Impacts of Climate Change on Saskatchewan's Water Resources

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Executive Summary

The purposes of this report are two-fold,
i) documenting the expected impacts of climate change on Saskatchewan's water resources,
ii) outlining the options for adaptation of water resource management practices, policies and infrastructure to minimize the risk associated with the impacts of climate change.

Prairie province hydrology is dominated by cold regions processes so that snowmelt is the primary hydrological event of the year for both the major rivers that derive from the Rocky Mountains and small streams and rivers that arise in Saskatchewan. Climate change impacts on water resources are therefore focussed on changes to snow accumulation, snowmelt and infiltration to frozen soils. Climate change scenarios suggest generally warmer and wetter winters for Saskatchewan. Large scale hydrological models that take these scenarios into account suggest changes in the annual streamflow of the South Saskatchewan River ranging from an 8% increase to a 22% decrease, with an 8.5% decrease being an average prediction. Small scale hydrological models for prairie streams suggest a 24% increase in spring runoff by 2050 followed by a 37% decrease by 2080 is possible as the winter snowcover becomes discontinuous. Both model results suggest that there is not a dramatic drying of the prairies to be anticipated under climate change and that in some cases streamflow will increase for certain scenarios and under moderate degrees of climate change.

For the major rivers draining from Alberta into Saskatchewan, more efficient water use for irrigation or a reduction in irrigated acreage in Alberta could compensate for the reduced water availability, which is due mainly to reduced mountain snowmelt. Current minimum tillage and continuous cropping systems are resilient for most climate changes to agricultural water resources. Initially there will be increases in prairie runoff but as climate change progresses later in the 21st C there will be dramatic drops in runoff and the flow of small streams to wetlands and depressions and to small prairie rivers. Infrastructure will have difficulty keeping up with this level of change unless agricultural land management is used to compensate for changes in hydrology. New crop varieties and tillage methods which are able to leave some water for runoff to natural ecosystems will need to be devised. Drainage of wetlands may have to be reversed to limit high spring streamflows and wetland/lake levels.

Integrated basin management of the South Saskatchewan River across both Alberta and Saskatchewan and for smaller watersheds in Saskatchewan is the preferred adaptation method for dealing with these uncertainties. Integrated basin management plans with apportionment powers, enforceable land use controls and agricultural management incentives will need to be

implemented to deal with rapid changes and increased uncertainties in water management designs.

In all cases the uncertainties in the model outputs and driving hydrometeorological data for current simulations make recommending adaptation measures very difficult as the range of predictions is from a decrease to an increase in available streamflow compared to current estimates. It is imperative that the scientific basis of these hydrological models be improved so that there is reduced uncertainty in model predictions. The current climate and water resources available in the headwater basins are themselves uncertain and need to be better quantified to permit more reliable comparisons of future climate and water resource predictions with the current situation.

1. Introduction.

Since the publication of the Intergovernmental Panel on Climate Change's 2007 report there can be little doubt amongst policy makers that we are undergoing rapid climate change and that the degree of climate change is expected to continue to increase in the near to medium range future, despite any efforts made to reduce greenhouse gas emissions or to sequester carbon dioxide. Saskatchewan's environment, ecology and economy are water dependent and so are strongly impacted by hydrological cycling and water supply fluctuations because of our extensive periods of water shortage and excess, our strong seasonality in surface water supply and our general cool semi-arid to cold sub-humid climate. Many of our ecological and economic activities use close to or all available water and so we are particularly vulnerable to further variations in water resources due to climate change. For instance, our two major economic disasters in the province have been due to lack of available water in the drought of the 1930s and the recent drought of 1999-2004. In 2001-2002, the loss of $6 billion in Gross Domestic Product (GDP) and the disappearance of 41,000 jobs due to lack of water largely occurred in Saskatchewan. It is therefore prudent to examine what features of our climate, hydrology and water resources make our response to changes in water supply potentially unique, what are the anticipated impacts of climate change on our water resources, and what water management options are available or should be considered to minimize the risk caused by climate change.

The purposes of this report are therefore two-fold,
i) documenting the expected impacts of climate change on Saskatchewan's water resources,
ii) outlining the options for adaptation of water resource management practices, policies and infrastructure to minimize the risk associated with the impacts of climate change.
The report addresses these objectives with an overview of Saskatchewan's unique hydrological and water resources characteristics, a review of anticipated climate change in the region, an assessment, based on the most up to date science, of the most likely impacts of climate change on water resources for the South Saskatchewan River and for a representative prairie stream in southwest Saskatchewan. It then interprets this information in outlining options for adaptation of future water resources management practises, policies and infrastructure in the context of risk management. A review and bibliography of recent literature on the impacts of climate change on water resources in the Province is provided as an Appendix. The focus is on the prairie region of the province where most of the population is collocated with limited water resources.

2. Review of Saskatchewan Hydrology and Water Resource Characteristics

2.1 Overview

Saskatchewan is characterized by relatively low precipitation especially in the southwest part due to the atmospheric flow barrier imposed by the Rocky Mountains and experiences frequent water deficits and low moisture reserves (Agriculture and Agri-Food Canada, 1998). Annual precipitation in the prairie region of Saskatchewan ranges from 300-400 mm (Pomeroy *et al*., 2007a), about one third of which occurs as snowfall (Gray and Landine, 1988). Saskatchewan is a cold region and exhibits classical cold regions hydrology with continuous snowcover and frozen soils over much of the winter. Great variations in hydrology exist across the Province, with fairly well-drained, semi-arid basins in the southwest part and with many wetlands and lakes in the relatively wetter north, central and eastern parts.

The hydrology of Saskatchewan is characterized by:

- long periods of winter (usually 4-6 months) with occasional mid-winter melts (frequent in the southwest and infrequent in the northeast), with the snowcover modified by wind redistribution and sublimation of blowing snow on the prairies and modified by snow interception in the boreal forest,
- high surface runoff from spring snowmelt as a result of frozen mineral soils at the time of the relatively rapid release of water from snowpacks (Gray *et al*., 1985),
- deep prairie soils characterized by good water-holding capacity and high unfrozen infiltration rates (Elliott and Efetha, 1999) and shallow boreal soils or organic layers with poor water holding capacities and high infiltration rates (Elliott et al., 1998),
- most rainfall occurring in spring and early summer from large frontal systems and the most intense rainfall in summer from convective storms over small areas (Gray, 1970),
- very low levels of soil moisture, plant growth, actual evaporation and runoff from mid-summer to fall due to low rainfall in the prairie region (Granger and Gray, 1989), with adequate soil moisture supplies in central to northern Saskatchewan (Pomeroy et al., 1997)
- poorly-drained stream networks in the prairies such that large areas are internally drained where local runoff does not contribute to the major river systems (Martin, 2001).

2.2 Prairie Hydrological Cycle

The main processes in the prairie hydrological cycle are shown in Figure 1. Snow is an important water resource on the Canadian Prairies. Approximately one third of annual precipitation occurs as snowfall, which produces 80% or more of annual local surface runoff (Gray and Landine, 1988). There are three scales describing the spatial variability of snow accumulation – micro (10 to 100 m), meso (100 m to 10 km), and macro (10 to 1,000 km) (Pomeroy and Gray, 1995).

Saskatchewan prairie snow accumulation is highly heterogeneous at micro and meso scales, due to wind redistribution of snow, also known as blowing snow. Redistribution is primarily from open, well exposed sites to sheltered or vegetated sites (Pomeroy and Gray, 1995). Blowing snow transport forms snowdrifts, usually in sloughs, drainage channels or river valleys; this windblown snow provides an important source of runoff and controls streamflow peak and duration (Pomeroy *et al*., 2007a; Fang and Pomeroy, 2008). Seasonal sublimation of blowing snow is equivalent to 15%-40% of seasonal snowfall on the Canadian Prairies (Pomeroy and Gray, 1995). Blowing snow in the open environments can transport and sublimate or redistribute as much as 75% of annual snowfall from open, exposed fallow fields in southern Saskatchewan, how much of this can end up in a drift depends on field size, temperature, humidity and wind speed (Pomeroy and Gray, 1995).

Snowmelt is one of the most important hydrological processes in Saskatchewan. Melting water from snow recharges the soil moisture and groundwater storage through infiltration and replenishes reservoirs, lakes, and rivers through surface runoff (Norum *et al.*, 1976). The amount of water from snowmelt is controlled by energy exchange at the snow surface, and meltwater is produced when the snowpack is at a temperature of 0°C (Male and Gray, 1981). Typically, 80% or more of prairie runoff is generated from snowmelt.

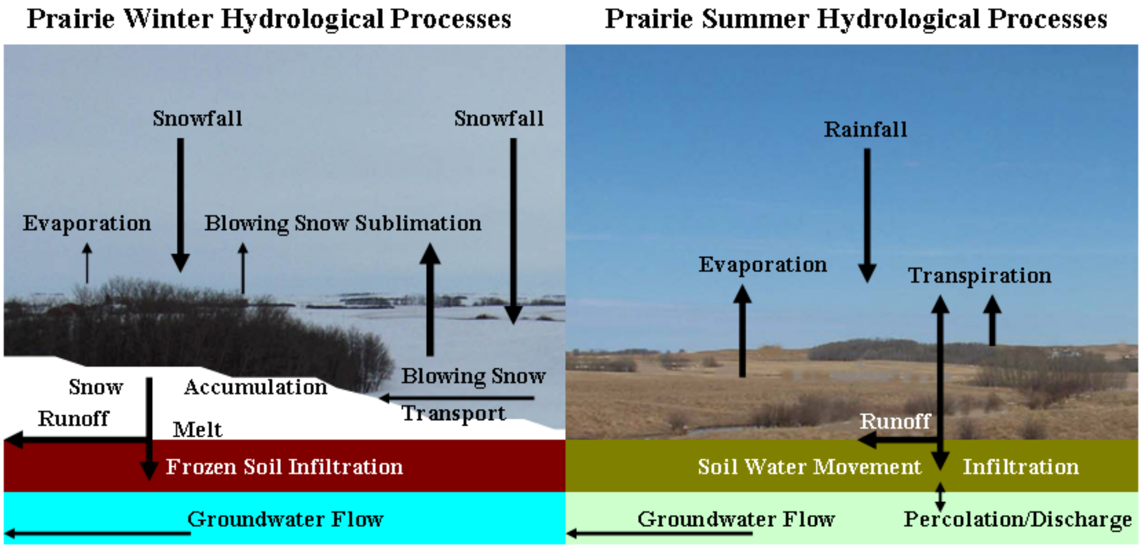


Figure 1. Prairie hydrological cycle: left – winter processes, right – summer processes.

Rainfall occurs primarily from May to early July and provides water for the growth of crops. Most of the rainfall is consumed by seasonal evaporation, which leads to little surface runoff during the summer period. A primary mechanism for most rainfall events during early summer on the Prairie is the frontal weather system, while the most intense short duration rainfalls are associated with local convective storms (Gray, 1970).

Infiltration is the process by which water flows through the soils and is strongly affected by soil properties, moisture content and the occurrence of frozen soils. Infiltration into frozen soils is controlled by the amount of snow available to melt, the soil moisture content in the previous fall and the occurrence of major melt events in mid-winter that can seal the frozen soil with a superimposed ice layer (Pomeroy *et al.*, 2007a). Variations in infiltration to frozen soils can exert a strong control on runoff generation from snowmelt; runoff efficiencies are near 100% over saturated frozen soils or those with superimposed ice layers and drop to near 0% for severely cracked or highly porous and dry frozen soils (Gray et al., 2001). In the summertime, infiltration from rainfall is generally enhanced when the soil is thawed and this usually leads to minimal surface runoff. Limited runoff is due to both infrequent rainfalls of short duration as well as the high infiltration capacity of prairie soils which are most often unsaturated at the surface. Exceptions are due to intense summer convective storms, but these normally occupy small areas and so have little impact on overall water resources.

Evapotranspiration (evaporation and transpiration) is driven by the net radiation to the surface and by convection of water vapour from wet surfaces to the relatively dry atmosphere. During summer, evapotranspiration consumes most rainfall on the prairies and occurs quickly via direct wet surface evaporation from water bodies, rainfall intercepted on plant canopies and wet soil surfaces; it occurs more slowly as unsaturated surface evaporation from bare soils and as transpiration from plant stomata (Granger and Gray, 1989). Evaporation, directly from bare soils and indirectly by transpiration, withdraws soil moisture reserves and eventually results in soil desiccation if there are no further inputs of water from rain or groundwater outflows. On average, seasonal evapotranspiration loss is close to seasonal rainfall in Saskatchewan, with amounts less than rainfall occurring in exceptionally wet or cool years, especially in the east and north of the agricultural region. It must be emphasized that actual evapotranspiration is almost always less than potential evapotranspiration and that this difference increases with aridity (Granger and Gray, 1989). Studies that rely on potential evapotranspiration (e.g. Schindler and Donahue, 2006) are not useful in water balance analyses and hydrological flow predictions in this dry environment, because potential rates display inverse behaviour to actual rates and cannot be directly related to any water resource variable (Armstrong et al., 2008; Fernandes et al., 2009).

Groundwater recharge usually occurs in depressions such as sloughs, wetlands and pothole lakes through infiltration into the soil columns and then deep percolation below the rooting depth (Hayashi *et al*., 2003). Much of the water that infiltrates is exhausted by evapotranspiration before percolation to deep groundwater can occur (Parsons *et al*., 2004). This leads to very low and steady deep groundwater flow rates; 5-40 mm is a reported range of annual groundwater recharge rates in the prairie (van der Kamp and Hayashi, 1998). In general, groundwater supplies are poorly connected to surface water resources because of heavy glacial till deposits overlying the major aquifers and so groundwater has little impact on lakes or base flow with the exception of certain upland streams (e.g. Cypress Hills).

2.3 Prairie Runoff Generation

The Canadian Prairies are characterized by numerous small depressions such as sloughs, wetlands and dugouts. These water bodies are often internally drained resulting in closed catchments (Hayashi *et al*., 2003), and there is a lack of connection amongst them as well as to the main prairie streams. Where there is internal drainage in normal conditions these catchments are termed non-contributing areas (Godwin and Martin, 1975) and are illustrated in Figure 2. Other areas do drain to streams.

The seasonality of Prairie surface water supply is marked. In fall and winter, the water is stored as snow, and lake and ground ice; in early spring, the water supply is derived from rapid snowmelt resulting in most runoff; in late spring and early summer, water stored as soil moisture and surface water, sustained by rainfall. Snowmelt water contributes 80% or more of annual surface runoff for Prairie streams (Gray and Landine, 1988). However, due to the aridity and gentle topography of the prairie, natural drainage systems are poorly developed, disconnected and sparse, resulting in surface runoff that is both infrequent and spatially restricted (Gray, 1970). Recent drainage activities have increase runoff to streams and wetlands in some regions.

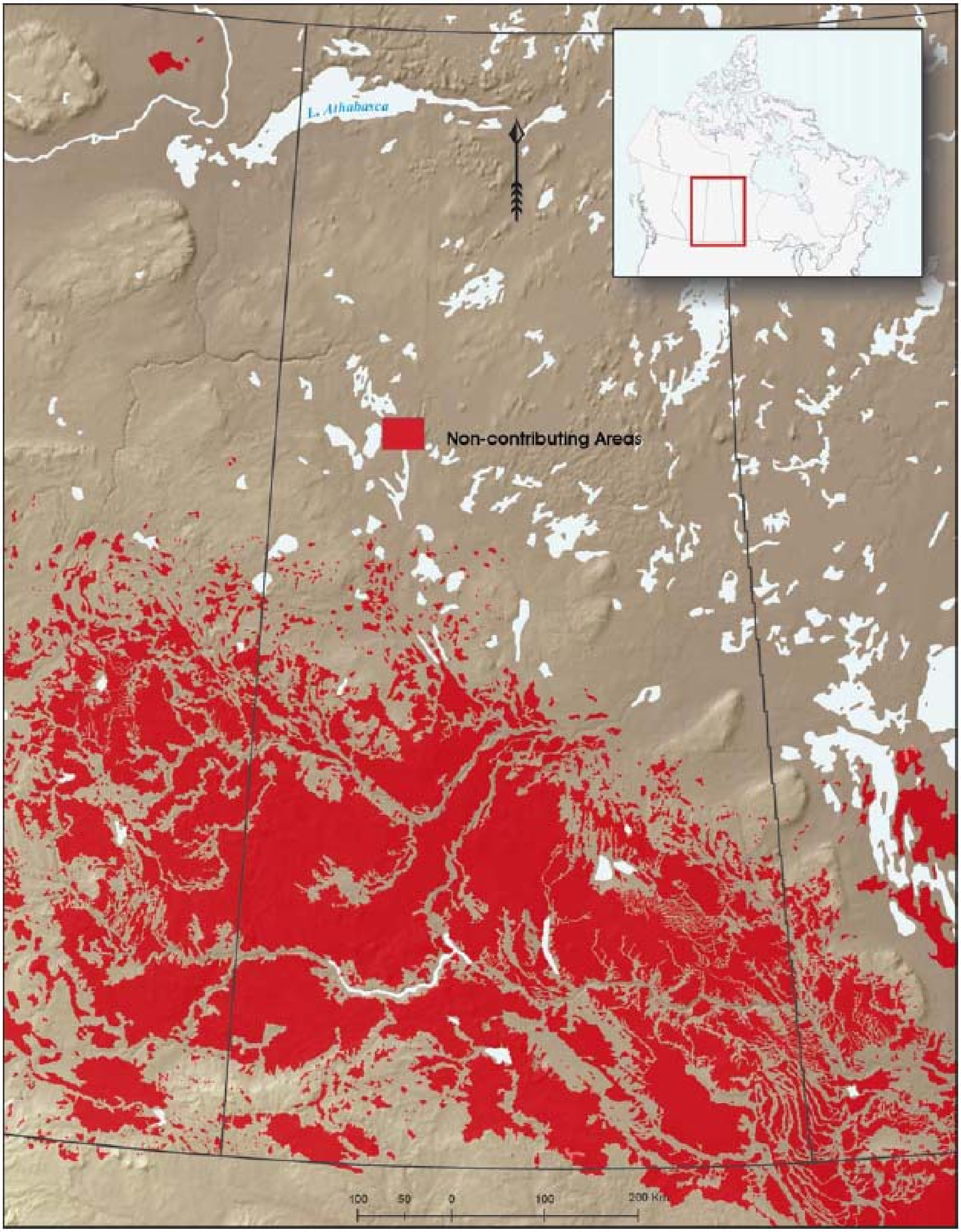


Figure 2. Non-contributing areas of drainage basins as delineated by PFRA (image from Pomeroy *et al*., 2007a).

Saskatchewan's hydrology is characterized by low precipitation which mostly evaporates leaving little for runoff. This means that local-scale water resources are quite limited and very sensitive to changes in climate and land cover. The perception of plenty caused by seeing stored water in lakes, snow covers, and wetlands does not match the reality of low flow rates in the hydrological cycle.

An example of a prairie streamflow regime is that of Smith Creek in the eastern part of the province. The creek drains up to about 400 km^2 and normally peaks during and just after snowmelt, becoming dry by midsummer, and remaining so until the subsequent spring (Figure 3). It is highly variable from year to year with daily peak flows of almost 24 m^3/s during flood to having minimal yearly flow in times of drought. Streams with such intermittent and variable flow regimes are not normally usable for water supply without impoundment as reservoirs. However, reservoir management of such variable streamflow is challenging in periods of extreme drought or water excess. Hence few prairie streams are managed for substantial water consumption or irrigation, with the perception that the most reliable water supply comes from groundwater and rivers that originate in the Rocky Mountains in Alberta.

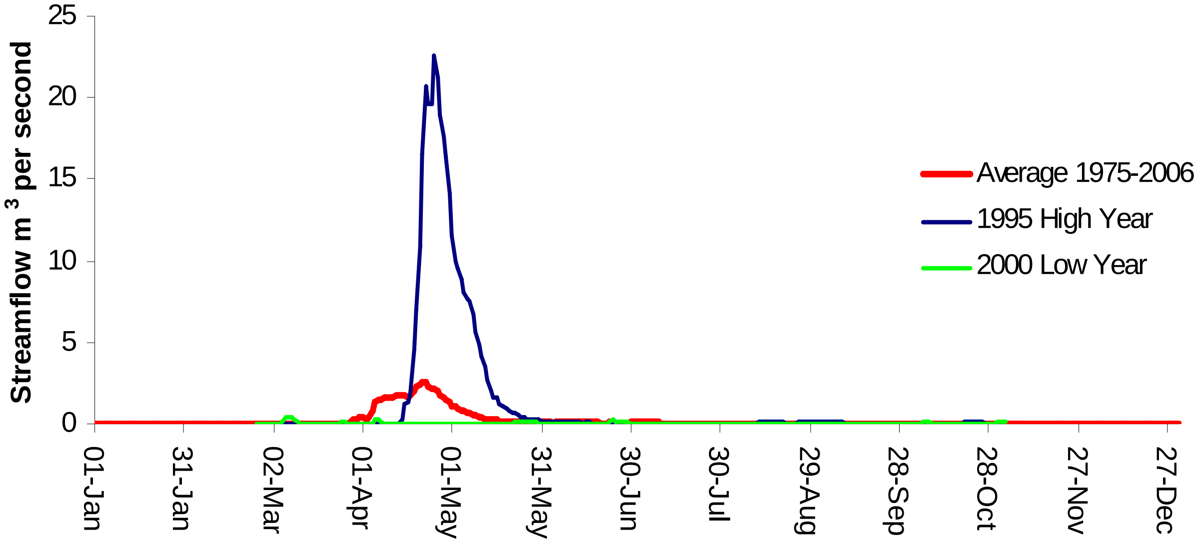


Figure 3. Annual hydrograph of a small prairie stream, Smith Creek near Langenberg.

2.4 Saskatchewan Rivers and their Flows

Figure 3 shows the major rivers and their mean annual discharge over the province. In the prairie region, the vast majority of streamflow in these rivers is derived from runoff upstream in the Rocky Mountains where it is dominated by snowmelt (Lapp et al., 2004; Stewart et al., 2007). Moving eastward and northward there is increased local runoff which makes some contribution to streamflow, but this never exceeds what is 'imported' from the mountains. The annual flow regime of the North Saskatchewan River and the South Saskatchewan River upstream of Lake Diefenbaker are dominated in the winter by the formation and melt of river ice, during the spring by the melting of snow on the prairies and during the summer by snowmelt in the mountains.

Figure 3. Map of Saskatchewan with annual discharge along the main rivers. © University of Saskatchewan, 2000.

Within Saskatchewan, the only significant tributary to the South Saskatchewan River is Swift Current Creek, which contributes less than 1% of the flow. The melt of glacier ice has a minimal effect on the flows of the North and South Saskatchewan Rivers entering Saskatchewan – most flow is derived from mountain snowmelt (Comeau, 2009). The Qu'Appelle River has a natural regime that would be dominated by prairie spring runoff but is substantially modified by water withdrawals from Lake Diefenbaker to supplement and stabilize natural flows.

River withdrawals for irrigation and municipal water use in Alberta have resulted in significantly reduced annual water flows of the South Saskatchewan River into Saskatchewan compared with annual flows that would have occurred without human intervention in the river's watershed in Alberta (Figure 4). Natural flows are calculated by Alberta Environment and recorded flows are measured by the Water Survey of Canada. The differences are due to water consumption and are most pronounced in dry periods but have been growing steadily since 1970. Note that in drought years (1988, 2001) consumption was 42% of the natural flow and that consumption has not been smaller than 10% of natural flow since a wet period in the early 1990s .

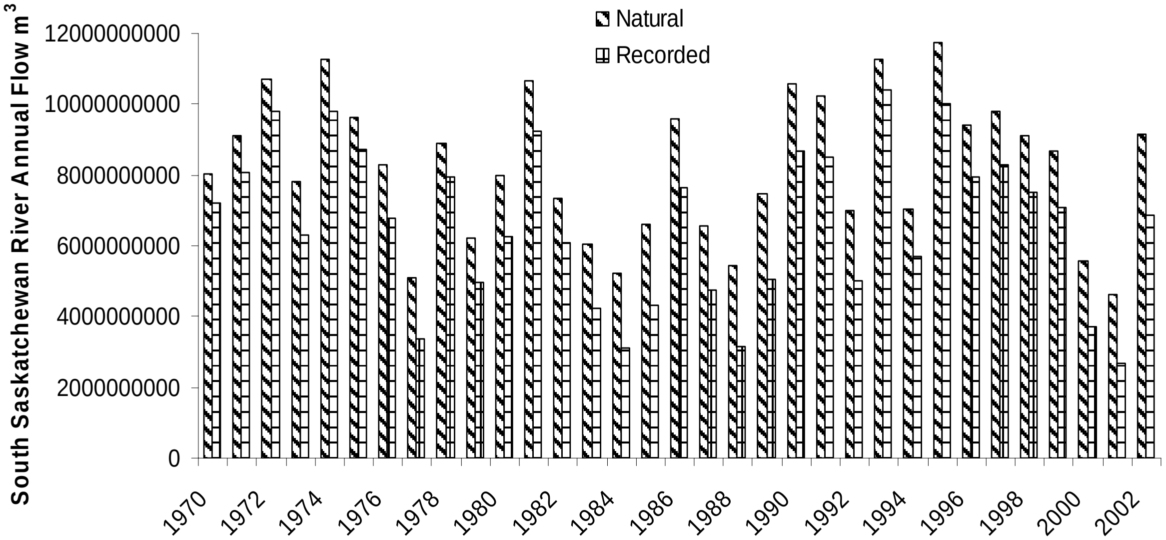


Figure 4: Impact of Upstream Water Consumption on South Saskatchewan River Annual Flows (after Pomeroy et al., 2007a).

2.5 Current Water Resource Management in Saskatchewan

Water resources in Saskatchewan are managed at small scales via agricultural land management on farms through resulting in impacts on soil moisture, streamflow and wetland storage regimes and at large scales through river diversions, irrigation and water supply pipelines. The water resources of the province have been developed and managed by farmers since the time of first agricultural settlement. Cereal grain growing in most of the province requires about 125 mm soil water reserves to ensure germination and an additional 175 mm of spring rainfall is needed for an adequate crop. Where soils have adequate nutrient status or fertilization, there is roughly a 300 kg/ha increase in wheat yield for each extra 25 mm of water added by early to mid summer rainfalls. Given that most of the prairie region of Saskatchewan receives only 300 to 400 mm per year of precipitation on average, this water is just enough to adequate cereal grain growth, but there is little in excess for streamflow, wetland or groundwater recharge. The efforts of the PFRA and other agricultural agencies since the 1930s have led to substantial increases in dryland agriculture water use efficiency; as a result there are better grain yields in times of drought, more stable surface supplies for livestock, and less runoff from cultivated land. Care must be taken so that land management practices that preserve water for crop use do not result in the drying out of small streams, sloughs and wetlands that are important for wildlife, aesthetics, groundwater recharge and small scale water supplies. There is evidence that surface water supplies are dwindling in much of the cultivated portions of the province and hydrological simulations suggest a decrease in the annual flow of small streams in the southern prairies of around 25% with conversion of traditional summer-fallow lands to continuous cropping systems (Fig 5).

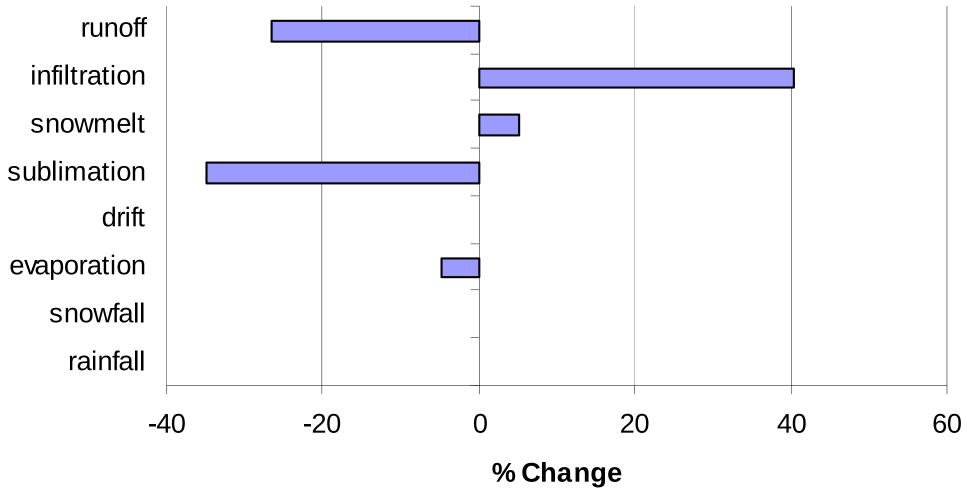


Figure 5. Percent change in water balance components by replacing 30% summer fallow coverage with continuous cropping/stubble at Creighton Tributary, southwest Saskatchewan, 1973-74 using the CRHM Model (Pomeroy et al., 2007c).

Most of Saskatchewan's water use is in the south, whilst most of the water is in the north of the province. Much of the provincial population is now located in several large centres which require secure, high quality and steadily increasing municipal supplies; these centres also produce waste water that must be treated. Drought in the south has shown that many local surface water supplies are unreliable and alternatives are being increasingly explored. The major water resource of the south is the South Saskatchewan River which has been substantially developed as a water resource.

Gardiner Dam on the South Saskatchewan River Project and a smaller dam across the Qu'Appelle River valley were completed in 1967 and resulted in the formation of Lake Diefenbaker. Currently, about 70% of the population of Saskatchewan, including Saskatoon, Regina and Moose Jaw, receive their drinking water from Lake Diefenbaker and the South Saskatchewan River. In addition, Lake Diefenbaker provides water for irrigation, industrial use, and recreation and exerts some flood control on the downstream flow of the South Saskatchewan River. Smaller municipal water users include the towns of Hanley, Guernsey, Humbolt and Lanigan and the rural municipality of Dundurn via canal and pipeline systems. The Qu'Appelle

River system is managed for a variety of purposes by a series of control structures and inflows from Lake Diefenbaker so that its flow is suitable for water use and recreation.

Other rivers have been developed in Saskatchewan, the primary example being the Rafferty-Alameda project on the Souris River. This project was built to address problems resulting from the cycles of drought and flooding and provides a long-term water supply for the Shand power station and other users, recreational benefits and flood protection. River flow during the proposal, environmental impact assessment, and construction stages was low due to a severe drought in the late 1980s, and consequently the flood protection benefits of the project were not directly obvious. High flows in 1994, 1996 and 1997, however, caused both reservoirs to be filled by the end of the 1997 spring season - much faster than anticipated. Clearly all of these water resource projects were developed to compensate for unreliable and often insufficient water supplies and to cope with a wide range of hydrological inputs due to the already extremely variable Saskatchewan climate.

3. Climate Change for Saskatchewan Water Resources

No assessment of water resource impacts from climate change is possible without a thorough analysis of climate change scenarios. These scenarios not only depend on the mathematical representation of the physics of atmospheric circulation, atmospheric chemistry, water cycling, land atmosphere interaction and solar forcing, but depend on the greenhouse gas emission scenarios which ultimately depend on political, policy and economic drivers. Greenhouse gas emissions range from optimistic to balanced to pessimistic. As such while there is certainty in the general trends (some warming is now inevitable) there is great uncertainty in the regional details of the degree of change in temperature and precipitation for future climates from these scenarios. No models predict rapid, catastrophic climate change though there is geological evidence for such changes in the past. Unfortunately, there is great uncertainty in predictive variables that are important to hydrology such as intensity of precipitation, phase of precipitation, net radiation and the duration of wet and dry periods. As well there are no reliable direct hydrology or water resource predictions from these models as their spatial scale is too coarse for hydrological calculations and so their outputs must be downscaled to be used.

Several studies have recently evaluated climate change scenarios for regions including Saskatchewan (Schindler and Donahue, 2006; IPCC, 2007; Sauchyn et al., 2007; Toyra et al., 2005;). The IPCC North American Regional Predictions using the A1B ‘balanced scenario’ are of great interest because of the number of models used in ensemble to generate a synthesized climate change prediction and because they are generally accepted by policy makers. These simulations compare the difference between the 2080-2089 climate and the 1980-1989 climates. Of particular interest are temperature and precipitation responses including the annual, winter (December-January-February) and summer (June-July-August) specific responses. They predict an annual warming of about 3.0^{o} to 3.5^{o} C and annual wetting of 5% to 10% over the province with the greatest warming and wetting in the North (Figure 6). For winter, a 3.5^{o} to 4.0^{o} C warming and a 10% to 15% wetting are predicted, whilst for summer, a 3.0^{o} to 3.5^{o} C warming and from no change to a 5% wetting are predicted – in all cases the largest increases in the north of the province. So in general there is a warming and a wetting predicted with the greatest degree of change in winter and in the north of Saskatchewan. Sauchyn et al (2007) discuss these predictions in much greater detail and include a range of scenario assumptions and models – their results are consistent in direction and magnitude with the IPCC in general though there is of course a much greater range and detail available. The range of predictions shown by Sauchyn is important in quantifying uncertainty for hydrological predictions – some scenarios showed drying occurring in the summer and most did not show significant summer wetting.

Barrow and Yu (2005) assessed detailed climate scenarios for Alberta, from which the Saskatchewan River system receives most of its runoff. In Alberta, changes in annual mean temperature by the 2050s are typically between 3°C and 5°C. For the 2050s, changes in annual precipitation are generally within the range –10% to +15%, and any decreases in annual precipitation are generally driven by decreases in summer precipitation. By the 2080s, however, all climate change scenarios indicate increases in annual precipitation of up to 15%. These are roughly consistent with the IPCC and Sauchyn assessments for Saskatchewan though mid-century drier conditions are possible for south-western Alberta.

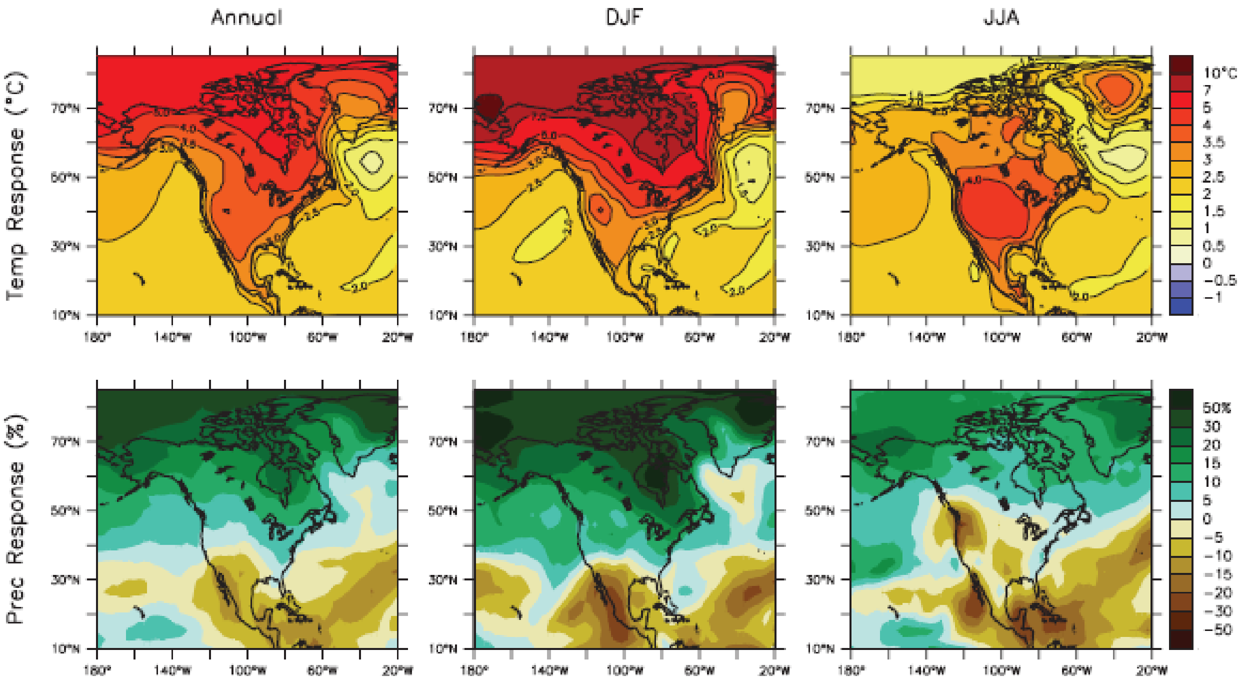
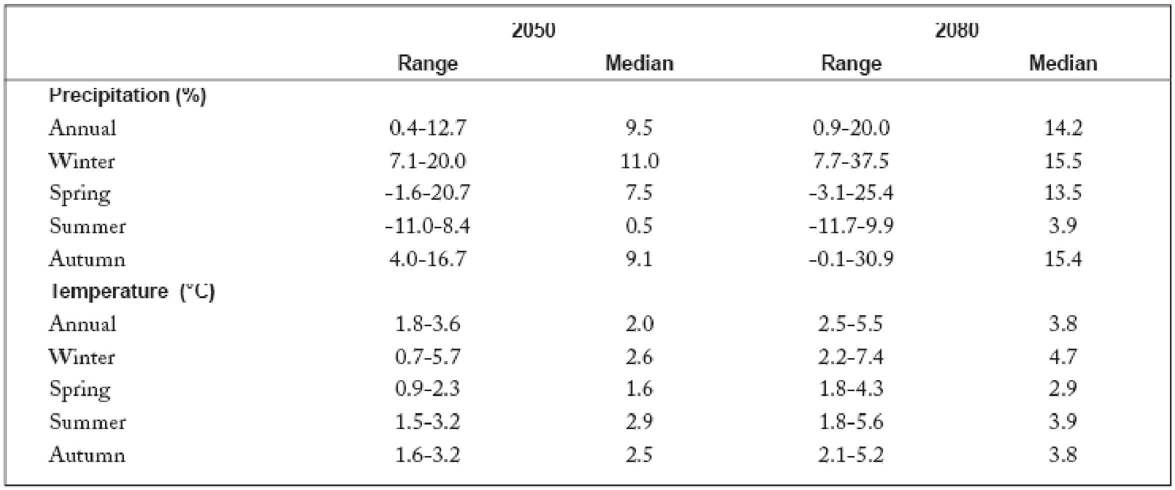


Figure 6. North American Regional Predictions from the IPCC (2007), difference between the 2080-2089 climate and the 1980-1989 climates.

Toyra et al. (2005) evaluated GCM output for current climate against gridded observations in order to select the most reliable climate model for use in generating scenarios for water resource predictions in the Prairies. They evaluated 11 GCM outputs and selected three as having the most reliable outputs for assessing future climate (Table 1). These models were then used to estimate the 2050 and 2080 climates under two different emission scenarios. Whilst there is a wide range in results, the median of the results suggest a wetting and warming consistent with the IPCC. Because these models were evaluated against gridded data there is somewhat greater confidence in the future climate results than for simple ensembles of all models which include those which could not predict current climate accurately. For this reason, these scenarios were used to drive the water resource predictions presented in the next section for the South Saskatchewan River (Pietroniro et al., unpublished) and for Creighton Tributary of Bad Lake Research Basin in southwestern Saskatchewan (Fang and Pomeroy, 2008).

Table 1. The range of mean temperature and total precipitation change for the 2050 and 2080 centred timelines as predicted by ECHAM4, HadCM3 and NCAR-PCM based on the SRES A2 and B2 emission scenarios. The median change based on the three GCMs is also provided as a reference. The values represent change in relation to the 1961-1990 climatology. From Toyra et al. (2005).



	2050		2080	
	Range	Median	Range	Median
Precipitation (%)				
Annual	0.4-12.7	9.5	0.9-20.0	14.2
Winter	7.1-20.0	11.0	7.7-37.5	15.5
Spring	-1.6-20.7	7.5	-3.1-25.4	13.5
Summer	-11.0-8.4	0.5	-11.7-9.9	3.9
Autumn	4.0-16.7	9.1	-0.1-30.9	15.4
Temperature (°C)				
Annual	1.8-3.6	2.0	2.5-5.5	3.8
Winter	0.7-5.7	2.6	2.2-7.4	4.7
Spring	0.9-2.3	1.6	1.8-4.3	2.9
Summer	1.5-3.2	2.9	1.8-5.6	3.9
Autumn	1.6-3.2	2.5	2.1-5.2	3.8

4. Water Resources under Climate Change for Saskatchewan

There is a dearth of rigorous studies that couple downscaled GCM outputs to physically based hydrological models for Saskatchewan. Studies such as Schindler and Donahue (2006) use overly simplistic potential evaporation calculations and do not estimate the basin scale hydrological response to climate change scenario products. The only studies found that addressed this for Saskatchewan are an incompletely published body of research led by Dr. Alain Pietroniro of Environment Canada for the South Saskatchewan River Basin Study and a short partly published simulation by Xing Fang and John Pomeroy of the University of Saskatchewan for a small representative basin in south-western Saskatchewan.

4.1 South Saskatchewan River Basin Study and Subsequent Analysis

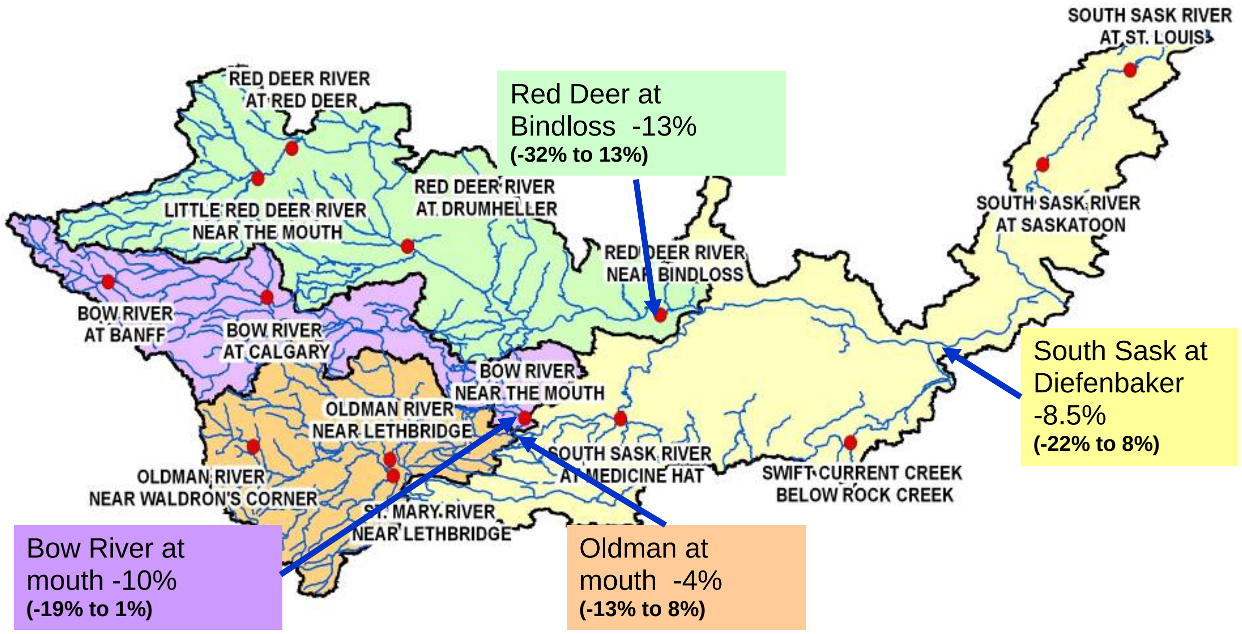
The purpose of this study was to identify the risks and the challenges facing the human and aquatic communities in the South Saskatchewan River Basin (SSRB) that derive from anticipated climate change and economic growth. The study was led by Dr. Alain Pietroniro of Environment Canada and is briefly described in the SSRB Report (Martz et al., 2007). The two driving factors considered were:

1) the hydrological impacts of climate change that might occur for the SSRB as a whole and for the individual sub-basins within the SSRB. Changes in temperature, precipitation, and evapotranspiration are all variables that affect these impacts.

2) expansion in human activities that create demand for water resources.

Focussing on the hydrological impacts of climate change the hydrology of the SSRB was modelled and calibrated to the normal period 1961-1990 using the WATFLOOD model. WATFLOOD is a conceptual hydrological model that was adapted and calibrated to naturalized flows of the SSR. It was then run for future GCM climatology as recommended by Toyra et al. (2005) for the IPCC (1999) A2, B2 scenarios with the three most reliable GCMs. This provided six scenario outputs from the model. The normal period produced reliable model outputs upstream of Lake Diefenbaker (but less so downstream) and so the flows into Lake Diefenbaker are the subject of the analysis here. The basin, and nodes and sub-nodes of the SSRB modelling exercise with streamflow changes as a percent of normal for the various scenarios and models are shown in Figure 7. It is seen that for the South Saskatchewan River entering Lake Diefenbaker the flow, as estimated from the mean of all model outputs, is expected to decrease by 8.5% with a range in this estimate from an increase of 8% in flow in the wettest scenario to a decrease of 22% in flow for the driest scenario. Further breakdowns of these results by sub-basin provides the basin water supply and this analysis suggests that under all scenarios there is a negligible to modest increase in local water supply over the (mainly) Saskatchewan portion of the lower SSRB with an average increase of 8% with a range from nought to 14%. This modest increase in the lower SSRB does not compensate for the decreases in the upper SSRB which results in the generally lower river flows entering Saskatchewan and being passed on to Saskatoon.

Climate change can alter water resources within the SSRB and make current water practices unsustainable from an ecological perspective. The current data and projections however, do not predict ecological collapse, nor do they say that current projections in economic and population growth are unstable. If on the other hand, current human consumption is close to ecological limits, then climate change can make current consumption unstable. With this in mind, if consumption does not change to accommodate the potential fall in water supplies, then extreme water stresses may transpire along with a potential ecological collapse within the SSRB.



Red Deer at Bindloss -13%
(-32% to 13%)

South Sask at Diefenbaker -8.5%
(-22% to 8%)

Bow River at mouth -10%
(-19% to 1%)

Oldman at mouth -4%
(-13% to 8%)

Figure 7. South Saskatchewan River Basin and SSRB Study Model nodes along with mean and range of change in annual streamflow for individual sub-basins. Changes for the normal period 1961-1990 to future period 2039-2070 as a percentage of naturalized annual flows in normal period (from Al Pietroniro and Bruneau and Toth, 2007).

These modelled changes in future flows need to be taken in the context of recorded changes in flow and changes in the estimated naturalized flow for the SSR entering Lake Diefenbaker (Figure 8). Analysis of flow records and naturalized flow calculations from Alberta Environment shows that naturalized flows have declined by approximately 1.2 billion m^3 over 90 years (-12%), and actual flows have declined by about 4 billion m^3 over 90 years (-40%). The 12% decline in naturalized flows from 1912 to 2002 can be primarily attributed to climate change, though it may be partly impacted by land use change (afforestation), changes in measurement technology and errors in the naturalized flow calculation. Of the 40% decline in actual flows from 1912 to 2002, 70% of this decline is due to upstream water consumption, and 30% is due to hydrological change in the naturalized flows. The modelled change in future flow due to future climate change is -546 million m^3 which would mean a reduction since 1912 of 1.7 billion m^3 over about 150 years. So the climate model scenario results suggest a smaller reduction in naturalized river discharge due to future climate change to the mid-21st C than has already occurred in the 20th C. In all cases the decline in river flow due to upstream consumption far exceeds the decline due to climate change and other hydrological factors. This suggests that modification of upstream consumption patterns through water management could completely compensate for the changes in SSR streamflow from that measured in the early 20th C due to existing and future climate changes.

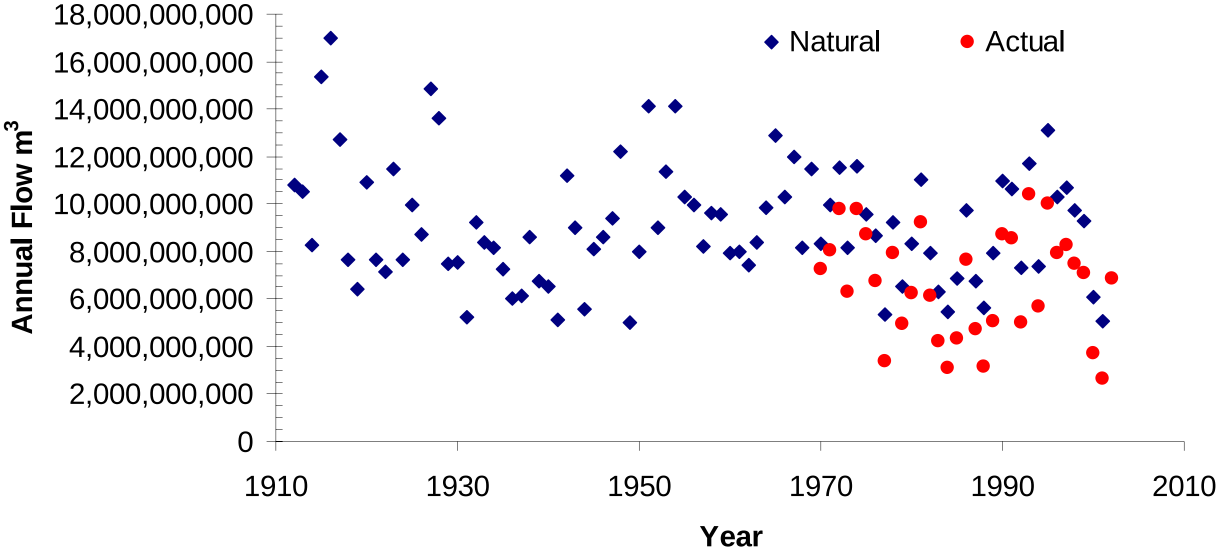


Figure 8. Naturalized and actual annual flows of the South Saskatchewan River entering Lake Diefenbaker. Naturalized flows are estimates with all water consumption "returned" to the streamflow, actual flows are measured and included consumption losses.

4.2 Representative Prairie Basin Analysis

Töyrä *et al*. (2005) from a review of several general circulation model simulations for the mid 21st century suggested that a warmer and 'wetter' climate is most likely for the middle and latter part of this century. The median of three most reliable scenarios (ECHAM4, HadCM3 and NCAR-PCM) suggest a rise in annual winter temperature and precipitation from the 1961-1990 average of 2.6 ºC and 11.0% by 2050, and to 4.7 ºC and 15.5% by 2080. These changes to climate were modelled for spring runoff at the Bad Lake Research Basin by perturbing the 1974-1975 hourly meteorology by the percentages described above and then recalculating the phase of precipitation, snowfall, blowing snow, snowmelt, infiltration to frozen soils and snowmelt runoff for Creighton Tributary of Bad Lake by Fang and Pomeroy (2007) using the Cold Regions Hydrological Model platform, CRHM (Pomeroy et al., 2007).

Cold Regions Hydrological Modelling Platform

CRHM is based on a modular, object-oriented structure in which component modules represent basin descriptions, observations, or physically-based algorithms for calculating hydrological processes. A full description of CRHM is provided by Pomeroy *et al.* (2007). CRHM permits the assembly of a purposely built model from a library of processes, and interfaces the model to the basin based on a user selected spatial resolution. Hydrological processes such as wind redistribution of snow, snowmelt, snowmelt infiltration into frozen soils, and evaporation are common in Prairie winter and early spring. These processes all influence spring snowmelt runoff. Snow accumulation (often call snow water equivalent, or SWE) controls the amount of available snow for melting and is affected by wind in open prairie environments. Blowing snow in open environments can erode and sublimate or redistribute as much as 75% of annual snowfall from open, exposed fallow fields in southern Saskatchewan (Pomeroy and Gray, 1995). Redistribution is from open, well exposed surfaces to sheltered vegetated surfaces. The amount of surface snowmelt runoff is governed by both snowmelt infiltration and SWE. Snowmelt infiltration reduces the direct surface runoff, decreasing amount of peak flows (Norum *et al.*, 1976).

Relevant modules chosen using CRHM for these simulations included the Prairie Blowing Snow Model (Pomeroy and Li, 2000), the Energy-Budget Snowmelt Model (Gray and Landine, 1988), Gray's expression for snowmelt infiltration (Gray *et al.*, 1985), Granger's evaporation expression for estimating actual evaporation from unsaturated surface (Granger and Gray, 1989; Granger and Pomeroy, 1997), a soil moisture balance model for calculating soil moisture balance and drainage (Leavesley *et al.*, 1983), and Clark's lag and route runoff timing estimation procedure (Clark, 1945). These modules were assembled along with modules for radiation estimation and albedo changes (Garnier and Ohmura, 1970; Granger and Gray, 1990; Gray and Landine, 1987) into CRHM. This enabled the estimation of SWE after wind redistribution, snowmelt rate, cumulative snowmelt, cumulative snowmelt infiltration into unsaturated frozen soils (INF), and actual evaporation (E). Actual evaporation is that calculated using the method of Granger and Pomeroy (1997) which is entirely an atmospheric energy balance and feedback approach, the approach is then modified by CRHM in that actual evaporation (E) is limited by a surface mass balance; when interception storage and soil moisture reserves are depleted evaporation cannot proceed. Snowmelt runoff over the event (R) was estimated based on a simplified conservation equation:

$$R = SWE - INF - E \tag{1}$$

where all terms are in mm of water equivalent.

Calculations in CRHM are made on hydrological response units (HRU). Based on the major land uses in the basin and on physiography, three HRU (fallow field, stubble field, and grassland [coulee]) were chosen for the snowmelt runoff simulation. The total snowmelt runoff from these HRU provided the cumulative basin snowmelt runoff as:

$$R_{basin} = R_{fallow}\frac{Area_{fallow}}{Area_{basin}} + R_{stubble}\frac{Area_{stubble}}{Area_{basin}} + R_{grassland}\frac{Area_{grassland}}{Area_{basin}} \tag{2}$$

where R_{basin}, R_{fallow}, $R_{stubble}$, and $R_{grassland}$ are basin snowmelt runoff, snowmelt runoff over fallow field, stubble field, and grassland, respectively; $Area_{basin}$, $Area_{fallow}$, $Area_{stubble}$, and $Area_{grassland}$ are area of basin, fallow field, stubble field, and grassland, respectively. The definition of several HRU within a basin permits consideration of effects due to variable contributing area – HRU are only part of the contributing area for streamflow when they produce infiltration excess or surface runoff.

Results for Toyra et al. Climate Change Scenario

The results of this scenario change in winter meteorology on spring runoff from Bad Lake Research Basin are a 24% increase and then a 37% decrease in cumulative runoff in the years 2050 and 2080, respectively, compared to the basin runoff (54 mm) in spring of 1975 (Figure 9). Runoff in 1975 started around 18 March, but by 2050 it is predicted to start around 22 February and by 20 February in 2080. The increased prairie spring runoff under moderate climate warming (2050) shows that increased winter precipitation is more important than increased winter temperatures in spring runoff generation processes. This model result counters commonly held assumptions that climate warming must lead to drier conditions (Schindler and Donahue, 2006) and the implicit assumption that temperature increases would overwhelm increases in precipitation in their effect on hydrology under a warming climate. However by 2080 the spring runoff has decreased substantially, showing that as climate change progresses, there is some thresholding behaviour causing the initial increase in streamflows to rapidly diminish.

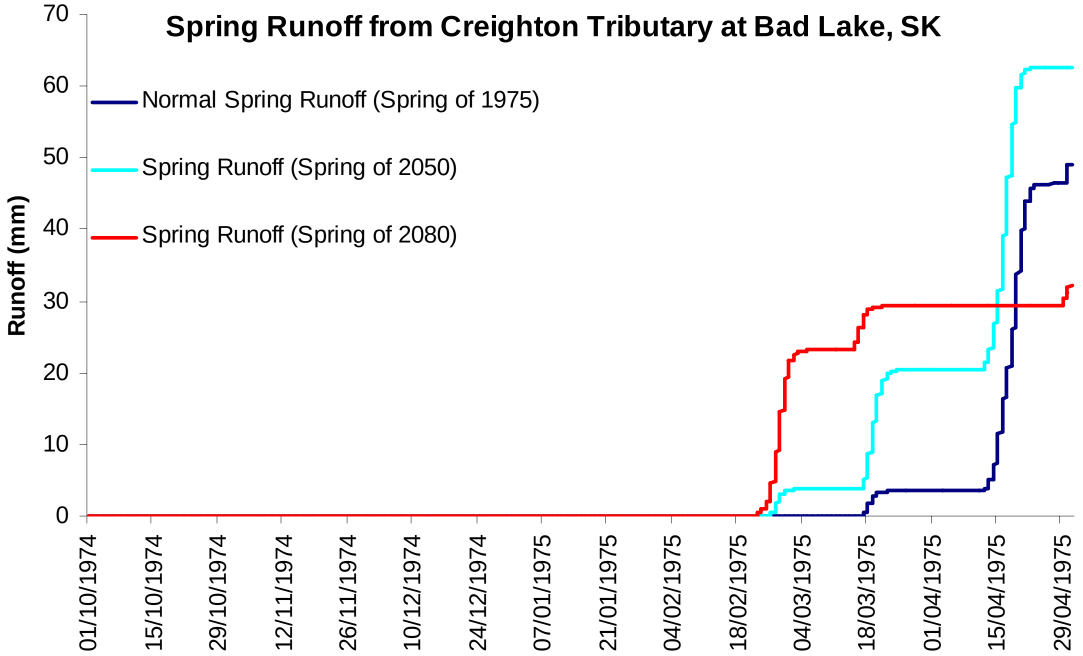


Figure 9. Spring runoff from Creighton Tributary, SW Saskatchewan as modelled by CRHM under 1974-1975 climate and then using the average Toyra et al. (2005) climate scenarios pertubations for 2050 and 2080.

To examine this the winter snowpack evolution is shown in Figure 10 for 1974-1975 and the 2050 and 2080 mean scenarios. It is seen that for the 2049-2050 winter there is little change in snow accumulation until late winter and a continuous snowpack is retained until mid April. Suppression of blowing snow sublimation by the warmer winter has partially offset the reduced snowfall due to increased rainfall. The increased runoff in this simulation is due to mid-winter melts causing an ice layer to form on top of the frozen soil and hence restricting spring infiltration and increasing the runoff ratio dramatically. However by 2079-2080 there is no longer a continuous snowcovered period in winter and the snowpack completely ablates in March with most melt occurring in February. The longer, slower mid-winter melt permits infiltration of the reduced snowpack and relatively little runoff. These results are very preliminary and further study of the climate change impact on prairie runoff using physically based models such as CRHM is clearly needed.

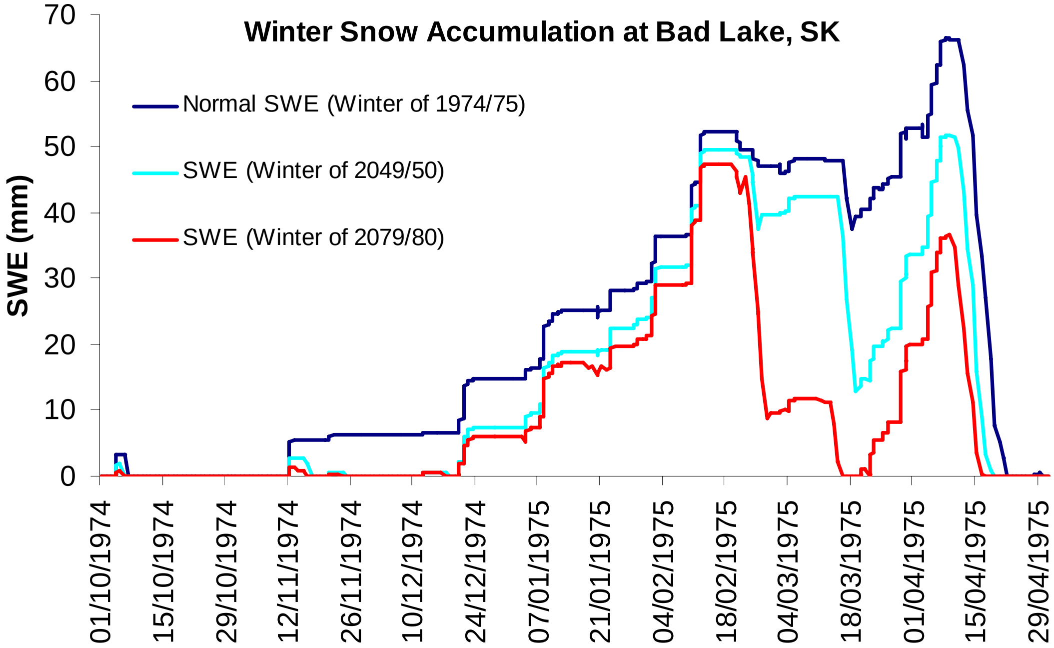


Figure 10. Winter snowpack accumulation at Creighton Tributary, SW Saskatchewan for 1974-1975 and under mean Toyra et al. climate scenarios for 2049-2050 and 2079-2080.

5. Options for Adaptation of Future Water Resources Management Practises, Policies and Infrastructure

This section will summarize and consider the previous results and literature review and then outline some options for water resources adaptation at the large river basin scale and for small scale prairie streams and agricultural lands.

5.1 Summary of Climate Change Impact on Water Resource Simulations.

The preceding modelling results are very provisional studies with many uncertainties in available data, modelling methodologies and climate scenarios. The simple climate data downscaling strategies for climate model outputs used in both studies were not fully satisfactory for hydrological modelling purposes. However both point in a similar direction, that there is not a dramatic drying of the prairies anticipated under climate change, as suggested by Schindler and Donahue (2006) and that streamflow will increase for certain scenarios and under moderate degrees of climate change. This is because much of the predicted warming and wetting occurs during winter and snowmelt is the primary mechanism for generation of streamflow in both the Saskatchewan River system and for local prairie streams. What these studies do not address is the longer summer periods and longer period for evapotranspiration will result in drier soils for a longer period in the summer, even without higher actual evapotranspiration rates as suggested by Fernandes et al., (2009). So while river and streamflows might be reduced by small amounts or even increase, water needs for agriculture will likely increase and so pressure for irrigation of farmland using river water will increase. These studies also do not address the year to year variability, for example drought years, where pressure on water resources from increased demand and diminished supply will likely cause a crisis in future years as both expand their range.

In all cases the uncertainties in the model outputs and driving hydrometeorological data for current simulations make recommending adaptation measures very difficult as the range of predictions is from a decrease to an increase in available streamflow compared to current estimates. So it is imperative that the scientific basis of these models be improved so that there is reduced uncertainty in model predictions. The models also need to be carefully verified with observations from research basins and test bed regions. The current climate and water resources available in the headwater basins in the mountains and prairies are themselves uncertain and need to be better quantified to permit comparisons of future climate and water resource predictions with the current situation.

5.2 Adaptation for South Saskatchewan River Water Resources

The anticipated declines in future annual streamflow on the South Saskatchewan River entering Saskatchewan of 8.5% (+8% to -22%) can be compensated for (if necessary at all) by decreasing water consumption upstream. Martz et al. (2007) note that the share of surface water used in the SSRB for agriculture is 86.5%, with only 8.7% going to municipal use, 3% for thermal and 1.8% for industrial use. It is clear that more efficient water use for irrigation or a reduction in irrigated acreage in Alberta could compensate for the reduced water availability, which is due mainly to reduced mountain snowmelt. Saskatchewan should evaluate its plans for increased irrigation very carefully in light of reduced water availability from Alberta due to consumption and climate change.

Uncertainties in the above analysis relate to drought years when irrigation demand is highest, runoff will be lowest and options to manage water resources by reduced irrigation acreage in Alberta could result in magnified economic damage, in excess of that due to the reduction in precipitation in the drought itself. It is unlikely that even stringent urban water conservation measures alone could make up for the reduced flows in such years. The recent prairie drought was multi-year (Stewart et al., 2008); even a large reservoir such as Lake Diefenbaker cannot sustain higher outputs than inputs for periods of several years. So it is possible in drought years that unless Alberta acted to reduce irrigation demand, streamflows downstream of Lake Diefenbaker could be negatively affected to a degree not experienced since the dam was constructed. This would have direct impact on ecological instream flow needs and water supplies for Saskatoon, Regina and Moose Jaw in addition to smaller centres. Further research is needed to explore the possibilities of low flows under these scenarios and whether the “patchy” spatial distribution of many droughts would permit water supplies in the North Saskatchewan River to compensate for reduced flow from the South Saskatchewan River downstream of the confluence.

Integrated basin management of the South Saskatchewan River across both Alberta and Saskatchewan is the preferred management method for dealing with these uncertainties in cross border situations. Integrated basin management is very successful in Europe where it is implemented in the Water Framework Directive. Since 50% of a very small naturalized flow may be insufficient for future Saskatchewan water uses, the Prairie Provinces Water Apportionment Agreement might need to be revisited in terms of absolute minimums, low flows and implementation of integrated basin management with actual apportionment powers.

5.3 Adaptation for Saskatchewan Prairie Water Resources

For small prairie streams the main economic water use is the water that does not runoff, but infiltrates soils and then can be used for crop and pasture growth. Farmers are currently very successful at retaining this water on the field through continuous cropping to reduce blowing snow sublimation and minimum tillage to promote infiltration into frozen soils through natural macropores (Figure 5). These methods likely ameliorated impacts on agricultural production in the last drought compared to what might have been with the former fallow-stubble rotation and frequent tillage methods, and will prove resilient under the increases and decreases in prairie water supply due to climate change. However the increased efficiency of agricultural water management currently leaves little water for replenishing sloughs and wetlands and recharging groundwater (Hayashi et al., 2003). Under moderate climate change (e.g. 2050) there will be an increase in small stream flows for many parts of the province, but as climate change progresses later in the century there will be dramatic drops in runoff and the flow of small streams to wetlands and depressions and to small prairie rivers. Infrastructure in roads, culverts, dugouts and reservoirs will have difficulty keeping up with this rapid change. Wetlands might initially increase and then ultimately decrease causing large fluctuations in waterfowl populations, difficulty in specifying sustainable yield from groundwater supplies as recharge changes and difficulties in maintaining suitable levels for recreational lakes and reservoirs such as Fishing Lake and Rafferty-Alameda. Since the impacts of late century climate change on Saskatchewan agricultural practises are uncertain (winter wheat or even corn and soy beans may be possible) there is time and opportunity to design new crop varieties and tillage methods to leave some water for runoff to natural ecosystems.

The coincidence of increased wetland drainage and climate change to a wetter and warmer winter might be already increasing streamflow from small watersheds in the eastern part of the province and this might increase dramatically if drainage and the initial scenario results from Figure 9 continue as expected. Figure 11 shows annual streamflow for Smith Creek in eastern Saskatchewan. The five peak years for streamflow are all since 1995. Reduced drainage of wetlands could compensate for this increase in streamflow (Pomeroy et al., 2008) but the effectiveness of reducing drainage and exactly which wetlands are important to retain intact in a streamflow network are still unknown. The current tendency to drain wetlands along with climate change impacts will result in reduced water storage for waterfowl and groundwater recharge as well as in increased streamflow.

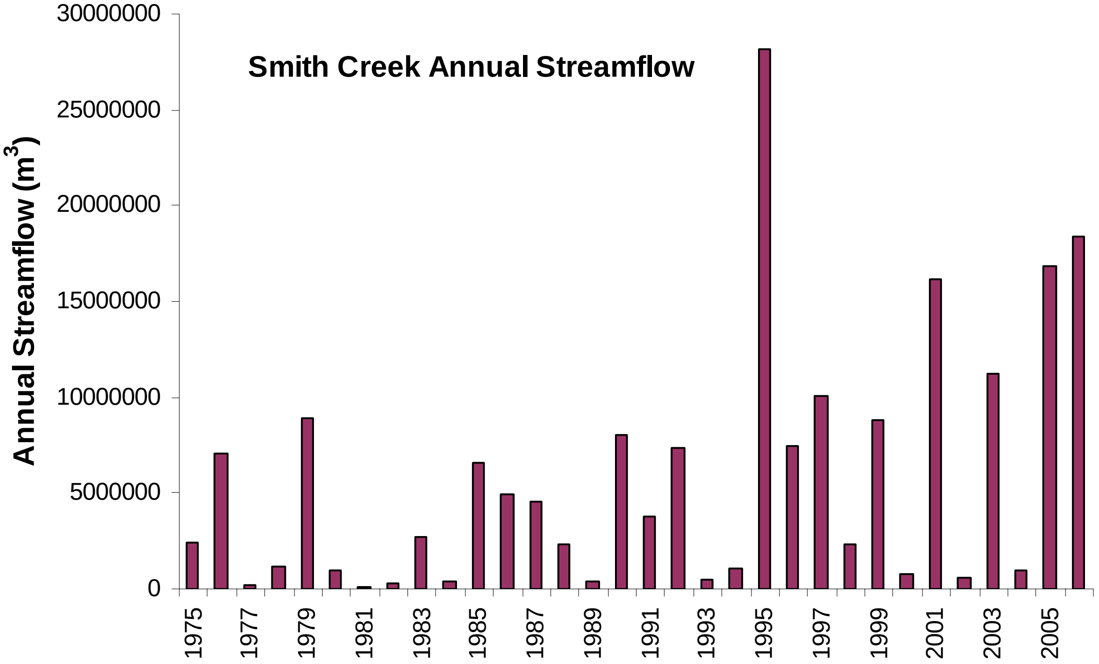


Figure 11. Annual measured streamflow for Smith Creek near Langenberg, Sask., 1975-2006.

Incentive programmes would be necessary to make these agricultural management techniques desirable for producers. Not only drainage exacerbates the drying of wetlands. Ironically, conservation tillage and conversion to grassland will likely exacerbate drying of wetlands – direct evidence of this is apparent from studies at St Denis in the prairie pothole region east of Saskatoon (van der Kamp et al., 2003); the effects of land use on this drying of wetlands are most pronounced during drought but can be ameliorated by reducing grassland coverage (Fang and Pomeroy, 2008). Physically based hydrological models such as CRHM run with carefully downscaled GCM scenario results could be used to develop hypothetical land management scenarios and predict how these might ameliorate the impacts of climate change on prairie soil, stream, wetland and groundwater water resources. Implementation of land management systems is best assessed at the watershed level, perhaps by implementing integrated watershed plans with enforceable land use controls and incentives at the watershed authority level in Saskatchewan, so that techniques could be tailored to the local climate change and watershed drainage characteristics. Experience has shown that economic incentives, regulations and enforcement are superior to best management practices in promoting land use changes. If land use changes cannot be effected then extensive infrastructure redesign for increased culvert size, changed road allowances, bridge redesign, beach resort location and town sewerage and drainage systems may be necessary.

6. Conclusions

Prairie province hydrology is dominated by cold regions processes so that snowmelt is the primary hydrological event of the year for both the major rivers that derive from the Rocky Mountains and small streams and rivers that arise in Saskatchewan. Climate change impacts on water resources are therefore focussed on changes to snow accumulation, snowmelt and infiltration to frozen soils. Climate change scenarios suggest generally warmer and wetter winters for Saskatchewan. Large scale hydrological models that take these scenarios into account have suggested changes in the annual streamflow of the South Saskatchewan River ranging from an 8% increase to a 22% decrease, with an 8.5% decrease being an average prediction. Small scale hydrological models for prairie streams suggest a 24% increase in spring runoff by 2050 followed by a 37% decrease by 2080 is possible as the winter snowcover becomes discontinuous. Both model results suggest that there is not a dramatic drying of the prairies to be anticipated under climate change and that in some cases streamflow will increase for certain scenarios and under moderate degrees of climate change.

What these modelling results cannot yet address is that the longer summer periods and longer period for evapotranspiration will result in drier soils for a longer period in the summer, even without higher actual evapotranspiration rates as suggested by Fernandes et al., (2009). So while river and streamflows might be reduced by small amounts or even increase, water needs for agriculture will likely increase and so pressure for irrigation of farmland using river water will increase.

For the major rivers draining from Alberta into Saskatchewan, more efficient water use for irrigation or a reduction in irrigated acreage in Alberta could compensate for the reduced water availability, which is due mainly to reduced mountain snowmelt. Current minimum tillage and continuous cropping systems are resilient for changes to agricultural water resources. However, as climate change progresses later in the 21st C there will be dramatic drops in runoff and the flow of small streams to wetlands and depressions and to small prairie rivers. This could result in the loss of waterfowl from the prairie pothole region, unsustainable groundwater supplies with reduced recharge and difficulties in maintaining recreational lakes and reservoirs. Since the impacts of late century climate change on Saskatchewan agricultural practises are uncertain (winter wheat or even corn and soy beans may be possible) there is time and opportunity to design new crop varieties and tillage methods to leave some water for runoff to natural ecosystems.

Integrated basin management of the South Saskatchewan River across both Alberta and Saskatchewan and for smaller watersheds in Saskatchewan is the preferred adaptation method for dealing with these uncertainties. The Prairie Provinces Water Apportionment Agreement and various conservation and development acts might need to be revisited so that they can be used to implement of integrated basin management plans with apportionment powers, enforceable land use controls and agricultural management incentives.

In all cases the uncertainties in the model outputs and driving hydrometeorological data for current simulations make recommending adaptation measures very difficult as the range of predictions is from a decrease to an increase in available streamflow compared to current estimates. It is imperative that the scientific basis of these hydrological models be improved so that there is reduced uncertainty in model predictions. The models also need to be carefully verified with observations from research basins and test bed regions in the prairies and mountains. The current climate and water resources available in the headwater basins are themselves uncertain and need to be better quantified to permit comparisons of future climate and water resource predictions with the current situation.

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Appendix A.
Review of Recent Selected Literature Relevant to the Impacts of Climate change on Saskatchewan Water Resources

Barnett T.P., Adam J.C., and Lettenmaier D.P. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, 438: 303-309.

This paper deals with many of the basics of climate change and the advantages and disadvantages of climate model predictions. Importance is given to the sensitivity of water resources in snowmelt-dominated regimes to temperature and a spatially distributed macroscale hydrology model is used to identify the regions of the globe where snowmelt plays a dominant role in the patterns of stream-flow. This review assumes the simplest of changes associated with global warming will be responsible for the changes in the hydrological cycle in snowmelt dominated regions via seasonal shifts in stream-flow. Some of the key/ interesting points of the paper are as follows:

- Temperature changes mostly affect the timing of runoff . Increasing temperatures lead to earlier runoff in the spring or winter, and reduced flows in summer and autumn—at least in the absence of changes in precipitation
- Near-surface air temperature predictions from existing global climate models that are forced with anthropogenic increases in atmospheric greenhouse gas concentrations imply a high degree of confidence that future changes to the seasonality in water supply will occur in snowmelt-dominated regions
- It is generally thought that increasing greenhouse gases will cause the global hydrological cycle to intensify, with benefits for water availability, although a possible exacerbation of hydrological extremes may counteract the benefits to some degree
- In regions where the land surface hydrology is dominated by winter snow accumulation and spring melt, the performance of water management systems such as reservoirs, designed on the basis of the timing of runoff, is much more strongly related to temperature than to precipitation changes
- **Canadian prairies**. Climate studies for the Canadian prairies generally agree that a doubling of atmospheric CO_2 will result in an increase in surface air temperature (possibly as much as 8 ^{o}C during winter), a decrease in snow pack, an earlier snowmelt, and a decrease in summer soil moisture. These effects and a longer period of low flows during summer and autumn could lead to an increase in the frequency and severity of droughts
- Global climate models do not predict great changes in precipitation for Canada, an earlier spring runoff peak will probably cause agriculture in the Canadian prairies to become more at risk in a warming climate

Bonsal B.R., Prowse T.D., and Alain Pietroniro. 2003. An assessment of global climate model-simulated climate for the western cordillera of Canada (1961-90). *Hydrological Processes* 17: 3703-3716.

This paper deals with GCM's and their ability to simulate the magnitude and spatial variability of current (1961-90) temperature and precipitation over the western cordillera of Canada**.** The data from the study helps reveal knowledge regarding GCM simulations of observed temperature and precipitation over the western cordillera of Canada. Information obtained from this paper may assist future hydro-climatic scenarios over various regions of Canada to become more reliable.

Bruneau, J., B. Toth. 2007. Dove-Tailed Physical and Socioeconomic Results in the SSRB. In, (eds. L. Martz, J. Bruneau, J.T. Rolfe) *Climate Change and Water: SSRB Final Technical Report.* University of Sasaktchewan. 207-234.

The purpose of this report is to identify the risks and the challenges facing the human and aquatic communities in the South Saskatchewan River Basin (SSRB) that derive from anticipated climate change and economic growth. The two driving factors considered in this study are: 1) the hydrological impacts of climate change that might occur for the SSRB as a whole and for the individual sub-basins within the SSRB. Changes in temperature, precipitation, and evapotranspiration are all variables that affect these impacts. The second driver is expansion in human activities that create demand for water resources. A third driver is also mentioned which relates to minimum inflow needs for ecological sustainability.

Through using climate scenarios and models, results indicate that changes in streamflows in individual basins for the next century can range from -32 % to +12%. The average of these scenarios suggests that a decrease in the river discharge will be around 9%.

Assessing the magnitude of climate change and economic growth is very important and whether economic growth can be sustained by the future water supply or whether ecological integrity is threatened by these joint processes is the goal at stake. There are three points of comparison are made and taken up below:
1) Consider future water supply with the current water demand. This identifies the effect climate change might have on our ability to manage current demands. It also isolates the effect of climate on future water stress.
2) Consider the future demand as a share of current water resources. This identifies stresses on water resources that derive purely from economic growth
3) Consider both future demand and supply to identify potential future water stresses.

This chapter is important in how it addresses different situations under different scenarios. It divides monthly and annual flows into best and worst case scenarios while further sub grouping them into low, medium, and high growth patterns of the populations. This allows one to get a good understanding of an overview of the different possible outcomes under a changing climate as well as population demands.

Key Points:

- Irrigation withdrawals are of potentially greater impact then climate change, and whether irrigation should be reduced to offset water shortages is an important question left for further research
- Summer flows can fall close to or below 50 % of the natural flows
- The difference between climate consumption and human consumption suggests that mitigation of climate change is quite possible
- In the Red Deer, Oldman, and Bow Rivers, human consumption is currently more than twice the average anticipated climate consumption
- In the SSRB as a whole it is four times as much
- We can mitigate the effects of climate change on the water supply for less than 0.11% of local GDP ($69B)
- This is not impossible, but whether or not it is a desirable way to spend $78M is an open discussion
- Monthly flows of the different rivers contributing to the SSRB are located on page 226 alone with hydrographs on page 227

Climate change can alter water resources within the SSRB and make current water practices unsustainable from an ecological perspective. The current data and projections however, do not predict ecological collapse, nor do they say that current projections in economic and population growth are unstable. If on the other hand, current human consumption is close to ecological limits, then climate change can make current consumption unstable. With this in mind, if consumption does not change to accommodate the potential fall in water supplies, then extreme water stresses may transpire along with a potential ecological collapse may within the SSRB.

- Water flows at Saskatoon are approximately 32.3% lower than the naturalized flows would generate
- Saskatoon is at the greatest risk of climate change but can do very little to mitigate the problem, it must be the entire SSRB working together
- Saskatoon, under the medium growth scenario, is predicted to have a total human consumptive use by 2046 to be about 5 times the climate-induced change
- Total human consumption of water is about 5 times larger than the anticipated average effect
- The average change in overall water availability in the SSRB could be as high as -8.4% by mid 21st century
- The sub-basins within the SSRB could experience decreased flows by mid-century as follows: Bow = -10%, Oldman = -4%, Red Deer = -13%, and the South Saskatchewan at Diefenbaker Lake = -8.5%
- Both the physical and socioeconomic teams found that actual water consumption will be less of an issue than the timing and quality of flows returning after water withdrawals

- Focusing solely on surface water is too limited. Indications suggest that climate change and its associated hydrology will affect water quality, groundwater depletion and recharge; as such, many aspects of the full water cycle are likely to have significant socioeconomic impacts, especially for human and ecological health, and rural populations in particular

Byrne J., Kienzle S., Johnson D., Duke G., Gannon V., Selinger B., and Thomas J. 2006. Current and Future Water issues in the Oldman River Basin of Alberta, Canada. *Water Science and Technology*, 53(10): 327-334.

In this paper a series of studies which cumulatively describe current and future water quantity and water quality issues was discussed. Overall, streamflow in the Oldman River watershed generally is declining. Low flows within the system are getting lower and the mean annual flows also are getting lower. The 5-year moving average of annual minimum monthly streamflow for the Castle River, an unregulated river in the upper reaches of the Oldman River watershed, has declined by ~10 % since 1949, while the 5-year moving average for the annual mean streamflow for this river has declined by ~26%. There are graphs within the paper that represent this data!

The streamflow in the Oldman River watershed is already utilized to more than 90% of all water. As rivers continue to experience Rivers decreasing streamflow, less water is available to dilute in-stream pollutants. These decreases can result in increased concentrations of harmful substances in the water (water pollution), negatively affecting aquatic ecosystems, and placing maintenance or creation of a healthy ecosystem at risk.

Managers should be alert to extended periods of low turbulence caused by drought or reduced water flow resulting from natural (global warming) or man-made (controlled flows through dams and weirs) disruptions to the drainage system. These reduced-flow conditions also could result in accumulation of water-borne contaminants at water intakes being used to supply drinking water to humans and animals, and deterioration of slow moving regions of lakes and rivers often used for recreational purposes.

This research indicates that decreases in the rate of flow of water can result in sedimentation of bacterial contaminants within the water column. With this in mind, concern must be expressed over the potential for contaminate build-up and disproportionate potential of these structures to pose a risk to human and animal health. With disruption of natural flow rates for water resulting from environmental change such as global warming, increased attention needs to be paid to use of best management practices which maintain scouring, dredging and/or treatment of critical water sources where contaminate build-up is likely.

Demuth M.N., and Pietroniro A. 2003. The impact of climate change on the glaciers of the Canadian Rocky Mountain eastern slopes and implications for water resource-related adaptation in the Canadian prairies: "Phase I" - Headwaters of the North Saskatchewan River Basin. *Geological Survey of Canada Open File 432*2.

Important Points:

- This study has established a framework with which to conduct glacio-hydro-meteorological modeling studies to predict runoff and river flows under future climate scenarios. It is suggested that the application of this framework could be extended to the South Saskatchewan River Basin.
- As glacier cover has decreased, so have the downstream flow volumes. While this finding appears to contradict the IPCC projection that warmer temperatures will cause glacial contributions to downstream flow regimes to increase in the short-term, historical streamflow and meteorological data indicate that this increased flow phase has already past, and that the basins have entered a potentially long-term trend of declining flows
- This study examines several glacial catchments of the North Saskatchewan River Basin (NSRB) headwaters.

- The advection of moisture over the Cordillera is determined, in part, by North Pacific climate variability and the influence of the Pacific Decadal Oscillation (PDO)
- The relationship between the PDO and its capacity to manifest anomalous Pacific North American (PNA) circulation and related Peyto Glacier winter mass balance and regional snow accumulation variability is remarkably clear, with the 1976 breakpoint identifying a shift from a PDO cool phase to the following warm phase.
- Part of this investigation has involved developing and constructing a framework with which to conduct glacio-hydro-meteorological modeling studies to predict runoff and river flows under future climate scenarios (pg 48)
- Hydrologic and ecological regimes dependant on the timing and magnitude of glacier-derived meltwater may already be experiencing the medium-long-term impacts of climate change discussed by the IPCC
- Exacerbating these responses are the extra-tropical influences of the El Niño Southern Oscillation (ENSO) on atmospheric circulation and the advection of moisture into the Cordillera, imparting dramatic inter-decadal effects on total winter snow pack amounts and the nourishment of glaciers throughout the entire southern Cordillera
- The study has established a framework with which to conduct glacio-hydro-meteorological modeling studies to predict runoff and river flows under future climate scenarios.

Gan T.Y. 2000. Reducing vulnerability of water resources of Canadian Prairies to potential droughts and possible climatic warming. *Water Resources Management*, 14: 111-135.

Gan emphasizes on the scarcity of water within the Prairie Provinces, how they are highly susceptible to drought, the decrease in glacier runoff (less stream flow), and the lack of precipitation western prairies. He then goes into detail on implications and some of the solutions that have been presented and what the general public can do to help mitigate/ slow down some of the adverse effects associated with climate warming.

His summary is as follows: Past studies (Gullet and Skinner, 1992; Burn, 1994; Gan, 1995; and Gan, 1998) and this study show that the Prairies have become warmer (likely due to the greenhouse effect) and may be drier in the last four to five decades but the drying trends are scattered and inconclusive. Also, analysis shows that only the winter precipitation is marginally related to ENSO and PNA, and streamflow is highly variable. With these findings, uncertainties on the potential impact of climatic change and other uncertainties, the proposed strategies to reduce the vulnerability of the Prairies to future droughts include the following small-scale, structural and nonstructural solutions:
(1) Continue to implement small-scale PFRA projects such as farm dugouts, stockwater dams, community reservoirs, small irrigation projects, water pipelines
and well developments; possibly increase water yield by snow management that involves trapping snow with certain stubble patterns and snow fence;
(2) Increase the robustness of the Prairies' water resources by providing more integration among existing water resources systems;
(3) Encourage water conservation through education programs, through enforcing
water use by-laws, dry-land farming, improved water use patterns, more advanced irrigation technologies, water pricing and water metering.

Key Points of this paper:

- drought probably still has the most significant impact on the Prairies' water resources, which are very sensitive to climate variations because of their semi-arid climate (IPCC, 1996a, b)
- Paleo-climatic data show that the Prairies have experienced far more severe drought over the past 500–1000 yr than in this century, and it seemed that the worst drought occurred roughly between 1791 and 1800
- The prairies generally get less than 500 mm of precipitation because cyclonic precipitation rarely reaches these places from either west or east coasts, and partly because of the frequent presence of dry Arctic air
- Meteorological drought refers to prolonged low precipitation, hydrological drought to prolonged low streamflow and groundwater levels, and agricultural drought to prolonged low soil moisture level. From the

perspective of the hydrologic cycle, precipitation is the forerunner of the drought signal, while streamflow is the end result of drought

- Summer droughts are usually linked to positive anomaly in air temperature, such as the abnormally high air temperature during summer droughts in the Great Plains (Namias, 1983). However, this may not be the case for the Canadian Prairies because using a bivariate test, Gan (1998) found no correlation of temperature/precipitation anomalies there
- IPCC (1966a) reported a general evidence of anthropogenic-induced warming, but at present there are only two directional changes associated with climatic warming that scientists are confident with – sea level rise and a shift in the snowmelt pattern (Frederick *et al*., 1997)
- Williams *et al*. (1988) concluded that ET in Saskatchewan would increase because of elevated temperature. Though warmer temperatures will lead to higher potential ET, the actual ET may increase or decrease, depending on the soil moisture available, and the counter effect of CO2-induced changes in plant growth and stomata responses. For Alberta, Gan (1998) found positive trends in the potential ET but negative trends in the actual ET. This could be attributed to the Prairies getting drier and so there is less moisture available for ET to take place
- The high temporal and spatial variability of annual streamflow in the Prairies probably implies that Prairies' water resources are likely vulnerable to drought

Lac S. 2004. A climate change adaptation study for the South Saskatchewan River basin. IACC Project Working Paper No. 12, University of Regina.

This article goes into basic assumptions about climate change, where it talks about how more recent climate change predictions indicate that glaciers and ice caps will continue to retreat, and places with decreased soil moisture will experience increased heat waves, reducing human and animal health. More key points this paper highlights are:

- Snow-melt dominated watersheds in western North America will experience a change in the timing of streamflow through the year, with a smaller proportion of precipitation during winter falling as snow (with proportionally more run off in winter) and, as there is less snow to melt, less runoff during spring (i.e. spring peak flows will happen earlier)
- Increasing temperatures will therefore reduce the size of the natural reservoir in winter, thus reducing water quality
- Due to the frequency of drought predicted in Southern Saskatchewan, the southern prairies could experience serious summer deficiencies in soil moisture by the end of this century
- Already the prairies have experienced less precipitation as snow, earlier spring runoff, and an increased length of growing seasons by 10-15 days compared to the 1940s and early 1950s
- glacial contributions to downstream flow regimes could be expected to first increase from initial retreat of glaciers (IPCC, 2001), this phase appears to have already passed for the North Saskatchewan River Basin due to the rapid decrease in the Canadian Rocky Mountains glacial cover (Demuth and Pietroniro, 2003), suggesting the SSRB may also have potentially entered a long-term trend of declining flow
- Biophysical response is likely to respond more slowly compared to environmental changes, and this could possibly cause reductions in ecosystems' size and changes in species composition and distribution
- Ecosystems are expected to migrate northwards, assuming soil physical and moisture conditions are favorable
- Pest and pathogen outbreaks are likely to increase as climate warms
- From Herrington et al. (1997) prediction were made that warmer temperatures could reduce/ compromise snow ski resorts activities; would encourage algae and plant growth that could lead to fish kills, reduce the quality of water to water-based activities
- The scarcity of water would in turn increase the demand for good quality water for human and animal consumption

Lapp S., Byrne J., Townshend I., and Kienzle S. 2005. Climate warming impacts on snowpack accumulation in an alpine watershed. *International Journal of Climatology*, 25: 521-536.

This paper uses a synoptic analysis to generate long term climate time series scenarios using the Canadian Centre for Climate Modelling and Analysis first-generation coupled general circulation model. The synoptic analysis and GCM output forecast a humble increase in both temperatures and winter precipitation in the study area of the upper Oldman River basin in southwestern Alberta. Climate warming is expected to produce a substantial increase in the frequency of synoptic patterns bringing wet winters to southwestern Canada (Byrne et al. 1999). The key objective of this paper is then to assess the impact of climate warming on spring snowpack in an alpine watershed in western Canada by using a variety of steps such as; developing historical and future scenario periods, incorporating a snowpack vapour transfer model, simulating snow accumulation/ablation for two scenarios for a daily time series of 25 years each over a study watershed, and comparing changes in snowpack for specific locations and dates.

The analysis assumes that the critical driving force of winter precipitation is synoptic meteorology and that global warming due to GHG increases will alter synoptic precipitation, and that combined changes in temperature and precipitation will alter regional hydrology. Also sea-surface temperature and the variability associated with this have substantial impacts on synoptic conditions and may have cyclical impacts on regional hydrology.

Overall, for the Oldman basin a decline in snow translates to a similar decline in spring runoff volumes. Therefore, in most years, the water supply will decline in the Oldman River basin in southern Alberta. This decline in water supply has grave implications for the region and, in particular, for the extensive irrigation agriculture developments downstream.

Milly P.C.D., Betancourt J., Faklenmark M., Hirsch R.M., Kundzewicz Z.W., Lettenmaier D.P., and Stouffer R. 2008. Stationarity Is Dead: Whither Water Management? Science 319: 573-574.

Stationarity—the idea that natural systems fluctuate within an unchanging envelope of variability—is a foundational concept that permeates training and practice in water-resource engineering. A key emphasis of this paper is how anthropogenic causes are changing the Earth's climate by altering the means and extremes of precipitation, evapotranspiration, and rates of discharge of rivers, contributing to the death of stationarity. It is a very short yet direct article that makes the point that it is now the time to update the analytic strategies used for planning such grand investments under an uncertain and changing climate.

Key points mentioned:

- Glacial meltwater temporarily enhances water availability, but glacier and snow-pack losses diminish natural seasonal and inter annual storage
- Anthropogenic climate warming appears to be driving a poleward expansion of the subtropical dry zone, thereby reducing runoff in some regions
- Projected changes in runoff during the multidecade lifetime of major water infrastructure projects begun now are large enough to push hydroclimate beyond the range of historical behaviors
- Water managers who are developing plans for their local communities to adapt to climate change will not be best served by a model whose horizontal grid has divisions measured in hundreds of kilometers
- Climate models need to include more explicit and faithful representation of surface- and ground-water processes, water infrastructure, and water users, including the agricultural and energy sectors
- Virtual construction of dams, irrigation of crops, and harvesting of forests within the framework of climate models can be explored in a collaboration between climate scientists and resource scientists and managers

Rood S.B., Pan J., Gill K.M. Franks C.G., Samuelson G.M., and Sheperd A. 2008. Declining summer flows of Rocky Mountain rivers: Changing seasonal hydrology and probable impacts on floodplain forests. *Journal of Hydrology*, 349: 397-410.

The basic goal of this study was to investigate historic changes in seasonal patterns of streamflows, by comparing mean monthly flow and analyzing cumulative hydrographs over the periods of record about a century. Fourteen free-flowing records were analyzed, snow-melt dominated rivers that drained relatively pristine parks and protected areas, thus avoiding watershed management, river damming and flow regulation. Four main results were obtained and included: 1) winter flows (especially March) were often slightly increased, 2) spring runoff and 3) peak flows occurred earlier, and most substantially, 4) summer and early autumn flows (July-October) were considerably reduced. The greatest impacts were observed from the rivers draining form the east-slope of the Rocky Mountains toward the northern parries and Hudson Bay, with late summer flow rates declining at approximately 0.2% per year.

Analyses of streamflows prove to be of great importance for studying mountain regions since the higher elevation generally receive abundant precipitation but are subject to minimal meteorological modeling. As was predicted, the reduced snow pack and earlier snow melt would result in reduced summer streamflows with a greater percentage reduced in the summer. This hydrological change could impose severe ecological stress on aquatic as well as riparian, or streamside ecosystems. The floodplain forests for example could be influenced greatly to the decline in late summer flows which in turn could impose chronic drought stress along river reaches in arid and semi-arid ecoregions. Already these late summer flows have decreased by around 20% over the twentieth century and within the twenty-first century, it is predicted that a further decline=e of about 10% will occur by 2050.

Sauchyn D., Pietroniro A., and Demuth M. 2006. Upland watershed management and global change-Canada's Rocky Mountains and Western Plains. *Fifth Biennial Rosenberg Forum on Water Policy*, Banff, Alberta 1-14.

This paper addresses three major investigations of recent and potential future trends in water resources within the headwater catchments of the Nelson River basin. The first focuses on cataloguing glacial extents within the North and South Saskatchewan River Basins using Earth observation data. The second component examines streamflow records for evidence of trends and variability related to change in glacial extent. The third component includes hydrological modeling of the change in flow regime under future climate/glacier-cover configurations. All together, these analyses provide an assessment of the impacts that climate change may impose on the “water-towers” of the Canadian Prairies.

This paper also describes research on stream hydrology and paleoclimatology of the plains region, suggesting that current perceptions of water scarcity and variability may be skewed by observation and experience of the 20th century which may be unrepresentative of both the natural and future hydroclimates. Also, the paper goes into detail about tree ring proxy dating and the correlations shown with streamflow proxies and hydrological peaks/ cycles. The analysis of this paper shows an importance of glacier runoff to the headwater catchments and the diminishing importance downstream with time. There are also some graphs presented in this paper showing streamflow trends etc.

Key points:

- Total glacier area change as a ratio of 1975 glacier extent was approximately 50% in the Southern Saskatchewan River basin and 23% in the North basin
- Most serious risk to Canadian Plains from climate change is the risk of water scarcity, which would have direct consequences on economic growth
- The impacts of climate change on resource economies are necessarily adverse because resource management practices have assumed a stationary hydrological regime. The realization that hydroclimates are far from stationary has come with the modeling of global warming (climate change forced by greenhouse gas emissions) and from studies of past climate
- Projected increases in precipitation may very well offset these reduction in mean annual flow resulting in increasing spring snowmelt peak, but less water availability in the transition to baseflow period due to the lack of natural storage

Schindler D.W.2001. The cumulative effects of climate warming and other human stresses on Canadian freshwaters in the new millennium. Journal of fisheries and Aquatic Science, 58 (1): 18-29.

This paper deals with climate change and the scarcity of freshwater for Canada, as well as exacerbated processes along with potential future problems if our water supply is not managed accordingly. Some of the key points of this paper are things such as:

- Human and livestock wastes causing eutrophication of many waters in southern Canada and contaminated them with pathogens that will greatly increase the cost of water treatment and health costs from water borne illnesses
- How much of the usable water emanates from the Rockies (total river flows to the Saskatchewan river system from the Rocky Mountains are 87% of the flow volume at the river's mouth
- Typically, from 25 to 30% of total annual flow occurs as winter snowpacks melt for Canadian streams and rivers outside the mountains
- As surface water becomes warmer, the ratio of mercury methylation to demethylation should increase, causing greater contamination of aquatic fauna

Schindler also addresses lessons from the past such as:

- Current global circulation models predict that warming in the 21st century will cause temperatures to greatly exceed those of the mid-Holocene, when temperatures were only 1-2°C warmer than in the mid-twentieth century. Lake Manitoba, one of the prairies great lakes was dry during the mid-Holocene, shown by prairie grasses embedded in the lake sediments.

Schindler, D.W. and W.F. Donahue (2006). An impending water crisis in Canada's western prairie provinces. *Proceedings of the National Academy of Sciences*, 103(19), 7210-7216.

This paper attempts to make the case that a general drying due to climate change is occurring in the western prairie provinces (wpp) during the summer months. It analyses output from climate scenarios, climate records, streamflow records, glacier extent. It however makes errors by selectively examining summer but not winter streamflow, by overattributing streamflow reduction to loss of glaciers rather than water consumption, by confusing potential with actual evapotranspiration and by assuming that increased potential evapotranspiration would reduce snowpacks and therefore streamflow from mountains. For instance, a polynomial is drawn through the summer flows of the South Saskatchewan River at Saskatoon over the 20th C to suggest a gradual drying. In fact upstream water use in Alberta and the building and filling of Gardiner Dam and subsequent operation of the dam for hydroelectricity and other purposes has accounted for much of this change. As such the paper does not make a convincing scientific case though the general drying may in fact be occurring.

The paper then recommends some management responses to reduced water resources under climate change that include integrated catchment management, improved use of science in decision making, recognition of ecological instream flow needs, restoring wetlands and riparian zones, selecting less water intensive agriculture and industry and keeping human populations in the western prairie provinces relatively low.

Toyra J., Pietroniro A., and Bonsal B. 2005. Evaluation of GCM simulated climate over Canadian Prairie provinces. *Canadian Water Resources Journal* 30(3): 245-262.

This paper assed the capability of GCMs to simulate the current climate and compares the future climate change predictions over the Canadian Prairie provinces. Out of the eleven models used the CCSR-NIES, CSIROMK2b, HadCM3 and NCAR-PCM models could best simulate the observed temperature data, while CGCM1, CGCM2, GFDLR15, GFDL-R30 and NCAR-DOE did not perform as well as the other models. The three GCMs that performed best in modeling current climate (NCARPCM, HadCM3 and ECHAM4) were used to obtain a better understanding of the range of predicted changes based on the SRES A2 and B2 emission scenarios. Overall, this study helps increase the knowledge regarding GCM-simulated current and future temperature and precipitation climatologies over the Canadian Prairie provinces. The results obtained from this experiment can further help in generating more reliable hydro-climate scenarios over the Prairie region.

Key Points:

- GCMs generally have higher horizontal resolutions when compared with their older counterparts, they still operate on large spatial scales of approximately 2.5°-5.5° latitude and longitude. This is commonly considered too coarse for regional representation
- All the grid cells in the experiment that were more than 50% beyond the borders of the Prairie provinces were deleted leaving 38 grid cells in total
- The spatial correlation coefficient was high (>0.9) for all temperature data sets
- Total annual precipitation was highly overestimated by most GCMs from 8-66% and five of the models overestimated winter and spring total precipitation amounts by as much as 70-170%