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TOWNSHIP OF CENTRE WELLINGTON MUNICIPAL WATER SUPPLY
CLIMATE CHANGE ASSESSMENT

Prepared for:
GRAND RIVER CONSERVATION AUTHORITY

Prepared by:
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EXECUTIVE SUMMARY

This report summarizes an assessment of the potential effects of climate change on the risk to groundwater supplies in the Township of Centre Wellington, Ontario. The assessment is based on the results of the Centre Wellington Tier Three Water Budget Assessment (Tier Three Assessment; Matrix 2020). This Tier Three Assessment evaluates the effects of groundwater pumping, changes to future land use areas, and drought conditions with respect to the potential impacts on future municipal water supplies in Centre Wellington (i.e., the Fergus and Elora municipal wells). The Grand River Conservation Authority retained Matrix Solutions Inc. to complete an assessment of the potential water quantity impacts that climate change may have on those same municipal wells.

The climate change assessment initially evaluated the effects of climate change on watershed hydrology, and then evaluated the effects of these hydrologic changes on the water supply. The assessment compiled multiple scenarios of future climate for the 2041 to 2070 (i.e., 2050) period from global climate models and then applied the Grand River hydrology model to assess how the hydrology in the area surrounding the Centre Wellington municipal water supply system may change. Multiple scenarios of future groundwater recharge were predicted using the hydrology model and used as input into the Centre Wellington Tier Three groundwater flow model. The Tier Three groundwater flow model used these groundwater recharge scenarios to assess the potential impact to groundwater levels at municipal wells. The simulated climate change results from the groundwater flow model suggested that:

- The range of future climate scenarios resulted in conditions with increased average annual groundwater recharge rates. These increased groundwater recharge rates are mostly a result of greater precipitation and warmer winter conditions in the future climate scenarios. Due to the projected increase in groundwater recharge, the groundwater modelling scenarios suggest that future climate change is not likely to pose an additional water quantity threat to the Centre Wellington groundwater supply.

- Vertical leakage of groundwater downwards into the municipal aquifer is predicted to increase with the future climate scenarios in response to higher groundwater recharge rates.

The conclusions are based on the assumptions and limitations of the future climate datasets and the surface water and groundwater modelling approach employed. The hydrology model, groundwater model and future climate datasets derived from global climate models are consistent with the state of the practice at the time of this assessment.

While the models have uncertainty, the approach used for this assessment was to consider multiple future climate scenarios based on worst case carbon emission estimates. All of the scenarios project greater amounts of groundwater recharge as compared to current conditions, and it is therefore concluded that given the current scientific understanding, climate change does not pose a negative threat to the groundwater supply up to the 2050 time horizon. It is recommended that this assessment be updated

approximately every 5 years to reflect any revisions in the hydrology model, groundwater flow model, water demand, and climate change models that may alter the conclusions presented here.

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1 INTRODUCTION

This report describes the completion and results of a desktop modelling assessment carried out to estimate the potential effects of climate change on the municipal drinking water systems of the Township of Centre Wellington (Centre Wellington) in the Province of Ontario (Figure 1). Centre Wellington contains the communities of Fergus and Elora, and the serviced population is projected to grow from approximately 19,000 in 2016 to more than 40,000 people in 2041 (AECOM 2019). A Tier Three Risk Assessment (Matrix 2020) concluded that the existing municipal drinking water wells have the capacity to meet Centre Wellington's water supply requirements until approximately 2031. However, Centre Wellington does not have the infrastructure in place to meet water supply requirements from 2031 to 2041, and this results in the classification of "Significant" Risk Level to the Groundwater Vulnerable Area in the vicinity of the municipal wells. The purpose of this climate change assessment is to estimate additional future threats on Centre Wellington's water supply that may be introduced by climate change.

Centre Wellington relies completely on groundwater resources to meet its municipal water demand. Three municipal water supply wells are located in Elora (wells E1, E3, and E4), and six municipal wells are located in Fergus (wells F1, F2, F4, F5, F6, and F7; Figure 1). Each of the water supply wells are completed in bedrock and each well was constructed between 1935 and 2002. The separate Fergus and Elora water distribution systems were combined into a single combined distribution system in October 2005. All the municipal wells, except Well F2, were assessed as part of the Tier Three Assessment (Matrix 2020); Well F2 is inactive and modifications such as replacing or deepening of the existing well are currently under consideration.

The Province of Ontario introduced the *Clean Water Act, 2006* (Bill 43; Government of Ontario 2019) to ensure that all residents have access to safe drinking water. Centre Wellington lies within the Grand River Source Protection Area (watershed), which is within the Lake Erie Source Protection Region (Lake Erie SPR). The Lake Erie Region Source Protection Committee was established in 2007 and has the responsibility under the *Clean Water Act*, *2006* to develop local Source Protection Plans and report on implementation in all four watersheds within the Lake Erie SPR. The goal of each Source Protection Plan is to develop policies and programs to eliminate, reduce, and/or manage existing Significant drinking water threats (i.e., water quality and water quantity threats) and ensure no future drinking water threats become Significant.

This report summarizes an assessment of the potential effects of climate change on the quantity of water available to the Centre Wellington municipal drinking water supply. The approach followed for this climate change assessment is the same as what was conducted in support of the City of Guelph and the Township of Guelph/Eramosa Water Quantity Policy Study (Matrix 2018) and relies on the same projected future climate datasets. The sections in this report describe the approach followed and conclusions and recommendations based on the results.

2 CLIMATE CHANGE ASSESSMENT APPROACH

The following subsections discuss future climate; hydrologic and groundwater models; alternative climate change hydrology scenarios; and the predicted impact of those alternative scenarios on the Centre Wellington municipal water supply wells.

2.1 Future Climate

The first phase of this project included the preparation of future local climate datasets. This phase leveraged existing information to achieve the overall outcome of constructing and analyzing an ensemble of future climate projections for temperature and precipitation variables. The analysis completed in this phase guided the development of scenarios for use in hydrologic modelling. Specifically, this phase included the compilation of an ensemble of future climates considering available Global Climate Models (GCMs) and completing a process known as downscaling to prepare local climate datasets from the GCMs.

The climate change methodology developed in the *Guide for the Assessment of Hydrologic Effects of Climate Change in Ontario* (EBNFLO and AquaResource 2010) was applied for this study. A selection of climate data from ten GCMs was used to develop climate change scenarios using the Grand River Conservation Authority's (GRCAs) watershed hydrology model (Guelph All-Weather Sequential Events Runoff [GAWSER]; Schroeter & Associates 2004) and the Centre Wellington Tier Three groundwater flow model (FEFLOW; Diersch 2014).

The future GCM climate datasets used in this study were originally compiled by Risk Sciences International (RSI) for a climate change assessment for the Grand River Mill Creek Subwatershed (Matrix 2016). These datasets were assumed to be valid for this study because they remain the most current GCM modelling results and are also relevant for the geographical area assessed by the Centre Wellington Tier Three groundwater flow model. RSI's report summarizing the selection of representative GCMs (RSI 2016) is provided in Appendix A.

2.1.1 Global Climate Models

The primary tools used to estimate future climate are GCMs. GCMs are complex, physically-based, three-dimensional models that represent the earth's atmosphere, oceans, and land surfaces and are used to simulate, over several decades, the interactions of processes that determine the climate for an area. These tools have evolved since the 1970s to their present level of sophistication. Numerous modelling centres around the world have developed GCMs that are used for long-term simulations (i.e., 250 year) to characterize the evolution of temperature, precipitation, solar radiation, winds, and other parameters into the future. GCMs produce global scale output at a relatively coarse grid spacing of 250 to 400 km. Simulations are designed to characterize future climate on an annual, seasonal, and monthly basis.

The Intergovernmental Panel on Climate Change (IPCC) is the most reliable source of climate change science guidance; the group consists of thousands of contributing scientists. The IPCC has released its fifth Assessment Report (AR5; IPCC 2013) which compiles the results of 40 different international climate change models. A new initiative in the IPCC AR5 is the introduction of Representative Concentration Pathways (RCPs). Each RCP defines a specific carbon emissions and greenhouse gas concentration trajectory and subsequent radiative forcing. Radiative forcing is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the earth's atmosphere, measured in watts per square metre (W/m^2). The lowest greenhouse gas concentration pathway (RCP 2.6) represents an increase of 2.6 W/m^2 of radiative forcing to the system, while the highest RCP (RCP 8.5) represents an increase of 8.5 W/m^2 of radiative forcing. This range encompasses the best estimate of what is possible under a small perturbation situation (RCP 2.6) and under a large increase in warming (RCP 8.5). Climate change scientists cannot know which RCP may represent the earth's future carbon emissions trajectory. However, greenhouse gas emissions have followed the highest emissions (RCP 8.5) pathway up until now.

2.1.2 Local Climate Datasets

While there are many GCMs available to describe future climates, the GCMs do not produce datasets that have the spatial or temporal refinement needed to support physically-based hydrologic modelling. The creation of locally-relevant climate datasets is described as downscaling. There are several approaches to downscaling including; dynamical downscaling, statistical downscaling, and the "change field" downscaling approach (EBNFLO and AquaResource 2010).

Dynamical downscaling is a computationally intensive approach that involves running high-resolution climate models on a regional subdomain (i.e., Regional Climate Model [RCM]). This allows for more higher-resolution datasets (e.g., topography) and more rigorous mathematical descriptions of physical processes (e.g., evapotranspiration) to be incorporated in order to reproduce local climates. An RCM is a model nested into a portion of a GCM. The boundary conditions for an RCM are determined from GCM output for an isolated geographical area. The RCM then uses these boundary conditions for computation of climate scenarios at higher resolution over the specified isolated area. Downscaling climate data is the general name of the procedure to generate locally relevant climate data from the results of a GCM or an RCM.

Statistical downscaling involves the development of empirical relationships between local climate variables and large-scale predictors. Future atmospheric variables projected by GCMs can then be used to predict future local climate variables. Statistical downscaling is easy to implement but requires historical climate observations and relies on assumption that currently observed relationships will carry into the future (Trzaska and Schnarr 2014).

The change field downscaling approach is an established methodology for projecting future local climates using the GCM simulations to estimate annual, seasonal, or monthly changes for each climate variable for a future time period relative to a baseline climate period. These relative changes, termed “change fields,” are used to adjust observed climate station data time series to reflect future conditions. This approach results in an altered input climate time series that reflects the average relative change in each climate parameter and, through the use of local observations, reflects historical local climate patterns that may be related to micro-climate factors such as water bodies (e.g., Great Lakes), topographic changes (e.g., Niagara Escarpment) and the effects of urbanization. The change field method is a simple approach to develop future local climates that reflect large-scale average features and allows the use of multiple GCM and greenhouse gas emission scenarios. The change field approach is used for this climate change assessment for the reasons described in this section and it can be applied consistently with the hydrologic and groundwater models applied in the Tier Three Assessment.

The process of identifying an ensemble of future climates in Ontario is summarized in EBNFLO and AquaResource (2010). This guide provides an extensive review of future climate scenarios being used in hydrologic models and provides step-by-step guidance for developing an ensemble of future time series for use in climate impact modelling. The guide recommends using the change field downscaling method, which has subsequently been applied for various Ontario water budget studies including the City of Guelph and Township of Guelph/Eramosa Tier Three Water Quantity Risk Assessment (Matrix 2017).

RSI provided the climatology and climate change analyses for this study using quality controlled and peer reviewed climate change model outputs. This analysis utilized climate change model results from the 40 GCMs in AR5 (IPCC 2013). The most recent climate normal period was selected for the baseline period (1981-2010) and the 2050s period (2041-2070) was selected for future scenarios. The greatest greenhouse gas concentration trajectory, RCP 8.5, was chosen since it best represents the current emissions trajectory.

2.1.2.1 Selection of Global Climate Models

Uncertainties in future climate predictions include unknown future emissions of greenhouse gases and aerosols, the conversion of emissions to atmospheric concentrations and to radiative forcing of the climate, modelling the response of the climate system to forcing, and methods for regionalizing GCM results (IPCC 2013). Uncertainties will remain inherent in predicting future climate change, even though some uncertainties will likely be narrowed in time due to improvements in climate change modelling and computation.

The IPCC (2013; Knutti et al. 2010) recommends that water resource practitioners utilize as many future climate simulations as possible when conducting a climate change impact assessment in order to encompass the wide range of uncertainty with future climate projections. However, in most assessments, it is impractical due to time and/or budget constraints to conduct an evaluation with the full set of over 60 future climate simulations. The ensemble approach to climate model analysis is widely recognized as being a reliable and efficient way to study local trends associated with climate change while also characterizing uncertainties associated with projecting future climate, particularly for use in hydrologic modelling. The ensemble approach involves using a "collection of model simulations characterizing a climate prediction or projection" (IPCC 2013). There are many possible ways of constructing an ensemble of future climates that captures the full range of uncertainty associated with the selection of the emission scenario, GCM, and downscaling method. Each of these elements within an ensemble (i.e., emission scenario, GCM, and downscaling) can greatly influence the outcome of an individual time series, which may also vary by location and time scale of interest.

RSI estimated the monthly and annual temperature and precipitation for 57 GCM scenarios within the GCM grid cells that included both the Guelph and Centre Wellington Tier Three Assessment areas. Chart 1 illustrates a scatter plot of simulated annual mean change in temperature and precipitation for the 2050s (2041-2070) for these 57 scenarios. This chart illustrates the level of disparity among GCM models as mean annual temperatures range from +1.7°C to +4.6°C, while annual precipitation changes range from -4% to +20%.

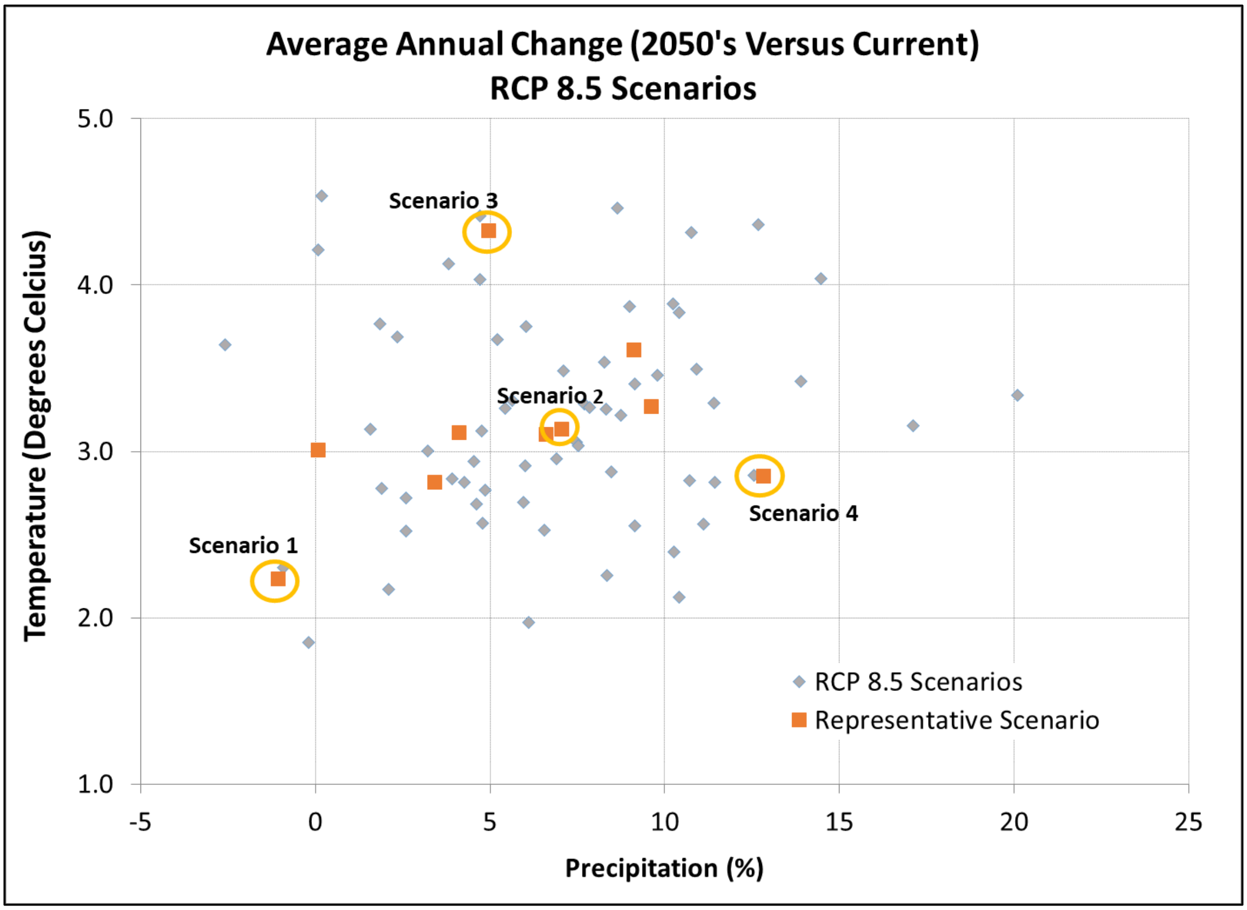

CHART 1 Scatter Plot of Annual Change Fields and Selected Scenarios for Surface Water and Groundwater Modelling

RSI (2016) provides a detailed review of the existing climate sets considered for this assessment. A subset of 10 GCM climate datasets was selected through assessment of the change in mean annual temperature and precipitation between baseline and future periods. Each GCM RCP 8.5 model was ranked and the 5th, 25th, 50th, 75th, and 95th percentile projections for each of these parameters (i.e., temperature and precipitation) were selected. This resulted in ten climate change scenarios which are summarized in Table 1. All GCM scenarios predict an increase in temperature and nine of ten scenarios predict an increase in precipitation on an annual average basis.

TABLE 1 Selected Ensemble of Global Climate Models

Scenario	Percentile	Parameter	Global Climate Model[1]	Annual Temperature Change (°C)	Annual Precipitation Change (%)
CLM1	5th	Temperature	FIO-ESM (Run 1)	2.23	-1.05
CLM2	25th	Temperature	CCSM4 (Run 1)	2.82	3.43
CLM3	50th	Temperature	CSIRO-Mk3-6-0 (Run 10)	3.14	7.05
CLM4	75th	Temperature	CESM1-CAM5 (Run 2)	3.61	9.12
CLM5	95th	Temperature	MIROC-ESM (Run 1)	4.33	4.96
CLM6	5th	Precipitation	IPSL-CM5A-MR (Run 1)	3.01	0.08
CLM7	25th	Precipitation	CNRM-CM5 (Run 1)	3.11	4.12
CLM8	50th	Precipitation	NorESM1-M (Run 1)	3.10	6.62
CLM9	75th	Precipitation	ACCESS1-3 (Run 1)	3.27	9.62
CLM10	95th	Precipitation	CMCC-CESM (Run 1)	2.85	12.82

[1] Additional information on the organization and country of origin of each Global Climate Model is provided in Appendix A.

2.2 Hydrologic Model

After assembling future climate datasets, the application of a hydrologic model is the next step in a climate change assessment. Hydrologic models have the capability to estimate change in the water budget parameters (e.g., runoff, evapotranspiration, and groundwater recharge) under future climate scenarios. This section describes the existing Grand River hydrology streamflow generation model, GAWSER, used to predict hydrologic water budget parameters across the watershed contributing to the Centre Wellington drinking water supplies.

2.2.1 Grand River Hydrology Model

As part of the Centre Wellington Tier Three Assessment, surface water and groundwater modelling tools were applied and/or developed to help assess the sustainability of the municipal water supply system. The models were developed based on a detailed characterization of the groundwater and surface water systems, and they were refined to a level supported by available data. The models were calibrated to represent typical operating conditions under average (steady-state) and variable (transient) pumping conditions. The continuous streamflow-generation model was developed using GAWSER (Schroeter & Associates 2004) and will be discussed in the following subsections.

GAWSER is a subwatershed-scale, deterministic, lumped-parameter, transient, streamflow generation model. Model inputs are precipitation, air temperature, and subwatershed characteristics; outputs include streamflow hydrographs of stormflow and baseflow components (Schroeter & Associates 2004). It can operate in both continuous and event-based modes and can be used to model recharge ponds and can predict sediment accumulation, wash off, and transport.

The GRCA developed and calibrated a continuous GAWSER model to simulate the hydrology of the Grand River Watershed (Schroeter & Associates 2004; AquaResource 2009). The hydrologic model was originally constructed for flood forecasting purposes in the late 1980s, and the model has continually improved and evolved with new information and updates in conceptualization. The event-based model was converted to a continuous model in the late 1990s when a substantial calibration and verification exercise was carried out.

More recently, the GAWSER model was calibrated to the available data in the Tier Two Assessment (AquaResource 2009) and updated as part of the Tier Three Assessments completed for the City of Guelph and Township of Guelph/Eramosa (Matrix 2017) and Region of Waterloo (Matrix and SSP&A 2014) to estimate groundwater recharge rates across the Grand River Watershed. The GAWSER model calibration was not updated for the Centre Wellington Tier Three Assessment (Matrix 2020) as the only streamflow gauge located outside the Grand River within the project study area was the Irvine Creek in Salem gauge, and only minor changes in land cover within the Irvine Creek Subwatershed area have taken place since the completion of the Tier Two Assessment.

Several minor modifications were made to the calibrated GAWSER model to make it suitable for assessing the 2050s future climate scenarios. Potential evapotranspiration was calculated for the 2050s period based on the estimated temperature for each of the GCMs. GAWSER also includes monthly infiltration factors which have been calibrated to 1950-2005 conditions. These factors account for the influence of frozen ground in limiting infiltration during the winter months. These monthly factors were adjusted to be consistent with predicted monthly temperature changes during the 2050s.

2.3 Climate Change Hydrology Scenarios

This section describes the application of the GAWSER model to simulate hydrologic parameters in response to the 2050s change fields calculated for ten GCMs. Although the model simulates a wide range of hydrologic parameters distributed over the watershed, this section focusses on the simulated results for groundwater recharge.

2.3.1.1 Modelling Approach

Chart 1 (Section 2.1.2.1) shows a scatter plot illustrating average annual temperature and precipitation change fields for all RCP 8.5 scenarios considered. The chart highlights in orange the ten representative scenarios selected using the percentile method described earlier in Section 2 to encompass the range in variability for all the GCMs; these ten scenarios were applied in the surface water hydrology modelling as summarized in Table 2.

The groundwater modelling scenarios described later in Section 2.5 are computationally demanding and, as a result, four of the ten GCM datasets originally selected for surface water modelling were selected for groundwater modelling to encompass the range of variability of all the GCMs (Chart 1 and Table 2).

TABLE 2 Selected Ensemble of Global Climate Models used for Surface Water and Groundwater Modelling

Climate Scenario	Global Climate Model	Temperature Change (°C)	Precipitation Change (%)	Surface Water Modelling	Groundwater Modelling
CLM1	FIO-ESM (Run 1)	2.23	-1.05	✓	✓(Scenario 1)
CLM2	CCSM4 (Run 1)	2.82	3.43	✓	
CLM3	CSIRO-Mk3-6-0 (Run 10)	3.14	7.05	✓	✓(Scenario 2)
CLM4	CESM1-CAM5 (Run 2)	3.61	9.12	✓	
CLM5	MIROC-ESM (Run1)	4.33	4.96	✓	✓(Scenario 3)
CLM6	IPSL-CM5A-MR (Run 1)	3.01	0.08	✓	
CLM7	CNRM-CM5 (Run 1)	3.11	4.12	✓	
CLM8	NorESM1-M (Run 1)	3.10	6.62	✓	
CLM9	ACCESS1-3 (Run 1)	3.27	9.62	✓	
CLM10	CMCC-CESM (Run 1)	2.85	12.82	✓	✓(Scenario 4)

Appendix B summarizes the 2050s monthly change fields for the ten selected GCMs. These monthly change fields describe the deviation of average monthly temperature and precipitation for each of the GCMs in the 2050s as compared to baseline conditions. Ten future (2050s) climate datasets were originally created as part of the climate change assessment in support of the Guelph-Guelph/Eramosa Water Quantity Policy Study (Matrix 2018) by modifying the 1950-2005 climate dataset from the Guelph Turfgrass Institute (GTI) by these monthly change fields. The use of this modified climate dataset was considered appropriate to use for this current assessment as the GTI station is located in the same GCM grid cell as Fergus and Elora, and projected monthly climate variability in Guelph can be considered the same as Centre Wellington for the purposes of this assessment. The ten modified 1950-2005 climate datasets were then run in the GAWSER model resulting in ten different time series describing the variability of water budget parameters (e.g., recharge) that might be expected in 2050.

2.3.1.2 Predicted Changes in Groundwater Recharge

Chart 2 illustrates mean daily recharge for the ten future representative 2050 scenarios as compared to baseline conditions for a silty sand soil for each month. Recall that the 2050s scenarios are derived from average GCM projections for the 2041-2070 period. The daily recharge predicted for the future climate scenarios is higher than baseline conditions during the December to April period (i.e., approximately 10% to 30% higher on average; Table 3) and this is a result of having less frozen soil and increased precipitation. Groundwater recharge during the summer months is generally less than baseline conditions and similar to baseline during spring and fall.

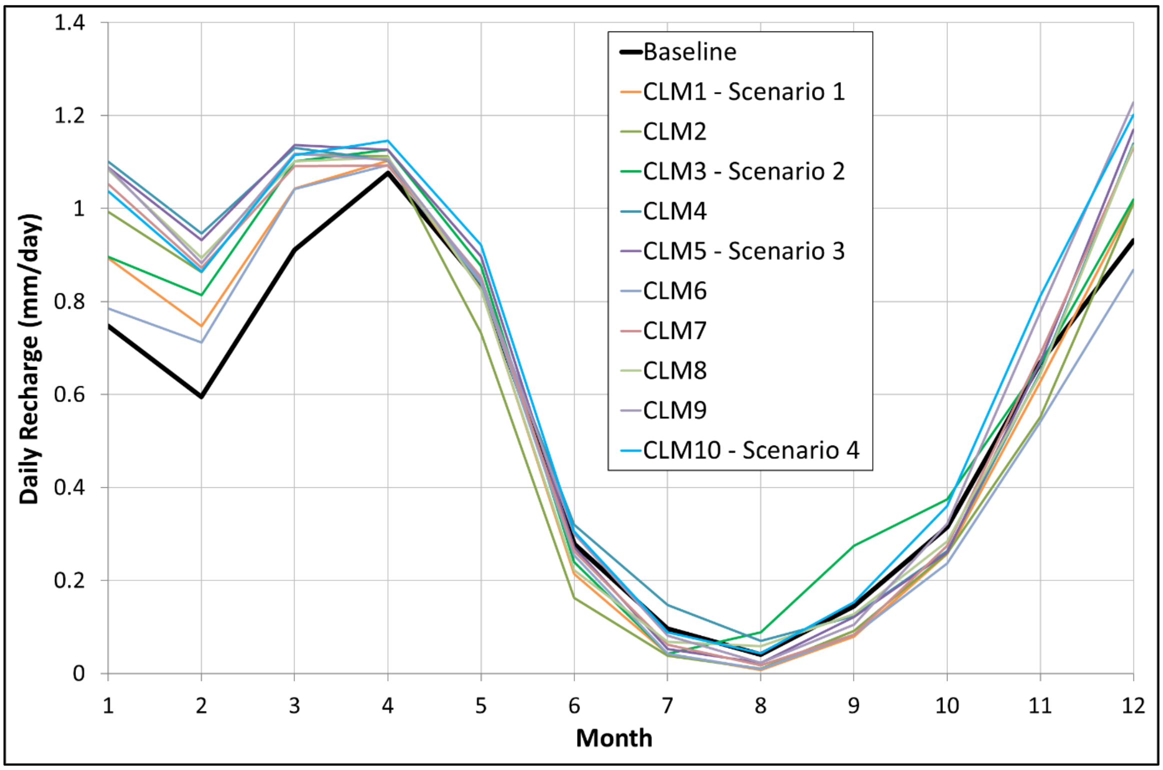

CHART 2 Estimated Mean Daily Recharge (2050s versus Baseline)

TABLE 3 Change in Estimated Mean Daily Recharge Relative to Baseline During December to April Period

Month	Climate Scenario - % Increase of Mean Daily Recharge Relative to Baseline Scenario									
	CLM1	CLM2	CLM3	CLM4	CLM5	CLM6	CLM7	CLM8	CLM9	CLM10
January	19%	33%	20%	47%	46%	5%	41%	45%	45%	39%
February	26%	45%	37%	59%	57%	20%	47%	50%	48%	45%
March	14%	23%	21%	24%	25%	14%	20%	21%	23%	22%
April	2%	3%	5%	2%	5%	2%	1%	3%	3%	6%
December	9%	9%	9%	22%	26%	-7%	21%	22%	32%	29%
Average	14%	22%	18%	31%	31%	7%	26%	28%	30%	28%

Chart 3 illustrates average daily recharge rates for each month over the 1960-1969 drought period and adjusted for each of the ten 2050s GCM change field scenarios during the that same period. This period has been referred to as the drought scenario in the Tier Three Assessment, as it is associated with the lowest average predicted groundwater recharge rates. As shown on the chart, most groundwater recharge occurs during the spring of each year, and there is little to no groundwater recharge during many of the summer months.

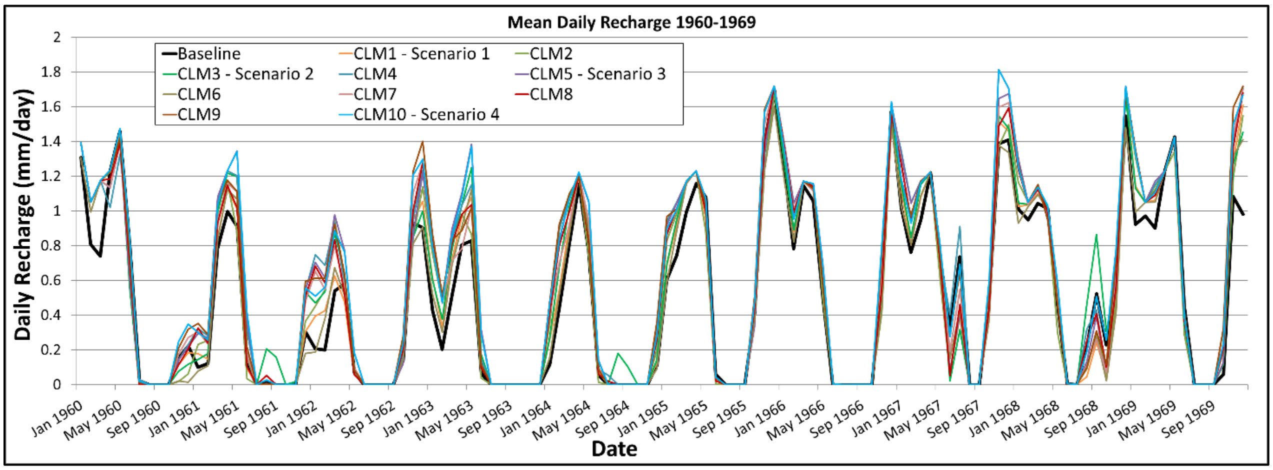

CHART 3 Estimated Recharge During Drought Scenario (Ten GCMs; 2050s versus Baseline)

Predicted average groundwater recharge rates under the drought period associated with the ten future climate scenarios are between 3% and 25% higher than under baseline conditions. Higher groundwater recharge rates are a result of the change in winter or early spring conditions when higher temperatures result in less snowpack, shorter periods of frozen ground, and a greater ability for water to infiltrate.

2.4 Groundwater Flow Model

A FEFLOW groundwater flow model (Tier Three model) was developed for the Centre Wellington Tier Three Assessment to assess the potential impacts of increased municipal groundwater demands, land use change, and drought conditions on water uses (Matrix 2020). The model was based on a detailed conceptual model of the geologic, hydrogeologic, and hydrologic systems in the regional area, with particular focus on the areas surrounding the municipal well fields.

The Tier Three model was calibrated to observed water levels in high-quality monitoring wells, to static water levels from the Ministry of the Environment, Conservation and Parks water well database, to observed baseflow at Irvine Creek, and using recharge estimates developed using the GAWSER streamflow generation model (as described in Section 2.2). The groundwater flow model was also calibrated to transient water level response data from a municipal well shutdown/pumping test over a 6-week period in 2012.

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The version of the Tier Three model used to carry out the baseline and climate change scenarios described in the following sections is based on the model developed for the Tier Three Risk Assessment Scenario H1 (Matrix 2020), which includes consideration of transient recharge, land use change in Fergus and Elora, future (≈2031) municipal pumping, and existing non-municipal pumping.

2.5 Climate Change Hydrogeology Scenarios

Five predictive scenarios were developed to compare and assess the potential impacts of climate change on water levels within Centre Wellington municipal wells, as well as the amount of vertical groundwater leakage into the deep bedrock formations (e.g., Goat Island and Gasport formations) where the municipal wells terminate. These scenarios include one baseline scenario representing past climatic conditions from 1961 to 2005 and four future climate scenarios representing a range of temperature and precipitation variations predicted by selected GCMs (i.e., scenarios 1 to 4; Table 2 and Chart 1). For each of the five scenarios, the groundwater model described in Section 2.4 was updated with a new transient time series of groundwater recharge generated by GAWSER.

2.5.1 Predicted Impact on Water Levels in Municipal Water Supply Wells

Charts 4 to 11 show the predicted water level variation for the baseline and four climate change scenarios at the Centre Wellington municipal wells (i.e., wells E1, E3, E4, F1, F4, F5, F6, and F7) as well as the safe operating levels for the 45-year time period between 1961 to 2005. These safe operating levels, or "set points," were used in the Tier Three Assessment and were based on those established as part of the Water Supply Master Plan for Centre Wellington (AECOM 2019). The thresholds were based on low level lock-out elevations provided by the municipal well operators for the pumps in each municipal well and were subsequently adjusted to consider model error and local geological/operator knowledge. The municipal well would be predicted to not meet its demands if the simulated water level dropped below the safe operating level.

The time period associated with the 1960s drought (i.e., year 0 to 10 on Charts 4 to 11) represents the greatest amount of water level decline predicted over the 45-year record. The results of these groundwater scenarios illustrate that the maximum water level decline occurs during baseline climate conditions during this drought period. Each of the four climate change scenarios shows an increase in the simulated water level for all the wells, over most of the 45-year period, with the average water level increase being approximately 25 cm. The increase in water level is in response to greater amounts of recharge predicted under future climate conditions. Most of this increased recharge is predicted to occur during the winter and early spring months of each year (Chart 2). While groundwater recharge is predicted to decrease during the summer months and early fall, the magnitude of this reduction is small compared to the amount of increased recharge predicted during the winter and spring. As a result, more water is predicted to recharge the groundwater system and buffer the impact of municipal demands.

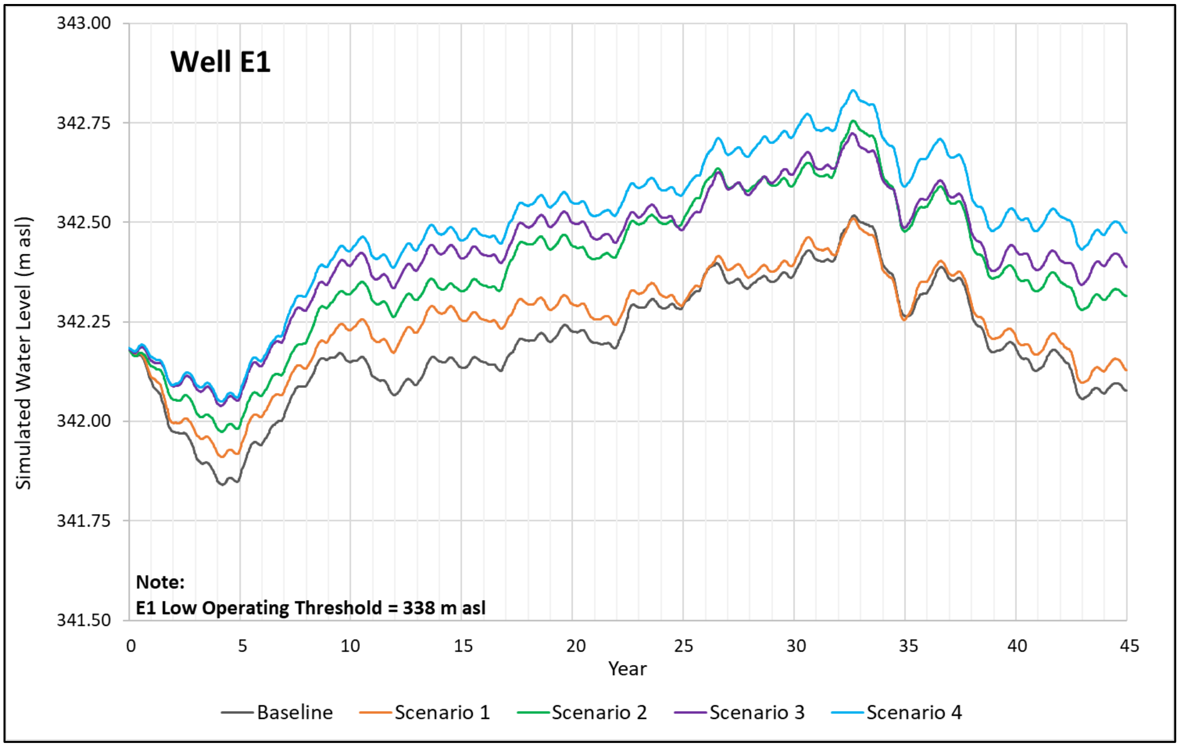

CHART 4 Simulated Water Levels Under Future Climates, Well E1 (2050s versus Baseline)

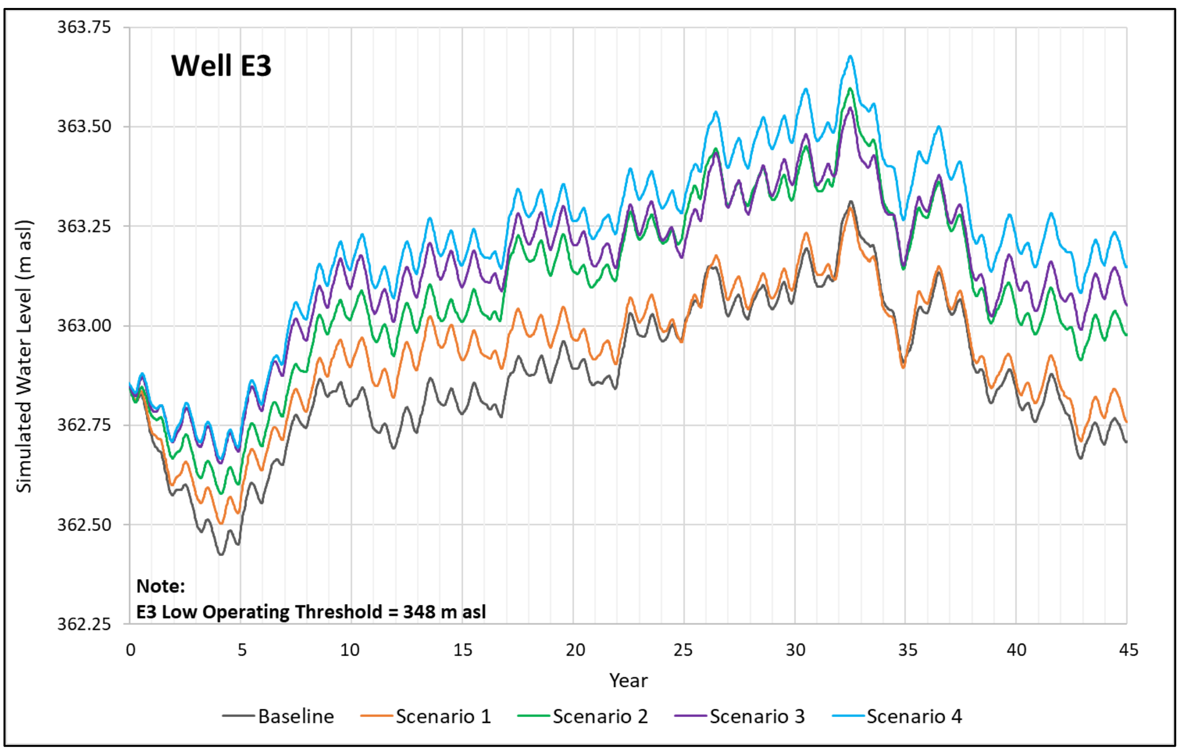

CHART 5 Simulated Water Levels Under Future Climates, Well E3 (2050s versus Baseline)

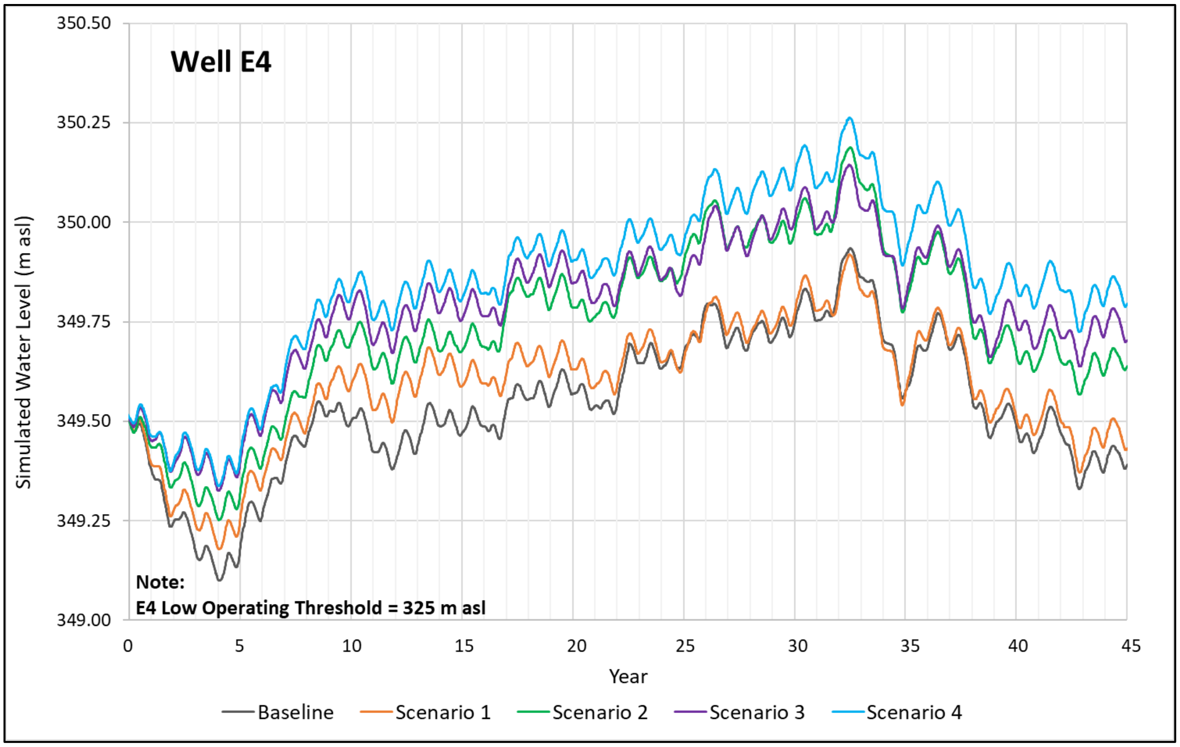

CHART 6 Simulated Water Levels Under Future Climates, Well E4 (2050s versus Baseline)

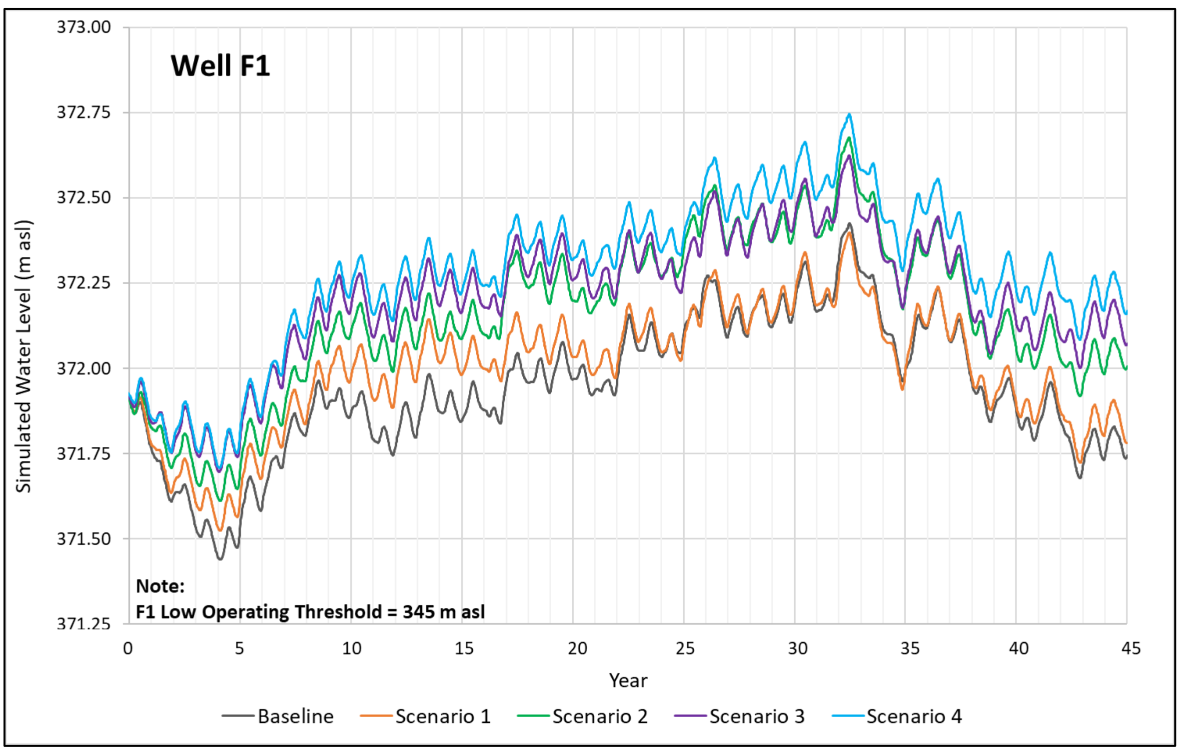

CHART 7 Simulated Water Levels Under Future Climates, Well F1 (2050s versus Baseline)

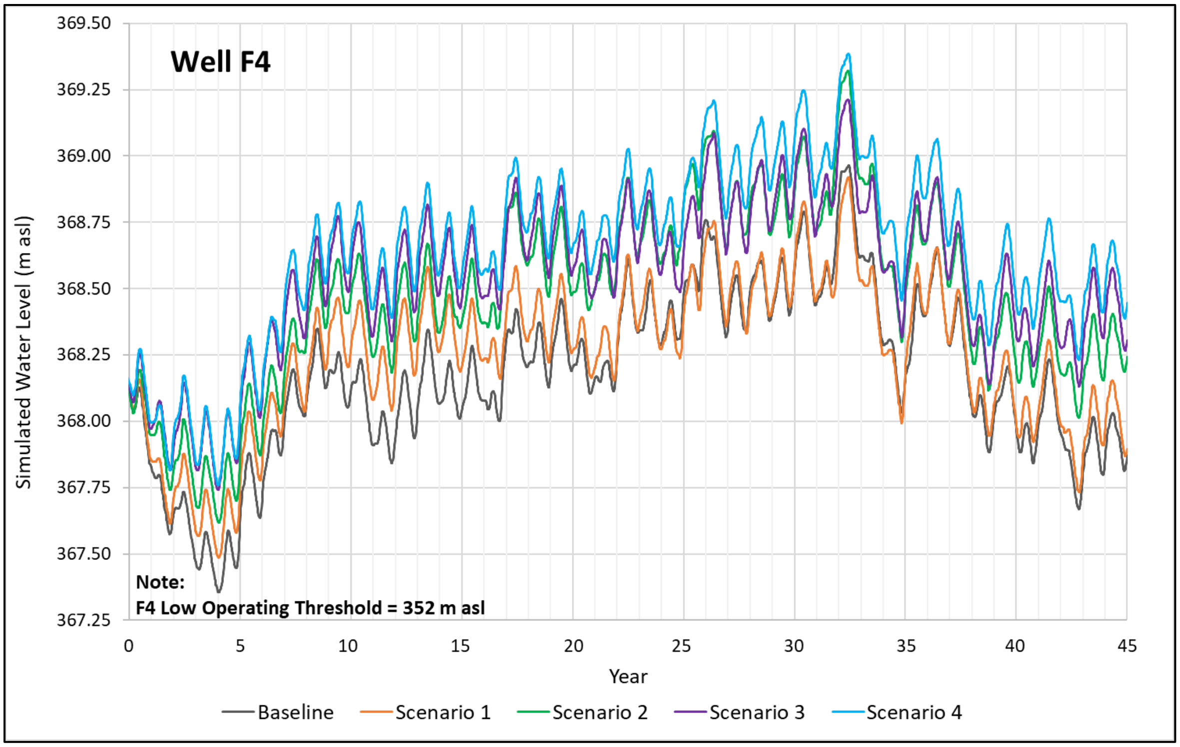

CHART 8 Simulated Water Levels Under Future Climates, Well F4 (2050s versus Baseline)

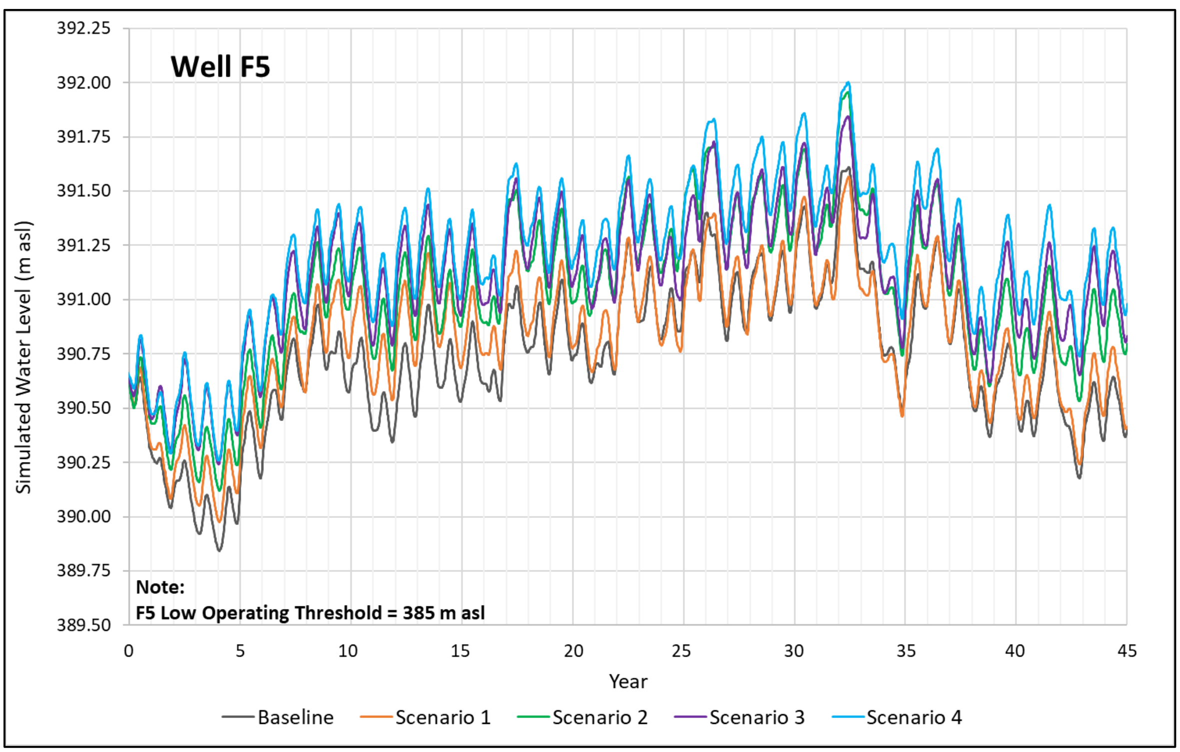

CHART 9 Simulated Water Levels Under Future Climates, Well F5 (2050s versus Baseline)

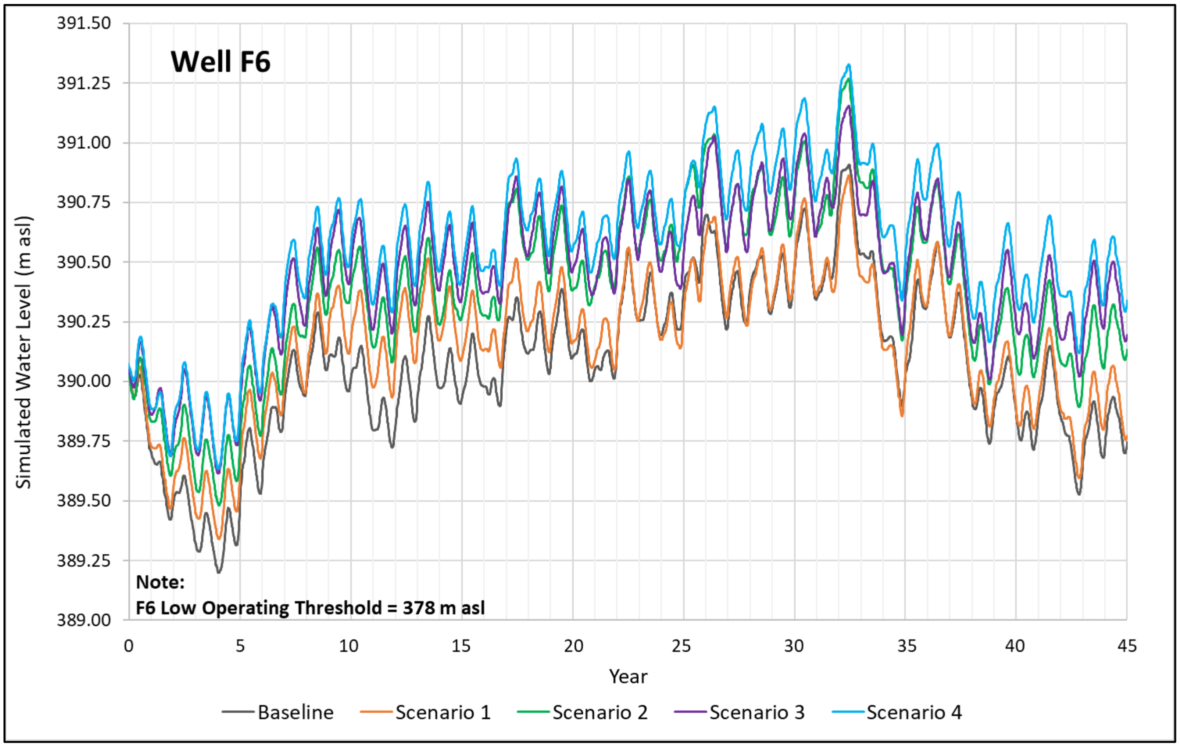

CHART 10 Simulated Water Levels Under Future Climates, Well F6 (2050s versus Baseline)

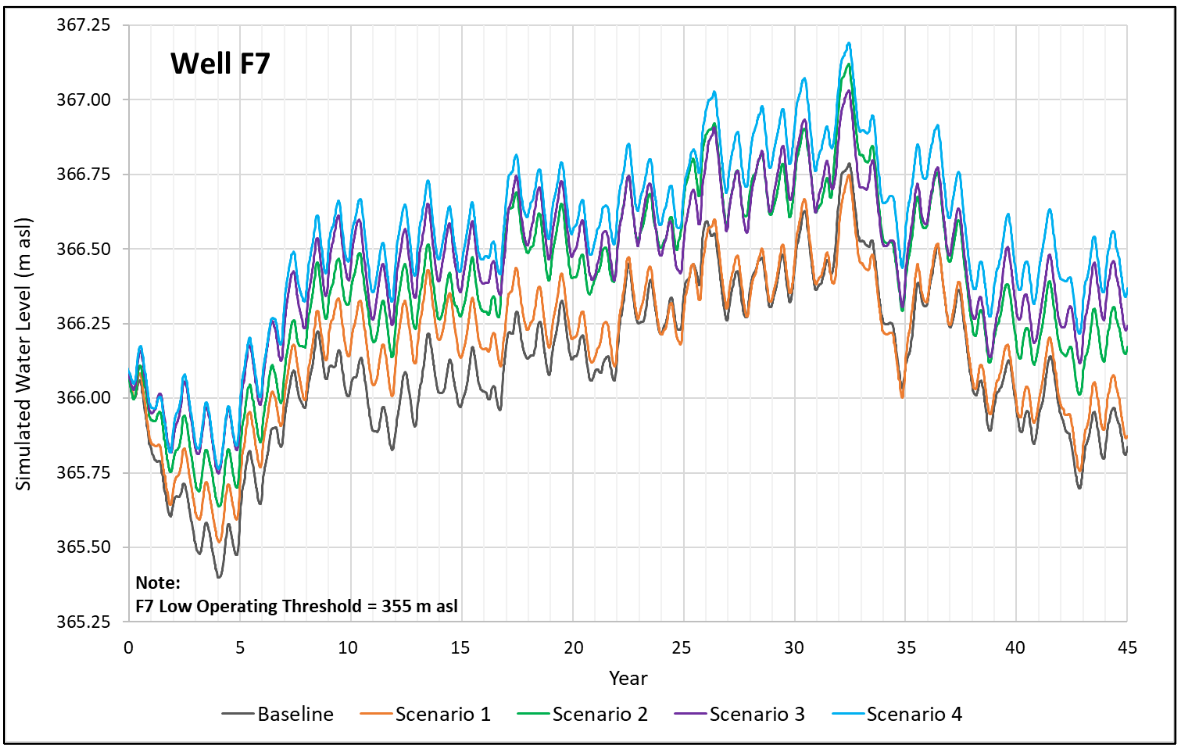

CHART 11 Simulated Water Levels Under Future Climates, Well F7 (2050s versus Baseline)

2.5.2 Predicted Impact on Leakage to Lower Bedrock Formations

A water budget for the groundwater flow system was summarized as part of the Tier Three Assessment (Matrix 2020). This water budget includes inflows (i.e., recharge and cross-boundary flow) and outflows (i.e., groundwater discharge to surface water features, water takings from wells, and cross-boundary flows). A water budget for the lower bedrock units (i.e., Goat Island and Gasport formations), which are interpreted to be the main source of water for the municipal wells, was evaluated during the Tier Three Assessment and the result suggested that a greater proportion of water in the lower bedrock units is sourced vertically from leakage through the overlying geological layers, rather than laterally from the regional flow system. The same water budget analysis was performed for the climate change assessment to evaluate the impact that the future climate scenarios may have on vertical leakage to the lower bedrock formations.

Chart 12 illustrates the predicted variation in vertical leakage to the lower bedrock for the baseline and four climate change scenarios. Chart 13 illustrates the average monthly leakage rates for each of the scenarios and shows that the increased recharge predicted during the winter and spring months under the future climate conditions results in higher rates of vertical leakage to the lower bedrock units.

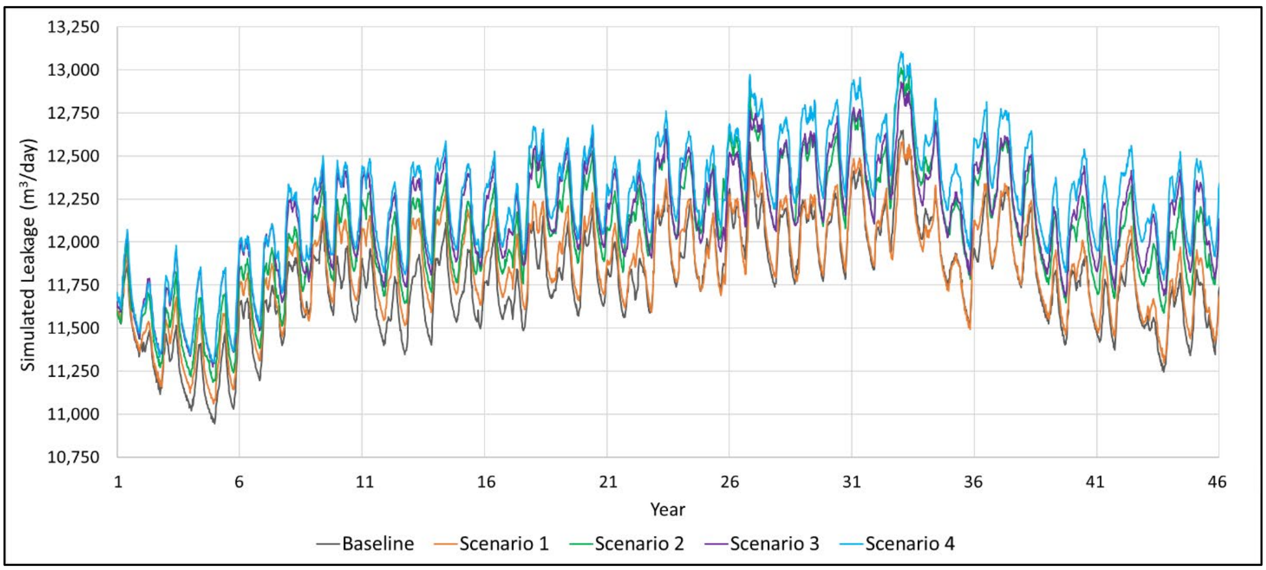

CHART 12 Simulated Vertical Leakage to Lower Bedrock Units (2050s versus Baseline)

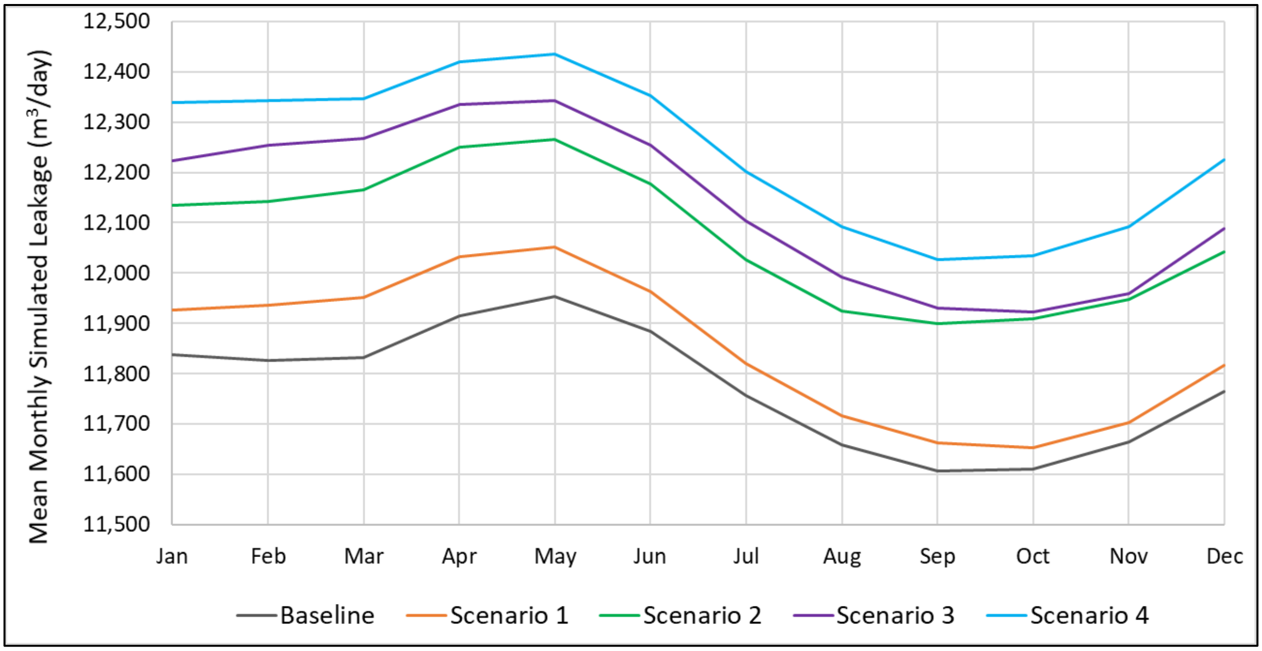

CHART 13 Mean Monthly Vertical Leakage to Lower Bedrock Units under Future Climates (2050s versus Baseline)

The overall average simulated leakage to the lower bedrock units under future climates and over the 45-year simulated period is summarized in Table 4 relative to the baseline climate scenario. The results suggest that, on average, the simulated vertical leakage to the deeper units may increase from the baseline from 1% to 4% for the future climate scenarios over the 45-year period.

TABLE 4 Average Simulated Leakage to Lower Bedrock Formations under Future Climates (2050s) and over 45-year Simulation Period (1960-2005)

Scenario	Average Leakage (m^3/day)	% Change Compared to Baseline
Baseline (Current Climate)	11,780	0%
Scenario 1	11,850	+1%
Scenario 2	12,070	+2%
Scenario 3	12,140	+3%
Scenario 4	12,240	+4%

3 CONCLUSIONS AND RECOMMENDATIONS

An assessment of the potential water quantity impacts on the Centre Wellington municipal water supply wells as a result of future climate change was conducted. Future climate datasets were compiled and used in conjunction with the GAWSER hydrology model to assess how future climates might change the hydrology in the area surrounding the Centre Wellington municipal water supply system. Changes in groundwater recharge due to climate change, as predicted by GAWSER, were input into the Centre

Wellington Tier Three groundwater flow model to assess the impact of future climates on water levels at municipal wells and the amount of vertical groundwater leakage into lower bedrock formations that supports the municipal wells. The simulated climate change results for the 2050 period suggested that:

- Climate change may not pose an additional threat to the quantity of the Centre Wellington municipal water supply wells due to predicted increase in groundwater recharge. The GCM models that were applied, and the hydrologic model applied, suggest that groundwater recharge rates will increase over time.

- Climate change may not pose an additional risk to the vertical leakage of water from the shallow groundwater flow system to the deeper flow system due to predicted increase in groundwater recharge.

These results are based on the modelling approach employed and the GCMs selected for this assessment. These water budget models and future climate datasets represent the state of the practice at the time of this assessment. As described earlier in this report, the future climate models and water budget models have uncertainty, and the approach used to address this uncertainty is the completion of multiple scenarios providing a range of plausible outcomes. None of these scenarios suggest that future climate change will pose a threat to the municipal water supply up to the 2050 time horizon. The key assumptions with the modelling approach employed are that the approach to select multiple climate change scenarios encompassing a range of temperature and precipitation variability is appropriate, and the change field method used to establish future climate datasets is appropriate. It is recommended that this modelling be updated approximately every 5 years to reflect any revisions in water budget models, water demand, and climate change models that may alter the conclusions presented here.

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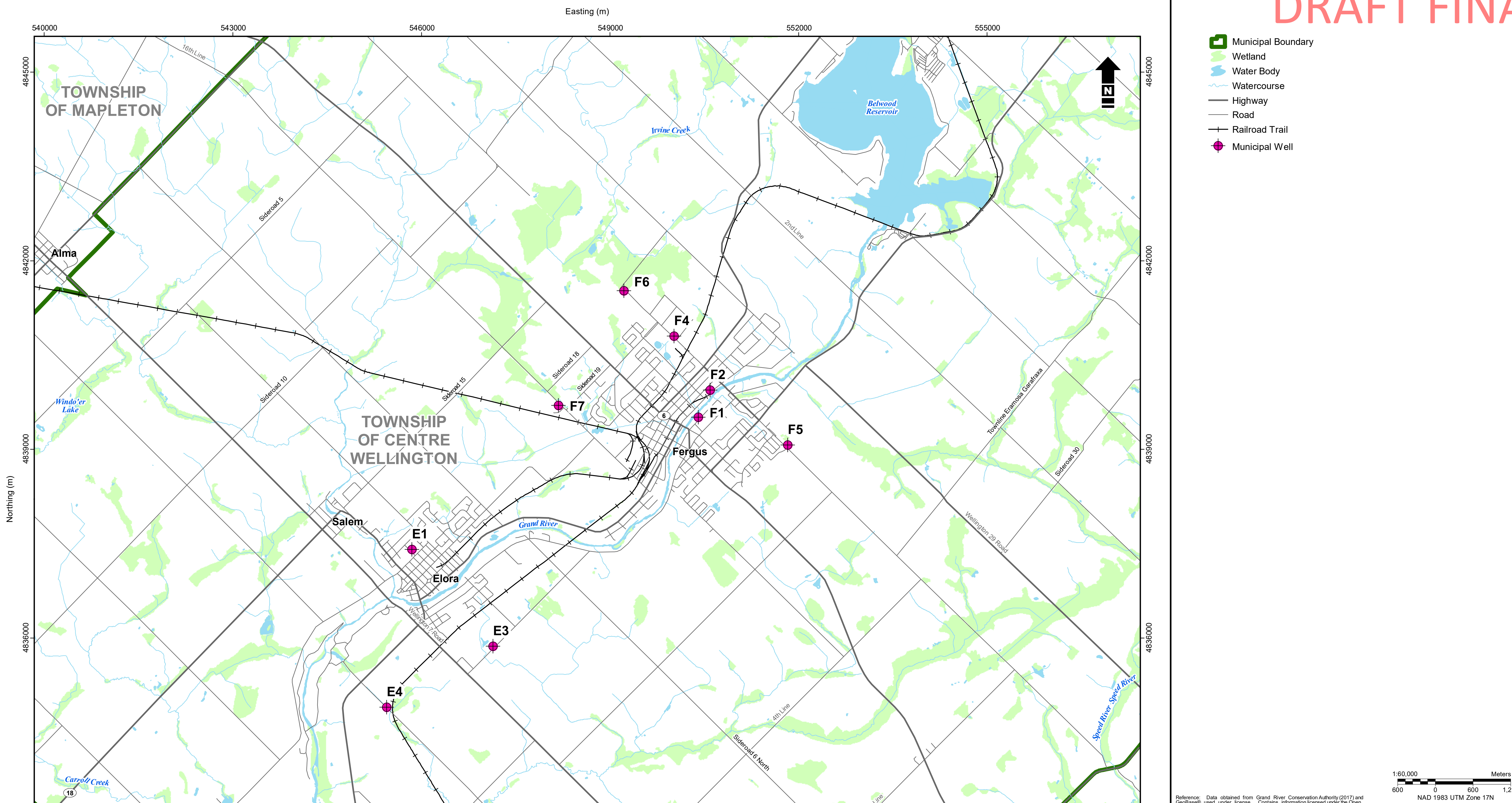

Reference: Data obtained from Grand River Conservation Authority (2017) and GeoBase® used under license. Contains information licensed under the Open Government Licence – Ontario.

Matrix Solutions Inc.
ENVIRONMENT & ENGINEERING

Grand River Conservation Authority
Township of Center Wellington Municipal Water Supply Climate Change Assessment

Tier Three Assessment Municipal Water Supply Wells

Date:	Project:	Submitter:	Reviewer:
December 2019	23876	J. Melchin	D. Van Vliet

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Figure 1

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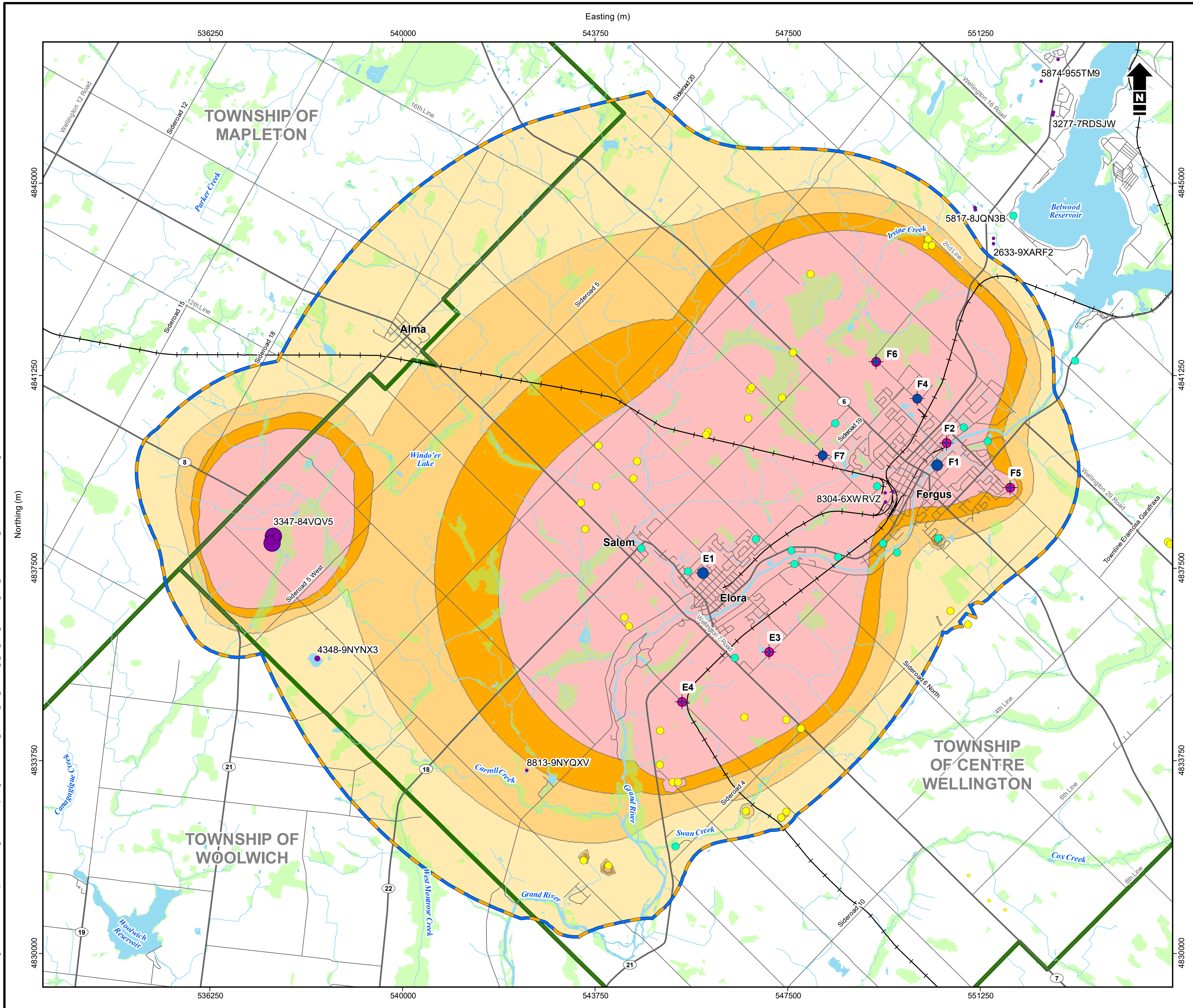

WHPA-Q1/WHPA-Q2/Groundwater Vulnerable Area
Municipal Boundary
Wetland
Water Body
Watercourse
Highway
Road
Railroad Trail
Municipal Well

Drawdown (m)

2 - 3
3 - 4
4 - 5
> 5

Simulated Municipal and Non-municipal Demands

Type

Municipal PTTW
Non-Permitted Agriculture
Non-Municipal PTTW
Well Representing a Cluster of Domestic Wells

Average Annual Consumptive Rate (m^3/day)

< 250
250 - 500
500 - 750
750 - 1000
1000 - 1250
1250 - 1500
1500 - 1750
> 1750

Note: the Risk Level assignment to the Groundwater Vulnerable Area does not imply that an individual groundwater taking or recharge reduction activity within that area will threaten the reliability of the municipal water supply.

1:75,000 metres
750 0 750 1,500
NAD 1983 UTM Zone 17N

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Grand River Conservation Authority
Township of Center Wellington Municipal Water Supply Climate Change Assessment

Groundwater Vulnerable Area Delineated in Tier Three Assessment (Matrix 2020)

Date:	Project:	Submitter:	Reviewer:
December 2019	23876	J. Melchin	D. Van Vliet

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Figure 2

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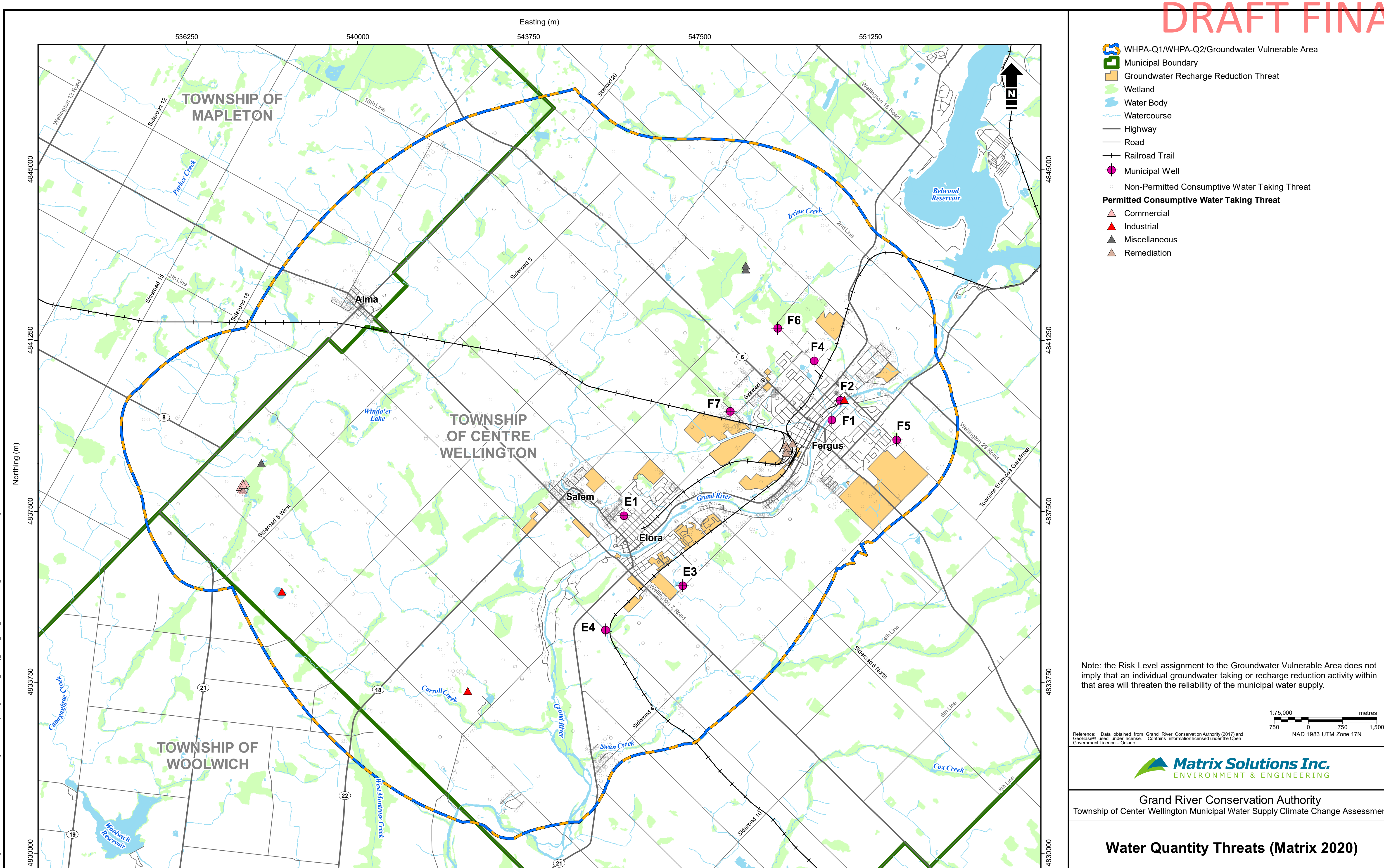

Grand River Conservation Authority

Township of Center Wellington Municipal Water Supply Climate Change Assessment

Water Quantity Threats (Matrix 2020)

Date:	Project:	Submitter:	Reviewer:
December 2019	23876	J. Melchin	D. Van Vliet

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Figure 3

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APPENDIX A

Grand River Conservation Authority (GRCA) Climate Change Analysis

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Report

Grand River Conservation Authority (GRCA)

Climate Change Analysis

Prepared for:
Matrix Solutions Inc

March 16 2016

55 Metcalfe Street, Suite 700 | Ottawa, ON K1P 6L5 | CANADA | Tel: 613.260.1424 | Fax: 613.260.1443

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Two Attached Spreadsheet Document with this report

1. Requirements and Deliverables

Risk Sciences International (RSI) is providing the climatology and climate change analyses for this study using quality controlled and peer reviewed climate change model outputs from the RSI climate analytical system. Inclusion of the most recent 2013 AR5 climate change model results will help in providing an up-to-date assessment of watershed vulnerabilities to guide planning for a more robust and resilient water resource system into the future.

The climate deliverables for this project require baseline climate and climate change differences (deltas) representative of the central portion of the GRCA sub-watershed for the 2050s, along with background and documentation of the approach taken.

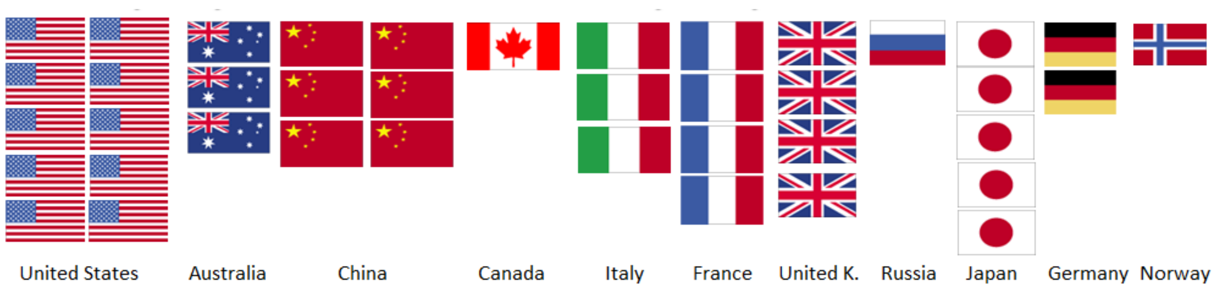
This work has been enabled through analyses of the 2013 IPCC released climate change models (40 AR5 GCMs), which have undergone additional quality control, and are archived in the RSI analytical system. The analyses also include at least one RCM output for comparison to the selected ensemble of Global Climate Models (GCMs). Key elements of the report include:

- Summary of output from each of the 2013 AR5 GCMs, represented as the mean annual change in temperature and precipitation
- From the entire set of models, rankings with respect to mean annual temperature and precipitation, and indications of the 5th, 25th, 50th, 75th and 95th percentile projections for each of these parameters;
- For each of the selected GCMs (5X2 = 10), provide the monthly changes in temperature and precipitation from the most recent observed and/or interpolated baseline or Normals period (e.g. 1981-2010 or a different period, as appropriate) to the 2050s period.
- Output from at least one of the RCMs, which may be included within or additional to the selected GCMs
- Baseline climate data as well as the future projected climate fields annually and monthly.

2. Climate Change Background

Climate change is defined as the longer-term change in atmospheric conditions of temperature, precipitation, etc., whether by natural or human-generated sources. It can affect both average conditions and extreme events. Climate change has occurred over all of Earth's history resulting in both warmer and cooler periods of various lengths. The current climate change discussion has focused on the most recent 100 years or so where a gradual and accelerated increase in global temperature has been observed, with regional differences, including the Grand River Conservation Authority territory. This global increase has been attributed predominantly to human-influence arising from the burning of fossil fuels which adds to the atmospheric concentration of greenhouse gases (predominantly carbon dioxide and methane). Global mean temperature has increased 0.85°C from 1880 to 2012 (IPCC,2013), whereas within Canada the temperature has increased by 1.6°C since 1948 to 2013 – much higher than the global average, with the greatest increase found in the far north (Gov. Canada,2015). The observed change is completely consistent with modelled climate output.

The Intergovernmental Panel on Climate Change (IPCC) is considered the most robust source of climate change science guidance, since it consists of thousands of contributing scientists from across the globe. The IPCC reports continue to provide the best science-based information on projected climate change assembled from the best climate researchers worldwide. Since the second IPCC Assessment released in 1995, the number of contributing international climate modelling centres, models, and their complexity, have increased significantly – from 11 models to the current 40 used in the most recent AR5 Assessment as shown below (RSI graphic).



With increased computing power, better refinement of atmospheric phenomena have been incorporated, and model spatial and temporal resolution has improved (Kharin et al. 2013). The development of regional climate models (even higher resolution) continues, although there are far fewer of these than global climate models. An important outcome of this increase in model availability is the ability to produce projections of future climate based upon an 'ensemble' of many models versus the use of single or only a few models. The use of multiple models to generate a 'best estimate' of climate change is preferred over a single model outcome and this approach is recommended by the IPCC. Research has indicated that the use of multi-model

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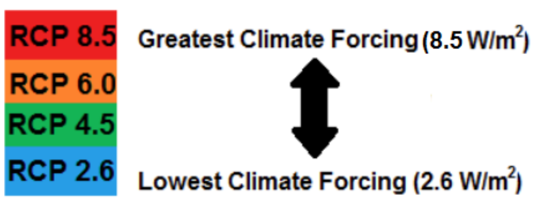
ensembles is preferable to the selection of a single or few individual models since each model can contain inherent biases and weaknesses (IPCC-TGICA, 2007, Tebaldi and Knutti, 2007). The use of the ensemble projection from the family of global modelling centres (40 models and dozens of estimates) is likely the most reliable estimate of climate change projections on a large scale (Gleckler et al, 2008). Environment Canada contributes to this IPCC ensemble with its own developed model (CanESM2). This RSI report considers all models and model runs available for the most recent assessment (AR5).

A new initiative in the IPCC AR5 is the introduction of RCPs (Representative Concentration Pathways). They represent a range of possible projection outcomes which depend upon different degrees of atmospheric warming. The lowest RCP 2.6, represents an increase of 2.6 W/m^2 to the system, while the highest RCP 8.5 represents an increase of 8.5 W/m^2 of energy. This range encompasses the best estimate of what is possible under a small perturbation situation (2.6) and under a large increase in warming (8.5). It is unknown which of the RCPs will apply in the future. However, it is important to note that historically, the GHG emissions have followed the highest (8.5) pathway (see chart below). Of course the magnitude of future climate change is greatly influenced by the forcing scenario selected.



With each subsequent IPCC Assessment report, the evidence of climate change builds and increasingly points towards greater confidence that human-kind is having and will continue to influence our future climate, from warming, to extreme events, to sea-level rise to melting sea-ice. Confidence wording in the IPCC documents are characterized by the use of specific terms such as ‘very likely’ or ‘virtually certain’, where in previous reports changes may have been referred to as ‘likely’. There has been a gradual increase in confidence of the projections from climate models over time. Some of the main points from the most recent IPCC AR5 report (IPCC, 2013) are identified below:

- Warming of the climate system is **unequivocal**, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased.

- Over the last two decades, the Greenland and Antarctic ice sheets have been losing mass, glaciers have continued to shrink almost worldwide, and Arctic sea ice and Northern Hemisphere spring snow cover have continued to decrease in extent.

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- The atmospheric concentrations of carbon dioxide (CO_2), methane, and nitrous oxide have increased to levels unprecedented in at least the last 800,000 years.

- Human influence on the climate system is clear. This is evident from the increasing greenhouse gas concentrations in the atmosphere, positive radiative forcing, observed warming, and understanding of the climate system.

- Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes. This evidence for human influence has grown since AR4. It is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-20th century.

- Observational and model studies of temperature change, climate feedbacks and changes in the Earth's energy budget together provide confidence in the magnitude of global warming in response to past and future forcing.

- Climate models have improved since the AR4. Models reproduce observed continental-scale surface temperature patterns and trends over many decades, including the more rapid warming since the mid-20th century and the cooling immediately following large volcanic eruptions.

- Global surface temperature change for the end of the 21st century is *likely* to exceed 1.5°C relative to 1850 to 1900 for all RCP scenarios except RCP2.6. It is *likely* to exceed 2°C for RCP6.0 and RCP8.5, and *more likely than not* to exceed 2°C for RCP4.5. Warming will continue beyond 2100 under all RCP scenarios except RCP2.6. Warming will continue to exhibit interannual-to-decadal variability and will not be regionally uniform.

- Changes in the global water cycle in response to the warming over the 21st century will not be uniform. The contrast in precipitation between wet and dry regions and between wet and dry seasons will increase, although there may be regional exceptions.

- Continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system. Limiting climate change will require substantial and sustained reductions of greenhouse gas emissions.

Among the most recent IPCC reports was the addition of a separate document on climate extremes, the IPCC SREX document (IPCC-SREX, 2012). In addition to changes in the mean climate, extreme climate events will also be impacted, and in many cases the changes in the extremes are expected to be greater than the changes in the mean.

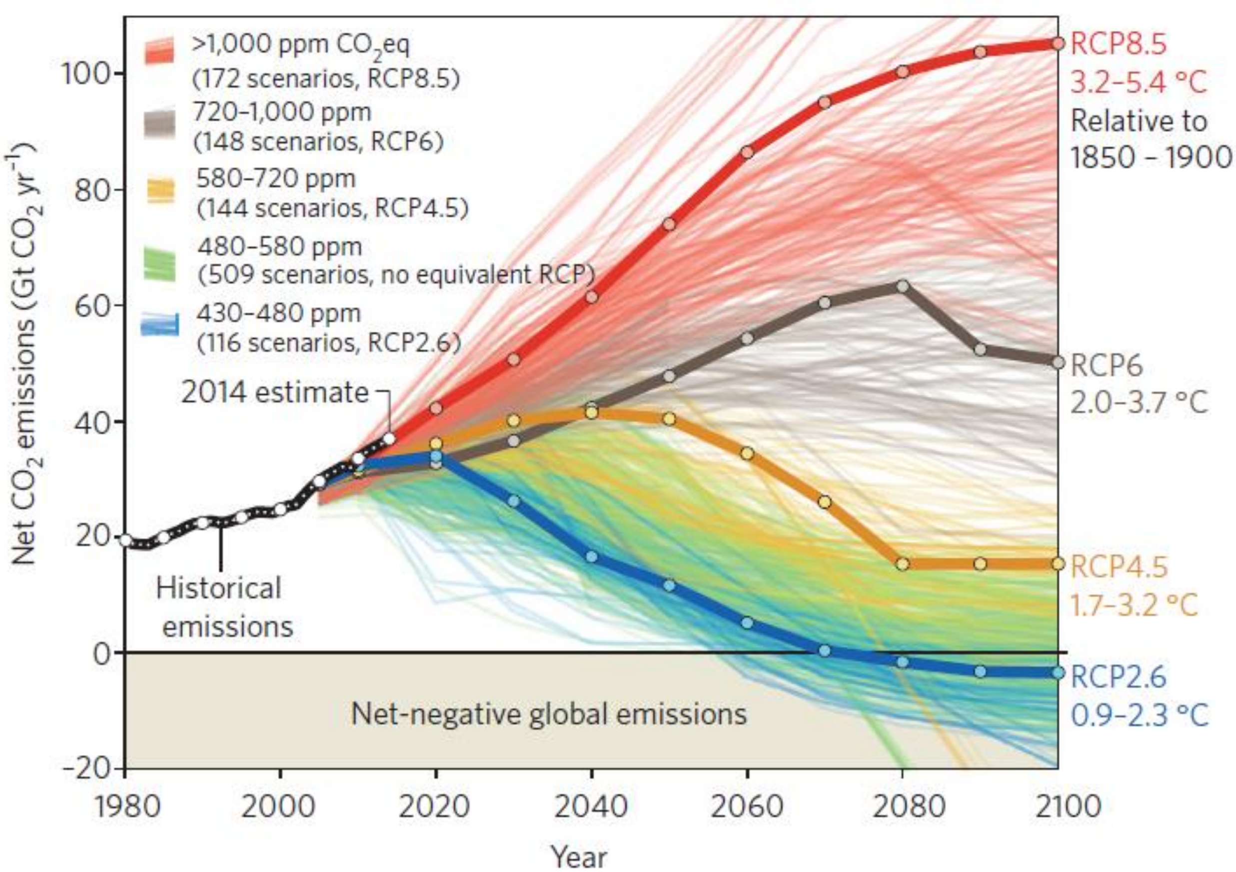
Of particular interest are the following conclusions from the extremes report (IPCC-SREX, 2012):

- It is *virtually certain* that increases in the frequency and magnitude of warm daily temperature extremes and decreases in cold extremes will occur in the 21st century at the global scale.
- It is *very likely* that the length, frequency, and/or intensity of warm spells or heat waves will increase over most land areas.
- It is likely that the frequency of heavy precipitation or the proportion of total rainfall from heavy falls will increase in the 21st century over many areas of the globe.
- Extreme events will have greater impacts on sectors with closer links to climate, such as water, agriculture and food security, forestry, health, and tourism.
- Attribution of single extreme events to anthropogenic climate change is challenging.

3. Projections of Future Climate

3.1. Mean Climate Change

Projected climatic change over Canada can be shown by using the assemblage of all models that contributed to the last IPCC assessment, with data available through the IPCC data portal. In Canada, the greatest temperature increases are expected north of 60 degrees latitude, where by the 2050s period (2041-2070), the average annual temperature is projected to be up to 5 degrees warmer than current conditions according to the current-trajectory RCP8.5 forcing pathway. In the GRCA, projected annual change is smaller but still significant under the projections. The RCP8.5 projections are shown below for Canada. The other RCPs show smaller changes than those presented, but again, seem less likely given the current emissions trajectory. SO although there are multiple RCPs, for this report, only the RCP8.5 trajectory is considered since this the pathway historically followed as seen below, up to 2014. Even with an immediate agreement on GHG reduction globally or even an immediate cut to zero GHG emissions, warming is already committed due to the long residence time of these gases (Figure from Fuss, 2014).



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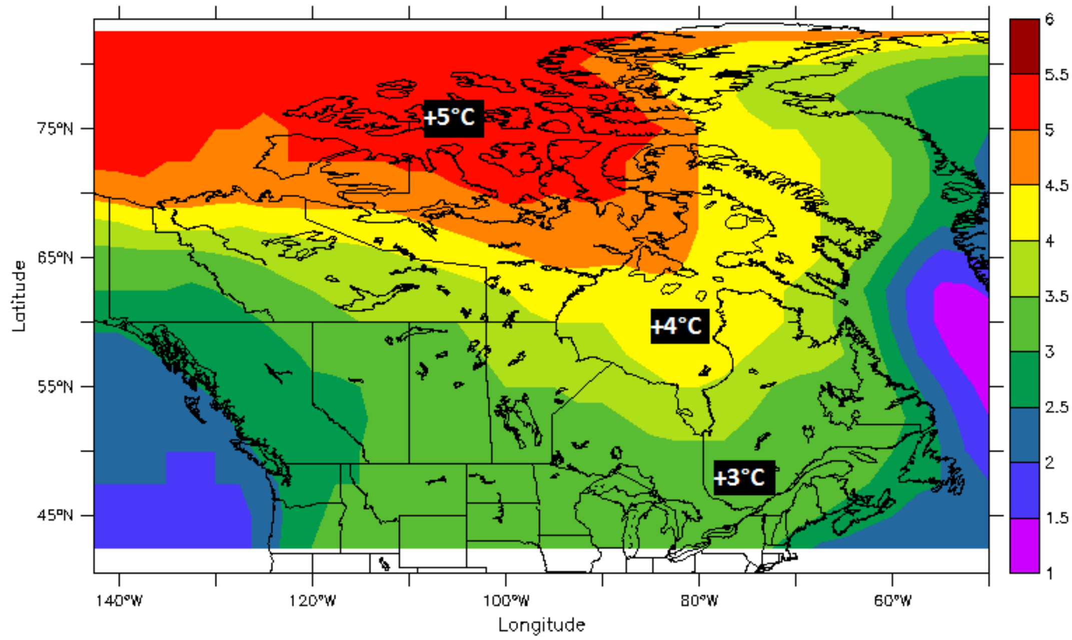
IPCC AR5 Model Ensemble Mean Annual Temperature Change in 2050s (from 1981-2010 baseline) -RCP8.5 Projection



Similarly, average ensemble projections of precipitation change over the same period and RCP is shown below. Again, the greatest percentage change in annual precipitation is envisioned in Canadas Arctic region, with increases of up to 35% from current levels. In the GRCA area, annual precipitation changes from the ensemble of models is near 5%, but this mean change does not consider reflect the nature of seasonality or extreme precipitation.

These are mean annual changes, and it is important to note that there are seasonal differences in the changes shown, with some seasons showing greater change than others. These seasonal changes can have profound effects on water supply and availability through both precipitation input and evapotranspiration changes (the water balance between input and output).

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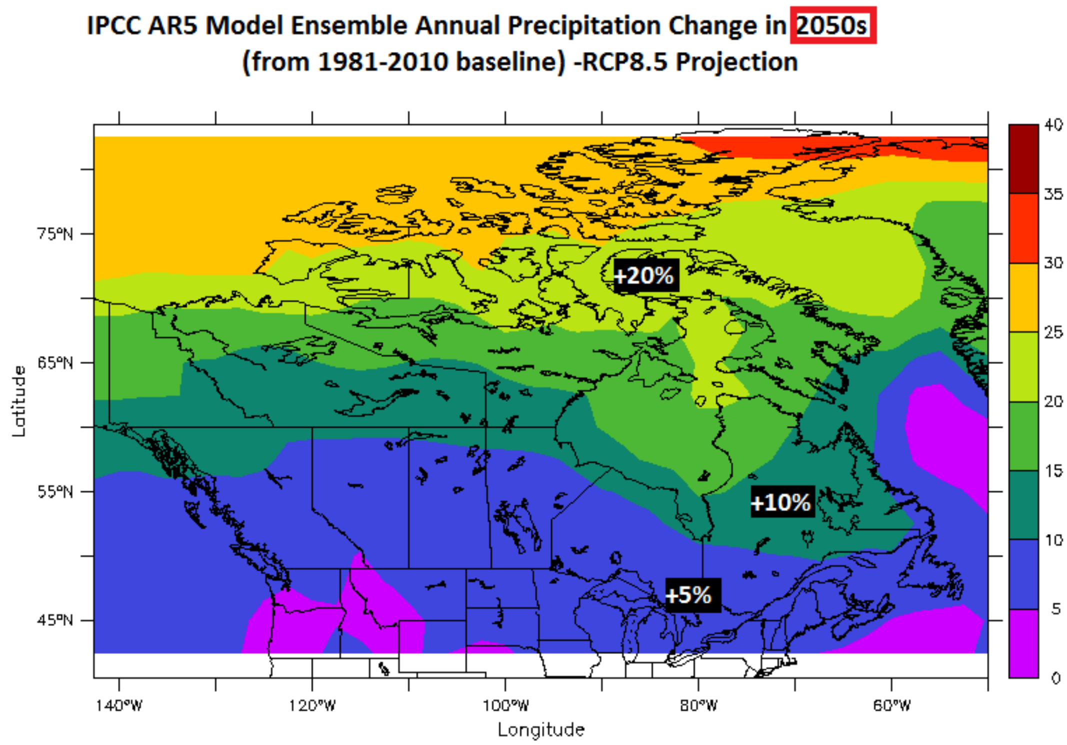


3.2. Changes in Extreme Precipitation

Changes in extremes of precipitation such as single-day rainfall and rainfall intensities (mm/h) are expected to be even greater than the mean changes shown here, and indeed in the south high-intensity rainfall events have been seen recently, although there is not yet any statistically significant trend in these short-term events (Shephard, 2014). This could simply be due to the short record length of monitoring rainfall intensities through the Environment Canada Intensity-Duration-Frequency observation network of tipping bucket rain-gauges.

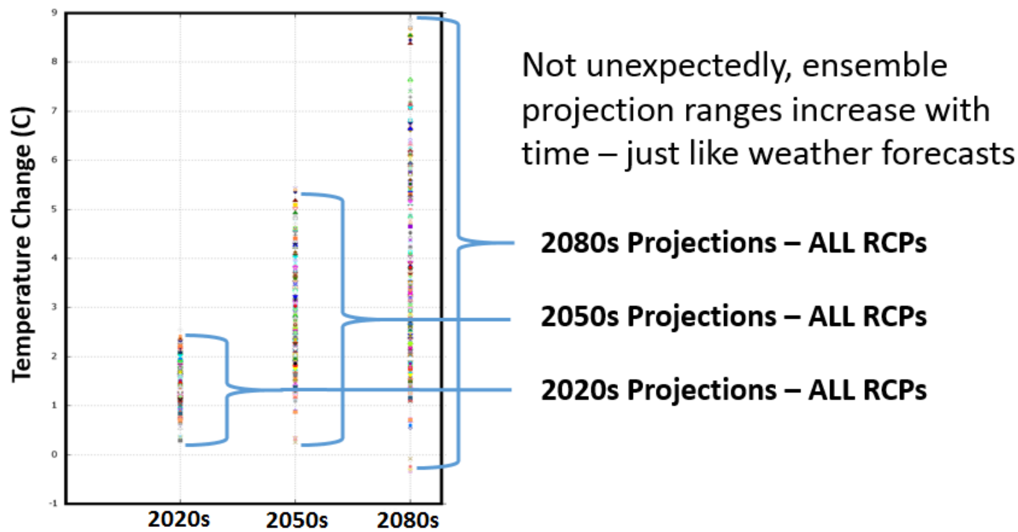
Future projections indicate that extremes will increase going forward with extreme event occurrence becoming twice as frequent as they are currently. This means an extreme event which occurred on average every 50 years would be expected every 25, and a 1 in 100 year event would occur on average every 50 years.

3.3. Uncertainty

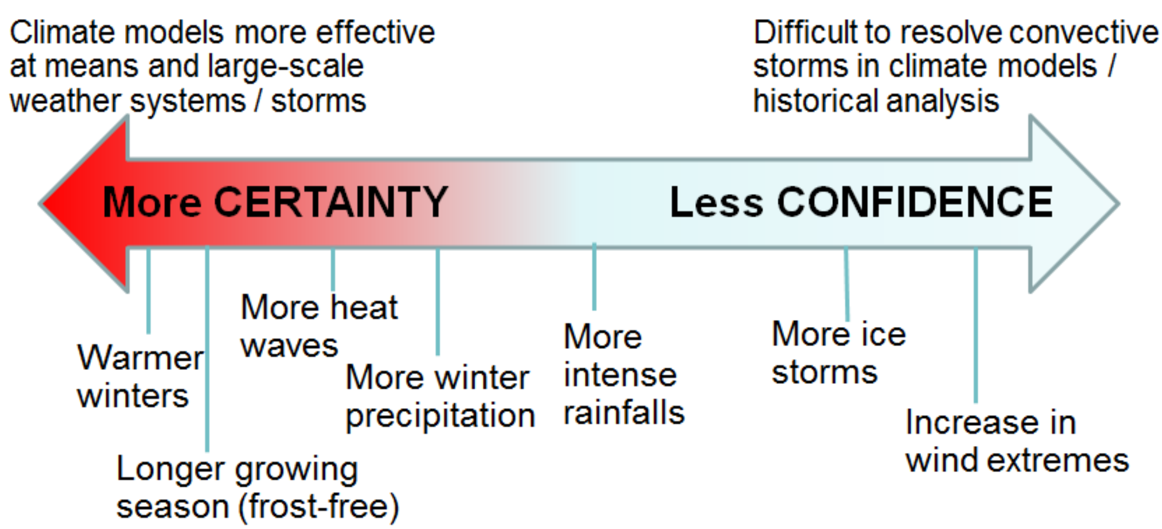
Although single extreme events are difficult to attribute directly to climate change, studies have shown that temperature-related events (heat waves) are very likely linked to changing climate.

Precipitation related extremes are more difficult to directly link, but these types of events are consistent with model projections going forward (Herring, et al, 2015).

Beyond the 2050s, these changes are projected to increase even more – although uncertainty from the models also increases going forward for all variables. This graphic shows the increase in model projected outcomes for temperature for all RCP options combined (RSI graphic).



Different model output projections have varying levels of uncertainty – for example, model projected temperature changes are more certain than precipitation or wind. A proxy measure of this uncertainty is the range of model projected values – where the projection range between models is smaller, there is expected to be greater confidence in the value, whereas when model projections are highly variable, confidence in that parameter is lessened. Some relative confidence in model projected variables is shown below (RSI graphic).



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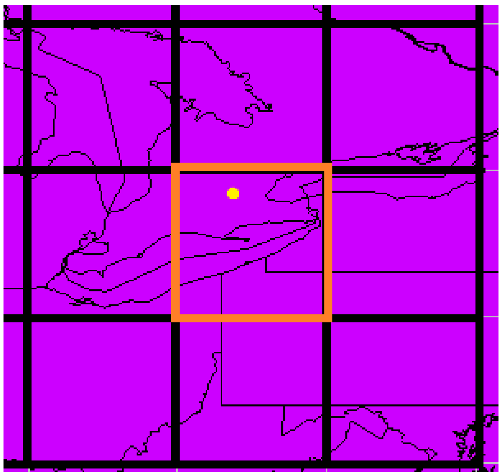
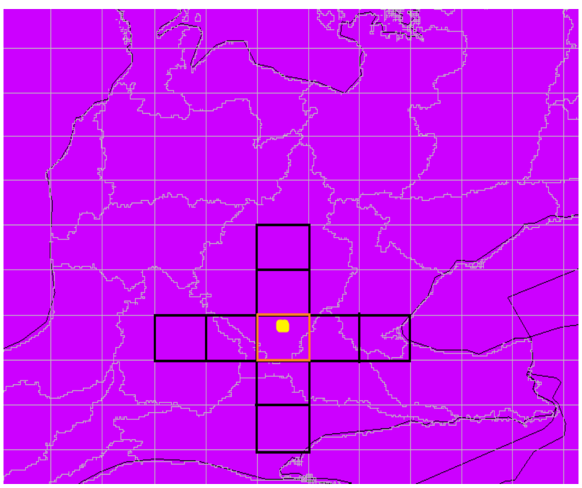
3.4. Procedure

The remainder of this report considers an investigation of climate change projections for the GRCA territory as assessed from the ensemble of AR5 GCM models. RSI has regridded all the GCM projection models used in this report to a common grid size as shown (approximately 150 x 150 km). In addition to this analysis of GCMs, time series data for the Canadian Regional Climate Model for this location is provided separately in its original resolution.



Map showing location of GCM grid cell considered for this report (highlighted) and the location of W-W-Airport



Map showing location of the RCM (CanRCM4 -25km) grid cell from which projections will be obtained (highlighted) and the location of W-W-Airport

From all of the GCM temperature and precipitation changes (deltas) between the baseline (1981-2010) and future period (2050s), summary statistics are provided. Based upon the deltas, the 5 models closest to the entire ensemble 5th, 25th, 50th, 75th and 95th percentiles for annual temperature and the 5 models closest to the entire ensemble 5th, 25th, 50th, 75th and 95th percentiles for precipitation are then used to provide monthly change fields for further hydrological model analysis (10 model outputs). This information is included on the attached spreadsheet.

4. Climate Model Ensemble Change and Individual Model Selection

Climate is simply defined as 'long-term weather'. It is the average weather conditions for a long enough period to average out natural fluctuations. The typical climatological normal period (or 'Normal') is considered by convention to be 30 years. The most recent climate normal period is 1981-2010. The future projection period considered for this report is the 2050s (2041-2070). The 'change' or 'delta' then represents the difference in temperature and precipitation between these 2 periods.

Using a 'delta' technique, the actual historical values of the models aren't used, since we only consider the CHANGE between the historical period and the future period of interest. It is this CHANGE or DELTA, which can then added to the real observations to obtain the future estimates or for input into a hydrological model. In this way, any model bias from historical observations is removed and only the signal is used. Other more complex techniques including statistical downscaling may be employed, but generally this process requires considerable expertise and customized input datasets which are not available for all models.

Comparison of Model 'DELTA' Values for Annual Temperature (top) and Annual Precipitation (bottom) from the entire Ensemble of GCMs (baseline 1981-2010, future period 2050s).

TOTAL ENSEMBLE STATISTICS FOR TEMPERATURE DELTA

(in degrees C change)	5th Perc	2.20728
	25th Perc	2.8146
	50th Perc	3.1347
	75th Perc	3.6101
	95th Perc	4.34302

TOTAL ENSEMBLE STATISTICS FOR PRECIPITATION DELTA

(in percent change)	5th Perc	-0.03356
	25th Perc	4.1196
	50th Perc	6.6161
	75th Perc	9.616
	95th Perc	13.25266

Models Obtained Most Closely Matching the Percentiles above:

Temperature:

FIO-ESM(Run 1)	RCP8.5	2.2328	(APPROX - 5TH PERCENTILE)
CCSM4(Run 1)	RCP8.5	2.8164	(APPROX - 25TH PERCENTILE)
CSIRO-Mk3-6-0(Run 10)	RCP8.5	3.1355	(APPROX - 50TH PERCENTILE)
CESM1-CAM5(Run 2)	RCP8.5	3.6101	(APPROX - 75TH PERCENTILE)
MIROC-ESM(Run 1)	RCP8.5	4.3289	(APPROX - 95TH PERCENTILE)

Precipitation:

IPSL-CM5A-MR(Run 1)	RCP8.5	0.0794	(APPROX - 5TH PERCENTILE)
CNRM-CM5(Run 1)	RCP8.5	4.1196	(APPROX - 25TH PERCENTILE)
NorESM1-M(Run 1)	RCP8.5	6.6161	(APPROX - 50TH PERCENTILE)
ACCESS1-3(Run 1)	RCP8.5	9.616	(APPROX - 75TH PERCENTILE)
CMCC-CESM(Run 1)	RCP8.5	12.8213	(APPROX - 95TH PERCENTILE)

5. Climate Model Projection Results for the 2050s period (years 2041-2070)

The detailed projection results for temperature and precipitation for the selected 10 models above, and the Canadian regional model (CanRCM4 at both 25 km resolution), are provided in the attached excel spreadsheets.

6. Conclusions

RSI has provided in this report and accompanying spreadsheet a comprehensive survey of projected temperature and precipitation projections from a baseline condition of 1981-2010 for the 2050s, as indicated by the full AR5 model ensemble. From this ranking, the 5 models for temperature and precipitation for the percentile values required are further investigated. From the resulting 10 models, monthly deltas for both temperature and precipitation are provided for the grid cell representing the K-W Airport location.

Projected monthly deltas from the Canadian RCM (CanRCM4) at 25km are provided in a separate spreadsheet for the grid cell representing the K-W Airport location.

Background data on the models used for the study and emissions assumptions, the reason behind the selection of the single RCP8.5 here, best practices for model ensembles and the delta technique employed here are described. Given a suitable baseline historical climatology of temperature and precipitation, the monthly changes provided here could be used to adjust the historical dataset to provide future projected datasets using whichever percentile adjustment might be of interest. This could range from a 'low' estimate of the 5^{th} percentile of the model ensemble, through to the 'extreme' estimate of the 95^{th} percentile of all models.

It should be noted however, that extremes of both temperature and precipitation are projected to increase a greater amount than simple monthly means. So if anything the current projections of mean change are most likely conservative. In fact, extreme precipitation events for southern Ontario under a warmer, more vigorous water cycle with greater convection is expected to produce larger short-duration precipitation events beyond that shown here. Certainly the values presented are representative of longer (monthly) expected change, but shorter duration (day or hourly events), are expected to increase even more. Further analysis of precipitation extremes is an ongoing, unresolved research area in climate change with a large degree of uncertainty.

Although extreme events may be increasing there is reasonable expectation from the ensemble that summertime precipitation totals will remain steady or perhaps even decrease for the GRCA area. Combined with warmer summer temperatures and higher evaporation, with longer dry periods between more extreme events, this could produce a larger challenge for water management in that season.

Appendix ONE:
All IPCC AR5 (Fifth Assessment) Models, Organizations and Country of Origin:

Model Name	Organization	Country	Organization Details
ACCESS1-0	CSIRO-BOM	Australia	CSIRO (Commonwealth Scientific and Industrial Research Organisation, Australia), and BOM (Bureau of Meteorology, Australia)
ACCESS1-3	CSIRO-BOM	Australia	CSIRO (Commonwealth Scientific and Industrial Research Organisation, Australia), and BOM (Bureau of Meteorology, Australia)
BCC-CSM1-1	BCC	China	Beijing Climate Center, China Meteorological Administration
BCC-CSM1-1-M	BCC	China	Beijing Climate Center, China Meteorological Administration
BNU-ESM	GCESS	China	College of Global Change and Earth System Science, Beijing Normal University
CanESM2	CCCma	Canada	Canadian Centre for Climate Modelling and Analysis
CCSM4	NCAR	US	National Center for Atmospheric Research
CESM1-BGC	NSF-DOE-NCAR	US	National Science Foundation, Department of Energy, National Center for Atmospheric Research
CESM1-CAM5	NSF-DOE-NCAR	US	National Science Foundation, Department of Energy, National Center for Atmospheric Research
CMCC-CESM	CMCC	Italy	Centro Euro-Mediterraneo per I Cambiamenti Climatici
CMCC-CM	CMCC	Italy	Centro Euro-Mediterraneo per I Cambiamenti Climatici
CMCC-CMS	CMCC	Italy	Centro Euro-Mediterraneo per I Cambiamenti Climatici
CNRM-CM5	CNRM-CERFACS	France	Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique
CSIRO-Mk3-6-0	CSIRO-QCCCE	Australia	Commonwealth Scientific and Industrial Research Organisation in collaboration with the Queensland Climate Change Centre of Excellence
FGOALS-g2	LASG-IAP	China	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences
FGOALS-s2	LASG-IAP	China	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences
FIO-ESM	FIO	China	The First Institute of Oceanography, SOA, China

GFDL-CM3	NOAA GFDL	US	Geophysical Fluid Dynamics Laboratory
GFDL-ESM2G	NOAA GFDL	US	Geophysical Fluid Dynamics Laboratory
GFDL-ESM2M	NOAA GFDL	US	Geophysical Fluid Dynamics Laboratory
GISS-E2-H	NASA GISS	US	NASA Goddard Institute for Space Studies
GISS-E2-H-CC	NASA GISS	US	NASA Goddard Institute for Space Studies
GISS-E2-R	NASA GISS	US	NASA Goddard Institute for Space Studies
GISS-E2-R-CC	NASA GISS	US	NASA Goddard Institute for Space Studies
HadCM3	MOHC	UK	MetOffice Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)
HadGEM2-AO	MOHC	UK	MetOffice Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)
HadGEM2-CC	MOHC	UK	MetOffice Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)
HadGEM2-ES	MOHC	UK	MetOffice Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)
INMCM4	INM	Russia	Institute for Numerical Mathematics
IPSL-CM5A-LR	IPSL	France	Institut Pierre-Simon Laplace
IPSL-CM5A-MR	IPSL	France	Institut Pierre-Simon Laplace
IPSL-CM5B-LR	IPSL	France	Institut Pierre-Simon Laplace
MIROC-ESM	MIROC	Japan	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
MIROC-ESM-CHEM	MIROC	Japan	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
MIROC4h	MIROC	Japan	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology
MIROC5	MIROC	Japan	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for

			Environmental Studies, and Japan Agency for Marine-Earth Science and Technology
MPI-ESM-LR	MPI-M	Germany	Max Planck Institute for Meteorology (MPI-M)
MPI-ESM-MR	MPI-M	Germany	Max Planck Institute for Meteorology (MPI-M)
MRI-CGCM3	MRI	Japan	Meteorological Research Institute
NorESM1-M	NCC	Norway	Norwegian Climate Centre
NorESM1-ME	NCC	Norway	Norwegian Climate Centre

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APPENDIX B
Monthly Change Fields for Selected Global Climate Models

APPENDIX B

MONTHLY CHANGE FIELDS FOR SELECTED GLOBAL CLIMATE MODELS

1 INTRODUCTION

A detailed review of the existing climate data sets considered for this climate change assessment (i.e., 40 global climate change models) was completed by Risk Sciences International (RSI; 2016) and a summary document is provided in Appendix A. A subset of 10 global climate model datasets was selected through assessment of the change in mean annual temperature and precipitation between baseline (i.e., 1981 to 2010) and the 2050s future period (i.e., 2041 to 2070). Each global climate model was ranked and the 5th, 25th, 50th, 75th, and 95th percentile projections for temperature and precipitation were selected. RSI (2016; Appendix A) provide detailed descriptions of the parameters and methods used to develop them.

Tables B1 and B2 summarize these percentile projections.

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TABLE B1 Monthly Change Fields for Global Climate Models Selected from Temperature Percentile

Temperature Percentile	Model Monthly Deltas (between baseline and 2050s)												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
5th	FIO-ESM (Run 1)												
	mean temperature change (°C)	2.98	2	2.49	1.86	1.84	1.98	2.17	2.27	1.56	1.72	2.87	3.38
	precipitation change (%)	-4.22	-3.8	30.03	14.69	1.28	-8.85	-10.57	-10.2	-4.12	1.83	-3.45	-9.66
25th	CCSM4 (Run 1)												
	mean temperature change (°C)	3.22	3.78	2.67	2.41	2.22	2.22	3.25	2.97	2.4	1.99	2.84	3.88
	precipitation change (%)	19.82	21.65	23.18	-1.87	-11.61	-4.2	-11.9	-3.25	-2.87	-0.57	-15.3	23.44
50th	CSIRO-Mk3-6-0 (Run 10)												
	mean temperature change (°C)	3.3	4.11	1.96	2.93	3.82	4.08	3.68	4.24	1.72	2.92	2.41	2.77
	precipitation change (%)	-0.97	30.11	32.59	16.18	19.36	-12.27	1.98	39.74	15.13	-6.28	-3.21	-7.28
75th	CESM1-CAM5 (Run 2)												
	mean temperature change (°C)	5.06	7.35	4.15	2.52	2.42	2.73	3.33	3.35	3.24	2.9	2.05	4.52
	precipitation change (%)	16.55	9.22	35.27	6.7	15.69	12.5	21.87	6.74	-5.33	3.5	3.23	16.9
95th	MIROC-ESM (Run 1)												
	mean temperature change (°C)	5.45	6.66	7.31	4.08	3.37	3.29	3.77	3.68	3.31	3.31	3.89	3.81
	precipitation change (%)	-5.93	20.23	22.47	29.06	14.79	-10.13	-4.04	-0.05	4.2	-7.44	7.72	15.48

*annual average may not exactly match monthly average due to rounding and regridding process

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TABLE B2 Monthly Change Fields for Global Climate Models Selected from Precipitation Percentile

Precipitation Percentile	MODEL MONTHLY DELTAS (between baseline and 2050s)												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
5th	IPSL-CM5A-MR (Run 1)												
	mean temperature change (°C)	2.32	2.65	2.71	2.69	2.88	3.16	3.4	3.49	4.08	3.35	3.05	2.3
	precipitation change (%)	3.71	0.16	18.77	16.08	12.31	-1.32	-19.99	-0.01	-3.45	1.1	-12.75	-12.22
25th	CNRM-CM5 (Run 1)												
	mean temperature change (°C)	4.6	3.49	3.39	2.14	2.67	2.52	2.7	3.61	3.51	2.84	2.08	3.84
	precipitation change (%)	-4.92	14.91	0.01	19.69	10.84	-1.5	-5.73	-0.48	-6.66	11.87	3.15	16.91
50th	NorESM1-M (Run 1)												
	mean temperature change (°C)	3.99	4.28	2.12	2.06	2.97	2.84	3.37	3.23	2.86	2.67	2.38	4.49
	precipitation change (%)	3.52	2.39	26.58	6.82	9.42	-8.61	14.09	11.76	-6.05	8.19	-5.61	27.97
75th	ACCESS1-3 (Run 1)												
	mean temperature change (°C)	3.22	3.06	3.84	2.63	2.68	2.45	3.08	3.43	2.95	4.44	3.32	4.15
	precipitation change (%)	20.97	15.61	12.2	4.43	18.91	4.54	-0.67	-1.23	-0.87	16.31	10.71	22.1
95th	CMCC-CESM (Run 1)												
	mean temperature change (°C)	3.52	2.9	3.32	3.79	2.21	2.92	2.44	2.32	2.92	2.51	2.15	3.23
	precipitation change (%)	18.89	18.58	25.31	30.84	11.82	3.7	4.37	6.25	7.92	11.58	15.12	11.51

*annual average may not exactly match monthly average due to rounding and regridding process

2 REFERENCES

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