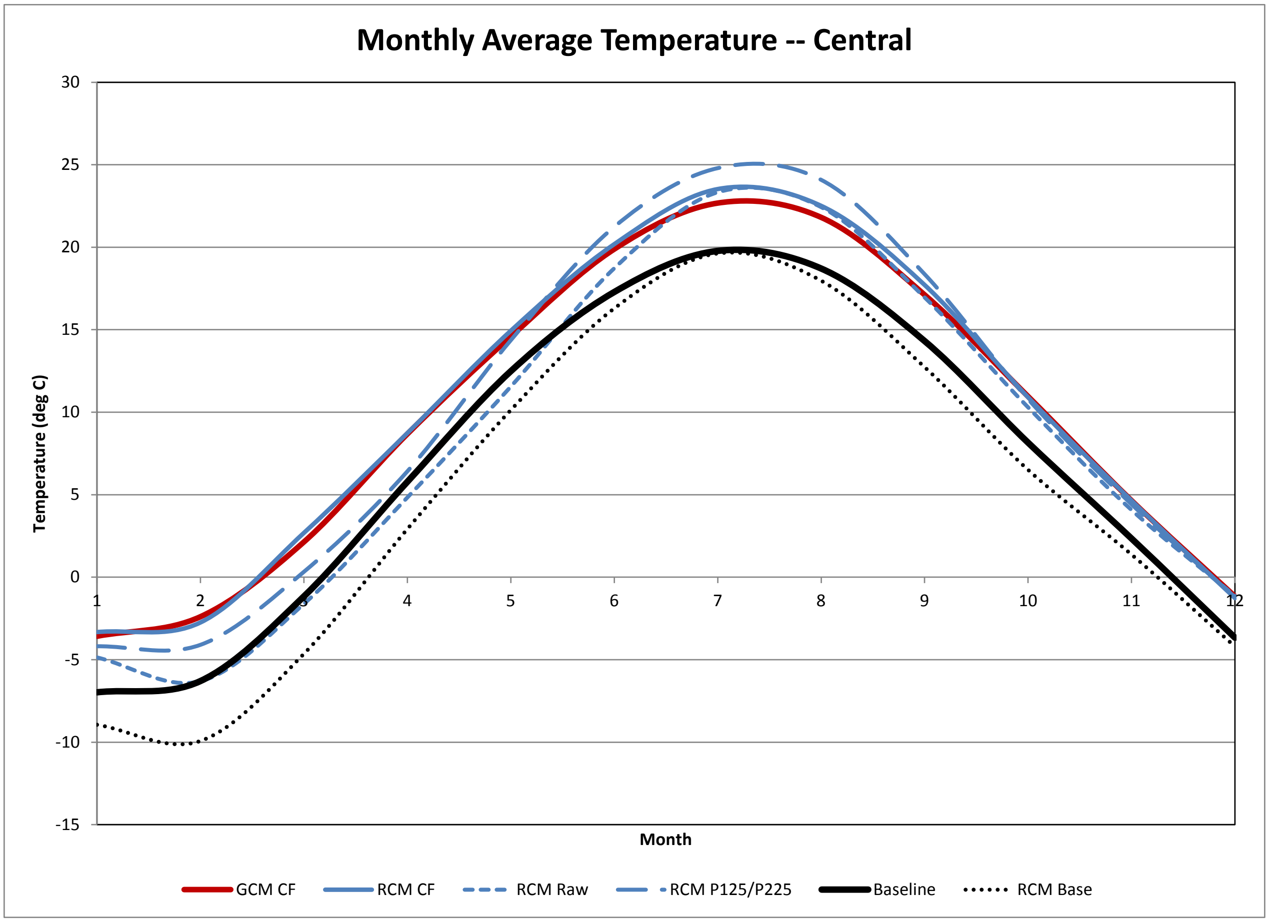


Figure 5–2: Average monthly temperature for the central part of the watershed for different climate data sets

Precipitation

Monthly precipitation varied between the GCM and RCM modeled output as shown by the two sets of change field values in Figure 5–3. The GCM predicted higher precipitation in the winter (December through March) than the RCM throughout the watershed. The GCM has an increase in December through March precipitation of 22%, while the RCM has only a 14% increase for the same months. The RCM also predicted lower summer precipitation with a decrease in precipitation from July to September of 12%, while the GCM predicted a decrease of 2% during the same period. This resulted in an annual increase in precipitation of only 4% for the RCM, while the GCM had an increase of 10%. These patterns were similar throughout the watershed.

The RCM model output was quite different than the GCM and RCM change field precipitation data for most months as shown in Figure 5–3. Changes in precipitation were greater with December to June having very large increases in precipitation, while July to October had a greater decrease in precipitation. July and August were similar between the RCM change field and RCM raw and corrected data sets.

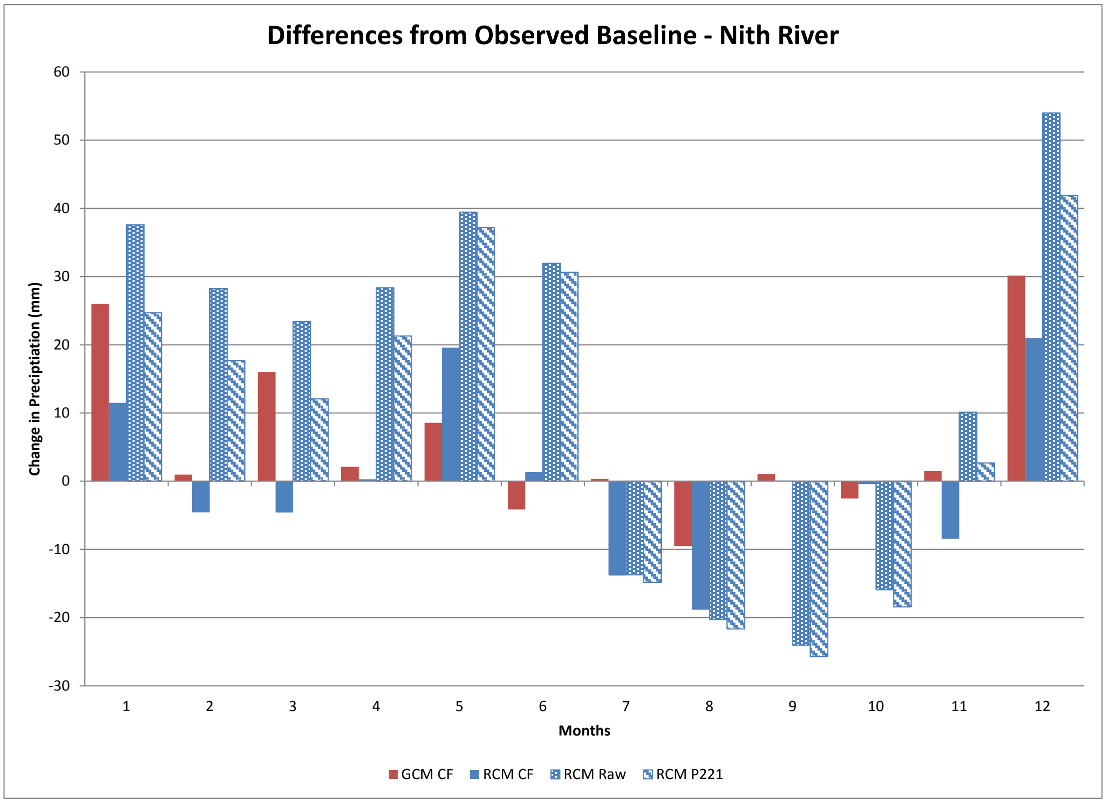


Figure 5–3: Monthly differences in precipitation from the observed baseline for different climate data sets

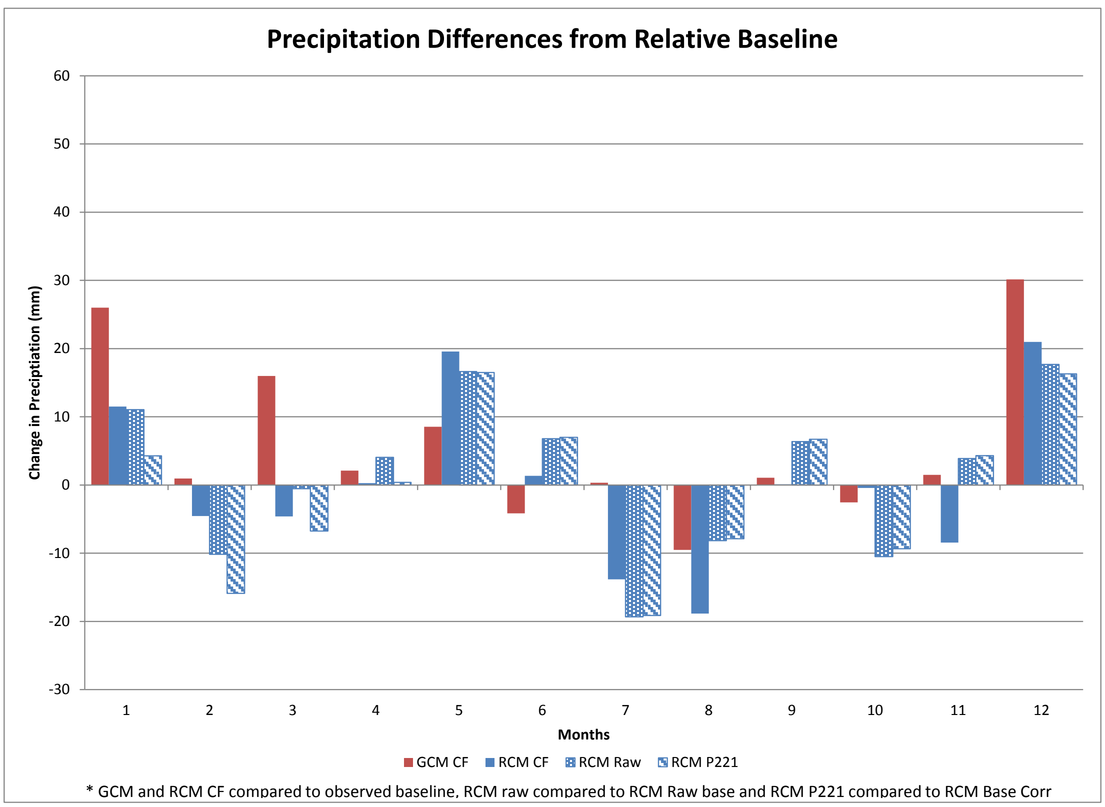


Figure 5–4: Monthly differences in precipitation from the relative baseline for different climate data sets

Figure 5–4 shows the relative increase or decrease in precipitation for each data set by comparing data against corresponding baselines and takes into account some of the bias in the RCM climate model such as the drizzle effect. When the bias from the RCM model is taken into consideration the changes to precipitation are not as big compared to the baseline. Of particular note is that the changes are different for each future data set and there are no consistent trends. Precipitation is highly uncertain in future predictions and even with the same scenario using the same GCM forcing data there are wide differences in the final precipitation estimates based on different correction techniques.

Storm Events

One of the biggest questions about climate change is the intensity and frequency of future storm events. Climate models predict an increase in the intensity and frequency of future storms, but the magnitude of the increase is still greatly unknown. Many studies to date have used change fields as a way to incorporate local weather patterns, but using change field methods limits analysis of frequency and intensity of storm events. Examining RCM output directly could provide an estimate of future storm intensity and frequency, while still incorporating some local weather conditions. Each of the RCM future climate data sets were examined and compared to the observed baseline climate data to see if an estimate of future storm intensity or frequency could be made.

The frequency of high precipitation events for different climate data sets is given in Table 5-3 as the average number of days per year with greater than the given precipitation. For the observed baseline, there is an average of 5 days a year with rainfall greater than 25mm, but the RCM baseline data gives only 2 days a year. For the future period, the RCM-CF shows no difference in the frequency of 25mm of precipitation compared to the observed baseline. The RCM output shows a slight decrease in frequency when compared with the observed baseline, but shows a doubling of the frequency when compared against the RCM baseline output, from 2 to 4 days. Interpretation of these results is problematic because of low numbers and high variability. The RCM data shows an increase in frequency, but quantifying the increase is difficult because of the high uncertainty.

Table 5-2: Frequency and intensity of precipitation for different climate data sets

	Average number of days per year				
	Observed Baseline	**RCMBase Raw**	**RCMBase Corr**	**RCM-CF**	**RCM-P221**
Without Precipitation	197	31	168	225	174
Greater than 5mm	55	60	58	58	57
Greater than 10mm	29	26	26	31	27
Greater than 15mm	16	12	12	16	14
Greater than 25mm	5	2	2	5	4
Greater than 50mm	0.6	0.1	0.1	0.3	0.3
	Max Daily Precipitation (mm)				
Average per year	52	35	35	47	44
Maximum	90	61	61	75	74

A brief analysis of the intensity of rainfall looked at the maximum daily rainfall for the same data sets, Table 5-3. Both the RCM-CF and RCM-P221 showed decreases in the maximum daily rainfall from the observed baseline data, but showed an increase when compared against the RCM baseline output. The RCM-P221 showed an increase of 23% for the average yearly maximum daily rainfall and a 21% increase in the maximum daily rainfall over the 30 year model period. More detailed analysis on the intensity of precipitation events is difficult given the 3-hourly timestep of the RCM output data.

5.1.4. Summary

Winter hydrology is highly temperature dependant and most climate models predict higher winter temperatures in the future. Raw and corrected RCM output predicts winter temperatures quite a bit lower than change field predictions. In fact, RCM future output was close to watershed observed baseline averages, especially during the March and April period. This affects the stability of the winter snowpack and could lead to higher predicted spring flows with RCM data compared to using RCM change field data. Although summer hydrology is less affected by temperatures then winter, summer temperatures are predicted to be hotter with the RCM than the GCM, which could lead to higher evaporation rates.

Climate model precipitation predictions have a high degree of uncertainty. The analysis of one scenario, with the original GCM output and various versions of the RCM output (forced with data from the GCM), shows that even a single scenario can have very different precipitation predictions. This uncertainty hampers the understanding of hydrologic response to climate change. Precipitation is a key driver of hydrology and without more accurate predictions it is difficult to determine hydrologic response to climate change. RCM output shows a trend to more frequent and intense high precipitation events, but uncertainty is too high and the time step too large to accurately quantify the increase in either frequency or intensity.

5.2. Modeled Stream Flow

All charts in this section are for one station, the Nith River at Canning. Hydrographs from a few other gauges were reviewed as part of the study. Generally, results across the watershed were similar. Modeled stream flow results are first presented using monthly averages, followed by brief discussions on high and low flows.

5.2.1. Change Field: Monthly Average

Stream flow generated from the two change field data sets was used to investigate the differences between GCM and RCM model output and how they affect hydrologic response in the watershed. The biggest difference between the two climate data sets was precipitation. In the winter months the GCM-CF had higher precipitation than the RCM-CF as shown in Figure 5–5. Other differences include higher RCM-CF precipitation in May and lower RCM-CF precipitation in the summer months (July and August) than the GCM data set. The largest difference for temperature between the two data sets was higher temperatures for the RCM-CF during the summer months (June through September).

Flow results for the two change field runs were similar for parts of the year and different in other parts, Figure 5–6. Both future climates produced higher flows at Canning during the winter months of January and February, but the GCM had higher average monthly flow rates corresponding to the higher precipitation during that period. In March, the GCM climate data produced higher average monthly flows than baseline, while the RCM climate set produced lower average flows. This is directly related to differences in precipitation for this month and the preceding months. The RCM data produced lower flows during the summer period, but they were similar to the GCM (i.e. less than baseline).

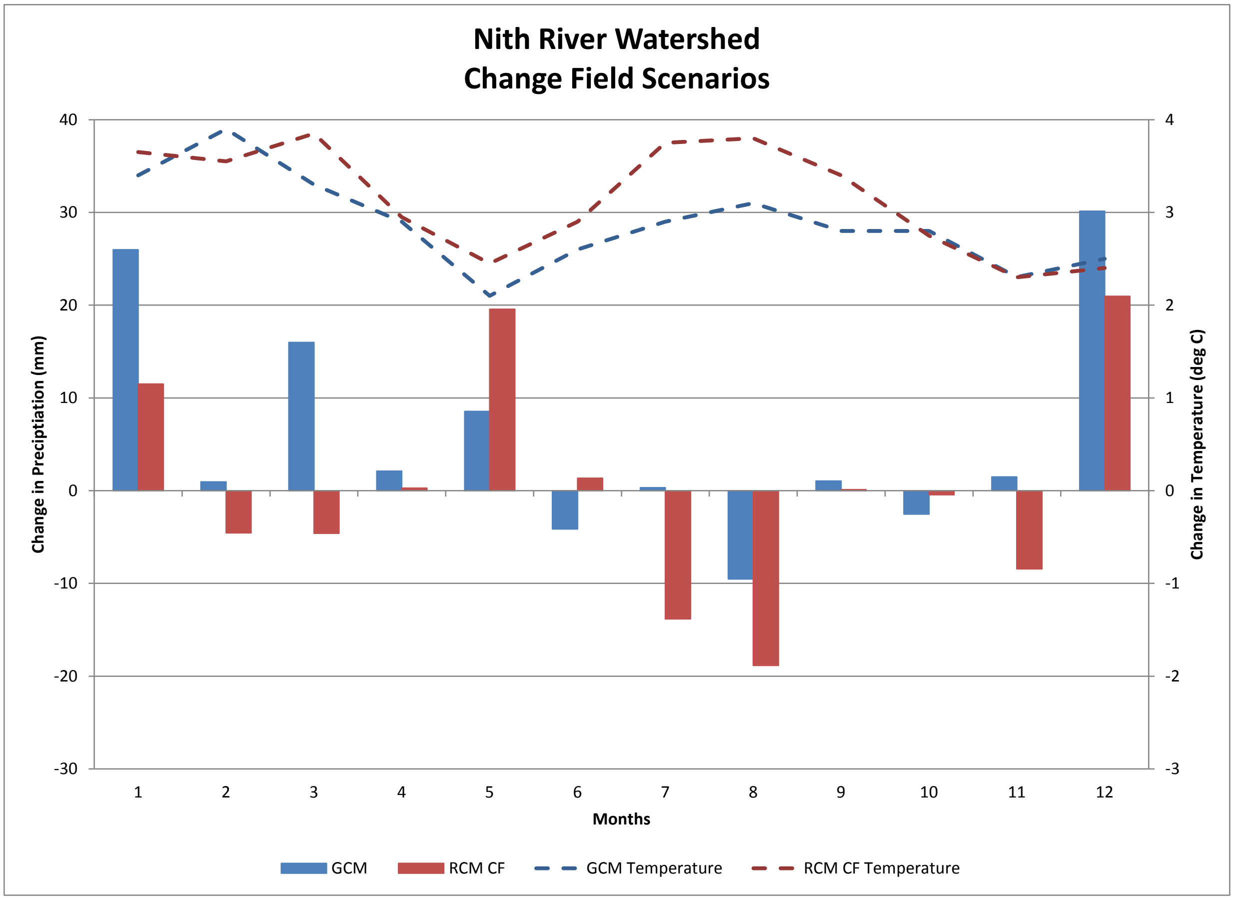


Figure 5–5: Change in temperature and precipitation for the change field data sets in the Nith River watershed

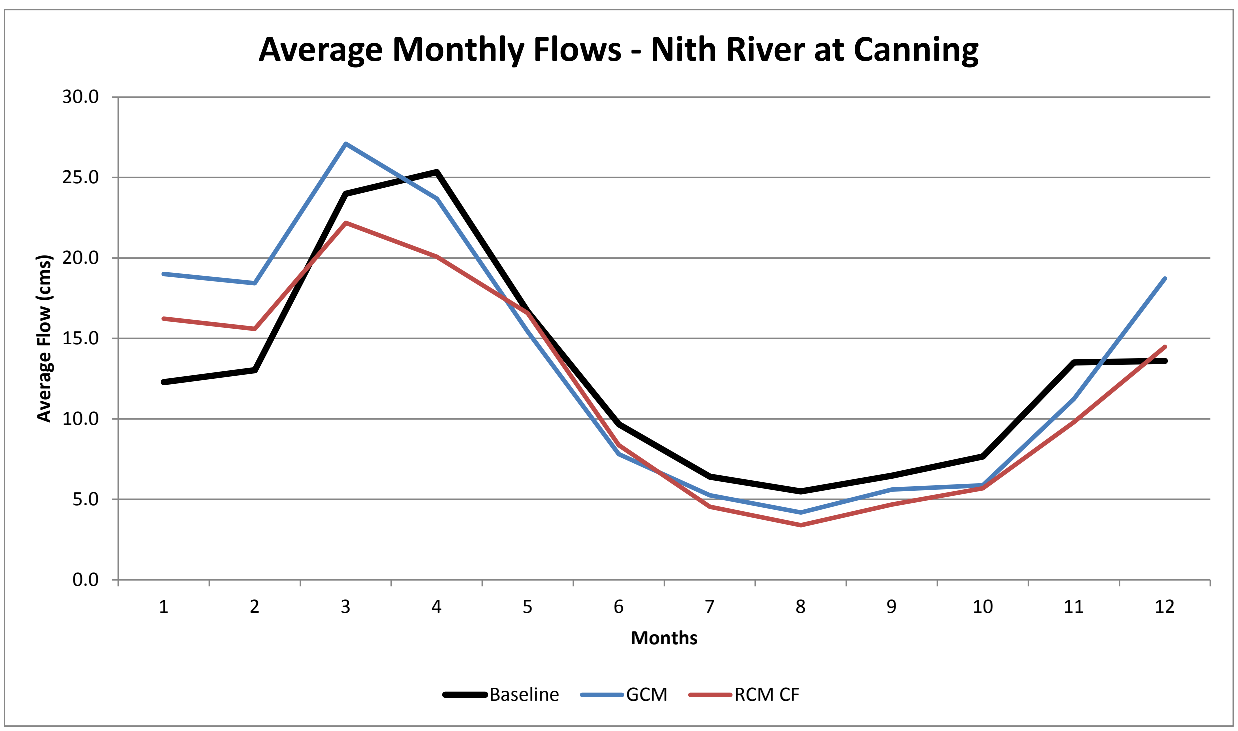


Figure 5–6: Average monthly flow in the Nith River at Canning for the change field climate data sets

Precipitation was the main difference in these climate data sets and all of the flow responses corresponded to precipitation changes. Temperature differences were minimal and did not appear to affect the results. The key months of differing flow rates are in the winter season, December through March. The large drop in summer precipitation and moderate increase in temperature only resulted in a small drop in summer flows for the RCM-CF.

5.2.2. RCM: Monthly Average Flows

There are a number of RCM scenarios that were run (see Table 5-1). Corrections were used to fix inaccuracies in climate modeling in some of the data sets, but there remained differences between the RCM baseline output and observed baseline. Figure 5–7 shows the monthly precipitation difference from the observed baseline for the RCMBase-Raw and RCMBase-Corr data sets. Most months had differences that were greater than 10mm, while other differences were as high as 30mm on an average basis. These differences complicate analysis of the RCM scenario hydrologic modeling results. Many differences in the predicted future are because of the inaccuracy of the RCM to model current conditions rather than the predicted future conditions.

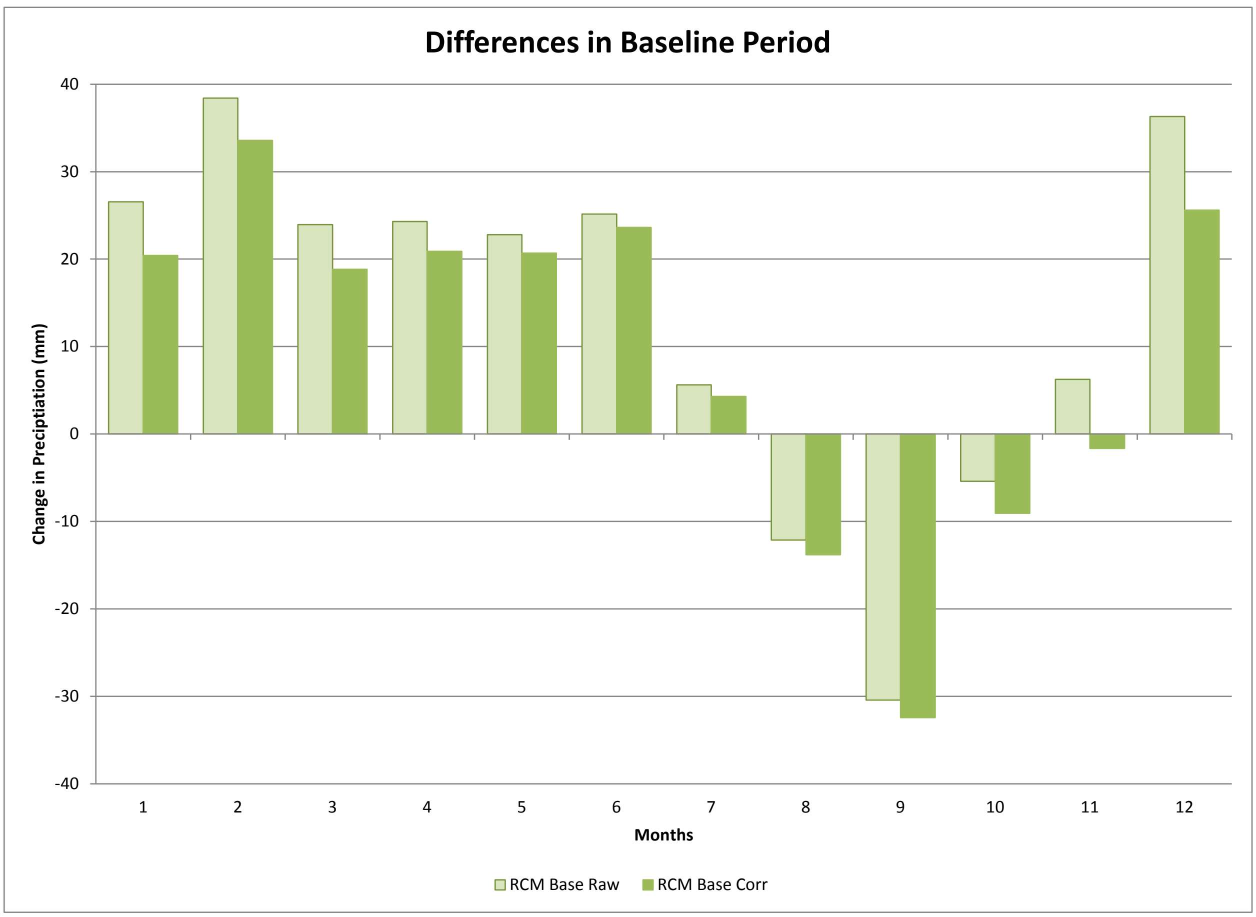


Figure 5–7: Difference in average monthly precipitation for the Nith River RCM output baseline data sets

In an attempt to lessen the uncertainty due to modeling bias, hydrologic model output for future periods was compared with the output from the relative baseline period. The observed baseline was used for reference only.

- **Raw Data:** compares the RCM-Raw with RCMBase-Raw output; and
- **Corrected Data:** compares RCM-P221 with RCMBase-Corr.

Raw data

Average monthly flows for the Nith River at Canning using the RCM-Raw climate data is given in Figure 5–8 along with flow results using the observed baseline data. Flows during the spring period are extremely high for both the baseline and future RCM scenarios compared to observed baseline. This is likely due to higher winter precipitation and low winter temperatures that result in a large snowpack followed by a typical spring melt. Low winter temperatures in the RCM climate data sets are the result of inaccurate modeling of winter temperature (See Section 5.1.3). These winter flows are contradictory to most other climate change predictions that indicate a warmer winter season with more melt events and a decrease in the instance of the traditional spring snow melt resulting in high winter flows and lower spring freshet flows. RCM future flows are higher in the winter than the RCM base flows and the spring peak flow is quite a bit less, showing that even with underestimated temperatures, the pattern of a reduction in spring snow melt still occurs.

The summer future flows are lower than the RCM base and observed baseline summer flows and can be seen better when using a log scale in the lower chart in Figure 5–8. The RCM baseline and observed baseline flows are similar for August and September, but the RCM baseline flows are quite elevated for July. In all of these months, the RCM future data produces lower flows and is a result of lower precipitation and higher temperatures. This result is similar to the surface water modeling results for both the GCM-CF and RCM-CF.

Corrected Data

The corrected RCM baseline data is only corrected for precipitation bias, while the RCM-P221 future data set is corrected for both precipitation and temperature bias. Winter and spring flows for the RCMBase-Corr were similar to the RCM Base Raw since there was no change to temperatures and temperature is a large driver of winter hydrology, Figure 5–9. Winter flows for the RCM-P221 data set were higher than the observed baseline, similar to RCM-CF findings. Spring flows were much higher than the observed baseline data and are likely the result of higher winter precipitation and lower winter temperatures resulting in a larger spring melt than the observed baseline data. Spring flows were much reduced compared to the corrected RCM baseline. Higher winter temperatures lead to more winter melt events and a reduction in the winter snow pack.

Summer and fall flows for RCM corrected data set were a bit smaller than the RCM-Raw flows, a result of lower precipitation because of the correction in the drizzle effect. Late summer and fall flows were similar to the RCM-CF results. Spring and early summer flows were quite elevated compared to the observed baseline and RCM-CF, most likely due to the much higher precipitation in May and June in the RCM output compared to the RCM-CF.

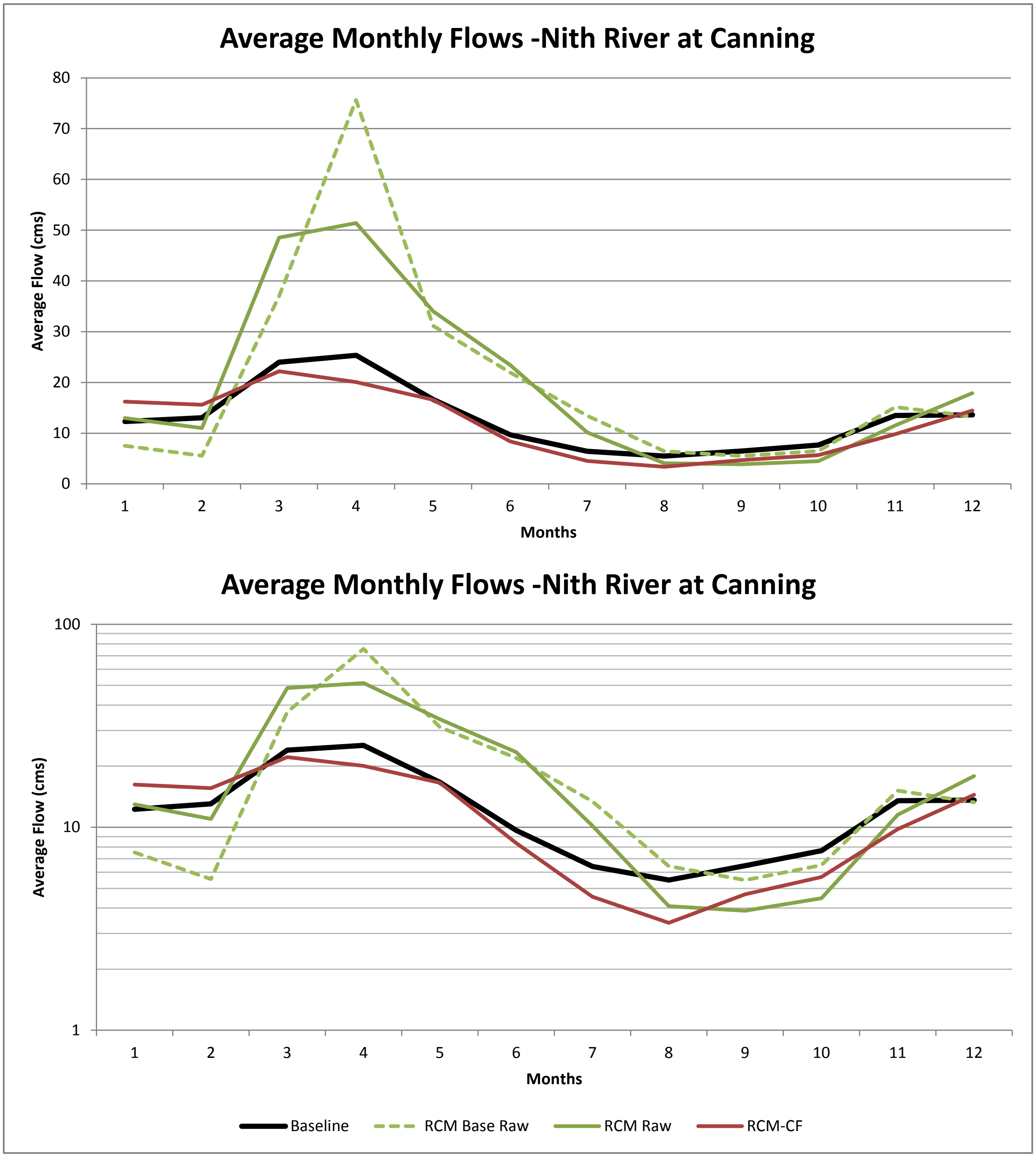


Figure 5–8: Average monthly flow in the Nith River at Canning for the Raw RCM data hydrologic model runs

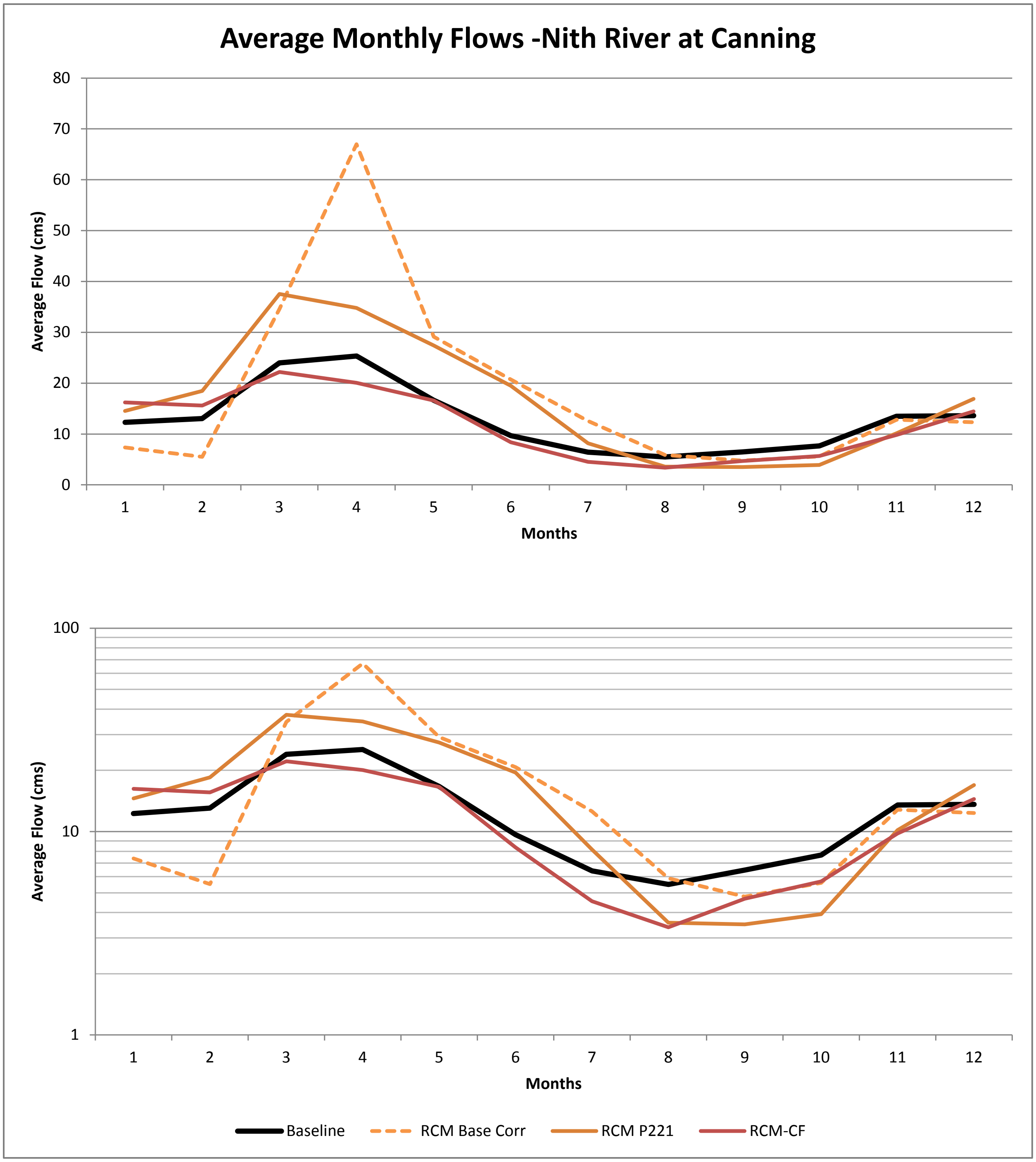


Figure 5–9: Average monthly flow in the Nith River at Canning for the corrected RCM data hydrologic model runs

5.2.3. Maximum Flows

One of the reasons for running the hydrologic model directly with RCM model output is to study changes to the magnitude and timing of high flow events. The change field climate data sets are good for looking at average changes in conditions, but are limited when looking at changes to frequency and intensity of events because they use the same pattern of storm events as the observed baseline.

An analysis of the maximum flows was done with the hydrologic model output for RCM and baseline data as shown on Figure 5–10. Observed baseline climate data resulted in maximum annual events occurring from December to May with a couple in September and November, this is consistent with observed flow rates at the Canning gauge. Observed maximum annual high flows are caused by spring snowmelt, rainfall on frozen ground, mid-winter melts and large precipitation events. Maximum annual high flows for the corrected RCM baseline data (RCMBase-Corr) all occur during March and April and are quite a bit higher than those observed during the same time period. These events are all tied to spring snow melt and are a result of RCM winter temperatures much lower than observed, causing the development of a large snowpack followed by a rapid spring melt.

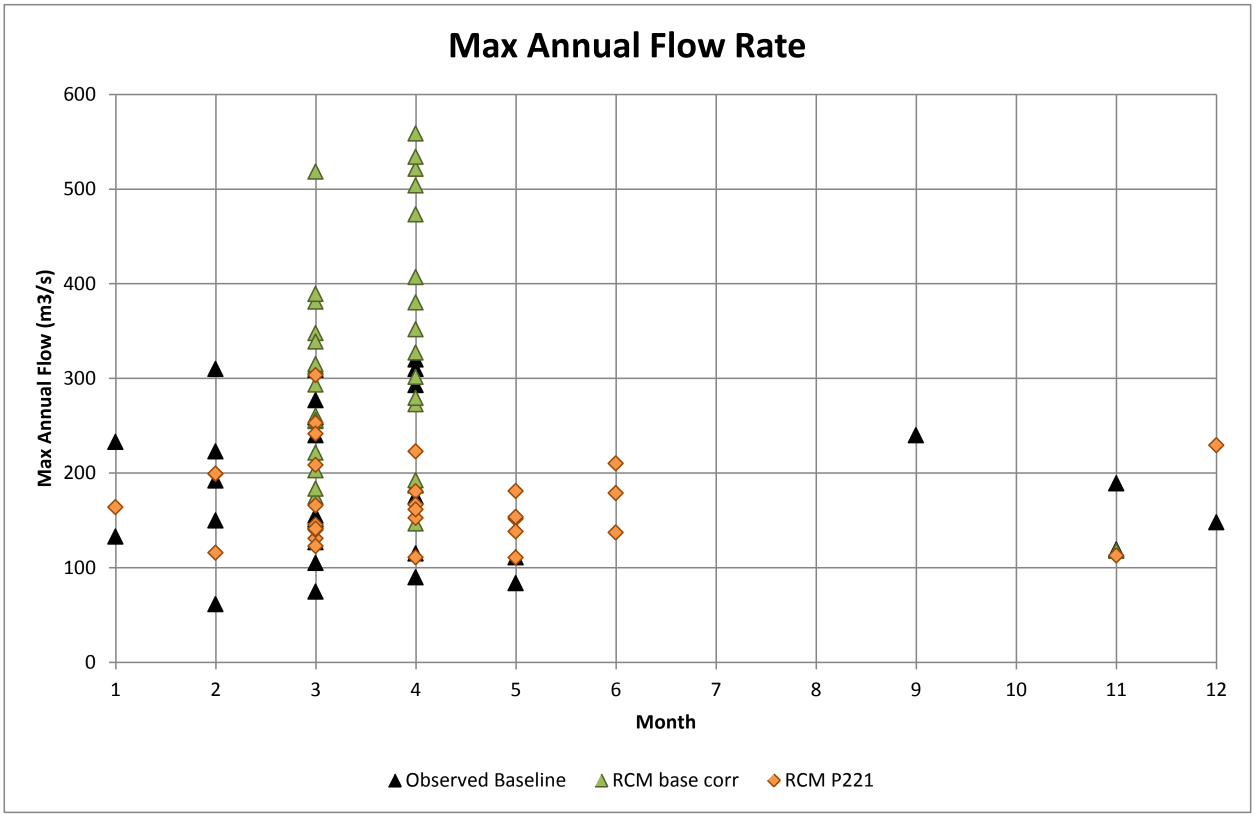


Figure 5–10: Maximum Annual Flow by month for the Nith River at Canning

The corrected RCM max flows for the future period (RCM-P221) more closely resemble the magnitude and timing of the observed maximum annual flows and are spread out more evenly during the year than the RCM baseline. This could be due to the temperature correction applied to the winter months with the RCM-P221 data set, or it could be an example of the increase in variability expected with climate change. Most likely it is a combination of both.

The large discrepancies between the RCM baseline and the observed baseline make it is difficult to attribute differences in maximum flow magnitude and timing to climate change. The results indicate that in the future there will be less high flow events tied to snow melt and more spread throughout the year. This pattern has already been observed over the past few decades, with yearly high flow events throughout the year and a decrease in spring snow melt events.

5.2.4. Low Flows

For low flows, magnitude and duration are key factors. There are limitations to the hydrologic model when modeling low flows. Low flows in the Grand River watershed are mostly from groundwater discharge and are only partially related to runoff. Groundwater discharge will change during extreme and prolonged dry periods because of a lowering of the water table. The hydrologic model does not model the groundwater system, including changes to the water table, instead it uses routines to route interflow and to match average groundwater discharge in the sub-basin. So changes to groundwater discharge because of a lower water table or reduced recharge are not captured.

Although the magnitude of low flows cannot be determined accurately with the hydrologic model, the duration of low flows can be investigated. The Nith River at Canning has a normal summer low flow of 2.9 m^3/s. Table 5-3 gives the number of days during the low flow period the average daily flow was below 2.9 m^3/s for each model run and the percent change in the number of days between the baseline and future. In all cases the future had a greater number of days below 2.9m^3/s, but the average number of days per year increased a greater amount than the maximum number. This indicates that stream flows would be low for a longer period of time each year, but the extreme droughts (or very long low flow periods) would only be a bit longer than in the baseline period. In other words, low flow conditions will happen more often, but the length of the longest low flow periods would not increase greatly.

Table 5-3: Number of days below normal summer low flow at the Nith River Canning gauge

	Comparison	Baseline	Future	% Change
May to Oct Average	Change Field	39 days	65 days	66% increase
	Raw Data	21 days	42 days	103% increase
	Corrected Data	25 days	53 days	111% increase
May to Oct Max	Change Field	115days	134 days	17% increase
	Raw Data	76 days	86 days	13% increase
	Corrected Data	81 days	98 days	21% increase

The RCM output low flow periods increase in length a larger amount than the change field results, more so for the average than the maximum. There was over a 100% increase of the time below 2.9 m^3/s between the baseline and future for the corrected RCM data compared to an increase of 66% for the change field model runs. The RCM data is showing longer periods below normal low flows, which could be an indication of more drought events in the future.

5.2.5. Summary

Stream flows generated using raw or corrected RCM climate data should not be used directly for analysis, but can be useful when compared with appropriate baseline modeled output. One of the biggest issues with the RCM data is the abnormally low winter temperatures that resulted in unrealistic snowpack and melt conditions that were contrary to the predicted increase in temperature. Although corrected RCM data still had some inconsistent temperature predictions, flows for the winter period were more realistic with periodic snow melts and the snowpack removed by the end of March.

Stream flow with the corrected RCM data was higher in May and June than the change field method. This was the result of increased precipitation and an increase in the number of days each month with precipitation compared to the change field. This result could be attributed to differences in the frequency of rainfall when using RCM output or it could be part of the drizzle effect. Many of the days with rainfall in the corrected RCM precipitation data have total precipitation of less than 2mm, indicating that there could still be some drizzle effect issues.

Differences in stream flow between the RCM-CF and GCM-CF occurred in the winter and summer season and appeared to be tied to differences in precipitation. Precipitation differences are most likely due to refined local features in the RCM. In particular, winter and summer flows were less with the RCM-CF than the GCM-CF.

The large discrepancies between the RCM baseline and the observed baseline make it difficult to attribute differences in maximum flow magnitude and timing to climate change. The results indicate that in the future there will be less high flow events tied to snow melt and more spread throughout the year. This pattern has already been observed over the past few decades, with yearly high flow events throughout the year and a decrease in spring snow melt events. Stream flows predicted with RCM output would be low for a longer period of time each year, but the extreme droughts (or very long low flow periods) would only be a bit longer than in the baseline period. In other words, low flow conditions will happen more often, but the length of the longest low flow periods would not increase greatly.

It is recommended that RCM data, whether corrected or not, should be evaluated with hydrologic model outputs generated with observed and modeled baseline data sets to ensure changes are the results of differences that can be contributed to climate change and not to climate model bias.

5.3. Conclusions

Access to raw and corrected RCM data allowed for more analysis of the model outputs and bias compared to relying on monthly change fields only. The RCM gave different predictions of precipitation compared to the GCM indicating that local scale processes in the RCM affected precipitation patterns as expected. There was little difference in temperature predictions between the GCM and RCM, with the exception of a hotter summer, indicating that local scale modeling does not affect temperatures to the same extent as precipitation. There was not a lot of variability between the RCM grid cells with the entire watershed with similar changes to temperature and precipitation. Additional scenarios or parings of GCM and RCM data are needed to confirm these observations.

Precipitation predictions with climate models have a high degree of uncertainty. The analysis of this single scenario with the GCM change field data and various versions of the RCM (forced with data from the GCM) data show that even a single scenario can have very different precipitation predictions. This uncertainty is the key to understanding hydrologic response to climate change. Generally, practitioners know how changes to temperature and precipitation will change stream flow, runoff and recharge, but there is still a need to gain a better understanding of how the weather patterns will change. Precipitation is a key driver of hydrology and without more accurate predictions it is difficult to determine how hydrology is affected.

Use of this type of climate model output in hydrologic modeling is not straight forward. Both the inputs and outputs should to be analysed with the appropriate baseline data, otherwise the results can easily be misinterpreted. Bias in climate models is the biggest issue with analysis. It is recommended that additional ways of applying climate model output be investigated such as weather generators or more refined change field methods.

6. Summary

Each of the climate change modeling exercises and future climate scenario analysis described in this report provides valuable information regarding how water resources could potentially change in the Grand River Watershed with a changing climate. Information gained from the climate change modelling work will be used to inform and support additional projects including water quality modeling and reservoir operation considerations as part of the Grand River Watershed Water Management Plan update.

For each season, a moderate increase in temperature occurs most often. A large increase in temperature occurs rarely except for the winter season. Precipitation trends are more seasonally based than temperature trends. For the winter season, just under half of the scenarios had a small increase in precipitation. The spring season was split between no change and a small increase in precipitation. The summer months are almost split three ways with a small decrease, no change and a small increase in precipitation. The summer period also has the most scenarios with decreased precipitation. Finally, the fall period is split between no change and a small increase in precipitation.

Annual modeling results provided general trends and suggested the need for more detailed analysis of climate change scenarios. As well, the water budget analysis gave insight into areas that might have higher water quantity stress issues with a changing climate with the majority of these areas already under stress conditions.

Seasonal analysis of climate change scenarios produced some more specific trends. During the winter season higher temperatures and more precipitation will lead to more runoff and stream flow. Higher temperatures will also decrease the stability of the snow pack, which could lead to an increase in melt events during the winter months and more precipitation falling as rain rather than snow. The start of the spring season will shift forward by approximately one month. With warmer temperatures predicted throughout the winter there will be a decreased risk for severe spring freshet flooding because of reduced snowpack. The forward shift in the spring season will also lead to an earlier start to the summer low flow season. In the summer, low flows may become lower, as indicated by scenarios with low and similar summer precipitation rates. Very few scenarios had higher precipitation rates in the summer. ET rates also dropped in the summer because of a decrease in available water. The scenario results were less conclusive for the fall season. There was a weak trend towards the low flow season extending into October. ET increased in the fall months while runoff and recharge rates decreased.

The reservoir yield modeling suggests that in the future it will be important that reservoirs be filled during the spring period. As the number of mid-winter melts increases there will be a greater need to capture and store the melt water as it becomes available. This will need to be balanced with maintaining required flood storage space for the protection of downstream communities. Flexibility will need to be built into reservoir operations to ensure low flow targets are met while still maintaining the ability of the reservoirs to mitigate flood risks. The number of flow violations may increase, but the reliability of meeting flow targets will most likely stay at or above 95% reliability based on the climate change scenarios run in this study.

Access to raw and corrected RCM data allowed for more analysis of the model outputs and bias compared to relying on monthly change fields only. The RCM gave different predictions of precipitation compared to the GCM indicating that local scale processes in the RCM affected precipitation patterns as expected. There was little difference in temperature predictions between the GCM and RCM, with the exception of a hotter summer, indicating that local scale modeling does not affect temperatures to the same extent as precipitation. Additional scenarios or parings of GCM and RCM data are needed to confirm these observations. Bias in climate models is the biggest issue with analysis. It is recommended that additional ways of applying climate model output be investigated such as weather generators or more refined change field methods.

Precipitation predictions with climate models have a high degree of uncertainty. This uncertainty is the key to understanding hydrologic response to climate change. Generally, practitioners know how changes to temperature and precipitation will change stream flow, runoff and recharge, but there is still a need to gain a better understanding of how the weather patterns will change. Precipitation is a key driver of hydrology and without more accurate predictions it is difficult to determine how hydrology is affected.

Climate change is an evolving science. There is no single answer to what the effects will be with a changing climate. A proper understanding of the uncertainty and how it pertains to the questions asked is important in decision making. In light of uncertainty, water managers can prepare for the challenges of a changing climate by building resiliency in the watershed. A healthy, well-managed watershed will be better able to adapt to changing conditions in the future.

7. References

AquaResource Inc., 2009a. Integrated Water Budget Report Grand River Watershed, Final Report June 2009

AquaResource Inc., 2009b. Tier 2 Water Quantity Stress Assessment Report Grand River Watershed, Final Report December 2009

AquaResource Inc. 2009c. Tier Three Water Budget and Local Area Stress Assessment: Hydrological Model Update (Draft). Prepared for: Regional Municipality of Waterloo and City of Guelph. August 2009.

AquaResource Inc. and EBNFLOW Environmental 2011. Future Climate Datasets Guide. Prepared for: Ontario Ministry of Natural Resources and Ministry of the Environment.

EBNFLOW Environmental and AquaResource Inc. 2010. Guide for Assessment of Hydrologic Effects of Climate Change in Ontario. Prepared for: Ontario Ministry of Natural Resources and Ministry of the Environment.

Disch J., F. Sosa-Rodriguez, L. Mortsch and P. Kay. 2012. Developing RCM scenarios for hydrologic impact assessments in the Grand River Watershed to inform water resource management.

Grand River Water Management Plan. 2014. Flow Reliability: Regulated Reaches of the Grand River Watershed. Prepared by Dwight Boyd and Stephanie Shifflett, Grand River Conservation Authority.

Appendix A: Climate Change Scenario Charts

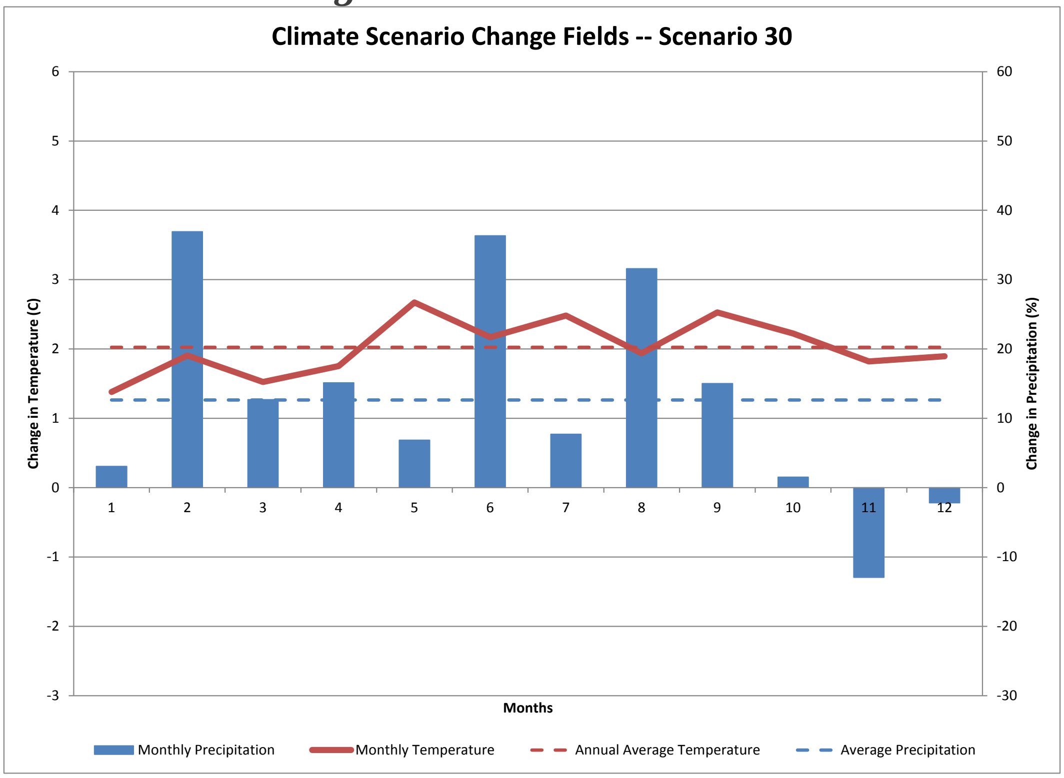


Figure 1: Monthly Change Fields for Waterloo-Wellington Climate Station Climate Change Scenario 30

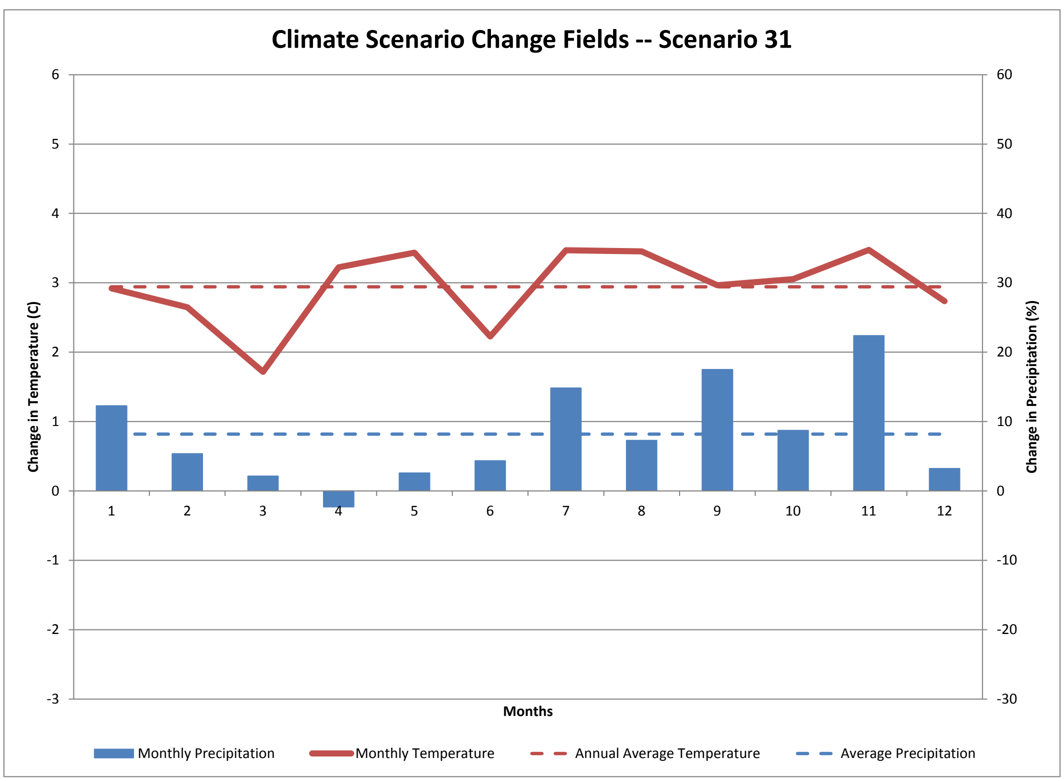


Figure 2: Monthly Change Fields for Waterloo-Wellington Climate Station Climate Change Scenario 31

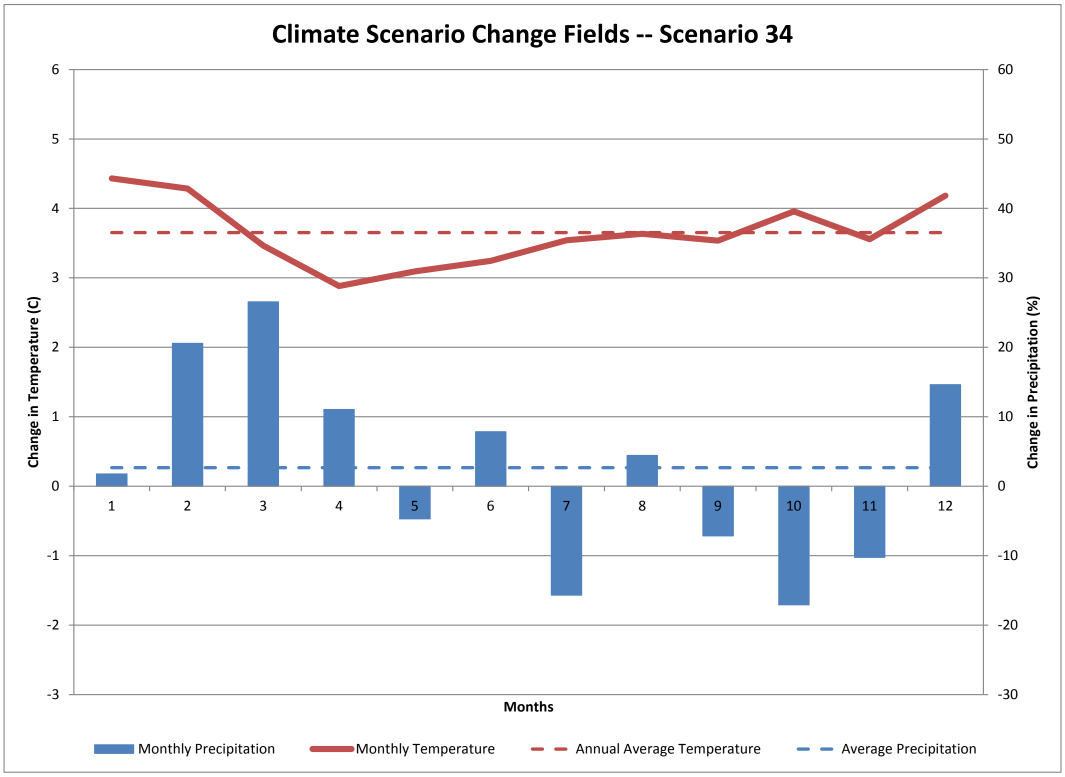


Figure 3: Monthly Change Fields for Waterloo-Wellington Climate Station Climate Change Scenario 34

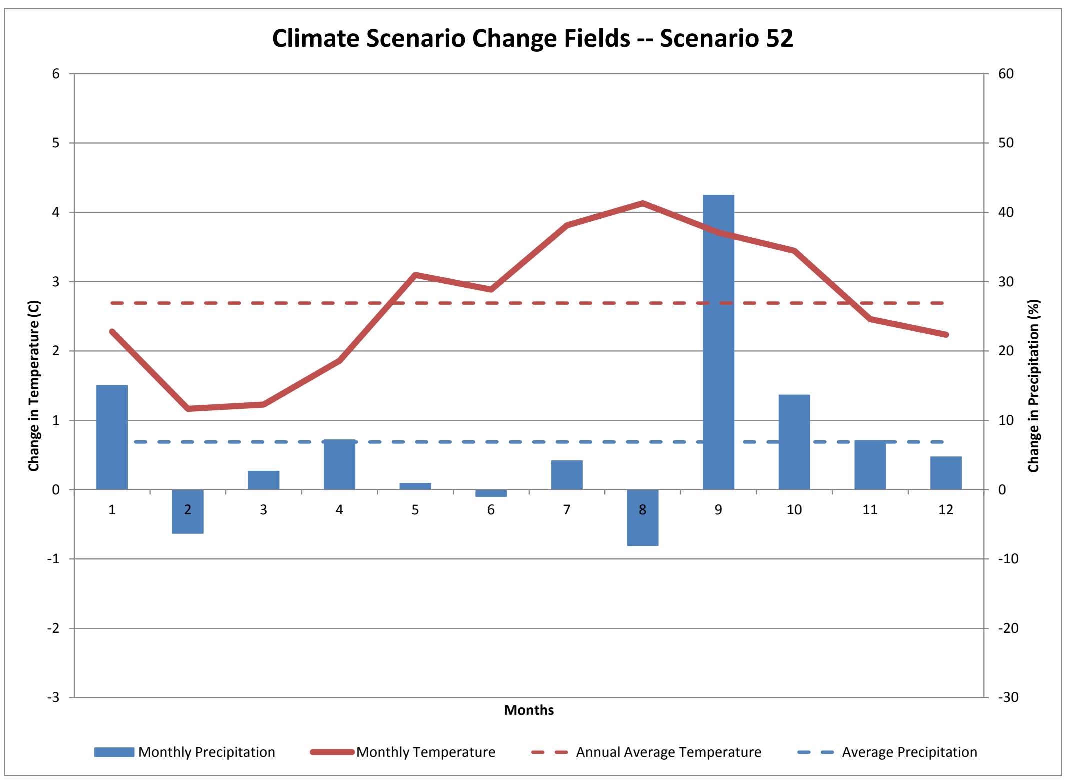


Figure 4: Monthly Change Fields for Waterloo-Wellington Climate Station Climate Change Scenario 52

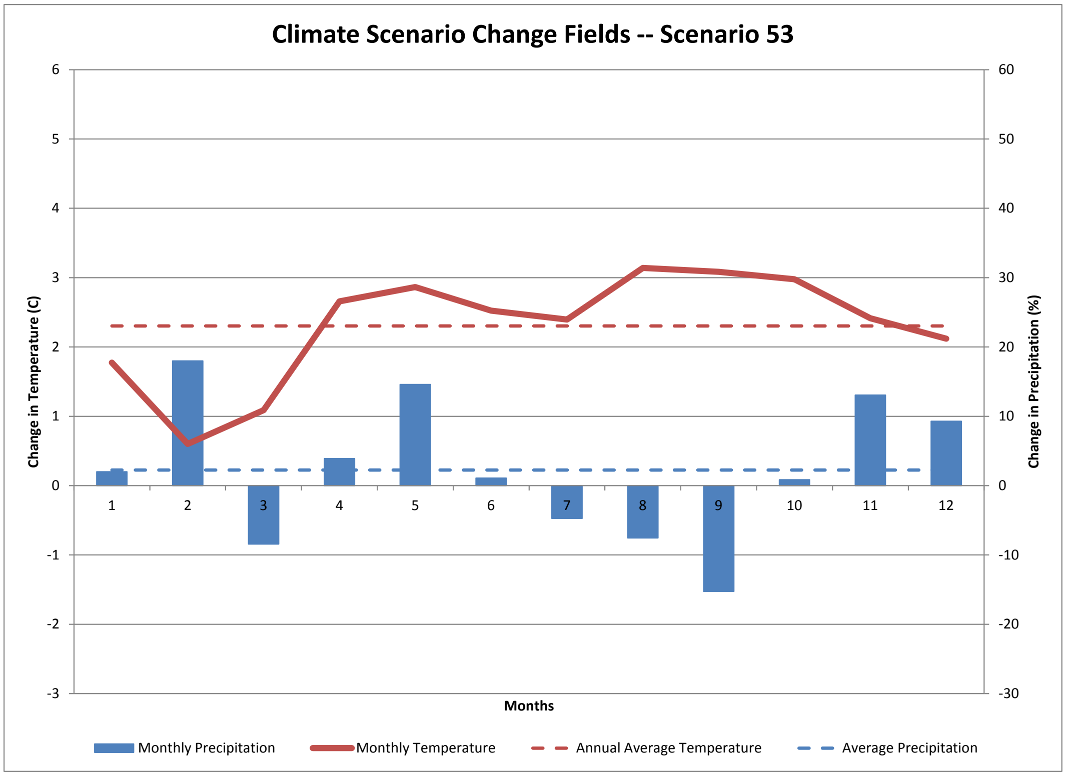


Figure 5: Monthly Change Fields for Waterloo-Wellington Climate Station Climate Change Scenario 53

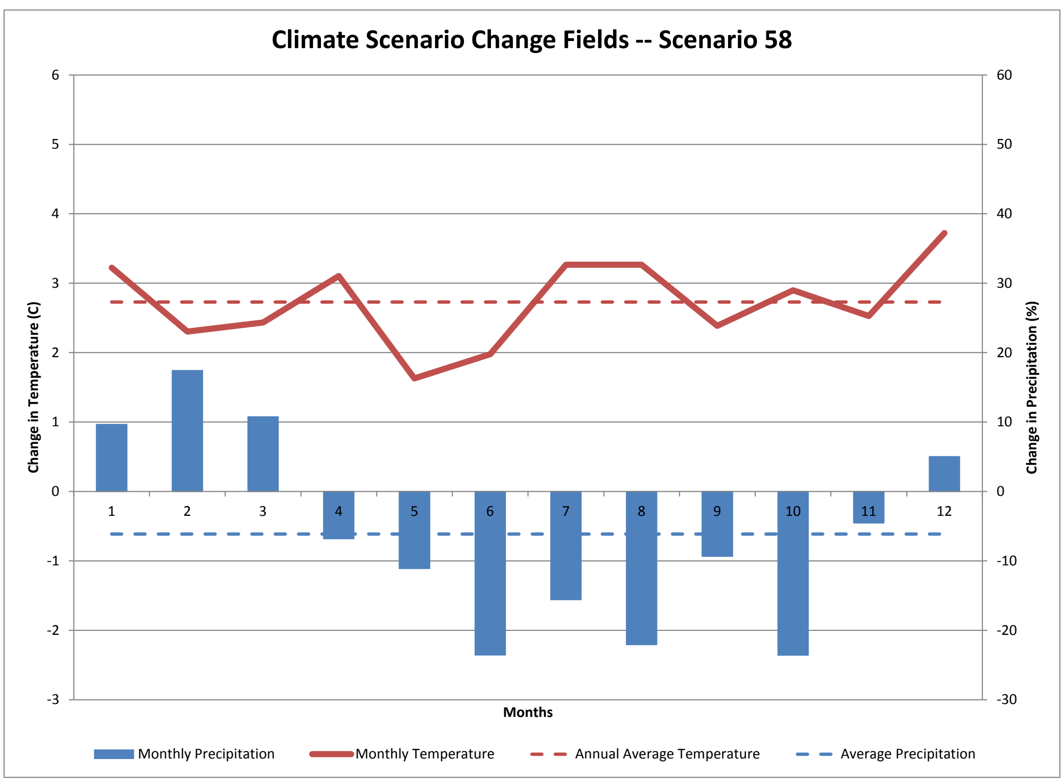


Figure 6: Monthly Change Fields for Waterloo-Wellington Climate Station Climate Change Scenario 58

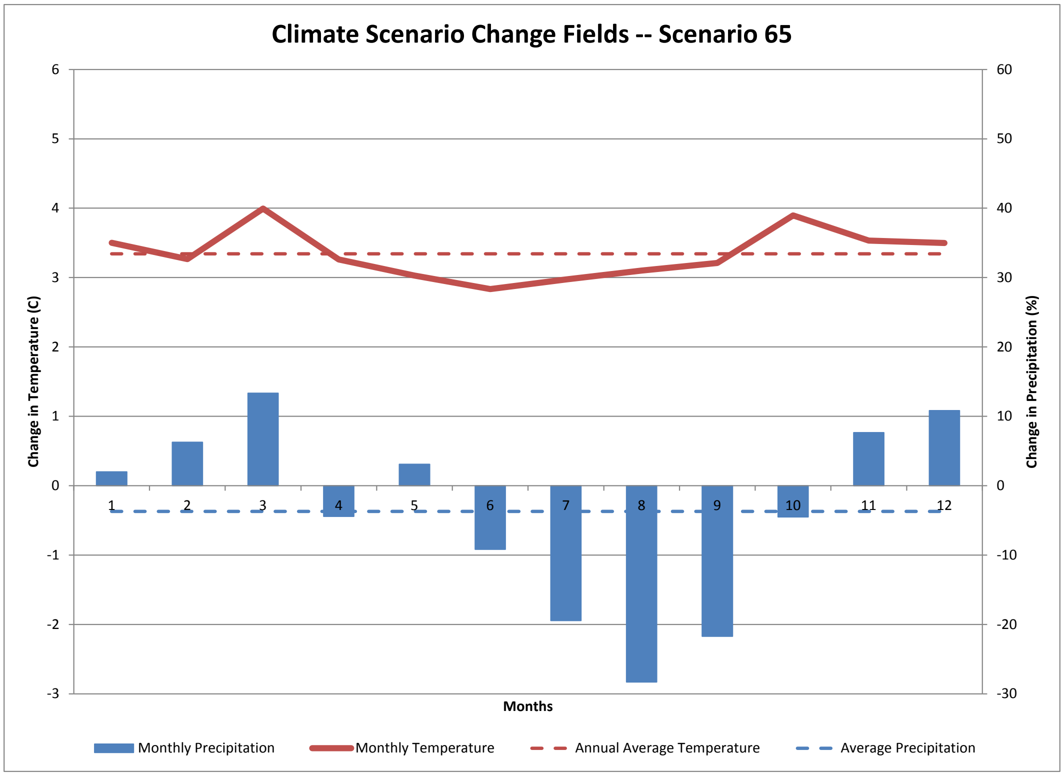


Figure 7: Monthly Change Fields for Waterloo-Wellington Climate Station Climate Change Scenario 65

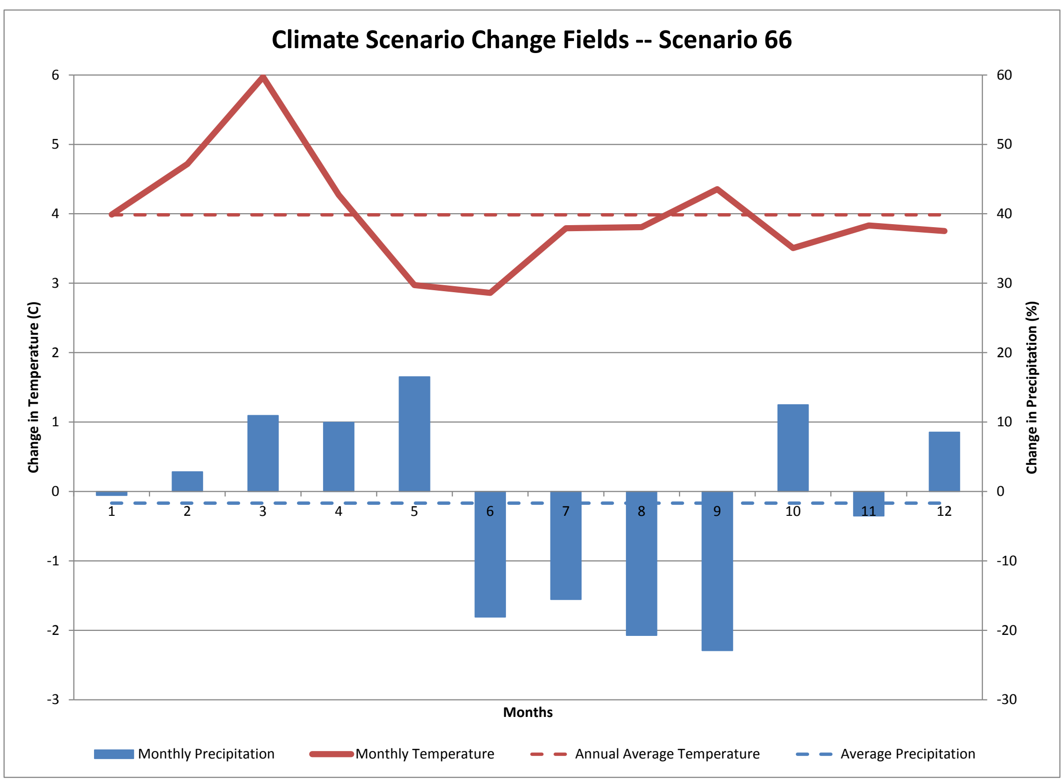


Figure 8: Monthly Change Fields for Waterloo-Wellington Climate Station Climate Change Scenario 66

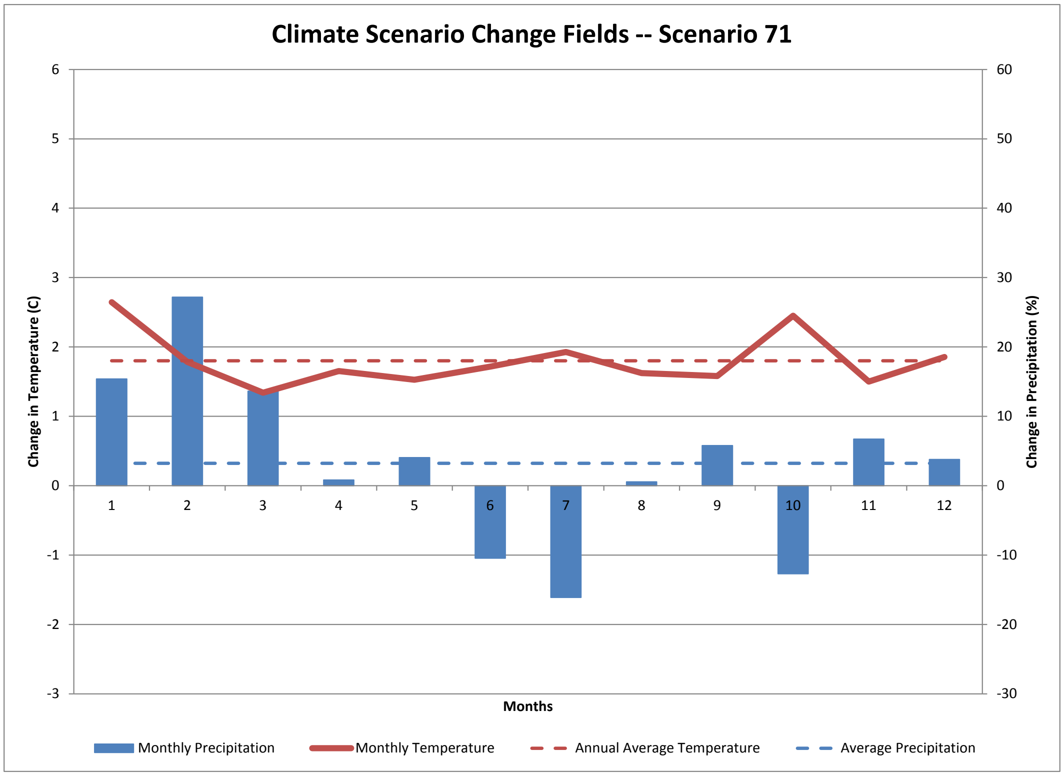


Figure 9: Monthly Change Fields for Waterloo-Wellington Climate Station Climate Change Scenario 71

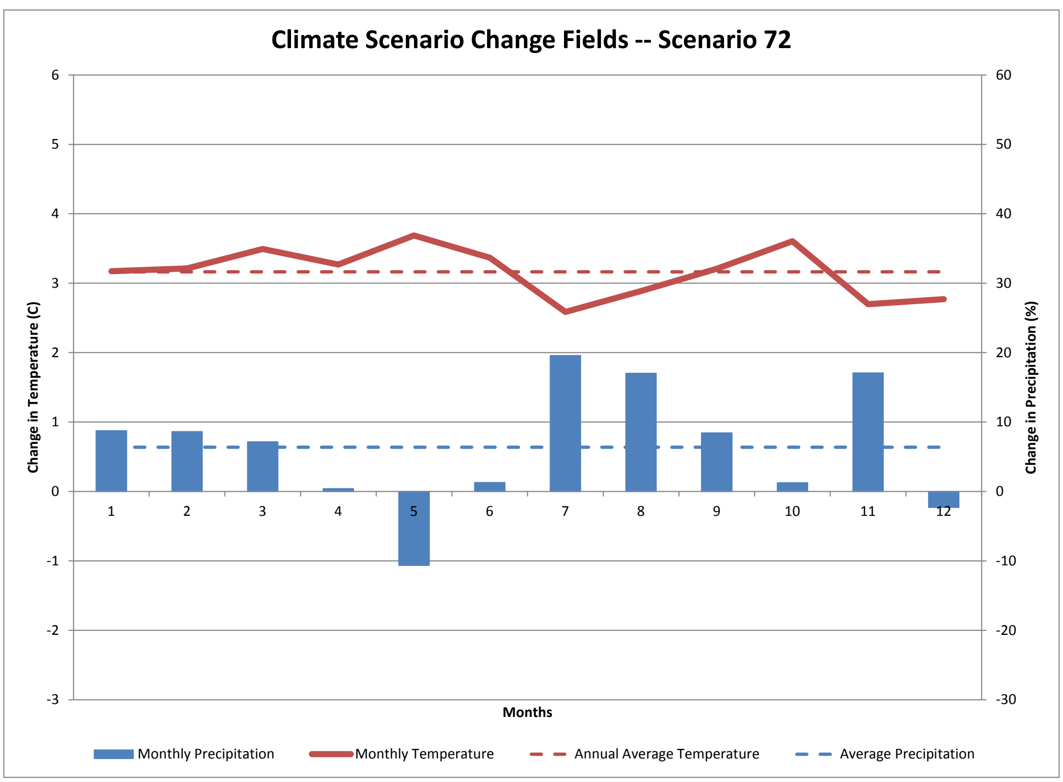


Figure 10: Monthly Change Fields for Waterloo-Wellington Climate Station Climate Change Scenario 72

Appendix B: Sub-basin Water Budget

The water budget for each of the GRCA minor sub-basins is discussed below in terms of changes under the climate change scenarios and compared with other sub-basins. Strong trends are identified and changes to the stress assessments are summarised. As in Section 2.1.1, changes in parameters greater than 2.5% are considered significant, while parameters with smaller changes are considered similar to baseline. Due to the nature of the steady state groundwater model, the groundwater budget does not always balance with the recharge input as calculated by the surface water model on a sub-basin level. As well, pumping of wells has not been discussed in this water budget, but they do play a role in the overall groundwater budget. Well pumping rates are the same for each scenario.

Grand Above Leggatt

The Grand Above Leggatt subwatershed contains the headwaters area of the Grand River and the Luther Marsh reservoir. It is characterized by low to medium permeable surficial materials over a general flat landscape with agriculture as the dominant landuse. Historically this sub-basin has received some of the highest precipitation in the watershed. The baseline water budget partitions precipitation such that 54% leaves as ET, 27% becomes runoff and 19% becomes recharge (Table 1). There is high groundwater discharge and moderate to low inter-basin groundwater flow out of the watershed. The groundwater model is set up such that there is no flow into or out of the sub-basin from outside of the watershed.

Table 1: Grand Above Leggatt

Scenario	Precip	ET	Runoff	Recharge	External GW Flow	GW Discharge	Inter-Basin GW
Baseline	937	502	257	177	0	-143	-20
30	1056	548	294	215	0	-169	-20
31	1030	553	268	209	0	-166	-20
34	985	540	239	206	0	-163	-21
52	1010	542	265	203	0	-160	-20
53	952	525	245	183	0	-143	-20
58	886	496	213	177	0	-138	-20
65	929	510	224	195	0	-154	-20
66	943	524	215	203	0	-162	-21
71	953	500	258	194	0	-152	-20
72	1015	555	249	211	0	-168	-20

Precipitation was significantly higher for five scenarios, but similar to baseline in four scenarios. Only one scenario had significantly less precipitation whereas most of the watershed had two scenarios with less. The sub-basin was similar to the watershed average for ET with seven scenarios being significantly higher than baseline. This sub-basin had the highest number of scenarios with increased recharge with nine and also had eight scenarios with increased groundwater discharge. There was an opposite result for runoff with more scenarios with decreased runoff rather than increased. Winter stream flow was higher than baseline for all scenarios and the maximum monthly median flow occurred one month earlier in six scenarios. Low stream flow generally started one month earlier and was lower than baseline with five scenarios extending the low flow period one month later into the fall.

There was no change to the stress assessment for this sub-basin. Both the surface water and groundwater stress assessments predicted a low potential for stress.

Grand Above Shand to Leggatt

The Grand Above Shand to Leggatt subwatershed is mostly agricultural with clayey soils and glaciofluvial deposits. It contains the largest reservoir in the watershed, Belwood Lake. The baseline water budget partitions precipitation such that 61% leaves as ET, 25% becomes runoff and 14% becomes recharge (Table 2). There is high groundwater discharge with a large portion discharging into the reservoir. There is virtually no inter-basin groundwater flow and very little flow into the sub-basin from outside of the watershed.

Table 2: Grand Above Shand to Leggatt

Scenario	Precip	ET	Runoff	Recharge	External GW Flow	GW Discharge	Inter-Basin GW
Baseline	844	516	209	119	8	-157	0
30	956	564	252	140	5	-185	1
31	925	561	231	133	7	-180	1
34	874	544	205	125	9	-172	0
52	892	539	227	125	7	-178	1
53	857	530	209	119	9	-167	0
58	787	498	180	108	12	-160	-1
65	826	514	193	120	10	-167	0
66	835	527	186	122	10	-169	0
71	852	509	218	125	8	-174	0
72	911	561	219	131	7	-178	1

Precipitation was similar to the Grand Above Leggatt sub-basin with five scenarios greater than baseline and four similar. ET did not increase in as many scenarios as the watershed average of seven, but was close with six. Recharge increased for six scenarios which was a bit higher than the rest of the watershed, but less than some of the other northern sub-basins. Runoff increased in five scenarios. Groundwater discharge increased for all ten scenarios. This was the only parameter and the only sub-basin which had an increase in all scenarios. It is most likely that this is caused by high predicted discharges to Belwood Lake. There was virtually no change to inter-basin groundwater flow, but groundwater flow into the basin from outside of the watershed increased for the lower precipitation scenarios. Winter stream flow was higher than baseline for all scenarios and the maximum monthly median flow occurred one month earlier in seven scenarios. Low stream flow generally started one month earlier and was lower than baseline with six scenarios extending the low flow period one month later into the fall.

There was no change to the stress assessment for this sub-basin. Both the surface water and groundwater stress assessments predicted a low potential for stress.

Grand Above Conestogo to Shand

The Grand Above Conestogo to Shand sub-basin includes the Irvine River, Canagagigue Creek, Swan Creek, Carroll Creek and parts of the Grand River. It is a large mainly agricultural sub-basin with three larger communities, Elora, Fergus and Elmira. The baseline water budget partitions precipitation such that 62% leaves as ET, 21% becomes runoff and 17% becomes recharge (Table 3). Discharge accounts for 76% of recharge and 10% of recharge leaves the basin as inter-basin groundwater flow.

Table 3: Grand Above Conestogo to Shand

Scenario	Precip	ET	Runoff	Recharge	External GW Flow	GW Discharge	Inter-Basin GW
Baseline	848	523	180	145	0	-110	-15
30	962	574	218	169	0	-126	-27
31	927	571	194	162	0	-121	-15
34	885	552	179	153	0	-116	-16
52	918	557	200	161	0	-121	-15
53	869	542	182	145	0	-110	-15
58	798	506	157	134	0	-104	-16
65	821	519	159	142	0	-109	-16
66	843	536	159	148	0	-114	-16
71	859	516	191	152	0	-115	-15
72	915	572	183	160	0	-120	-15

Precipitation changes were at the watershed average with five greater, three similar and two less than baseline. Changes to ET and recharge were similar to the Grand Above Shand to Leggatt sub-basin with six greater and one less than baseline for both ET and recharge. Runoff response was also similar to Grand above Shand to Leggatt, but with four instead of five scenarios greater than baseline. Groundwater discharge to surface water was higher than baseline in seven scenarios, which continues the pattern of higher discharge in the northern sub-basins. The only change to inter-basin groundwater flow was for the scenario with the highest increase in precipitation and recharge, which produced more inter-basin flow leaving the basin. Winter stream flow was higher than baseline for all scenarios and the maximum monthly median flow occurred one month earlier in five scenarios. Low stream flow generally started one month earlier and was lower than baseline with six scenarios extending the low flow period one month later into the fall.

There was no change to the stress assessment for this sub-basin under different scenarios of climate change. The surface water stress assessment predicted a low potential for stress. The groundwater stress assessment predicted a moderate potential for stress. This is higher than the Tier 2 water budget where only part of this sub-basin was classified as having a moderate potential for stress for groundwater under future conditions only.

Conestogo Above Dam

The Conestogo Above Dam sub-basin is characterized by tight soils that produce large amounts of runoff and very little recharge. Most the land area is tile drained to facilitate agriculture and very little natural water storage remains on the landscape. The baseline water budget partitions precipitation such that 56% leaves as ET, 32% becomes runoff and 12% becomes recharge (Table 4). Discharge accounts for 63% of average recharge and flow out (inter-basin and external) 46% of average recharge.

Table 4: Conestogo Above Dam

Scenario	Precip	ET	Runoff	Recharge	External GW Flow	GW Discharge	Inter-Basin GW
Baseline	919	514	294	110	-25	-70	-25
30	1045	556	361	128	-29	-78	-12
31	1019	555	337	127	-28	-76	-25
34	978	551	306	121	-26	-72	-26
52	986	527	335	124	-28	-75	-25
53	918	499	310	109	-24	-66	-25
58	875	496	273	106	-23	-63	-25
65	915	509	291	115	-25	-68	-26
66	934	524	288	122	-27	-72	-26
71	942	503	323	116	-25	-70	-25
72	1005	558	322	125	-28	-75	-25

Precipitation changes were similar to other northern sub-basins with five scenarios greater than and four scenarios similar to baseline. ET reacted differently in this sub-basin with only four scenarios higher than baseline and two less than baseline. Recharge was higher than baseline in eight scenarios, the second highest number of scenarios greater than baseline in any of the sub-basins. Runoff was higher for seven scenarios, tied with Mill Creek for the most scenarios with increased runoff. Groundwater discharge was higher than baseline in six scenarios, continuing the trend of more groundwater discharge in the northern basins under climate change scenarios. The only change to groundwater flow was for the scenario with the highest increase in precipitation and recharge, which produced less inter-basin flow leaving the basin, but also slightly more groundwater flow leaving the watershed. Winter stream flow was higher than baseline for all scenarios and the maximum monthly median flow occurred one month earlier in five scenarios. Low stream flow generally started one month earlier and was lower than baseline in six scenarios.

There was no change to the stress assessment for this sub-basin under climate change scenarios. Both the surface water and groundwater stress assessments predicted a low potential for stress as water use is low in this sub-basin.

Conestogo Below Dam

The Conestogo Below Dam sub-basin has a mixture of surficial geology with tight materials in the upper portions and more permeable materials and hummocky topography in the lower portions. Most of the watershed is used for agriculture and the community of St. Jacobs is located near the confluence with the Grand River. The baseline water budget partitions precipitation such that 58% leaves as ET, 18% becomes runoff and 25% becomes recharge (Table 5). Discharge to surface water from groundwater accounts for 90% of recharge. Inter-basin groundwater flow into the sub-basin is high.

Table 5: Conestogo Below Dam

Scenario	Precip	ET	Runoff	Recharge	External GW Flow	GW Discharge	Inter-Basin GW
Baseline	890	513	157	220	0	-197	87
30	1003	559	217	227	0	-208	90
31	971	555	202	214	0	-203	89
34	926	546	181	198	0	-196	85
52	929	532	193	214	0	-201	89
53	889	521	154	213	0	-190	84
58	834	496	144	193	0	-185	82
65	856	509	153	195	0	-189	83
66	881	525	160	195	0	-193	85
71	899	503	181	213	0	-197	86
72	958	557	191	210	0	-201	88

Precipitation changes were at the watershed average with five greater, three similar and two less than baseline. ET only increased for five scenarios, which is less than the watershed average of seven, but more than the Conestogo Above Dam sub-basin. Recharge decreased for nine scenarios which was the most number of scenarios with decreased recharge of any of the sub-basins. Runoff increased from baseline for six scenarios, which is higher than the watershed average. There was little affect to groundwater discharge under the scenarios with five scenarios similar to, two greater and three less than baseline. Inter-basin groundwater flow was also split with five scenarios predicting less flow and four predicting more flow into the basin. Modelled stream flow in this basin is highly affected by reservoir operations and was not included in the analysis.

There was no change to the stress assessment for this sub-basin under climate change scenarios. Both the surface water and groundwater stress assessments predicted a low potential for stress.

Grand Above Doon to Conestogo

The Grand Above Doon to Conestogo sub-basin is comprised of a mixture of landscapes. The surficial geology is highly variable with a mixture of tills and moraine features. Landuse is a combination of rural and urban. The baseline water budget partitions precipitation such that 57% leaves as ET, 18% becomes runoff and 25% becomes recharge. Discharge to surface water from groundwater accounts for 90% of recharge. Inter-basin groundwater flow into the sub-basin is moderate. Groundwater use is high in this sub-basin and there is a surface water intake for municipal supply.

Precipitation changes were at the watershed average with five greater, three similar and two less than baseline. The sub-basin was similar to the watershed average for ET with seven scenarios being higher than baseline. Recharge was also similar to the watershed average with five scenarios greater than baseline. There was no trend to runoff with four scenarios similar to baseline and three each greater and lower than baseline. Groundwater discharge to surface water was similar to other central sub-basins with five scenarios lower, three higher and two similar to baseline. There was no change in the inter-basin flow in this sub-basin under any of the climate change scenarios. Winter stream flow was higher than baseline for all of the scenarios and the maximum monthly median flow occurred one month earlier in five scenarios. Low stream flow generally started one month earlier, was lower than baseline with six scenarios, and extended into the fall by one month in six scenarios.

Table 6: Grand Above Doon to Conestogo

Scenario	Precip	ET	Runoff	Recharge	External GW Flow	GW Discharge	Inter-Basin GW
Baseline	862	494	155	212	0	-192	32
30	978	548	189	240	0	-208	32
31	942	544	166	231	0	-199	32
34	893	529	152	212	0	-185	32
52	932	532	163	237	0	-199	32
53	883	518	153	212	0	-182	32
58	807	483	131	193	0	-170	32
65	829	498	132	199	0	-175	32
66	849	514	131	204	0	-179	32
71	871	494	160	217	0	-191	32
72	928	546	159	223	0	-194	32

There was no change to the stress assessment for this sub-basin under climate change scenarios. It has a significant potential for stress for groundwater and a low potential for stress for surface water under the baseline scenario and all ten climate change scenarios. Part of this sub-basin also had a significant potential for stress for groundwater in the Tier 2 assessment.

Eramosa Above Guelph

The Eramosa Above Guelph sub-basin has very unique hydrology with extensive closed drainage, exposed bedrock, karst and moraine features. The landscape also has a large percentage of tree cover. The baseline water budget partitions precipitation such that 65% leaves as ET, 8% becomes runoff and 27% becomes recharge. Discharge to surface water accounts for 95% of recharge. There is groundwater flow into this basin from neighbouring basins and flow out to adjacent watersheds outside of the Grand River. Groundwater use is high in this sub-basin and there is a surface water intake for an enhanced recharge system as part of a municipal supply.

Precipitation changes were at the watershed average with five greater, three similar and two less than baseline. The sub-basin was also at the watershed average for ET with seven scenarios higher than baseline. There were five scenarios with recharge greater than baseline and only four with runoff greater than baseline. Groundwater discharge to surface water decreased for five scenarios. Inter-basin groundwater flow did not change much under climate change scenarios, but groundwater flow switched from out of to into the sub-basin from outside of the watershed under low precipitation scenarios. Winter stream flow was higher than baseline for all of the scenarios and the maximum monthly median flow occurred one month earlier in about half of the scenarios. Low stream flow generally started one month earlier and was lower than baseline in nine scenarios.

Table 7: Eramosa Above Guelph

Scenario	Precip	ET	Runoff	Recharge	External GW Flow	GW Discharge	Inter-Basin GW
Baseline	837	543	69	225	-5	-215	41
30	946	612	82	253	-9	-232	43
31	916	602	72	242	-6	-222	42
34	867	581	66	221	-3	-208	40
52	906	587	75	244	-7	-224	42
53	857	571	67	219	-2	-206	40
58	782	527	58	198	1	-192	39
65	807	542	58	206	0	-197	39
66	828	563	56	209	-1	-200	40
71	847	542	73	232	-5	-216	41
72	901	602	67	232	-5	-216	41

The groundwater stress assessment remained moderate for all climate change scenarios. The surface water stress assessment increased from a moderate potential for stress under baseline conditions to a significant potential for stress for three scenarios and decreased to a low potential from stress under one scenario.

Speed Above Dam

The Speed Above Dam sub-basin is composed of ice-contact and outwash deposits and Port Stanley Till. Land use is predominately agricultural. Flow in watercourses reacts quickly to rain events and there is moderate to low baseflow. The baseline water budget partitions precipitation such that 64% leaves as ET, 11% becomes runoff and 24% becomes recharge. The groundwater model predicts high groundwater discharge, but some of that is into the Guelph Lake reservoir. There is groundwater flow out of this basin mostly into the Eramosa Above Guelph basin. Water use is low in the basin with no municipal supplies.

Table 8: Speed Above Dam

Scenario	Precip	ET	Runoff	Recharge	External GW Flow	GW Discharge	Inter-Basin GW
Baseline	863	555	99	210	0	-211	-11
30	979	622	118	240	0	-230	-12
31	942	615	99	227	0	-220	-11
34	894	595	91	207	0	-203	-10
52	934	599	105	230	0	-221	-11
53	883	583	95	205	0	-200	-10
58	804	540	80	183	0	-182	-9
65	829	557	79	193	0	-191	-9
66	852	575	76	200	0	-197	-9
71	871	555	101	214	0	-208	-10
72	928	616	93	220	0	-214	-10

Precipitation changes were at the watershed average with five greater, three similar and two less than baseline. The sub-basin was also at the watershed average for ET with seven scenarios higher than baseline. There were four scenarios with recharge greater than baseline and three similar. Runoff decreased for six scenarios and only increased for three. Groundwater discharge to surface water decreased for five scenarios. Inter-basin groundwater flow did not change much under climate change scenarios. Winter stream flow was higher than baseline for all of the scenarios. Maximum monthly median flow was spread between more months. Additional analysis into when the max yearly flow occurred is needed. Low stream flow generally started one month earlier and was lower than baseline in nine scenarios with a large number of scenarios showing an extended low flow season into October.

The groundwater stress assessment remained low for all climate change scenarios. The surface water stress assessment increased from a low potential for stress under baseline conditions to a moderate potential for stress for five scenarios. This basin has fairly low water use, but also low baseflow during the summer months when takings are active in the sub-basin.

Speed Above Grand to Dam

The Speed Above Grand to Dam contains the urban area of the City of Guelph. Surface water flows are influenced by discharges from Guelph Dam as well as two waste water treatment plants. There is also a known area of groundwater discharge through the reaches below Guelph. The baseline water budget partitions precipitation such that 58% leaves as ET, 23% becomes runoff and 19% becomes recharge. There is high groundwater discharge and some groundwater flows into this basin from adjacent sub-basins. Groundwater use is high with the City of Guelph taking most of its municipal supply from bedrock aquifers.

Table 9: Speed Above Grand to Dam

Scenario	Precip	ET	Runoff	Recharge	External GW Flow	GW Discharge	Inter-Basin GW
Baseline	829	483	192	154	0	-174	17
30	936	538	223	175	0	-188	17
31	909	532	209	168	0	-180	16
34	860	514	194	151	0	-166	16
52	897	519	210	168	0	-181	16
53	849	504	194	151	0	-166	17
58	778	468	172	138	0	-153	17
65	800	481	176	143	0	-158	16
66	820	501	176	143	0	-161	16
71	840	480	199	161	0	-173	17
72	893	532	200	161	0	-174	16

Precipitation changes were at the watershed average with five greater, three similar and two less than baseline. The sub-basin was also at the watershed average for ET with seven scenarios higher than baseline. There were five scenarios with recharge greater than baseline and two similar. Runoff increased for five scenarios and decreased for three. Groundwater discharge to surface water decreased for five scenarios. Inter-basin groundwater flow did not change much under climate change scenarios. Winter stream flow was higher than baseline for all of the scenarios. Maximum monthly median flow occurred one month earlier in seven scenarios. Stream flow during the summer months was lower than baseline for just less than half of the scenarios and extended into October in about half of the scenarios.

The groundwater stress assessment remained at a significant potential for stress and the surface water stress assessment remained a low potential for stress for all climate change scenarios.

Mill Creek

The Mill Creek sub-basin is the smallest sub-basin in the watershed. It is characterised by outwash deposits and moraine features. Groundwater use is quite high, but there are no municipal water systems in the sub-basin. The baseline water budget partitions precipitation such that 66% leaves as ET, 4% becomes runoff and 30% becomes recharge. There is high groundwater discharge and high groundwater flow out of the sub-basin.

Precipitation changes were at the watershed average with five greater, three similar and two less than baseline. The sub-basin was also at the watershed average for ET with seven scenarios higher than baseline. Recharge decreased from baseline for five scenarios and was similar for two. Runoff increased for seven scenarios, decreased for three and was similar for none. Runoff is so low in this sub-basin that only a change of less than 1 mm/yr would result in a similar to baseline category. Groundwater discharge to surface water decreased for six scenarios. Inter-basin groundwater flow went down for scenarios with less precipitation and increased for scenarios with more precipitation. Winter stream flow was higher than baseline for all of the scenarios and the maximum monthly median flow occurred one month earlier for most scenarios. Stream flow during the summer months was lower than baseline for just less than half of the scenarios and extended into October in about half of the scenarios.

Table 10: Mill Creek

Scenario	Precip	ET	Runoff	Recharge	External GW Flow	GW Discharge	Inter-Basin GW
Baseline	853	564	35	254	0	-172	-37
30	965	633	46	287	0	-195	-42
31	929	624	39	265	0	-177	-38
34	879	604	36	239	0	-158	-34
52	919	609	41	270	0	-181	-39
53	870	591	37	242	0	-159	-35
58	797	546	32	219	0	-139	-31
65	816	562	32	223	0	-143	-31
66	837	583	31	223	0	-144	-31
71	862	563	39	259	0	-173	-37
72	918	628	38	253	0	-168	-36

The groundwater stress assessment remained at a moderate potential for stress and the surface water stress assessment remained a low potential for stress for all climate change scenarios.

Grand Above Brantford to Doon

The Grand Above Brantford to Doon sub-basin contains most of the central urban areas of Waterloo, Kitchener and Cambridge. It continues south of Cambridge to encompass a stretch of the Grand River called the recovery reach where high level of groundwater discharge enters the river. There is very high groundwater use for the Region of Waterloo's Integrated Urban System. The baseline water budget partitions precipitation such that 51% leaves as ET, 37% becomes runoff and 11% becomes recharge. There is very high groundwater discharge and high groundwater flow into the sub-basin.

Precipitation changes were at the watershed average with five greater, three similar and two less than baseline. The sub-basin was close to the watershed average for ET with seven scenarios higher than baseline, but with no scenarios less than baseline. Recharge decreased from baseline for five scenarios and was similar for two. Runoff increased for five scenarios and decreased for three. Groundwater discharge to surface water decreased for five scenarios. There was no change to inter-basin groundwater flow with climate change scenarios. Winter stream flow was higher than baseline for all of the scenarios and the maximum monthly median flow occurred one month earlier for four scenarios. Stream flow during the summer months was lower than baseline for most scenarios and extended into October in about half of the scenarios.

Table 11: Grand Above Brantford to Doon

Scenario	Precip	ET	Runoff	Recharge	External GW Flow	GW Discharge	Inter-Basin GW
Baseline	889	457	331	101	0	-241	100
30	1005	502	383	121	0	-258	101
31	965	501	356	108	0	-245	100
34	917	491	333	92	0	-228	100
52	954	487	356	111	0	-248	100
53	902	472	333	96	0	-232	100
58	830	448	298	84	0	-214	99
65	852	460	305	86	0	-220	100
66	872	476	308	88	0	-222	100
71	897	457	338	102	0	-243	101
72	956	507	346	103	0	-237	100

The groundwater stress assessment remained at a significant potential for stress and the surface water stress assessment remained a low potential for stress for all climate change scenarios.

Nith Above New Hamburg

The Nith Above New Hamburg sub-basin is comprised of mostly low permeability till material with a large percent of the area classified as hummocky. The sub-basin is almost entirely actively farmed with a few small communities. Water use is generally low in this basin. The baseline water budget partitions precipitation such that 59% leaves as ET, 23% becomes runoff and 18% becomes recharge. There is moderate groundwater discharge and moderate groundwater flow out of the sub-basin to other basins as well as outside of the watershed.

Precipitation changes were at the watershed average with five greater, three similar and two less than baseline. The sub-basin was close to the watershed average for ET with seven scenarios higher than baseline, but with no scenarios less than baseline. Recharge increased from baseline for five scenarios and was similar for two. Runoff decreased for five scenarios and increased for four. Groundwater discharge to surface water decreased for five scenarios. There was no change to inter-basin groundwater flow with climate change scenarios. Winter stream flow was higher than baseline for all of the scenarios and the maximum monthly median flow occurred one month earlier for six scenarios. Stream flow during the summer months was lower than baseline for most scenarios and extended into October in about half of the scenarios.

Table 12 Nith Above New Hamburg

Scenario	Precip	ET	Runoff	Recharge	External GW Flow	GW Discharge	Inter-Basin GW
Baseline	937	551	219	167	-23	-67	-33
30	1052	618	249	185	-24	-72	-34
31	1025	611	233	180	-23	-69	-34
34	975	600	207	169	-22	-62	-32
52	984	580	225	179	-23	-68	-33
53	928	568	201	159	-21	-60	-31
58	879	539	186	154	-20	-57	-30
65	902	553	190	160	-21	-59	-31
66	928	572	191	165	-27	-61	-31
71	949	552	222	174	-22	-65	-33
72	1018	617	224	177	-23	-68	-34

Both groundwater and surface water stress assessments remained at a low potential for stress for all climate change scenarios.

Nith Above Grand to New Hamburg

The Nith Above Grand to New Hamburg sub-basin contains a large part of the Waterloo Moraine. The sub-basin is a mix of high permeability outwash materials and low permeability till materials. Most of the landuse is agricultural with a mix of crop types. Water use is moderate in this basin. The baseline water budget partitions precipitation such that 63% leaves as ET, 11% becomes runoff and 26% becomes recharge. There is high groundwater discharge and moderate groundwater flow out of the sub-basin to other basins.

Precipitation changes were at the watershed average with five greater, three similar and two less than baseline. The sub-basin was at the watershed average for ET with seven scenarios higher than baseline and one scenario less than baseline. Recharge increased from baseline for only three scenarios and decreased for five. Runoff increased for four scenarios and decreased for three. Groundwater discharge to surface water decreased for five scenarios and increased for three. There was no change to inter-basin groundwater flow with climate change scenarios. Winter stream flow was higher than baseline for all of the scenarios and the maximum monthly median flow occurred one month earlier for six scenarios. Stream flow during July was lower than baseline for most scenarios, but August and September had roughly an equal number of scenarios above and below the baseline. The low flow season extended into October in about half of the scenarios.

Table 13: Nith Above Grand to New Hamburg

Scenario	Precip	ET	Runoff	Recharge	External GW Flow	GW Discharge	Inter-Basin GW
Baseline	855	542	91	222	0	-177	-31
30	970	609	110	251	0	-195	-32
31	932	601	95	236	0	-183	-32
34	886	579	91	216	0	-167	-32
52	921	584	98	239	0	-185	-32
53	874	568	91	215	0	-167	-32
58	799	525	79	194	0	-152	-32
65	821	540	80	202	0	-157	-32
66	843	561	78	204	0	-159	-32
71	864	540	97	227	0	-176	-32
72	920	606	89	225	0	-175	-31

The groundwater stress assessment remained low for all climate change scenarios. The surface water stress assessment increased from a low potential for stress under baseline conditions to a moderate potential for stress for three scenarios. All of the moderate stress assessments occurred in the month of September only.

Whitemans Creek

The Whitemans Creek sub-basin can be broken into two parts. The headwaters part is characterised by tight till material with low permeability, while the lower part is highly permeable sand plain. Most of the landuse is agricultural with a mix of crop types. Crops in the lower part of the watershed are often irrigated resulting in high seasonal water use in the sub-basin. The baseline water budget partitions precipitation such that 61% leaves as ET, 15% becomes runoff and 24% becomes recharge. There is high groundwater discharge and low groundwater flow out of the sub-basin to other basins as well as outside of the watershed.

Precipitation changes were at the watershed average with five greater, three similar and two less than baseline. The sub-basin was close to the watershed average for ET with seven scenarios higher than baseline, but no scenarios less than baseline. Recharge increased from baseline for only three scenarios and decreased for five. Runoff increased for five scenarios and decreased for four. Groundwater discharge to surface water decreased for five scenarios and increased for only two. There was no change to inter-basin groundwater flow with climate change scenarios. Winter stream flow at the Mt. Vernon gauge was higher than baseline for all of the scenarios and the maximum monthly median flow occurred one month earlier for about half of the scenarios. June stream flow was much less than baseline for most scenarios. Late summer flows were only less than baseline for six scenarios. Two scenarios had very similar summer flows to baseline and one scenario had much higher flows.

Table 14: Whitemans Creek

Scenario	Precip	ET	Runoff	Recharge	External GW Flow	GW Discharge	Inter-Basin GW
Baseline	905	555	132	218	-15	-178	-12
30	1019	618	154	246	-18	-193	-13
31	981	614	136	231	-15	-182	-12
34	935	604	125	206	-10	-165	-11
52	963	590	139	234	-15	-185	-12
53	910	577	126	208	-10	-167	-11
58	844	544	110	190	-7	-153	-11
65	866	561	111	194	-8	-157	-10
66	887	582	108	197	-9	-158	-10
71	911	555	135	221	-13	-175	-11
72	971	620	129	222	-13	-176	-12

The groundwater stress assessment remained low for all climate change scenarios. The surface water stress assessment increased from a moderate potential for stress under baseline conditions to a significant potential for stress for nine scenarios. This sub-basin was given a moderate potential for stress in the Tier 2 water budget.

Grand Above York to Brantford

The Grand Above York to Brantford sub-basin includes Mt. Pleasant Creek and Big Creek as well as the main Grand River. Mt. Pleasant Creek watershed is characterised by permeable material and high baseflow, while the Big Creek watershed is on the Clay plain with low permeable material and a tight drainage networks. The baseline water budget partitions precipitation such that 62% leaves as ET, 28% becomes runoff and 10% becomes recharge. There is moderate to high groundwater discharge in parts of the sub-basin. The basin gains groundwater from nearby basins and losses some to flow out of the watershed.

Precipitation changes were at the watershed average with five greater, three similar and two less than baseline. The sub-basin was at the watershed average for ET with seven scenarios higher than baseline and one scenario less than baseline. There was no clear trend with recharge response to climate change scenarios with four greater than, four less than and two similar to baseline. There was a slight trend to increases runoff with five scenarios compared to four with less runoff. There was a trend for less groundwater discharge to surface water with six scenarios predicting less recharge and only one predicting more. There was no change to inter-basin groundwater flow with climate change scenarios. Winter stream flow at York was higher than baseline for all of the scenarios and the maximum monthly median flow occurred one month earlier for about half of the scenarios. June stream flow was much less than baseline for most scenarios. Late summer flows were only less than baseline for six scenarios. Three scenarios had very similar summer flows to baseline and one scenario had much higher flows.

Table 15: Grand Above York to Brantford

Scenario	Precip	ET	Runoff	Recharge	External GW Flow	GW Discharge	Inter-Basin GW
Baseline	840	522	236	82	-20	-110	42
30	943	572	279	92	-22	-114	42
31	912	568	256	88	-20	-111	41
34	862	556	230	76	-17	-102	41
52	908	551	266	91	-21	-112	42
53	855	537	238	80	-18	-104	41
58	785	508	206	71	-16	-98	41
65	803	524	207	72	-16	-99	41
66	834	549	210	74	-17	-101	41
71	872	524	260	87	-21	-109	42
72	902	575	244	82	-19	-107	41

Both groundwater and surface water stress assessments remained at a low potential for stress for all climate change scenarios.

Fairchild Creek

The Fairchild Creek sub-basin has areas of exposed bedrock, moraine deposits and clay plain. There is a current study underway to re-evaluate how the exposed bedrock is represented in the numerical models. It is a fairly responsive watershed with flashy event flows and low but steady baseflow. The baseline water budget partitions precipitation such that 57% leaves as ET, 26% becomes runoff and 17% becomes recharge. There is fairly high groundwater discharge within the sub-basin. The basin gains a small amount of groundwater from outside of the watershed and losses about the same amount to nearby basins.

Precipitation changes were different than most of the watershed with six scenarios with more precipitation compared to the average of five. Fairchild Creek also had the most scenarios with increased ET with eight scenarios and no scenarios with less than baseline. There was a slight trend to less recharge with five scenarios with less compared to four scenarios with more than baseline. There was a slight trend to increased runoff with five scenarios compared to three with less runoff. There was a trend for less groundwater discharge to surface water with six scenarios predicting less recharge and only one predicting more. There was no change to inter-basin groundwater flow with climate change scenarios. Winter stream flow at the gauge was higher than baseline for all of the scenarios and the maximum monthly median flow occurred one month earlier for more than half of the scenarios. Summer flows were less than baseline about half of the time, but the current model does not represent the low flow season well for this gauge. There was a great variability in flows in the late summer and fall period for the different scenarios.

Table 16: Fairchild Creek

Scenario	Precip	ET	Runoff	Recharge	External GW Flow	GW Discharge	Inter-Basin GW
Baseline	847	480	223	144	5	-130	-6
30	960	530	267	163	5	-141	-6
31	921	528	243	151	5	-131	-6
34	873	516	223	133	6	-118	-6
52	916	515	248	153	5	-133	-6
53	863	502	225	137	6	-121	-6
58	788	472	196	121	7	-109	-6
65	806	486	197	124	6	-111	-6
66	849	514	206	129	6	-115	-6
71	893	493	247	153	5	-132	-7
72	912	534	234	144	5	-126	-6

Both groundwater and surface water stress assessments remained at a low potential for stress for all climate change scenarios.

Mckenzie Creek

The Mckenzie Creek sub-basin starts in the Norfolk sand plain with highly permeable material, a shallow groundwater table, high groundwater discharge and high seasonal water use for agriculture. The sub-basin's lower half is in the Haldimand Clay plain with low permeable material and varied landuse. The baseline water budget partitions precipitation such that 61% leaves as ET, 28% becomes runoff and 11% becomes recharge. There is moderate groundwater discharge within the sub-basin. The basin gains a small amount of groundwater from outside of the watershed and losses about twice as much to nearby basins.

Table 17: Mckenzie Creek

Scenario	Precip	ET	Runoff	Recharge	External GW Flow	GW Discharge	Inter-Basin GW
Baseline	866	531	243	92	16	-76	-39
30	970	578	286	106	13	-78	-39
31	933	578	257	98	15	-75	-38
34	883	568	230	84	20	-67	-37
52	931	559	271	101	14	-76	-39
53	878	548	241	89	18	-70	-38
58	797	517	203	78	22	-64	-37
65	821	532	209	80	22	-65	-37
66	859	563	213	83	21	-67	-38
71	904	539	265	101	15	-75	-39
72	920	587	243	91	17	-72	-38

Precipitation changes were at the watershed average with five greater, three similar and two less than baseline. The sub-basin was at the watershed average for ET with seven scenarios higher than baseline and one scenario less than baseline. There was a slight trend to less recharge with five scenarios with less compared to four scenarios with more than baseline. There was no trend to runoff with four scenarios with more runoff, four with less runoff and two with similar runoff to baseline. There was a trend for less groundwater discharge to surface water with six scenarios predicting less recharge and only one predicting more. There was no change to inter-basin groundwater flow with climate change scenarios. Winter stream flow at the outlet to the Grand River were generally higher than baseline for most of the scenarios. There was no change in the month of maximum monthly median flow, but six scenarios predicted lower max month median flow. Early summer flows were less than baseline for most scenarios, but late summer and early fall flows were split with about half of the scenarios predicting less and half predicting more or similar.

The groundwater stress assessment remained low for all climate change scenarios. The surface water stress assessment increased from a moderate potential for stress under baseline conditions to a significant potential for stress for nine scenarios. This sub-basin was given a moderate potential for stress for surface water in the Tier 2 water budget.

Grand Above Dunnville to York

The Grand Above Dunnville to York sub-basin includes local drainage to the lower part of the Grand River. The entire sub-basin is on the Haldimand Clay plain with low preamble material and flat terrain. The baseline water budget partitions precipitation such that 56% leaves as ET, 33% becomes runoff and 10% becomes recharge. There is moderate groundwater discharge mostly to the main channel of the Grand River. The basin gains groundwater from nearby basins and losses some to flow out to Lake Erie.

Table 18: Grand Dunnville to York

Scenario	Precip	ET	Runoff	Recharge	External GW Flow	GW Discharge	Inter-Basin GW
Baseline	878	493	293	91	17	-83	-8
30	948	526	309	113	17	-80	-8
31	949	527	319	102	17	-82	-8
34	895	525	270	100	21	-75	-8
52	942	518	324	100	17	-82	-8
53	891	506	297	88	20	-77	-8
58	809	480	247	82	23	-72	-8
65	833	493	252	88	22	-73	-8
66	873	523	259	90	21	-74	-8
71	919	499	322	99	17	-82	-8
72	931	543	291	97	19	-79	-8

Precipitation changes were at the watershed average with five greater, three similar and two less than baseline. The sub-basin was a little below the watershed average for ET with six scenarios higher than baseline and one scenario less than baseline. More scenarios showed increased discharge than the other lower watershed sub-basins. There were six scenarios with increased recharge and only one with less recharge than baseline. There was no trend to runoff with four scenarios with more runoff, four with less runoff and two with similar runoff to baseline. There was a strong trend for less groundwater discharge to surface water with seven scenarios predicting less recharge and none predicting more than baseline. There was no change to inter-basin groundwater flow with climate change scenarios and some small changes to external groundwater flow to Lake Erie. Winter stream flow at Dunnville was higher than baseline for all of the scenarios and the maximum monthly median flow occurred one month earlier for about half of the scenarios. June stream flow was much less than baseline for most scenarios. Late summer flows were only less than baseline for five scenarios. Three scenarios had very similar summer flows to baseline and two scenarios had much higher flows.

The surface water stress assessment remained at a low potential for stress for all of the climate change scenarios. The groundwater stress assessment increased from a low to a moderate potential for stress under one scenario. This was the only sub-basin to see a change in the groundwater stress assessment. There are no groundwater municipal water supply systems in this sub-basin.

Appendix C: Monthly Median Flow Charts

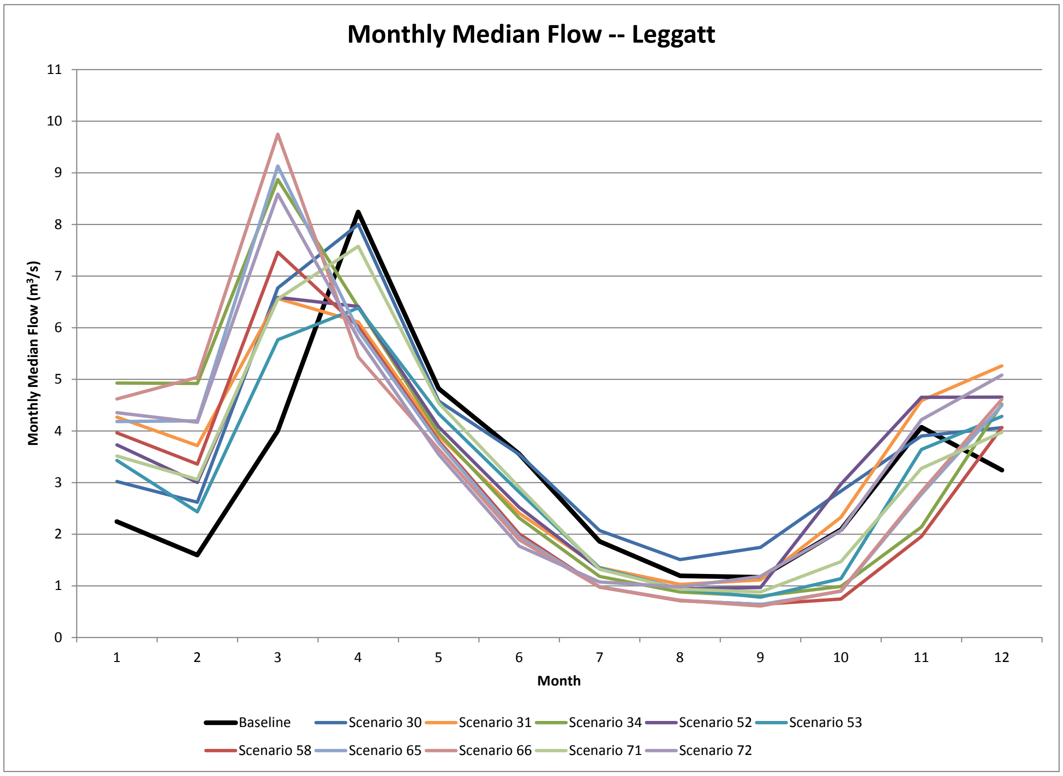


Figure 1: Monthly median flows in the Grand River at Leggatt under scenarios of climate change

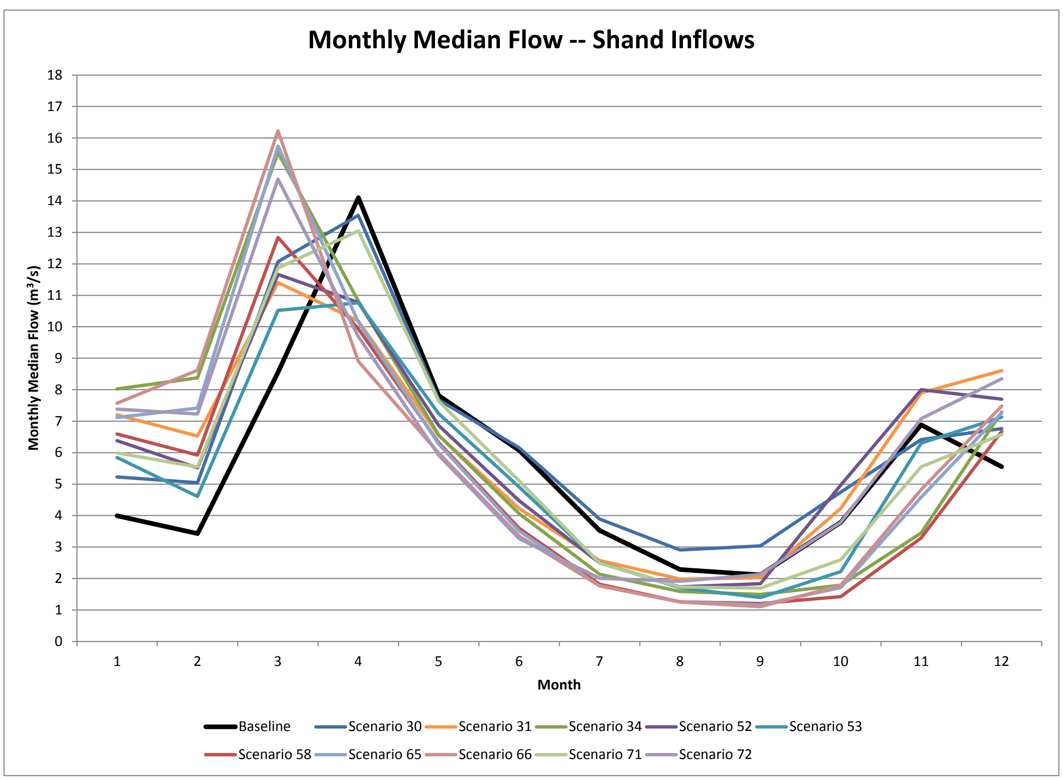


Figure 2: Monthly median inflows to Shand Dam Reservoir under scenarios of climate change

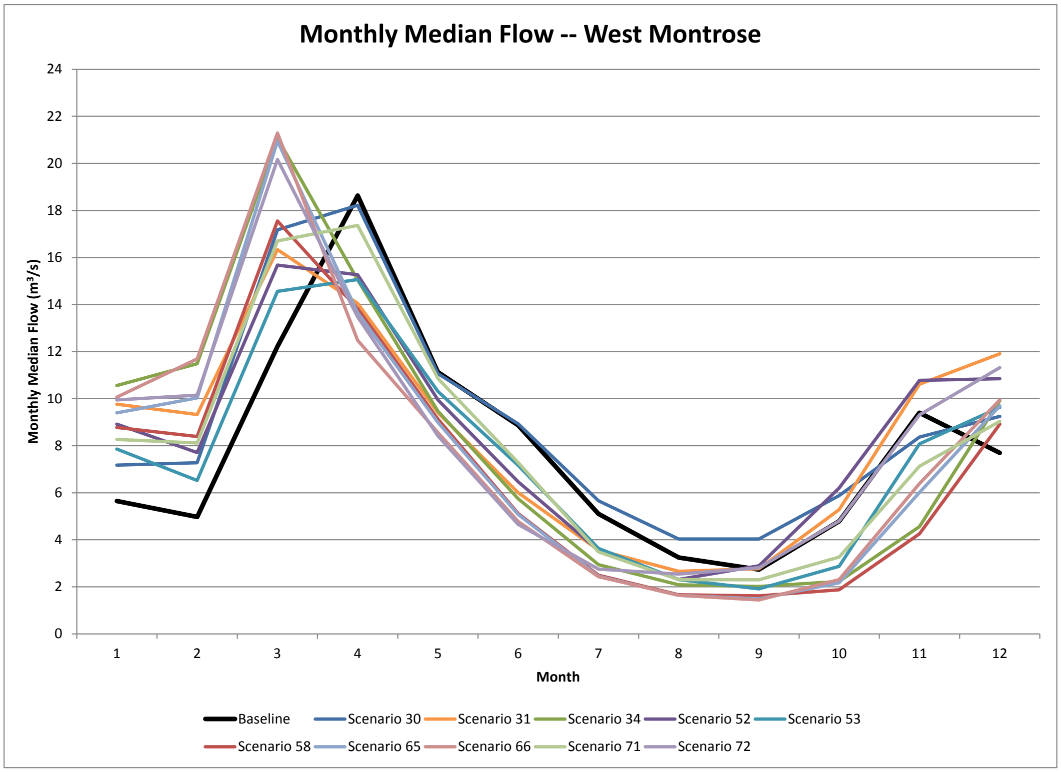


Figure 3: Monthly median flows of the Grand River at West Montrose under scenarios of climate change

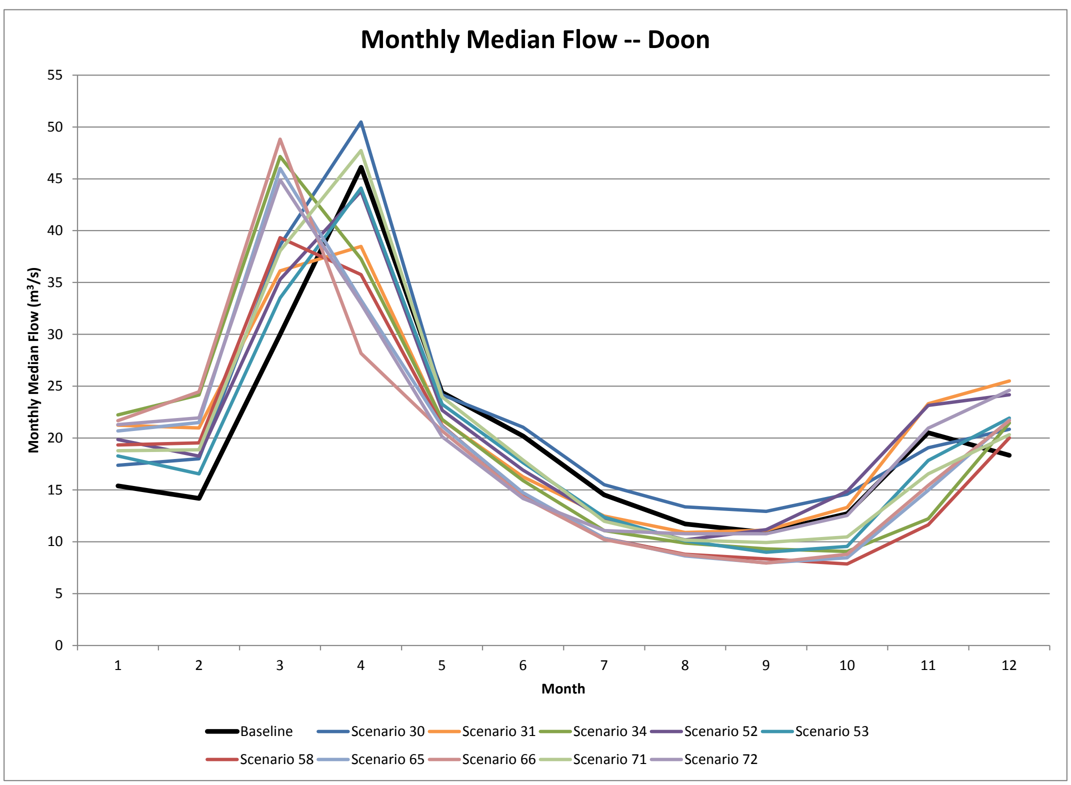


Figure 4: Monthly median flows of the Grand River at Doon under scenarios of climate change

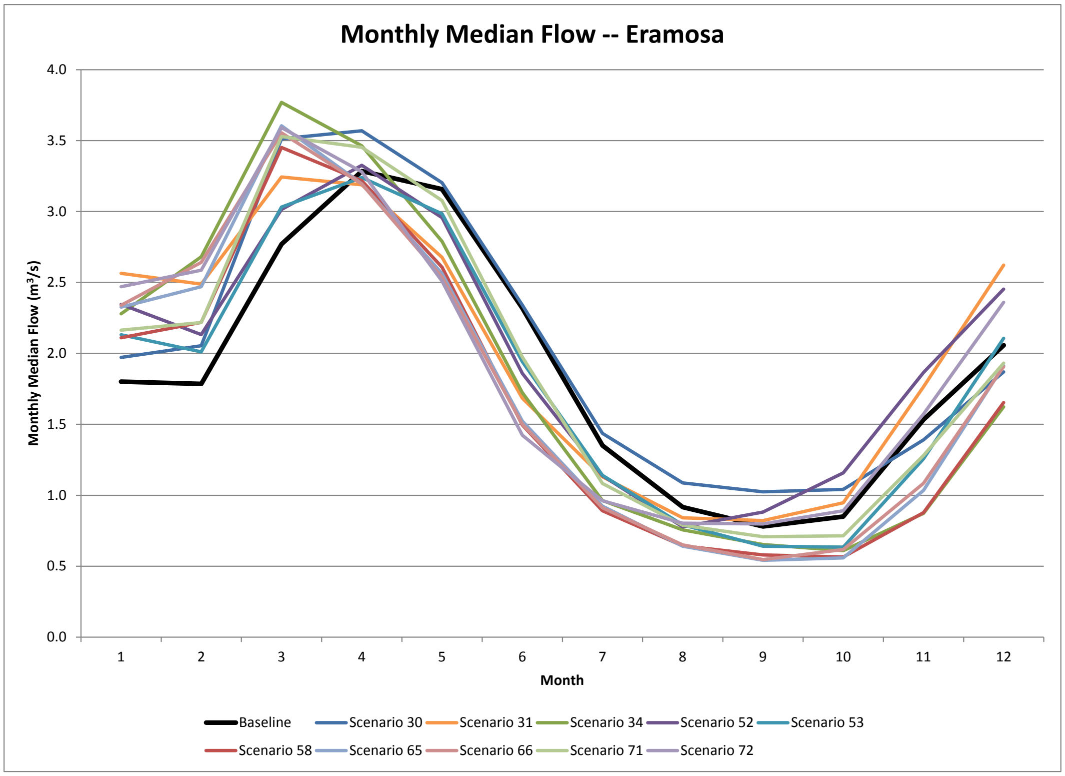


Figure 5: Monthly median flows in the Eramosa River at Watson Rd under scenarios of climate change

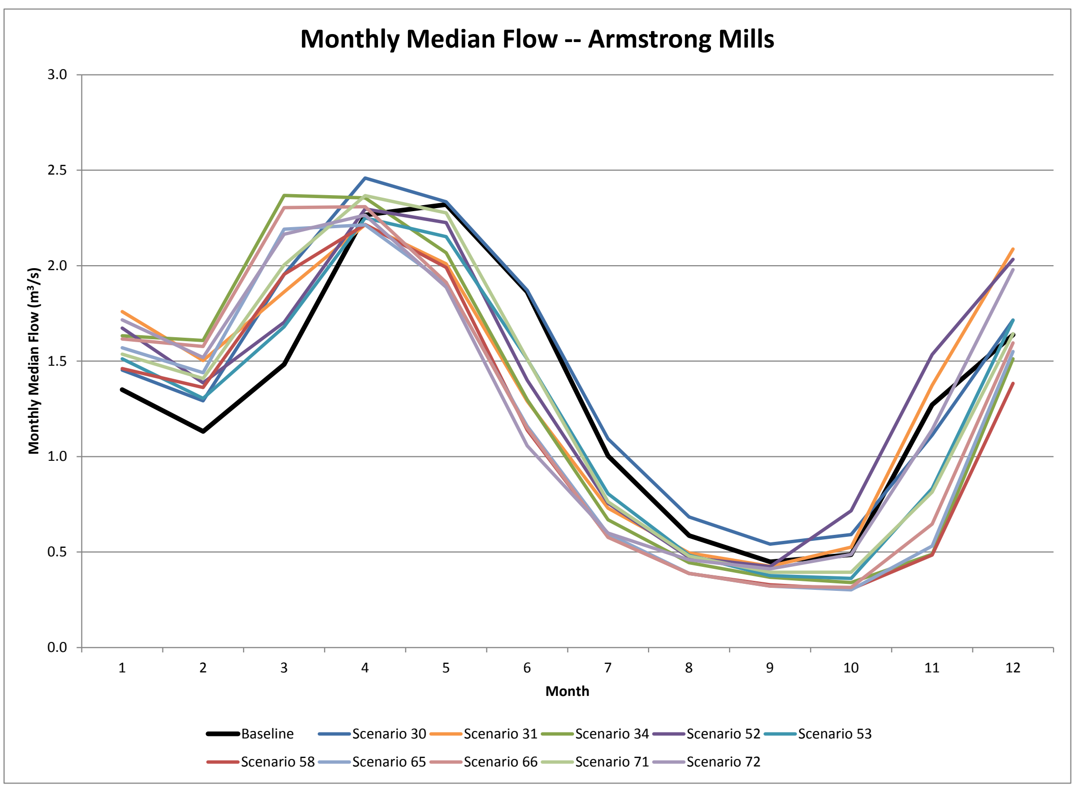


Figure 6: Monthly median flows in the Speed River at Armstrong Mills under scenarios of climate change

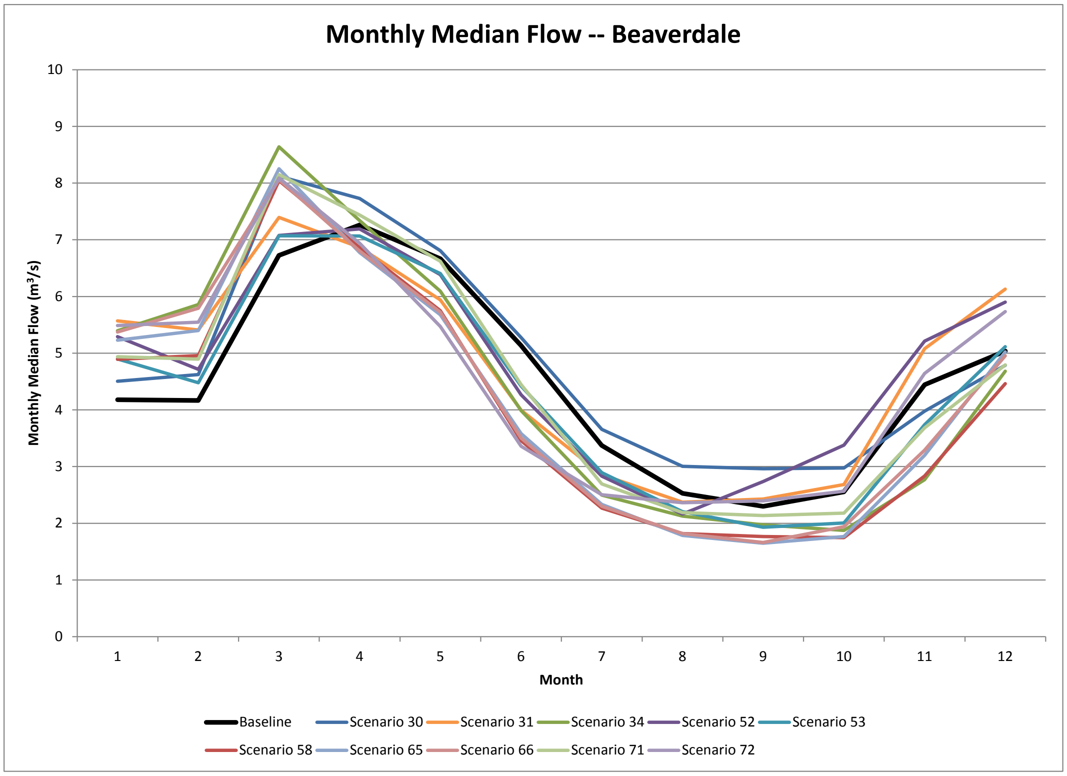


Figure 7: Monthly median flows in the Speed River at Beaverdale under scenarios of climate change

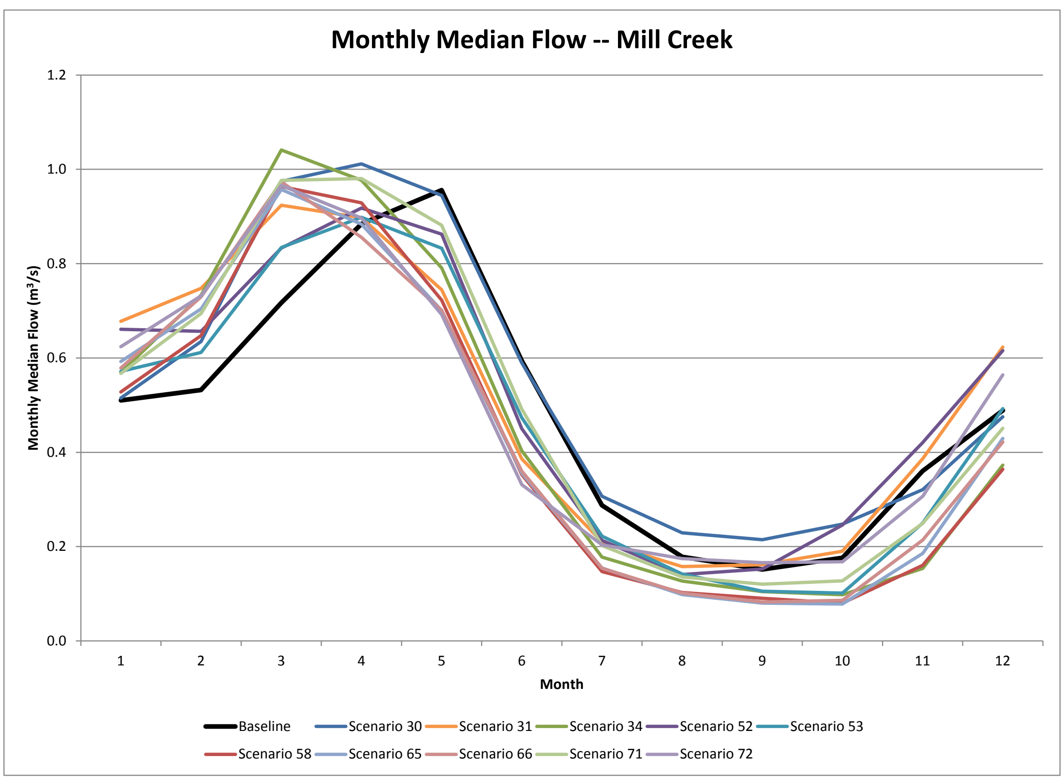


Figure 8: Monthly median flows in Mill Creek at Side Rd 10 under scenarios of climate change

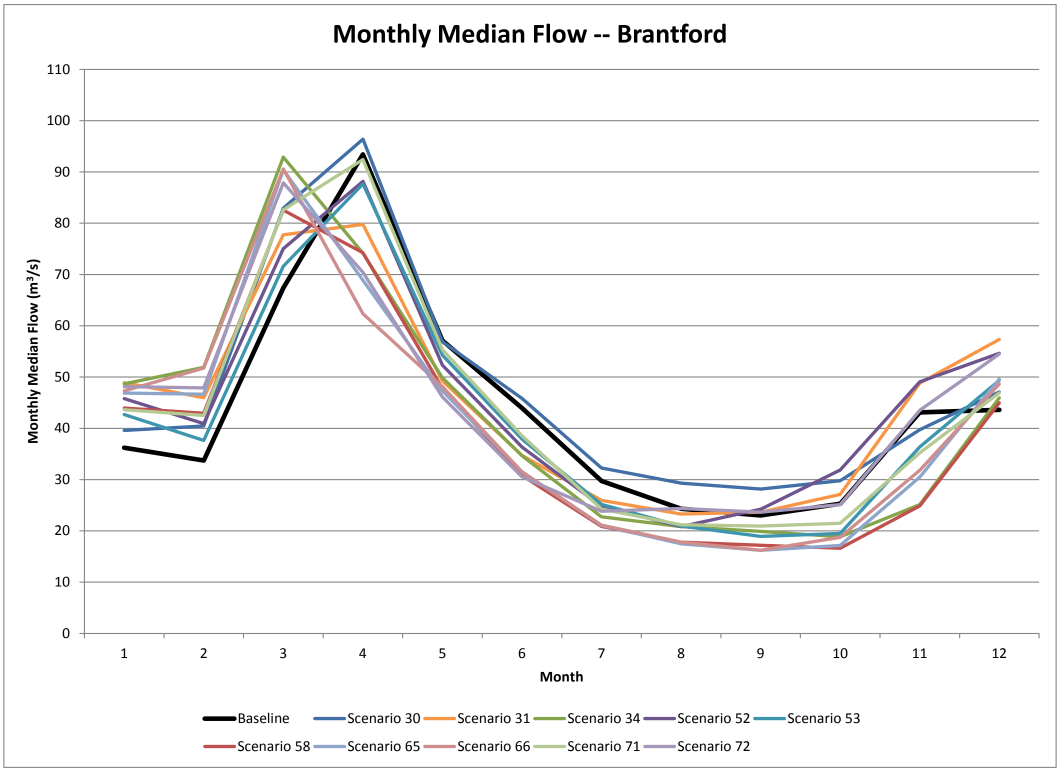


Figure 9: Monthly median flows in the Grand River at Brantford under scenarios of climate change

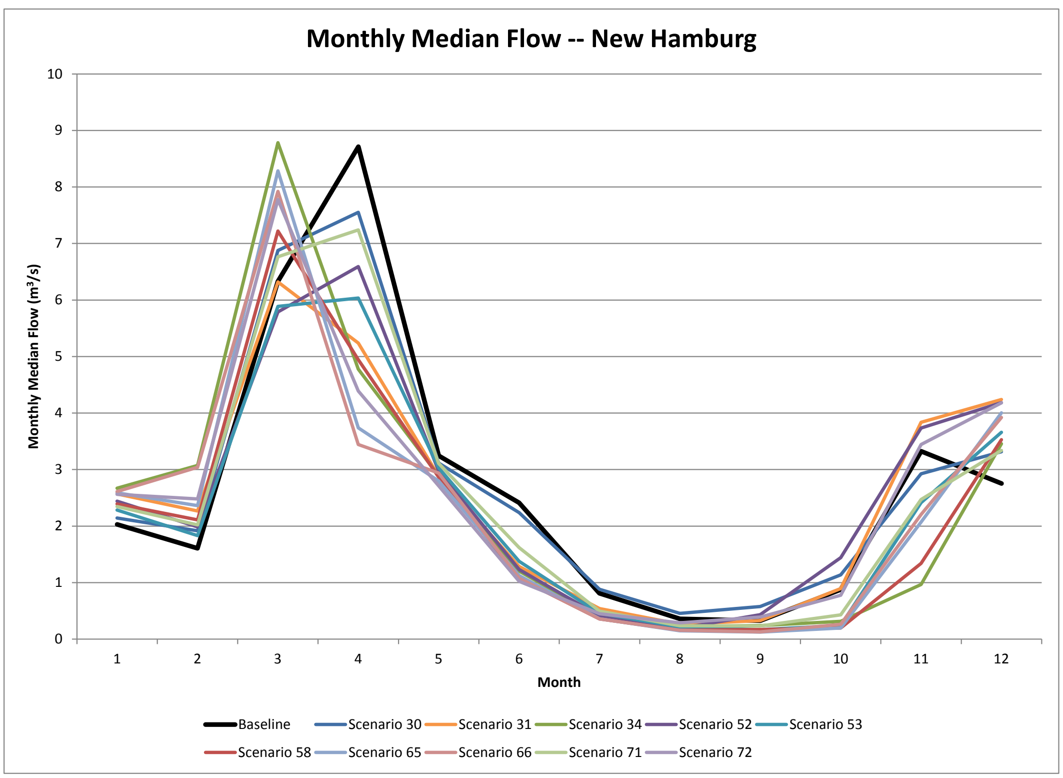


Figure 10: Monthly median flows in the Nith River at New Hamburg under scenarios of climate change

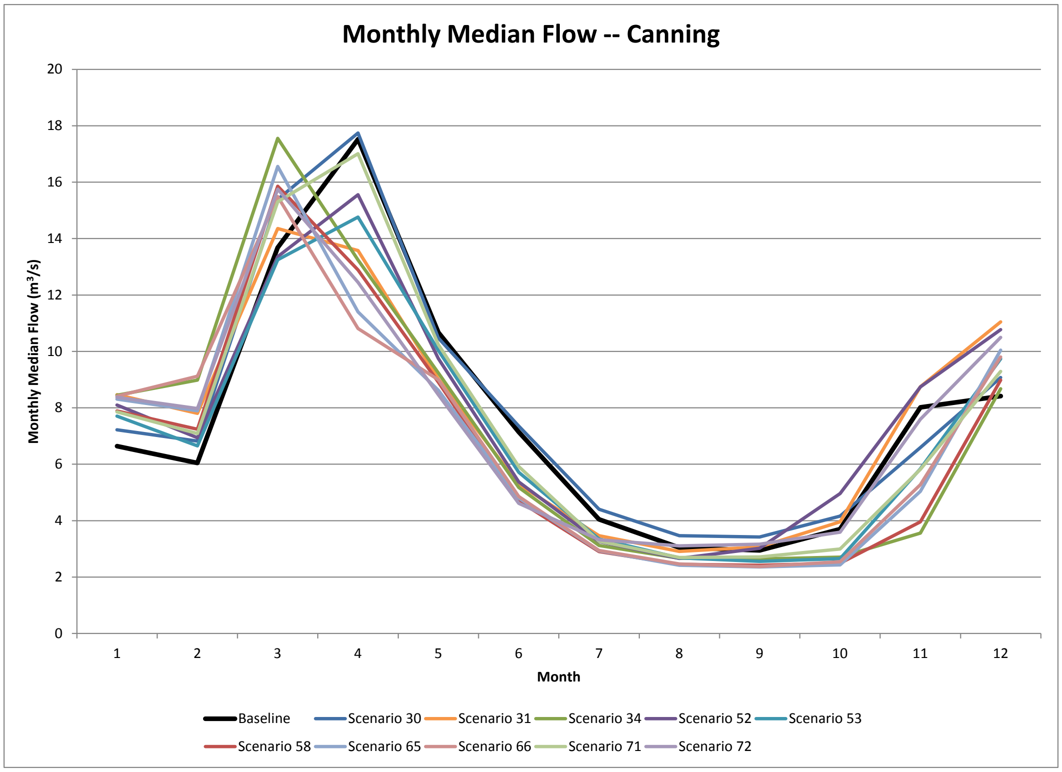


Figure 11: Monthly median flows in the Nith River at Canning under scenarios of climate change

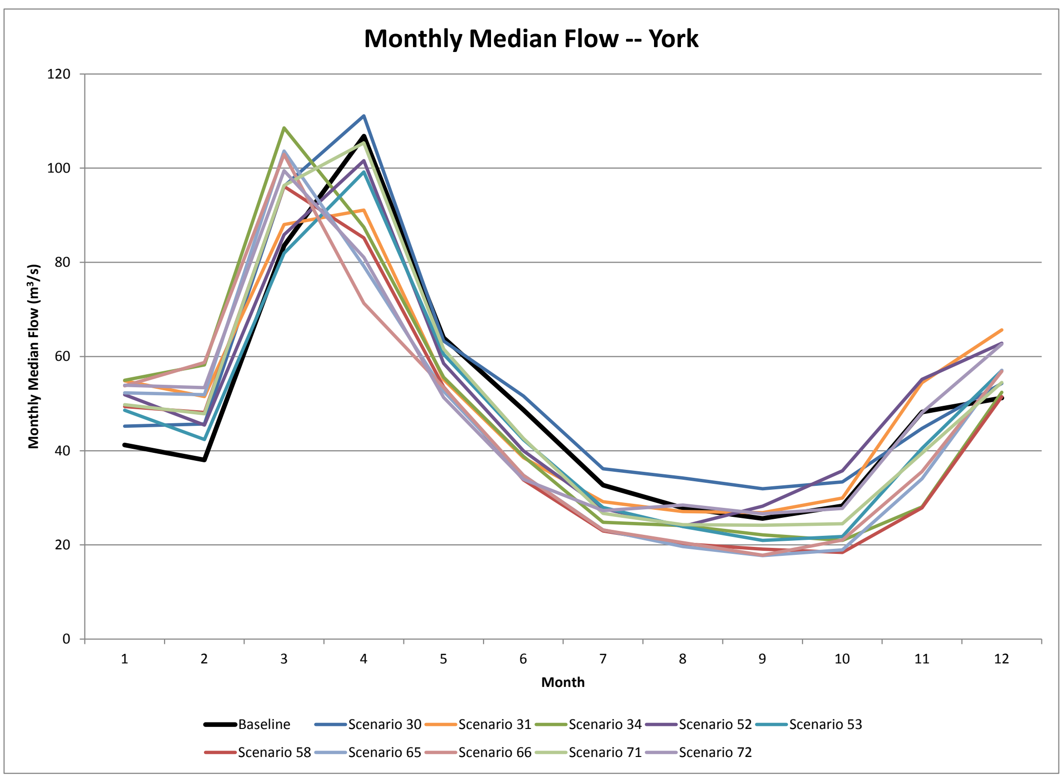


Figure 12: Monthly median flows in the Grand River at York under scenarios of climate change

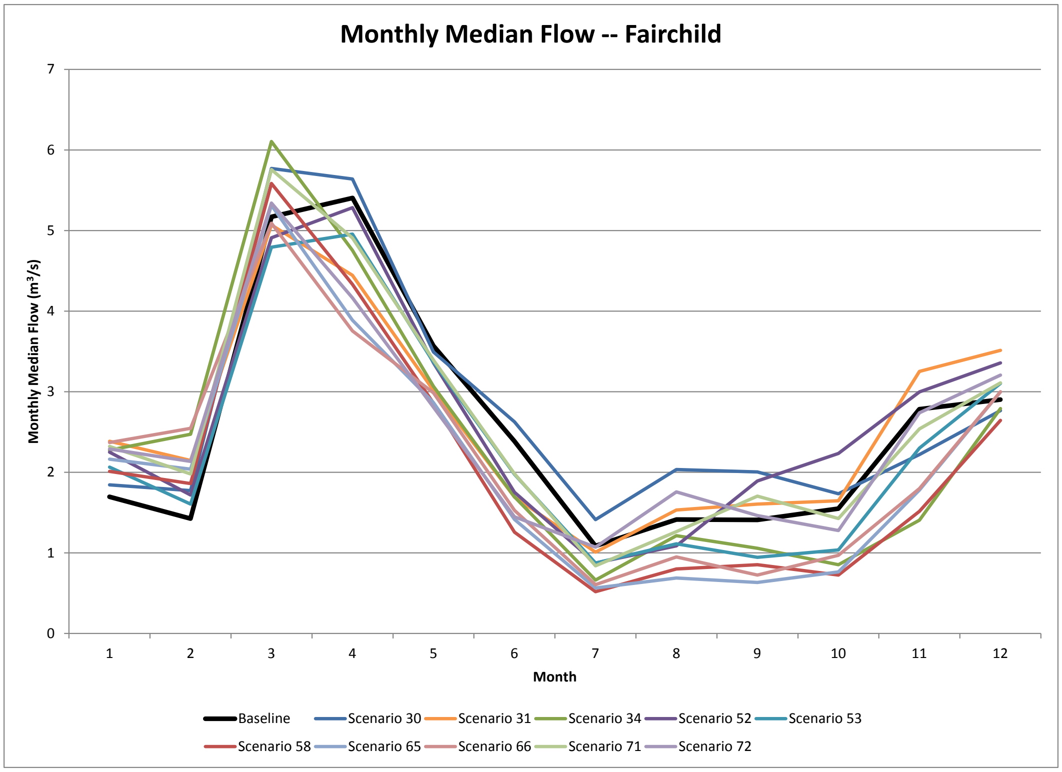


Figure 13: Monthly median flows in Fairchild Creek under scenarios of climate change

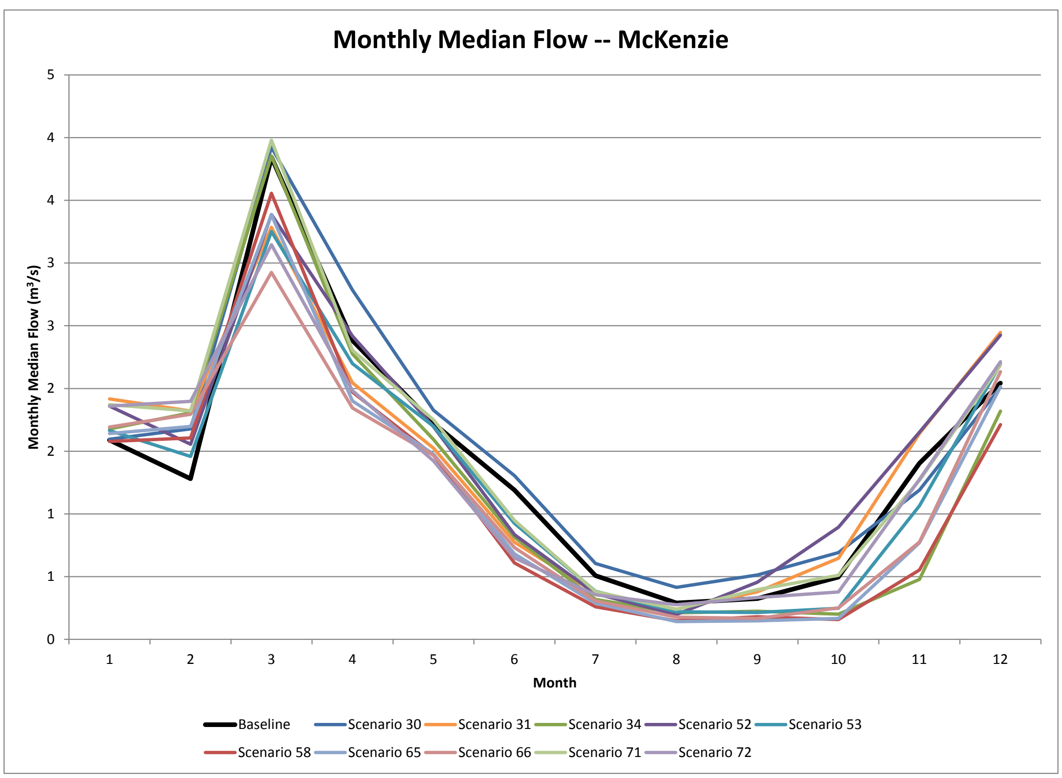


Figure 14: Monthly median flows in Mckenzie and Boston Creeks under scenarios of climate change

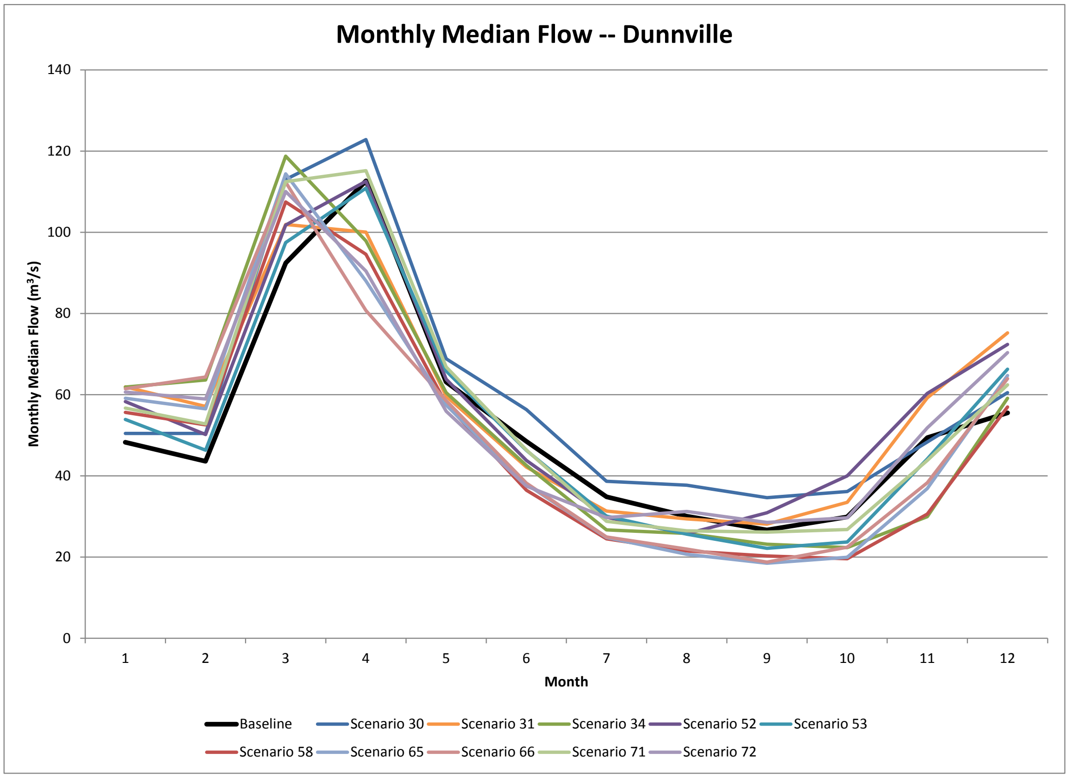


Figure 15: Monthly median flows in the Grand River at Dunnville under scenarios of climate change

Appendix D: Climate Change Scenarios – Preliminary Analysis

This following describes the initial analysis of climate change scenarios using the continuous surface water model for the Grand River Watershed as part of the Water Management Plan update. The purpose of this report is to show an example of possible analysis and describe limitations of the process to help direct discussion and future work on this project. Four scenarios were chosen for this initial analysis to represent a range of different future conditions. The focus of the analysis and the results presented are for 3 sub-basins in the watershed, although model results are available for the entire watershed.

Introduction

Sub-basins

Three sub-basins were chosen for this analysis to represent different hydrological and land use conditions in the watershed. Each of the sub-basins chosen has a stream gauge with a long period of record that is not influenced by reservoir operations.

The first sub-basin is the Upper Conestogo River. This sub-basin is runoff driven with flashy high flows and low baseflow. Land use is almost entirely agricultural with till drainage on tight till soils. The representative gauge for this basin is the Conestogo River Above Drayton gauge, but some observed data from the Conestogo River at Drayton gauge was also used in the analysis to extend the period of record.

The second sub-basin is the Eramosa River. This sub-basin has a high amount of forest cover. High flows are dampened and there is high baseflow year round. The basin is characterized by moraines with closed drainage and exposed bedrock. This basin is in the middle part of the watershed with the Eramosa River Above Guelph gauge used for analysis.

The last sub-basin included in this preliminary analysis is the Whitemans Creek Sub-basin in the lower part of the Grand River. This sub-basin is characterized by tight tills in the upper parts and sand plain in the lower part of the watershed. Land is predominately agricultural with a high amount of seasonal water use. Baseflow is very stable in the lower part of the watershed near the gauge at Mt. Vernon.

Climate Change Data Sets

The baseline chosen for climate change scenarios is the 1961 to 1990 climate period. This period was chosen since it included both a prolonged dry period and a very wet period with many of the highest observed flows on record. The future period for all scenarios is the 2050s (2041-2070) to coincide with the planning horizon of the water management plan.

The data sets were provided by AquaResource to the GRCA as part of an MNRF water budget project through the Source Water Protection Program. The baseline data was from a climate data project for Source Water Protection Water Budget project and represents the best data available for the 21 climate stations used in the current version of the Grand River Watershed continuous surface water model. Monthly change fields were applied to daily temperature and precipitation data and hourly precipitation data. The precipitation data set was then corrected for type of precipitation based on the temperature (e.g. snow during positive temperatures was changed to rain). All data was used as provided by the consultant, except for a minor clean-up of a few data points.

Change fields vary for each scenario and for most of the climate stations. Change fields are based on downscaling of global climate model grids so some of the climate stations used have the same change field values while others do not. Change fields from the Waterloo-Wellington climate station were used to pick climate scenarios since this is the central climate station in the watershed and shares change fields with many nearby climate stations.

Scenarios

Initially five scenarios were chosen based on annual change field values for the Waterloo-Wellington climate station. Inspection of the monthly change fields for these scenarios showed that two were quite similar and so one was dropped. The monthly change fields showed that the remaining four scenarios represented very different conditions overall. The main purpose in choosing the scenarios was to ensure that different conditions were covered to encourage discussion and to help direct next steps in the project. Monthly change fields for the four chosen scenarios are shown in Figure 1 and described below.

The first scenario chosen is the CGCM3T47-Run3 SRA2 (Scenario 11). Annually this scenario has a high increase in precipitation (approximately 17%) and a moderate increase in temperature (approximately 3°C). This scenario is characterized by increased precipitation in the winter, spring and late fall and a decrease in precipitation in the summer and early fall period from the climate baseline. Temperature increases are fairly balanced throughout the year with a slightly greater increase in temperature during the winter period.

The second scenario modeled is the CSIROMk3.5 SRA1B (Scenario 28). Annual change fields for this scenario are moderate with a slight increase in precipitation (approximately 4%) and temperature (approximately 2.5°C). This scenario has an increase in precipitation in the winter, spring and summer and a decrease in precipitation in the fall. Temperature increases are steady throughout the year with a slightly higher increase in July.

The third scenario is the HADGEM1 SRA2 (Scenario 55). Annual change fields for this scenario show no increase in precipitation and a large increase in annual average temperature (approximately 4.8°C). Although there is no change in the average annual precipitation, there is a change in the seasonal precipitation from the baseline. This scenario is characterized by higher precipitation in the late fall, winter and spring period and lower precipitation through the summer and early fall. Seasonal temperature increases most in the winter and summer periods with December having the highest temperature increase.

The final scenario in this report is the INMCM3.0 SRA2 (Scenario 59). This scenario has an average annual decrease in precipitation of approximately 5% and an increase in temperature of 2.7°C. Precipitation is predicted to increase or stay the same in the winter months and decrease through the rest of the year. Temperature increases are highest in the winter and later summer.

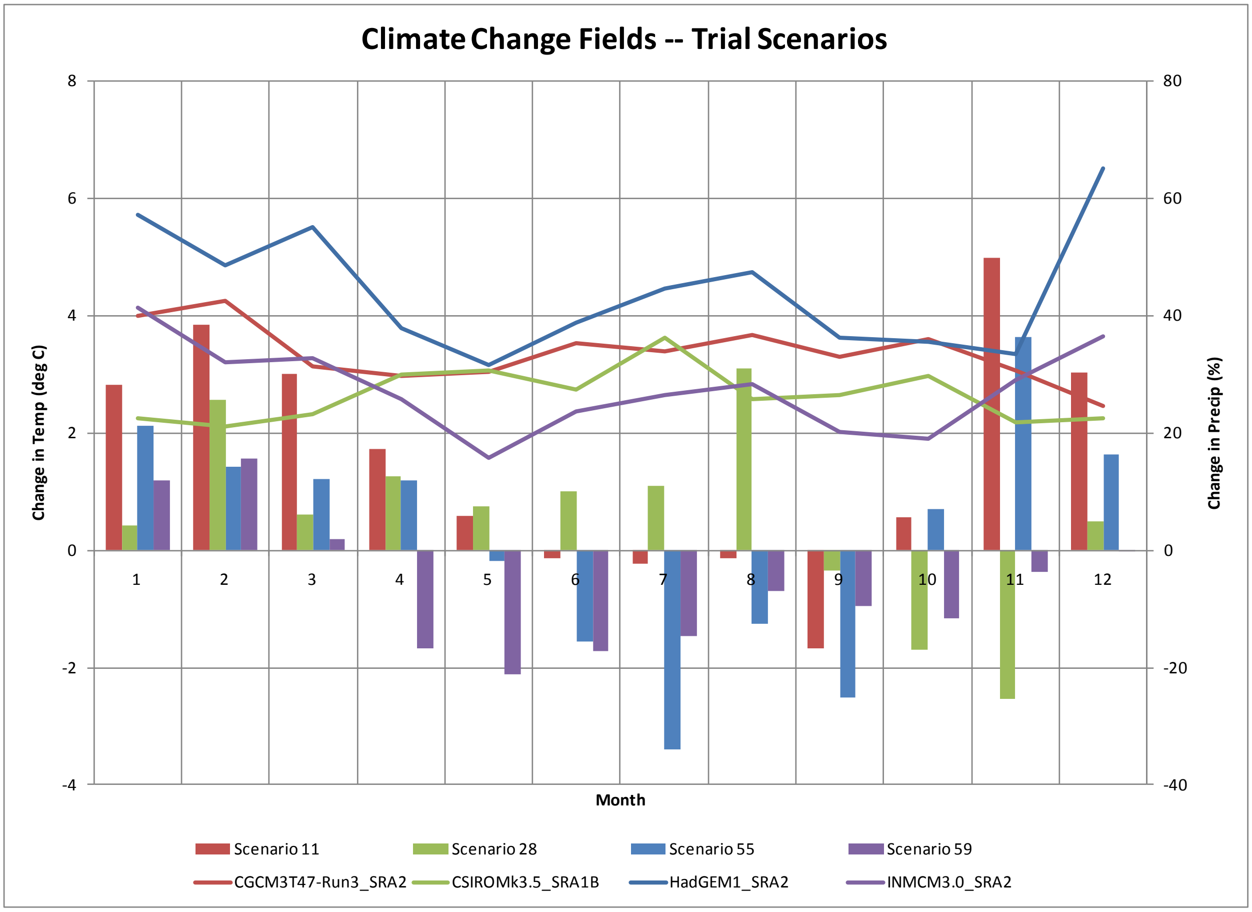


Figure 1: Climate change fields for the 2050s for the Waterloo-Wellington climate station and the four trial climate change scenarios

Model Results

Water Budget Parameters

Water Budget parameters included in this analysis are runoff, recharge, and evapotranspiration (ET). They were looked at on both an annual and a monthly basis for each of the three sub-basins. Annual changes in water budget parameters from the baseline for the three sub-basins are given in Figures 2, 3 & 4. Figures showing monthly changes are included in Appendix A.

Upper Conestogo

In the Upper Conestogo basin the timing of changes in precipitation are just as or more important than the amount of change in annual precipitation. Three scenarios predict higher annual precipitation, but only two of three scenarios result in more runoff and recharge. The third scenario, 28, predicts 50mm more annual precipitation, but since most of the additional precipitation occurs in the summer period it is lost to ET. Scenario 59 was the only scenario with lower annual precipitation. It also resulted in lower annual runoff and recharge. All scenarios had an increase in ET from the base case.

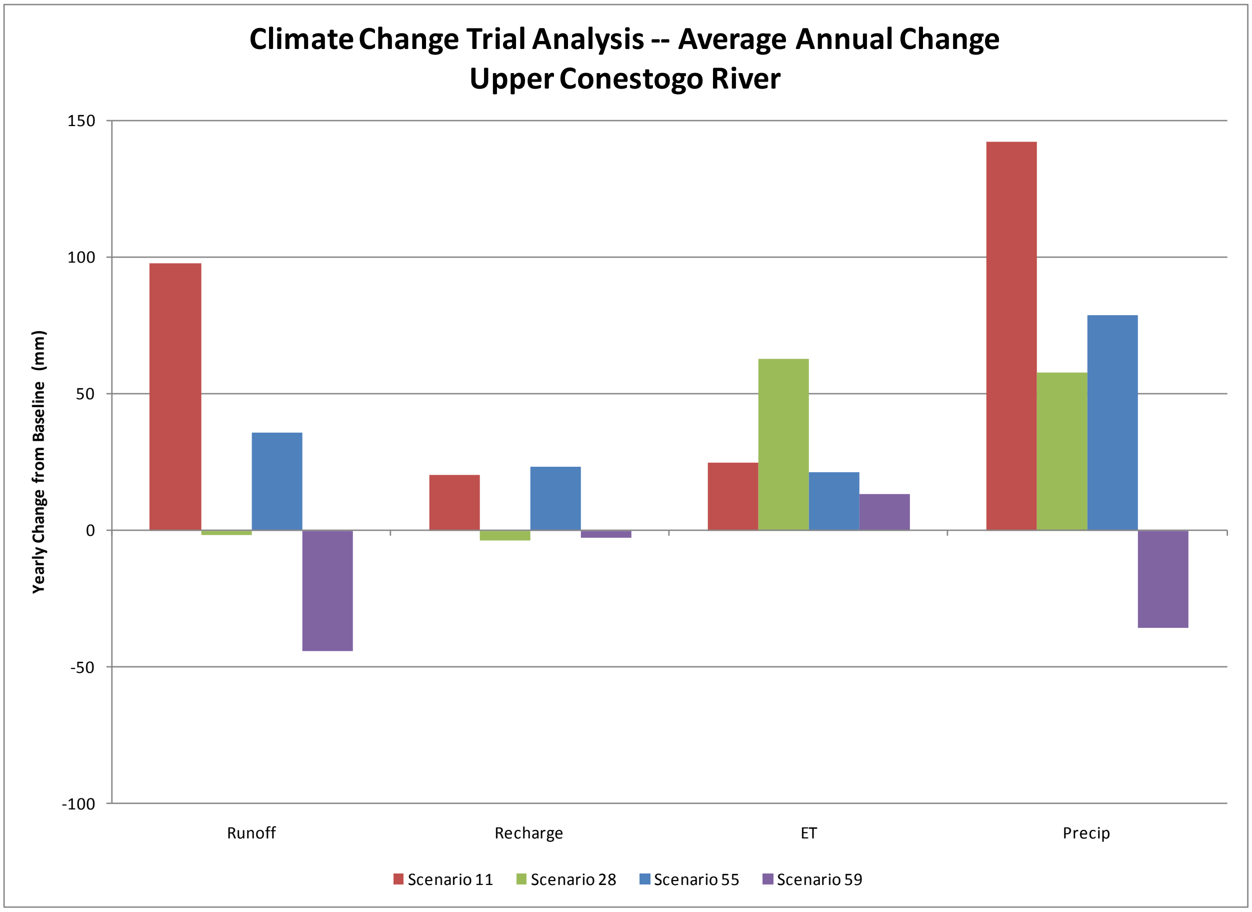


Figure 2: Average annual change in water budget parameters for the Upper Conestogo

Generally, runoff increased the most in the fall through winter period and dropped for the spring and summer with the degree of response dependant on the scenario. Scenario 28 showed some increase in runoff during the summer which coincides with higher summer rainfall. Recharge followed a similar pattern to runoff. Recharge increased for the winter and early spring and then decreased through the summer and early fall. Scenario 28 was slightly different with a small increase in recharge in August and September. ET increased in the spring and fall, decreased in the summer and was close to average in the winter for all scenarios except Scenario 28. Scenario 28 had increased ET in the summer.

Eramosa River

On an annual basis the Eramosa River sub-basin reacted similarly to the climate change scenarios as the Upper Conestogo River did, but to different degrees. Scenario 55 had a lower increase in annual precipitation in this sub-basin compared to the Upper Conestoga resulting in less runoff than the base case. Runoff increased in only Scenario 11, which also had equal increases in recharge and ET. Runoff was virtually unchanged for Scenarios 28 and 55 and decreased for Scenario 59. Recharge increased for Scenario 55 in addition to Scenario 11. The other scenarios had decreases in average annual recharge. ET increased for all of the scenarios although only slightly for Scenario 59.

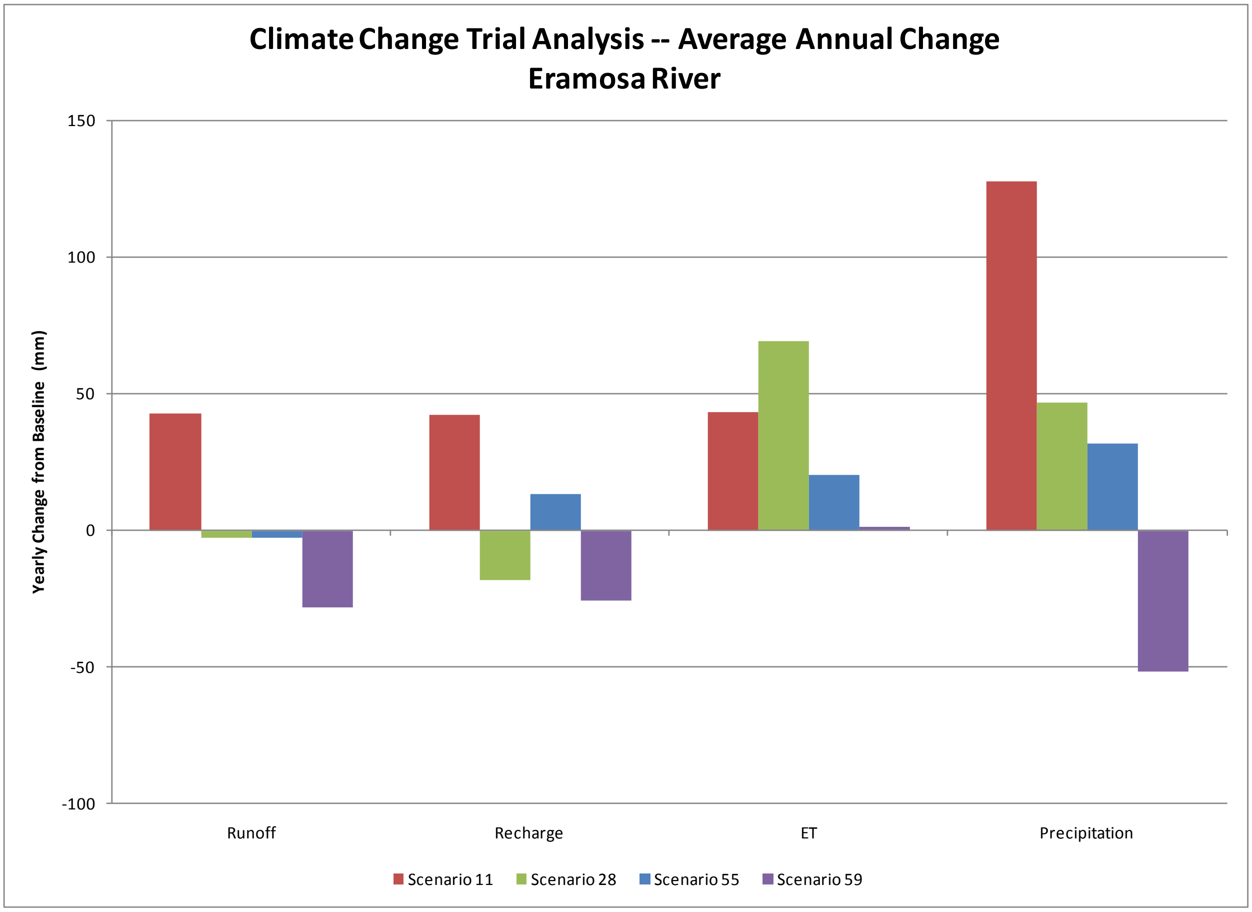


Figure 3: Average annual change in water budget parameters for the Eramosa River

Annually there was little change in runoff for Scenarios 28 and 55, but seasonally runoff changed quite a bit. Generally, all Scenarios showed higher runoff in the winter and lower runoff in the spring, summer and early fall. Scenario 28 was slightly different with increased runoff in the summer and decreased runoff through the late fall and early winter. Changes in recharge followed a similar pattern for all of the scenarios with higher recharge in the winter and lower recharge in the rest of the year compared to the baseline. The amount of the change varied between scenarios with the highest increases occurring in Scenario 11 and the largest decreases in Scenario 59. ET generally increased throughout the year, except for the summer period. Scenario 28 also had increases in ET in the summer, but the other scenarios saw a decrease in ET during the summer. Scenario 55 had an average decrease of over 30mm in July.

Whitemans Creek

Changes to water budget parameters in the Whitemans Creek sub-basin were similar to the Eramosa River sub-basin on an annual basis, but did have some noticeable differences. The main difference is that Scenario 55 had a decrease in average annual recharge compared to an increase in the Eramosa River.

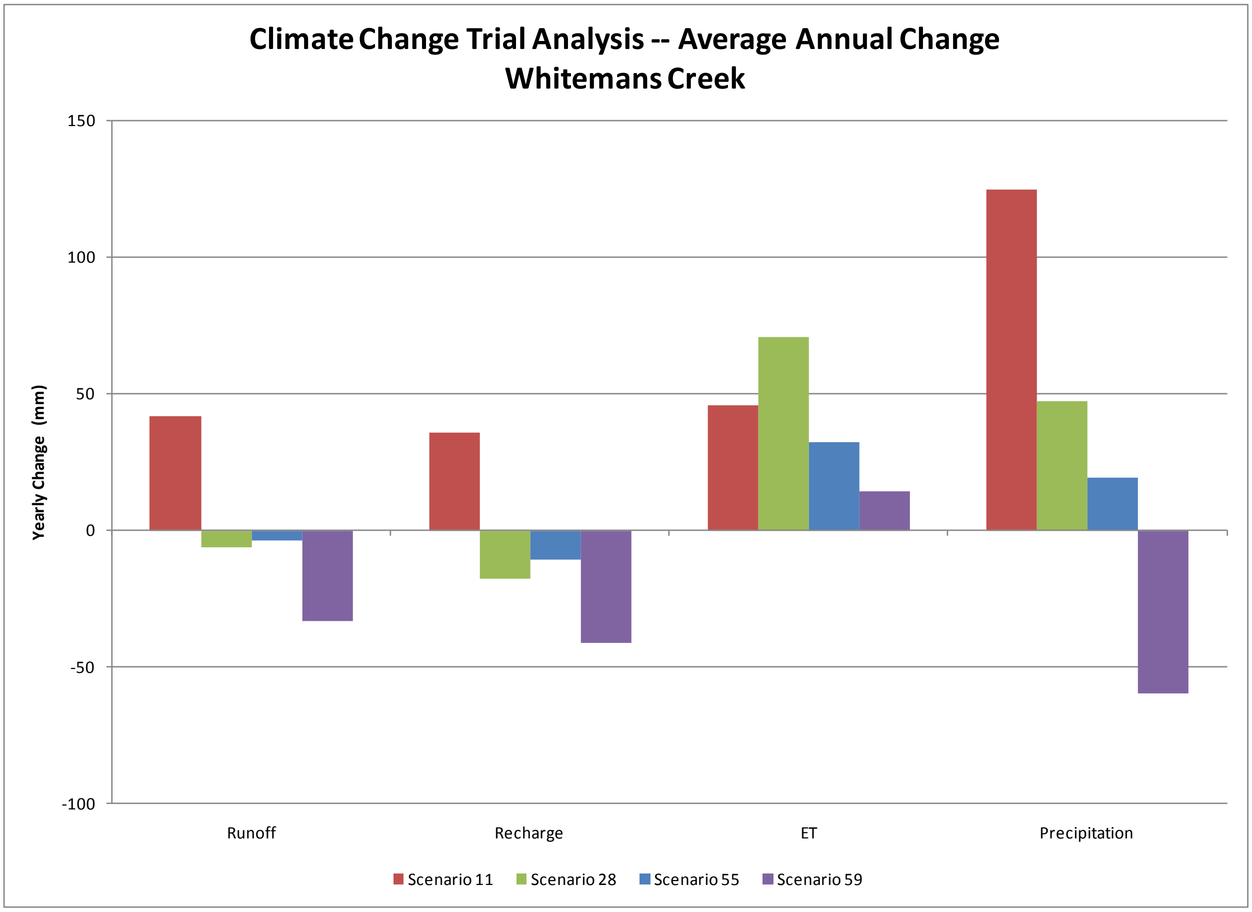


Figure 4: Average annual change in water budget parameters for Whitemans Creek

Runoff increased in January and February for all scenarios. Scenario 11 also had increases in runoff in March, November and December. Scenario 28 had a slight increase in July and August, while Scenario 55 had increases in November and December. Recharge increased in the winter months except for Scenarios 28 and 59 in December. For most of the rest of the year recharge decreased from baseline except for the summer months in Scenario 28 and November in Scenario 11. The highest decrease in recharge was during the spring period. ET increased for all months except for the summer months. In the summer Scenario 28 increased and Scenarios 55 and 59 decreased. Scenario 11 increased in June, decreased July and was close to the baseline in August and September.

Water Budget Parameter Summary

The response of water budget parameters on an annual basis was more scenario dependant then sub-basin dependant. Scenario 55, which produced different results in the different basins, had different amounts of precipitation between the sub-basins. Generally, changes in runoff were greater in the runoff driven basin and changes in recharge were greater in the high recharge basins. ET was similar between the different sub-basins.

The seasonal response of water budget scenarios was very scenario dependant and a little sub-basin dependant, but there were some general trends:

- Runoff increased in the winter and early spring;

- Recharge increased in the winter and decreased throughout the rest of the year dependant on seasonal precipitation;
- ET increased throughout the year, except in the winter when it remains close to the Base case.

Flows

The climate change data sets are made using the change field method. This method adjusts the climate parameters based on a monthly average change field. The pattern of precipitation has not been changed. This means that the frequency of storms or droughts and their length will not change, but the associated precipitation from a past storm may be greater or less depending on the change field applied. An example is included in Figure 5 that shows daily modeled and observed flows for the Conestogo River Above Drayton Gauge for July 1982. The same pattern of peak flow occurs, but because of differences in the amount of precipitation and the temperature the model produces different flow rates.

Modeled flow data is not the same as observed data. It approximates actual flow conditions as shown in Figure 5 with the modeled flow data and the observed flow data (dashed line). When analyzing climate change flow data both modeled flow data from the baseline climate data and observed flow data has been used to discuss changes in the flow regime.

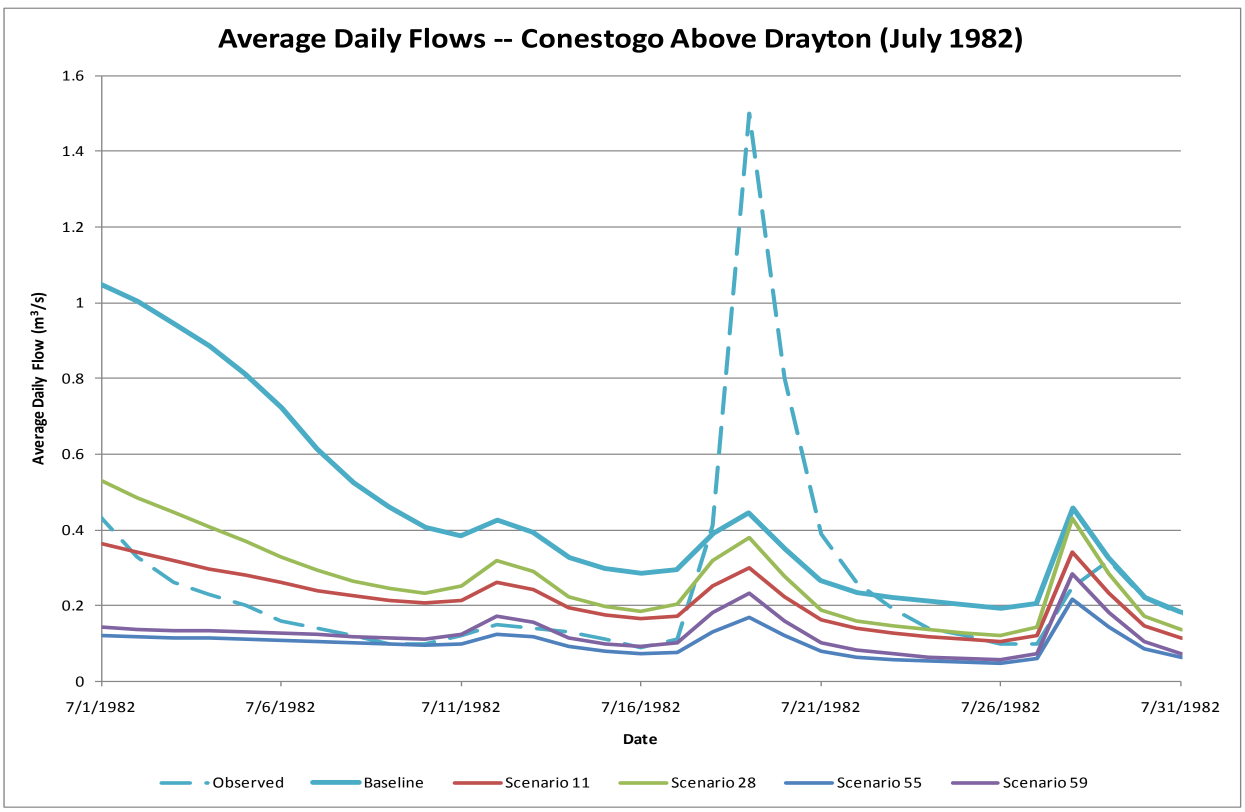


Figure 5: Observed and modeled average daily flow for Conestogo Above Drayton July 1982

The model is calibrated based on observed conditions including the baseflow routines. A change in recharge and precipitation patterns may also change the groundwater discharge to surface water relationship. Further work with the groundwater flow model will explore changes in groundwater discharge. This work has not been included in this preliminary analysis.

Upper Conestogo

The Upper Conestogo River is a runoff driven system that reacts quickly to rain events and has very little base flow. The WSC gauge Above Drayton (02GA039) was used to represent flows in this sub-basin with some observed data from previous location of the gauge at Drayton for the period prior to 1973.

On an average annual basis flows increased for two scenarios: Scenario 11 and Scenario 55. Scenario 11 had the highest increase in precipitation and also the highest increase in runoff, while Scenario 55 had the second largest increase in precipitation in this sub-basin. Average annual flows were similar for Scenario 28 and were less for Scenario 59 compared to the baseline.

Figure 6 shows the monthly median flows for the Above Drayton gauge. January and February have higher flows than the baseline for all of the scenarios. The spring freshet is predicted to occur one month earlier (March instead of April) for all scenarios, but Scenario 11 shows high flows for both March and April. Summer flows are less than baseline for all scenarios except 28 and extend later into the fall by one month (October). November and December are variable with modeled flows both higher and lower than the baseline depending on the scenario.

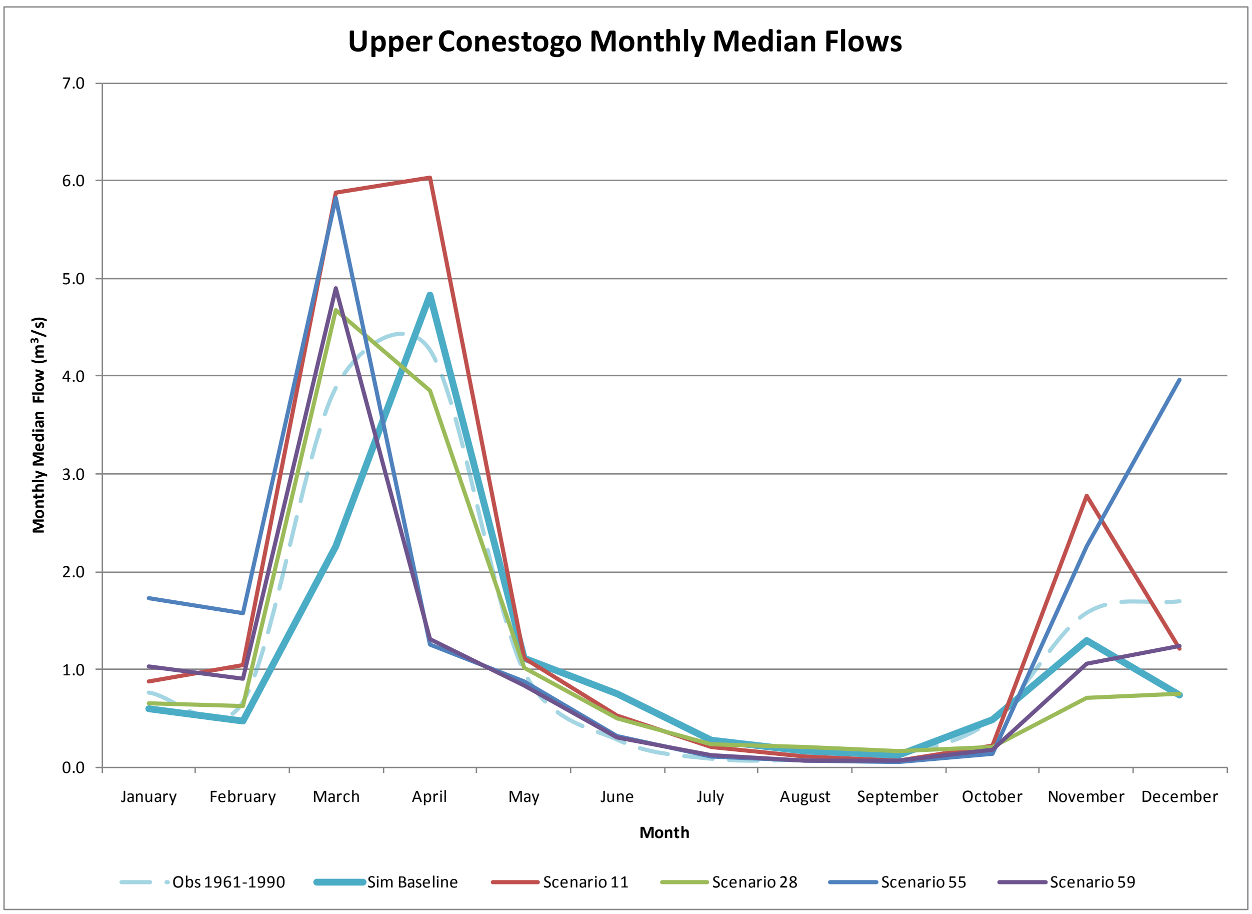


Figure 6: Monthly median flows for the Conestogo Above Drayton gauge

Observed flows are similar to the baseline in the winter, early spring and mid-fall, but are a bit less in the late spring and summer period when the Upper Conestogo usually sees the lowest flows. Three of the scenarios predict lower flows in the summer months than the baseline. Since it is known that the watercourse at this gauge can virtually go dry in the summer months, the scenarios indicate that it might go dry more frequently. Baseflow contributions from groundwater should be verified with the groundwater flow model for this sub-basin especially during the summer dry period.

Eramosa River

The Eramosa River has high baseflow and responds slowly to precipitation events. The WSC gauge Eramosa River at Watson Road (02GA029) was used to represent flows in this sub-basin. It has an observed period of record from 1962 to present. On an average annual basis flows increased for Scenarios 11. Scenario 11 had the highest increase in precipitation of all of the scenarios and was the only scenario to produce an increase in runoff in this sub-basin. Scenarios 28 and 55 showed a slight decrease in average annual flow, while Scenario 59 had the greatest decrease in average annual flow. Scenario 59 was the only scenario with a decrease in precipitation.

Figure 7 shows the monthly median flows for the Eramosa River. January and February have higher flows than the baseline for all of the scenarios except Scenario 28. The spring freshet is predicted to occur earlier for all scenarios and be more defined than the baseline, which shows a prolonged high flow season from March to June. Summer flows are less than the baseline for all scenarios, but Scenario 28 is very similar to the baseline. Low flow season is predicted to extend later into the fall for Scenarios 28 and 59. The scenarios have variable predictions for December with two above the baseline and two below the baseline.

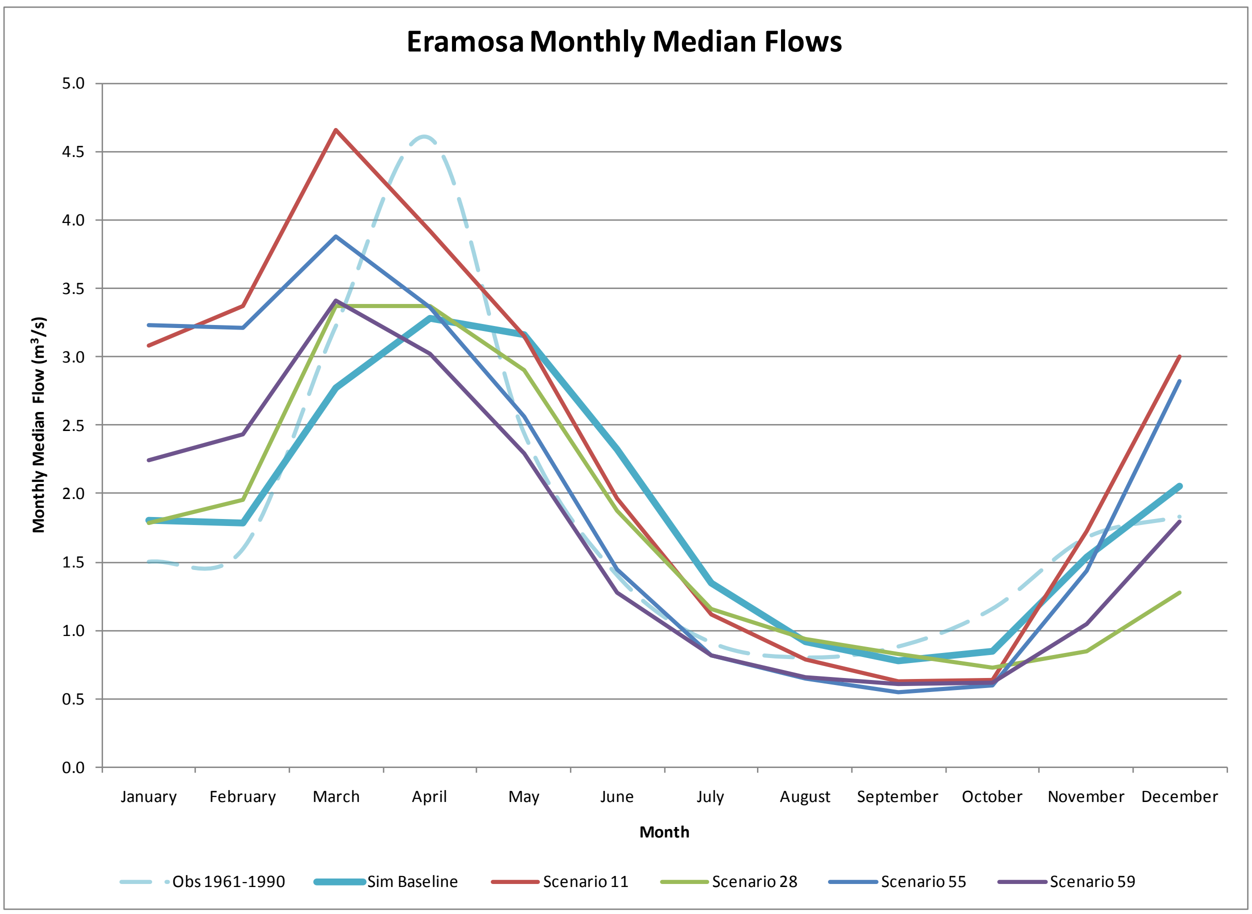


Figure 7: Monthly median flows for the Eramosa River at Watson Road gauge

Observed flows do not match the baseline flows well for this gauge especially through the early summer and the spring freshet. The Eramosa River has fairly consistent baseflow from groundwater discharges. Three of the scenarios predict a decrease in recharge that may affect the amount of groundwater discharge to this watercourse. An analysis using a groundwater model is needed to fully understand the flow system in the Eramosa River watershed.

Whitemans Creek

Whitemans Creek has a runoff driven upper portion (Horner and Kenny Creeks) that reacts quickly to rain events and a high groundwater discharge lower portion (Whitemans Creek) with high baseflow. The WSC gauge at Mt. Vernon (02GB008) in the lower part of the watershed was used to represent flows in this sub-basin.

On an average annual basis the model produced flows similar to the Eramosa River with increased flow occurring only in Scenario 11. This scenario had the highest increase in precipitation of all of the scenarios and was the only scenario to produce an increase in runoff in this sub-basin. Scenarios 28 and 55 showed a slight decrease in average annual flow, while Scenario 59 had the greatest decrease in average annual flow. Scenario 59 was the only scenario with a decrease in precipitation.

Monthly median flows are shown in Figure 8. January and February flows were generally higher with the spring freshet occurring earlier in the year. Summer flows for three scenarios were much less than the baseline, but unlike the other two sub-basins, summer low flows were not predicted to extend farther into the fall than the baseline. The exception is Scenario 28, with higher summer flows, but a longer period of summer low flows than the baseline. As with the other two sub-basins December flows were variable.

The model under estimates summer flows compared to the observed record. This is different than in the Eramosa River where summer flows are overestimated with the model. A reduction in summer flows compared to the observed record is predicted, but baseflow from the shallow groundwater system drives summer baseflows in this watershed. An increase in water taking and a decrease in recharge can reduce the amount of groundwater discharge. In addition surface water takings have not been included in this model run. It is important to investigate the effects of reduced recharge and increased water takings on baseflow in this sub-basin.

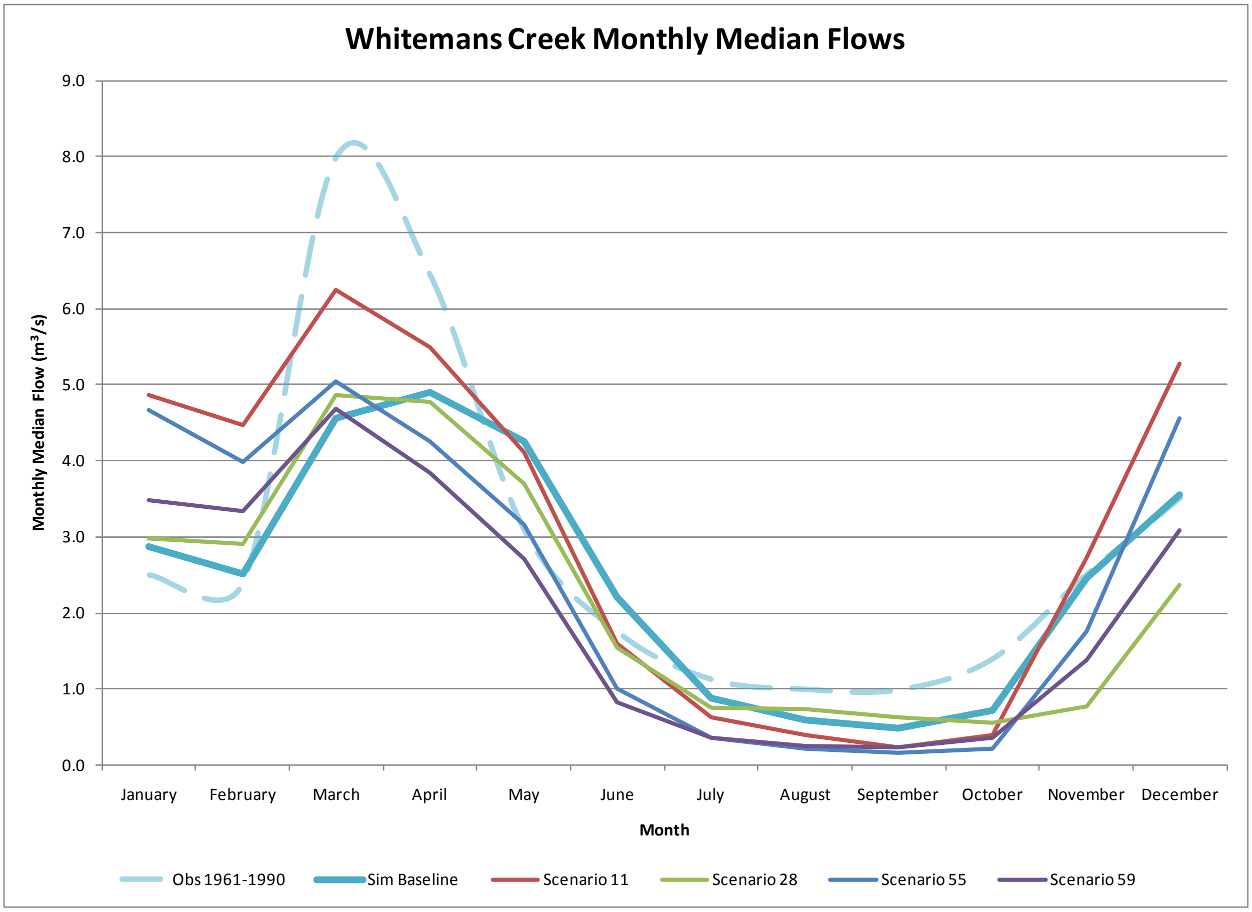


Figure 8: Monthly median flows for the Whitemans Creek at Mt. Vernon Gauge

Flow Summary

There are some trends in flow that occur in all of the sub-basins. They are listed below under annual trends and monthly or seasonal changes.

Annual Trends:

- a large increase in precipitation leads to an increase in flows;
- a slight increase or no increase in precipitation with higher temperatures leads to a small decrease in flows; and
- a decrease in precipitation leads to a decrease in flows.

Monthly or Seasonal Trends:

- higher flows in the winter (January and February);
- an earlier spring freshet;
- summer flows were lower, except for one scenario with increased precipitation in the summer;
- summer low flows are expected to extend later into the fall although less so in the Whitemans Creek sub-basin;
- December flows were variable and depended on both temperature and precipitation; and

- the four scenarios produced a similar pattern of changes to flow from the baseline in the different sub-basins.

Calibration of the model is weakest for the summer period, but also for the spring freshet. Additional work is needed to determine changes to baseflow contributions from groundwater with changing rates of groundwater recharge.

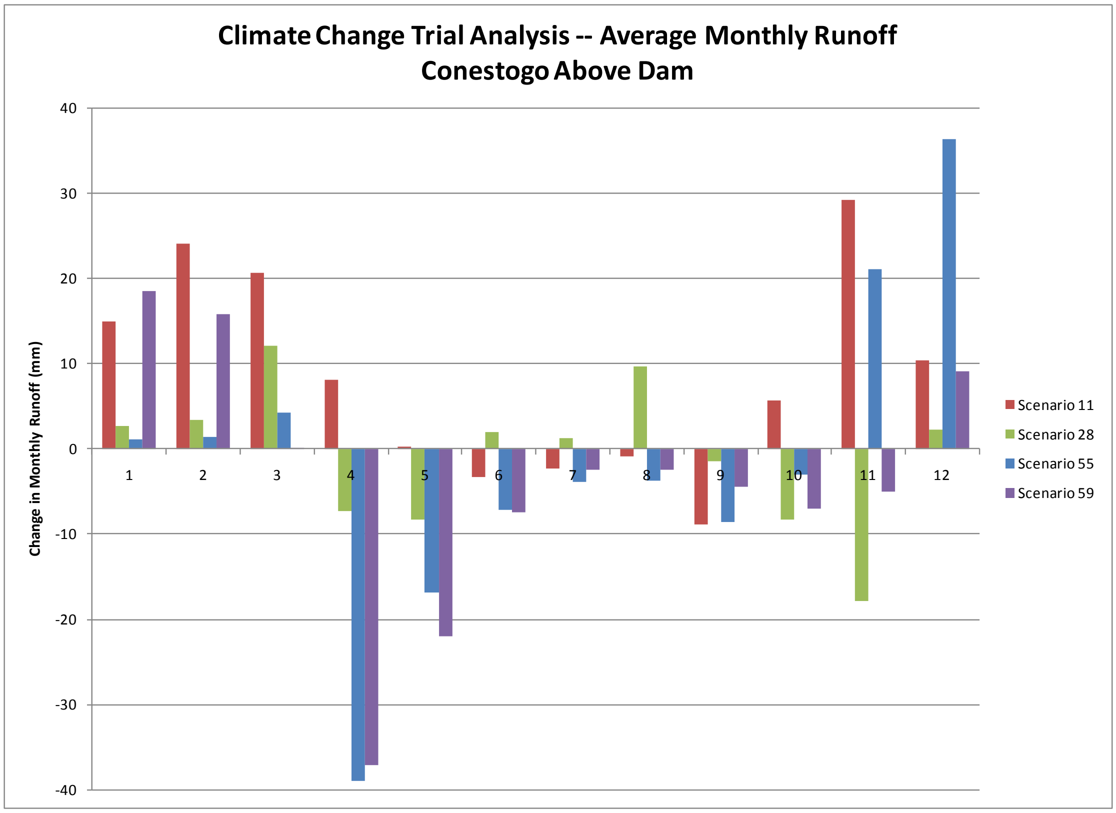
Summary and Next Steps

This memo is set up to provide an example of results from climate change scenario modeling using the GRCA's continuous surface water model. Four of 76 scenarios were selected and run through the model to represent the range of annual results. Four scenarios are not enough to focus on trends and additional scenarios are required. The scenarios picked for each project should be dependent on the expected vulnerabilities of the system being investigated.

Running scenarios in the surface water model is fairly straight forward and can be done quickly. Analysis of the results and working the results into other models is more time consuming and there is a need for direction on which scenarios to use for further analysis.

Next steps currently planned for include:

- Running 10 scenarios as suggested by the Source Water Protection Program guide;
- Climate trending analysis of observed data;
- Trial run of one scenario through the steady state groundwater model; and
- Additional analysis on more sub-basins.


Climate Change Trial Analysis -- Average Monthly Runoff
Conestogo Above Dam
Change in Monthly Runoff (mm)
40
30
20
10
0
-10
-20
-30
-40
1
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3
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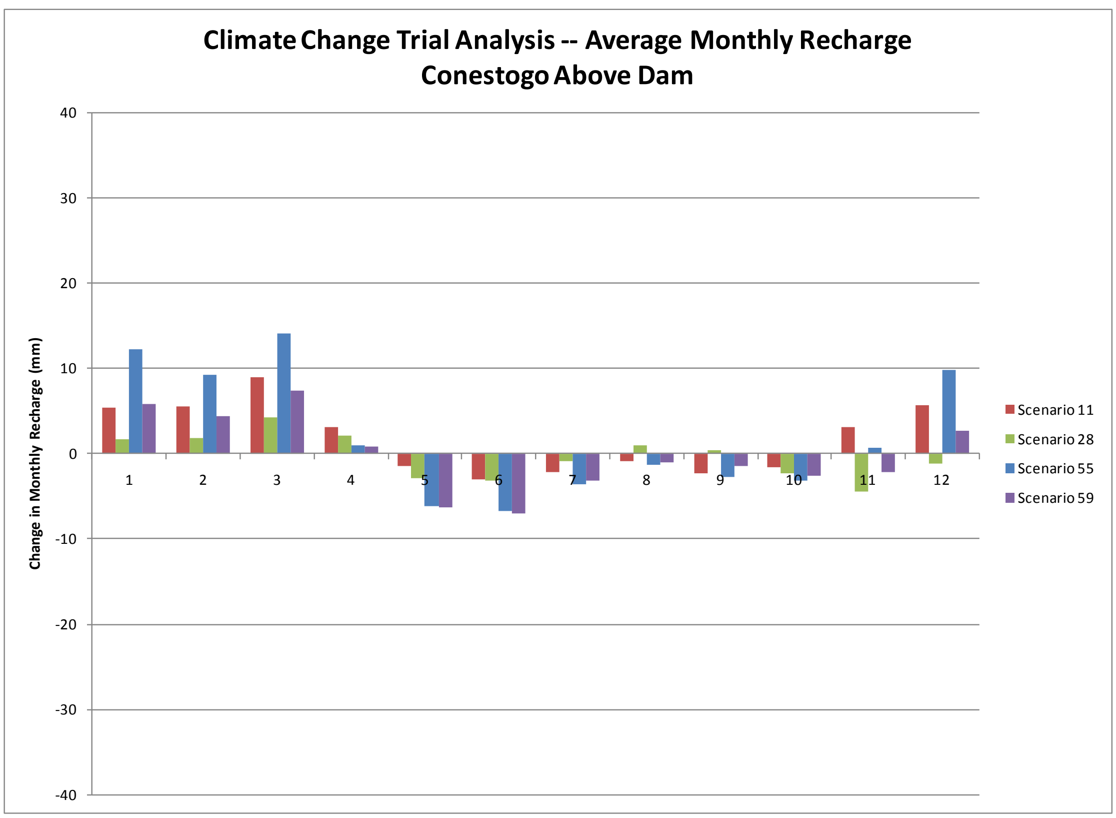
Scenario 11
Scenario 28
Scenario 55
Scenario 59


Climate Change Trial Analysis -- Average Monthly Recharge
Conestogo Above Dam
Change in Monthly Recharge (mm)
40
30
20
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0
-10
-20
-30
-40
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Scenario 11
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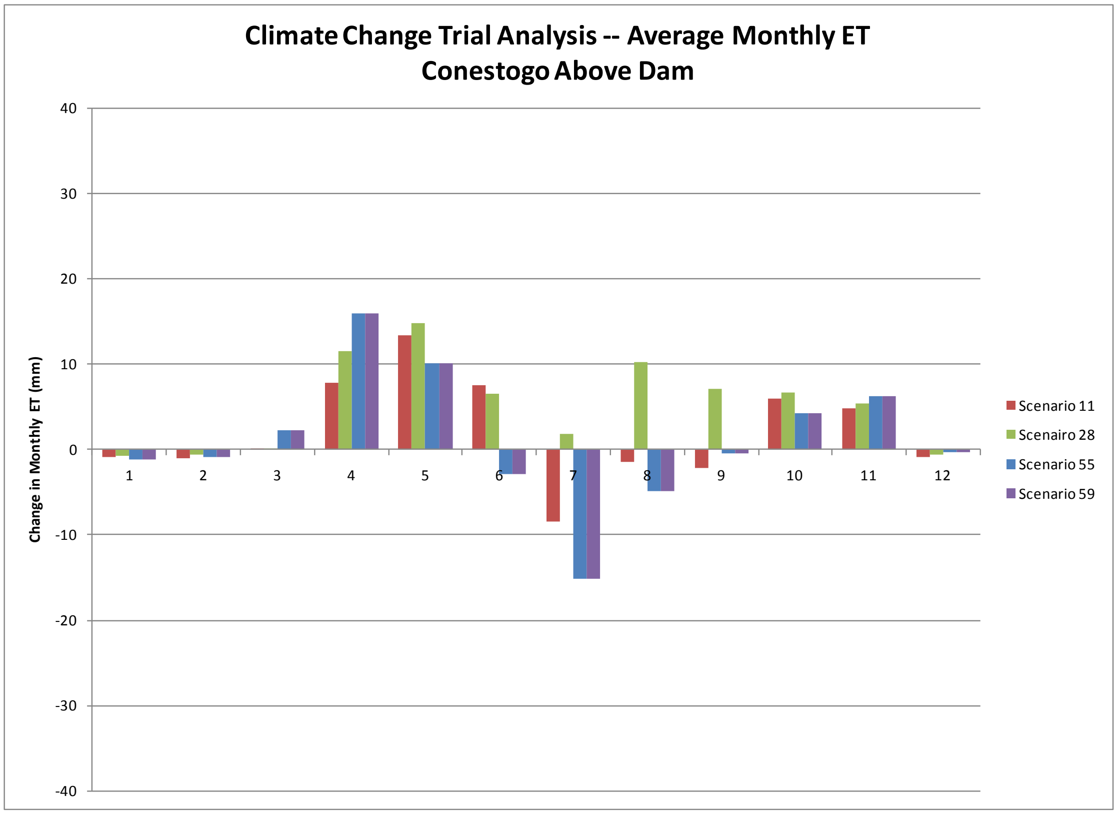
Scenario 59


Climate Change Trial Analysis -- Average Monthly ET
Conestogo Above Dam
Change in Monthly ET (mm)
40
30
20
10
0
-10
-20
-30
-40
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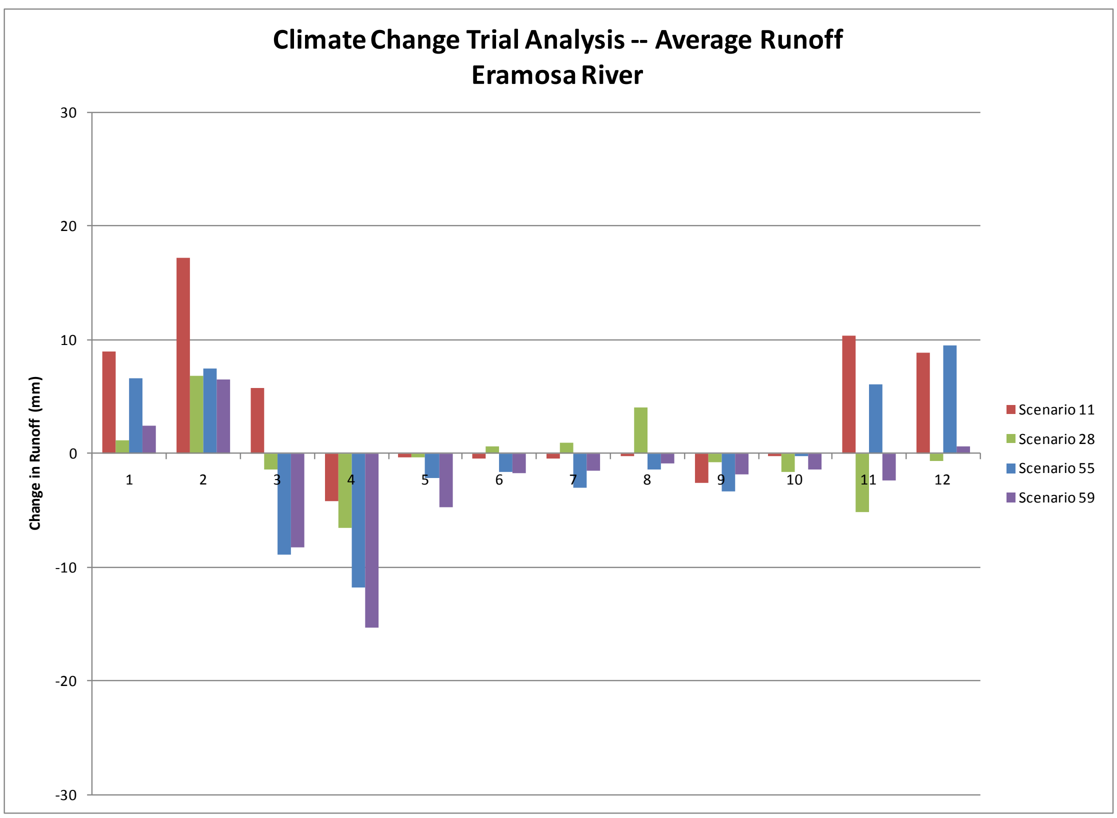
Scenario 59


Climate Change Trial Analysis -- Average Runoff
Eramosa River
Change in Runoff (mm)
30
20
10
0
-10
-20
-30
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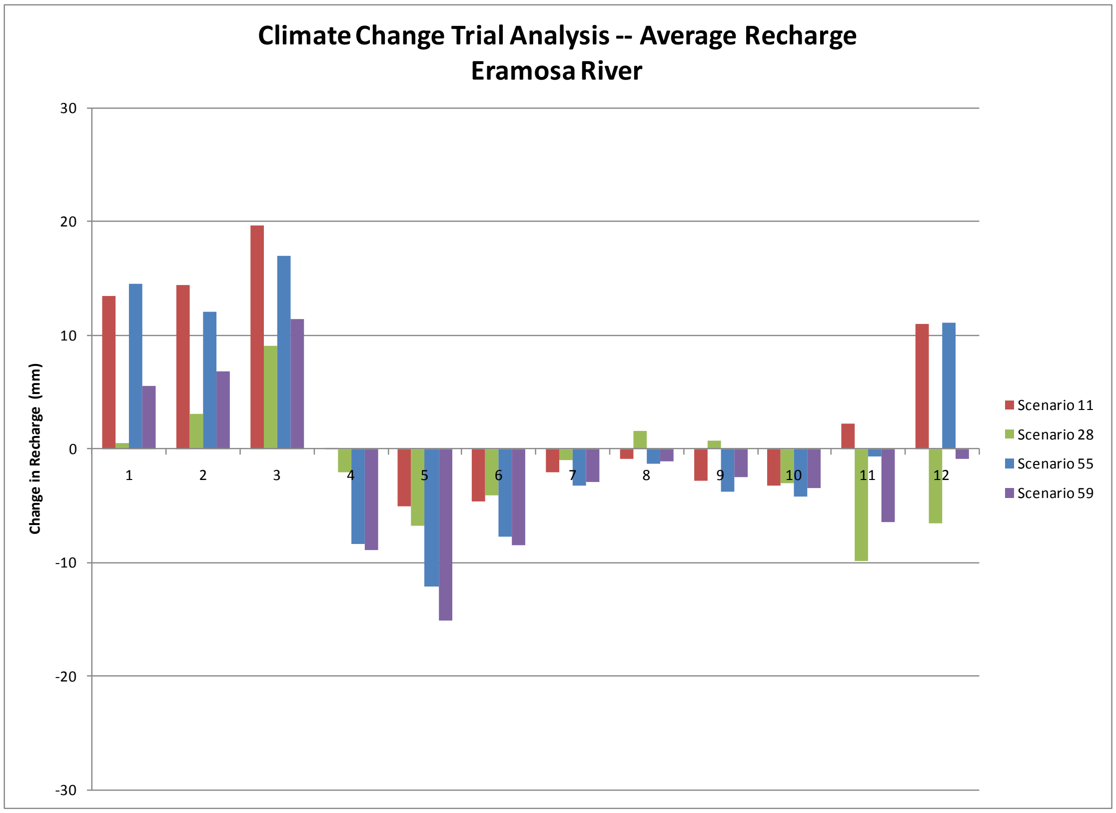
Scenario 11
Scenario 28
Scenario 55
Scenario 59



Climate Change Trial Analysis -- Average Recharge
Eramosa River
Change in Recharge (mm)
30
20
10
0
-10
-20
-30
1
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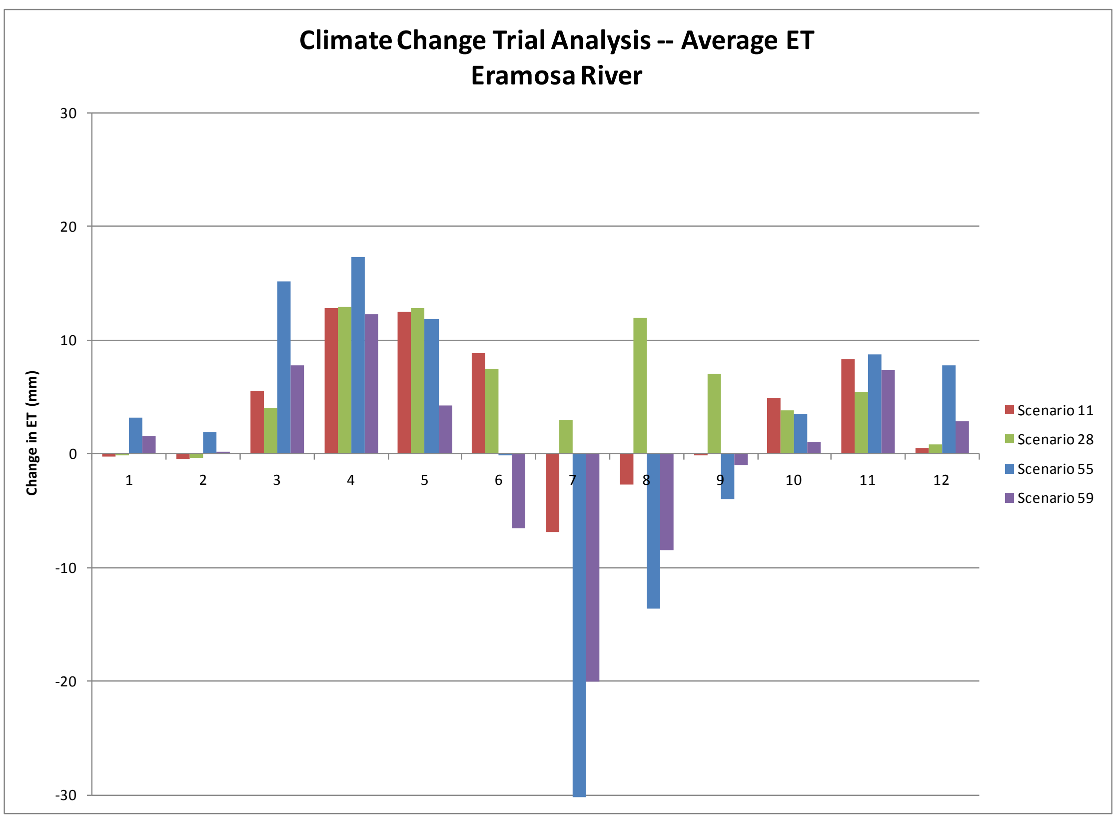
Scenario 11
Scenario 28
Scenario 55
Scenario 59



Climate Change Trial Analysis -- Average ET
Eramosa River
Change in ET (mm)
30
20
10
0
-10
-20
-30
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7
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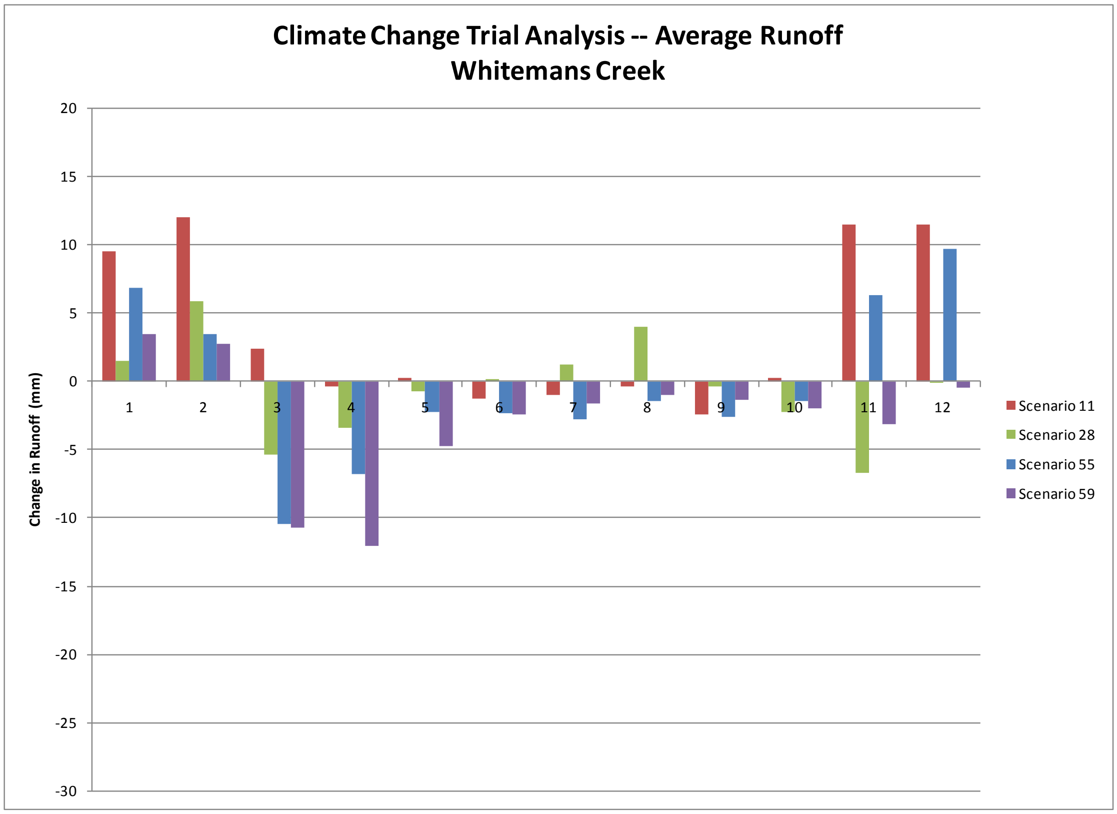
Scenario 11
Scenario 28
Scenario 55
Scenario 59


Climate Change Trial Analysis -- Average Runoff
Whitemans Creek
Change in Runoff (mm)
20
15
10
5
0
-5
-10
-15
-20
-25
-30
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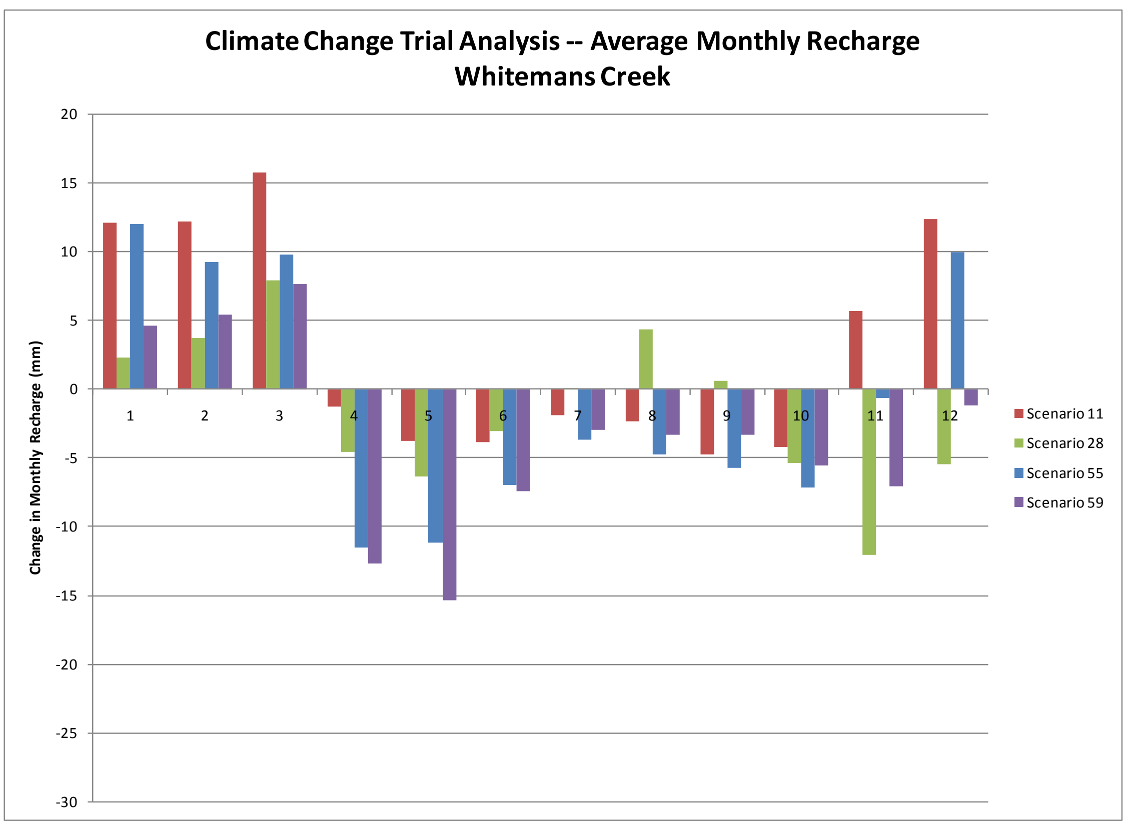
Scenario 11
Scenario 28
Scenario 55
Scenario 59


Climate Change Trial Analysis -- Average Monthly Recharge
Whitemans Creek
Change in Monthly Recharge (mm)
20
15
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5
0
-5
-10
-15
-20
-25
-30
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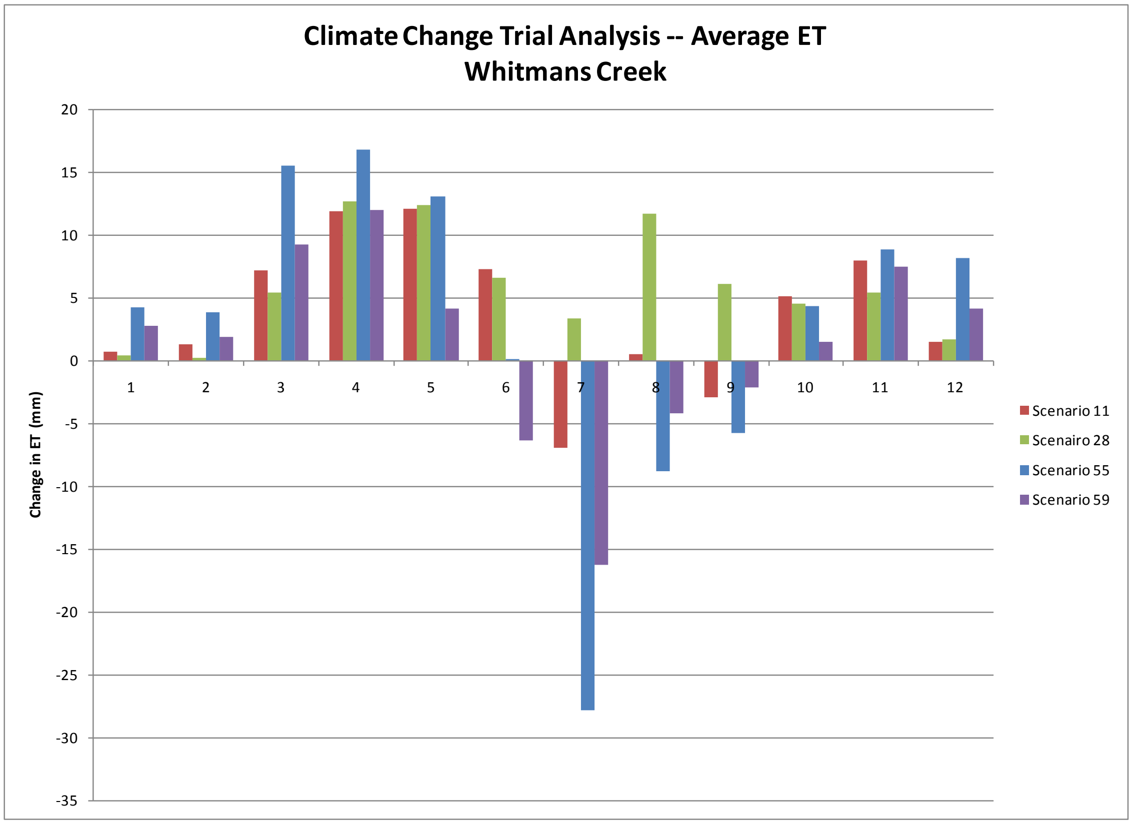
Scenario 11
Scenario 28
Scenario 55
Scenario 59



Climate Change Trial Analysis -- Average ET
Whitmans Creek
Change in ET (mm)
20
15
10
5
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-5
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-20
-25
-30
-35
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Scenario 55
Scenario 59

Appendix E: Evaluation GAWSER Output for use in the Grand Reservoir Yield Model

Summary

The output from the surface water model was evaluated with the Grand Reservoir Yield model to determine if the modeled flow output can be used as direct input into the Reservoir Yield model to evaluate the effects of climate change on meeting low flow targets. Preliminary results suggest that the flow data from the surface water model cannot be input directly into the Reservoir Yield model because of over estimation of flows during the low flow season. To resolve the differences between observed and simulated flow data it is recommended that monthly change fields be applied to the observed input data set to approximate flow changes due to climate change scenarios.

Background

The Grand River Surface Water Model (GAWSER) was run with 10 different climate change scenarios provided by the Ministry of Natural Resources and Forestry (MNRF) to study the potential effects of climate change at the watershed level. Some of the trends with respect to stream flow were an increase in winter flows and a decrease in summer and early fall flows. The GAWSER model uses a very basic representation of the operation of the reservoirs and as such is not appropriate for evaluation of reservoir operations and low flow augmentation. To investigate the effects of climate change on reservoir operations it is more appropriate to use the Reservoir Yield model (RY model) which requires inputs of flow to the reservoirs and local flows at key locations downstream. For climate change analysis these inputs would come from the GAWSER model climate change runs.

There are differences between simulated flow data from the GAWSER model and observed flow data. In particular the GAWSER model over estimates low flows because of a simplified representation of the groundwater system leading to differences in groundwater fed base flows. These differences are considered acceptable for most model applications, but should be evaluated to determine if the differences are acceptable for Reservoir Yield modeling. This memo provides a brief description of evaluation of these differences and provides a method as to how the differences can be overcome so that climate change scenarios can be run through the Reservoir Yield model.

Methods

The first step in evaluating GAWSER output for use in the RY model was to compare simulated flow output generated with baseline date (Baseline CC input) to the recently updated observed input into the reservoir yield model (observed input). The next step was to run the CC Baseline input through the RY model and then compare the output to output from the observe input run of the RY model for the same time period. Finally one climate change scenario was run through the RY model using both GAWSER simulated flow as direct input and by using a monthly change field approach to modify the observed input data to represent changes to flow resulting from the climate change scenario.

Results

Input Comparison

Average monthly flows for the period of interest were used to determine differences between the simulated Baseline CC input and observed input data sets. For the inflows to the reservoirs the Baseline CC data was lower for peak flow months (March and April) and higher for the later reservoir filling months of May and June. Shand and Conestogo inflows were higher for the Baseline CC data set during the summer and early fall, while Guelph inflows were higher in July, equal in August and less through the fall. Winter flows were comparable between the two data sets.

The biggest difference between the data sets for the local flow for the Grand River gauges was during the May to August period where the Baseline CC flows were generally higher than the observed input data set. The differences became less for each downstream gauge. The Hanlon local flows were fairly good during the late spring and summer period, but the Baseline CC flows were much lower than the observed flow through the fall and winter period. The spring high flow period had flows much less than the observed data set.

Most of the described differences may be significant when running the reservoir yield model. Higher inflows during the summer period will artificially help maintain reservoir levels during the draw down period. Higher local flows during the summer can lessen the need for augmentation from the reservoirs and help to keep reservoir levels high. Lower local flows for the fall period for Hanlon may result in the need for more augmentation. Lower March and April flows will affect the reservoir filling cycle and may cause some issues with the assumptions of the RY model including reaching May 1st filling levels. To investigate these issues further the Baseline CC input data was run through the RY model and the output compared to the output from the observed input run.

Baseline Data Reservoir Yield Model Run

Simulated GAWSER flow output produced using the Baseline CC data set (1961 to 1990) was input into the RY model directly and the results compared with RY model results using the observed data set for the same time period.

The Baseline CC reliabilities for meeting low flow targets were a bit higher than for the observed input with fewer instances of flow target violations. This is most likely caused by higher modeled flows during the May to Sept period for both inflows to the reservoirs and for local flows downstream of the reservoirs compared to observed data. Years with flow target violations with the Baseline CC input were similar to the observed input data results.

Reservoir levels were more constant with fewer extreme high level events and fewer extreme low flow events. The difference in high level events may be a function of the climate data sets used to drive the model. Not all large precipitation events are captured at the climate stations used in the GAWSER model. The fewer extreme low flows is related to the difficulty in modeling low flows. The GAWSER model uses a simplistic routine to model groundwater fed baseflow which is the predominant source of flow during low precipitation conditions in the watershed. Over estimating low flows is a known issue with the GAWSER model. Recent calibration of the model has helped, but there are limitations with the GAWSER model code that will limit additional calibration in this area.

Scenario 58 Flow Data RY Model Run

Input flow data for one climate change scenario was prepared and run through the RY model to investigate if issues with the Baseline CC input data would translate into the climate change runs. Scenario 58 was chosen. It had the least precipitation (-55mm/yr) of any of the climate change scenario and resulted in the lowest summer and fall flows in the non-regulated system of any of the scenarios. Theoretically, this scenario should show a large change from historic conditions.

Reliability decreased with Scenario 58 compared to the Baseline run, but was similar to reliability using the observed input data. The results did not seem consistent with what was expected based on the results of Scenario 58 compared to baseline. In light of these findings, it appears that the issues with the GAWSER model calibration for low flows and flows during the late spring season are great enough to give misleading results if the simulated GAWSER flow output data is used directly in the Reservoir Yield Model.

Scenario 58 Monthly Change Field Model Run

Instead of using the output from GAWSER directly in the reservoir yield model for the climate change runs an input data set was created that took the relative change between the climate change run and the baseline climate data and applied it to the observed input data set. Monthly total flows were calculated for both the baseline and Scenario 58 data sets for each year of data. The percent difference between the valves for each month was calculated and then applied to the daily observed input data set. This modified daily input set was then run through the RY model and the results compared against the observed results. Monthly change fields were chosen to be similar to the monthly change field used to build the climate change scenario data set.

Reliability dropped for the most part compared to the observed input RY model run with the largest drop during the fall period. This was expected because of the reduced flows during that period for Scenario 58. The filling cycle of the reservoirs was also affected with the May 1st target not being met as often and the reservoir levels dropping significantly during the fall and winter period. These results are closer to what was expected from the understanding of changes to the flow system. It is recommended that this method of modifying the observed input files be used for the other climate change scenarios.

Reliability results for the different runs are presented in Tables 1, 2 and 3. Table 1 gives the reliability based on time. Table 2 shows the number of years with flow violations seasonally and annually. Finally, Table 3 gives some statistics on reaching May 1st reservoir levels. Scenario 58 Final represents the results for climate change Scenario 58 using the recommended method for including climate change scenarios in the reservoir yield model.

Table 1: **Reliability based on Time**

Location	Scenario	Jan-Apr	May-Sep	Oct-Dec	Annually
Doon	Observed input	100%	99.4%	95.9%	98.7%
	Baseline CC	100%	100%	98.2%	99.5%
	Scen 58 direct	100%	100%	98.5%	99.6%
	Scen 58 final	**100%**	**99.5%**	**88.9%**	**97.0%**
Brantford	Observed input	98.5%	99.9%	95.7%	98.4%
	Baseline CC	99.6%	100%	97.3%	99.2%
	Scen 58 direct	99.5%	100%	96.8%	99.0%
	Scen 58 final	**97.8%**	**97.5%**	**80.4%**	**93.3%**
Hanlon	Observed input	100%	97.6%	99.3%	98.8%
	Baseline CC	100%	98.6%	99.9%	99.4%
	Scen 58 direct	99.9%	97.1%	96.9%	98.0%
	Scen 58 final	**100%**	**97.5%**	**97.5%**	**94.6%**

*based on 30 year period

Table 2: **Number of years with Target Violations**

Location	Scenario	Jan-Apr	May-Sep	Oct-Dec	Annually
Doon	Observed input	0	2	3	4
	Baseline CC	0	0	3	3
	Scen 58 direct	1	0	4	4
	Scen 58 final	**0**	**5**	**14**	**15**
Brantford	Observed input	3	2	4	6
	Baseline CC	1	0	3	3
	Scen 58 direct	3	0	4	5
	Scen 58 final	**6**	**8**	**18**	**20**
Hanlon	Observed input	0	4	1	4
	Baseline CC	0	2	2	2
	Scen 58 direct	1	4	4	6
	Scen 58 final	**0**	**13**	**5**	**13**

*based on 30 year period

Table 3: **Statistics for Reservoirs to reach May 1st Levels**

	Scenario	Shand	Conestogo	Guelph
Number of years <98% on May 1	Observed input	3	6	1
	Baseline CC	2	4	5
	Scen 58 direct	7	14	7
	Scen 58 final	**15**	**17**	**0**
Lowest % of May 1 on May 1	Observed input	90%	79%	92%
	Baseline CC	69%	95%	78%
	Scen 58 direct	66%	83%	69%
	Scen 58 final	**85%**	**76%**	**100%**

*based on 30 year period

Output from the GAWSER model cannot be used directly as input into the RY model because of over estimation of low flows and flows during the late spring season (May and June). These are key times for reservoir operations and the errors in flow estimation although small are significant enough to give misleading results. It is recommended that modifying the observed input data sets with monthly change fields calculated based on the percent difference between the baseline and Climate Change Scenario flow data from the GAWSER model is the recommended method to include climate change scenarios in the Reservoir Yield model. There is still a high degree of uncertainty in this method, as with all modeling and climate change work. It is important to recognize the uncertainty in future discussions.

It is recommended that all ten scenarios be run with current reservoir operating rule curves and flow targets to determine a baseline of effects of climate change scenarios. The results of Scenario 58 may show a low precipitation scenario, but in order to plan for climate change it is recommended that as many scenarios as possible are run. Additional scenario runs are in progress.

Appendix F: Luther Reservoir Yield Model

Summary

A request was made to complete a similar climate change reservoir yield analysis for the Luther Reservoir as was completed for the other three large reservoirs (Belwood, Conestogo and Guelph). Assessing the effects of climate change on the ability of the Luther Reservoir to provide flow augmentation is not a straightforward exercise. The source of water for Luther Reservoir, local drainage and direct precipitation, is much different from the other reservoirs that have more defined inflow streams. This difference in inflow has limited the use of simulated inflow from the hydrologic model climate change scenarios.

A modified approach was used to evaluate five climate change scenarios with the Luther Reservoir Yield model and the output and inputs were used to determine relative differences in meeting flow augmentation targets at the Leggett gauge. Two of the five scenarios may have trouble in meeting flow targets in the future based on an increased need for augmentation and lower inflows to the reservoir, but the reservoir yield model did not confirm these results. These two scenarios represent the worst case scenarios, about 10% of the 76 scenarios evaluated, and changes to the operation of Luther Dam including modifications to the rule curve to allow holding of more winter melt water would increase the reliability of meeting downstream summer flow targets in a changed climate.

Background

Eleven future climate scenarios were run through the Grand River hydrologic model to investigate changes to stream flow with a changed climate. General results were that the winters would have higher precipitation and warmer temperatures, leading to more mid-winter melt events. The low flow season would be longer with a weak trend to drier conditions. Changes to the winter period would affect the ability of the reservoirs to be filled, while a longer and drier summer may affect the ability of the reservoirs to augment flows. The effects of climate change on reservoir operations was included in (GRWMP 2013) and included in (Section 4) using the Grand River Reservoir Yield model. This model focuses on the lower river system and includes three reservoirs: Conestogo Dam, Shand Dam and Guelph Dam reservoirs. The effects of Luther Dam on the upper Grand River has been assessed in the past with a separated model specific to the Luther Reservoir and was not included in the original climate change assessment.

Assessing the effects of climate change on the ability of the Luther Reservoir to provide flow augmentation is not a straight forward exercise. The Luther Reservoir does not have an inflow watercourse. Instead, it receives water from the local drainage basin through direct runoff, direct precipitation on the reservoir, snow melt and interflow. The reservoir is in a naturally wet area of the landscape in a location of a historic, large wetland complex. Inflow to the reservoir has been calculated in the past by assessing the change in lake level while taking into account precipitation, evaporation and discharges.

Methods

Five climate change scenarios were chosen to run through the Luther Reservoir Yield model. Two of the scenarios, CC66 and CC65, represented a worst case scenario with large decreases in precipitation during the late spring and summer period. These two scenarios produced the lowest reliabilities for meeting flow targets in the lower Grand River (Section 4). Two of the scenarios, CC52 and CC14, represented moderate future conditions. The final scenario, CC30, represented wet future conditions with an increase in precipitation year round. All future scenarios are considered equally plausible by the climate change community.

The hydrologic model produces inflow to the Luther Reservoir from the local drainage basin by calculating runoff from the local sub-basin of the reservoir accounting for ET from the soil. The simulated inflow does not take into account inputs from direct precipitation to the reservoir, or loses from direct evaporation from the reservoir and discharge. The back calculated inflows used in the Reservoir Yield model are calculated differently and sometimes result in negative inflows to represent periods when discharge is greater than inflow or evaporation losses are high (Boyd 2004). The two series are not interchangeable and this created an issue when preforming the reservoir yield analysis on the climate change scenarios.

Similar to the larger reservoir yield modeling, output from the hydrologic model could not be input directly in the Reservoir Yield model because of limitations on how the GAWSER model handles baseflows (Appendix E). For the local flows to Leggett and Marsville a monthly change field method was used similar to the method used with the larger reservoir yield model. A change field was calculated for each gauge for each month and year by comparing the total monthly volume of water between the base case and the climate change scenario. Then the change field was applied to the daily flow series from the observed data set. This created a new flow data set that incorporated the relative change in flows that can be expected with each scenario of climate change, but that did not include the bias from how the hydrologic model produces low flow conditions.

The inflow data was not treated in the same way as the stream flow data. The change field method used on observed data would not work because the inflow data from the hydrologic model was not calculated in the same way as the inflow data used in the reservoir yield model. In order to account for changing inflows with climate change, simulated inflow from the climate change hydrologic model runs was input directly into the reservoir model as is. To make comparisons with current conditions the baseline data was first run with output from GAWSER for the baseline period used for the reservoir inflows and observed data used for the locals to Leggett and Marsville.

Changes to the reservoir yield results first have to be investigated as relative changes from the baseline conditions and then related back to changes compared to observed values. A review of some of the lowest flow years was completed to see if reservoir levels could be maintained with the discharge rates required to meet flow target. An analysis of changes to inflows and augmentation needs is also included.

Results

Generally, the baseline output from the hydrologic model resulted in higher reservoir levels than using the observed data in the model. The only thing that was changed in the baseline run was the inflow to Luther Dam, so the resulting higher levels is most likely the result of the difference in reservoir inflow calculation methods. Patterns were similar between the baseline and observed output data with the same high and low flow years.

Climate Change Runs

The climate change scenarios ran from 1977 to 1990, except for CC14, which ran from 1977 to 2000. The driest period common to all of the scenarios is 1988 -1989. 1988 had a dry summer period, while 1989 had a dry winter and spring period. None of the climate change reservoir yield runs resulted in flows below 0.42 m^3/s at Leggett, even in the driest years.

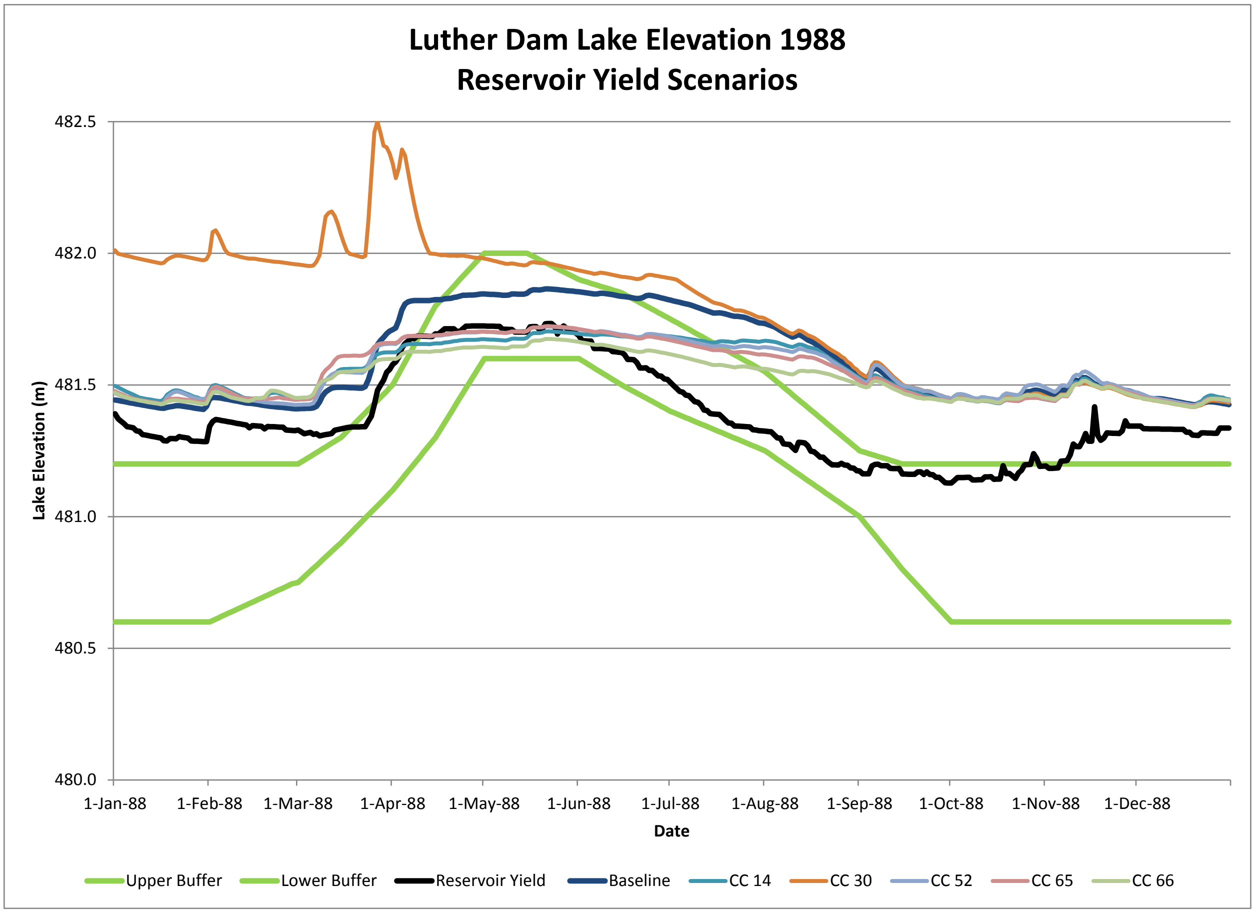

Figure 1: 1988 Luther Reservoir climate change reservoir yield scenarios

Figure 1 shows the 1988 results for the original reservoir yield model run with observed data, and the climate change runs including the climate change baseline scenario. The baseline results have higher reservoir levels than the model run using observed data. The climate change scenairos had lower reservoir levels than the baseline, but in every case they were above the lower rule curve. The fall period was similar between the baseline and the climate change scenarios indicating no change. It is difficult to make solid conclusions from the climate change scenario results because of the difference between the baseline scenario and the reservoir yeild results using observed data.

Analysis of the change in augmentation that is needed between the climate change scenarios and the baseline scnearios show that in 1988 CC65 needed 32% and CC66 needed 34% more augmentation during the summer period than the baseline case. Both of these scenarios had a decrease in inflows to the reservoir of about 20% in total for 1988. It is likely that it would have been more difficult to meet the flow target at Leggett in 1988 with these future scenarios. On an annual basis there is 4 times more inflow than the amount of augmentation required for scenarios CC65 and CC66, so the water is there, but it might require a change to the operation of the reservoir to capture more winter runoff to ensure a higher reservoir level at the start of the augmentation season.

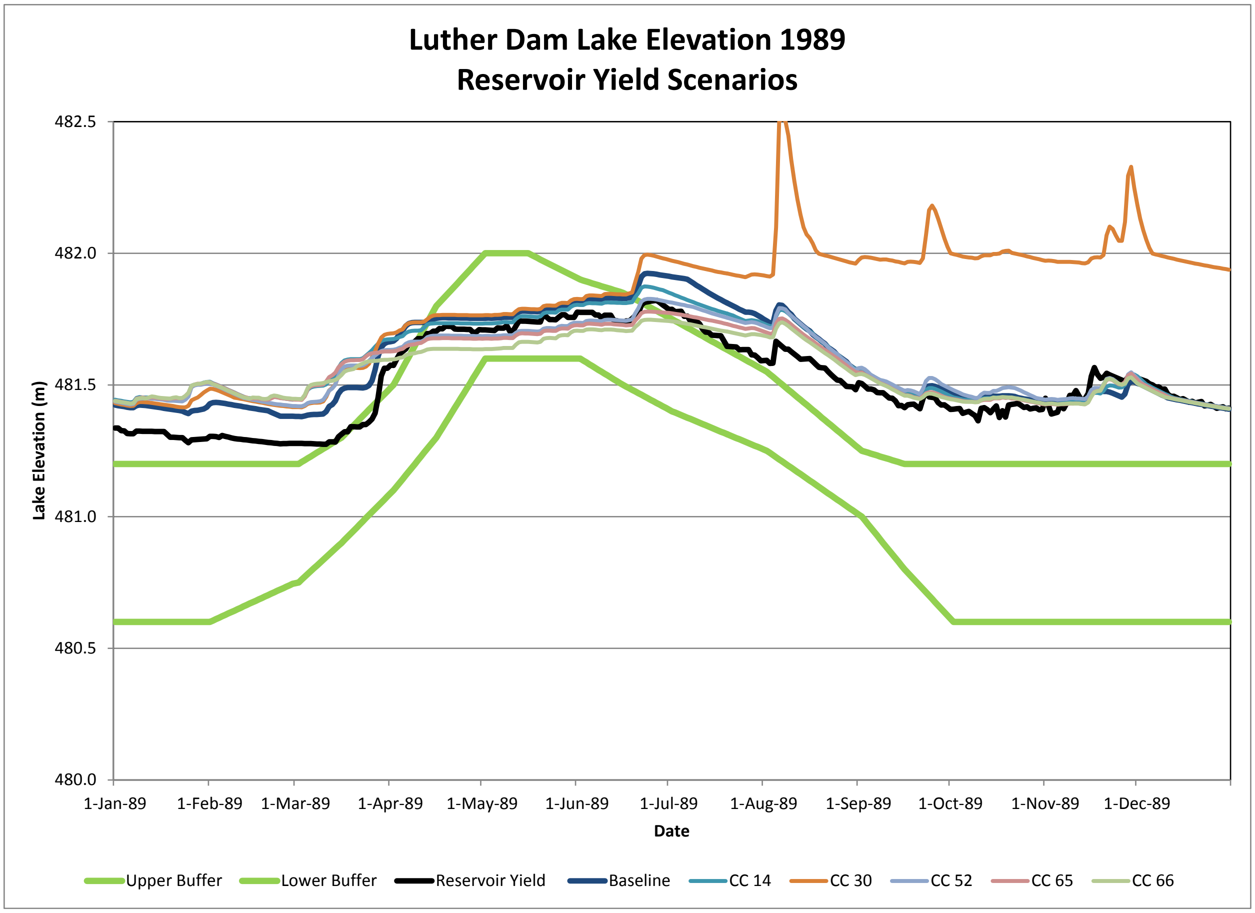

Figure 2: 1989 Luther Reservoir climate change reservoir yield scenarios

Figure 2 shows the results for 1989. The results are similar for each of the scenarios with very close reservoir levels during the summer period. Augmentation needs for CC65 and CC66 were about 26% higher than baseline with inflows about 5% lower. Total inflow was approximately 6 times augmentation required on an annual basis.

Conclusions

Output from the Grand River hydrologic model cannot be used directly in the Luther Reservoir Yield model. The inflow data sets calculated from observed data and from hydrologic model output are not interchangeable because of differences in the way that inflow is calculated. This has resulted in a need to use a combined approach to running climate change scenarios through the reservoir yield model and has increased the uncertainty in the results. Additional analysis of changes to augmentation needs and inflow amounts help to analyze the impacts of different future scenarios.

Based on changes to augmentation needs and inflow to the reservoir, two of the five scenarios may have trouble in meeting flow targets in the future. The Luther Dam reservoir yield model did not confirm these results. Total yearly inflow to the reservoir is well above augmentation needs even in the driest years. These two scenarios represent the worst case scenarios, about 10% of the 76 scenarios evaluated. Changes to the operation of Luther Dam including modifications to the rule curve to allow holding of more winter melt water would increase the reliability of meeting downstream summer flow targets in a changed climate.

References

Boyd, DB. 2004. Luther March Reservoir Yield Analysis. July 2004. Prepared for the Grand River Conservation Authority.

Grand River Water Management Plan. 2013. *Flow Reliability: Regulated Reaches of the Grand River Watershed*. Prepared by Dwight Boyd and Stephanie Shifflett, Grand River Conservation Authority.