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ASSESSMENT OF CLIMATE CHANGE EFFECTS ON WATER YIELD FROM THE NORTH SASKATCHEWAN RIVER BASIN

Report submitted to:

North Saskatchewan Watershed Alliance

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EXECUTIVE SUMMARY

In an Agreement dated 22 January 2008, the North Saskatchewan Watershed Alliance (NSWA) contracted Golder Associates Ltd. (Golder) to assess the water yield from the North Saskatchewan River Basin (NSRB) and its variability under natural hydrologic conditions and present climatic conditions. An additional request was to carry out data analyses and hydrologic modeling to assess potential changes in the water yield under forecasted future climatic conditions. The effects of climate change on the water yield from the NRSB will affect water uses and water management in the basin. There is a need to assess the potential effects so that watershed planners can adapt their plans to take advantage of positive effects and implement mitigation measures to minimize the negative effects. The scope of the study also included a review of the literature on climate change as it pertains to the prairie regions and an assessment of trends in observed temperature, precipitation and stream flow data in the NSRB. This report summarizes the assessment of the potential effects of climate change on the water yield from the NSRB.

Trend analyses on air temperature data at the selected climate stations in the NSRB, namely, Nordegg, Rocky Mountain House, Edmonton and Vermilion, suggest that there is a generally increasing trend in air temperature. The general trend seems to be towards increasing precipitation, but the trends in monthly, seasonal and annual precipitation data at the four selected locations in the NSRB are not statistically significant.

The annual mean stream flow data at selected hydrometric stations in the headwater basins of the Athabasca River and western portion of the NSRB generally show a decreasing trend in recent years. Trend lines fitted to recent flow data are not necessarily accurate predictors of future increases or decreases in flows. Notwithstanding the foregoing statement, linear trend lines fitted to the data suggest that the predicted annual mean flows would decrease by between 4% and 9%, depending on station location, by the year 2035 compared to the baseline period of 1961-1990. These predicted changes in annual yield by 2035 are, however, well within the variability in annual yield from year to year.

The 1961 to 1990 period was selected as the climatological baseline period for the modelling work. The future conditions have been represented by the 30-year period between 2021 and 2050, which would be representative of the mid-2030s. The ECHAM50M, NCARCCSM3, GFDLC2.1 and CGCM3T47 General Circulation Models, also known as Global Climate Models, (GCMs) were selected for assessing the effects of climate change on the water yield in the NSRB based on a comparison of GCM predictions with observed climate data in the NSRB. The A1B, A2 and B1 climate scenarios were selected for each GCM. Scenario A1B represents future balanced socio-economic and environmentally-based development; scenario A2 assumes that the current global socio-economic situation will continue in the future; and, scenario B1 represents future development that is more environmentally-based than at present.

The forecasts indicate that NCARCCSM3-SRA1B predicts the largest increase in temperature (about 2.2^{o}C), while ECHAM50M-SRB1 predicts the smallest increase (about 0.3^{o}C). Predictions of changes in precipitation tend to vary significantly between GCMs and even between scenarios for a given GCM. The change in mean annual total precipitation for the forecast period of 2021-2050 from the baseline period of 1961-1990 ranges from a decrease of about 8% (GFLDLC2.1-SRA2) to an increase of about 19% (NCARCCSM3-SRA2), with 10 of the 12 scenarios predicting an increase in precipitation. The forecasted increasing trend in precipitation appears to be consistent with trends in observed data at the climate stations in the NSRB.

The European Centre for Mid-Range Weather Forecast global re-analysis (ERA-40) climate data from 1961 to 1990 was used to represent the baseline climate conditions in the NSRB. The modified Interactions Soil-Biosphere-Atmosphere land surface model (MISBA) of Météo France was set up for the North Saskatchewan River Basin (NSRB). The study area was limited to the portion of the NSRB west of Edmonton because ERA-40 data east of Edmonton was not available for this study.

For the purposes of this study, simulated water yield in the NSRB for the baseline period was assessed against natural flows recorded at the Environment Canada WSC Hydrometric Station 05DF001 at Edmonton. The simulated flows from the MISBA model with ERA-40 data are reasonably close to the observed flows at 05DF001. However, while the observed maximum monthly yields tend to occur in June and July, the highest monthly simulated yields occur earlier in May and June. Notwithstanding the differences, the simulated flows were considered reasonable for the purposes of this study and are used to assess the relative effects (simulated

2021-2050 model outputs compared with simulated 1961-1990 model outputs) of climate change on water yield in the NSRB at WSC Station 05DF001.

The European Centre for Mid-Range Weather Forecast global re-analysis (ERA-40) baseline (1961-1990) climate data was adjusted to reflect the changes forecasted by the combination of the four selected GCMs and three scenarios. Five of the six ECHAM50M and NCARCCSM3 GCM-scenario combinations are predicting increases in annual yield from the baseline 1961-1990 period to the 2021-2050 forecast period that range from 5% to 15%. Only the ECHAM50M-SRA1B combination predicts a decrease of about 11%. The CGCM3T47 and GFLDC21 GCM-scenario combinations are predicting decreases in annual yield that range from 3% to 23%. The predictions of the CGCM3T47 and GFLDC21 GCMs tend to follow trends in observed flow data. However, the ECHAM50M and NCARCCSM3 GCMs are the more representative GCMs of the baseline climate of the runoff-producing headwater basins of the NSRB, and the results of the simulations using these models may indicate the more likely trend in future yield from the NSRB.

The percent changes in monthly yield are much larger than would be implied by the percent changes in annual yield. The percent changes tend to be higher for the winter months when flows are generally low. Increases in mean monthly yields tend to occur during the spring months. This result reflects the predicted increase in precipitation (snow) and increase in temperature. Decreases in mean monthly yield tend to occur during the summer months and into the fall. This result suggests that the predicted increase in temperature is causing an increase in evapotranspiration losses during the summer months

The simulations of the forecasted climate scenarios result in a range of possible impact on water yield from the NSRB. Notwithstanding that the GCMs most representative of baseline climate in the NSRB predict increases in future annual yield, the range of possible impacts should be considered in watershed planning because the model predictions have some degree of uncertainty associated with them.

Recommendations

- Continued refinement of the MISBA model to improve its capability to represent the complex and varied hydrologic processes significant in mountainous to prairie areas should be undertaken. The application of other hydrologic models should also be investigated.
- Statistical and/or dynamic downscaling should be investigated for alternative means of developing climate scenarios from GCMs and forecasting changes in other climate parameters such as solar radiation, wind speed and humidity.
- Complete coverage of the NSRB with ERA-40 data or other downscaled data should be acquired to implement the selected hydrologic model to the entire NSRB.

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1. INTRODUCTION

1.1 Background

During a meeting with the North Saskatchewan Watershed Alliance (NSWA) on December 13, 2007, Golder Associates Limited (Golder) was requested to provide a scope of work to assess water supply and its variability in the North Saskatchewan River Basin (NSRB) under natural hydrologic conditions and present climatic conditions. An additional request was to scope the modeling work required to predict changes in the water yield under potential future climatic conditions. Subsequent to a letter dated January 17, 2008 from Golder that described the methods for assessing the effects of climate change on the water supply from the NSRB, NSWA authorized Golder in an Agreement dated 22 January 2008 to undertake the climate change assessment.

1.2 Scope of Work

The scope of work included a summary of the literature on climate change studies relevant to Alberta; analysis of climate and streamflow data within the NSRB and/or in adjacent basins to assess any trends; a review of climate change scenarios and models; and implementation of a hydrologic model on the NSRB with climate change scenarios as inputs to estimate possible effects on water supply.

1.3 Outline of Report

Section 2 of the report summarizes key findings of a literature review of climate change studies pertinent to Alberta and/or the Prairie Provinces. Section 3 reports on analyses of trends carried out on climate and streamflow data collected within the NSRB and in adjacent basins. Section 4 provides general information on climate change models and scenarios, discusses inputs to the model and outputs from the model, and presents the results of an assessment of the effects of climate change on water yield from the NSRB by simulating several forecasted climate scenarios with a hydrologic model.

2. REVIEW OF LITERATURE ON CLIMATE CHANGE STUDIES

2.1 Introduction

General scientific literature on trends in climate parameters and stream flows, and specific studies specifically as they pertain to effects on hydrology in Alberta and the North Saskatchewan River Basin were reviewed.

There is a general agreement in the existing literature on the evidence showing that global surface air temperatures have been increasing during the past decades. The increase in air temperature is postulated to be the result of either an increase in greenhouse gases emission (GHG) or climate variability (i.e., due to variations in sun or volcanic activity or El Niño and La Niña events) during past decades, or both. General Circulation Model or Global Climate Model (GCM) simulations suggest that air temperature may continue to increase in the future.

Simulations using GCMs predict warming of 1 to 5°C by the mid 2050s, with the most pronounced changes taking place in northern latitudes (Nicholls *et al*. 1996). However, predictions of changes in climate at a watershed scale or even a larger regional scale using GCMs are less reliable than global predictions (Arnell *et al*. 1996; Georgievskii *et al*. 1996; Zhang *et al*. 2000). The predicted rise in the Earth's surface air temperature could cause an increase in average global evaporation and an increase or decrease in precipitation (Bloomfield 1992; Mann *et al*. 1998; Vinnikov *et al*. 1990; Gan 1995; Zhang *et al*. 2000). Detection of historic trends, changes and variability in climatic variables is essential for understanding or estimating potential future hydrologic changes associated with climate change.

2.2 Changes in Air Temperature

GCMs, such as the Canadian Climate Center model, predict warming trends of 1.0 to 1.5°C from 2001 to 2050 over the Canadian Prairies under a $2\times CO_2$ (doubling of atmospheric carbon dioxide concentration) level scenario, with the largest seasonal increase in temperature occurring in winter. The $2\times CO_2$ scenario used previously by the Intergovernmental Panel on Climate Change (IPCC) has been replaced by the new emissions scenarios (IPCC 2000). Increases in the near surface air temperature could change precipitation amounts and storm patterns. In turn, changes in air temperature and precipitation could affect the hydrology of Canadian rivers, including changes to the volume and timing of streamflow and river ice conditions.

Using proxy data, Mann *et al*. (1998) and McIntyre and McKitrick (2003) showed that the air temperature index (i.e., mean annual air temperature) in the late 20th century was higher than from 1500 to 1980 for the northern hemisphere. Many researchers have also shown that the 1980s and 1990s were the warmest years on record. However, the increase in surface air temperatures has not been continuous. In fact, the recorded data indicate a cooling period from the 1940s to 1970s in the middle and high latitudes of the northern hemisphere (Moran and Morgan 1997).

Outputs from the CGCMI (Canadian GCM) show a warming trend of about 0.3°C per decade for Alberta over the 1900 to 2001 period, with greater increases in the minimum air temperature than in the maximum air temperature (Chaikowsky 2000). The amount of warming estimated using the CGCMI outputs over the 1938 to 1995 and 1960 to 1995 periods were less than the warming observed in Alberta over these periods. The most rapid warming was estimated for the period following the year 2000. Over the 2000 to 2100 period, the CGCMI run, which included only greenhouse gas forcing, estimated a mean increase of 5°C. Chaikowsky (2000) concluded that the CGCMI results differed greatly from observations (i.e., about 0.5 to 1.0°C) and hence were not likely useful in estimating temperature variations at the provincial scale (Alberta).

Gan (1998) applied Kendall's trend analysis method to the maximum, minimum and average air temperature data from 37 weather stations (14 in Alberta, 14 in Saskatchewan, eight in Manitoba and one in Ontario). The results indicate that between 1949 and 1989 the Canadian prairies have experienced warming, especially in January, March, April and June. The March and June data at more than 60% of the stations exhibited statistically significant warming at the 5% level of significance. Zhang *et al*. (2000) and Hengeveld (1991) observed similar trends for the prairies in winter and spring.

2.3 Changes in Precipitation

Predictions of changes in precipitation using GCMs are less definite than predictions in air temperature (Schlesinger and Mitchell 1985; Hennessy *et al*. 1997; Gregory *et al*. 1997). Cohen (1991) found no consensus in the projected changes in precipitation over regions encompassing Alberta from five GCMs. GCMs are based on simple land phase hydrology processes and coarse grid resolutions. Their simulations of possible changes in hydrologic processes are not expected to be reliable, particularly at regional and local scales.

Results reported in IPCC (2001) suggest that winter, spring, summer and fall average precipitation amounts have increased by about 30, 0, 15 to 20 and 20%, respectively, for regions encompassing Alberta over the time period of 1900 to 1999 (100 years) compared to the 1961 to 1990 normal. The study concluded that an increase in mean annual precipitation had occurred over the last century, with an approximately 20% rise for the period 1900 to 1999. The segment of that time period with the largest rising precipitation trend appeared to be from 1946 to 1975 (IPCC 2001).

Studies of trends in precipitation based on recorded historical long-term data show a range in the magnitude of change, and sometimes differing directions of change. Zhang *et al*. (2000) analyzed precipitation totals and the ratio of snowfall to total precipitation using climate data from 1900 to 1998 across Canada. Their analysis shows that annual precipitation totals have changed by -10 to +35%, with the strongest increases occurring in the northern regions of the country. The ratio of snowfall to total precipitation has also increased as a result of an increased winter precipitation, which generally falls as snow.

Gan (1998) analyzed monthly precipitation data at 37 stations in the Canadian prairies from 1949 to 1989 and showed that, between November and February, 8 to 18% of the stations experienced decreases in precipitation. The remaining stations showed no trend at the 5% level of significance. Other studies indicate less confidence in precipitation trends in Canada for climate warming scenarios. There is no consensus on whether precipitation will increase or decrease or how climate change may affect severe weather events in the Canadian prairies (Gan 1995).

Van Wijngaarden and Vincent (2003) examined daily precipitation data for the time period 1953 to 2003 for 75 stations across Canada. The total precipitation for each season was computed along with the percentage change compared to the average seasonal amount received during 1961 to 1990. The results indicate that precipitation appears to increase slightly for the spring, summer and fall but decrease significantly in winter.

Snow cover is considered to be a useful indicator of climate change because of its sensitivity to air temperature (Karl *et al*. 1993). Myeni *et al*. (1997) reported an earlier disappearance of spring snow cover in response to the recent trend toward warmer spring air temperatures. Other researchers have reported similar findings over much of North America (Foster 1989; Stuart *et al*. 1991; Robinson *et al*. 1991; Brown and Goodison 1996). Linear regression analysis has been used to assess Canadian monthly snow depth and seasonal snow cover duration changes between 1946 and 1995 (Brown and Braaten 1998). The trends over this time period in the average inter-annual change in mean monthly snow depth were determined to be decreasing in nature in nearly all months.

2.4 Changes in Evaporation and Evapotranspiration

Potential Evapotranspiration (PET) has been incorporated in GCMs and climate impact models in various ways. Rind *et al*. (1997) discussed four methods by which PET has been formulated in various climate change related applications. Future projections using these PET formulations often disagree, even though they use the same temperature and precipitation forecasts from GCMs. For example, the aerodynamic formulation, which is used in most GCMs, resulted in a relatively large increase in PET values compared to observed changes (i.e., almost four times the observed values).

Actual Evapotranspiration (AET) was determined by McGinn *et al*. (2001) using a coupled Canadian Climate Center General Circulation Models (GCMII and GCMI-A) and a modified Versatile Soil Moisture Budget model (mVSMB). The GCMII model predicted an increase in AET of about 7 to 18% in Canadian Prairies, with the greatest increase in Alberta. A GCMI-A model that included influences from oceans coupling and the effects of aerosols, predicted a 6% increase in Alberta prairies although other prairie provinces show a decrease in evapotranspiration of about 5% (Saskatchewan and Manitoba). Model scenario that combined historic precipitation (less precipitation) with the GCM warming scenarios (CGCMI-HP) indicated an increase of only about 2% for AET in Alberta. The GCMI-A model seemed to give more consistent results relative to historic patterns and may better reflect future climate patterns.

Martin (2002) conducted estimates of mean annual gross evaporation from a free water surface of small to moderate-sized waterbodies in Canada over a 30 year period (1971 to 2000) at 55 locations. The station locations were in the Prairie Provinces in Canada, including British Columbia (east of the Rocky Mountains), Alberta, Saskatchewan and Manitoba. Indirect measurements using the Meyer formula was used to calculate gross evaporation in this study. Data on monthly mean air temperature, dew point temperature, relative humidity and wind speed data were obtained from Environment Canada archives. The 1971 to 2000 normal are low compared to the 1961 to 1990 normals. The mean decrease in gross evaporation over a period of 30 years (i.e., 1971 to 2000) is about 2.7% compared to the mean over a period of 30 years from 1961 to 1990.

Schindler and Donahue (2006) state that regional general circulation models coupled with a modified method of calculation of PET (Thornthwaite 1948) indicate that the predicted warming could increase evaporation by up to 55% in some regions of the western prairie provinces in the 21st century.

Analysis of trend in evapotranspiration data has resulted in mixed conclusions as to whether actual evapotranspiration or PET is showing an increasing or decreasing trend. Hence, the uncertainty associated with predicting future changes in evapotranspiration is even higher. Barnett *et al*. (2005) argued that in snowmelt dominated regions, these uncertainties are reduced since changes in the timing of snowmelt runoff induce a negative feedback on changes in evapotranspiration. Earlier snow melt results in increased soil moisture (and so also the water available for evapotranspiration) earlier in the season, a time when potential evaporation (dominated by net radiation) is low. Later in the year, when potential evaporation is higher, the shift in snowmelt timing reduces soil moisture, and hence evaporative resistance is increased, again reducing the effect of evaporation changes.

2.5 Changes in Stream Flows

The Canadian prairies (Alberta, Saskatchewan and Manitoba) have experienced about 20 serious droughts in the nineteenth century and over 10 serious droughts in the twentieth century (Godwin 1986). While it is certain that droughts will continue to occur in the prairies, it is not certain if future droughts will be more severe, more frequent, or both.

Based on an analysis of 50 sets of natural streamflow data, Gan (1998) showed that negative trends are much more prevalent than positive trends. Most of the positive trends occur in March and might be attributed to an earlier onset of spring melt caused by climatic warming. Higher flows in March could result in lower flows later in May and June. It seems that the Canadian prairies have experienced a warmer and somewhat drier climate in the last four to five decades. However, it is not clear that the drier climate has increased the frequency and severity of prairie droughts.

Zhang *et al*. (2001) also presented trends computed using Regional Hydrometric Baseline Network data from 1947 to 1996. Systematic analysis of 30-, 40- and 50-year study periods provided a significant trend of decreasing annual mean streamflow at the 10% level of significance across southern Canada. The monthly mean streamflow has decreased for most calendar months (except March and April) with the strongest decrease in summer and autumn months. However, significant increasing trends have been observed for the months of March and April. This might be attributed to an earlier snowmelt due to warmer spring air temperatures. The minimum annual flow and various percentiles of daily flows (below 40th percentile and above 90th percentile) indicate significant decreasing trends (i.e., at the 10% level of significance) in southern Canada and increasing trends in northern British Columbia and Yukon Territory.

2.6 Climate Change Studies in Alberta

Studies on the effects of potential climate change on flows in watersheds in Alberta include Kerkhoven and Gan (2005) on the Athabasca River Basin (ARB), Martz *et al.* (2007), Gan (2002), and Pietroniro *et al*. (2006) on the South Saskatchewan River Basin (SSRB), and Tanzeeba *et al*. (2007) on the Oldman River Basin and its tributaries.

2.6.1 SSRB Climate Change Study

Some of the largest potential changes in surface water quantity under the currently predicted climate scenarios are in the Canadian Prairies. Pietroniro *et al*. (2006) present and discuss the results of a study of the water availability in the South Saskatchewan River Basin (SSRB) under climate change scenarios. The objective of the study was to predict the future water availability in the SSRB under the potential impact of climate change using hydrologic models calibrated to SSRB and forced by downscaled climate scenarios projected by some selected GCMs.

Down-scaled GCMs were used to project changes in local temperature and precipitation patterns. The climate information was then used to simulate future river flows in the SSRB using the WATFLOOD, SACRAMENTO and MISBA hydrologic models. Hydrographs produced from the current climatology forcing showed good agreement with observations at nodes across the basin. The results of the simulation were used to assess the impact of changes in water availability on the economy and society in the basin.

The conclusions of the study that are relevant to the modelling of the effects of climate change on water availability were:

- There was good agreement between MISBA and WATFLOOD in the modelling of current and future climate scenarios on stream flows in the Oldman and Bow river sub-basins;
- GCM replication of current climate generally over predict precipitation, therefore estimates of flow for future climates are potentially optimistic; and
- Flow predictions vary by sub-basin, with general reduction in flows for the modelled sub-basins ranging from -13% to -4%.

2.6.2 ARB and Oldman River Basin Climate Change Studies

Tanzeeba *et al*. (2005) used the Modified Interactions Soil-Biosphere-Atmosphere (MISBA) land surface scheme of Meteo-France to predict future water availability in the Oldman River Basin under forecasted climate scenarios. Four GCMs (CCSRNIES, CGCM2, ECHAM4 and HadCM3) for two SRES (Special Report on Emission Scenarios) climate scenarios (A1F1 and A21) were used to provide climate forecasts. The MISBA model was then driven by the

European Centre for Mid-Range Weather Forecast global re-analysis (ERA-40) climate data that were adjusted to reflect the forecasts from the GCMs. ERA-40 has 6-hourly data coverage from 1957 to 2002, with a spatial resolution of 2.5° latitude and 2.5° longitude. The 1961-1990 ECMWF ERA-40 climate data for grids covering the Oldman River Basin was used as the baseline data. The predicted changes to mean monthly temperature and precipitation provided by the GCMs were used with an Adaptive Gaussian Window interpolation procedure on the ERA-40 data to obtain possible future climate scenarios. Under most GCM projections, MISBA predicted decreasing runoff and an earlier onset of spring runoff.

Similar to the Oldman River Basin study, Kerkhoven and Gan (2006) applied MISBA to the Athabasca River basin (ARB) using the ERA-40 re-analysis data of ECMWF (European Centre for Mid-range Weather Forecasts). Although most of the scenarios used for simulations predicted increased precipitation in the basin, all the scenarios resulted in significantly decreased stream flows by the end of the century (2070-2099). This was primarily because of a predicted decrease in the size of the winter snow pack due to warmer winters. Warmer winters result in less snow accumulation and increased evaporation. Mean annual flows were predicted to decrease by almost 25% by the last 3rd of the century. The high flow season also became much shorter.

3. TRENDS IN CLIMATE AND STREAM FLOW DATA IN THE NORTH SASKATCHEWAN RIVER BASIN

Precipitation, temperature and streamflow data collected in the North Saskatchewan River Basin (NSRB) and adjacent basins were analyzed for trends. The trend analyses were conducted to assess potential future climatic conditions and to compare with forecasts from General Circulation Models (GCMs) for this region of Alberta. Trend lines fitted to recent climate and stream flow data are, however, not necessarily accurate predictors of future increases or decreases in temperature, precipitation and flows.

3.1 Climate

The precipitation and temperature data in the NSRB were analyzed for the presence or absence of statistically significant trends. The following sections present the methods and results of the analyses.

3.1.1 Air Temperature

The analysis of trends in air temperature used data recorded at four stations: Nordegg (1915 to 2007), Rocky Mountain House (1978 to 2007), the City of Edmonton (1880 to 2005) and Vermilion (1913 to 2007). Eight statistical parameters at each station, including monthly mean, seasonal average (spring, summer, fall and winter), annual mean, and annual maximum and minimum air temperatures were examined. The Spearman (parametric) and Mann-Kendall (non-parametric) tests were used to determine statistical significance of trends.

<u>Nordegg</u>

The results indicate an overall increasing trend in air temperature at Nordegg, with the exception of the fall season when the air temperature data shows a decreasing trend. The latter trend is however not statistically significant at the 5% level. Annual maximum daily temperatures show a statistically significant decreasing trend, while annual minimum daily temperatures show an increasing trend at the 5% level.

Rocky Mountain House

At Rocky Mountain House, air temperature data shows decreasing trends in the spring, summer, and fall seasons, and apparently increasing trends in winter. These trends are not statistically significant at the 5% level. Annual maximum daily temperatures show a decreasing trend and annual minimum daily temperatures show an increasing trend, however, neither trend is statistically significant at the 5% level.

Edmonton

The air temperature data at Edmonton show a consistently increasing trend. The increasing trends for all seasonal average temperatures are statistically significant at the 5% level. Edmonton has over the decades developed into a large and dense urban area, and the urban heat island effect may account for part of the observed increasing trend in the temperature data.

Vermilion

The temperature data at Vermilion suggest a generally increasing trend, except in the spring, mainly for the month of May. However, these trends are not statistically significant at the 5% level.

Summary

The temperature data series at Nordegg, Rocky Mountain House, Edmonton and Vermilion are of different record lengths. Edmonton has the longest data set, which starts in 1880 and ends in 2005. The shortest data set from 1978 to 2007 (30 years) is for Rocky Mountain House.

With the exception of Rocky Mountain House, trend analyses on air temperature data at the selected locations generally agree that there is an increasing trend in air temperature. Since the record at Rocky Mountain House is only 30-years long, the result at this location is not as reliable as the results derived for the other stations.

The increasing trend in temperature at Edmonton appears the strongest, while at other locations, sometimes decreasing trends were observed (i.e. spring at Vermilion and fall at Nordegg). However, the decreasing trends are not statistically significant at the 5% level and the statistically significant increasing trend at Edmonton may be partly influenced by the urban heat island effect of the city.

3.1.2 Precipitation

The analysis of trends in precipitation used data recorded at four stations: Nordegg (1915 to 2007), Rocky Mount House (1978 to 2007), the City of Edmonton (1880 to 2005) and Vermilion (1913 to 2007). Monthly, seasonal and annual precipitation data were analysed. The Spearman (parametric) and Mann-Kendall (non-parametric) tests were used to determine statistical significance of trends.

<u>Nordegg</u>

The data at Nordegg shows a weak increasing trend for summer and fall precipitation, while winter and spring precipitation show a weak decreasing trend. However, these trends are not statistically significant at the 5% level. Overall, the annual precipitation data shows a statistically not significant increasing trend.

<u>Rocky Mountain House</u>

The data at Rocky Mountain House show an increasing trend in monthly precipitation for most months, however, these trends are not statistically significant. Overall, the annual precipitation data shows a statistically not significant increasing trend.

<u>Edmonton</u>

The data at Edmonton show weak increasing trends in monthly precipitation for most months, however, these trends are not statistically significant. There is a statistically not significant decreasing trend in winter total precipitation data. Overall, the annual precipitation data shows a statistically not significant increasing trend.

<u>Vermilion</u>

The data at Vermilion show weak increasing trends in monthly precipitation for most months, however, these trends are not statistically significant. There is a statistically not significant decreasing trend in the spring total precipitation data. Overall, the annual precipitation data shows a statistically not significant increasing trend.

Summary

The analysis of monthly and seasonal precipitation data at the four selected locations in the NSRB showed no statistically significant trend. Precipitation in the summer months (July, August, and September) tend to exhibit an increasing trend at three locations: Nordegg, Edmonton, and Vermilion. These three stations tend to have relatively long precipitation records. At all the four stations, the annual precipitation data shows a statistically not significant increasing trend.

3.2 Stream Flow

The stream flow data at Environment Canada WSC Stations 07AA002 (Athabasca River near Jasper), 07AD002 (Athabasca River at Hinton), 07AE001 (Athabasca River near Windfall), 07AF002 (Mcleod River above Embarras River), 05DF004 (Strawberry Creek near the Mouth) and 05EA001 (Sturgeon River near Fort Saskatchewan) were analyzed for possible trends in monthly, seasonal and annual mean flows as well as in the 7-day low flow using the Spearman and Mann-Kendall tests. Data at stations located on streams in the headwaters of the Athabasca River Basin were selected because their water sources are in the same region as the headwater streams of the North Saskatchewan River (NSR) and the flows are not regulated. Flows in the headwaters of the NSR are regulated for hydro power generation and such data series are not suitable for trend analysis.

Trend lines fitted to recent flow data and that are based on linear regression are not necessarily accurate predictors of future increases or decreases in flows. Notwithstanding the foregoing statement, the trend lines fitted to annual mean flow data at the selected hydrometric stations were extended to future years to obtain an indication of the possible changes in annual yield. In the linear regression equations for the trend lines, the year 1975 was used to represent a baseline period of 1961-1990 and 2035 was used to represent the future period of 2021-2050. See Section 4.3.1 for a discussion on the baseline climate period (1961-1990) and modelling time horizon (2021-2050) selected for the climate change modelling study.

3.2.1 Athabasca River near Jasper

The basin drained by Athabasca River at the Jasper hydrometric station 07AA002 (drainage area of 3,870 km^2) represents a high altitude area with glacial melt contribution to runoff. The flow data from 1913 to 1931 and 1970 to 2006 for the Athabasca River near Jasper (Station 07AA002) show decreasing trends for annual mean, summer and fall mean flows and an increasing trend for spring mean, winter mean, and 7-day minimum flows. However, only the trends for annual mean, summer, and 7-day minimum flows are statistically significant at the 5% level. The December to May monthly mean flows appear to have an increasing trend, while the monthly mean flows in the summer and fall months (June to November) indicate decreasing trends. Except for March, August, and September, neither the increasing nor decreasing trends in monthly mean flows are statistically significant at the 5% level.

A linear extension of the trend line for annual mean flows suggests that the annual mean flow in 2035 (representing the period 2021-2050) could be about 5% lower than that in 1975 (representing the baseline period of 1961-1990). The predicted change in annual yield by 2035 is well within the variability in annual yield from year to year.

3.2.2 Athabasca River at Hinton

The basin drained by Athabasca River at the Hinton hydrometric station 07AD002 (drainage area of 9,720 km^2) represents a high altitude area with glacial melt contribution to runoff. Data from 1961 to 2006 were available at Station 07AD002 for analysis. Annual mean and fall flows at this station indicate decreasing trends that are not significant at the 5% level. The summer flow data show decreasing trends that are significant at the 5% level. Spring and winter flows show increasing trends that are not significant at the 5% level. The 7-day low flows indicate an increasing trend that is significant at the 5% level.

A linear extension of the trend line for annual mean flows suggests that the annual mean flow in 2035 (representing the period 2021-2050) could be about 4% lower than that in 1975 (representing the baseline period of 1961-1990). The predicted change in annual yield by 2035 is well within the variability in annual yield from year to year.

3.2.3 Athabasca River near Windfall

The spring and fall flow data in Athabasca River near Windfall (Station 07AE001 and a drainage area of 19,600 km^2) from 1960 to 2006 indicate decreasing trends, however, the trends are not significant at the 5% level. The summer flow data show a decreasing trend that is significant at the 5% level. Winter flow data were not available from 1978 to 2006, hence, trends for winter and annual mean flows for the recent years cannot be determined.

3.2.4 McLeod River above Embarras River

The annual mean, summer and fall flows in McLeod River above Embarras River (Station 07AF002 and a drainage area of 2,550 km^2) from 1954 to 2006 show decreasing trends that are not significant at the 5% level. Spring flow data suggest a decreasing trend that is significant at the 5% level. The winter and 7-day low flows show increasing trends that are not significant at the 5% level.

A linear extension of the trend line for annual mean flows suggests that the annual mean flow in 2035 (representing the period 2021-2050) could be about 10% lower than that in 1975 (representing the baseline period of 1961-1990). The predicted change in annual yield by 2035 is within the variability in annual yield from year to year.

3.2.5 Strawberry Creek near the Mouth

The spring flows at Strawberry Creek near the Mouth (Station 05DF004 and a drainage area of 589 km^2) from 1966 to 2007 show a decreasing trend that is not significant at the 5% level. The summer flows indicate an increasing trend that is not significant at the 5% level. Winter flow data were not available over the period of record, hence, trends for winter and annual mean flows for the recent years cannot be determined.

3.2.6 Sturgeon River near Fort Saskatchewan

The summer flows at Sturgeon River near Fort Saskatchewan (Station 05EA001 and a drainage area of 2,390 km^2) from 1935 to 2006 indicate a decreasing trend that is not significant at the 5% level. Spring flows indicate an increasing trend that is not significant at the 5% level. Winter flow data were not available over the period of record, hence, trends for winter and annual mean flows for the recent years cannot be determined.

3.2.7 Summary

The annual mean flows at the selected stations generally show a decreasing trend in recent years. Based on linear trend lines fitted to the data at selected hydrometric stations in Athabasca River and North Saskatchewan River basins, the predicted annual mean flows could decrease by between 4% and 9%, depending on station location, by the year 2035 compared to the baseline period of 1961-1990. The predicted changes in annual yield by 2035 are however well within the variability in annual yield from year to year.

4. POTENTIAL EFFECTS OF CLIMATE CHANGE ON WATER YIELD FROM THE NORTH SASKATCHEWAN RIVER BASIN

4.1 Introduction

Temperature data suggest that areas of Alberta have warmed over the past 50 years. Trends in precipitation are less well defined. Studies suggest that changes in annual precipitation totals range from an increase by -10% to decreases of up to 35%, with the strongest increases occurring in the northern regions of Canada. Trends in seasonal precipitation can be different from annual trends depending on season and location. The trends tend to be spatially dependent as well. Depending on the hydrologic response to climate change, the effects on water yield from a basin can increase or decrease or there may be shifts in seasonal patterns.

The effects of climate change on the water yield from the North Saskatchewan River Basin (NRSB) will affect water uses and water management in the basin. There is a need to assess the potential effects so that watershed planners can adapt their plans to take advantage of positive effects and implement mitigation measures to minimize the negative effects. Hydrologic models have commonly been used to assess the effects of climate change on watershed hydrology. One approach is to use simulated outputs from GCMs for the next few decades as inputs into hydrologic models to assess the hydrological responses of the NSRB under future modelled climate regimes.

The objective of this study is to assess the potential effects of climate change on the expected monthly and annual water yield of the NSRB in the North Saskatchewan River (NSR) under natural (undisturbed or pre-development) land conditions. For watershed planning purposes, a 25-year horizon will be assumed, that is, till 2035. In reality, one would expect land uses to change over time, either as responses to economic pressures and/or drivers or in adaptation to climate change. These changes are difficult to predict even over the short term, hence the 30-year planning horizon.

This section describes the method and results of using forecasted climate scenarios from GCMs with a hydrologic model (MISBA) to evaluate the potential effects of climate change on water supply in the North Saskatchewan River Basin (NSRB).

4.2 General Circulation Models and Forecast Scenarios

4.2.1 General Circulation Models

Future climate forecasts require the use of sophisticated mathematical computer programs called General Circulation Models or Global Climate Models (GCMs). These models simulate the interactions of airborne emissions (greenhouse gases and aerosols), the atmosphere (e.g., solar radiation), land surfaces (e.g., terrestrial heat loss) and oceans and can take several months to run. The Intergovernmental Panel on Climate Change (IPCC), which has been charged with providing state-of-the-art reviews of climate change science, has made use of a number of different GCMs. Seven of these models are presented in Table 4.1.

Table 4.1
General Circulation Models (GCMs)

Model Name	Abbreviation	Country	Model Resolution[(a)] [km²]
Centre for Climate System Research / National Institute for Environmental Studies	CCSR/NIES	Japan	168,000
Canadian Global Coupled Model (Version 2)	CGCM2	Canada	74,000
Commonwealth Scientific and Industrial Research Organization Mark 2	CSIRO MK2	Australia	95,000
Max Planck Institute for Meteorology / Deutsches Klimarechenzentrum	ECHAM4/OPYC3	Germany	41,000
Geophysical Fluid Dynamics Laboratory	GFDL R30	United States	44,000
Hadley Centre Coupled Model	HadCM3	United Kingdom	50,000
National Centre for Atmospheric Research Parallel Climate Model[(b)]	NCAR-PCM	United States	41,000

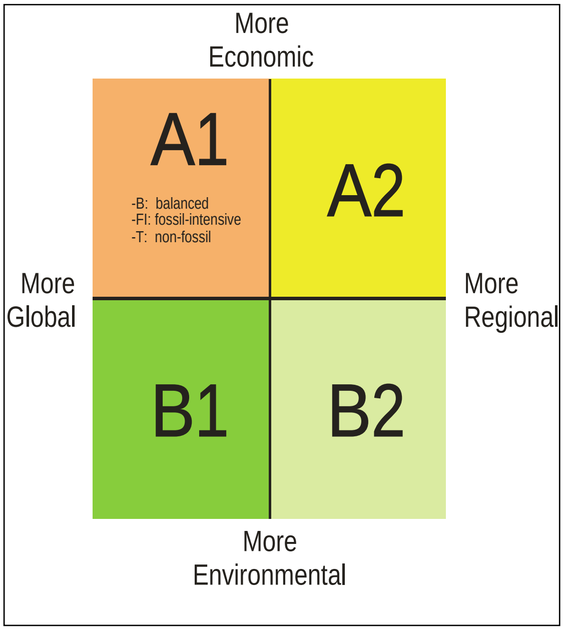
(a) The model resolution represents the area of each grid cell used in the respective models.

4.2.2 Forecast Scenarios

Given the wide range of inputs available to GCMs, the IPCC has established a series of global greenhouse gases (GHG) emission scenarios based on four potential socio-economic development paths. The Third Assessment Report (IPCC 2001) identifies these scenarios as A1, B1, A2 and B2. The A1 and A2 scenarios represent a focus on economic growth, while the B1 and B2 scenarios represent a shift towards more environmentally conscious solutions to growth. Both scenarios A1 and B1 include a shift towards global solutions while the A2 and B2 scenarios include growth based on more localized and regional approaches. Figure 4.1 provides an illustrative summary of the four emission scenarios.

Although the IPCC has not stated which of the emission scenarios is most likely to occur, the A2 scenario most closely reflects the current global socio-economic situation. In relation to the A2 scenario, scenarios A1, B1 and B2 result in lower long-term GHG emissions over the next century. Of the A1 scenario family, scenario A1FI yields high emissions in the first half of the 21st century due to increasing population and high dependence on fossil fuels for energy. While the IPCC supports all of these scenarios, forecast data from each of them are not available for all the GCMs.

Figure 4.1: Intergovernmental Panel on Climate Change Emission Scenarios



4.2.3 Downscaling GCM Outputs for Use with Hydrologic Models

The coupling of GCMs with hydrologic models faces a key challenge: GCMs simulate climate variables at a global scale, while hydrologic models require local meteorological inputs to drive them. Several methods are available to transfer the GCM outputs to the watershed scale.

4.2.3.1 Delta Method based on GCM Outputs

A widely used method, called the delta method, relies on the calculation of the monthly deviation between future and present periods (Quilbe *et al*. 2008). This approach is still used in many studies because of its simplicity.

In this method, mean monthly values of precipitation, minimum temperature and maximum temperature are taken directly from the GCM outputs. Adjustment factors are then calculated by comparing the mean monthly values for the future and reference periods. The adjustment factors are then applied to the measured daily values at each climate station selected for a study basin. Quilbe *et al*. (2008) describe this approach in detail.

Major assumptions implicit in this approach are that the effect of climate change is spatially homogeneous over the whole watershed, and that precipitation occurrence remains the same between the past and future periods.

4.2.3.2 Downscaling of GCM Climate Scenarios

Downscaling and other more sophisticated methods have been developed recently as attempts to bridge the gap between GCMs and hydrologic models (Quilbe *et al.* 2008). The two common approaches are dynamic and statistical downscaling.

Dynamic downscaling uses regional climate models (RCMs) with GCM data as lateral boundary conditions. The main drawback of RCMs is that they require significant computing resources (due to their much finer spatial resolution) and, for most of them, generate data that still need to be downscaled to a finer spatial scale to be useful for distributed hydrologic models. Researchers report that statistical downscaling is much simpler and more suited for use with hydrological models (Quilbe *et al*. 2008) than dynamic down-scaling.

In the statistical downscaling approach, regional-scale climatic variables (predictors) are linked to local climate variables (predictands) such as temperature and precipitation. Of the several ways of making the linkages, the regression-based statistical downscaling is considered to be the simplest to implement. The predictors are linked to the predictands by regression on measured data, and then to calculate future daily values of predictands based on GCM outputs (i.e., the predictors).

4.2.3.3 Use of Re-Analysis Data with GCM-Predicted Changes

In the absence of downscaled data, one approach is to use re-analysis global data such as ERA40. The European Centre for Mid-Range Weather Forecast global re-analysis (ERA-40) climate data can be adjusted to reflect the forecasts from the GCMs. ERA-40 has 6-hourly data coverage from 1957 to 2002, with a spatial resolution of 2.5^o latitude and 2.5^o longitude. Mean differences between the GCMs' representations of current climate (say, a baseline period of 1961-1990) and the future period (say, a future period of 2021-2050) are calculated and combined with the ERA-40 baseline climate data set to obtain climate scenarios. Since the GCM model output grids and ERA-40 data set grids are not the same, the GCM model grids that belong in each of the ERA-40 data grid blocks should be averaged before calculating mean differences.

4.2.4 Baseline Climate

An analysis of climate change depends not only on future conditions but also on the baseline climate to which the predictions are compared. Baseline climate information is important for describing average conditions, spatial and temporal variability and anomalous events as well as calibrating and testing climate models (CICS 2005).

The IPCC recommends that 1961 to 1990 be adopted as the climatological baseline period in impact assessments (CICS 2005). This period has been selected since it is considered to:

- Be representative of the present-day or recent average climate.
- Be of a sufficient duration to encompass a range of climatic variations, including a number of significant weather anomalies.
- Include data of sufficiently high quality for use in evaluating impacts.
- Be comparable with baseline climatologies used in other impact assessments.

4.2.5 Modelling Time Horizons

The IPCC currently recommends that three fixed time horizons in the future, the 2020s (2010-2039), the 2050s (2040-2069) and the 2080s (2070-2099), be considered in impacts studies. To obtain a *climate scenario*, i.e., a representation of the "actual" future climate rather than simply the change in climate relative to the baseline period, the climate change scenario is combined with the baseline *observed* climate data set.

Notwithstanding the recommendation of IPCC, it is important to determine the time horizon of interest for assessing the effects of climate change. For example, for water supply assessment, the planning period could be 20-30 years as opposed to 100 years. The uncertainty in the predictions of the effects of climate change on water supply in the distant future may be larger than the predicted effects themselves. In any case, there is a greater possibility for adaptation over the long-term as better models become available and predictions become more reliable.

4.3 Climate Change Scenarios for the NSRB

4.3.1 Baseline Climate Period and Modelling Time Horizon

The reference period for characterizing baseline hydrologic conditions in the NSRB is defined by the availability of climate data within the basin. The period from 1970 to 1999 appears to be one where climate data are available at a few key climate stations in the NSRB (See Section 3).

Climate forecast data from various models and emissions scenarios can be analyzed to determine potential climate change in the NSRB. Since the models are susceptible to inter-decadal variability, the analysis uses the average of 30 years of data, centred on the decade of interest. The future conditions have been represented by the 30-year period between 2021 and 2050, which would be representative of the mid-2030s, or an approximately 25-year planning horizon. This forecast range is most useful for planning purposes and is within the range that GCM predictions can be viewed as “reasonable”.

4.3.2 Selection of Forecast Scenarios and GCMs for the NSRB

The hydrologic model MISBA model set up for the NSRB requires forecasts of future climate from GCMs. As shown in Table 4.1, several GCMs are available. The IPCC recommends that several climate scenarios need to be considered because a single climate model scenario does not provide a reliable description of the climatic evolution, while ensembles of state-of-the-art climate models, on the other hand, capture the main features of the past climatic evolution

(Benestad, 2003). Given that the total number of combinations of GCMs and scenarios can be excessive, a few combinations of GCMs and scenarios should be initially selected so that the range of climate scenarios can represent dry, medium and wet scenarios, while avoiding excessive runs that may be redundant (Barrow and Yu, 2005).

For the purposes of the climate change assessment for the NSRB, the A1B, A2 and B1 scenarios were selected. Referring to Figure 4.1, scenario A1B represents future balanced socio-economic and environmentally-based development; scenario A2 assumes that the current global socio-economic situation will continue in the future; and, scenario B1 represents future development that is more environmentally-based than at present.

The GCMs initially selected for the NSRB study were ECHAM50, NCARCCSM3, GFLDLC2.1, CGCM3T47 and HADCM3 out of the seven listed in Table 4.1. The forecasts from these GCMs tend to span a reasonable range of the changes in temperature and precipitation predicted by most GCMs. Each GCM is assessed with three scenarios (A1B, A2 and B1). In combination with the forecast scenarios (A1B, A2 and B1), the outputs from these five GCMs tend to encompass the possible future warm-wet, warm-dry, cool-wet and cool-dry climatic conditions relative to baseline conditions.

The final selection of the appropriate GCMs for the NSRB was made based on a comparison of the outputs of each of the five GCMs for the 1961-1990 baseline climate period with the observed climate data in the NSRB for the same baseline period. The mean annual observed precipitation and temperature data derived from four stations in the NSRB (Nordegg, Rocky Mountain House, Edmonton and Vermillion) located within the NRSB were compared with different model simulation outputs. Table 4.2 shows the mean annual temperature and mean annual total precipitation predicted by the five GCMs for the baseline period as well as the statistics at each of the four climate stations for the period for which data are available. Table 4.3 provides the ranking of the five GCMs based on each GCM’s ability to replicate the annual precipitation and temperature statistics at the four climate stations in the NSRB, with ranking 1 being the closest and 5 being the least close among the five models.

Table 4.3 shows that the ECHAM50M GCM is ranked as the model that most closely replicate baseline mean annual temperature statistic for three of the four climate stations in the NSRB. The exception is the temperature statistic at Vermillion. The NCARCCSM3 GCM is ranked second based on temperature at all four climate stations. Unlike for temperature, there is no clear pattern for the selection of suitable GCMs based on the mean annual precipitation statistic. This is not unexpected as GCMs are less able to model precipitation. Based on mean annual total precipitation, the ECHAM50M GCM ranked first for Nordegg, and the CGCM3T47 GCM was ranked second at Nordegg and Rocky Mountain House. These two stations are located in the upper portion of the NSRB, an area that generates almost 70% of the total yield of the NRSB at the Alberta-Saskatchewan boundary. The NCARCCSM3 GCMs ranked first for mean annual precipitation at Rocky Mountain House.

There is no clear choice for one GCM that can replicate both baseline precipitation and temperature conditions in the NSRB. Considering that the headwaters of the NSRB, represented by the Nordegg and Rocky Mountain House climate stations, generate the bulk of the water yield, it is apparent that the ECHAM50M can be considered as the GCM that most closely represent the climate conditions in the NRSB. The NCARCCSM3 and CGCM3T47 GCMs are the next two most representative GCMs for the upper basins of the NSRB. However, it is necessary to consider an ensemble of scenarios for effects assessment. Therefore, all GCMs that ranked either first or second for temperature and precipitation were selected for modeling purposes. These four GCMs are ECHAM50M, NCARCCSM3, CGCM3T47 and GFLDC2.1. The outputs of each GCM were obtained for the three selected forecast scenarios (A1B, A2 and B1).

4.3.3 Generation of Forecasts from GCMs-Scenarios Selected for the NSRB

As discussed in Section 4.2.3, outputs from GCMs are still not sufficiently accurate at regional scales to be used directly in watershed-level impact studies. Given the significant effort required to downscale the GCM outputs using either the dynamic or statistical approach (Section 4.2.3.2) and the lack of complete observed data for the baseline period of 1961 to 1990 to use the delta method (Section 4.2.3.1), a decision was made to use the ERA-40 data (Section 4.2.3.3). The European Centre for Mid-Range Weather Forecast global re-analysis (ERA-40) climate data can be adjusted to reflect the forecasts from the GCMs. ERA-40 has 6-hourly data coverage from 1957 to 2002, with a spatial resolution of 2.5^{o} latitude and 2.5^{o} longitude, and is available for most of Alberta. This resolution is still fairly coarse, but is better than the resolution of the GCMs.

Table 4.2
Predicted Baseline Mean Annual Temperature and Precipitation by GCMs at Climate Stations in the NSRB

	PREDICTED DATA							
	Nordegg		**Rocky Mountain**		**Edmonton**		**Vermillion**	
GCM Model	Mean Annual Total Precipitation (mm)	Mean Annual Temperature (°C)	Mean Annual Total Precipitation (mm)	Mean Annual Temperature (°C)	Mean Annual Total Precipitation (mm)	Mean Annual Temperature (°C)	Mean Annual Total Precipitation (mm)	Mean Annual Temperature (°C)
CGCM3T47	642	-1.07	573	-0.60	504	-0.13	487	-0.13
ECHAM50M	583	-0.09	604	1.36	548	2.63	485	3.45
GFDLC2.1	719	-1.72	615	-1.28	485	0.10	462	0.97
HADCM3	711	-1.35	599	-0.17	596	0.79	596	0.79
NCARCCSM3	664	-0.31	573	0.64	502	1.17	440	1.84
	OBSERVED DATA							
Data Record Length (years)	20	20	12	12	30	30	22	21
Measured Data (Mean)	591	1.05	522	2.31	461	3.66	422	1.37
Measured Data (Standard Deviation)	116	1.17	78	1.2	69	1.18	96	1.07

Note: The colour of shaded cells indicates the GCM (similarly shaded in the first column) that most closely matches the measured data.

Table 4.3
Ranking of GCM Climate Baseline Predictions against Measured Data

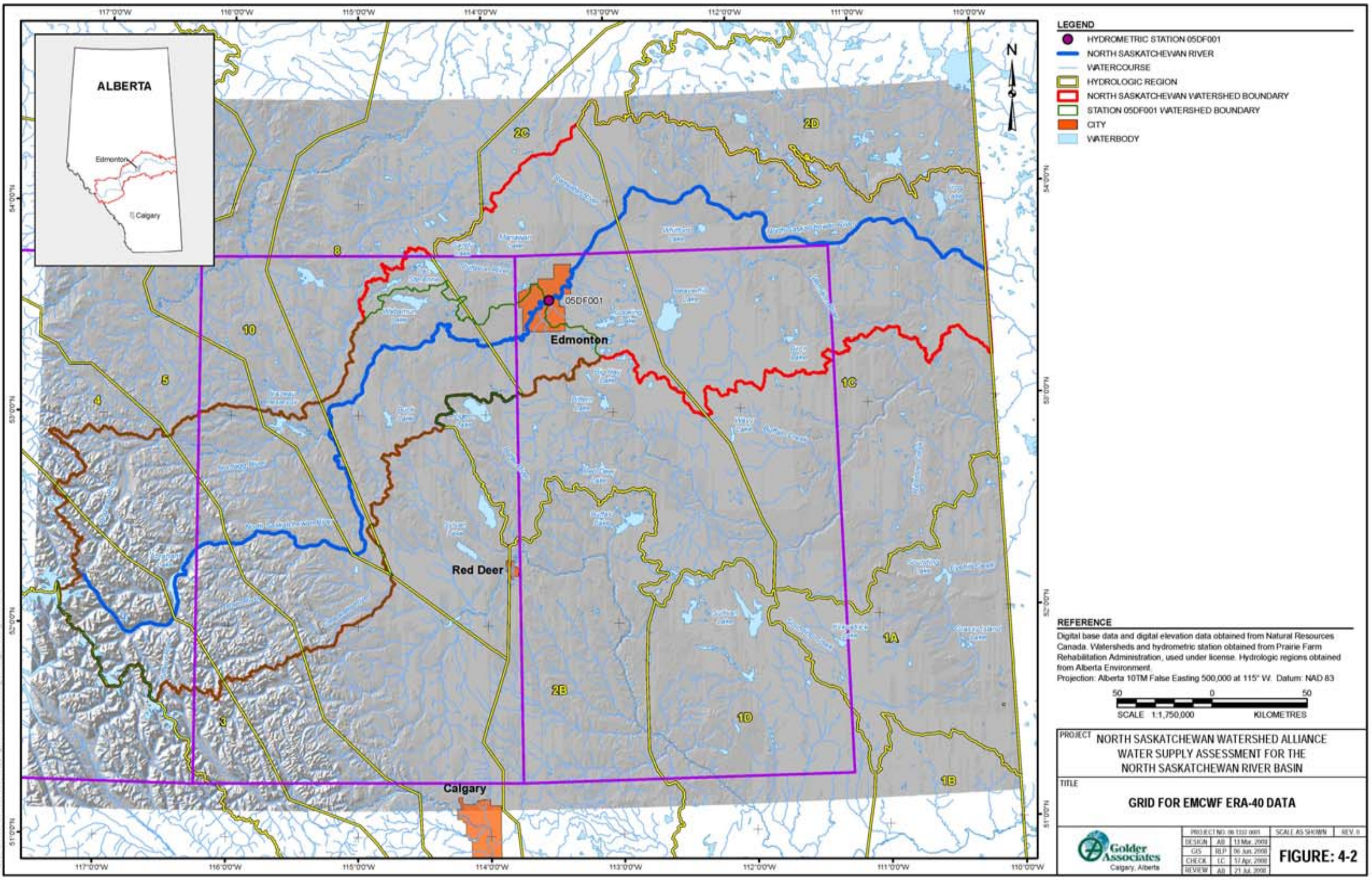
Station	Available Data (years)	Rank for MEAN ANNUAL TOTAL PRECIPITATION				
		1	2	3	4	5
Nordegg	20	ECHAM50M	CGCM3T47	NCARCCSM3	HADCM3	GFDLC2.1
Rocky Mountain House	12	NCARCCSM3	CGCM3T47	HADCM3	ECHAM50M	GFDLC2.1
Edmonton	30	GFDLC2.1	NCARCCSM3	CGCM3T47	ECHAM50M	HADCM3
Vermillion	22	NCARCCSM3	GFDLC2.1	ECHAM50M	CGCM3T47	HADCM3
		Rank for MEAN ANNUAL TEMPERATURE				
		1	2	3	4	5
Nordegg	20	ECHAM50M	NCARCCSM3	CGCM3T47	HADCM3	GFDLC2.1
Rocky Mountain House	12	ECHAM50M	NCARCCSM3	HADCM3	CGCM3T47	GFDLC2.1
Edmonton	30	ECHAM50M	NCARCCSM3	HADCM3	GFDLC2.1	CGCM3T47
Vermillion	21	GFDLC2.1	NCARCCSM3	HADCM3	CGCM3T47	ECHAM50M

Figure 4.2 shows the grids for which ERA-40 data were available for this study. Data coverage for significant areas east of Edmonton was not available. In addition, significant portions of the basin areas east of Edmonton are classified as “non-contributing”, that is, the contribution to flows in the NSR from these areas is insignificant during average hydrologic conditions because of extensive depression storage areas. Such areas are difficult to incorporate in the hydrologic models available for this study. Hence, for the purposes of this study, the WSC hydrometric station 05DF001 site was selected as the downstream boundary of the study area.

The process to adjust the ERA-40 data to reflect the predictions of the GCMs was as follows. The mean monthly temperatures for the baseline period (1961-1990) were estimated. The difference between these values and the monthly means for the forecast period (2021-2050) were calculated for each GCM-forecast scenario. The ERA-40 6-hour temperature data for a given month was then adjusted by the difference predicted by each GCM-scenario for that particular month. For precipitation, the mean monthly total precipitation amounts for the baseline period (1961-1990) were estimated. The ratios of the (2021-2050) forecasted monthly total precipitation amounts to the baseline values were obtained for each month for each GCM-scenario. The ERA-40 6-hour precipitation data for a given month was then adjusted by the ratio predicted by each GCM-scenario for that particular month. Figure 4.3 shows that the ERA-40 annual precipitation data (precipitation amounts from three ERA-40 grids covering the NRSB weighted by the area of the NSRB within each grid) closely matches the observed annual amounts as well as the trends at the Nordegg, Rocky Mountain House and Edmonton climate stations.

Since the output grids for the selected four GCMs do not match the ERA-40 data set grids, the outputs of the GCM model grids that belong in each of the ERA-40 data grid blocks are averaged before calculating differences in temperatures and ratios of precipitation. Figure 4.4 presents the data grid blocks for each GCM and ERA-40 data. The ERA-40 grids and the corresponding GCM grids used for averaging are also presented in Figure 4.4.

Figure 4.2: Grid for EMCWF ERA-40 DATA



REFERENCE

Digital base data and digital elevation data obtained from Natural Resources Canada. Watersheds and hydrometric station obtained from Prairie Farm Rehabilitation Administration, used under license. Hydrologic regions obtained from Alberta Environment.

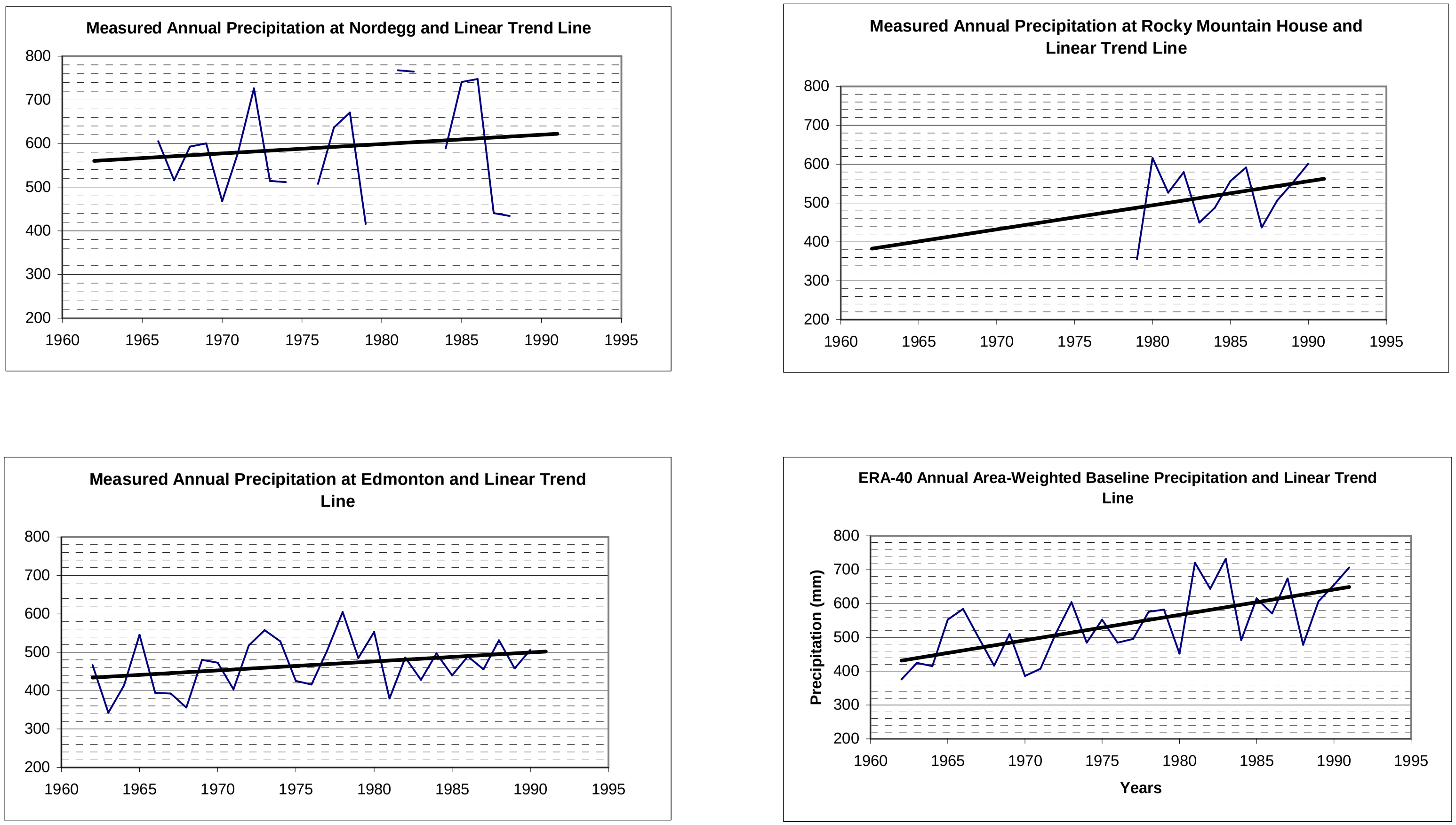
Projection: Alberta 10TM False Easting 500,000 at 115° W. Datum: NAD 83

PROJECT NORTH SASKATCHEWAN WATERSHED ALLIANCE
WATER SUPPLY ASSESSMENT FOR THE
NORTH SASKATCHEWAN RIVER BASIN

TITLE GRID FOR EMCWF ERA-40 DATA

PROJECT NO. 08-1337-0001			SCALE AS SHOWN	REV. 0
DESIGN	AB	13 Mar. 2008	FIGURE: 4-2	
GIS	RLP	06 Jun. 2008		
CHECK	LC	17 Apr. 2008		
REVIEW	AB	21 Jul. 2008		

Figure 4.3: Comparison of Observed Trend in Precipitation Data with Trend Predicted by GCMs for the Baseline Period



Measured Annual Precipitation at Nordegg and Linear Trend Line

Measured Annual Precipitation at Rocky Mountain House and Linear Trend Line

Measured Annual Precipitation at Edmonton and Linear Trend Line

ERA-40 Annual Area-Weighted Baseline Precipitation and Linear Trend Line

Figure 4.4: GCM Output Grid Assignment for Averaging to Match ERA-40 Grid

Grid for Model ECHAM50

(1) - 116.25 53.16	(2) - 114.375 53.16	(3) - 112.5 53.16
(4) - 116.25 51.294	(5) - 114.375 51.294	(6) - 112.5 51.294
(7) - 116.25 49.429	(8) - 114.375 49.429	(9) - 112.5 49.429

Grid for Model CGCM3T47

(1) - 116.25 53.81027	(2) - 112.5 53.81027
(3) - 116.25 50.09945	(4) - 112.5 50.09945

Grid for Model NCARCCSM3

(1) -115.313 53.92937	(2) - 113.906 53.92937	(3) - 112.5 53.92937
(4) - 115.313 52.52862	(5) - 113.906 52.52862	(6) - 112.5 52.52862
(7) - 115.313 51.12787	(8) '- 113.906 51.12787	(9) '- 112.5 51.12787
(10) - 115.313 49.72711	(11) - 113.906 49.72711	(12) - 112.5 49.72711

Grid for Model GFLDLC2.1

(1) - 116.25 53.5955	(2) - 113.75 53.5955	(3) - 111.25 53.5955
(4) - 116.25 51.57303	(5) - 113.75 51.57303	(6) - 111.25 51.57303
(7) - 116.25 49.55056	(8) - 113.75 49.55056	(9) - 111.25 49.55056

Grid for ERA-40 Data

(A) - 117.5 52.5	(B) - 115.0 52.5	(C) - 112.5 52.5

Grids Assignment

ERA-40 Grids	ECHAM50	CGCM3T47	NCARCCSM3	GFLDLC2.1
A	1, 4	1, 3	4	1, 4
B	1, 4, 2	1, 2	2, 4	1, 2, 4
C	3	2	2,3	2, 3

The NSRB is covered by three ERA-40 grid cells. The westernmost grid cell tends to cover the mountain areas of the NSRB, the next cell covers the foothills, followed by a cell that covers the area near Edmonton and east, and a fourth cell covers the easternmost section of the NSRB. For this study, the easternmost cell was not modelled because the data was not available for this study. This portion of the NSRB contributes very little to the basin's water yield and effects of climate change on the yield from the western portions of the NSRB are significantly more critical. Nevertheless, the effects of climate change on local water supplies in the eastern-most part of the NRSB could be critical with already low water yield, especially for household use, dugouts, crops and stock watering, etc., and therefore should be given considered in future climate change studies.

Table 4.4 summarizes the area-weighted mean annual temperature differences and percentage change in mean annual precipitation predicted by each GCM-scenario. The results indicate that NCARCCSM3-SRA1B predicts the largest increase in temperature (about 2.2°C), while ECHAM50M-SRB1 predicts the smallest increase (about 0.3°C). Predictions of changes in precipitation tend to vary significantly between GCMs and even between scenarios of a given GCM. Table 4.4 shows that the change in mean annual total precipitation for the forecast period of 2021-2050 from the baseline period of 1961-1990 ranges from a decrease of about 8% (GFLDLC2.1-SRA2) to an increase of about 19% (NCARCCSM3-SRA2), with 10 of the 12 scenarios predicting an increase in precipitation.

4.4 Hydrologic Modelling of Climate Change Effects for the NSRB

The modified Interactions Soil-Biosphere-Atmosphere land surface model (MISBA) of Météo France (Noilhan and Plantin, 1989) was set up for the North Saskatchewan River Basin (NSRB). The original model was ISBA (Interaction between Soil, Biosphere and Atmosphere), a land surface vertical water budget model, was modified to provide for non-linear formulations for surface and subsurface runoff. Kerkhoven and Gan (2006) applied MISBA to the Athabasca River Basin (ARB) to investigate the effects of climate change on stream flows in the Athabasca River and obtained good results using the ERA-40 re-analysis data of ECMWF (European Centre for Mid-range Weather Forecasts).

Table 4.4
Watershed Area-Weighted Differences in Mean Annual Temperature and Percent Change in Mean Annual Precipitation Outputs between Baseline Period 1961-1990 and Forecast Period 2021-2050

Climate Parameter	**GCM-Scenario**		
	ECHAM50M-SRA1B	**ECHAM50-SRA2**	**ECHAM50-SRB1**
Temperature	1.06	0.98	0.31
Precipitation	0%	9%	6%
	NCARCCSM3-SRA1B	**NCARCCSM3-SRA2**	**NCARCCSMS-SRB1**
Temperature	2.18	2.09	1.34
Precipitation	15%	19%	11%
	CGCM3T47-SRA1B	**CGCM3T47-SRA2**	**CGCM3T47-SRB1**
Temperature	1.68	1.92	1.83
Precipitation	6%	5%	15%
	GFLDLC2.1-SRA1B	**GFLDLC2.1-SRA2**	**GFLDLC2.1-SRB1**
Temperature	1.63	1.29	1.57
Precipitation	-1%	-8%	1%

The MISBA model for the NSRB was driven by the European Centre for Mid-Range Weather Forecast global re-analysis (ERA-40) climate data that were adjusted to reflect the forecasts from the GCMs as described in Section 4.3.3. The 1961-1990 ECMWF ERA-40 climate data for grids covering the NSRB near Edmonton and west was used as the baseline data. The predicted changes to mean monthly temperature and precipitation provided by the GCMs were used on the ERA-40 data to obtain possible future climate scenarios. The simulations with MISBA assumed that other climate parameters such as solar radiation, wind speed and relative humidity remain unchanged in the future climate scenarios. Detailed analysis, including statistical and/or dynamical downscaling would be required for estimating changes to these climate parameters. Such analyses were outside the scope for this study.

4.4.1 Comparison of Modeled and Observed Baseline Flows

As discussed in Section 4.3.3, the downstream boundary of the study area for the NSRB was selected as the location of the WSC Hydrometric Station 05DF001. Natural (unregulated) daily flow data are available at this location for the period from 1912 to 1959. Simulated flows obtained using MISBA and the ERA-40 baseline data from 1961 to 1990 were compared to the natural flows at 05DF001. Table 4.5 shows the comparison of mean monthly flows (expressed as mm of runoff).

Table 4.5
Comparison of Simulated and Observed Mean Monthly Flows at WSC Station 05DF001

Month	Mean Monthly Yield (mm)	
	From Observed Data (1912-1959)	Simulated from ERA-40 Data (1961-1990)
January	3.41	2.18
February	3.11	2.63
March	3.55	7.03
April	13.5	24.3
May	28.0	62.4
June	53.4	51.6
July	53.1	21.0
August	40.3	16.9
September	25.0	15.1
October	12.8	7.08
November	6.52	3.67
December	5.82	2.61
Annual	**246**	**217**

The results in Table 4.5 show that the simulated flows from the MISBA model using ERA-40 data are reasonably close to the observed flows. However, the observed annual and summer (July and August) yields tend to be higher than the respective simulated yields. In addition, while the maximum monthly yields tend to occur in June and July, the highest monthly simulated yields occur earlier in May and June. Some of the differences can be attributed to the different time periods of the observed and simulated data. However, a more significant reason for the difference may be due to the large area covered by each ERA-40 grid cell such that local temperature regimes in mountainous areas are not being captured well. Similarly, localized summer rainfall events may not be captured in enough spatial detail by the ERA-40 data set. It is also possible that snowmelt routines in MISBA may not be fully capturing the snowmelt process in the mountains. Further refinement of the climate input parameters, particularly, the generation of more spatially refined climate data, and the model set-up would be necessary to reduce the differences between observed and simulated flows. Notwithstanding the differences, the simulated flows are reasonable for the purposes of this study and are used to assess the relative effects (simulated 2021-2050 model outputs compared with simulated 1961-1990 model outputs) of climate change on water yield in the NSRB at WSC Station 05DF001.

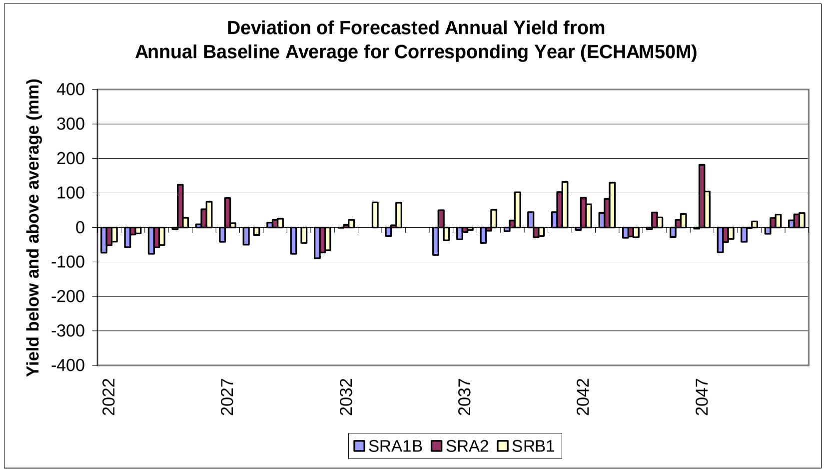
4.4.2 Effects on Yield - Results of Climate Change Simulations

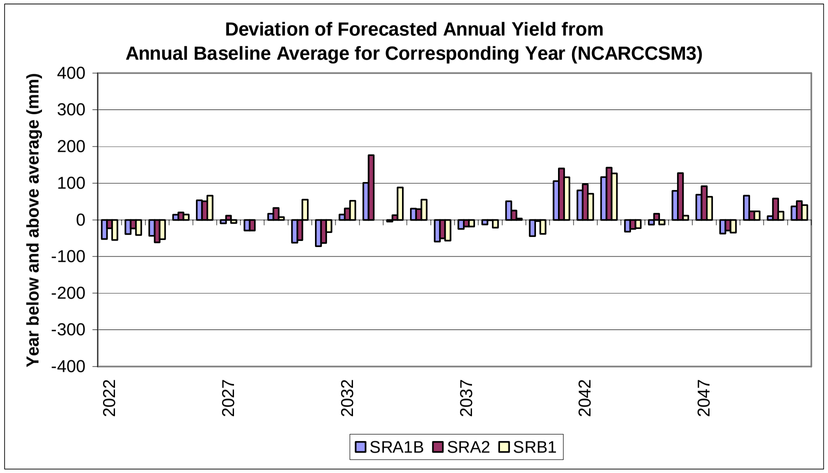
Figure 4.5 illustrates the changes in annual yield (as deviation in mm from baseline for the corresponding year) predicted by the four selected GCMs and associated scenarios. Table 4.6 shows the average annual percent changes in yield from baseline conditions to the 2021-2050 forecasted conditions by the GCMs. Five of the six ECHAM50M and NCARCCSM3 GCM-scenario combinations are predicting increases in annual yield that range from 5% to 15%. Only the ECHAM50M-SRA1B combination predicts a decrease of about 11%. The CGCM3T47 and GFLDC21 GCM-scenario combinations are predicting decreases in annual yield that range from 3% to 23%.

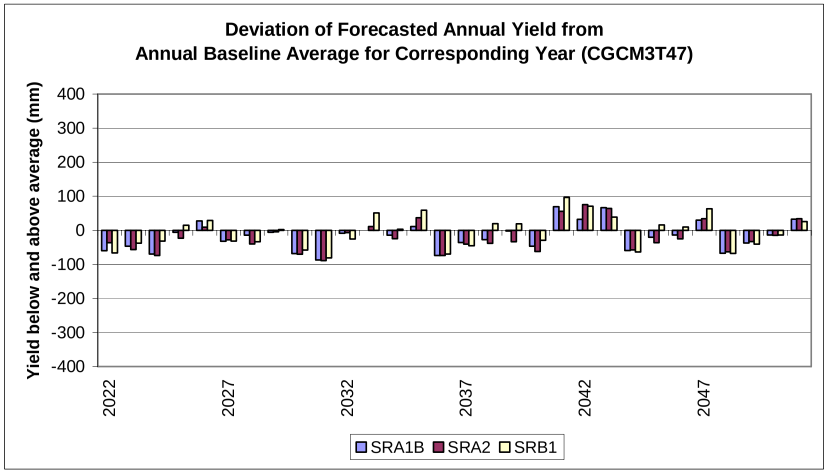
As discussed in Section 3.2.7, the observed annual mean flows at selected hydrometric stations in the NSRB and adjoining basins generally show a decreasing trend in recent years. Based on linear trend lines fitted to the data, the predicted annual mean flows would decrease by between 4% and 9%. These decreases, which are statistically not significant and well within the natural variability of annual yield, would appear to be in line with the predictions using the CGCM3T47 and GFLDC21 GCM-scenario combinations. However, as discussed in Section 4.3.2, the ECHAM50M and NCARCCSM3 GCMs are likely the more representative GCMs of the baseline climate of the runoff-producing headwater basins of the NSRB. The results of the simulations using these GCMs may therefore indicate the more likely trends in future yield from the NSRB.

Notwithstanding that the GCMs most representative of baseline climate in the NSRB predict increases in annual yield, the range of possible predicted impacts should be considered in watershed planning because the model predictions have some degree of uncertainty associated with them. The IPCC recommends that several climate scenarios need to be considered because a single climate model scenario does not provide a reliable description of the climatic evolution, while ensembles of state-of-the-art climate models, on the other hand, capture the main features of the past climatic evolution (Benestad, 2003).

Figure 4.5: Annual Deviation in Yield Predicted by GCMs for 2021-2050 Relative to Baseline (1961-1990)


Deviation of Forecasted Annual Yield from Annual Baseline Average for Corresponding Year (ECHAM50M)


Deviation of Forecasted Annual Yield from Annual Baseline Average for Corresponding Year (NCARCCSM3)


Deviation of Forecasted Annual Yield from Annual Baseline Average for Corresponding Year (CGCM3T47)

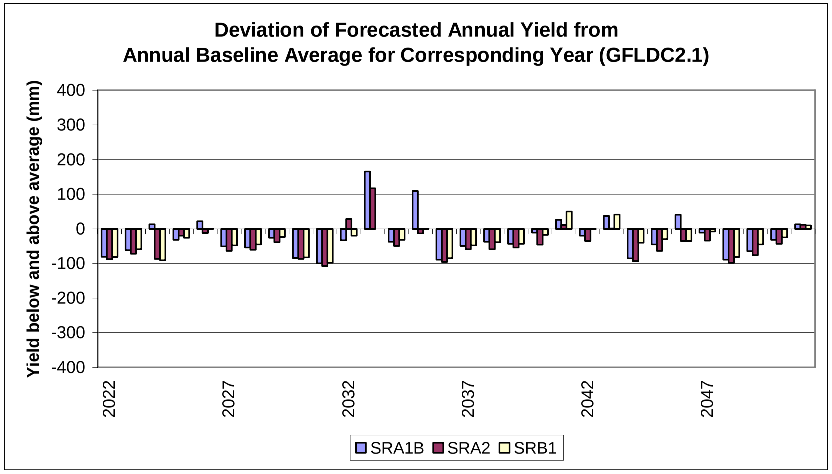

Deviation of Forecasted Annual Yield from Annual Baseline Average for Corresponding Year (GFLDC2.1)

Table 4.6
Predicted Changes in Annual Yield over the Forecast Period of 2021-2050 from the Baseline Period of 1961-1990

GCM	Simulated Baseline (1961-1990)	ECHAM50M			NCARCCSM3			CGCM3T47			GFLDC2.1		
Foecast Scenario		SRA1B	SRA2	SRB1	SRA1B	SRA2	SRB1	SRA1B	SRA2	SRB1	SRA1B	SRA2	SRB1
Mean Annual Yield (mm)	217	192	250	249	227	242	231	196	193	211	181	166	181
Deviation (%)	NA	-11%	15%	15%	5%	12%	7%	-9%	-11%	-3%	-16%	-23%	-17%

Figure 4.6 shows the mean monthly yield predicted by the four GCMs and their three scenarios, as well as the baseline yield. Tables 4.7 and 4.8 summarize the results as the average monthly percent changes and average monthly absolute changes from the baseline values. It is apparent that the percent changes in monthly yield are much larger than would be implied by the percent changes in annual yield as summarized in Table 4.6. The percent changes tend to be higher for the winter months when flows are generally low. Increases in mean monthly yields tend to occur during the spring months. This result reflects the predicted increase in precipitation (snow) and increase in temperature. Decreases in mean monthly yield tend to occur during the summer months and into the fall. This result suggests that the predicted increase in temperature is causing an increase in evapotranspiration during the summer months.

Figure 4.6 Deviation in Mean Monthly Yield Predicted by GCMs for 2021-2050 Relative to Baseline (1961-1990)

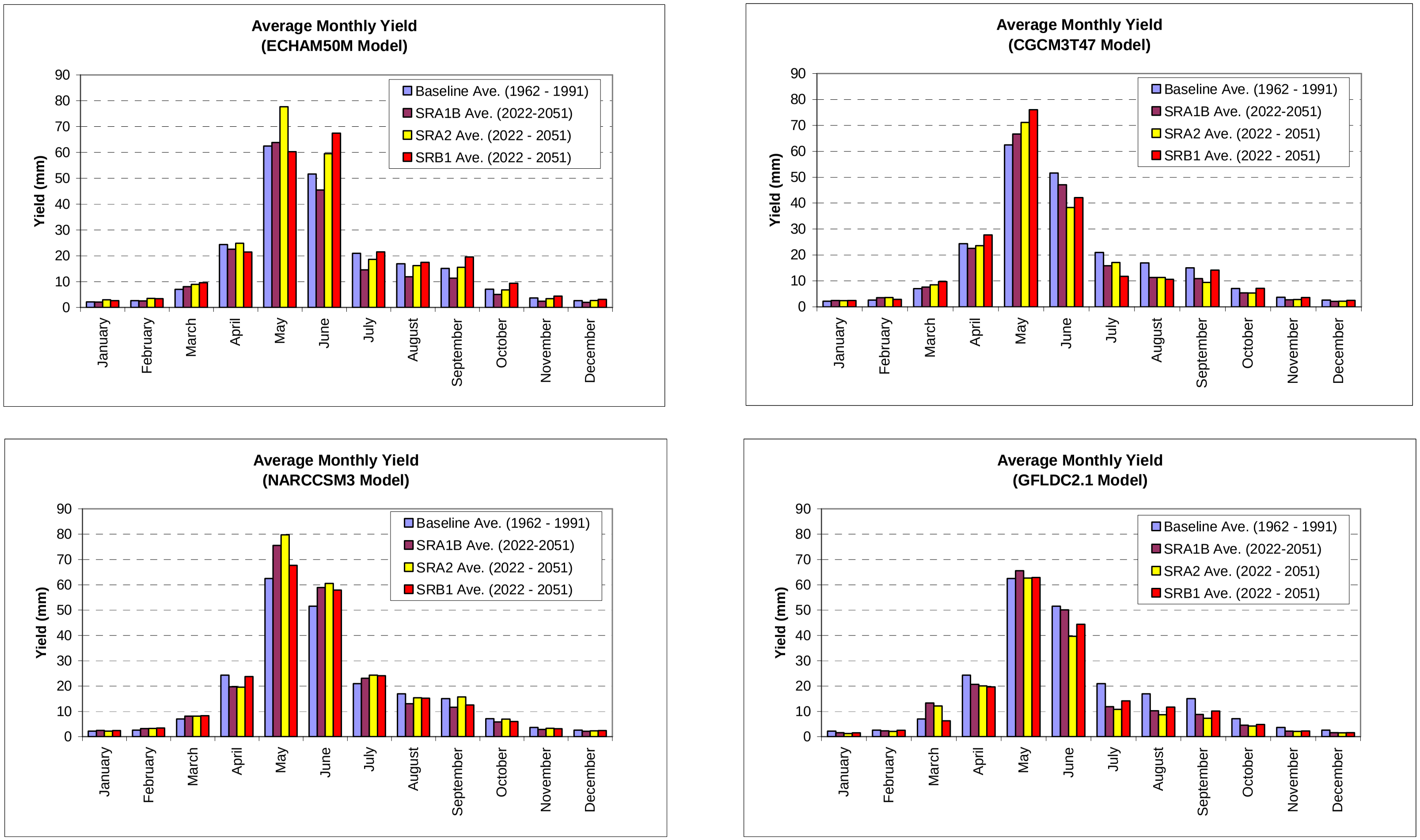


Table 4.7
Percent Changes in Monthly Yield Predicted by GCMs for 2021-2050 Relative to Baseline (1962-1991)

GCM	Deviation from 1961-1990 Baseline Mean Yield											
	ECHAM50M			NCARCCSM3			CGCM3T47			GFLDC2.1		
Forecast Scenario	**SRA1B**	**SRA2**	**SRB1**	**SRA1B**	**SRA2**	**SRB1**	**SRA1B**	**SRA2**	**SRB1**	**SRA1B**	**SRA2**	**SRB1**
January	-4%	34%	19%	13%	2%	12%	12%	8%	12%	-26%	-40%	-30%
February	-3%	34%	31%	23%	26%	29%	35%	36%	9%	-12%	-21%	-3%
March	15%	27%	36%	15%	15%	18%	8%	21%	39%	90%	72%	-10%
April	-7%	2%	-12%	-19%	-20%	-2%	-7%	-3%	14%	-15%	-18%	-19%
May	2%	24%	-3%	21%	28%	8%	7%	14%	22%	5%	0%	1%
June	-12%	15%	31%	14%	17%	12%	-9%	-26%	-18%	-3%	-23%	-14%
July	-31%	-11%	3%	10%	16%	15%	-25%	-19%	-44%	-44%	-49%	-33%
August	-30%	-5%	3%	-23%	-9%	-10%	-33%	-33%	-38%	-39%	-49%	-31%
September	-25%	3%	30%	-23%	4%	-17%	-28%	-37%	-6%	-42%	-52%	-33%
October	-28%	-3%	32%	-18%	-1%	-14%	-24%	-25%	1%	-36%	-40%	-32%
November	-34%	-7%	20%	-21%	-9%	-15%	-27%	-24%	-3%	-40%	-44%	-38%
December	-26%	3%	19%	-18%	-11%	-8%	-20%	-16%	-6%	-37%	-42%	-38%

Table 4.8
Absolute Changes in Monthly Yield Predicted by GCMs for 2021-2050 Relative to Baseline (1962-1991)

Simulated Baseline Mean Volume (Mm3)	GCM	Change from 1961-1990 Baseline Mean Volume (Mm^3)						Change from 1961-1990 Baseline Mean Volume (Mm^3)					
		ECHAM50M			NCARCCSM3			CGCM3T47			GFLDC2.1		
	Forecast Scenario	SRA1B	SRA2	SRB1	SRA1B	SRA2	SRB1	SRA1B	SRA2	SRB1	SRA1B	SRA2	SRB1
61	January	-2	21	12	8	1	7	7	5	7	-16	-25	-18
74	February	-2	25	23	17	19	22	26	26	7	-9	-16	-2
198	March	29	53	71	31	30	35	16	41	76	177	142	-20
683	April	-49	15	-81	-129	-133	-16	-49	-20	97	-102	-120	-129
1755	May	39	429	-60	368	487	148	118	246	383	87	6	12
1450	June	-173	223	445	205	251	178	-127	-373	-266	-42	-336	-202
590	July	-180	-66	15	59	94	87	-145	-111	-259	-257	-287	-193
476	August	-143	-22	13	-109	-43	-49	-159	-158	-179	-188	-232	-148
424	September	-104	12	125	-96	19	-71	-118	-159	-27	-177	-218	-140
199	October	-57	-7	64	-35	-3	-29	-48	-50	2	-72	-80	-63
103	November	-35	-7	21	-22	-9	-15	-28	-25	-3	-41	-45	-39
73	December	-19	2	14	-13	-8	-6	-15	-12	-4	-27	-30	-28

4.5 Discussion

The simulations of the forecasted climate scenarios result in a range of possible impact on water yield from the NSRB, reflecting various factors such as uncertainty in the GCM predictions, uncertainty in the representation of the amount and spatial variability of precipitation in the NSRB where the change topography from the mountains to the prairies is very substantial, and the ability of the MISBA model to simulate runoff from snow melt in mountainous areas. The simulation results are not too different from those of other recent climate change and water yield studies on the South Saskatchewan River Basin and the Athabasca River Basin.

The results of this study should be interpreted in terms of trends rather than absolute changes because the possible impacts on water yield have some degree of uncertainty associated with them. The uncertainty can only be reduced with improved predictions from GCMs, particularly for the long-term forecasts, availability of downscaled climate data able to represent the spatial climate variability in the NSRB, and continued improvement in the capabilities of hydrologic models to represent the complex and varied hydrologic processes significant in mountainous to prairie areas.

5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The effects of climate change on the water yield from the North Saskatchewan River Basin (NRSB) will affect water uses and water management in the basin. There is a need to assess the potential effects so that watershed planners can adapt their plans to take advantage of positive effects and implement mitigation measures to minimize the negative effects. The objective of this study was to assess the effects of climate change on the expected monthly and annual water yield of the NSRB at selected locations on the North Saskatchewan River (NSR) under natural land conditions. The study also included a review of the literature on climate change as it pertains to the prairie regions and an assessment of trends in observed temperature, precipitation and stream flow in the NSRB.

It was assumed that a 25-year horizon would be most appropriate for watershed planning purposes. The IPCC recommends that 1961 to 1990 be adopted as the climatological baseline period in impact assessments (CICS 2005). This period has been selected as the baseline period for the NSRB. The future conditions have been represented by the 30-year period between 2021 and 2050, which would be representative of the mid-2030s. In reality, one would expect land uses to change over time, either as responses to economic pressures and/or drivers or in adaptation to climate change. In addition, the uncertainty in the predictions of the effects of climate change on water supply in the distant future may be larger than the predicted effects themselves. There is also a greater possibility for adaptation over the long-term as better GCMs become available and predictions become more reliable, hence, the 30-year planning horizon. The conclusions and recommendations of the study are summarized in the following sections.

5.1 Conclusions

5.1.1 Trends in Observed Climate and Stream Flows

- Trend analyses on air temperature data at the selected climate stations in the North Saskatchewan River Basin (NSRB), namely, Nordegg, Rocky Mountain House, Edmonton and Vermilion, suggest that there is a generally increasing trend in air temperature.
- The analysis of monthly and seasonal precipitation data at the four selected locations in the NSRB showed no significant trend. Precipitation in the summer months (July, August, and September) tend to exhibit an increasing trend at three locations: Nordegg, Edmonton, and

Vermilion. These three stations tend to have relatively long precipitation records. At all the four stations, the annual precipitation data shows a statistically not significant increasing trend.

- The annual mean flow data at selected hydrometric stations in the headwater basins of the Athabasca River and western portion of the NSRB generally show a decreasing but statistically not significant trend in recent years. Based on linear trend lines fitted to the data, the predicted annual mean flows would decrease by between 4% and 9%, depending on station location, by the year 2035 compared to the baseline period of 1961-1990. The predicted changes in annual yield by 2035 are, however, well within the variability in annual yield. Trend lines fitted to recent flow data are not necessarily accurate predictors of future increases or decreases in flows.

5.1.2 Selection of GCM and Scenario for the NSRB

- A comparison of mean annual total precipitation and mean annual temperature predicted by several GCMs for the baseline period of 1961 to 1990 with climate statistics based on observed data at Nordegg, Rocky Mountain House, Edmonton and Vermilion indicate that the ECHAM50M, NCARCCSM3, GFDLC2.1 and CGCM3T47 GCMs were the best in replicating the observed statistics. These four GCMs were selected for assessing the effects of climate change on the water yield in the NSRB.
- For the purposes of the climate change assessment for the NSRB, the A1B, A2 and B1 scenarios were selected. Scenario A1B represents future balanced socio-economic and environmentally-based development; scenario A2 assumes that the current global socio-economic situation will continue in the future; and, scenario B1 represents future development that is more environmentally-based than at present.
- NCARCCSM3-SRA1B predicts the largest increase in temperature (about 2.2°C) from the baseline period (1961-1990) to the forecast period (2021-2050), while ECHAM50M-SRB1 predicts the smallest increase (about 0.3°C).
- The change in mean annual total precipitation for the forecast period of 2021-2050 from the baseline period of 1961-1990 ranges from a decrease of about 8% (GFLDLC2.1-SRA2) to an increase of about 19% (NCARCCSM3-SRA2), with 10 of the 12 scenarios predicting an increase in precipitation. The forecasted increasing trend in precipitation appears to be

consistent with trends in observed data at the Nordegg, Rocky Mountain House and Edmonton climate stations in the NSRB.

5.1.3 Simulation of Baseline Climate with MISBA

- The European Centre for Mid-Range Weather Forecast global re-analysis (ERA-40) climate data from 1961 to 1990 was used to represent the baseline climate conditions in the NSRB. The ERA-40 annual precipitation data (precipitation amounts from three ERA-40 grids covering the NRSB weighted by the area of the NSRB within each grid) closely matches the observed annual amounts as well as the trends at the Nordegg, Rocky Mountain House and Edmonton climate stations.
- The study area was limited to the portion of the NSRB west of Edmonton because ERA-40 data east of Edmonton was not available for this study.
- The modified Interactions Soil-Biosphere-Atmosphere land surface model (MISBA) of Météo France was set up for the North Saskatchewan River Basin (NSRB).
- For the purposes of this study, the effects of climate change on water yield in the NSRB were assessed between simulated flows for the baseline period (1961-1990) and for the forecast period (2021-2050).
- Model calibration was based on a comparison of simulate flows using the ERA-40 data from 1961 to 1990 against natural flows recorded at the Environment Canada WSC Hydrometric Station 05DF001 at Edmonton.
- The simulated flows from the MISBA model with ERA-40 data from 1961 to 1990 are reasonably close to the observed flows at 05DF001. However, while the observed maximum monthly yields tend to occur in June and July, the highest monthly simulated yields occur earlier in May and June. Some of the differences can be attributed to the different time periods of the observed and simulated data. A more significant reason for the difference may be due to the large area covered by each ERA-40 grid cell such that local temperature regimes in mountainous areas are not being captured well. Similarly, localized summer rainfall events may not be captured in enough spatial detail by the ERA-40 data set. It is also possible that the snowmelt routines in MISBA may not be fully capturing the snowmelt process in the mountains. Further refinement of the climate input parameters, particularly, the generation of more spatially refined climate data, and the model set-up would be necessary to reduce the differences between observed and simulated flows. Notwithstanding the differences, the simulated flows are reasonable for the purposes of this study and are used to assess the

relative effects (simulated 2021-2050 model outputs compared with simulated 1961-1990 model outputs) of climate change on water yield in the NSRB at WSC Station 05DF001.

5.1.4 Simulation of Forecast Climate Scenarios with MISBA

- The European Centre for Mid-Range Weather Forecast global re-analysis (ERA-40) baseline (1961-1990) climate data was adjusted to reflect the changes forecasted by the combination of the four selected GCMs and three scenarios. Only changes in temperature and precipitation were considered. Changes in other climate parameters such as solar radiation, wind speed and humidity would require more detailed analyses.

5.1.5 Forecasted Yield in the NSRB

- Five of the six ECHAM50M and NCARCCSM3 GCM-scenario combinations are predicting increases in annual yield that range from 5% to 15% from baseline 1961-1990 period to the 2021-2050 forecast period. Only the ECHAM50M-SRA1B combination predicts a decrease of about 11%.
- The CGCM3T47 and GFLDC21 GCM-scenario combinations are predicting decreases in annual yield that range from 3% to 23%.
- The ECHAM50M and NCARCCSM3 GCMs are likely the more representative GCMs of the baseline climate of the runoff-producing headwater basins of the NSRB and the results of the simulations using these models may indicate the more likely trends in future yield from the NSRB.
- The deviations of the simulated monthly yield from the baseline value are much larger than would be implied by the deviations in the mean annual yield.
- The maximum increase in monthly yield tends to occur during the spring. This result reflects the predicted increase in precipitation and increase in temperature.
- It appears that the maximum decrease in monthly yield occurs during the summer months and into the fall.
- The simulations of the forecasted climate scenarios result in a relatively wide range of possible impact on water yield from the NSRB. Notwithstanding that the GCMs most representative of baseline climate in the NSRB predict increases in future annual yield, the range of possible impacts should be considered in watershed planning because the model predictions have some degree of uncertainty associated with them.

5.2 Recommendations

- Continued refinement of the MISBA model to improve its capability to represent the complex and varied hydrologic processes significant in mountainous to prairie areas should be undertaken. The application of other hydrologic models should also be investigated.
- Statistical and/or dynamic downscaling should be investigated for alternative means of developing climate scenarios from GCMs and forecasting changes in other climate parameters such as solar radiation, wind speed and humidity.
- Complete coverage of the NSRB with ERA-40 data or other downscaled data should be acquired to implement the selected hydrologic model to the entire NSRB.

6. CLOSURE

We trust the above meets your present requirements. If you have any questions or require additional details, please contact the undersigned.

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