Stantec

Assiniboine River Basin Hydrologic Model – Climate Change Assessment

Prepared for:

Manitoba Conservation
Climate Change Branch

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Partner Organizations

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Executive Summary

Goal and Objectives

Development of a Manitoba climate change adaptation strategy is a priority, where it is anticipated future droughts and floods will have increased impacts in river basins across Manitoba. The goal is to use this and other Prairies Regional Adaptation Collaborative (PRAC) Manitoba studies to assist in developing a climate change adaptation strategy for province.

The objective of this PRAC Manitoba study is to model the hydrologic aspects of climate change over the 21st century, i.e., to assess the potential effects of climate change on stream flow (for water supply, aquatic biota) and soil moisture (for agricultural production).

Study Area and Time Periods

The study area is the Assiniboine River basin (ARB), located in North Dakota, Saskatchewan, and Manitoba is shown on Figure E-1. The Assiniboine River basin consists of three distinct sub-basins; the Souris River Sub-basin, the Qu'Appelle River Sub-basin, and the Assiniboine River Sub-basin.

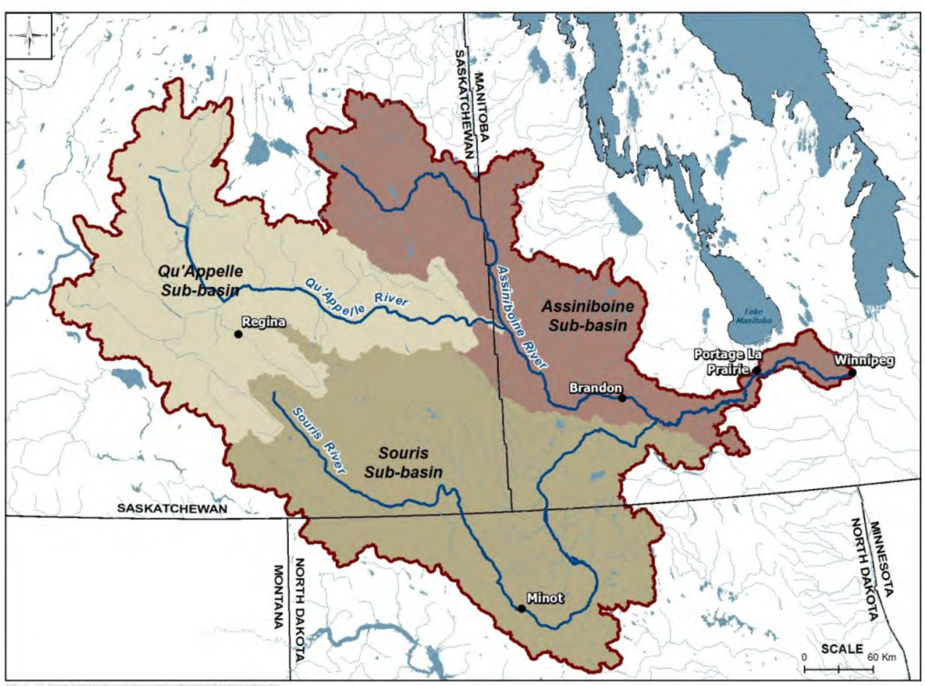

Figure E-1: Assiniboine River Basin

Three future time periods were modelled to compare historical data. The three future time periods are early 21st century (2011-2040), middle 21st century (2041-2070) and late 21st century (2071-2099).

Hydrologic Model

The Danish Hydrologic Institute (DHI) MIKE-SHE computer model was used to generate modelled historical stream flow and soil moisture data (using historical meteorological inputs) and to generate modelled future stream flow and soil moisture (using regional climate model generated meteorological inputs) for comparison purposes.

The MIKE-SHE hydrologic model was constructed using inputs for topography, precipitation, temperature, storage, surface roughness, soil hydraulic conductivity, and soil field capacity. MIKE-SHE outputs selected for comparison purposes are soil moisture and stream flow.

Hydrologic Model Calibration and Verification

Calibration took place iteratively through comparison of MIKE-SHE outputs to monitored historical unregulated stream flow data from 1961 to 1990 and subsequently verified by comparison of MIKE-SHE outputs to monitored historical unregulated stream flow data from 1991 to 2003. The historical unregulated stream flows are without the operation of Shellmouth Dam and the Portage Diversion.

Modelled stream flow outputs and historical stream flow were converted to monthly flow duration curves (FDC) for comparison purposes at each of five hydrometric stations throughout the basin (Russell, Welby, Brandon, Wawanesa and Headingley). The model represents Assiniboine River basin hydrology well enough to be used to compare streamflow and soil moisture of modelled historical data with modelled future climate change scenarios, where the modelled simulation of major spring flooding closely resembles historical events during years of high soil moisture and significant snow pack. A statistical assessment using the Nash–Sutcliffe coefficient indicates that Headingley, Brandon and Wawanesa measured versus modelled streamflow data correlations have very high statistical confidence. The Russell and Welby measured versus modelled streamflow data correlations, although good, are not quite as strong.

Regional Climate Model

Meteorological data generated by a regional climate model were used as MIKE-SHE inputs for hydrologic modelling of the three future time periods (2011-2040, 2041-2070, and 2071-2099).

Run “aet” data from the Canadian Regional Climate Model (CRCM) were chosen because average monthly means of CRCM simulated temperature and precipitation from 1960 to 2000 are relatively close to average historical monthly means when compared to other CRCM runs. CRCM data bias was analyzed and corrected.

CRCM “aet” predicts temperature increases over the 21st century. For example, the average July temperature is predicted to increase from approximately 17ºC (1961-1990) to 23ºC (2071-2099). CRCM “aet” predicts precipitation increases for fall, winter and spring, and decrease for summer over the 21st century.

Assessment of Climate Change on Stream Flow

A review of natural variation of historical stream flows was undertaken prior to assessing the three future climate change scenarios. The study site was Headingley for three periods over the 20th century (1913-1944, 1945-1976 and 1977-2009).

The subsequently developed future scenarios (2011-2040, 2041-2070 and 2071-2099) stream flows generated by MIKE-SHE were compared against historical stream flows by plotting flow duration curves (Figure E-2). Future scenarios are within historical variation, and no major trend is apparent with respect to the variability of annual stream-flow. However, certain conclusions can be made with respect to 10%, 50% and high average annual stream flows.

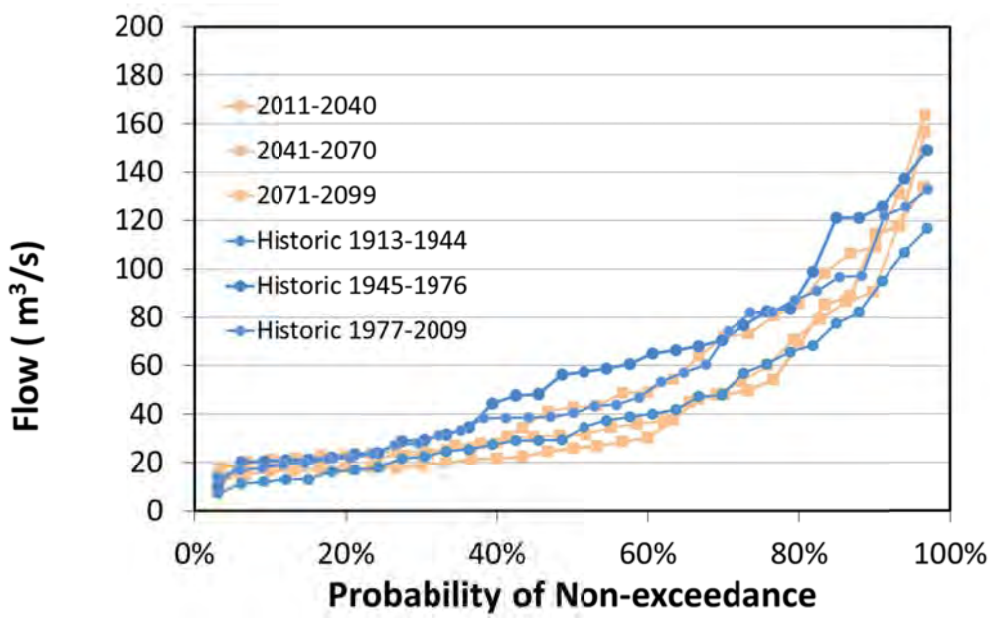

Figure E-2: Comparison of Historic and Predicted Future Annual Flow Duration Curves for Headingley

Only one CRCM run (“aet”) was used to develop future meteorological data for the study. Therefore, variability and uncertainty in this study may be less than would be reported in a study using multiple CRCM runs.

This study did include a detailed analysis of month to month changes in stream flows and soil moisture due to climate change. However, because only one CRCM run was used to develop future stream flows strong conclusions cannot be drawn with respect to monthly soil moisture and stream flows.

Assessment of Climate Change on Soil Moisture

Future scenarios MIKE-SHE soil moisture outputs for the Assiniboine River Sub-basin indicated annual average soil moisture would decline in the latter third of the 21st century. This is due to decreased summer rainfall, and due to increased summer temperature with resultant increased evapotranspiration (Figure E-3).

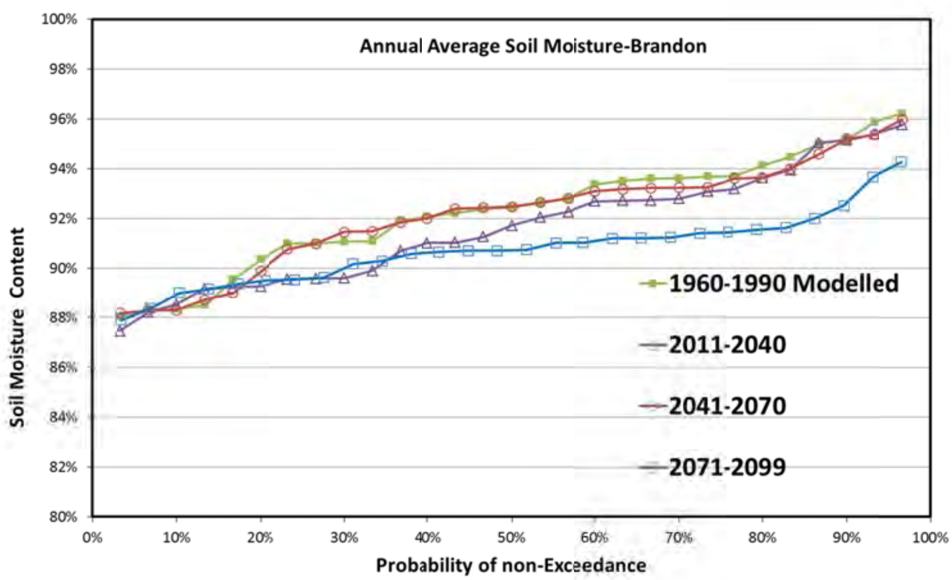

Figure E-3: Annual Soil Moisture Duration Curve as % of Field Capacity – Brandon (Assiniboine Sub-basin)

Future scenarios MIKE-SHE soil moisture outputs for the Souris River Sub-basin indicated annual average soil moisture will generally decline for the same reasons as the Assiniboine River Sub-basin, having the lowest value in the latter third of the 21st century (Figure E-4).

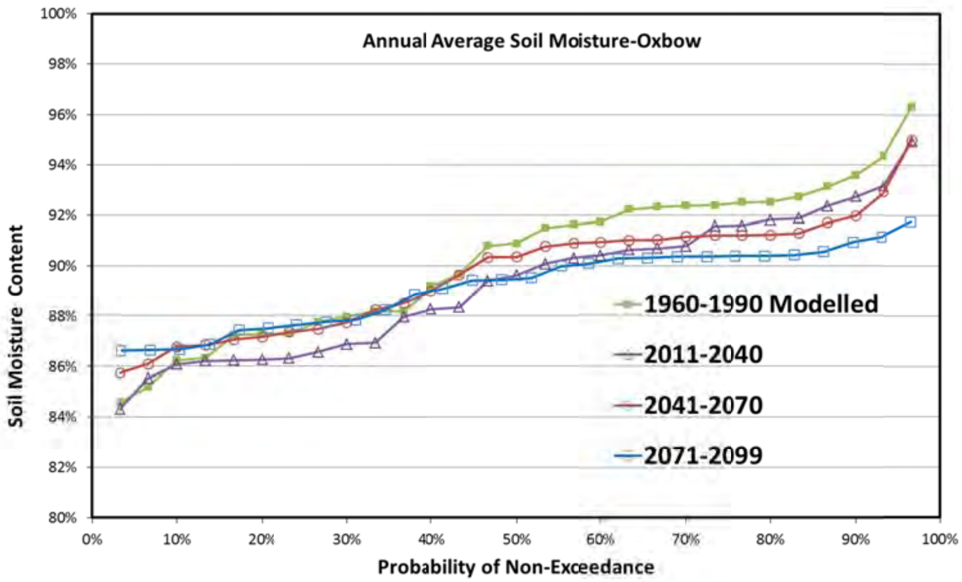

Figure E-4: Annual Soil Moisture Duration Curve as % of Field Capacity – Oxbow (Souris Sub-basin)

Future scenarios MIKE-SHE soil moisture outputs for the Qu'Appelle River Sub-basin basin indicated annual average soil moisture will generally decline for the same reasons as the Assiniboine River Sub-basin, having the lowest value in the latter third of the 21st century (Figure E-5).

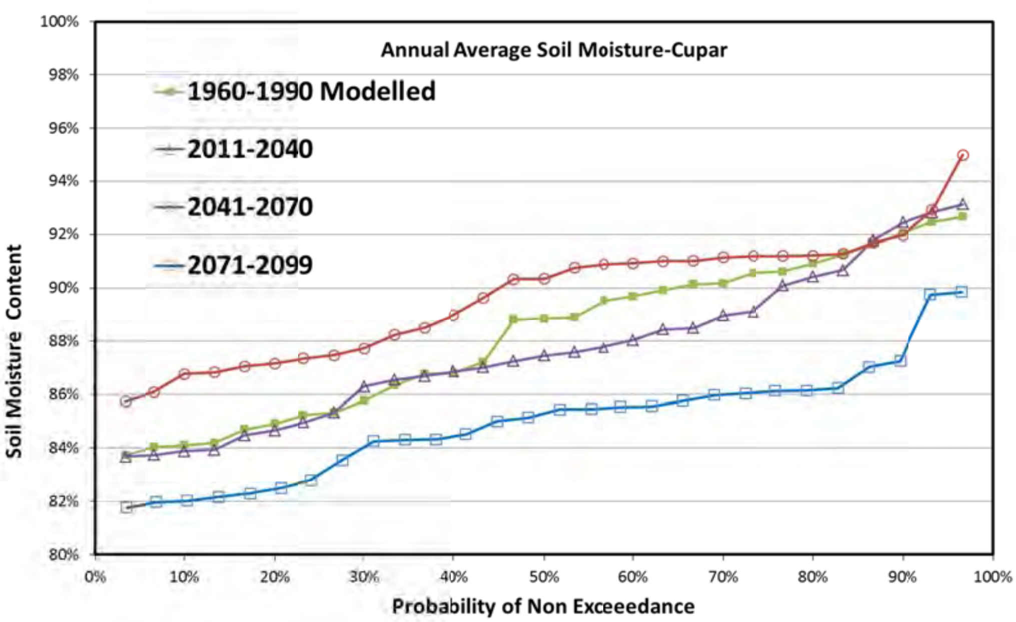

Figure E-5: Annual Soil Moisture Duration Curve as % of Field Capacity – Cupar (Qu'Appelle Sub-basin)

Major Conclusions

Average annual future soil moisture is predicted to be lower than today. This is mainly due to increased temperature and evapotranspiration. Greater seasonal variation in soil moisture is expected, where the following conclusions can be made:

- Summer and fall soil moisture is predicted to be lower than today. An increase in summer water demand, would, therefore, be expected.
- Spring soil moisture is predicted to be similar to today. This is due to lower fall soil moisture levels being offset by increased fall, winter, and spring precipitation.

Annual future stream flow is expected to remain within historical natural variation. Modelling predicts that increased temperature and evapotranspiration would generally be offset by increased annual precipitation. Soil moisture for summers and fall will generally be lower, but there will be greater fall, winter and spring precipitation, so on average we expect that spring soil moisture will remain on average about the same as today. If soil moisture going into fall is unusually wet, with the greater probability of larger precipitation over fall, winter and spring, therefore the large flood events are likely to increase in magnitude in the future.

The following broad conclusions can be made with respect to stream flows:

- 10% probability of non-exceedence (low) annual flows is predicted to be similar in future. These flow years are generally not critical to summer water supply, given that the current method of water allocation is based upon the drought of record, which is a more severe (low) flow event.
- High probability of non-exceedence annual flows is predicted to be larger in future. Therefore, the risk of extreme spring floods may increase. This is due to predicted increases to fall, winter and spring precipitation, which could lead to higher flood flows if unusually high fall soil moisture is experienced.
- Average monthly flows showed no discernible trend in the future.
- An earlier spring melt is predicted to cause an earlier spring freshet.

Major Recommendations

Continue development of MIKE-SHE as a planning (e.g., climate change impacts) and operations (e.g., flood forecast) tool, with the following direct applications:

- MIKE-SHE analysis of potential changes to seasonal and monthly stream flow (for water supply, aquatic biota) and soil moisture (for agricultural production) with climate change using additional CRCM runs to illustrate potential variability.
- MIKE-SHE analysis of manmade changes to drainage and its impact on streamflow.

- MIKE-SHE climate change analysis of the ARB using a range of bias adjusted CRCM meteorological outputs.

Review the adequacy of the existing meteorological stations system in the ARB and determine what level of data gathering is essential for hydrologic planning and operations.

Acknowledgements

This study was financially supported by Manitoba Government. Stantec would like to acknowledge the Technical Advisory Committee (TAC) for its comments and suggestions, and for all the time spent in reviewing and improving the study. We would like to extend our thanks to Natural Resources Canada for providing the gridded temperature and precipitations data.

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1.0 Introduction

1.1 BACKGROUND AND GOALS

Manitoba's goal is to develop a climate-change adaptation strategy informed through the collective results and outcomes of Prairies Regional Adaptation Collaborative (PRAC) funded studies, including those under the Water Resources Management theme. The focus of this PRAC Manitoba study is on hydrologic aspects of climate change. The river basin chosen for analysis, which is critical to Manitoba's water supply, has been subject to damaging historical floods and droughts. Development of a Manitoba climate-change adaptation strategy is a priority as it is anticipated that future droughts and floods will have increased impacts in the subject basin and in all others across Manitoba.

This study is focused on construction and use of a hydrologic model for the Assiniboine River Basin (ARB). The model is used to assess potential effects of climate change on surface-water flow and soil moisture. This is accomplished through comparison of modeled historical data (including historical meteorological inputs) to modeled climate change scenarios data (including meteorological inputs generated by regional climate model). With anticipated further refinement, the model can also be used as a general planning and operational tool.

The ARB covers 162,000 km^2 in the provinces of Manitoba and Saskatchewan, and the State of North Dakota (Figure 1-1). For the purposes of this study, the basin has been divided into three sub-basins: the Souris River Sub-basin, the Qu'Appelle River Sub-basin, and the remaining portion of the basin is referred to as the Assiniboine River Sub-basin. The most common land use across the basin is agriculture with annual cropland being the most common land cover in the area.

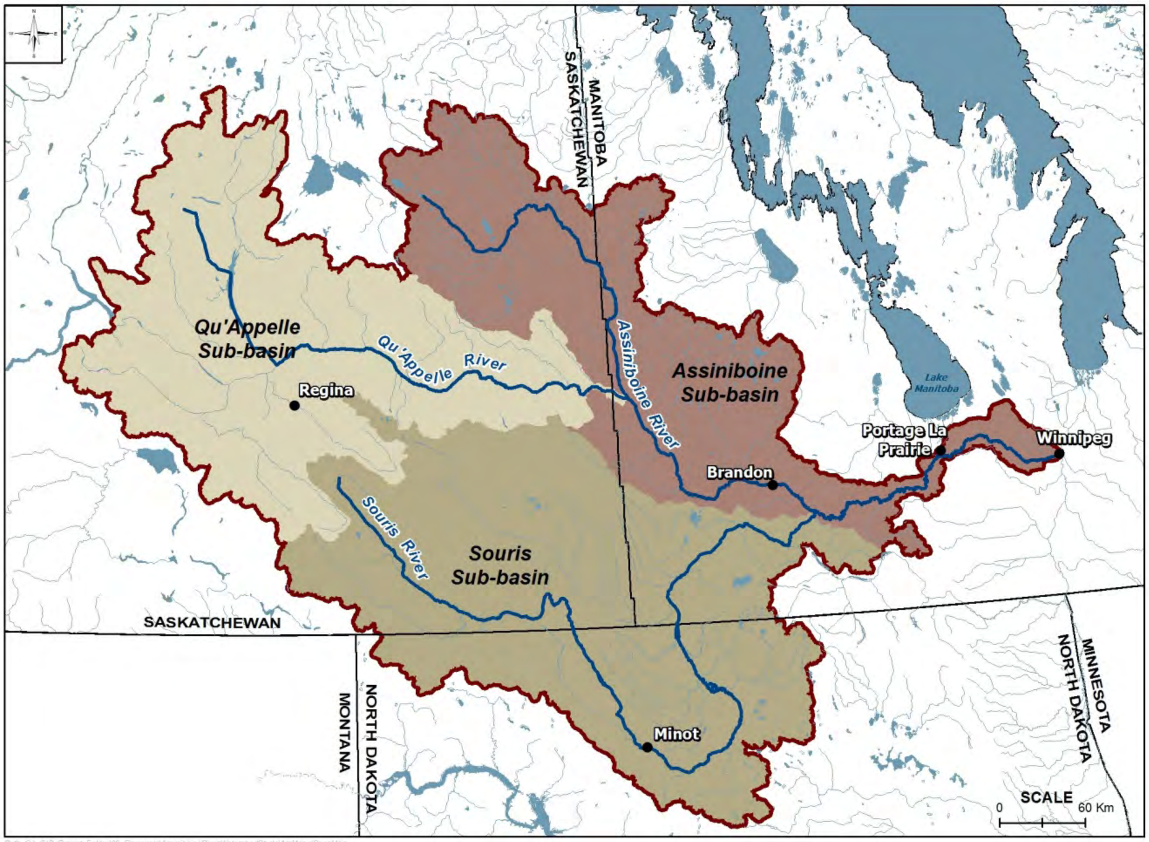

Figure 1-1: Assiniboine River Basin

This report does not include analysis of the 2011 flood which was the largest ARB flood in recorded history. The scope of work and timeframe did not allow for model analysis of the 2011 flood, which analysis is anticipated to be undertaken as a follow-up activity.

1.2 GENERAL APPROACH

The general approach was to develop a physically based distributed hydrologic model for the entire ARB to its outlet near Headingley, Manitoba, calibrate the model to a period of historic recorded hydrologic data, verify the model against a second period of historic recorded hydrologic data, and finally simulate climate-change scenarios using meteorological outputs from the Canadian Regional Climate Model (CRCM) (NARCCAP 2007) for the purpose of assessing changes.

The Danish Hydraulic Institute (DHI) MIKE-SHE (DHI 1998) model was selected for this study, which was run on a daily time step and is described further in Section 2. The model was calibrated iteratively through comparison of outputs to monitored historical flow data from 1961 to 1990 (Section 5), and verified by comparison of outputs to monitored historical flow data from 1991 to 2003 (Section 6). Initial inputs included measured historical precipitation and temperature data from meteorological stations, and other relevant data (e.g., topography, soil type, evapotranspiration, others).

Hydrologic stations used for calibration, verification, and climate change scenarios analysis are located at Headingley, Brandon, Russell, Welby and Wawanesa.

Following calibration and verification, a future soil-moisture and streamflow scenario was simulated for the entire ARB. Daily precipitation and temperature inputs for these model runs were obtained from the CRCM for the periods of 2011 to 2040 (early 21st century), 2041 to 2070 (middle 21st century) and 2071 to 2099 (late 21st century). The CRCM outputs has been generated and supplied by Ouranos to Manitoba Hydro (Crawford 2011) which provided data to the study team. Only one of the scenarios was directly used in the simulation of future conditions.

A CRCM baseline was also obtained by running the ARB MIKE-SHE hydrologic model using CRCM precipitation and temperature outputs for 1961 to 1990. The CRCM climate-model baseline simulation was first compared to historic and modeled soil moisture and streamflow outputs (1961 to 1990) to assess model bias. Monthly streamflow and soil-moisture changes were compared between the historic (baseline) conditions (1960 to 1990) and the three future scenarios i.e., early 21st century, middle 21st century and late 21st century. Uncertainties involved in estimating future hydrology, including an assessment of natural variability, were discussed along with the results. The conclusions of the study were summarized and are followed by recommendations for future work.

2.0 Model Description

A fully distributed, physically based hydrological model known as MIKE-SHE (DHI 1998) was selected to model the ARB. MIKE-SHE offered several advantages compared to other options. These included:

- The model is based on the “finite difference” representation and solution of the partial differential equations of mass and energy balance. The model simulates the entire hydrological system on a catchment scale.
- MIKE-SHE is comprehensive in its application to this study. It models the whole process of the hydrological system including evapotranspiration, overland flow, unsaturated soil/water, interception, snowmelt, infiltration, groundwater movements and routing of streamflows (Figure 2-1).
- MIKE-SHE allows for use of empirical linear reservoir models for basins that are too large to be modeled purely by physically based parameters.
- MIKE-SHE integrates well with existing Manitoba government modeling efforts. It is part of the DHI suite and is therefore consistent with the MIKE11 and MIKE 21 series of models being utilized by the Government of Manitoba in the parallel hydrodynamic modeling study of the Assiniboine River.
- MIKE-SHE offers a Geographical Information System (GIS) user interface built into the system, allowing direct use of spatial GIS databases (such as soil maps, land-use maps and a Digital Elevation Model for model inputs).
- MIKE-SHE has a strong visualization utility that facilitates interpretation of modeling outputs. MIKE-SHE pre-processing and post-processing data abilities facilitate the modeling and assessment of model results.
- MIKE-SHE offers the flexibility to generate and use customized FORTRAN subroutines for pre- and post-processing, allowing for comparison to measured data for calibration and for presenting results in a manner to allow easy interpretation.

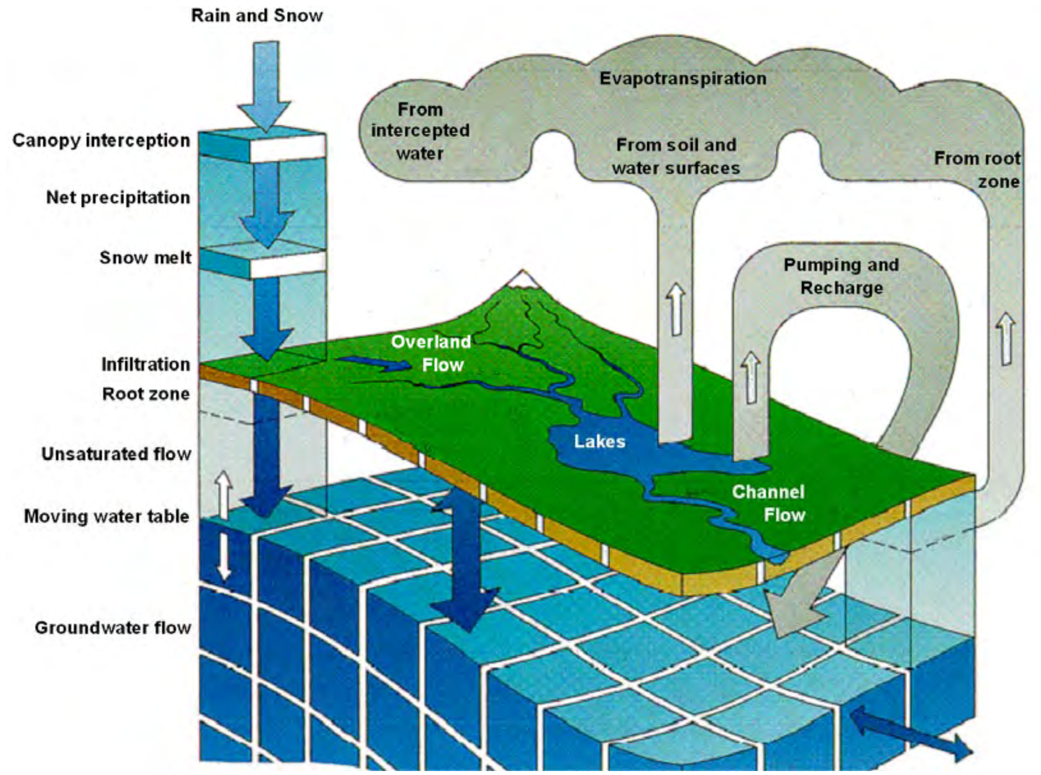

Figure 2-1: Hydrological Processes in MIKE-SHE (DHI 1998)

3.0 Data Review

A key task in setting up the model is dataset development. Several key datasets were collected and processed for use as direct inputs to the model (e.g., precipitation), while other datasets were reviewed for the purpose of determining how parameters should be adjusted for calibration. These key datasets include:

- Meteorological data.
  - Daily precipitation.
  - Daily temperature.
  - Snow storage.
  - Potential evapotranspiration (calculated based on Hargreave's equation which has a link to solar radiation (Hargreaves and Samani 1982 and 1985; Yates and Strzepek 1994).
- Land use data.
- Soil data.
- Digital elevation model (DEM).
- Streamflow data at key locations.
- Future climate-change scenarios (precipitation and temperature).

3.1 METEOROLOGICAL DATA

Historical daily climate data for various stations across the ARB within Manitoba and Saskatchewan were selected from the Environment Canada National Climate Data and Information Archives(2011). Data pertaining to precipitation, temperature and snow on the ground were retrieved where available (Figure 3-1). For the North Dakota portion of the basin, meteorological data was downloaded from High Plains Regional Climate Center (HPRCC 2011).

Daily precipitation and temperature data were retrieved from over 40 meteorological stations in the Canadian portion of the basin, which includes data from 1960 to 2009. Many of the stations have data going back to the beginning of the 20th century or even to the 19th century; however our review focused on the calibration and verification period 1960 to 2003. A review of the data indicated that although the stations had consistently good data for the calibration period of 1961 to 1990, certain datasets became incomplete after 1990 due to discontinuation of monitoring programs at many of the stations. Figure 3-1 shows the period of record for which data is collected on the various stations throughout the Canadian portion of the basin. Density of stations and completeness of datasets were better in the USA portion of the basin.

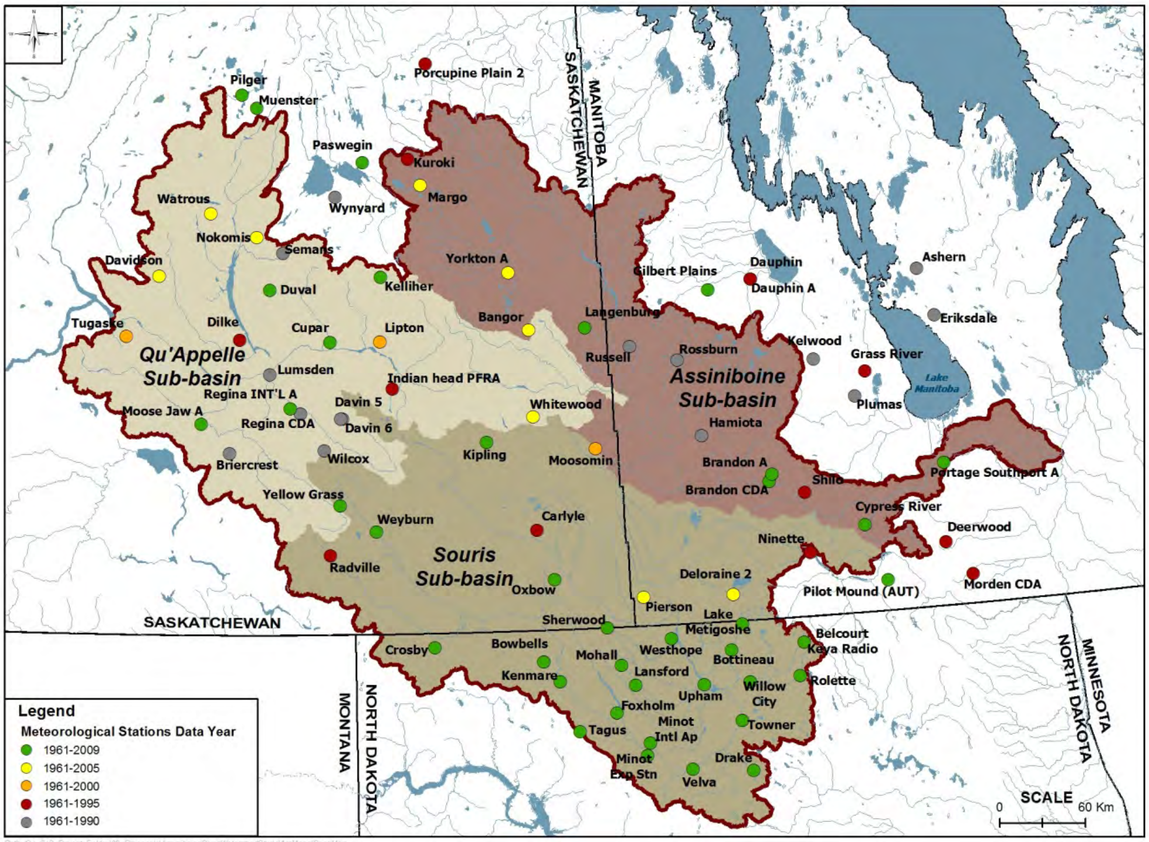

Figure 3-1: Meteorological Stations

To maximize the use of the relatively sparse dataset within the Canadian portion of the study region, Stantec contacted Natural Resource Canada (NRCan) which provided spatially distributed precipitation and temperature data for model input. NRCan developed a 10-km gridded meteorological dataset for Canada using the latest interpolation techniques (Hopkinson *et al.* 2011; Hutchinson *et al.* 2009). The data was forwarded in an ASCII grid format and was received for the whole of Canada. As the data was provided in a format that cannot be directly read by the MIKE-SHE hydrologic model, Stantec developed a FORTRAN code to read the ASCII data and convert it to a MIKE-SHE-compatible dataset file. Stantec's data conversion tool processed approximately 15,700 ASCII files and converted these to a MIKE-SHE DSM2 format compatible with the model. Following conversion, the data was trimmed to contain only the data needed for the ARB modeling. An indication of the size of the entire spatial data grid across Canada is shown on Figure 3-2.

As the entire US portion of the watershed was within the Souris Sub-basin, a simpler method was used to generate uniform daily precipitation and temperature across the North Dakota portion. All station records were averaged on a daily basis and uniform daily precipitation and temperature were inputted to represent the North Dakota portion of the basin.

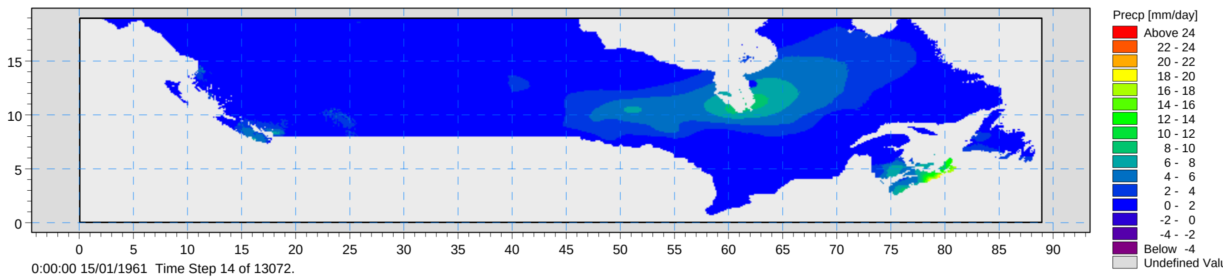

Figure 3-2: Entire Spatial Gridded Precipitation Data Domain for January 15, 1961

3.2 DIGITAL ELEVATION MODEL (DEM)

A critical aspect in the development of the hydrologic model is the input of the DEM. The following two sources were reviewed for DEM input:

- Geobase Canadian Digital Elevation Data (CDED) for Saskatchewan and Manitoba.
- Shuttle Radar Topography Mission (SRTM) database for North Dakota within the USA.

The CDED provided a 30- x 30-m grid of elevation data and the SRTM provided a 90- x 90-m grid of elevation data. Our review of the data indicated that along the US/Canada border there were elevation differences between the CDED and SRTM datasets, as large as 20 m. The important need for a hydrologic model is that the relative elevations across the basin be consistent. The SRTM database extends across the US and Canada, where the CDED does not cover the US portion of the Souris River Basin. Therefore, the SRTM database was used for the DEM of the entire ARB. The 90- x 90-m SRTM database is sufficient in terms of spatial resolution of the data as spatial resolution of the model was set at 5 x 5 km. This dataset was averaged across the 5- x 5-km resolution to develop a DEM with sufficiently high resolution to be used as an input for the model. The DEM is shown on Figure 3-3.

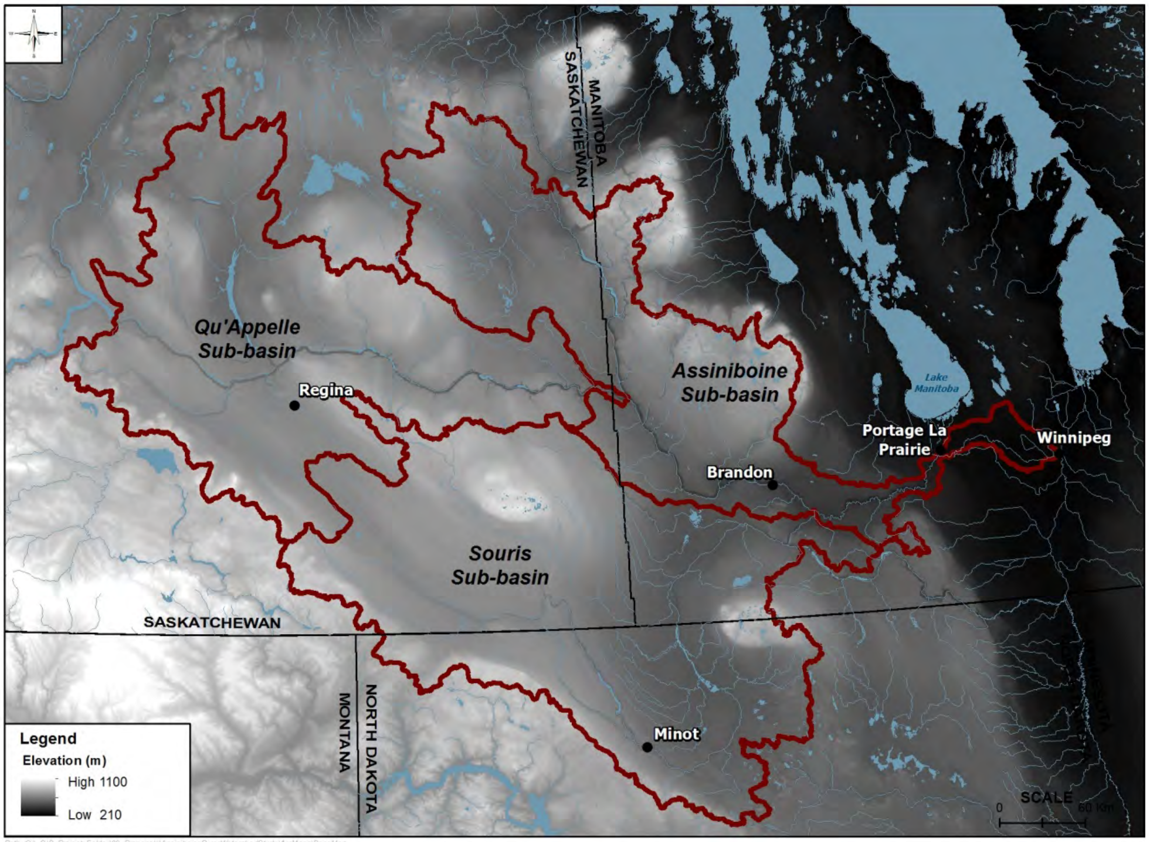

Figure 3-3: Digital Elevation Model (DEM)

3.3 LAND USE AND COVER

Stantec downloaded complete land cover data for the whole ARB from the following website sources:

For Manitoba, the Manitoba Land Initiative (MLI).

For Saskatchewan, Agriculture and Agri-Food Canada (AAFC).

For North Dakota, the State of North Dakota.

Land cover classes are shown on Figure 3-4 and illustrate how land use across the study area is dominated by agriculture land use; specifically annual cropland. Key parameters such as the Leaf Area Index (LAI) and the Root Depth (RD) were used as calibration parameters in the MIKE-SHE model, as discussed in Section 4. These parameters are not directly available from any dataset. This Land Use dataset did indicate how generally uniform land cover was across the area; therefore, allowing for a basin-wide selection of LAI and RD.

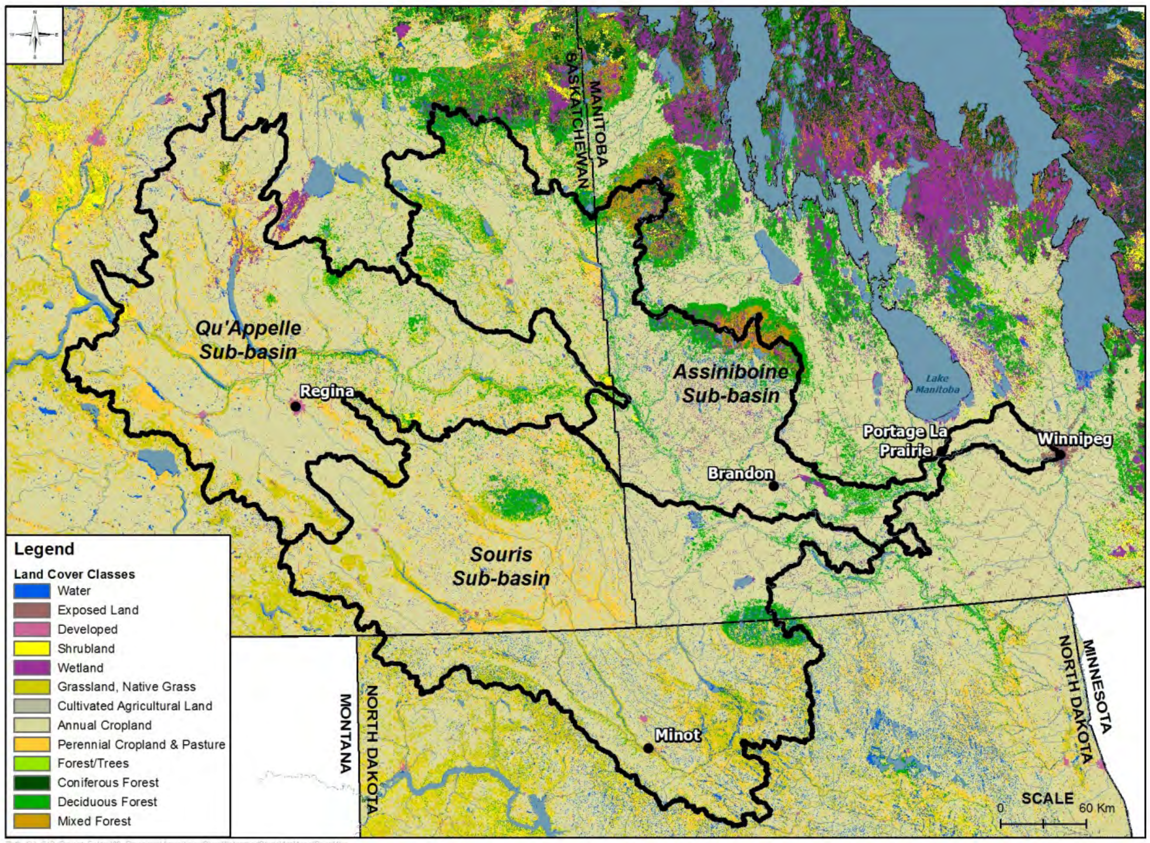

Figure 3-4: Land Cover

3.4 SOIL TYPE

Stantec received soil type data from various sources throughout the basin. For Manitoba, Manitoba Conservation provided soil type data. For Saskatchewan portions of the Souris and Qu'Appelle sub-basins, soil data was obtained from Agriculture and Agri-Food Canada. For the Upper Assiniboine Basin within Saskatchewan, Manitoba Conservation provided this information. For the North Dakota portion of the Souris Sub-basin, soil type data was obtained from the US Department of Agriculture (USDA) Natural Resources Conservation Service website. The soil data received from all sources were provided from different soil classification systems. Stantec's soil scientist and GIS specialist developed a common classification for the entire ARB, as shown on Figure 3-5. The most significant determination of this assessment was that medium soils dominate the entire ARB, with some fine soil found in the Qu'Appelle Sub-basin and some coarse soils found in the Manitoba portion of the ARB. The soil type can have an impact on hydraulic conductivity, porosity and other soil parameters such as saturation, field capacity, and wilting point.

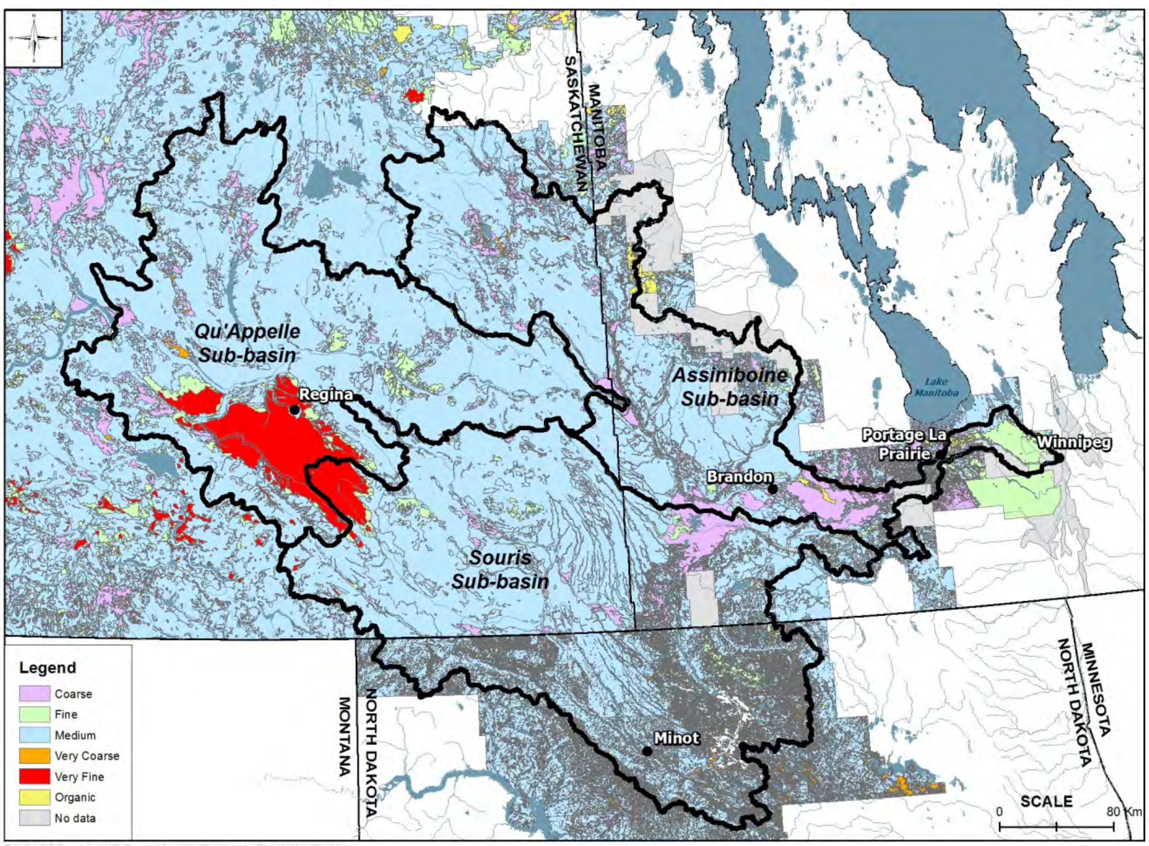

Figure 3-5: Soil Type

3.5 STREAMFLOW

Streamflow data at various hydrometric stations were reviewed and five stations were selected for use in the calibration of the ARB model: Russell, Welby, Brandon, Wawanesa and Headingley (Figure 3-6). To determine the total flow of the ARB, a dataset was developed that included the daily flows from Headingley plus the Portage Diversion, which diverts flood water flows from the ARB to Lake Manitoba. A review of the data collected for the Headingley and Portage Diversion indicated that when these data were summed, the daily total was almost the same as the station at Holland. Holland is just upstream of the Portage diversion and would be expected to have a similar flow record. The station at Holland does not have as complete a record as the Headingley and Portage Diversion stations, and was therefore dropped from the calibration exercise (Holland was originally considered as a calibration station). The station at Wawanesa was selected to measure the flows leaving the Souris Sub-basin and flows at Welby are a measurement of flows leaving the Qu'Appelle Sub-basin. Two additional stations were added for review and calibration – one at Russell to measure flows in the Upper Assiniboine Sub-basin and at Brandon, which is a combination of Qu'Appelle River flows and Upper Assiniboine River flows.

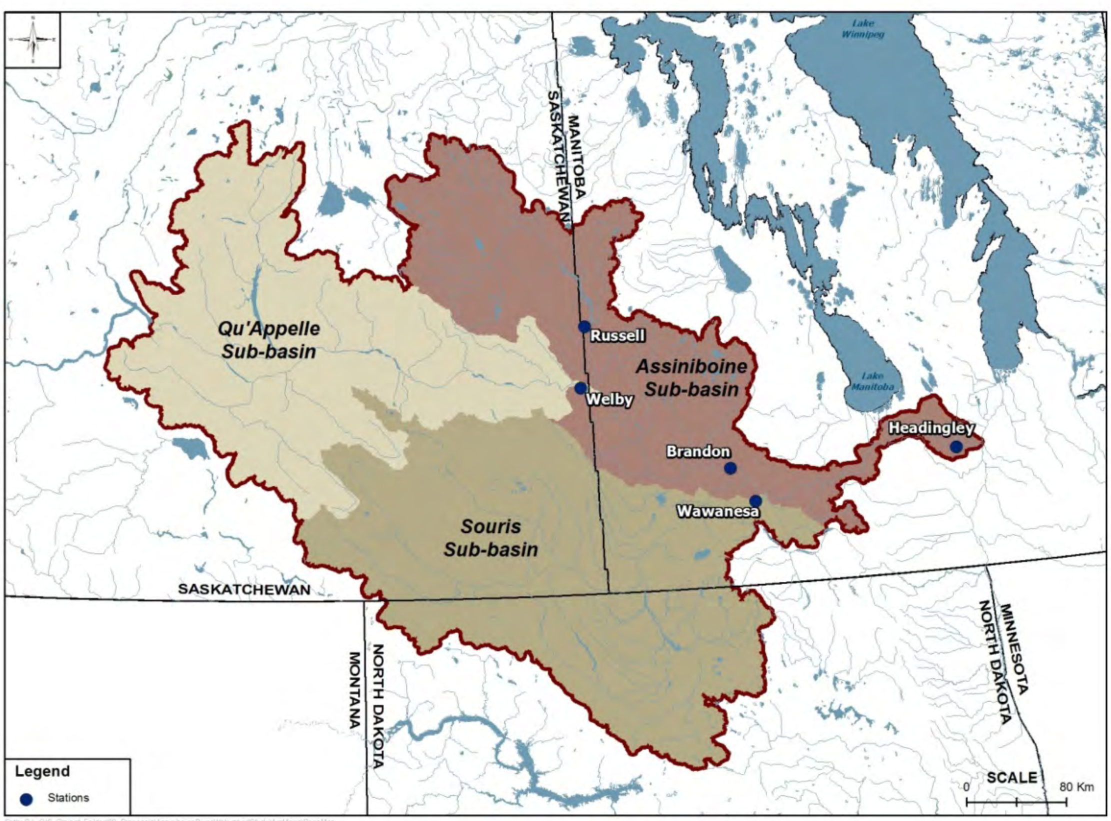

Figure 3-6: Locations of Selected Hydrometric Stations

A review of the annual flows at the various stations, shown in Figure 3-7, indicates that in some years, annual flow at Headingley is dominated by flow from one of the three sub-basins. For example, in 1976 and 1999, Assiniboine River flows at Headingley were dominated by the flow at Wawanesa coming from the Souris Sub-basin. In addition, the total annual basin runoff in units of millimetres was calculated and is shown on Figure 3-8. This indicates that unit flow was generally highest at Russell, measuring flows coming from the Upper Assiniboine sub-basin. Maximum runoff observed in 1995 for the Upper Assiniboine Sub-basin was estimated to be 74 mm.

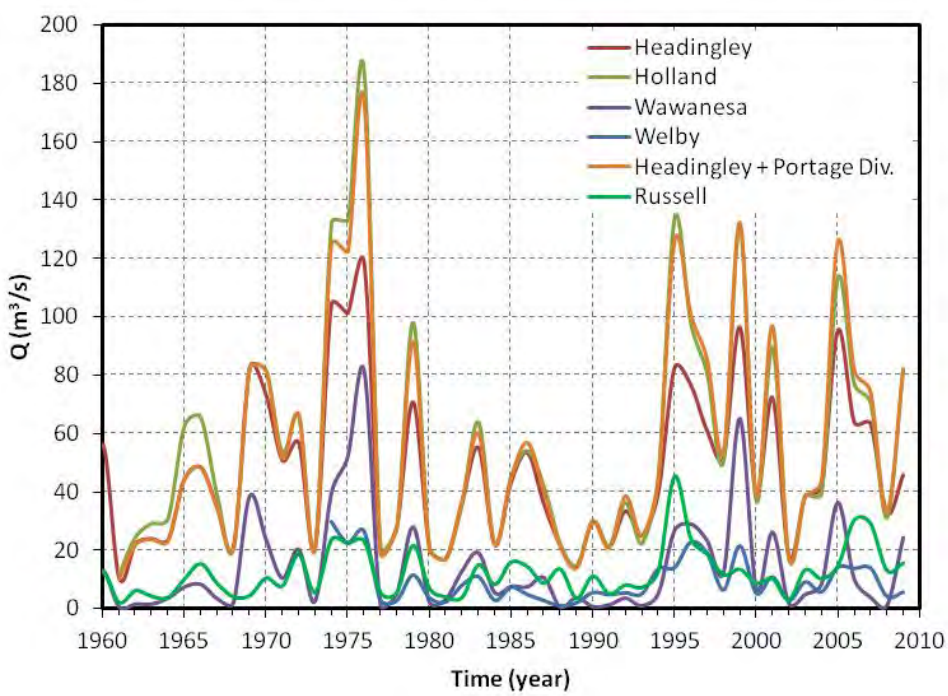

Figure 3-7: Average Annual Streamflow at Various Stations

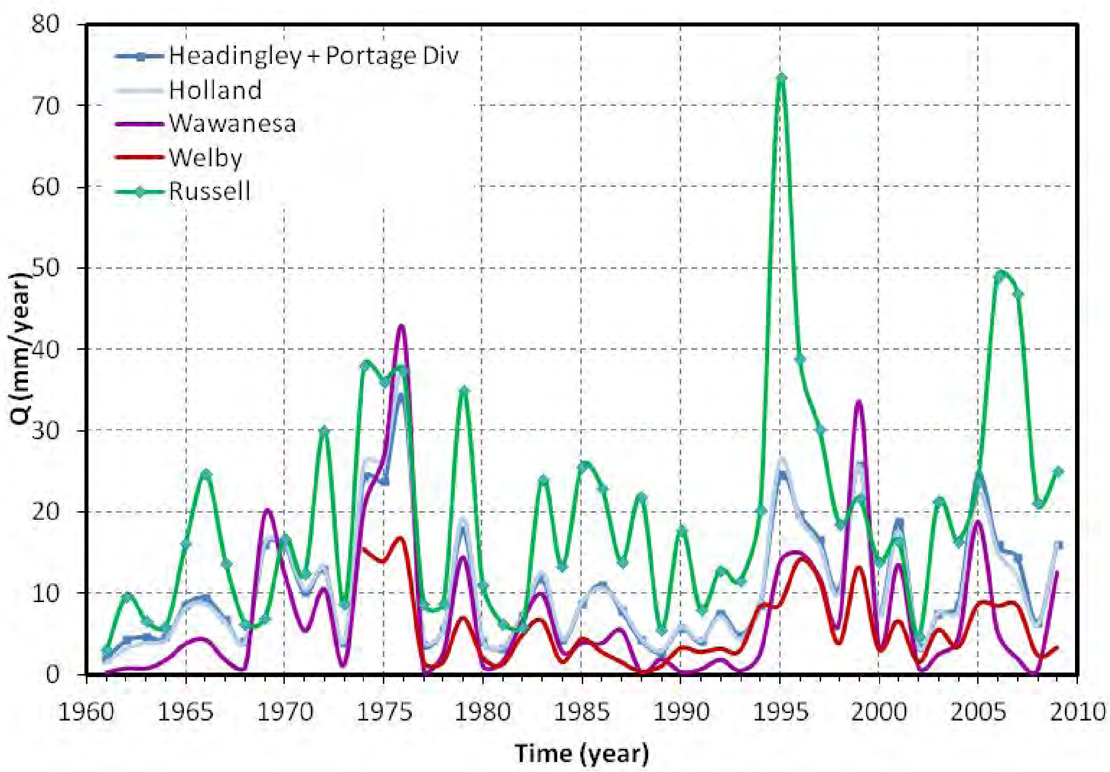

Figure 3-8: Average Annual Streamflow at Various Stations (mm/year)

3.6 GLOBAL CLIMATE MODEL DATA

3.6.1 Modelling our Climate

Climate change is accelerating due to increasing levels of greenhouse gases (GHGs) worldwide, where resultant temperature increases and changes in frequency and occurrence of extreme weather are expected to lead to accelerated ecosystem degradation and economic impacts. The best climate change information is required for better adaptation planning.

Although study of historical climate gives important knowledge on the natural variability of global climate and ecosystems responses to change, it is not possible to simply extrapolate future changes from past data. Sophisticated computer models are the most advanced tools at our disposal to test responses of our climate system (e.g., temperature, precipitation) to changes in variables (e.g., GHG emissions). The use of computer models simulating climate change allows us to better answer questions relating to future climate impacts on our economy and daily life.

The Manitoba agricultural and energy sectors are sensitive to climate change in general, and quantity and timing of water supplies in particular.

One commonly used method of simulating detailed regional climate change information is by use of a Regional Climate Model (RCM) nested within a Global Climate Model (GCM). The low-resolution GCM (350- to 500-km grid) is run with a range of possible greenhouse gas emission scenarios to simulate global climate. GCM outputs provide large-scale boundary conditions to a nested high-resolution RCM (45-km grid. The RCM can be used to project high resolution climate change data for a particular region. In the case of this study, Assiniboine River Basin climate change meteorological scenarios are outputs of the Canadian Regional Climate Model (CRCM) nested within the Canadian Global Climate Model (CGCM). CRCM meteorological outputs were used to run the MIKE-SHE hydrologic model.

3.6.2 Future Emission Scenarios

The Intergovernmental Panel on Climate Change (IPCC) published scenarios in 2000 to explore the future global environment, with consideration of production of greenhouse gases and aerosol precursor emissions. Several storylines (Figure 3-9), with resultant scenarios were envisioned and are documented in the Special Report on Emission Scenarios (IPCC SRES (2000):

- A1 storyline and scenario family: a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies.
- A2 storyline and scenario family: a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other storylines.
- B1 storyline and scenario family: a convergent world with the same global population as in the A1 storyline but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies.
- B2 storyline and scenario family: a world in which the emphasis is on local solutions to economic, social, and environmental sustainability, with continuously increasing population (lower than A2) and intermediate economic development.

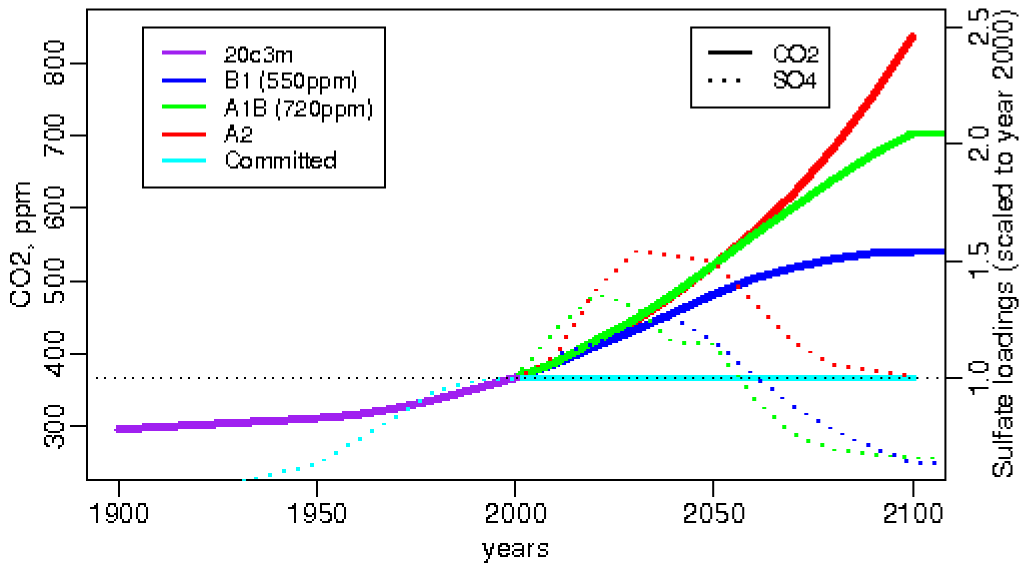

Figure 3-9: Carbon Dioxides Concentrations for Various SRES Storylines

3.7 CANADIAN REGIONAL CLIMATE MODEL (CRCM)

The CRCM was originally developed at Université du Québec à Montréal (UQAM). It is a state-of-the-art RCM capable of producing high-resolution climate simulations, where the distance between horizontal grid points is smaller than 45 km, with a time step of 15 minutes. The Canadian Regional Climate Modelling and Diagnostics Network (CRCMD), located at UQAM, is leading future development, application and evaluation of regional climate models within Canada. The Network includes researchers from Université du Québec à Montréal (UQAM), University of Victoria, Ouranos Consortium, Environment Canada (Canadian Centre for Climate Modelling and Analysis (CCCma), and Recherche Prévision Numérique (RPN). CRCMD objectives are to develop/evaluate a new high-resolution CRCM, develop diagnostic tools for high-resolution climate data evaluation, and make CRCM available to the regional climate scientific community.

The CRCM is in a continuous state of improvement; the version used in this study was Version 4.2.3 has shown promise over earlier versions and new version are in development.

3.7.1 CRCM Version 4.2.3 Data

Meteorological output data from three CRCM 4.2.3 runs (“aet”, “aev”, and “agx”) were considered for use as inputs to the MIKE-SHE hydrologic model. These runs were selected because they contained complete simulations for the time of interest of this study (1960 to 2000 and 2011 to 2099).

The "aet, aev and agx" simulations were performed using CRCM4.2.3 over the North-American (AMNO) domain. The CRCM includes a 45-km horizontal grid mesh, 29 vertical levels, and 15-minute time step. The AMNO domain is covered by 200 x 192 grid points, with the inner 182 x 174 grid points considered. CRCM4.2.3 was nested in either CGCM3/T47 or ECHAM5 with evolution of carbon dioxide concentrations following the IPCC observed 20th century 20C3M scenario for years 1961-2000 and the conservatively high SRES A2 scenario for years 2001-2100. A three-year spin-up was used for the model to reach equilibrium. Each of the runs had a different initial condition, as initial conditions are found to influence the simulation results. Using a series of different runs would provide simulations that represent a range of potential future climate scenarios. The runs are:

"aet" corresponds to run # 4 driven by CGCM3/T47

"aev" corresponds to run # 5 driven by CGCM3/T47

"agx" correspond to run # 1 driven by ECHAM5

Additional runs were provided however these runs were the only one that contained a full set of data for baseline conditions (1960-2000) as well as for the full time period required for the assessment of future conditions (2011-2099). The use of this data is discussed in the following sub-section.

3.7.2 Use of CRCM Data in the ARB Model Future Projections

In order to project the range of future potential soil moisture and flow across the ARB, meteorological datasets were obtained from the Canadian Regional Climate Model (CRCM) as provided by Manitoba Conservation. The CRCM data was generated and supplied by Ouranos and was transferred by Manitoba Hydro to the Province of Manitoba for use by the study team (Crawford 2011). These datasets contain daily precipitation and temperature data across a 45- x 45-km grid covering the ARB (Figure 3-10). Datasets include daily precipitation and temperature predictions for three periods in the 21st century. The periods are designated as:

Early 21st century (2011-2040)

Middle 21st century (2041-2070)

Late 21st century (2071-2099)

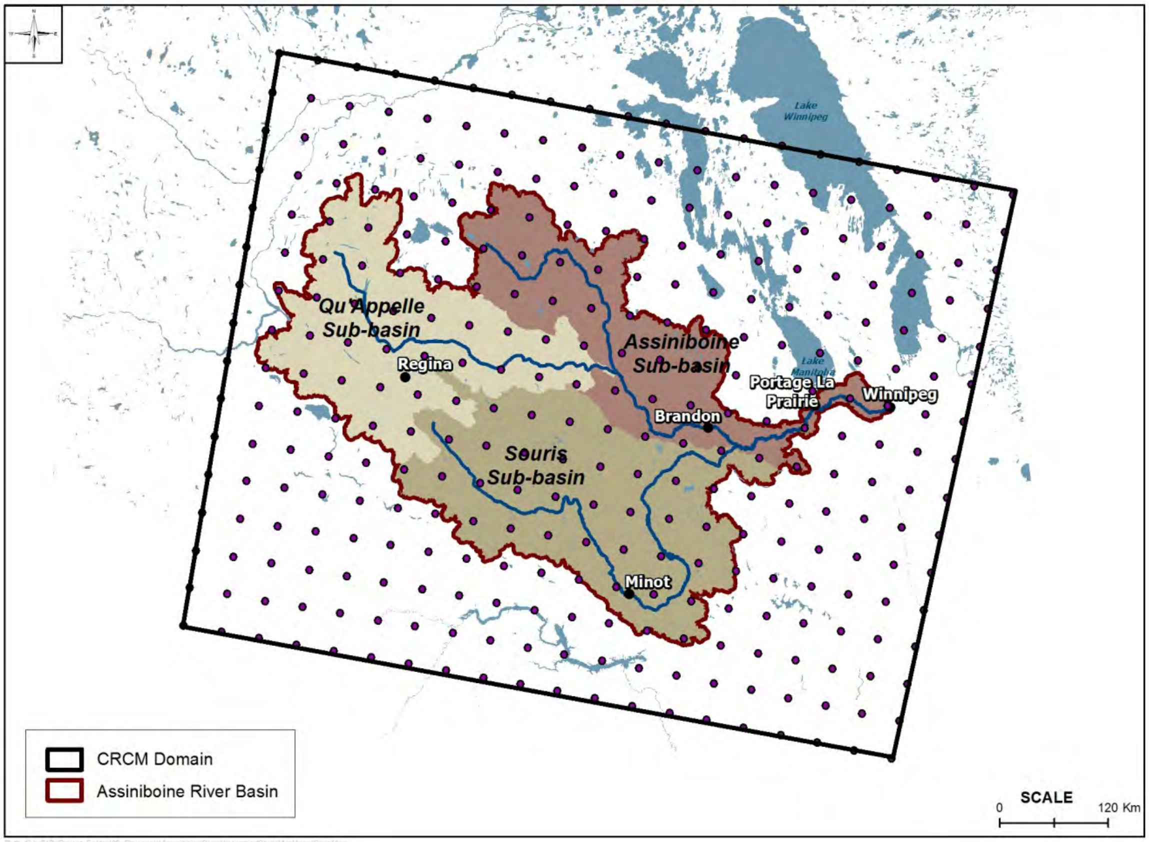

Figure 3-10: Location of Canadian Regional Climate Model Precipitation and Temperature Outputs

All data files were received in text format. In addition, a CRCM baseline run was provided, which runs a modeled outputs of daily precipitation and temperature, for the observed historic data record period from 1961 to 2000. Three sets of CRCM outputs were furnished by Manitoba Conservation and were labeled as aet, aev and agx. Table 3-1 shows the runs that were provided and the various attributes of the model.

To understand the bias inherent in climate model projections, temperature and precipitation were analyzed for the baseline period of 1961 to 2000. These model-predicted values for 1961 to 2000 were then compared against actual historic monitored data for the same 1961 to 2000 period. This period was used as it covers both of the model calibration and verification periods. Average monthly temperature data was compared with the baseline "model-predicted" scenario and the historic observed data record scenario. Temperature outputs from the baseline model shows a bias in that the simulated temperature are lower than the historic data, as shown at

Brandon, Cupar and Oxbow, on Figure 3-11. Temperatures predictions are 5°C lower than historical data in the summer months although are closer to historical normals during the critical spring months. On an annual basis historical average temperature is 2.2°C while the CRCM data for the ARB is -0.6 to -0.7°C.

To compare the CRCM precipitation data to the historic data, average precipitation across the entire ARB was calculated using each of the baseline model runs (aet, aev and agx) and comparing to the historic database. Comparison of monthly precipitation historic data to each of the model outputs is shown in Figure 3-12. The comparison indicates that the CRCM precipitation predictions are generally consistent with historic records in the fall and winter months, but are over-predicting precipitation in the spring and summer months. The bias is consistent in all the model runs, indicating that averaging the three model runs or running all three CRCM model runs with the ARB model will not correct this bias. More discussion on uncertainty and bias and the approach used to account for this is found in Section 7.0.

Table 3-1: Future Climate Change Scenarios

Run Name	Model Name	Run#	Driver	Time Series
aet	CRCM4.2.3	#4	CGCM3	1961-2000
aet	CRCM4.2.3	#4	CGCM3	2011-2040
aet	CRCM4.2.3	#4	CGCM3	2041-2070
aet	CRCM4.2.3	#4	CGCM3	2071-2099
aev	CRCM4.2.3	#5	CGCM3	1961-2000
aev	CRCM4.2.3	#5	CGCM3	2011-2040
aev	CRCM4.2.3	#5	CGCM3	2041-2070
aev	CRCM4.2.3	#5	CGCM3	2071-2099
agx	CRCM4.2.3	#1	ECHAM5	1961-2000
agx	CRCM4.2.3	#1	ECHAM5	2011-2040
agx	CRCM4.2.3	#1	ECHAM5	2041-2070
agx	CRCM4.2.3	#1	ECHAM5	2071-2099

pcp = precipitation
st = surface air temperature
All simulations were originally run over the AMNO domain.
Emission Scenario: SRES A2

The precipitation and temperature predicted by each of the models for the three future scenarios over the next 90 years were analyzed to understand the general changes in precipitation and temperature. The percent of baseline precipitation for each month for the three periods from 2011 to 2099, as well as the degree changes in temperature are shown in Appendix A. The precipitation changes for the AET model run are shown in Figure 3-13. The variation between each of the model outputs (Appendix A) illustrates some of the uncertainty in trying to predict future changes in precipitation and temperature. There are some general trends that seem consistent for all of the model runs. Winter and fall precipitation generally shows an increase in the later part of the 21st century and summer precipitation shows less change in the first two-thirds of the 21st century but appears to decrease for two of the three models in the latter third of the 21st century (Appendix A).

Temperature changes show a consistent increase across all months over the next century (Appendix A). The temperature increases in the AET and AEV model runs are significantly higher, in the 6-degree range in summer and fall months from 2041 to 2070. The range of temperature changes are well represented by the AET model run (Figure 3-14). This study includes ARB hydrologic model analysis of one set of CRCM model outputs. The AET model run was chosen because a review of the data indicated that the AET baseline model monthly average precipitation output appeared closest to the monthly average historical precipitation and had a similar trend in future precipitation changes to the other model runs. The AET baseline average monthly temperature was very close to the historic average monthly temperature and showed similar changes to future temperature as the other CRCM model runs. The largest difference between the model runs is in the last third of the century from 2071 to 2099, in which AET has the highest summer temperatures and the largest decrease in summer precipitation, compared with the other model runs.

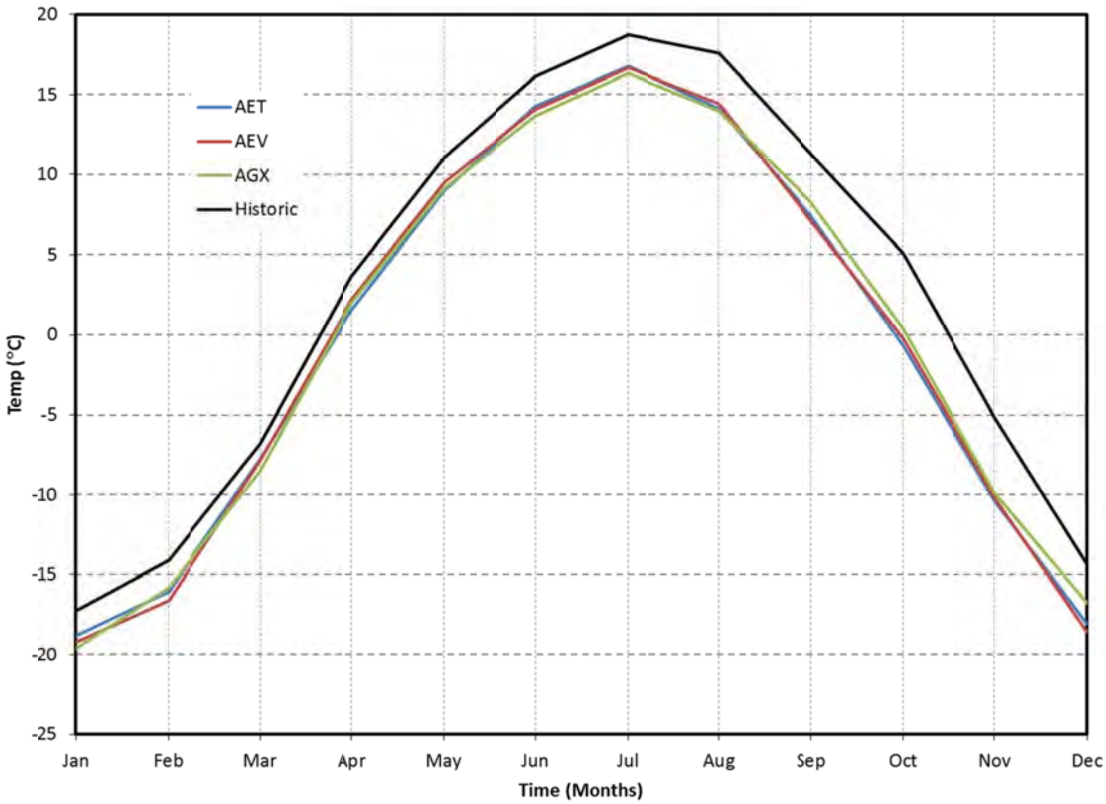

Figure 3-11: CRCM Baseline (1961-2000) and Historic (1961-2000) Temperature Data Comparison (Average AT Brandon, Cupar and Oxbow)

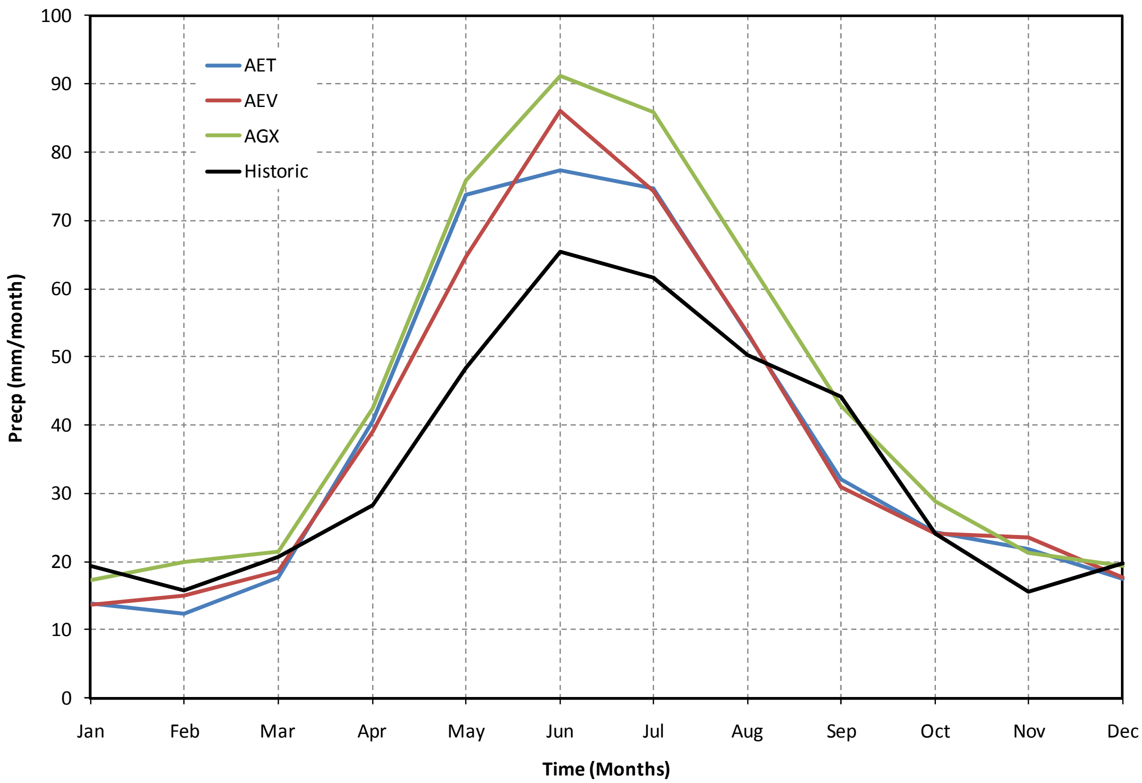

Figure 3-12: CRCM Baseline (1961-2000) and Historic Precipitation Data (1961-2000) Comparison (average across entire ARB)

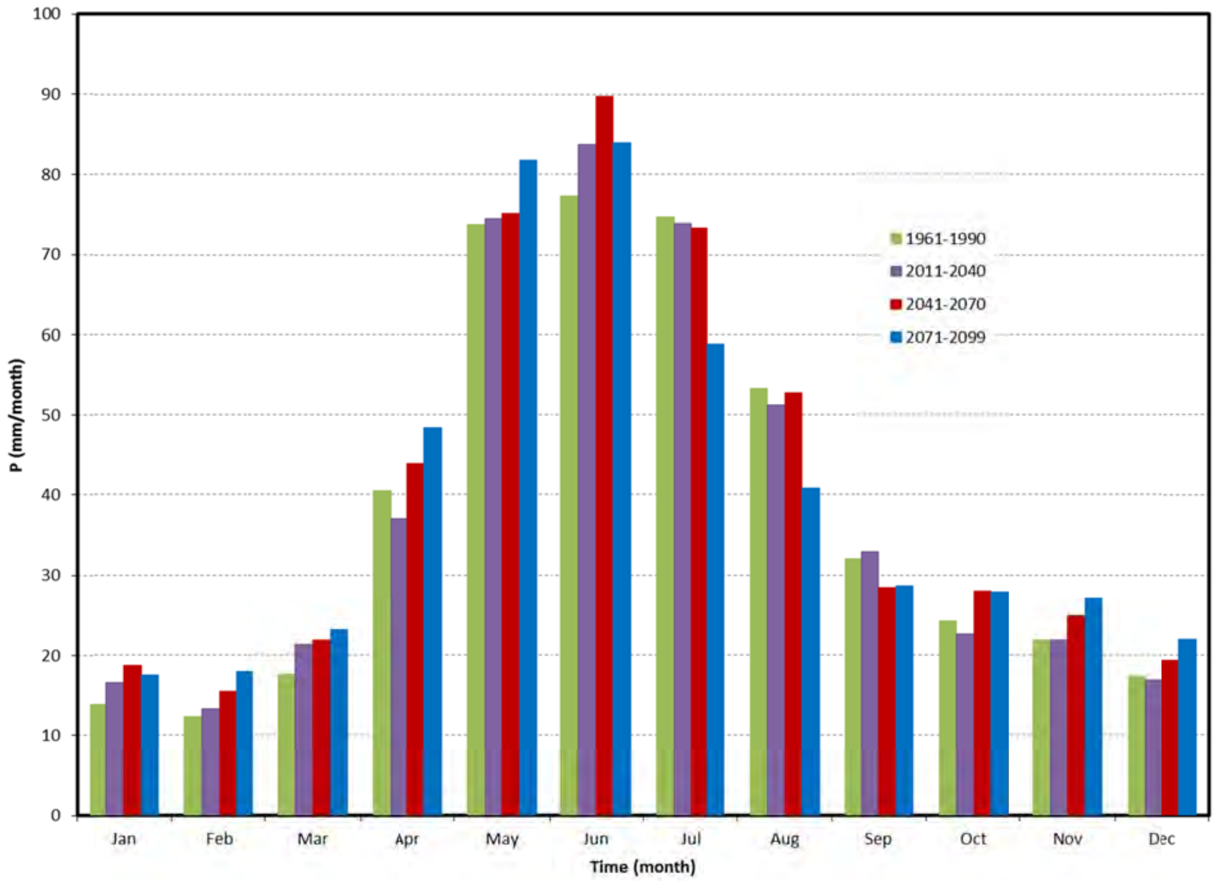

Figure 3-13: Average Precipitation Over CRCM Domain: AET

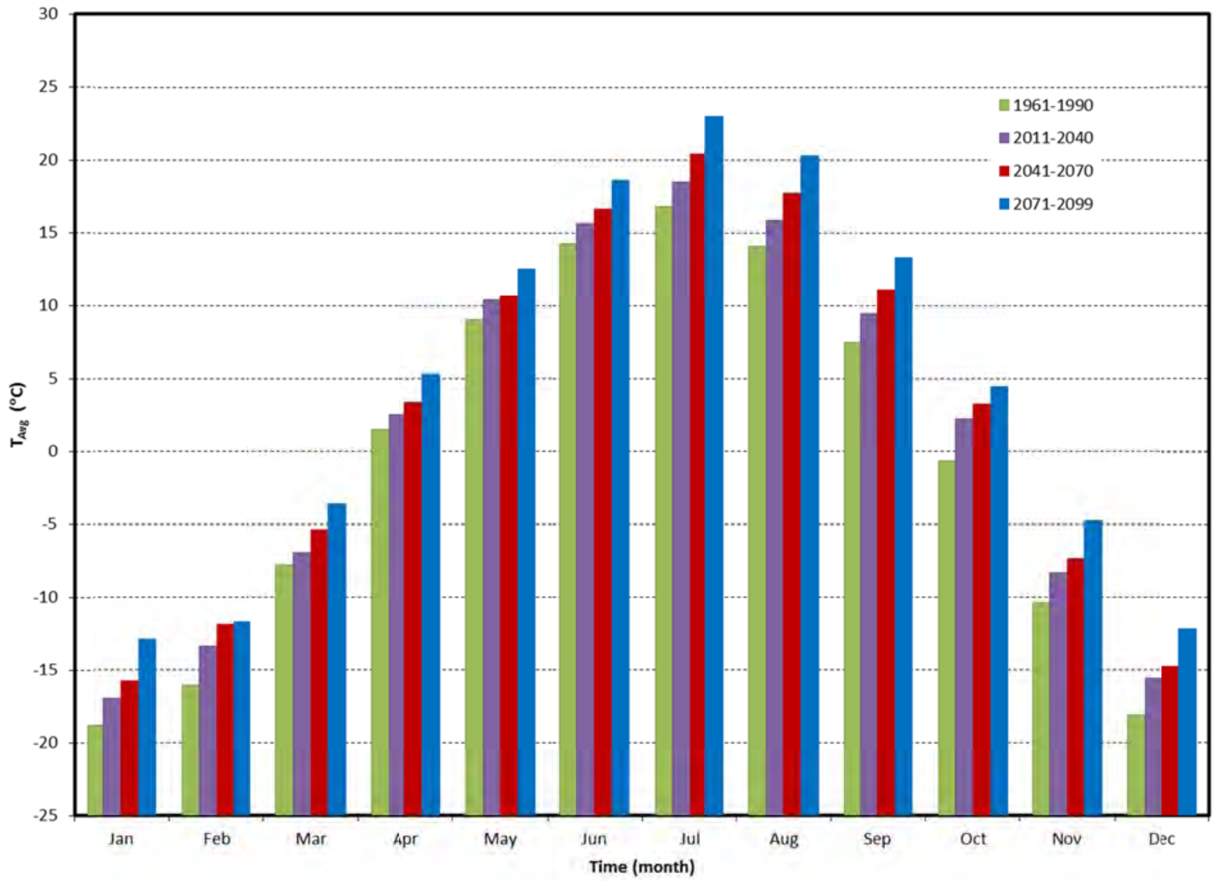

Figure 3-14: Average Temperature Over CRCM Domain: AET

4.0 Model Setup

This section deals with the setup of the MIKE-SHE model, and the selection of key input parameters and how they are defined across the ARB. The details of the actual model input parameter values in each sub-basin across the ARB are discussed in Section 5, Calibration.

The model effort consists of a hydrological model and a hydraulic model. The hydrologic model predicts the runoff associated with rainfall or snowmelt events, with the hydrological model yielding hydrographs at locations along a waterway to describe the quantity, rate and timing of streamflow resulting from these events. These hydrographs were an important input into the hydraulic model, which simulate the movement of water through waterway reaches.

MIKE-SHE does not allow certain physical parameters such as land use to vary from year to year but must remain the same throughout the whole simulation period. Other inputs, such as potential evapotranspiration (PET) are varied on a daily basis to reflect the change of seasons and weather. A list of important parameters and whether they can be varied or are constant is shown in Table 4-1. Further discussion of these parameters and how they are selected follows in Section 5, Calibration.

Table 4-1: List of Input Parameters Used in MIKE-SHE Model

Input Parameters	Varying(Time wise)	Constants
Dead storage fraction		X
Degree-day coefficient		X
Digital Elevation Model (DEM)		X
Evapotranspiration surface depth		X
Interflow threshold depth		X
Interflow time constant		X
Leaf area index	X	
Manning’s coefficient		X
Percolation time constant		X
Porosity or void fraction		X
Potential evapotranspiration	X	
Precipitation	X	
Root depth	X	
Saturated hydraulic conductivity		X

Table 4-1: List of Input Parameters Used in MIKE-SHE Model

Input Parameters	Varying(Time wise)	Constants
Soil suction at wetting front		X
Specific yield		X
Temperature	X	
Threshold depth for base flow		X
Threshold melting temperature		X
Time constant for base flow		X
Unsaturated Zone (UZ) feedback fraction		X
Water content at field capacity		X
Water content at saturation		X
Water content at wilting point		X

4.1 MODEL CELL

The model was set up on a 5- x 5-km resolution across the whole ARB. The MIKE-SHE hydrological model does not allow varying resolutions of the cell size. The elevation for each 5- x 5-km cell (the DEM) was selected based on sampling from the 90- x 90-m SRTM dataset that covers the whole study area (Section 3).

4.2 RIVER CHANNELS

To model the transport of hydrographs, the major river channels in the ARB were modeled with the MIKE11 hydraulic model which was linked to the MIKE-SHE hydrologic model. The cross-sections for this river model were developed using the data from the SRTM DEM. These are simple uniform cross-sections which are only used to assist in routing. The kinetic waves routing method was used by MIKE11 to transport hydrographs along the river channels.

4.3 SYSTEM STORAGE

Although physical parameters such as soil moisture and runoff are calculated in each cell, the size of this basin does not lend itself to a full physically based model. A fully physically based model would need to model each pot hole and gulley through the basin. This is not practical for a planning level model of a 162,000-km^2 basin. MIKE-SHE allows the use of linear reservoirs to model interflow storage and groundwater base-load storage. More discussion on the parameters used in the interflow basin is in Section 5, Calibration.

4.4 SOIL PARAMETERS

The majority of soil texture across the ARB is in the “medium” classification. The soil parameters were averaged over each sub-basin to run the model. Some key parameter values cannot be measured and input directly into the model, however the values are varied during the calibration until an overall model calibration is accepted. Some of these key soil parameters within the model are:

- Water content at saturation.
- Water content at field capacity.
- Water content at wilting point.
- Saturated hydraulic conductivity.
- Soil suction at wetting front.
- Evapotranspiration surface depth.

The key parameters that were varied during calibration were the saturated hydraulic conductivity and the water content at field capacity. Varying the water content at field capacity in the MIKE-SHE model is one of the defining parameters in terms of when the soil storage capacity was “full.” When water content reached field capacity values, then runoff within that sub-basin increased dramatically. For example in spring 1976 a large portion of the basin had soil water content at field capacity, which created high runoff and a large flood. Parameter values are discussed in greater detail in Section 5, Calibration.

4.5 POTENTIAL EVAPOTRANSPIRATION

One of the key parameters developed outside the model was the potential evapotranspiration (PET) on a daily basis across each sub-basin. To calculate this, the Hargreaves equation was used (Hargreaves and Samani, 1982 and 1985). The Hargreaves equation is a relatively simple method which uses average minimum and maximum daily temperatures. Maximum and minimum daily temperatures at three stations (Brandon for the Assiniboine Sub-basin, Oxbow for the Souris Sub-basin and Cupar for the Qu’Appelle Sub-basin) were used to calculate PET (Figure 4-1).

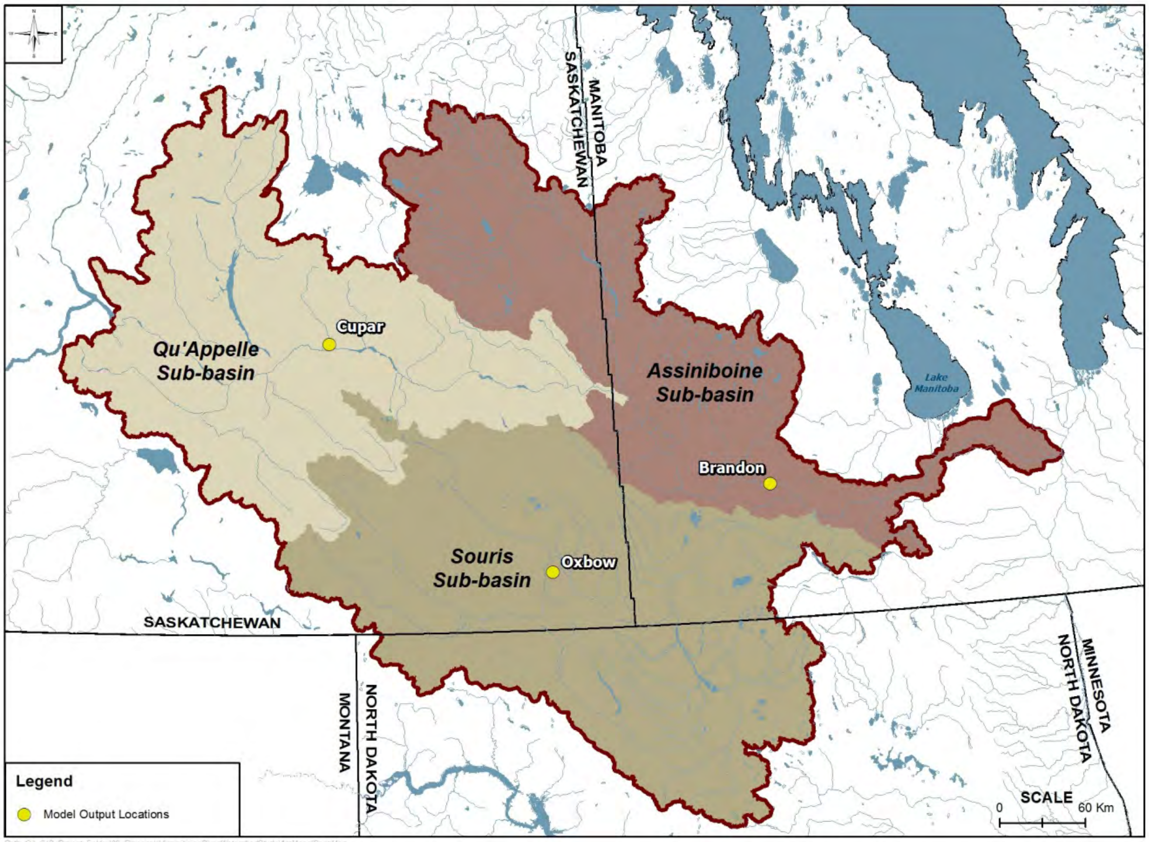

Figure 4-1: Stations Used for PET Calculations

The potential rates of evapotranspiration for the global climate model simulation output also had to be calculated for the historic period and the future scenarios. The global climate model output did not provide maximum and minimum daily temperatures so these were estimated based on the relationship of historic average versus maximum and minimum temperatures at the three stations (Brandon, Oxbow and Cupar; Appendix B). The PET was quite close between the historic measured data and baseline CRCM outputs (Figure 4-2). The full baseline output from 1961-2000 was trimmed to 1961 to 1990 to compare to the calibration period selected from the historic data (1961-1990). The PET for generated baseline data across the basin was also very consistent between the three stations used (Brandon, Oxbow and Cupar; Figure 4-3).

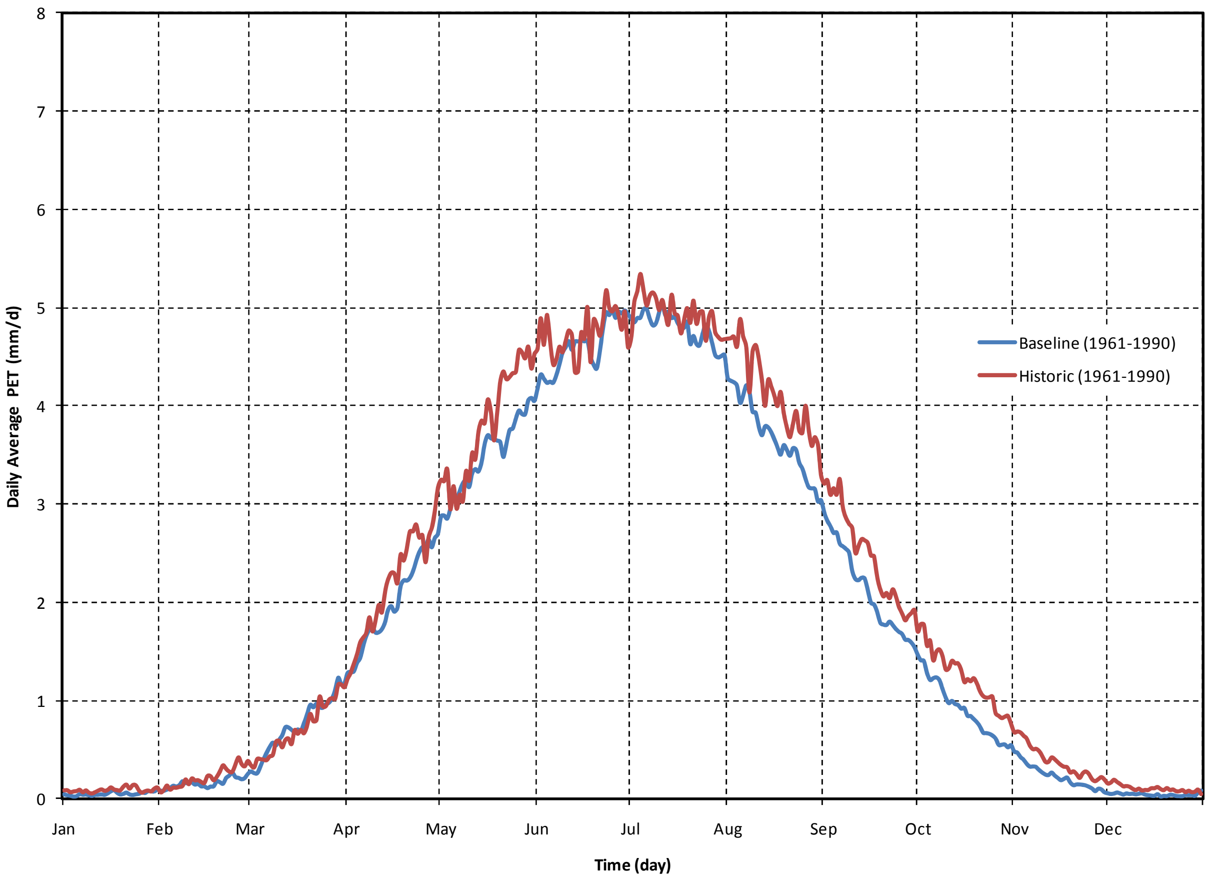

Figure 4-2: Potential Evapotranspiration Comparison at Brandon for the Historic and Baseline Conditions (1961-1990)

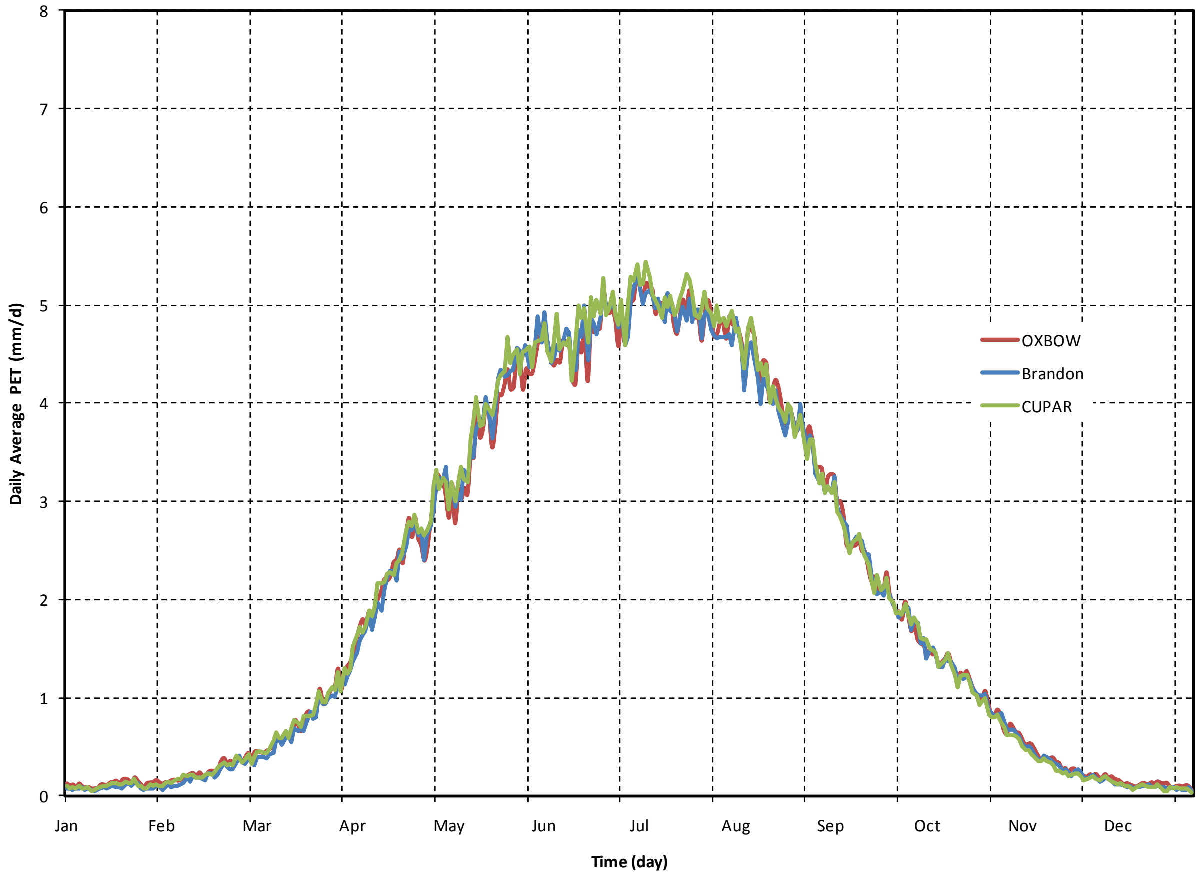

Figure 4-3: Potential Evapotranspiration Comparison at Three Locations in the ARB Baseline Conditions (1961-1990)

4.6 LAND COVER

The vegetative land cover is an important parameter in calculating changes in soil moisture on a day-to-day basis. Active vegetative land cover will increase evapotranspiration from the soil. As discussed earlier, the land cover throughout the ARB is dominated by cropland and pasture. The two modeled vegetative land cover parameters that can vary daily over the year are leaf area index (LAI) and active root depth (RD). In this model setup, the daily leaf area index and active root depth were the same for each cell across the whole ARB, but varied daily, dependent upon the expectant amount of plant activity which changes from season to season and day to day.

4.7 SOIL MOISTURE AND RUNOFF

Each 5- x 5-km cell uses all the parameters discussed in the model setup to calculate the key parameters such as soil moisture and runoff in each cell. Even though some of the parameters were constant across the whole sub-basin, other parameters such as digital elevation, precipitation and temperature varied for each cell. An example of an output calculation at a specific time is shown in Figure 4-4. This is an output from the MIKE-SHE model for soil moisture on November 15, 1975. It can be seen on this date that the soil moisture does vary across the basin, being wetter in some areas of the central and northeastern parts of the ARB, and being drier towards the northwest ARB. It should be noted that for each day the soil moisture is calculated for each one of these cells. Runoff is also generated in each of the cells across the ARB.

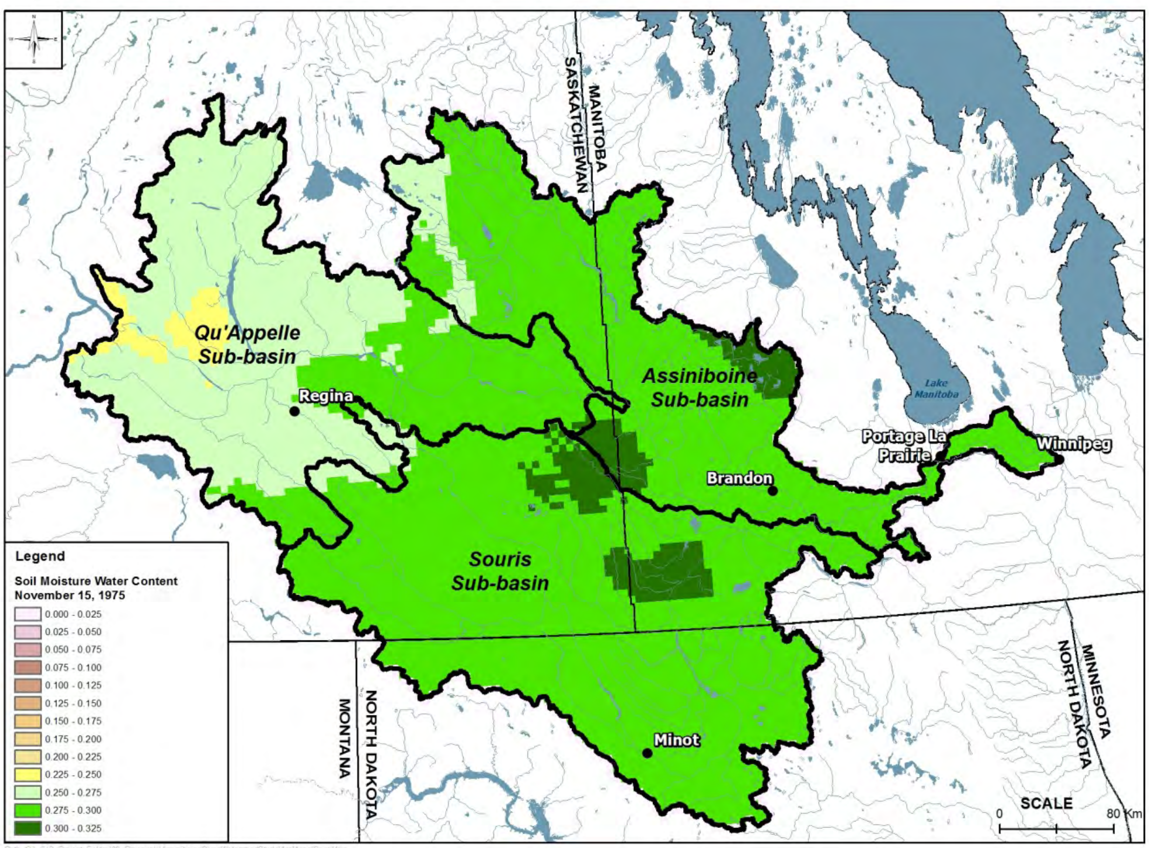

Figure 4-4: Soil Moisture (as fraction of soil by volume – November 15, 1975)

5.0 Model Calibration

Models are a mathematical approximation of physical systems. Calibration is a process wherein certain parameters of the model are altered in a systematic fashion and the model is run repeatedly until the completed solution matches the field observed values within a range that is considered acceptable. Model performance is measured in terms of the ability to reasonably predict key response variables such as streamflow. The hydrologic model for the Assiniboine River Basin was calibrated based on streamflow measurements for the period 1961 to 1990.

An iterative process was used for model calibration: Stantec would develop interim calibrations and review these results in meetings with a technical subgroup of the Technical Advisory Committee. Three meetings were held in June and July of 2011. The process was to present the calibration, receive feedback and refine the calibration before the next meeting.

The overall calibration strategy was to compare the model results to measured datasets for the complete period of record from 1961 to 1990. That period contained all seasons, drought years and wet years, as well as some high flood periods. As an initial step, the Stantec modelers would run the model for a shorter period of time. This was done because running the model for the full 30 years of record took considerable time (about three to four hours). There was an ability to run a five-year period in about 20 minutes and then process the data to compare against measured data. The period of record that was used for initial calibration was 1975 to 1980 as this period had a wide range of flow. It included the flood of 1976 and the extreme drought low-flow year of 1977. Once the calibration run matched well for the five years, the model was then run for 30 years and compared against streamflow records at the five selected locations within the study area.

The calibration was done by generating and comparing monthly flow duration curves (FDC) for model streamflow outputs and streamflow records (see Figure 5-1 for a typical FDC). The FDC is a plot developed by ranking the flows in order of magnitude and assigning a probability to each point, resulting in an actual percentage of events that a given flow rate will not be exceeded (i.e. % non-Exceedance). This type of curve gives a good range of the mean as well as the variation of flows at each station. If the mean and the variation of model generated flows at each station in the model are relatively similar to the historic measured flow, then it is considered calibrated at that location.

During the calibration period (1961 to 1990) various dams (e.g., Shellmouth Dam, and other works (e.g., Portage Diversion) were brought on line in the ARB, where it is not possible to vary physical parameters with time in the MIKE-SHE model. Manitoba Water Stewardship provided a streamflow dataset that had been adjusted to represent the historic flow without regulation. The model was calibrated to the “unregulated flow” dataset. This type of analysis is appropriate for the development of a hydrologic model calibrated to monthly flows.

Flow duration curves for the calibration were developed for stations at Headingley (which included Portage Diversion plus Headingley flows), Brandon, Welby, Russell and Wawanesa (Figure 5-2). The model was run on a daily basis and daily outputs were generated. The output data was then post-processed to calculate monthly streamflow for each month from 1961 to 1990. This was then matched to the measured monthly streamflow at each of those stations.

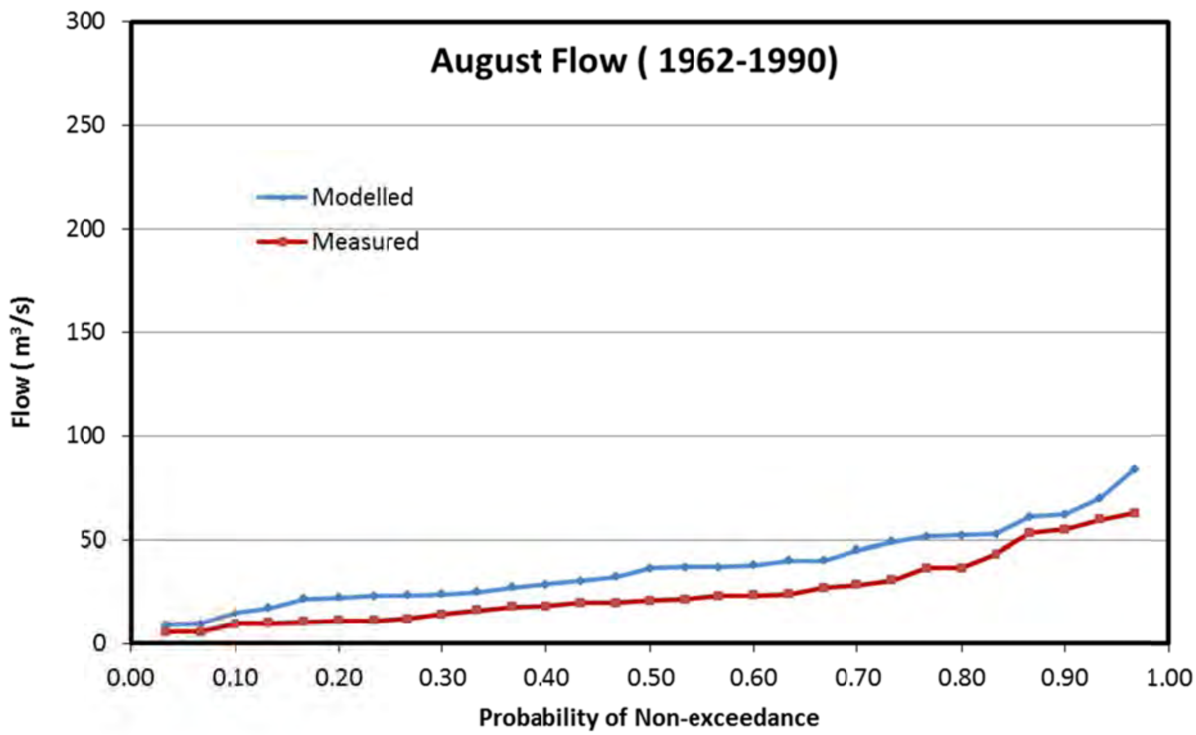

Figure 5-1: Monthly Flow Duration Curve for Headingley

Some of the key parameters are selected and remain the same for each of the runs, such as the elevation of each of the cell, while other key parameters were varied during each model run. Although the parameters are set for each cell, they were often set the same across the whole ARB or the same for each sub-basin (Qu'Appelle, Souris or remaining ARB sub-basin). Our approach was to start with a common ARB-wide value and then compare how well the modeled output matched the measured data. Initially, the total flow at Headingley was compared and then moving upstream, comparisons were made with predicted and measured flows at Brandon, Russell, Welby and Wawanesa. To match flows at Wawanesa or Welby, parameters within the sub-basins upstream of those stations were varied. Flows were not calibrated to a single spring flood or a single year but were matched to 30 years of data at five stations for all 12 months for droughts, floods, and all flows in between.

Various parameters were adjusted during calibration until modeled monthly FDC for all five hydrometric stations were reasonably accurate representations of the historic measured flow data. The entire procedure took 59 iterations of the calibration process and post-processing of data to review streamflows and soil moisture. Discussions on the key parameters that were selected in the final calibration and how these input parameters were arrived at follows below.

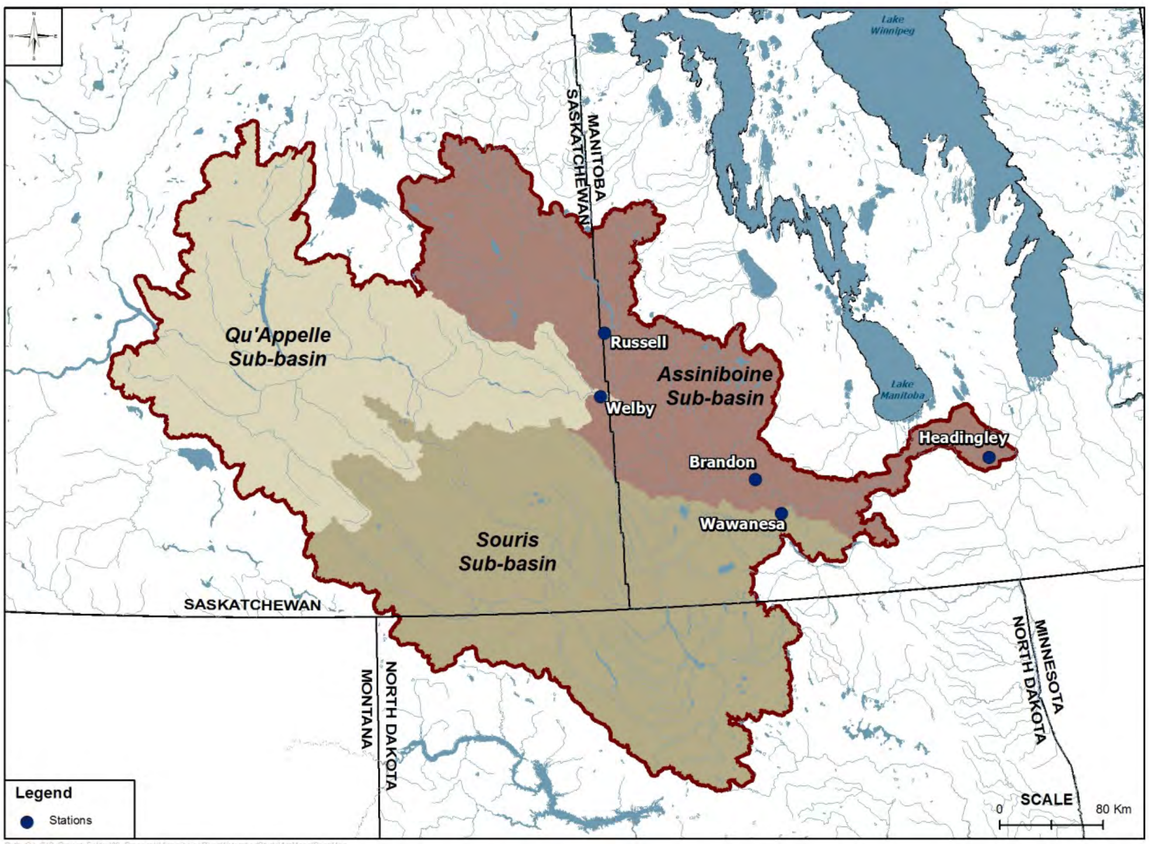

Figure 5-2: Model Calibration – Key Stations

5.1 SNOWMELT PARAMETERS

The threshold melting temperature is the average daily temperature in which the snow starts to melt. The threshold melting temperature was found to be -3°C. This is the average daily temperature at which snow starts to melt. Snow will not melt at exactly -3°C, but on a day when the average temperature is -3°C, the daytime temperature would generally rise above 0°C melting temperature and be as high as +5°C. Using -3°C as the threshold temperature resulted in modeled decrease and disappearance of the snowpack generally matching decrease and disappearance of the actual snowpack. If the threshold melting temperature was set higher, snowmelt occurred too soon and the spring peaks of snowmelt would occur too early in the year. If the threshold melting temperature was set lower, observed March snowmelt did not occur in the model.

The rate at which snow melts is described by the degree-day coefficient. This was set to 1.5 mm/°C/day. Degree day coefficient is the amount of snow that melts per day for every degree the air temperature is above the threshold melting temperature (-3°C). Figure 5-3 shows the total snow pack at one sample location in the ARB. The increase in the snow pack depth is dependent on how much snow falls over the winter, while the drop in snowpack depends upon the snowmelt parameters discussed above.

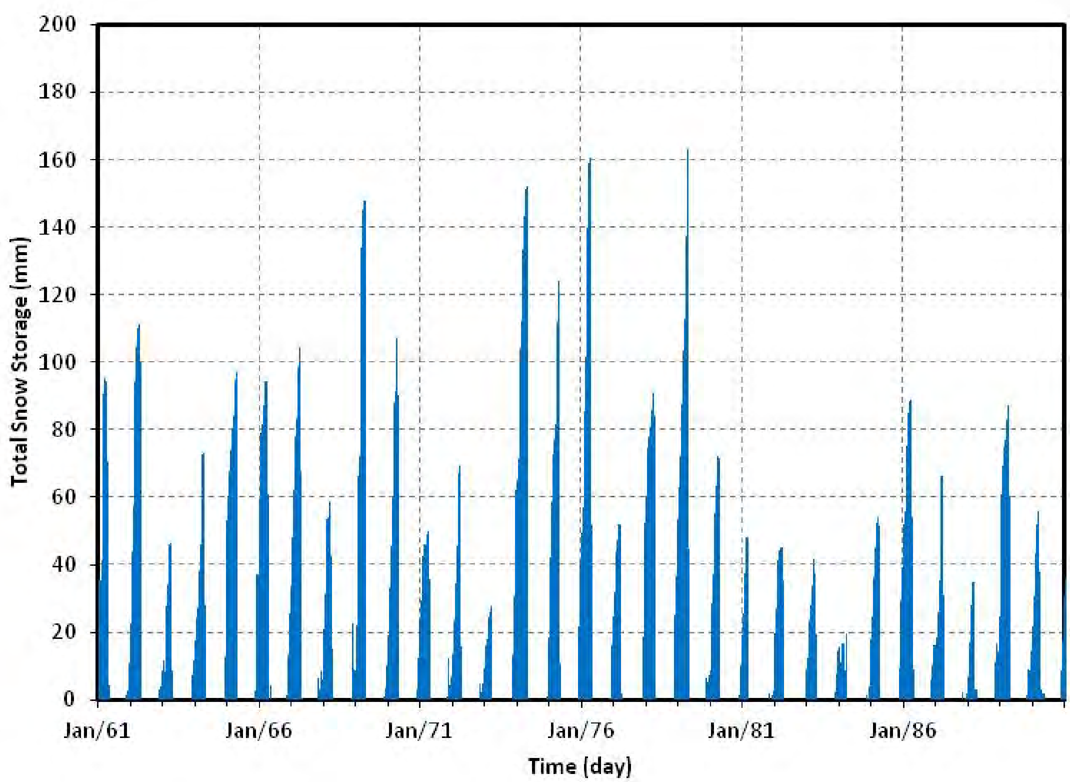

Figure 5-3: Modelled Snow Storage at One Location in the Model (near Brandon)

5.2 SOIL PARAMETERS

The soil parameters determine water storage and runoff in the unsaturated zone of the soil. The unsaturated zone is soil above the groundwater table. These parameters are critical in determining how much water can be stored in the soil in each cell in the model and how much will run off and flow into surface watercourses. The parameters for soil storage are shown in Table 5-1. Water content at saturation, water content at field capacity and water content at wilting point are used as parameters to describe critical stage of water content in the soil.

- **Water Content at Saturation (Porosity** or **Void Fraction)** is a measure of the void (i.e., "empty") spaces in a material, and is a fraction of the volume of voids over the total volume, between 0–1, or as a percentage between 0–100%. For example, If the porosity is 0.4 (40%) water content at saturation will be 0.4 of total volume.

- **Water Content at Field Capacity** is the maximum amount of soil moisture or water content as a fraction of the total volume that can be held in soil after excess water has drained away and the rate of downward movement has materially decreased.

- **Wilting Point** (**WP**) is defined as the minimal point of soil moisture the plant requires not to wilt. (Was not a critical parameter in this study).

- **Saturated Hydraulic Conductivity**, symbolically represented as K, is a property of soil or rock that describes the ease with which water can move through pore spaces or fractures.

- **Soil Suction at Wetting Front** controls the rate of infiltration.

Table 5-1: Soil Parameters Used in Model Calibration

Parameter	Value			Unit
	Assiniboine	Souris	Qu'Appelle	
Water content at saturation (porosity)	0.4	0.4	0.4	unitless
Water content at field capacity	0.305	0.305	0.305	unitless
Water content at wilting point	0.1	0.1	0.1	unitless
Saturated hydraulic conductivity (K)	7.50E-08	5.50E-08	6.50E-08	m/s
Soil suction at wetting front	-0.2	-0.2	-0.2	m
ET surface depth	0.5	0.5	0.5	m

The experience with the model indicated the critical factor in determining rate of runoff during spring melt and/or rainfall is water content at field capacity, which is consistent with historical experience in flood forecasting. Once the water content increased so that it was beyond field capacity, runoff dramatically increased in the model. Another important factor is the saturated hydraulic conductivity which governs the rate at which water can enter the soil or else runoff over land. These parameters were adjusted during calibration for each sub-basin and it was found that they were essentially the same for all sub-basins. The only varying factor was the hydraulic conductivity which was still within an order of magnitude indicating very little variation for this type of parameter.

5.3 LAND USE PARAMETERS

The amount and type of vegetative land cover will control the rate of evapotranspiration. The key parameter is the Leaf Area Index (LAI). This parameter represents the density of active crop growth during the growing season. In the MIKE-SHE model it is an index of the area of leaves above the unit area of ground surface and it ranges from 0 to 7, with 0 being no leaf area and 7 being full coverage (7 being the highest value). It was found that for the ARB calibration, LAI was at the maximum value during June to August. This maximum value was required to obtain the evapotranspiration needed to calibrate the model. It was then reduced to 3 during the month of September, at which time the plant cycle of life is waning or crops are being harvested. Table 5-2 shows final calibrated leaf area index values for all cells across the ARB by month.

Another key model parameter is active root depth (RD). This parameter indicates the depth at which the root can take moisture from the unsaturated zone. It varies over the year, as shown in Table 5-2. It was found that from late fall to early spring (October to April) active root depth would be set at 0, indicating no evapotranspiration was occurring. Various calibration runs included some level of active root depth in May, although it was found that the best calibrations occurred with active route depth set to 0 in May. Active route depths were highest in June and July (1,700 mm), and then decreased in August and again in September (1,200 mm and 400 mm respectively.

Table 5-2: Land Use Parameters Used in Model Calibration

Parameter	Oct-Apr	May	June	July	August	Sept	Unit
LAI	0	0	7	7	7	3	
RD	0	0	1700	1700	1200	400	Mm

5.4 OVERLAND FLOW

The key parameter for predicting the rate of overland flow was the Manning's number "M", which is the inverse of the Manning's coefficient "n." M represents the resistance of the ground surface on overland flow ("roughness") and was set at 1.5 (this is equivalent to a Mannings 'n' of 0.67, or very high) indicating high resistance to overland flow (Oogathoo, 2006). Detention storage represents the amount of overland flow that would be held in low areas on the landscape and was set at 20 mm for the total surface area of the Assiniboine Sub-basin and at 30 mm for the total surface areas of the Souris and Qu'Appelle sub-basins. Table 5-3 shows parameters used in overland flow. These parameters were not very sensitive because overland flow was not a driving factor in the runoff. The model does not simulate overland flow directly, but used linear reservoir to simulate flow as discussed below.

Table 5-3: Overland Flow Parameters Used in Model Calibration

Parameter	Value			Unit
	Assiniboine	Souris	Qu'Appelle	
Manning Number (M = 1/n)	1.5	1.5	1.5	$m^{(1/3)}/s$
Detention Storage	20	30	30	mm

5.5 SATURATED FLOW (BASE FLOW)

The parameters used in the linear interflow and base flow (groundwater) reservoirs are shown in Tables 5-4 and 5-5 respectively. The linear interflow reservoir is a single simulated reservoir substituted for storage in the actual myriad potholes, wetlands and rivers, which are too numerous and complex to be modeled individually. Linear reservoir parameters were adjusted in calibration to shape modeled streamflow hydrographs to match historical measured streamflow hydrographs. The linear interflow reservoir also accounts for storage within the creeks and rivers as flow moves downstream.

Table 5-4: Interflow Reservoir Parameters Used in Model Calibration

Parameter	Value	Unit
Specific yield	0.3	unitless
Interflow time constant	100	day
Percolation time constant	120	day
Bottom depth	5	m
Threshold depth	5	m

Table 5-5: Base Flow Reservoir Parameters Used in Model Calibration

Parameter	Value	Unit
Specific yield	0.35	unitless
Time constant for base flow	730	day
Dead storage fraction	0.4	unitless
UZ feedback fraction	0	unitless
Threshold depth for base flow	6	m
Depth to the bottom of the reservoir	6	m

The interflow time constant regulates how much flow moves towards the river, while the percolation time constant regulates how much flow moves into the base flow or groundwater reservoir.

The groundwater reservoir parameters (Table 5-5) control the base flow that occurs over the winter. In this case base flow has a very high base flow time constant of 730 days, which was used to regulate the base flow towards the river from the groundwater. Specific yield, the fraction of the volume of pore space in the aquifer was set at 0.35. Other parameters such as the fraction of dead storage (0.4 or 40%) indicate the percentage of the groundwater flow lost to deep groundwater storage which does not reach the river system. No feedback to the unsaturated zone (UZ) was used in this calibration.

5.6 RIVER HYDRAULICS

The major channels in the ARB were modeled with a MIKE11 hydraulic model linked to the MIKE-SHE hydrologic model. Figure 5-4 shows the location of the MIKE11 model channels within the ARB (Assiniboine, Souris, Qu'Appelle). These were simple, uniform cross-sections to assist in transferring hydrographs downstream. The Manning coefficient for the channels was n=0.035. The kinematic wave method was used for routing. With this routing method, there is very little hydrograph transformation, i.e., flattening as the hydrograph moves downstream to account for storage transformation.

As discussed earlier (in Section 5.5), the system storage from rivers, wetlands and potholes in overland flow is accounted for in the detention storage and interflow basins. To calibrate the low-flow conditions which occur in late fall and into the winter, a parameter was needed to account for water losses that are likely due to evaporation from multiple reservoirs in the Souris and Qu'Appelle area. Water will be lost from the river system due to evaporation occurring in the reservoirs. MIKE11 has no parameter that directly allows for this phenomenon. There are however leakage parameters that allow for either loss or gain from the river channel to the groundwater. Table 5-6 shows the parameters for leakage, either gaining or losing in the MIKE11 model. Gaining indicated flow is moving into the channel while losing indicates flow is leaving the channel. The Souris and Qu'Appelle channels were modeled with a leakage coefficient. The Assiniboine River was modeled with a gaining coefficient to match the local inflow around the Assiniboine Delta Aquifer.

Table 5-6: MIKE11 Parameters Used in Model Calibration

Parameter	Value			Unit
	Assiniboine	Souris	Qu'Appelle	
Leakage coefficient	1.00E-07	1.00E-20	1.00E-20	l/s
Reach type	Gaining	Losing	Losing	

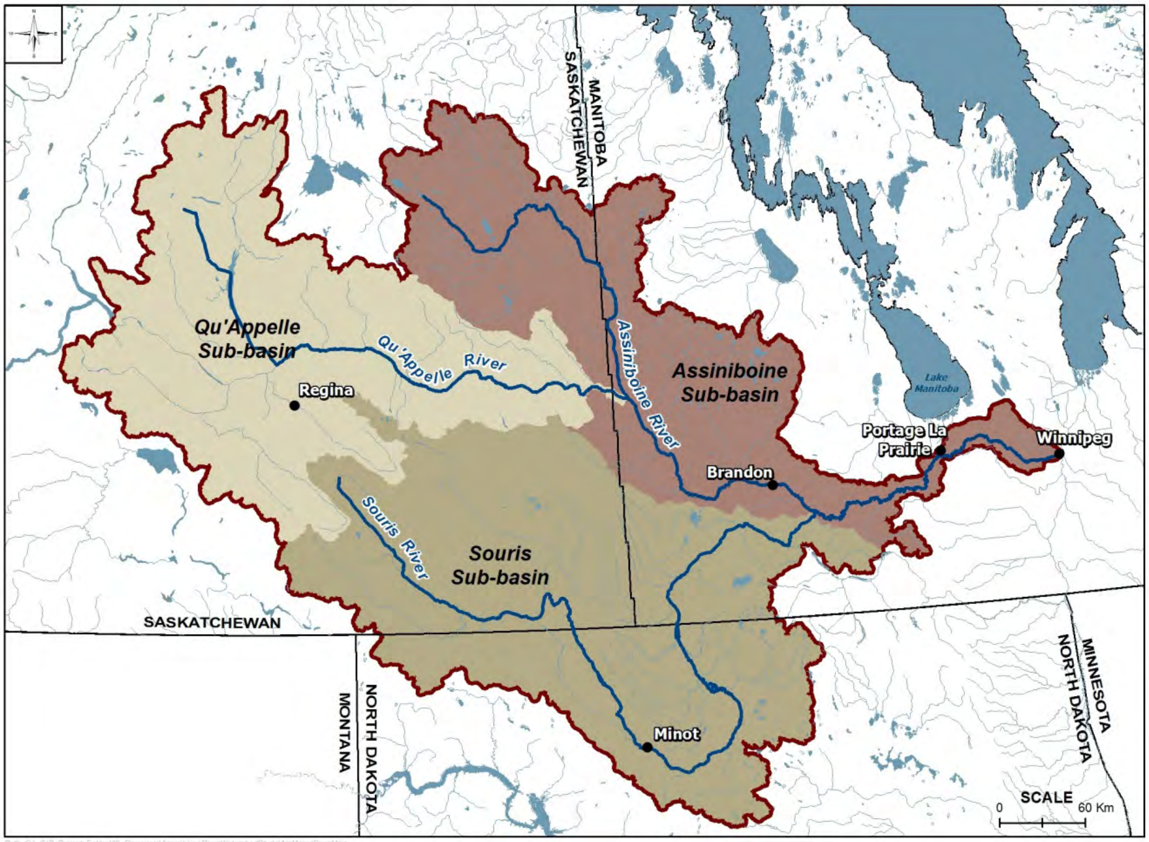

Figure 5-4: MIKE11 Model Channels Used

5.7 SOIL MOISTURE CAPACITY – KEY TO RUNOFF GENERATION

The key to simulating runoff generation on prairie watersheds within the ARB using MIKE-SHE is determining the point at which soil moisture has reached the level where runoff will dramatically increase. The two key parameters calibrated to record data to produce the volume of runoff were field capacity and active root zone depth in each month.

It was found that when soil moisture reached the level of field capacity, then runoff and interflow started increasing dramatically. Soil moisture increases when snowmelt or rainfall adds to the soil moisture in a specific cell. Evapotranspiration removes soil moisture from each cell. Evapotranspiration is driven by temperature and active root zone. In this model daily evapotranspiration for each cell is calculated from the interpolation of recorded temperature data from meteorological stations for each day from 1960 to 1990. The active route zone was estimated and varied for each day of the year to control the simulated soil moisture across the basin.

The years 1975, 1976, and 1977 represented the significant potential for flooding when soil moisture is high. Figure 5-5 shows soil moisture in the watershed as calculated by the MIKE-SHE model for November 15, 1975. This date was chosen because it was one of the highest soil moisture levels on record going into winter, resulting in the spring 1976 flood, the highest on record until 2011. Figure 5-5 shows that certain parts of the basin have soil moisture at or above field capacity, while much of the basin is just below field capacity. Only areas to the west in the Qu’Appelle watershed have lower soil moisture. Figure 5-6 shows a dramatically different condition one year later. On November 15, 1976, soil moisture was relatively low, at about 65% of field capacity throughout the basin. Spring 1977 runoff was minimal because of low fall soil moisture and a low snow pack in late winter. When the snow pack melted in, there was not enough moisture to bring the soil moisture at field capacity across the basin.

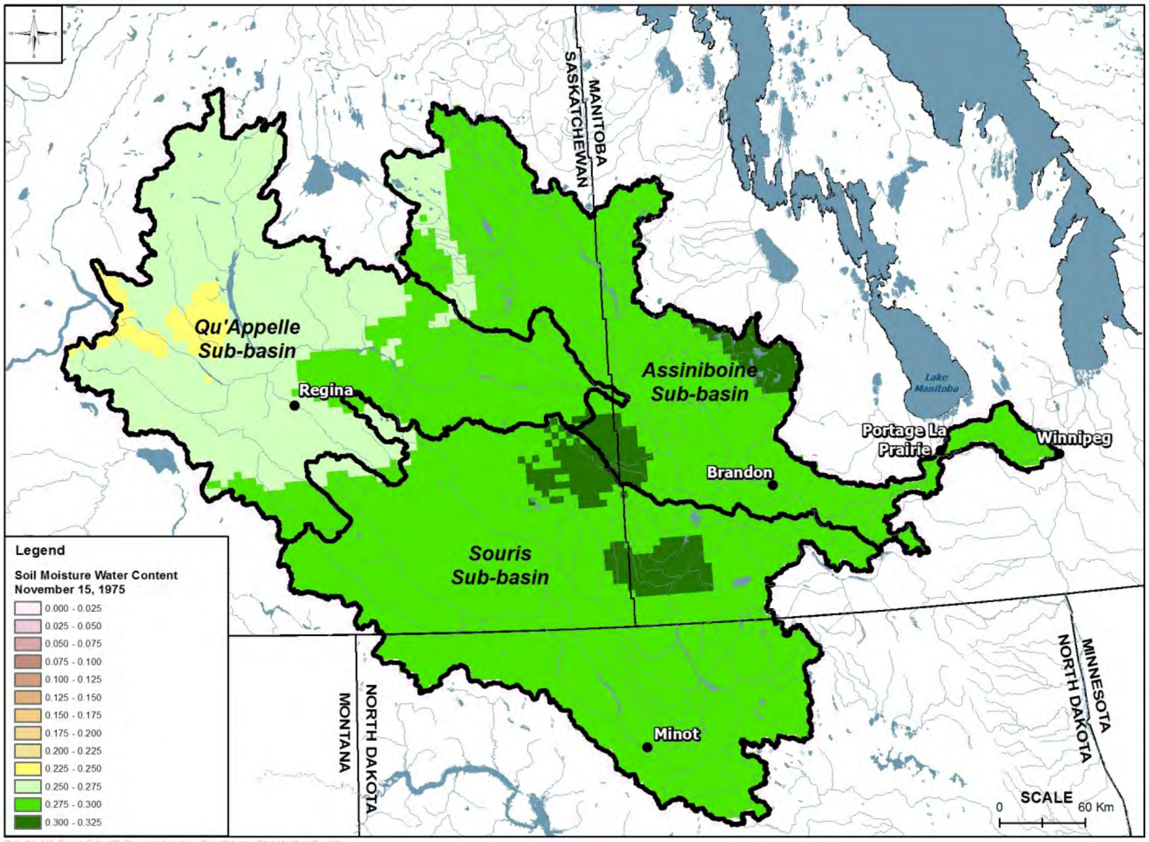

Figure 5-5: Soil Moisture (November 15, 1975)

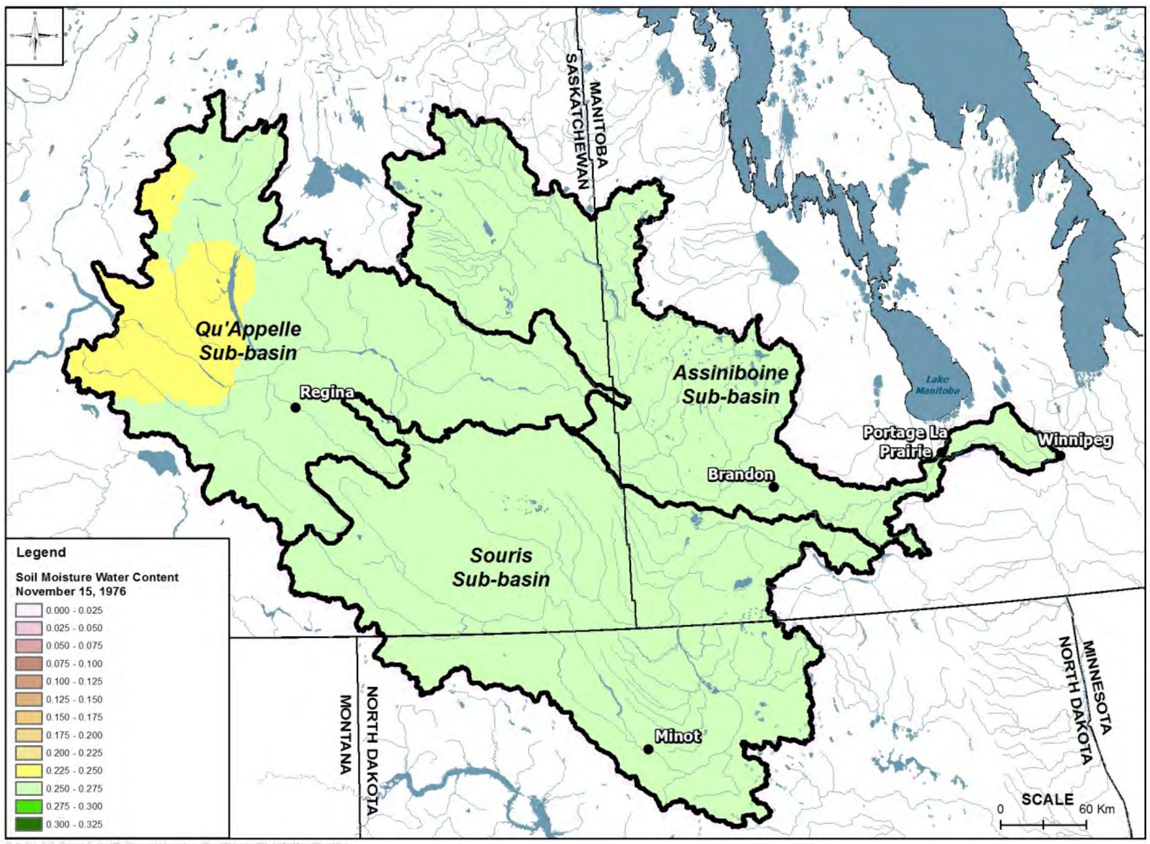

Figure 5-6: Soil Moisture (November 15, 1976)

Another key driving factor in terms of spring floods is the snow pack available for snowmelt and runoff at the end of winter. Melting snowpack increases soil moisture in the spring leading to large runoff. As mentioned before the years 1976 and 1977 data provided the significant potential for flooding where March 15, 1976 had very high snow pack across the ARB (Figure 5-7), coincident with areas (Figure 5-5) that had high soil moisture. One year later, on March 15, 1977, the snow pack was virtually non-existent throughout most of the basin (Figure 5-8); hence, 1977 became a drought year.

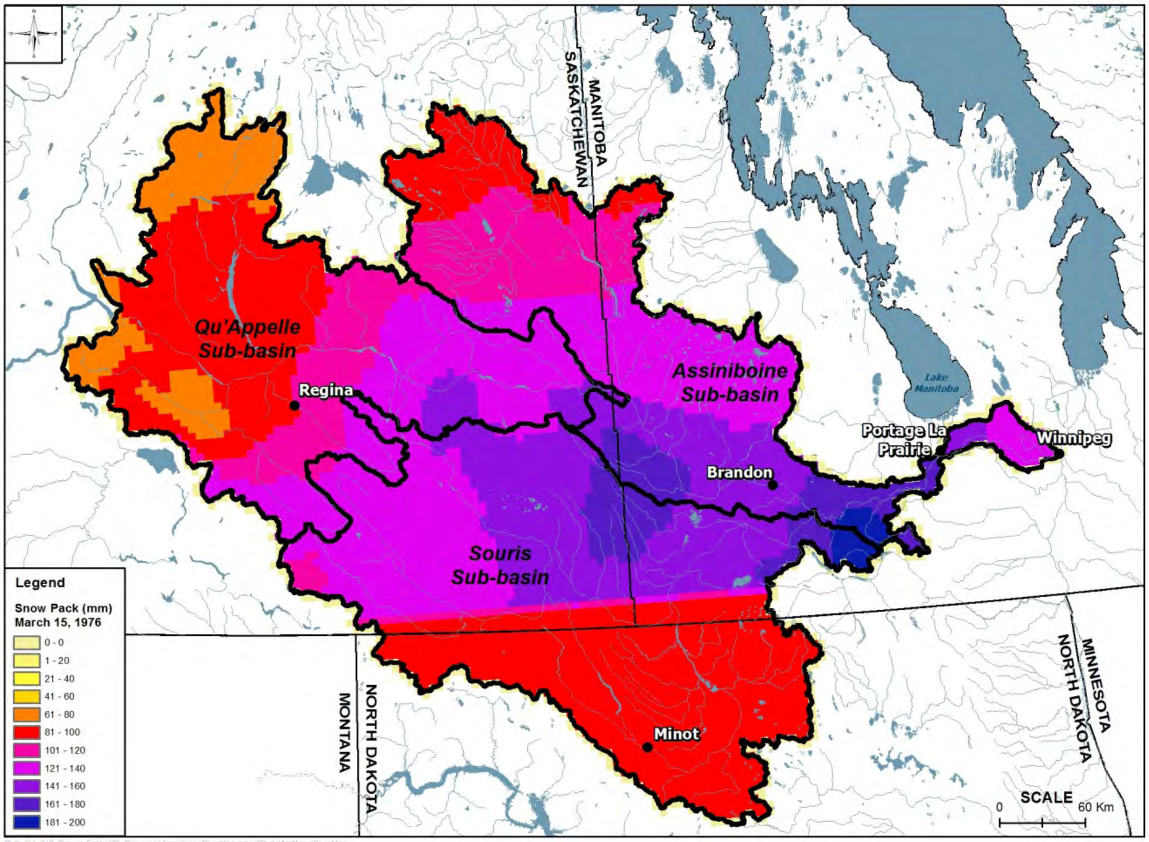

Figure 5-7: Modelled Snow Pack (Equivalent Moisture March 15, 1976)

The above discussion focused on soil moisture throughout the basin at one snapshot in time, where soil moisture is modeled and varies on a daily basis throughout the year. In order to show variation throughout the year and from year to year, three representative stations within the basin were selected and a soil moisture time series was shown for each stations from 1975 to 1980 (Figure 5-9). The three stations chosen are Cupar representing the Qu'Appelle sub-basin, Oxbow representing the Souris basin, and Brandon representing the Assiniboine sub-basin.

Soil moisture varies seasonally. Each spring when the snowmelt occurs, soil moisture increases throughout the basin and then will drop over the summer as evapotranspiration removes moisture from the soil. Once fall comes in October (fall starts September 21), evapotranspiration becomes very limited and any further precipitation prior to freeze-up will increase soil moisture. For example, in 1975 soil moisture increased dramatically in the fall to fairly high levels in the Assiniboine and Souris sub-basins. Then when spring came in 1976, the high snow pack across the ARB melted and increased the soil moisture to full capacity during the months of April and May. This resulted in a large runoff which caused the flood of 1976. That summer offered very little rainfall and warm temperatures, and soil moisture dropped dramatically to very low levels across the basin by October 1976. The next spring when snowmelt occurred, neither the soil moisture nor the snow pack was high enough in any of the locations shown on Figure 5-9 to cause significant runoff. Figure 5-10 shows monthly streamflow for Headingley, which demonstrate how soil moisture can affect stream runoff in the basin. Note the large flood in spring 1976 following a wet fall and heavy winter snows, followed by several years where there was little flooding. Concurrent with increased soil moisture, another flood occurred in spring 1979.

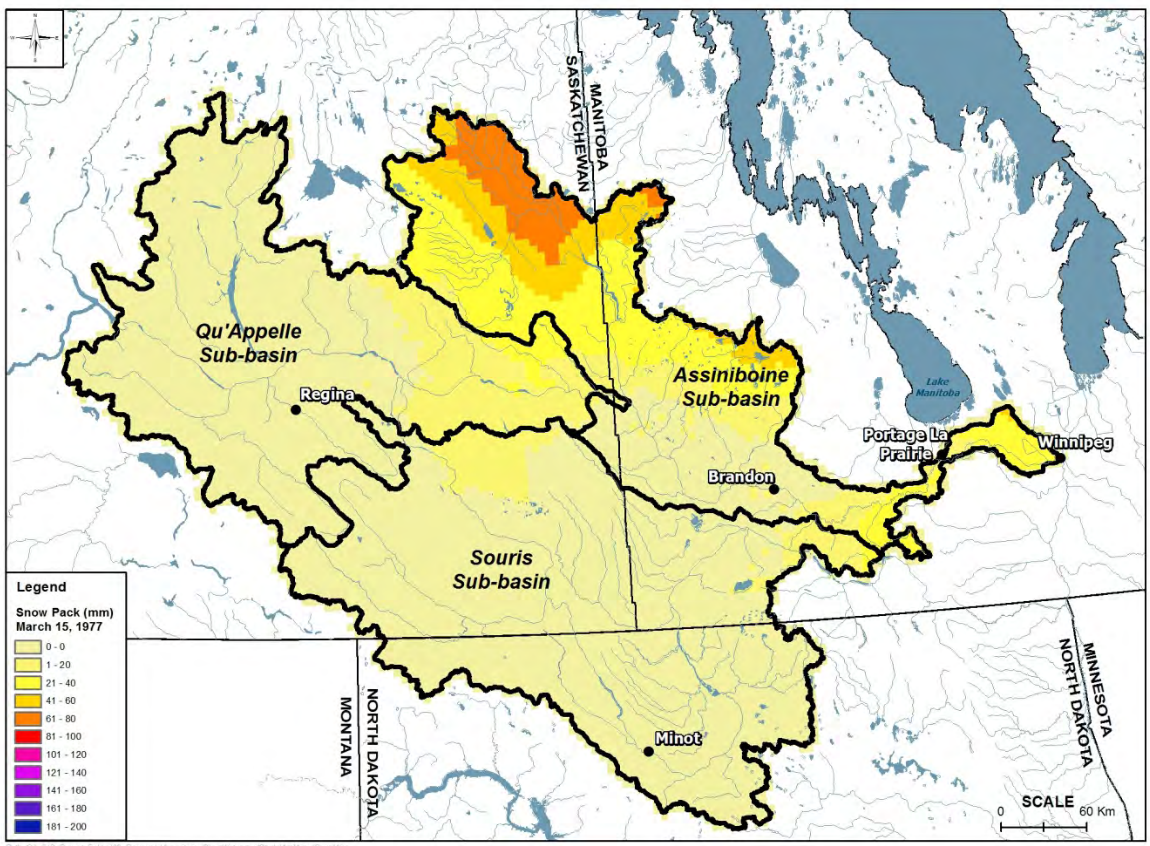

Figure 5-8: Modelled Snow Pack (Equivalent Moisture March 15, 1977)

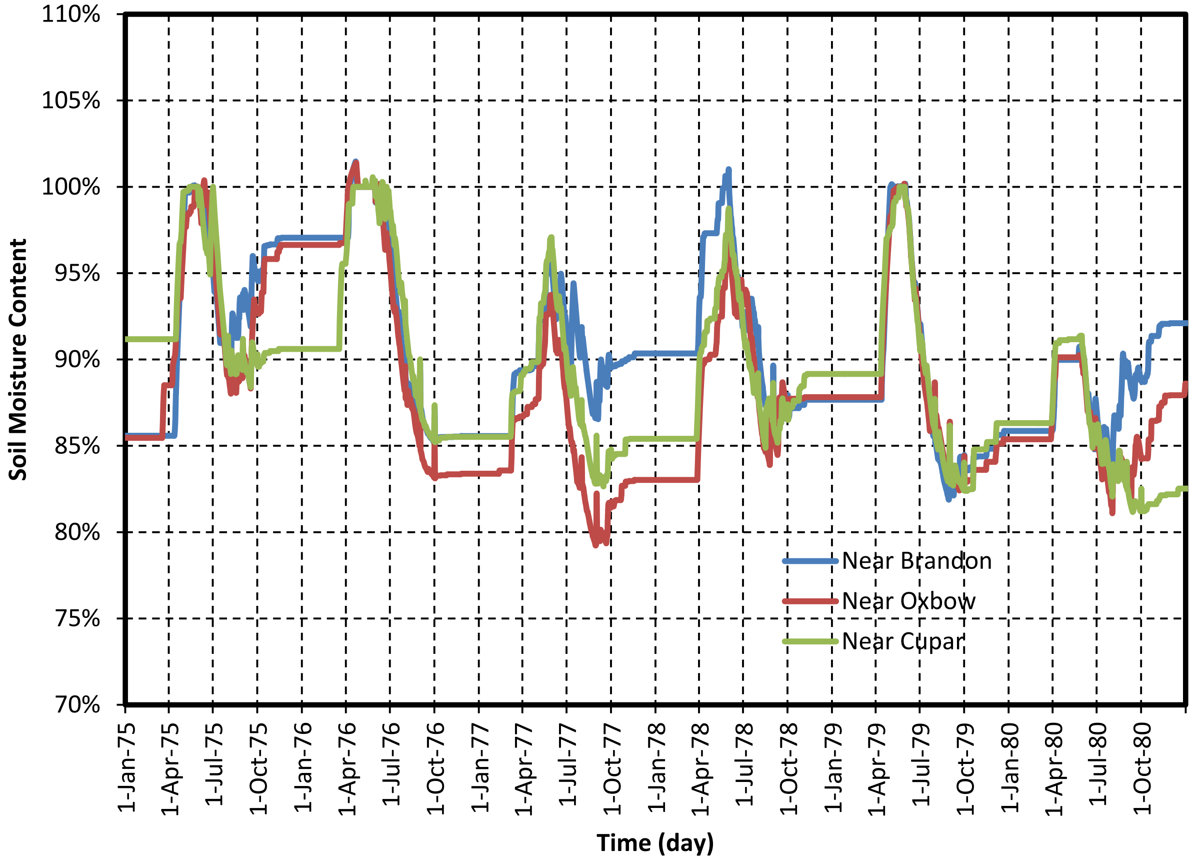

Figure 5-9: Model Results – Soil Moisture – Percent of Field Capacity

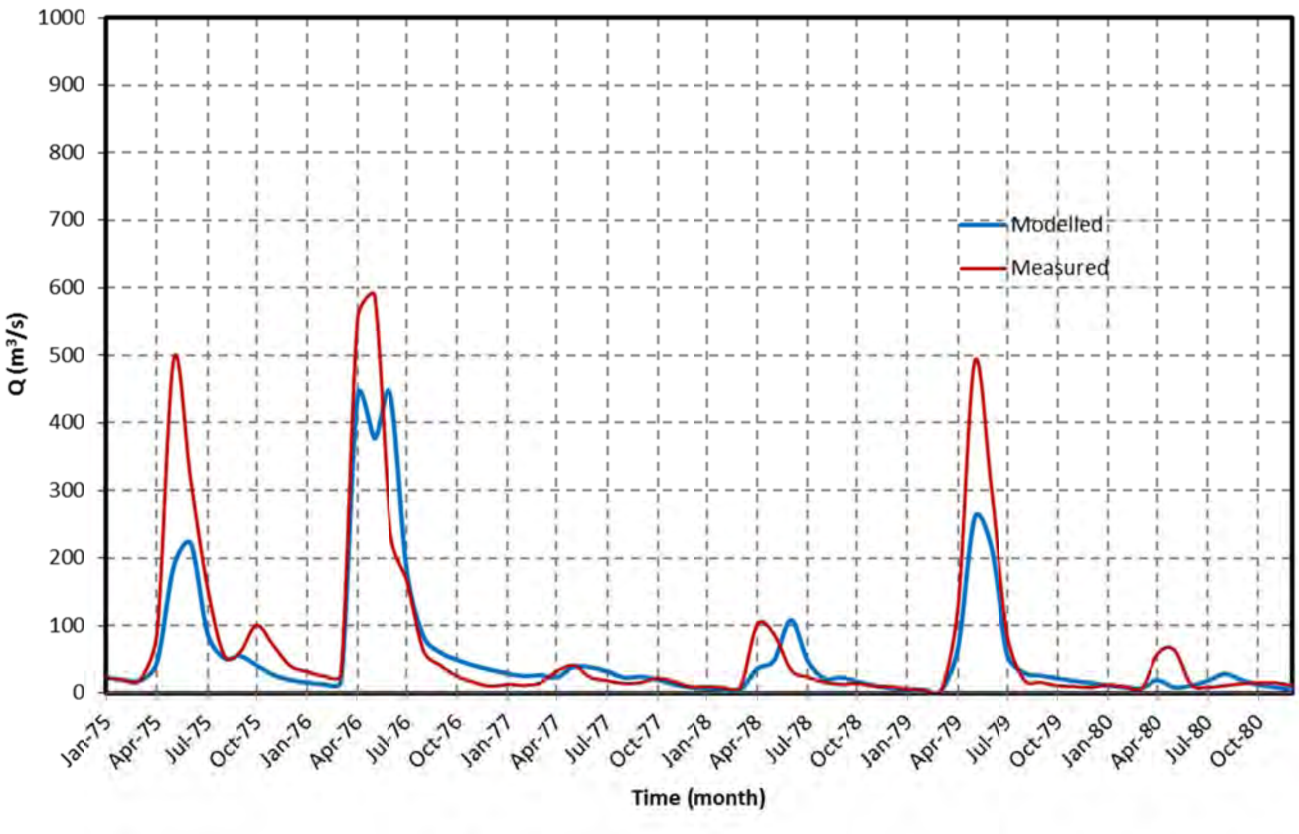

Figure 5-10: Monthly Runoff Headingley (1975-1980)

5.8 MONTHLY FLOW CALIBRATION

The model was run for a 30-year period from 1961 to 1990 on a daily time step from which average monthly flow was calculated. The first year 1960, does not provide an accurate prediction, as the hydrologic model needs to stabilize for about a year before it starts predicting accurately. This “spin-up” period is necessary because all model parameters start at 0, and a full year is needed to stabilize calculated parameters at expected conditions. Once the monthly flows are calculated, calibration was checked by comparing monthly predicted flows to monthly measured flows. This checking is done in two ways, as follows.

First, a time series of modeled and recorded data are plotted and compared (Figure 5-11). The comparison indicates that sometimes flows are under predicted and sometimes they are over predicted.

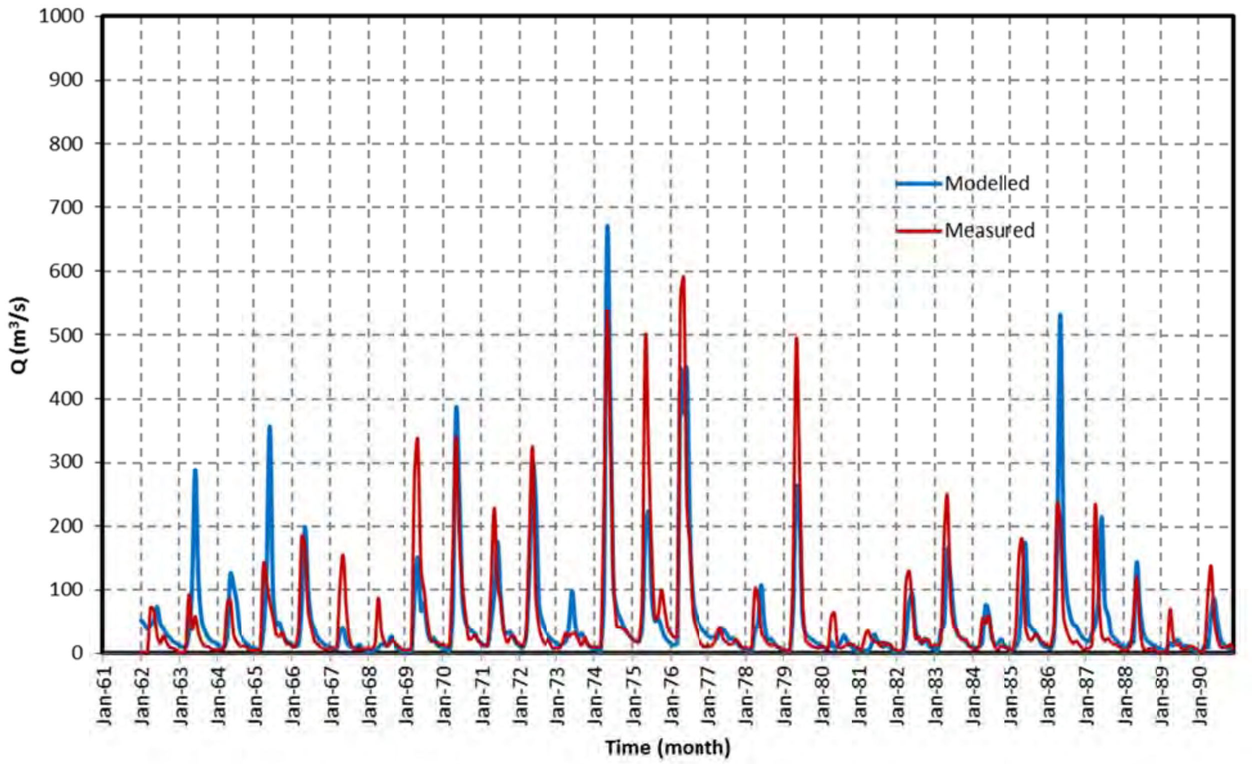

Figure 5-11: Time Series of Monthly Flows Headingley (1960-1990)

Secondly, in order to determine whether monthly flows are accurate in terms of the mean monthly flow and the variation of monthly flows, a flow duration curve of measured and modeled and 30 recorded monthly flows for each month of the year at each of the five stations was chosen for calibration. As there are 30 years of data, there are 30 monthly flows available for each month of the year. These flows are ranked from highest to lowest and then plotted on a flow duration curve. Figure 5-12 shows a flow duration curve for the month of May at Headingley. The ranked flows are plotted from left to right, with the lowest flow on the left and the highest flow on the right. The ‘x’ axis represents the probability that the flow is not exceeded. The 50% (0.50) probability is the median flow for that month. The 90% (0.9) probability indicates 90% of the measured or predicted monthly flows would be less than the 90% measured and modeled flow values. These graphs are useful in understanding whether the model is calibrating average flows, low flows and high flows accurately. If the modeled flows at the 90% (0.90) probability are higher than the measured flows, then flood flows are being over predicted. If modeled flows at the 10% (0.10) probability are less than the measured flows, there is likely not enough base flow occurring in the model.

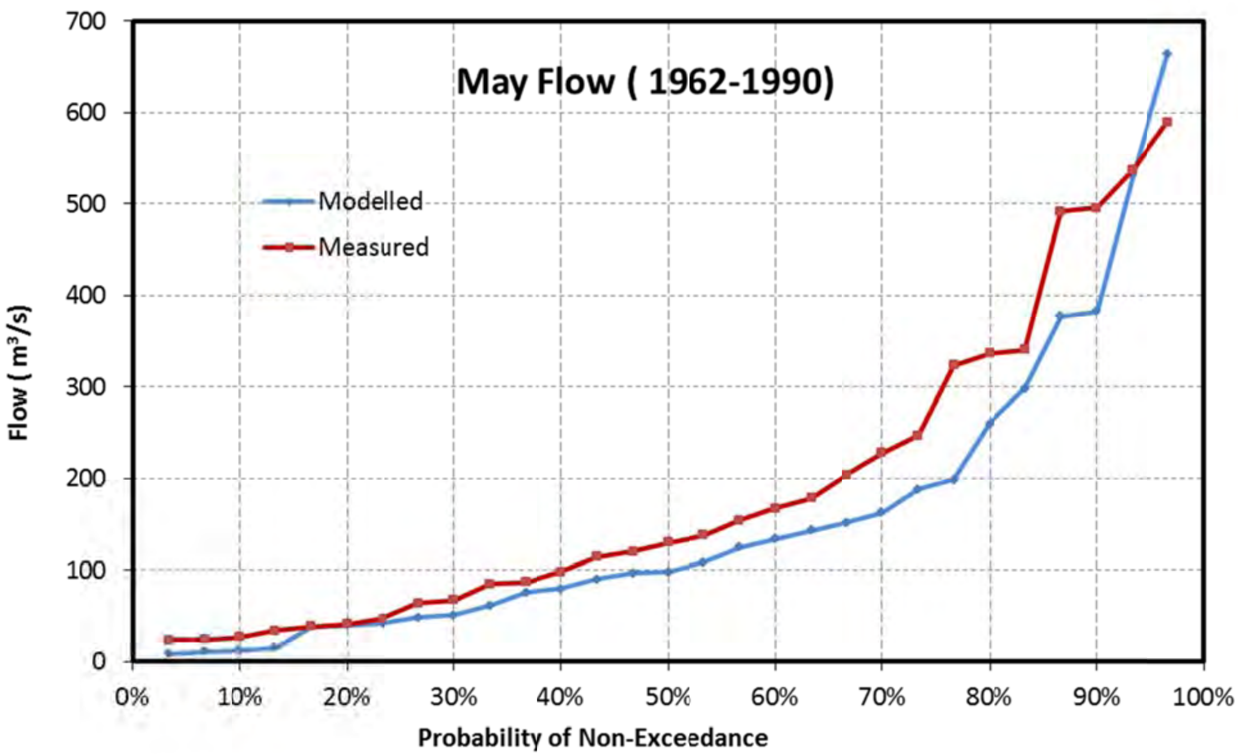

Figure 5-12: Monthly Flow Duration Curve for Headingley

For example, it was found that the modeled low flows in November, December and January were too low compared to historical values. This indicated that more base flow from groundwater was entering the rivers than the model predicted. An adjustment to baseflow interflow time constant was made in the calibration to correct modeled base flow.

Flow duration curves of unregulated flows at five locations throughout the basin were compared on a monthly basis for modeled and recorded historical data. The locations are as follows:

- Headingley, which includes the Portage Diversion plus Headingley flows, is a measure of overall flows in the ARB.
- Brandon was used as an intermediate flow measuring combined flows from flows the Qu'Appelle and Upper Assiniboine rivers.
- Wawanesa was a measure of flows coming out the Souris River basin.
- Welby was a measure of flows coming out the Qu'Appelle River basin.
- Russell was a measure of flows coming out of the Upper Assiniboine basin.

Flow duration curves for each of the above described stations, on an annual basis and for each month, are shown in Appendix C.

The calibration indicated that the model represents hydrology of the ARB reasonably well, and could therefore be used to compare streamflow and soil moisture of modeled historical data (using historical meteorological inputs) versus modeled climate-change scenarios data (using regional climate model generated meteorological inputs) over the 21st century.

5.9 STATISTICAL ASSESSMENT OF CALIBRATION

In order to assess the predictive power of the ARB hydrological model, the Nash–Sutcliffe model efficiency coefficients were calculated for the five hydrometric stations. The Nash–Sutcliffe model efficiency coefficient (E) is defined as (Nash and Sutcliffe, 1970):

$$E = 1 - \frac{\sum_{t=1}^{T}(Q_o^t - Q_m^t)^2}{\sum_{t=1}^{T}\left(Q_o^t - Q_{o,avg}\right)^2}$$

where Qo is observed discharge, Qm is modeled discharge, and Qo,avg is average observed discharge. Generally, Nash–Sutcliffe coefficient ranges from $-\infty$ to 1 with a value of 1 indicates a perfect match of modeled discharge to the observed data (i.e., the closer the model efficiency to 1, the more accurate the model is). An efficiency of 0 indicates that the model predictions are as accurate as the mean of the observed data, whereas efficiency less than zero occur when the observed mean is a better predictor than the model.

Table 5-7 shows the Nash–Sutcliffe coefficient values for the ARB at Headingley, Brandon, Wawanesa, Welby and Russell. As shown in this table, the predictive power of the model at Headingley, Brandon, Wawanesa is better than the observed mean as the coefficients at these hydrometric stations are positive. Whereas, at Welby and Russell hydrometric stations, the observed means at the respective stations are better predicator than the model.

Table 5-7: Nash-Sutcliffe Model Efficiency Coefficients

	Headingley	Brandon	Wawanesa	Welby	Russell
Nash-Sutcliffe Coefficient (E)	0.59	0.47	0.42	-1.38	-1.00

6.0 Model Verification and Uncertainties in the Hydrologic Model

To verify the calibrated model results, a separate independent set of data was used to compare modeled and measured flows. Meteorological data from 1991 to 2003 was used as inputs into the ARB model, and then modeled streamflows were verified against historical streamflows at the five calibration stations (Headingley, Brandon, Wawanesa, Russell and Welby). Flow duration curves for each station were developed using the model outputs and the measured data. The flow duration curves for annual average flow and each monthly flow are shown in Appendix D.

The model verification generally shows the model was well calibrated, although does not perfectly match every flow. Given model verification is not a second calibration step; input parameters are not readjusted to match historical flows more closely. The verification illustrates how accurate any future predictions may be. This verification shows that although most of the years were predicted fairly well in the verification, 5-10% of the years are not predicted accurately. This relative accuracy can be extended to use of the ARB MIKE-SHE hydrologic model in general, where the model will replicate most years very well and a smaller proportion poorly.

A review of input parameters indicates that the most likely reason for an imperfect calibration and verification is limited rainfall and precipitation data across the Canadian portion of the prairies. Precipitation between widely spaced meteorological stations is highly uncertain where the data used is extrapolated. The methods used to do the precipitation interpolation were developed by NRCan, have been reviewed in published papers, and therefore are likely the best methods available. Model calibration would be improved in future by increasing the number of permanent meteorological stations throughout the prairies. Another major reason for error is simulation of flow changes caused by operation of over 100 storage reservoirs was not explicitly modeled. Instead, reservoirs storage effects were simulated using non-site-specific interflow reservoirs in MIKE-SHE and evaporation losses were accounted for using the leakage coefficient in MIKE11.

Another uncertainty is the lack of detailed understanding of the land cover and cropping practices and the inability to model this as a changing variable. These factors would likely change from year to year and this change is not considered in the ARB MIKE-SHE hydrologic model. The time that a crop is planted in the spring will change the evapotranspiration from the soil, a critical factor in the hydrologic model.

The developed MIKE-SHE model forms the hydrologic basis for development of a more sophisticated operation model that could be used to forecast daily flows. It would need added details such as storage reservoirs and more detailed channel representation within the connected MIKE11 model to be used for operational purposes. Another factor that may be important, however cannot be determined at this time, is that a detailed large model may have run times so long that it may make the use of MIKE-SHE impractical for operation purposes.

7.0 Uncertainties Arising from the Climate Model Input Data

7.1 UNCERTAINTIES RELATED TO CANADIAN REGIONAL CLIMATE MODEL

There is inherent uncertainty in developing a model for predicting future hydrological changes due to various factors such as uncertainties due to limitations in the calibration of the ARB hydrologic model. These factors include:

- A lack of understanding of the physical basin parameters.
- A lack of good data on the key drivers such as precipitation (there is limited information between sparse meteorological stations).

The limitation and uncertainty due to the ARB hydrologic model were discussed in the Model Verification and Uncertainties in the Hydrologic Model (Section 6.0). This section deals with uncertainties related to use of CRCM data in projecting future potential hydrologic scenarios. Uncertainties are inherent in the CRCM's ability to predict temperature and precipitation for current conditions, as evidenced where the "baseline" MIKE-SHE run using CRCM data for 1961-1990 could not be closely verified against either the MIKE-SHE "modeled" run using historic data or "measured" historic data.

MIKE-SHE generated streamflow data calibrates reasonably well to recorded historical flows where the MIKE-SHE model uses historical input data (comparison of "modeled" to "measured" streamflow). MIKE-SHE generated streamflow data does not calibrate well to historical data where the MIKE-SHE model uses CRCM (AET) generated input data for the 1960 to 1990 period (comparison of "baseline" to "measured" streamflow). It is not realistic to expect the "baseline" data to produce "calibrated" results as the CRCM is not calibrated to the ARB and only produces one possible realization of the climate that could be expected for the atmospheric carbon dioxide (and other greenhouse gases) assumed in the model run.

It should be recognized that projections of climate far into the future (2080s) will be less certain than those in the near future (2020s). This model uncertainty is due to uncertainty in the emission scenarios for greenhouse gases (see Section 3.6).

To understand how CRCM generated data may create uncertainty in ARB MIKE-SHE model outputs, CRCM AET daily precipitation and temperature outputs were used as ARB MIKE-SHE model inputs and flows were simulated from 1961-1990 at each calibration station. This is the MIKE-SHE "baseline" run, which was then compared to "measured" (recorded historical) and "modeled" (MIKE-SHE) 1961-1990 streamflow data, as follows. Annual and monthly flow duration curves were developed for the baseline run and compared with measured and modeled flow duration curves. Headingley annual average curves are shown in Figure 7-1. The full set of flow duration curves for selected hydrometric stations is in Appendix E. The biggest difference in flows comes in May and June when ARB baseline model results using the CRCM model input produce higher than expected average and flood flows. Low flows are similar in magnitude.

To compare the difference between the measured flow data, the calibrated model predictions and the flows simulated using the climate model input data, average annual hydrographs were developed. These "average" hydrographs are shown in Figures 7-2 and 7-3 at Headingley and Brandon. These "average" hydrographs indicate that the calibrated dataset matches the measured annual volume of flow fairly well, although the peak in spring occurs slightly later than the measured data indicates. The CRCM baseline data also shows later floods but at peaks that are measured 20-30% higher at Headingley or Brandon on average.

The foregoing indicates that when combining the CRCM (AET) and MIKE-SHE models (hydrologic and climate models), uncertainties in model prediction increase. These uncertainties are taken into consideration when assessing the final results of climate change scenarios.

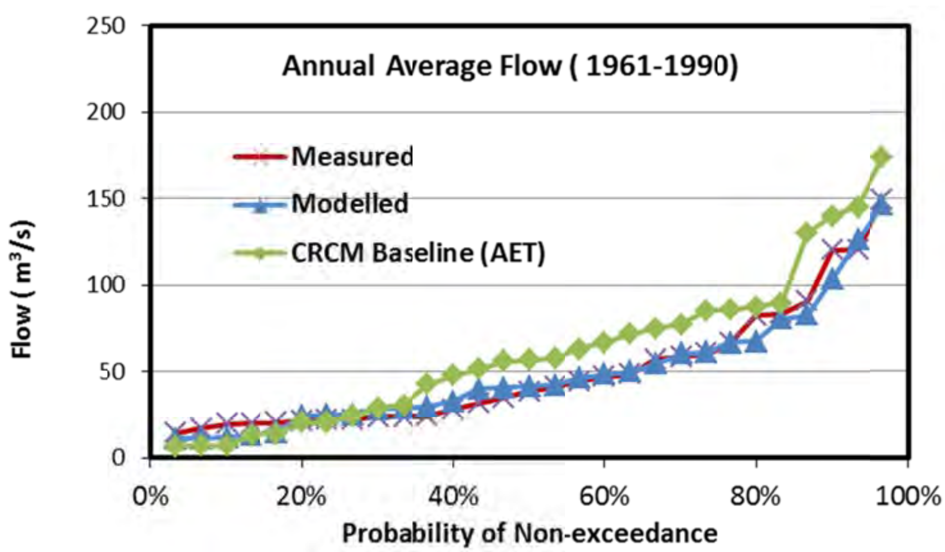

Figure 7-1: Annual Flow Duration Curves for Headingley

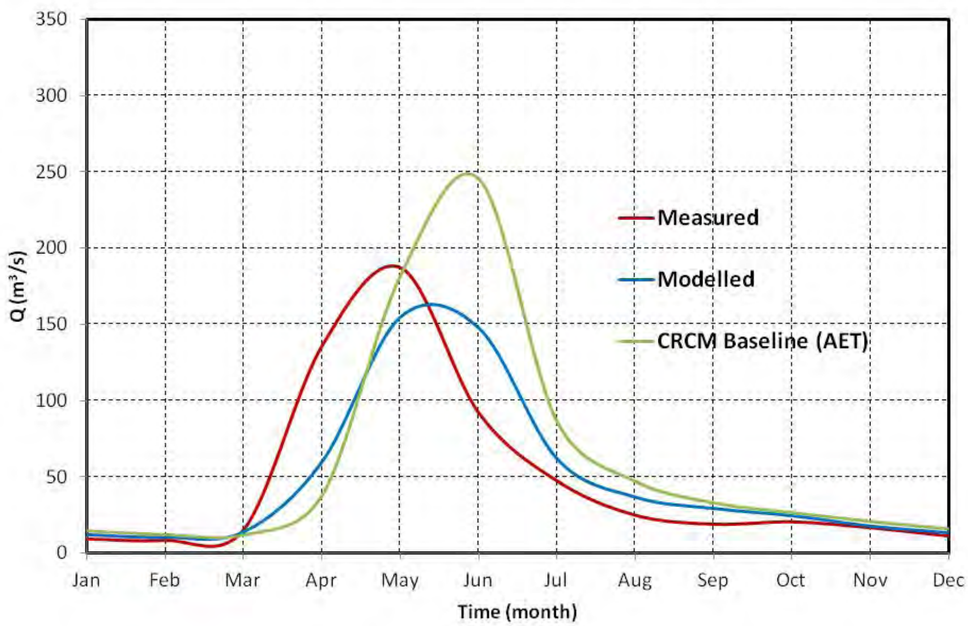

Figure 7-2: Average Monthly Hydrographs for Headingley (measured, modelled and CRCM Baseline Model)

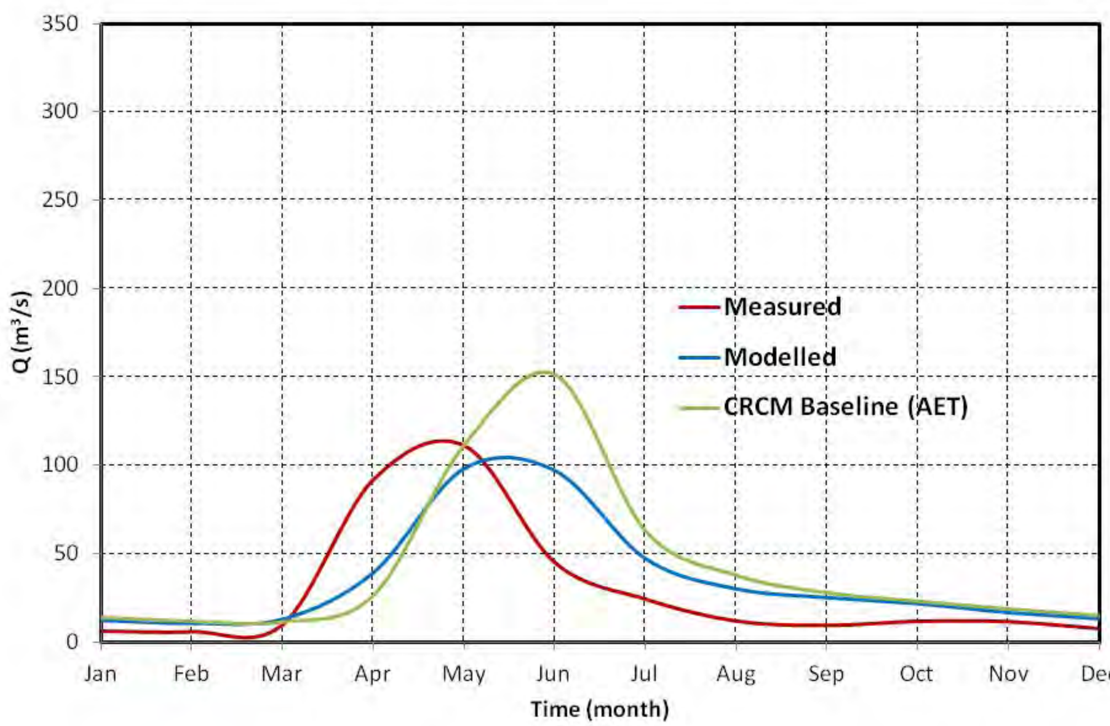

Figure 7-3: Average Monthly Hydrographs for Brandon (measured, modelled and CRCM Baseline Model)

7.2 ADJUSTING RESULTS TO PREDICT FUTURE CHANGES FROM CURRENT HISTORIC FLOWS

When future streamflows and soil moisture are predicted using Canadian Regional Climate Model output from 2011 to 2099 for MIKE-SHE modeling, spring floods are over predicted due to the biases in the climate model precipitation outputs.

A bias is when a model consistently under- or over-predicts an output parameter. Uncertainty is when the model both under- and over-predicts the parameter. Temperature outputs from the baseline model (aet) show a bias in that the simulated temperature is lower than the historic data. Temperatures predictions are 5°C lower than historical data in the summer months although are closer to historical normals during the critical spring months.

Precipitation was consistently over-predicted during the 1961 to 1990 baseline simulation period. It is expected that this over prediction will continue in the projection of future precipitation over the next 90 years.

Adjustments to soil moisture and streamflow results will be required to remove some of the biases created by the climate model precipitation output. Ideally, future GCM and CRCM models will become more sophisticated and provide outputs with no or limited temperature and precipitation bias in their output. However the current practice is that it is the responsibility of the data user to understand and compensate for the bias to suit their needs.

There are two conceptual methods that could be used to remove this bias, as follows.

The first method would be to adjust the temperature and precipitation inputs that are provided from the climate model in order to better match the measured data. There are many practical difficulties in performing CRCM output adjustments. The historic precipitation datasets provided by NRCan are on a 10- x 10-km grid across the ARB. The climate model results are on a 45- x 45-km grid which does not align with the historic results. The bias in precipitation may be spatially distributed across the ARB and would need to be corrected differently for each area. The monthly bias for each 45-km x 45-km grid point could be calculated and then the ratio calculated to adjust each daily precipitation at each of the grid points. The application of methods to adjust the bias in CRCM precipitation output over the ARB is beyond the scope of this study but should be considered in future studies.

If the three available CRCM model runs (aet, aev, agx) showed different biases then using ensemble averages could possibly correct the bias. As shown in Section 3.0 (Figure 3-11) all three CRCM model runs showed the same precipitation biases so this method would not correct the bias.

A second and simpler method was adopted, in which the flow duration curves developed for future scenarios were compared to “baseline” instead of “measured” or “modeled” streamflow data. For example, if a predicted flow from a **future** scenario climate model run at Headingley is 20% higher at a probability of 5% exceedence than the **baseline** climate model run, then it would be assumed that future predicted flow at Headingley would be 20% higher than **measured** flow at a probability of 5% exceedence. This adjustment is done for each probability on each of the three future scenarios. More discussion on the steps used in correcting the biases on soil moisture (Section 8.3) and streamflow (Section 8.4) are presented in the following Section.

8.0 Results from the Future Climate Change Scenarios

8.1 REVIEW OF HISTORIC FLOW DURATION CURVES

To provide perspective into predictions of changes in flows in the next century, a review of flows at Headingley in the last 97 years was undertaken. Flows at Headingley plus the Portage Diversion were adjusted to create an unregulated flow scenario and then used to perform an analysis to assess natural variation in flows over the past century. The period of record was divided in simple thirds as follows:

- from 1913 to 1944 (32 years)
- from 1945 to 1976 (32 Years)
- from 1977 to 2009 (33 years)

Flow duration curves for each of these periods were calculated and are shown on Figure 8-1. The first duration curve (Figure 8-1A) shows the average annual flow at Headingley. This curve illustrates that there is a large natural variation in flows over the past century. The median flow (0.5 or 50%) ranged from as low as 38 m^3/s in the early part of the century, to as high as 58 m^3/s in the middle period of the last century. This is a 50% difference in flow. The late part of the century had flows in between the other two periods. This indicates the historic variability that has occurred in the last century and could be expected to occur in the next century, even without climate change. The flow duration curves for the maximum daily peak flow is also shown in Figure 8-1B. As well, the historic flow duration curves for the month of May are shown in Figure 8-1C.

These flow duration curves indicate that from the early to middle part of the 20th century, monthly May flows could vary by as much as 50-80%, depending on the probability of exceedance of any given flow value .

This analysis highlights the wide natural variability of flows in the ARB, including major floods and droughts greatly affecting measured flows. Even with the assumption of a constant CO_2 level, annual flow volumes can vary widely, and even 30-year average flows can vary by more than 50%, depending on the relative magnitude of the driving mechanisms like precipitation, soil moisture, temperature, snowmelt and others. When 30-year-flow scenarios under future CO_2 condition are simulated it will be difficult to separate natural variability from hydrologic changes driven by climate change.

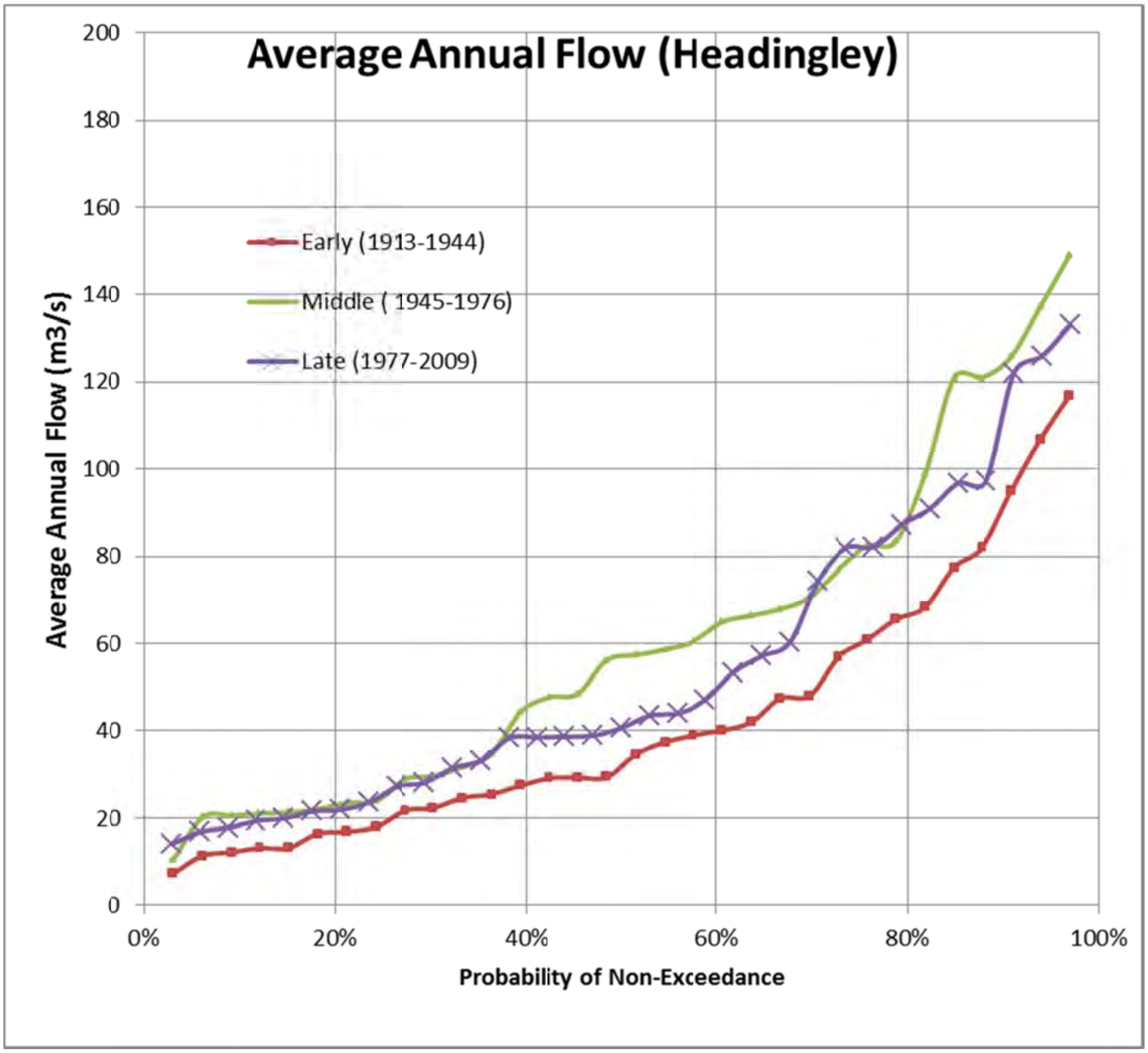

Figure 8-1A: Historic Range Flows at Headingley (last 100 years unregulated)

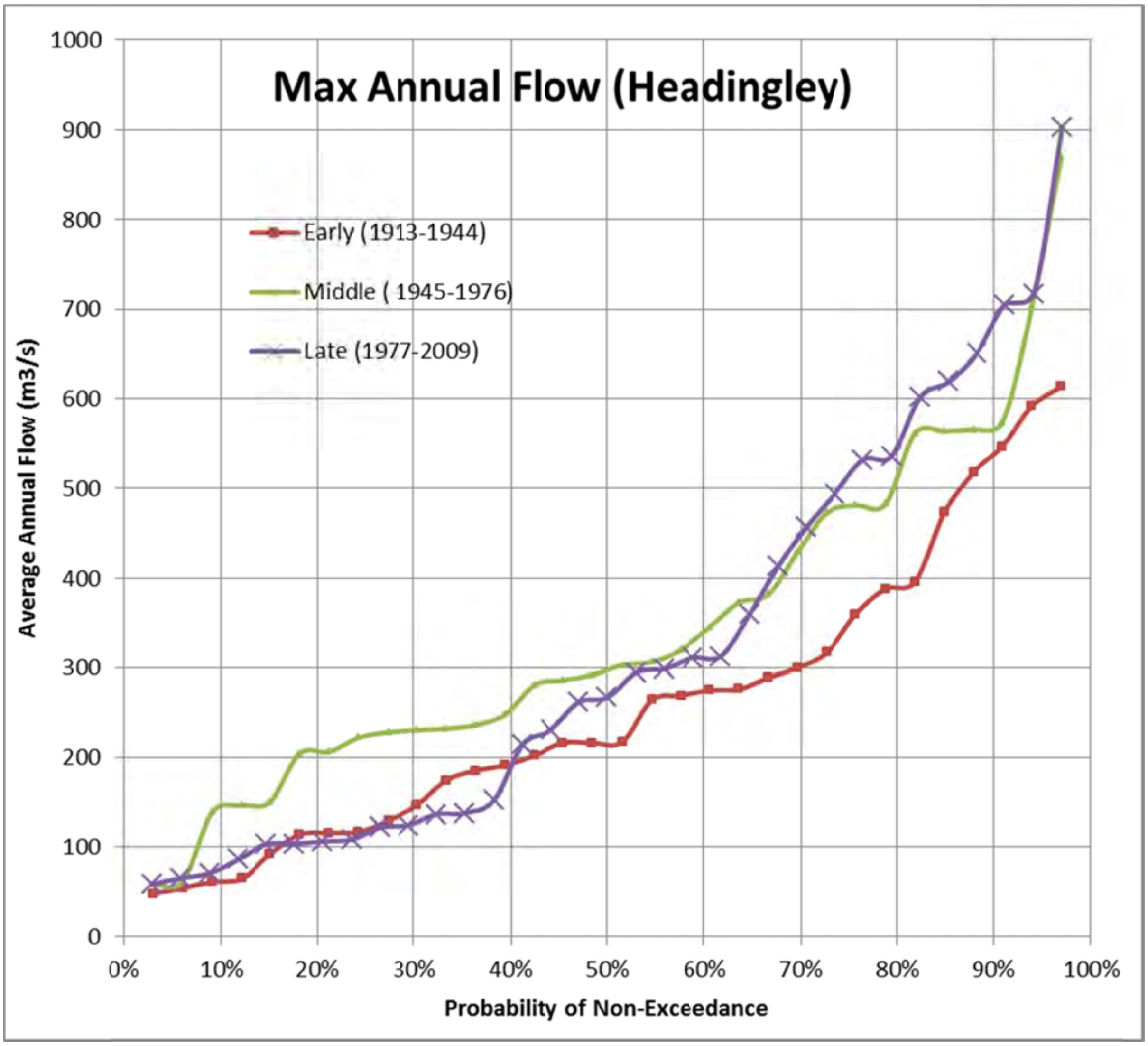

Figure 8-1B: Historic Peak Day Flows Each Year

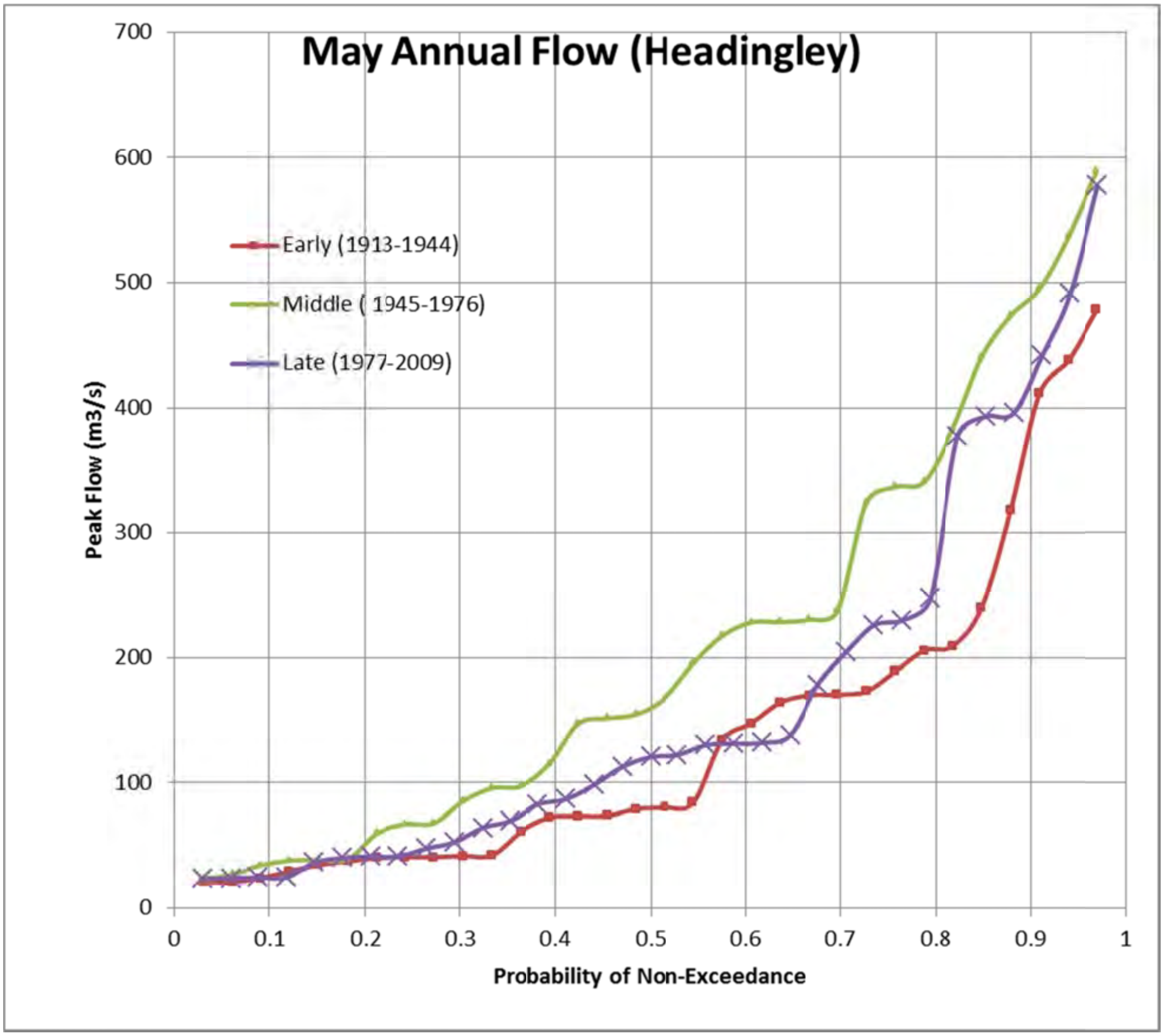

Figure 8-1C: Historic Monthly Flow – May

8.2 DEVELOPMENT OF FUTURE FLOW DURATION CURVES AND SOIL MOISTURE DURATION CURVES

Using the CRCM-aet run precipitation and temperature outputs from 2011 to 2099, the ARB MIKE-SHE model was run to create three soil moisture and streamflow scenarios (from 2011 to 2040, 2041 to 2070 and 2071 to 2099). In addition, the CRCM aet run precipitation and temperature outputs from 1961 to 1990 were used to create an ARB CRCM MIKE-SHE baseline run for comparison to the future scenarios.

Streamflows and soil moisture were simulated on a daily time step for each of the climate baseline and three future climate-change scenarios MIKE-SHE model runs.

The following datasets were used for the assessment of climate change on streamflow and soil moisture.

The measured monthly flow duration curves for 1961 to 1990.

The soil moisture duration curves calculated from the model runs using the historic precipitation 1961-1990 (i.e. the “modeled” or calibration run)

The monthly soil moisture and flow duration curves calculated from the CRCM (AET) baseline MIKE-SHE simulation for 1961 to 1990.

The monthly soil moisture and flow duration curves calculated from the CRCM (AET) early 21st century MIKE-SHE simulation for 2011 to 2040.

The monthly soil moisture and flow duration curves calculated from the CRCM (AET) the middle 21st century MIKE-SHE simulation for 2041 to 2070.

The monthly soil moisture and flow duration curves calculated from the CRCM (AET) the late 21st century MIKE-SHE simulation for 2071 to 2099.

Flow duration curves were developed on a monthly and annual basis in order to assess climate change hydrologic impacts on streamflow. A general discussion on the detailed development of flow duration curves is discussed in Section 5.8, Monthly Flow Calibration.

Three representative locations for soil moisture analysis were used across the basin. These include Brandon in the Assiniboine sub-basin in Manitoba, Oxbow in the Souris sub-basin and Cupar in the Qu’Appelle sub-basin, which selection is discussed in Section 5.7. Monthly soil moisture for each of the three 30-year records future scenarios simulations at each of the three stations was calculated as a percentage of field capacity and then grouped into early, middle and late 30-year periods for the 21st century. The soil moisture values at the three stations were calculated as a percentage of field capacity.

8.3 CLIMATE CHANGE ASSESSMENT FOR SOIL MOISTURE

Soil moisture has not been measured throughout the basin, where there is no historical basis for comparison. There are also practical considerations in the use of soil moisture data for hydrologic purposes, where locally measured soil moistures can vary widely from specific location (e.g., relatively wet low ground) to specific location (e.g., relatively dry high ground) and may not be generally representative of sub-basins or basins.

Therefore, the baseline MIKE-SHE soil moisture outputs for various months of the year were compared to the three future scenarios MIKE-SHE outputs, relative change was calculated, and the calculated change was applied to calibrated model soil moisture outputs derived from historical data. The detailed procedure for calculating soil moisture is as follows:

- Monthly and annual soil moisture was calculated from the CRCM MIKE-SHE baseline (1961-1990) outputs and the three MIKE-SHE future scenarios outputs.
- The ratio of soil moisture for each of the three future CRCM scenarios divided by the CRCM baseline soil moisture was calculated. The calculated results are the monthly and annual soil moisture ratios for 2011-2040, 2041-2070 and 2070-2099.
- Finally, the simulated, i.e., "modeled," soil moisture duration curves under calibrated conditions were multiplied by the monthly soil moisture ratios calculated in the previous step in order to create soils moisture duration curves for each period: 2011-2040, 2041-2070 and 2070-2099.

Annual soil moisture duration curves (SMDC) for three locations are shown in Figures 8-2, 8-3 and 8-4. The annual soil moisture duration curve for Brandon indicates that there is little difference for soil moisture in Brandon (i.e., Manitoba portion) until after 2070. After 2070, soil moisture generated is predicted to be lower than the current conditions. The soil moisture at Oxbow (Figure 8-3) in the Souris sub-basin which represents the southern portion of the ARB indicates that the soil moisture will generally become drier in the future, again having the lowest values in the latter part of the century (after 2070). Monthly soil moisture duration curves were calculated for each station (Brandon, Cupar and Oxbow) representing regions across the ARB and are shown in Appendix F.

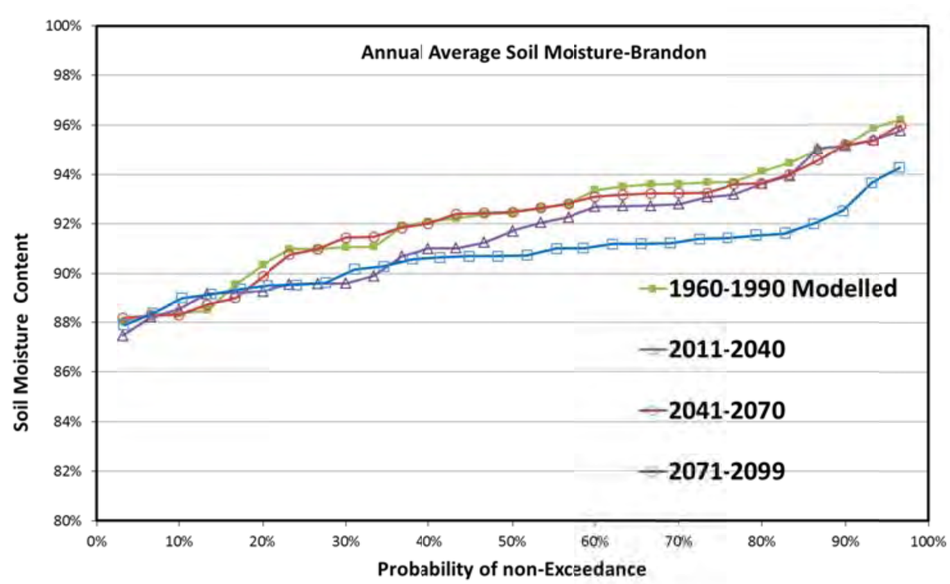

Figure 8-2: Annual Soil Moisture Duration Curve as % of Field Capacity – Brandon

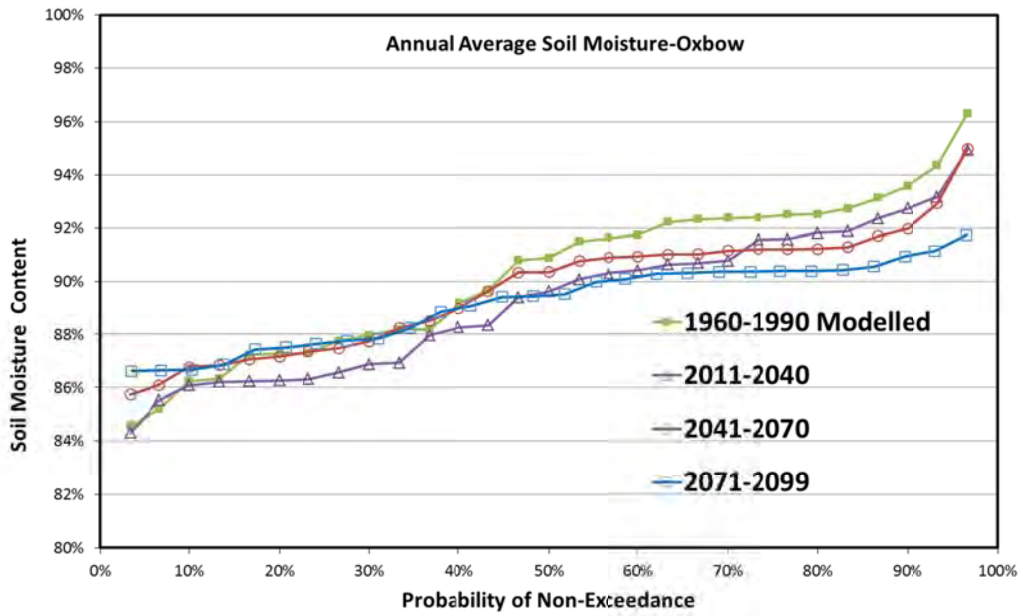

Figure 8-3: Annual Soil Moisture Duration Curve as % of Field Capacity – Oxbow (Souris sub-basin)

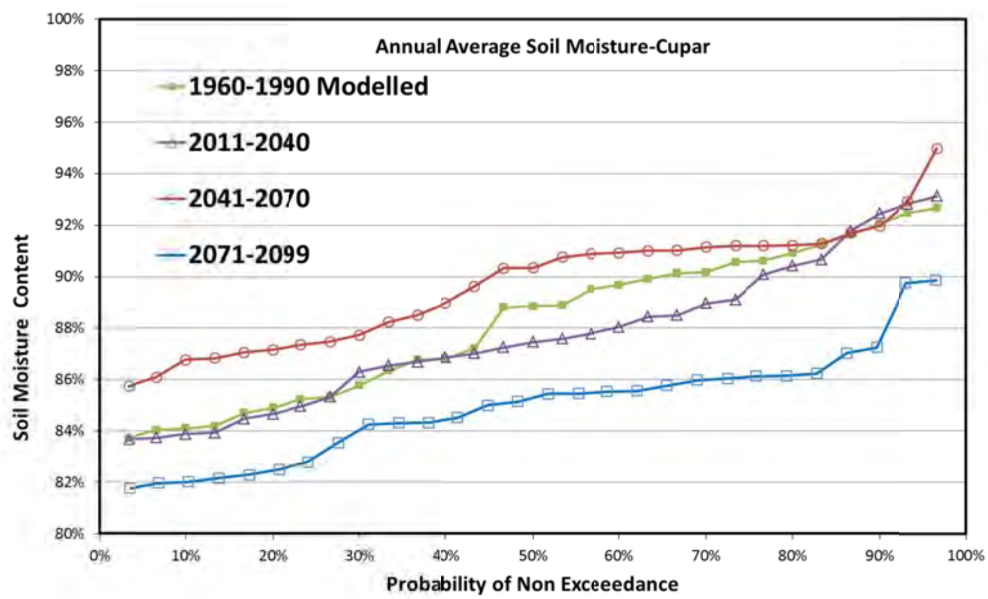

Figure 8-4: Annual Soil Moisture Duration Curve as % of Field Capacity – Cupar (Qu'Appelle sub-basin)

The soil moisture simulated at Cupar in the middle of the Qu'Appelle basin predicts soil moisture will decrease in the first third of the 21st century, again in the second period and greatly in the last part of the 21st century.

To compare trends on a monthly basis, 50% soil moisture was calculated for each month at each of the three stations and is shown in Figures 8-5, 8-6 and 8-7. Figure 8-5 shows median monthly soil moisture (50% probability of being exceeded) at Brandon. The prediction is that soil moisture will generally be lower in most months in the lower Assiniboine basin, except in April, May and June when soil moisture is near or equal historic soil moisture levels.

The 50% soil moisture for Oxbow (Figure 8-6) is predicted to be lower in all months except in March, April, May and June.

The 50% near Cupar (Figure 8-7) is predicted to have lower soil moisture. In the later part of the century (after 2070), conditions are much drier for all months compare to current conditions.

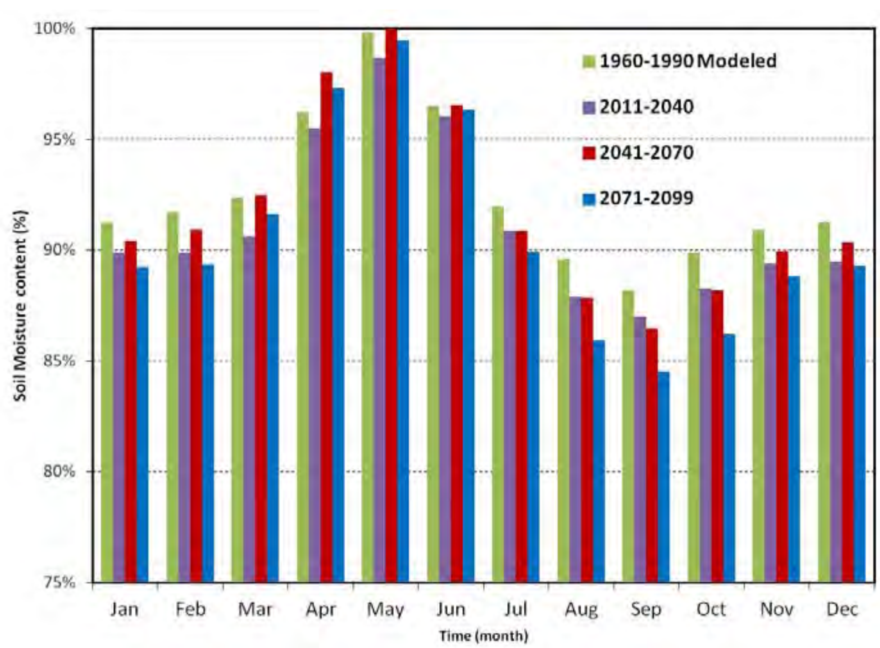

Figure 8-5: Median (50th percentile) Monthly Soil Moisture Near Brandon as % of Field Capacity

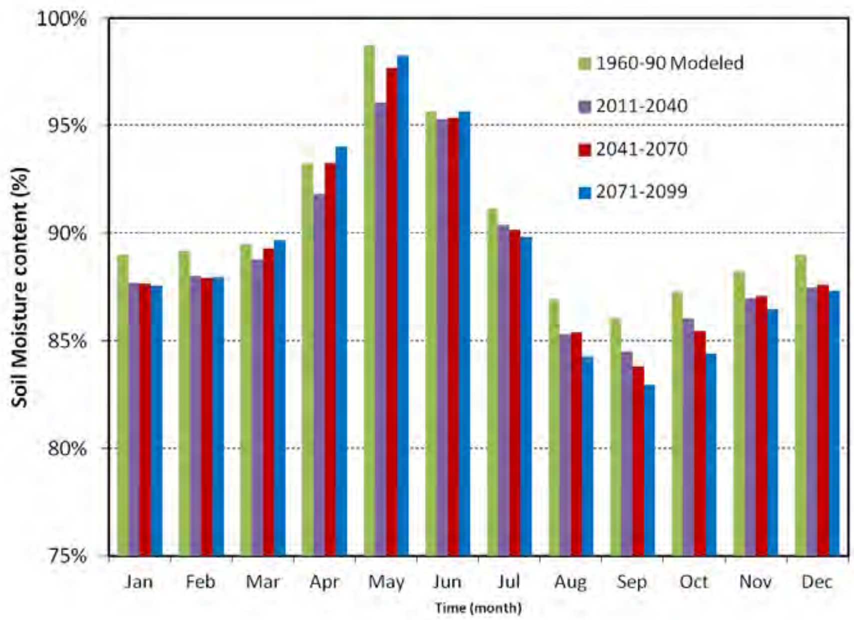

Figure 8-6: Median (50th percentile) Monthly Soil Moisture Near Oxbow as % of Field Capacity (Souris Sub-basin)

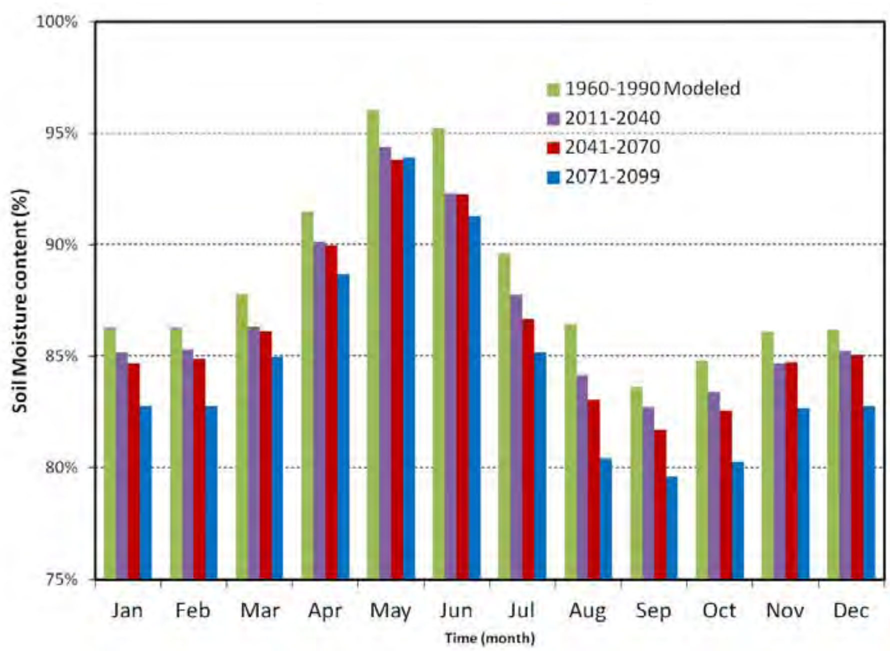

Figure 8-7: Median (50th percentile) Monthly Soil Moisture Near Cupar as % of Field Capacity (Qu'Appelle Sub-basin)

8.4 CLIMATE CHANGE ASSESSMENTS OF STREAMFLOW

Annual and monthly flow duration curves (FDCs) were developed for five calibration stations (Headingley, Brandon, Welby, Wawanesa and Russell) to calculate potential changes in streamflow due to future climate change.

Future scenario MIKE-SHE model runs have a bias associated with the precipitation datasets obtained from the CRCM (AET) model, as discussed in Section 7.0. The following procedure was developed to adjust the simulated future streamflows for bias:

- Monthly and annual flows were calculated for the CRCM (AET) MIKE-SHE model run (“baseline”), and the three CRCM (AET) future scenarios MIKE-SHE model runs (2011-2040, 2041-2070 and 2070-2099).
- Ratios between the three modeled future scenarios flows and baseline flows were calculated. These are the monthly and annual flow ratios for each period: 2011-2040, 2041-2070 and 2070-2099.
- Measured record flows were multiplied by the flow ratios calculated in the previous steps to create three sets of future scenarios data for comparison to historical records, i.e., to “measured.”

The annual average flow duration curves of measured and predicted flows for early, middle and late 30-year periods in the 21st century for Headingley are shown in Figure 8-8. **There is no clear trend towards greater or lesser flows** shown in Figure 8-8, where, the future flow duration curves indicate both higher and lower flows than current in the next 90 years. This is similar in the four other stations analyzed, except Welby, which shows marginally reducing future flows. A complete set of FDCs is shown in Appendix G.

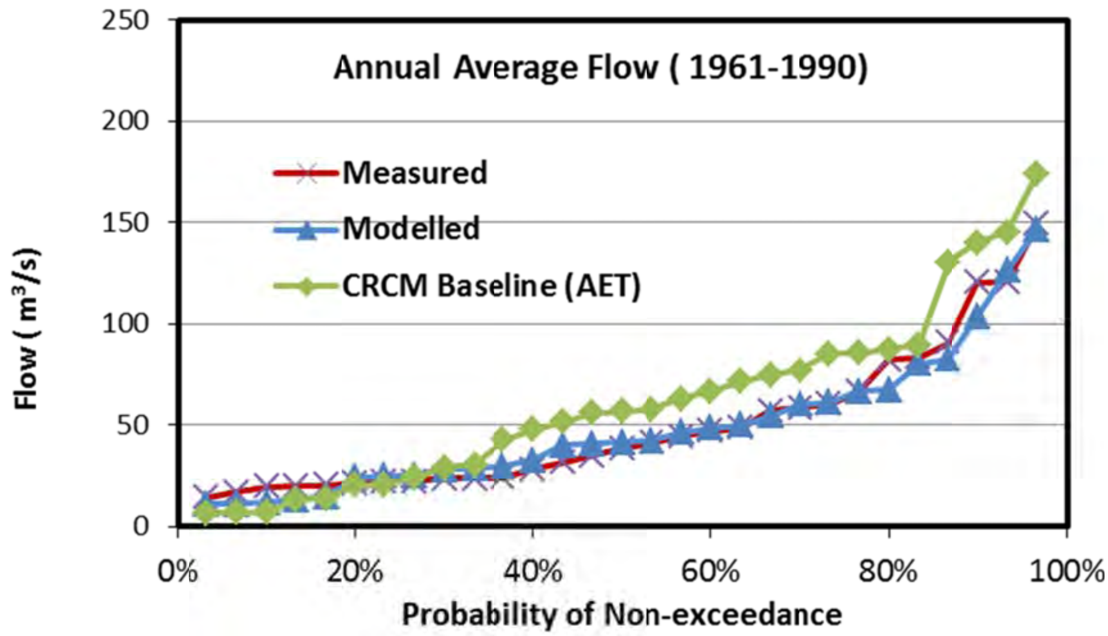

Figure 8-8: Average Annual FDC – Headingley

8.5 COMPARISON OF MEASURED AND PREDICTED FUTURE SCENARIOS FLOW DURATION CURVES

The measured historic annual flows for the past century were divided into three periods, as discussed in Section 8.1, to demonstrate natural variability. They are:

- 1913-1944
- 1945-1976
- 1977-2009

The average annual flows from the above three periods were ranked and flow duration curves were developed. Likewise, annual flow duration curves were developed for the future scenario periods, which are:

- 2011-2040
- 2041-2070
- 2071-2099

Both sets of the flow duration curves were plotted in Figure 8-9, so a comparison can be made of the range of past and predicted future streamflows. The graph shows that historically, flow duration curves are quite variable from period to period. Historical measured variability appears to be as large, if not larger, than that shown by future scenarios flow duration curves predicted by CRCM (AET) MIKE-SHE simulations over the next century. This indicates that the streamflow in the ARB is highly variable and that historically climate in this region has been variable. There are some trends towards warmer weather and wetter spring conditions; however, the variability of flows in the ARB is predicted to remain with approximately the same variation as historic flows.

Some trends which may be discerned from this graph are that:

- Low flows (one in ten year or 10%) will be about the same in the future as they have been in the past. This should not impact on water supply or wastewater assimilation.
- Extreme flow years have occurred in the past and will occur in the future. The graphs do show that future extreme events may be slightly higher than past events. Due to the possibility of the combination of wet fall, winter and spring conditions in the same year (i.e., October through June), this may results in greater extreme flood events with resultant impact on flood planning.
- Historic variation has been large, and the future flow variation may be large, but not much different than in the past.

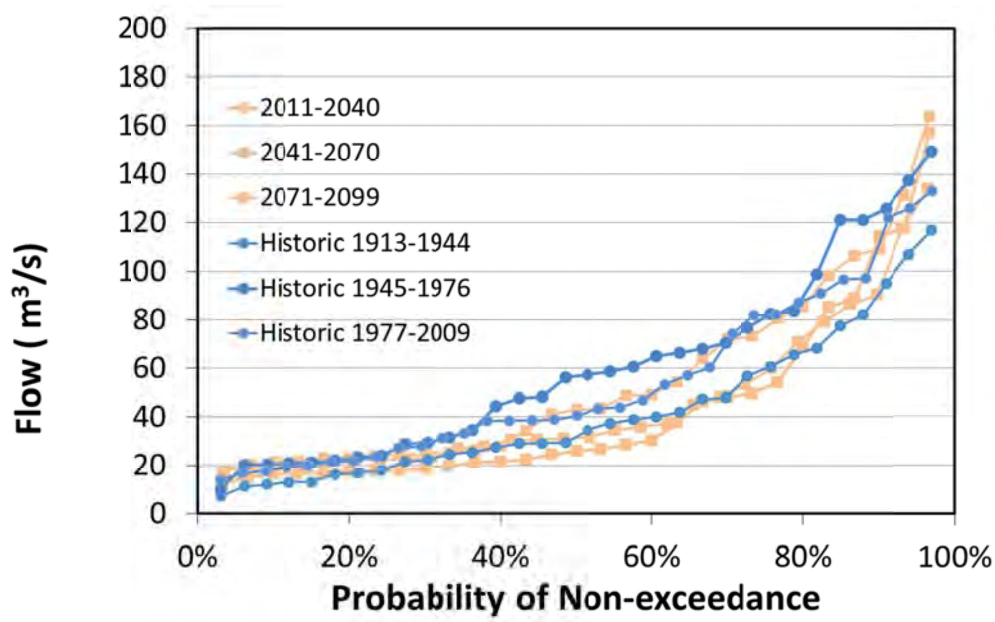

Figure 8-9: Comparison of Historic and Predicted Future Annual FDC for Headingley

To estimate how future average flows may change, the 50th percentile (median) monthly flow at Headingley is shown in Figure 8-10. When future monthly flows are compared against the measured monthly flows, there is variation but it is both increasing and decreasing for most months. Average flows at Headingley show no discernible trend in the future. The 50th percentile flows of Brandon (Figure 8-11) show a similar pattern of no discernible trend in the future.

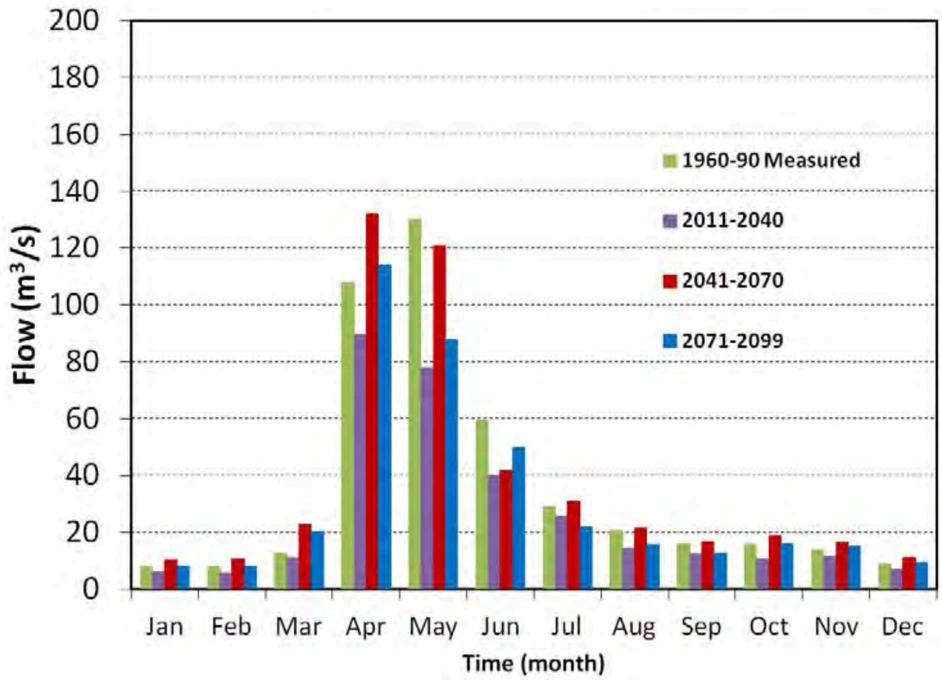

Figure 8-10: Median (50th percentile) Monthly Flow at Headingley

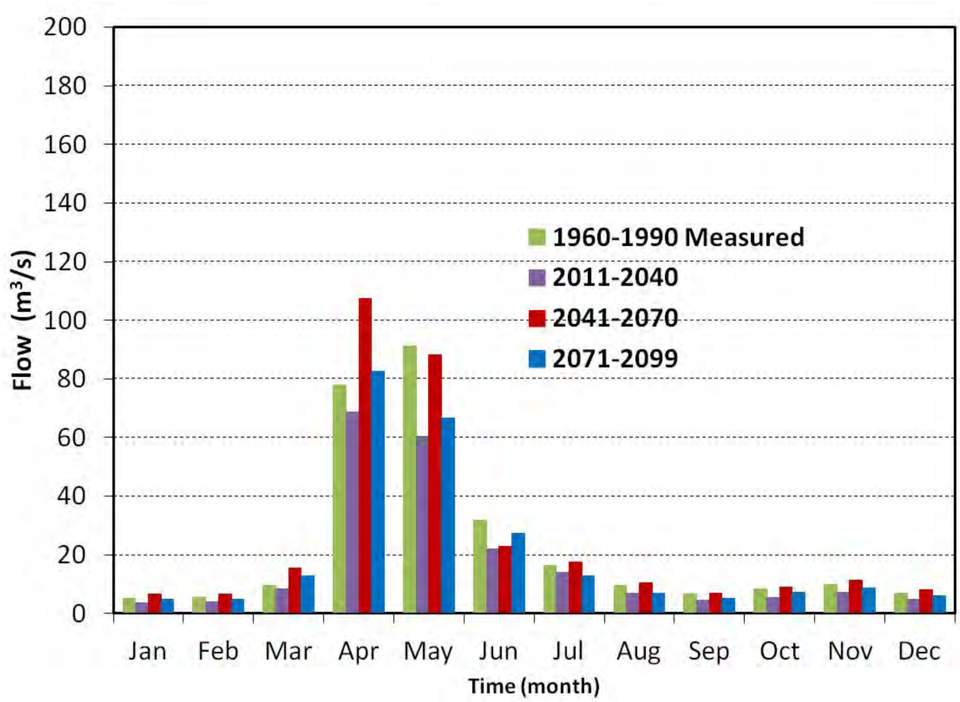

Figure 8-11: Median (50th percentile) Monthly Flow at Brandon

9.0 Conclusions

Canadian Regional Climate Model (CRCM):

- Temperature changes show a consistent increase across all months over the next century. The temperatures in the CRCM model runs (2011 to 2100) are higher than baseline (1960-1990). For example, temperatures are expected to increase above baseline by 4-6 degrees in summer and fall months.
- A single CRCM model run (aet) was used to generate meteorological data for MIKE-SHE simulation of future scenarios for ARB stream flow and soil moisture. The use of multiple CRCM model runs to generate multiple MIKE-SHE stream flow and soil moisture outputs would better demonstrate the range of possible changes to future stream flow and soil moisture.
- Current CRCM model outputs contain bias. CRCM baseline (1960-1990) temperature predictions are low when compared with historical (1960-1990) measurements. CRCM baseline (1960-1990) precipitation predictions are high when compared with historical (1960-1990) measurements.
- CRCM output data bias was adjusted by inputting the biased CRCM precipitation and temperature data to MIKE-SHE, then correcting MIKE-SHE stream flow predictions for bias by comparing baseline runs to historical records and applying a correction factor to future scenarios MIKE-SHE outputs. This method was used due to budget limitations, and due to the relatively large effort that would be required to adjust CRCM output data.

MIKE-SHE Hydrologic Model:

- The MIKE-SHE model represents hydrology of the ARB well enough to assess stream flow and soil moisture changes over the next century by using CRCM predicted future precipitation and temperature data.
- MIKE-SHE is limited in its ability to model snow drifting, where snow drifting is not explicitly considered.
- MIKE-SHE is limited in its ability to model changes to infiltration due a frozen top layer of soil. A wet top layer of soil can freeze during late fall or winter and create an impervious layer, which will result in rapid spring surface runoff. MIKE-SHE does not change hydraulic conductivity of soil due to changing environmental conditions, where hydraulic conductivity is set constant throughout the year.
- Measured historical precipitation was based on the existing relatively sparse network of Canadian meteorological stations and the relatively dense network of stations in the U.S.A.

The lack of historical and current Canadian precipitation data will continue to make it difficult to calibrate MIKE-SHE to ARB stream flow.

- Combining the CRCM (AET) and MIKE-SHE model results in a multiplier effect with respect to uncertainties of predictions. Although the amount of uncertainty is non-quantifiable it must be considered when reviewing future hydrologic projections.

Soil Moisture:

- Warmer future summer and fall weather is predicted to lead to higher summer and fall evapotranspiration. Higher evapotranspiration would result in future soil moisture dropping more quickly and being generally lower than current conditions through summer into fall. The greatest decline in summer and fall soil moisture is predicted to take place after 2070.
- Higher predicted future precipitation for winter and spring (through June) is expected to offset lower future summer and fall soil moisture. Future spring soil moisture is predicted to generally rebound from lower predicted summer and fall levels to remain similar to current spring soil moisture conditions.
- Soil moisture is one of the key drivers in generating runoff and stream flow. When soil moisture is high, the soil does not have the capacity to store additional precipitation, resulting in swift runoff and greater stream flows. A good example of this is the spring 2011 flood, which was initially driven by very high fall 2010 soil moistures, then compounded by high winter and spring precipitation.
- Soil moisture has been historically higher in the Manitoba portion of the ARB than in Saskatchewan. Model projections suggest that Saskatchewan would experience accelerated decreases in soil moisture when compared to Manitoba.

Stream Flow:

- Low flows (one in ten year or 10th percentile) are predicted to be about the same in future as they have been, and should not impact on Assiniboine River water available for water supply or wastewater assimilation. There is not enough information to predict potential changes to other more extreme low flow conditions.
- Future extreme floods may be slightly higher than in the past. Future soil moisture is predicted to be lower in fall, which should generally balance spring flood risk caused by predicted higher winter and spring precipitation. However, if unusually wet fall conditions occur, giving high fall soil moisture, the risk of an extreme spring flood would be greater than today due to predicted higher winter and spring precipitation.

- Historic year to year and decade to decade variation in flow has been large. Future flow variation is predicted to be large, but not much different than in the past. When 30 year long future predicted flow scenarios (2011 to 2040, 2041 to 2070, 2071 to 2099) are compared to historical periods of record (1913 to 1944, 1945 to 1976, 1977 to 2009), it is not possible to separate natural variability from climate change.

- An earlier spring melt due to generally higher temperatures in March and April is predicted to cause an earlier spring freshet. There is no indication that the melt rate will be any faster than current conditions.

- When predicted future monthly flows are compared against historical monthly flows, there is variation but it is both increasing and decreasing for most months. Average flows at Headingley show no discernible change in the future. Brandon 50th percentile flows also show no discernible change in the future

General:

- The MIKE-SHE model forms the basis for future development of a more sophisticated and detailed operations model that could be used to forecast daily flows. Current challenges include sparse precipitation networks and computational capacity.

- Other studies, including determination of effects of land use change on hydrology, are possible with MIKE-SH. Parameters such as depression storage, timing and extent of Leave area Index (LAI) and Active Root Depth (RD) can be varied to reflect changes due to development. In a more detailed model addition channels could be added to directly changes in drainage.

- Modeling of past and predicted conditions in the ARB has reinforced understanding of the driving factors of soil moisture and stream flow across the basin. The key to simulating runoff generation on prairie watersheds within the ARB using MIKE-SHE is correctly simulating the level of soil moisture where runoff will dramatically increase.

Some of the key findings of the calibration and verification exercise include:

- The MIKE-SHE model represents hydrology of the ARB reasonably well and can be used to assess the streamflow and soil moisture changes with predicted changes in rainfall and temperature over the next century.

- The MIKE-SHE hydrologic model has a limitation that may affect its ability to model factors that are important to Canadian prairie hydrology such as snow drifting and the change in the infiltration rate into the ground due a frozen top layer of soil. If wet, the top layer of soil can freeze during late fall /winter freeze up and create an impervious layer. MIKE-SHE does not have the ability to change hydraulic conductivity of the soil due to changing environmental conditions, therefore in the ARB model hydraulic conductivity was set to remain constant throughout the year. Also the drift of snow pack is not considered in the ARB model.

- the MIKE-SHE model forms the hydrologic basis for development of a more sophisticated and detailed operations model that could be used to forecast daily flows. Other studies such as determine effects of land use change on hydrology are possible with this type of hydrologic model.
- Measured historical precipitation was based on the existing relatively sparse network of Canadian meteorological stations and the relatively dense network of stations in the U.S.A.. This will continue to make it difficult to calibrate Canadian hydrologic models accurately.
- It should be recognized that the above limitations in the model and the calibration exercise does create uncertainty in predictions of future streamflows and soil moisture.

Some of the key findings about the use of global climate model generated precipitation and temperature date include:

- Current CRCM model outputs appear to be biased; temperature predictions are low when compared with historical measurements and precipitation predictions are higher than measured when CRCM model precipitation outputs for past years are compared to historical records.
- Due to budget limitations, a simplified method that consisted of inputting the biased precipitation and temperature data and correcting streamflow predictions for bias after the simulation of future streamflows within the ARB was used. This method is not typical of the methods used in correcting for precipitation bias, which usually involve adjusting temperature and precipitation input data to correct for the bias.
- Due to budget limitations, a single CRCM model run was used to simulate future (2011 to 2100) ARB streamflow and soil moisture scenarios. Multiple scenarios are possible and the use of multiple input scenarios to create multiple streamflow predictions would better demonstrate the actual uncertainties in using global climate model to predict the range of potential future streamflow and soil moisture scenarios.
- It should be recognized that the use of global climate model outputs and the limitation of how the output where applied does create uncertainty in predictions of future streamflows and soil moisture.

10.0 Recommendations

- Pursue development of a more detailed coupled MIKE-SHE and MIKE 11 model of the ARB to use for operational (i.e., to forecast daily flows) and planning purposes. A small-scale watershed should be modeled to test effectiveness and practicality in a cost effective way, which may eventually be applied to whole ARB. The model would need added details, including:
  - Storage reservoirs and more detailed channel representation within the connected MIKE11 model to be used for operational purposes.
  - A finer resolution of cell size and soil parameters distribution
- Use MIKE-SHE to assess changes in hydrology due to physical changes in a watershed. A pre- and post-development (either past or planned) scenario could be modeled using the same meteorological inputs to determine changes in stream flow caused by physical changes. A smaller sub-watershed of the ARB would be the most effective way of initially assessing this effect.
- Review the adequacy of the existing meteorological station system in the ARB and establish a permanent adequate system of meteorological stations.
- Apply methods to adjust the bias in CRCM precipitation and temperature outputs and use the ARB MIKE-SHE model to predict future soil moisture and flow scenarios. Using the delta change in predicted temperature and precipitation between the baseline and future climate change scenarios and applying (on a monthly basis) it to the 1960-1990 precipitation and temperature data set would be the most straight forward way to accomplish this. A comparison could then be made with the results presented in this study to determine if conclusions would change.
- Use a range of potential future precipitation and temperature CRCM model output data-sets for each 21st century scenario (2011-2040, 2041-2070, 2071-2099) in a follow up analysis to better represent the range of uncertainty in using global climate models for predicting future hydrology. It may be that different CRCM outputs are appropriate to different tasks (e.g., flood control planning versus drought planning).

11.0 Glossary

Dead storage fraction – the fraction of the received percolation that is not added to the reservoir volume but is removed from the available storage in the reservoir.

Degree-day coefficient – the degree day factor is the amount of snow that melts per day for every degree the Air Temperature is above the Threshold Melting Temperature.

Evapotranspiration surface depth – the depth equals the thickness of the capillary zone. It is used as the water table depth at which the Evapotranspiration starts to decrease.

Interflow threshold depth – the depth below the ground surface when interflow stops.

Interflow time constant – the time it takes for water to flow through the reservoir to the next reservoir.

Leaf Area Index – the area of leaves above a unit area of the ground surface.

Manning's coefficient – the resistance of the ground surface on overland flow or a channel ("roughness").

Percolation time constant – the time it takes for water to seep down into the base flow reservoir.

Porosity or void fraction – a measure of the void (i.e., "empty") spaces in a material, and is a fraction of the volume of voids over the total volume.

Root Depth – the maximum depth of active roots in the root zone.

Saturated hydraulic conductivity – a property of soil or rock that describes the ease with which water can move through pore spaces or fractures.

Soil suction at wetting front – the suction head due to capillary attraction in the soil voids.

Specific yield – the capacity of an aquifer to release groundwater from storage in response to a decline in hydraulic head.

Threshold depth for base flow – the depth below the ground surface when base flow stops.

Threshold melting temperature – the threshold melting temperature is the temperature at which the snow starts to melt.

Time constant for base flow – the time it takes for water to flow through the reservoir.

Unsaturated Zone (UZ) feedback fraction – the fraction of base flow to the river that is available to replenish the water deficit in the unsaturated zone adjacent to the river.

Water content at field capacity – the maximum amount of soil moisture or water content that can be held in soil after excess water has drained away and the rate of downward movement has materially decreased.

Water content at saturation – the maximum water content of the soil, which is usually approximately equal to the porosity.

Water content at wilting point – the minimal point of soil moisture the plant requires not to wilt.

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