Hydrology and Water Resources of Saskatchewan

Centre for Hydrology Report #1

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1. Introduction

There is little in the natural environment, economy and society of Saskatchewan that is not intimately tied to and sustained by the flow and storage of water. Nowhere else in Canada does the lack or excess of water cause such widespread concern, nor are there many Canadian environments subject to greater seasonal change in precipitation and surface-water storage. Most major landforms of Saskatchewan were created by the deposition and erosion of sediments and rock by water and ice during the glacial and immediate postglacial periods. Saskatchewan's contemporary hydrology determines the type and location of natural vegetation, soils, agriculture, communities and commerce. However, the scarcity, seasonality and unpredictability of the province's water resources have proved critical impediments to the productivity of natural ecosystems and to sustainable settlement and economic activity.

The hydrology of Saskatchewan is marked by several distinctive characteristics that govern the behaviour of water as a resource in the province (Gray, 1970):

i) The extreme variability of precipitation and runoff results in frequent water shortages and excesses with respect to natural and human storage capacities and demand.

ii) The seasonality of water supply is manifest in fall and winter by the storage of water as snow, and lake and ground ice, in early spring by rapid snowmelt resulting in most runoff, and in late spring and early summer by much of the annual rainfall.

iii) The aridity and gentle topography result in poorly developed, disconnected and sparse drainage systems, and surface runoff that is both infrequent and spatially restricted.

iv) The land cover and soils exert an inordinate control on hydrological processes because of small precipitation inputs and limited energy for evaporation and snowmelt.

v) The flows in the major rivers of the southern half of the province are largely derived from the foothills and mountains in Alberta.

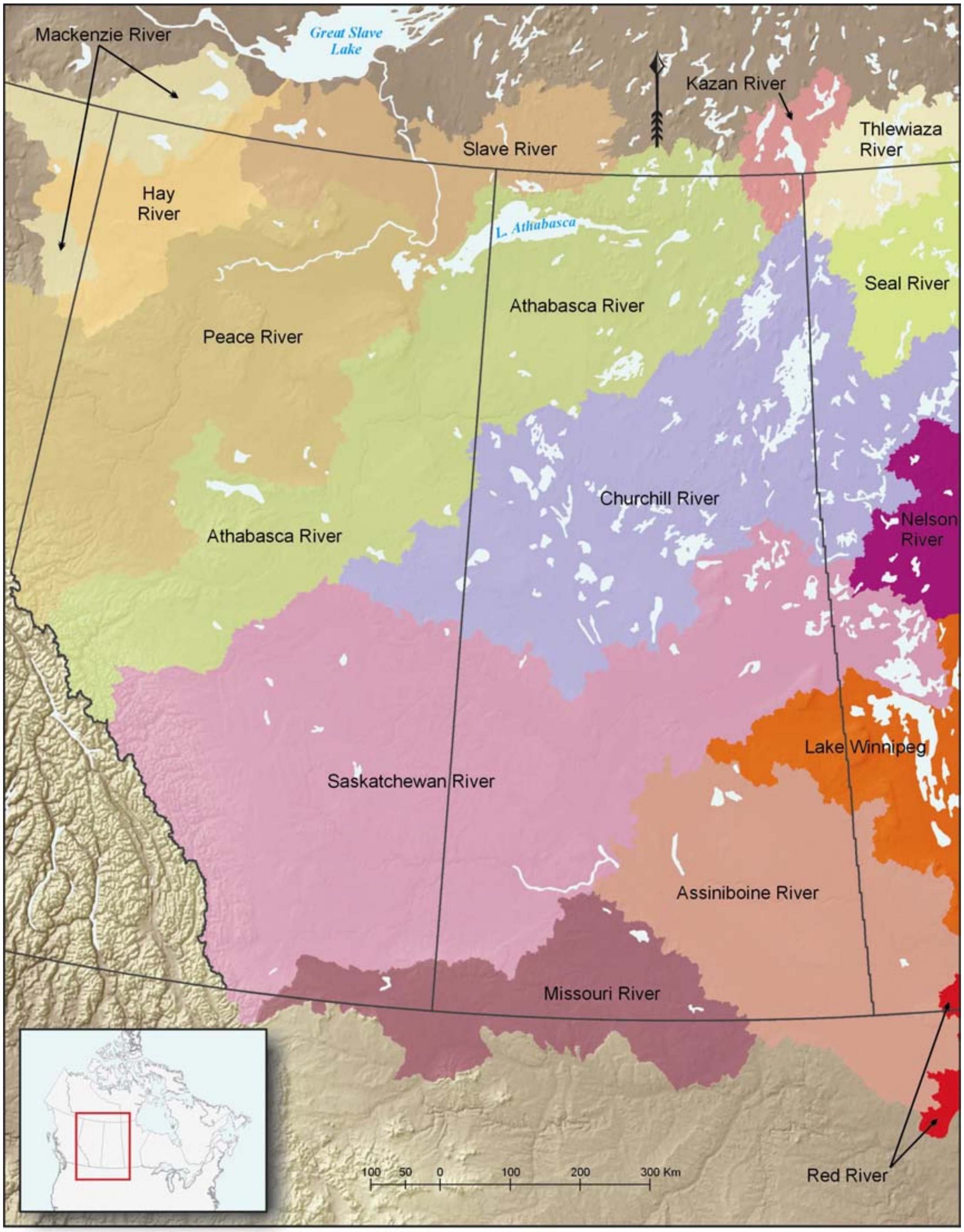
In dry years, arable agriculture can fail over large parts of the province, whilst in wet years, flooding has caused widespread damage to rural and urban infrastructure. Climate change may increase the incidence of both drought and flooding, with earlier spring thaws and increased interannual and interseasonal variability of temperature and precipitation (Covich et al., 1997; Cutforth et al., 1999, Herrington et al., 1997). Changes to the seasonal timing of precipitation can have very severe effects on agriculture and ecosystems; runoff to water bodies and replenishment of groundwater are primarily supplied by spring snowmelt, growth of cereal grains is related to the quantity of rainfall falling between May and early July, maturing and timely harvesting of crops are dependent upon warm dry weather in mid to late summer, and spring runoff is governed by soil moisture reserves in the preceding fall and snowfall the preceding winter (de Jong and Kachanoski, 1987). Saskatchewan's water resources are vulnerable, as there is little local runoff to the single greatest water resource of the southern prairies, the South Saskatchewan River, which derives overwhelmingly from the Rocky Mountains. Water supplies in the Alberta portion of the South Saskatchewan River system are approaching full apportionment in dry years and the uncertainty imposed by climate change impacts on runoff generation in the mountains makes managing the river increasing difficult. Local water bodies (streams, sloughs, dugouts) are fed by groundwater or small surface drainages, and little runoff is provided by most land surfaces within the 'topographic catchment'. The effect of soils and vegetation on Saskatchewan hydrology is profound because of the interaction of snow, evaporation and vegetation. In the southern Prairies, water applied from rain or snowmelt to summer-fallowed fields contributes inordinately to runoff, whereas continuously cropped fields, grasses and trees undergo greater infiltration to soils and hence greater evaporation. In the North, evergreen forest canopy and root structures promote infiltration of rainfall or snowmelt to soils and subsequent evaporation. There is much greater runoff and streamflow in boreal forest drainage basins with large cleared areas.

This chapter will discuss the key physical aspects of Saskatchewan's hydrology and water resources, focussing on its drainage basins and the contribution of runoff to streams and lakes within them, its major rivers and their flows, water supply pipelines and river diversions, prairie hydrology, boreal forest hydrology, groundwater and an assessment of the future. Because of its sub-humid, cold region hydrology and low population, water quality concerns in Saskatchewan are primarily related to algal growth in dugouts, and a few cases of contaminated groundwater or immediate downstream effects from sewage outflows, rather than widespread diffuse-source pollution; this chapter will therefore focus on water quantity rather than quality.

2. Drainage Basins

Based on surface topography and the resulting flow of water, the surface of a continent can be divided into drainage basins, each with a specific area that would deliver surface runoff to a point along the river. An important feature of drainage basins is that they can be divided into smaller and smaller sections, each of which is a drainage basin in its own right. **Figure 1** shows the major drainage basins in the province as delineated by the Prairie Farm Rehabilitation Administration. At the highest level, the province of Saskatchewan can be divided into three drainage basins. The first of these drains to the Arctic Ocean, the second to Hudson Bay, and the third to the Gulf of Mexico. The northernmost portion of the province drains towards Lake Athabasca and, through the Slave River and Great Slave Lake, to the Mackenzie River and ultimately the Arctic Ocean. The central portion of the province drains towards Hudson Bay. Within this portion there are two major basins. The first of these is the Churchill River basin which ultimately drains towards Hudson Bay. Directly south of the Churchill basin is the Saskatchewan River basin which can be subdivided into the North and South Saskatchewan River basins. Both the North and South Saskatchewan Rivers have their headwaters on the eastern slopes of the Rocky Mountains and flow

Figure 1. Size and nature of Saskatchewan's drainage basins.



Map Source: DEM - GTopo30, USGS; Base map - Natural Resources Canada, Government of Canada; Watershed Data - PFRA - Agriculture and Agri-Food Canada, Government of Canada
Map Projection: Lambert Conformal Conic - SP1 - 50°N, SP2 - 70°N, Latitude of Origin 40°N, Central Meridian -105° W
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towards the east and northeast across the Canadian Prairies; they merge and form the Saskatchewan River which flows through Cedar Lake, Lake Winnipeg and the Nelson River into Hudson Bay. The Saskatchewan River system is the fourth longest in North America and drains an area of about 336,900 km^2. In addition to the Saskatchewan River basin there are a few smaller drainage basins in eastern Saskatchewan that are part of the Hudson Bay drainage basin, such as the Red Deer River basin, the Assiniboine River basin, the Qu'Appelle River basin and the Souris River basin. The far southwestern corner of Saskatchewan is part of the Missouri-Mississippi basin that drains to the Gulf of Mexico. Battle Creek and the Frenchman River are two of the larger streams in this region.

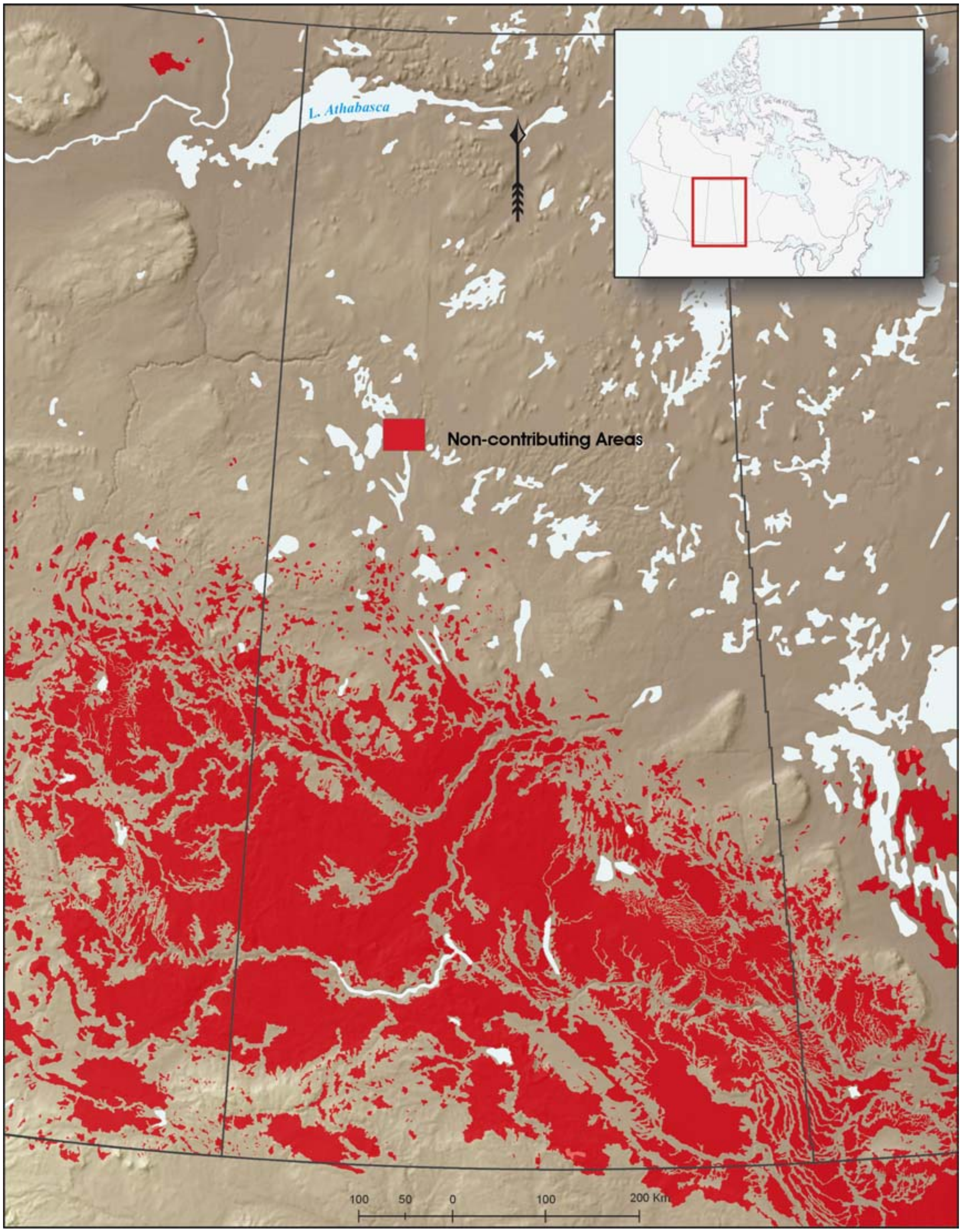
A prominent hydrological property of the prairie landscape in the southern part of the province is the occurrence of areas with internal drainage, i.e., areas that do not drain to an ocean or sea, but instead to local lakes, sloughs or wetlands. On the prairies there is a significant different between the gross drainage area and the effective drainage area. The gross drainage area is defined as the area that may be expected to contribute runoff to a main stream under extremely wet conditions, and is delineated based on topography. The gross drainage area is divided into the effective drainage area, which contributes runoff to the main stream during a flood with a return period of two years, and the non-contributing area which does not contribute runoff (Godwin and Martin, 1975). Non-contributing areas for Saskatchewan are shown in **Figure 2**, as determined by the Prairie Farm Rehabilitation Administration Watershed Project (Martin, 2001). On the prairies, some parts of the landscape will never contribute runoff to the main stream, not even during extremely wet years. These areas have been designated as dead drainage (Godwin and Martin, 1975). The non-contributing drainage areas are located primarily in the central and southern parts of the province. Examples of large non-contributing drainage areas with relatively well-developed stream networks are the Quill Lakes, Old Wives Lake and Redberry Lake drainage basins. Other non-contributing drainage areas have poorly integrated stream networks that contribute runoff to local small lakes and wetlands such as, for example, the upland between Saskatoon and Humboldt and the area between the North and South Saskatchewan Rivers in western central Saskatchewan.

The many small local wetlands that mark the Prairie surface of southern Saskatchewan reflect the irregular topographic surface produced when the continental ice sheet retreated at the end of the last glacial period. Glacial sediments deposited directly from melting ice produced vast stretches of ground moraine and hummocky moraine pitted with depressions. These depressions collect local runoff and produce wetlands often referred to as "sloughs" or "prairie potholes". Under natural conditions, they collect enough water to support aquatic vegetation and ecosystems.

While the distribution of these features is highly variable, moraine landscapes average about 20 wetlands per square kilometre. It has been estimated that the agricultural portion of Saskatchewan contains about 1.5 million wetlands covering some 1.7 million hectares. Over 80% of these wetlands are less than 1 ha in area. The change in land use associated with European settlement of the Canadian Prairies has had a significant impact on sloughs and wetlands. It is estimated that up to 40% of natural wetlands have been lost through the introduction of a variety of artificial drainage works (Huel, 2000).

Sloughs and wetlands store runoff generated by snowmelt and rainfall, slowing its discharge into streams and rivers. This can help to sustain flow and, in many cases, to

Figure 2. Contributing area of drainage basins.



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reduce flood peaks. A detailed study of the hydrology of a slough in the St. Denis National Wildlife Area near Saskatoon, illustrates the importance of such wetlands in buffering the year-to-year variability of precipitation (Woo and Roswell 1993). During dry years, the water stored in sloughs provides input to local groundwater systems in excess of that available from precipitation, while in wet years, the storage of water in the sloughs is replenished. This capacity to carry over water from one year to the next is also critical to maintaining habitat for wildlife and waterfowl. Wetlands and depressions also help mitigate some of the negative impacts of soil erosion. In the rolling agricultural landscape in central Saskatchewan, it was found that over 80% of the sediment produced by soil erosion in a small drainage basin was deposited in local depressions and sloughs, thereby greatly reducing the input of sediment and nutrients to downstream waterways (Martz and de Jong 1991).

3. Rivers and their Flows

Figure 3 shows the major rivers and their mean annual discharge and **Figure 4** shows the annual discharge regimes of some major rivers over the province. The South Saskatchewan River is formed by the confluence of the Oldman River and the Bow River in south central Alberta. Its third major tributary, the Red Deer River, flows into the South Saskatchewan River just east of the Saskatchewan-Alberta border. All three major tributaries have their headwaters on the eastern slopes of the Rocky Mountains, and as a result, the annual flow regime of the South Saskatchewan River upstream of Lake Diefenbaker is 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. Within Saskatchewan, the only significant tributary to the South Saskatchewan River is Swift Current Creek, which contributes less than 1% of the flow. The discharge is lowest during the winter months when the river has a near continuous ice cover. Prior to the construction of the Gardiner Dam (1912-1958 flows), the lowest mean monthly discharge at Saskatoon occurred in January at 68 $m^3 s^{-1}$ (Figure 4). From March to April, the mean monthly discharge increased rapidly to 397 $m^3 s^{-1}$, predominantly as a result of prairie snowmelt. During the spring and summer, the mean monthly discharge continued to increase to peak at 816 $m^3 s^{-1}$ in June as a result of the melt of snow in the mountains. Contrary to popular belief, the melt of glacier ice has a minimal effect on the flow of the South Saskatchewan River entering Saskatchewan. The construction and subsequent operation of the Gardiner Dam radically changed the runoff regime of the South Saskatchewan River. The seasonal variation in discharge was drastically reduced, and the monthly mean discharge at Saskatoon now (1968-1993 flows) peaks in January (301 $m^3 s^{-1}$), with a second peak in June (220 $m^3 s^{-1}$). The dam operation guidelines are to provide a minimum flow in Saskatoon of about 50 $m^3 s^{-1}$ and Lake Diefenbaker is operated for irrigation water supply, hydroelectric power, some flood protection, and recreation as well as to sustain the South Saskatchewan River instream flow needs.

The North Saskatchewan River originates at the Saskatchewan Glacier in the Rocky Mountains (Figure 3). Its main tributary, the Battle River, however, originates in the aspen parkland region of central Alberta. There is no dam on the North Saskatchewan River in Saskatchewan. The North Saskatchewan River at Deer Creek (hydrometric station 05EF001), about 25 km east of the Alberta border and upstream of the Battle River confluence, has its lowest monthly mean discharge (1970-1993) in January (104 $m^3 s^{-1}$) during the ice-on period (Figure 4). The monthly mean discharge increases rapidly from

Figure 3. Map of Saskatchewan with annual discharge along the main rivers.

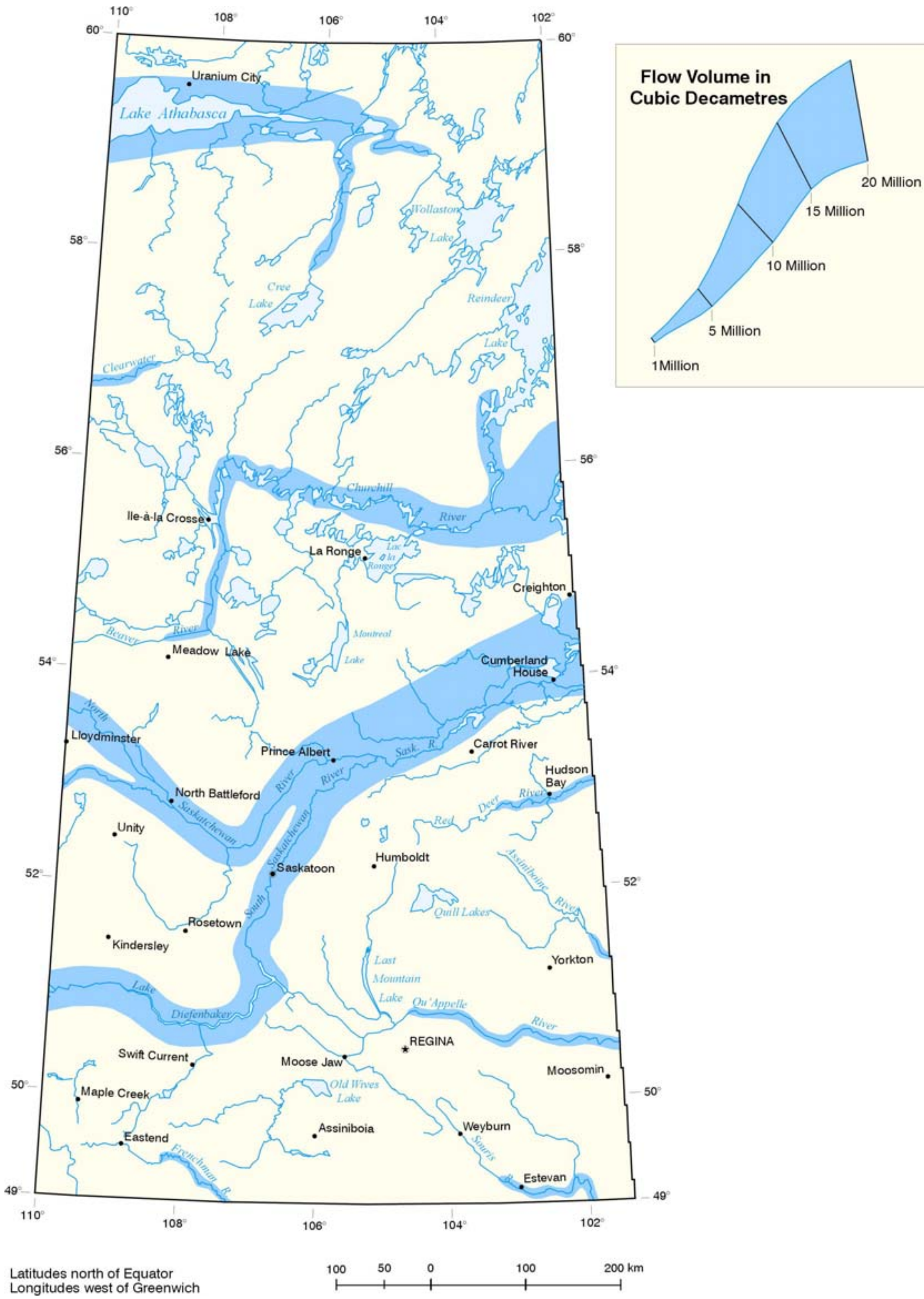

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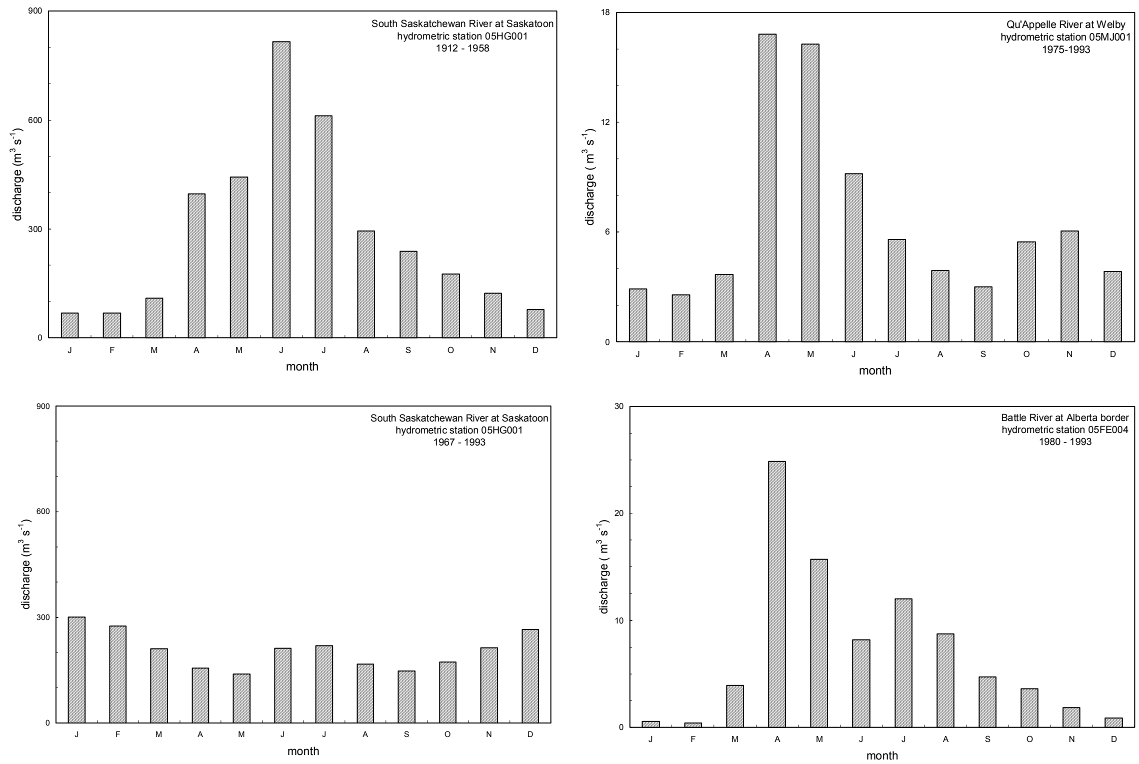
Figure 4. The discharge regimes of the South Saskatchewan, North Saskatchewan, Qu'Appelle, Battle and Churchill Rivers in Saskatchewan (bar graphs of monthly mean discharges)



March (124 m^3 s^{-1}) to April (286 m^3 s^{-1}) due to prairie and parkland snowmelt, and peaks in July (404 m^3 s^{-1}) as a result of snowmelt in the Rocky Mountains. Again, the net effect of glacial ice accumulation and melt in the Rockies on the annual flow of the North Saskatchewan River is very small in Saskatchewan. The hydrological regime of the Battle River at the Alberta border (hydrometric station 05FE004) is typical for a river that originates in the aspen parkland region. The lowest monthly mean discharge (1980-1993) occurs in February under ice (0.4 m^3 s^{-1}), and in April the discharge rapidly increases to reach a monthly mean of 25 m^3 s^{-1} due to the spring snowmelt. Unlike the North and South Saskatchewan Rivers, during the rest of the spring and summer the discharge continues to be low because of the absence of contributions from high mountain snowmelt.

The Qu'Appelle River extends east from the Qu'Appelle Valley Dam on Lake Diefenbaker to the Manitoba border, and it joins the Assiniboine River near St. Lazare, Manitoba (Figure 3). The Moose Jaw River and Wascana Creek are the major tributaries of the Qu'Appelle River. A series of seven dams and control structures along the river have created reservoirs such as Buffalo Pound Lake, Pasqua Lake and Katepwa Lake along the Qu'Appelle River valley. The largest lake in the Qu'Appelle system is Last Mountain Lake. The discharge regime of the Qu'Appelle River is a mix of the regimes of a typical prairie river and lake drainage, and is modified by water additions from the South Saskatchewan River system at Lake Diefenbaker (Figure 4). Near Welby, just west of the Manitoba border (hydrometric station 05JM001), the lowest monthly mean discharge (1975-1993) occurs in February (2.6 $m^3 s^{-1}$), and from March to April the monthly mean discharge increases sharply from 3.7 to 17 $m^3 s^{-1}$ as a result of prairie snowmelt. Following the spring snowmelt, the monthly mean discharge decreases sharply and remains low during the rest of the season with a slight rise in October and November to draw down lake levels in preparation for the spring runoff in the following year.

The Churchill River originates in the boreal forest-covered Canadian Shield of northern Saskatchewan (Figure 3). Even though its basin extends as far as the aspen parkland north of Edmonton, Alberta, through the Beaver River, most of the Churchill River discharge originates in northern Saskatchewan. In this region, the Churchill River system consists of a series of lakes connected by short stretches of rapids, fast flowing streams and narrows. Essentially, one lake spills into the next. Some of the major lakes in this system are Churchill Lake, Lac Ile-à-la-Crosse, Pinehouse Lake, Otter Lake, Lac La Ronge and Reindeer Lake. The presence of a large number of interconnected lakes in its drainage systems strongly moderates the flow of the Churchill River. Overall, the discharge regime is very even, and the range in the monthly mean discharge is relatively small (Figure 4). For the Churchill River at Sandy Bay (1929-1993), for example, April is the month with the lowest mean discharge (607 $m^3 s^{-1}$), and July is the month with the highest mean discharge (784 $m^3 s^{-1}$).

Water quality on the Prairies Water uses have direct impacts on water quality. Urban centres like Calgary, Edmonton and Saskatoon discharge effluent from sewage treatment plants and industrial sources. In addition, runoff from urban surfaces results in a transfer of contaminants to the river. In rural areas, irrigation return flow and runoff from other point and non-point sources can result in the transfer of nutrient and organic compounds to the stream. Human activity frequently results in deterioration of water quality, and the degree of deterioration generally increases during times of water shortage when lower discharges result in less dilution. Thus, there are direct links between water quantity and quality issues.

4. Water Supply Pipelines and Diversions

In 1948, federal government and the provincial governments of Alberta, Saskatchewan, and Manitoba formed the Prairie Provinces Water Board (PPWB) with the mandate to provide recommendations on the best use of interprovincial waters and on water allocations amongst the three provinces. In 1969, the four parties signed the Master Agreement of Apportionment that still is in place. Under this agreement, Alberta is allowed to consume the greater of 2,600,000,000 m^3 per year or 50% of the natural flow to Saskatchewan. Alberta must, however, maintain a discharge to Saskatchewan of the lesser of 42.5 $m^3 s^{-1}$ or 50 % of the natural flow. Similar rules apply to the flow of water from Saskatchewan to Manitoba. The natural flow referred to in the Master Agreement of Apportionment is defined as the flow that would occur in the river in the absence of human activity, and is calculated from data from more than 90 monitoring sites.

Overall, Alberta uses 24.5% of its natural flows in the South Saskatchewan River. In drought years however, Alberta uses most of its 50% apportionment. In the 21st century, changes in precipitation and temperature associated with global warming and increased demand resulting from increases in population will exacerbate water shortages up to the point that availability of clean water will become a key limiting factor to economic and community development in the Prairie Provinces of Canada. As a result, water quantity is a significant and ever-increasing concern in the Prairie Provinces.

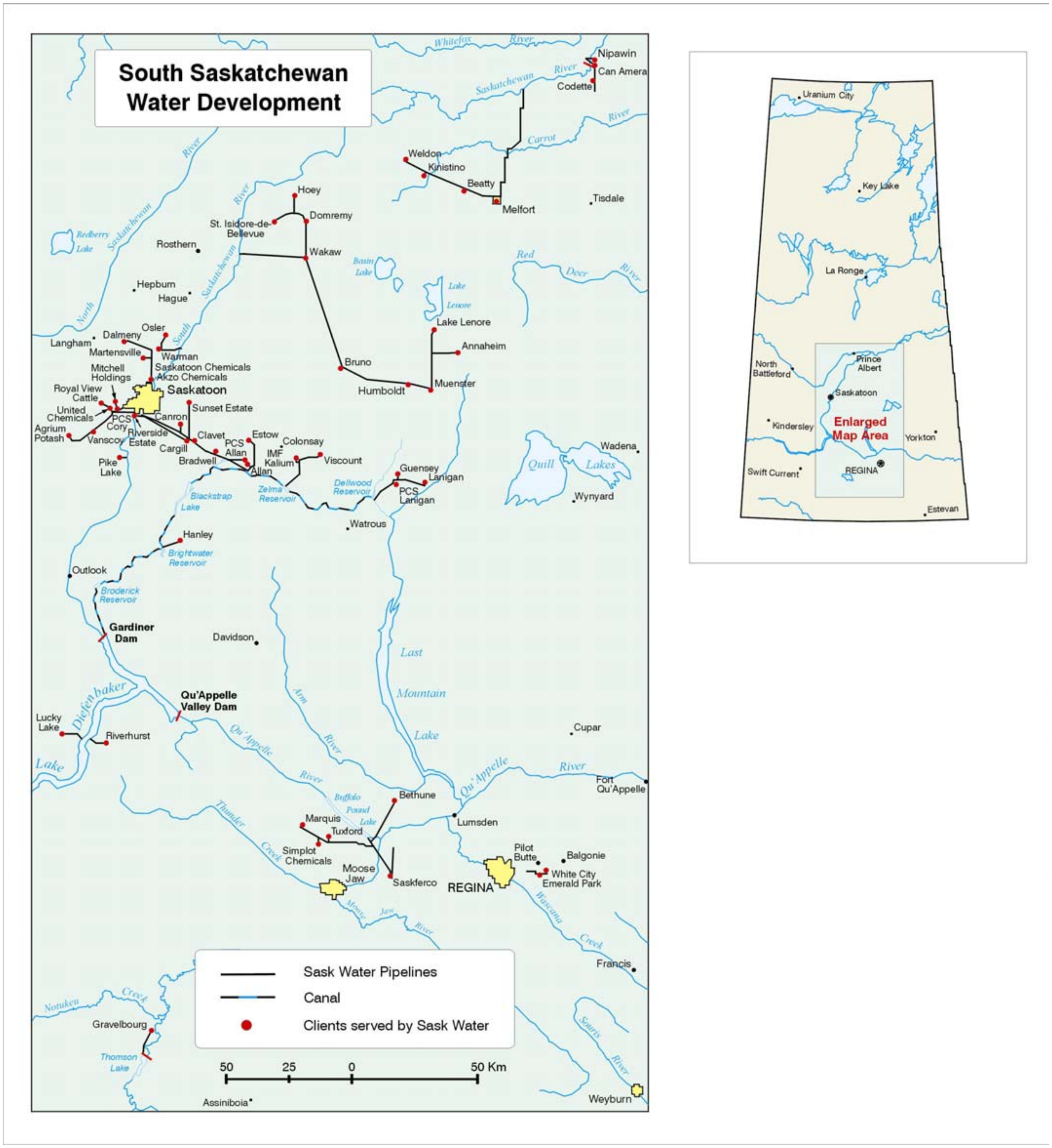
In 1959 construction was started on the Gardiner Dam as part of the South Saskatchewan River Project. The project, which also included the construction of a smaller dam across the Qu'Appelle River valley to prevent the water from escaping to the east, was completed in 1967 and resulted in the formation of Lake Diefenbaker. Currently, about 70% of the population of Saskatchewan gets drinking water from Lake Diefenbaker and the South Saskatchewan River. In addition, Lake Diefenbaker provides water for irrigation, industrial use, and recreation. Because of its capacity to store and subsequently release water, it plays an important role in flood control for the downstream areas, except for the largest floods at frequencies of less than 1 in 10 years. At the maximum water level the total storage in Lake Diefenbaker is 9.4×10^9 m^3, of which 4.3×10^9 m^3 is usable storage between the minimum and the maximum water levels during ordinary operating conditions. The Saskatoon Southeast Water Supply System (SSEWS) delivers water from Lake Diefenbaker, from the Broderick Reservoir near Outlook, through 158 km of canals, associated pipelines and six reservoirs such as Brightwater Reservoir and Blackstrap Lake to, ultimately, the Lanigan area (**Figure 5**). Municipal water users include the towns of Hanley, Guernsey and Lanigan and the rural municipality of Dundurn. In addition, the SSEWS system supplies water to three potash mines, and a variety of irrigation, waterfowl and recreation projects are also served. About 16,000,000 m^3 of water are delivered from Lake Diefenbaker each year. Sask Water, the Crown corporation that provides water and wastewater services to municipal, industrial, government and domestic customers in the province, also operates eight systems for the transmission of treated and raw water in the Saskatoon, Buffalo Pound, Regina, Humboldt, Melfort and Nipawin areas (Figure 5).

The Qu'Appelle River system (Figure 5) is managed for a variety of purposes including municipal, agricultural and industrial water use, recreation, and wildlife and fisheries management. A series of control structures operated by the Prairie Farm Rehabilitation Administration (PFRA) and Sask Water are primarily used to manage water levels in the lakes and to maintain a flow of water down the river during low-flow periods rather than for flood control. A special feature of the Qu'Appelle River system is the flow in Last Mountain Creek which can be towards or away from the Qu'Appelle River. The area between the south end of Last Mountain Lake and the Qu'Appelle River near Craven is extremely flat. The level grade permits the direction of flow to depend on the relative water levels in the lake and the river. By operating the control structures at Valeport, at the south end Last Mountain Lake, and Craven, downstream of the confluence of Last Mountain Creek and the Qu'Appelle River, water can be directed into Last Mountain Lake to maintain water levels in the lake or the prevent flooding further downstream in the Qu'Appelle River valley. Subsequently, the control structures allow a controlled release of the stored water down the Qu'Appelle River.

5. Hydrology of the Prairies

Prairie runoff and resulting streamflow are largely derived from snowmelt whilst evaporation and water for plant growth are largely derived from rainfall (Gray, 1970). Precipitation in the prairie region of the province is low, ranging from 300-400 mm per year with 30% falling as snow. If it were not for the long winter period, such low

Figure 5. Map of water supply pipelines and major diversions.



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precipitation would result in desert conditions. There is substantial variation in hydrology across the prairie region of Saskatchewan, from semi-arid conditions and relatively good drainage in the south and west, to sub-humid conditions with substantial wetland and lake storage in the north and east. Notwithstanding this variation, the hydrology of the Saskatchewan prairie can be characterized as including (Gray, 1970):

i) 4-5 month long winters with mid-winter thaws (frequent in the SW, infrequent in the NE), and substantial wind redistribution and sublimation of snow,

ii) mineral soils that are frozen at the time of snowmelt, resulting in high runoff (Gray et al., 1985),

iii) deep soils with good water-holding properties and high unfrozen infiltration rates (Elliott et al., 1999),

iv) most rainfall days in spring and early summer from large frontal systems, but the most intense rainfalls from summer convective storms over small areas (Gray, 1970),

v) periods of low rainfall from mid-summer to fall such that soil moisture, plant growth, evaporation and runoff are regularly reduced to very low levels (Granger and Gray, 1989).

vi) a poorly developed stream network such that much land does not normally drain to any stream or river system (Godwin and Martin, 1975),

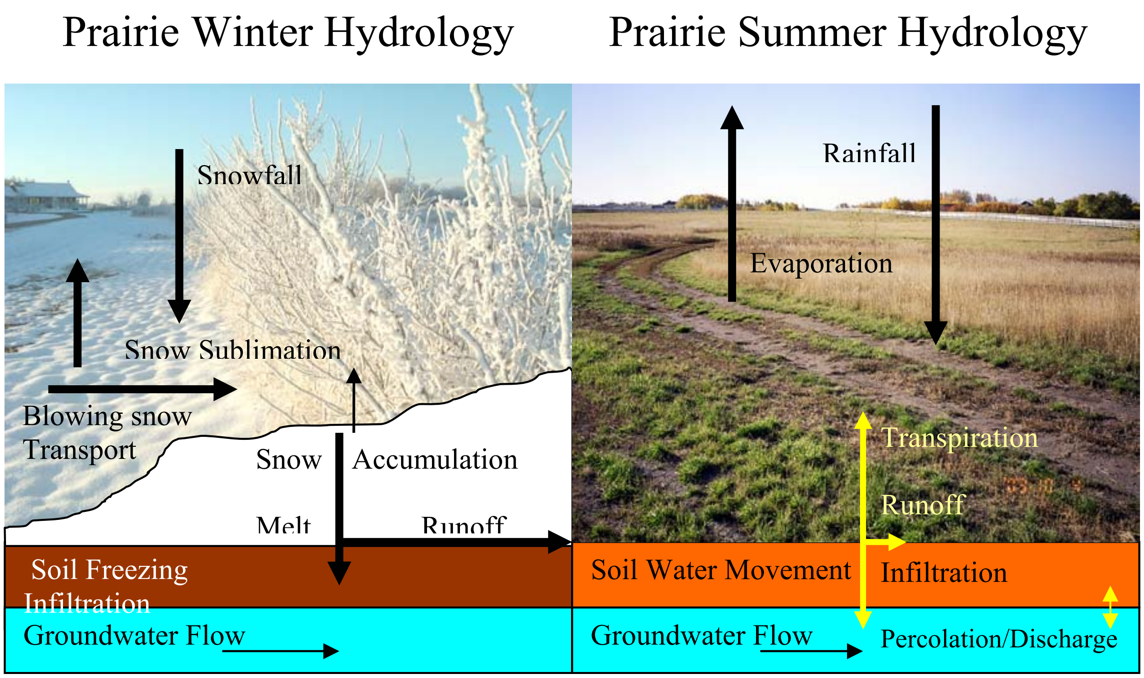
vii) large areas of internal drainage that do not contribute to the major river systems (Martin, 2001).

Prairie hydrological processes are shown in **Figure 6** and are discussed below. Blowing snow storms not only redistribute snow from open, exposed sites to sheltered, vegetated sites but sublimate snow in transit (Pomeroy et al., 1993). Sublimation occurs because blowing snow crystals are well ventilated, numerous and travel long distances. Transport from a field results in accumulation in a drift and so the snow is still available for snowmelt and is not a 'loss' of water resource. Transport usually relocates snow to sloughs, drainage channels or valleys where it is more likely to run off to a water body upon melt. The result of sublimation and transport from prairie fields is to substantially reduce snow accumulation by the end of winter. **Table 1** shows sublimation and transport losses for fallow and stubble fields in various parts of the Province (Pomeroy and Gray, 1995).

Table 1. Blowing snow transport and sublimation losses for fallow and stubble fields of 1 km length in Saskatchewan.

Station	Snowfall (mm)	Winter Temperature (^oC)	Winter Wind Speed (m/s)	Land Use	Transport (mm)	Sublimation (mm)	Accumulation (mm)
Prince Albert	103	-11.6	4.5	Stubble	9	24	70
				Fallow	13	28	62
Yorkton	125	-10.6	4.7	Stubble	10	19	96
				Fallow	16	29	80
Regina	113	-8.9	6.0	Stubble	21	38	54
				Fallow	41	46	26
Swift Current	132	-6.7	6.6	Stubble	15	29	88
				Fallow	38	38	56

Figure 6. Major hydrological processes in the prairie environment: left side – winter processes, right side – summer processes.



Evaporation 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 from bare soils and via transpiration involves withdrawing soil moisture reserves and eventually results in soil desiccation if there are no further inputs of water via rain or groundwater outflows. Saskatchewan soils generally have good water-holding capacity and most infiltrated water is held in the root zone until withdrawn by the plant for transpiration. Evaporation is driven by the net radiation to the surface and by convection of water vapour from the wet surface to a dry atmosphere; both are in good supply on the Saskatchewan prairie and so evaporation generally proceeds rapidly until near-surface water supplies are exhausted. On average, seasonal evaporation loss is close to seasonal rainfall in the Province, with amounts less than rainfall occurring in exceptionally wet or cool years, especially in the east and north of the agricultural region. Locally higher rates of evaporation occur from sloughs and wetlands where redistribution of spring snowmelt runoff water into topographic depressions or groundwater outflows provide for wet surface conditions through much of the summer (van der Kamp et al., 2004).

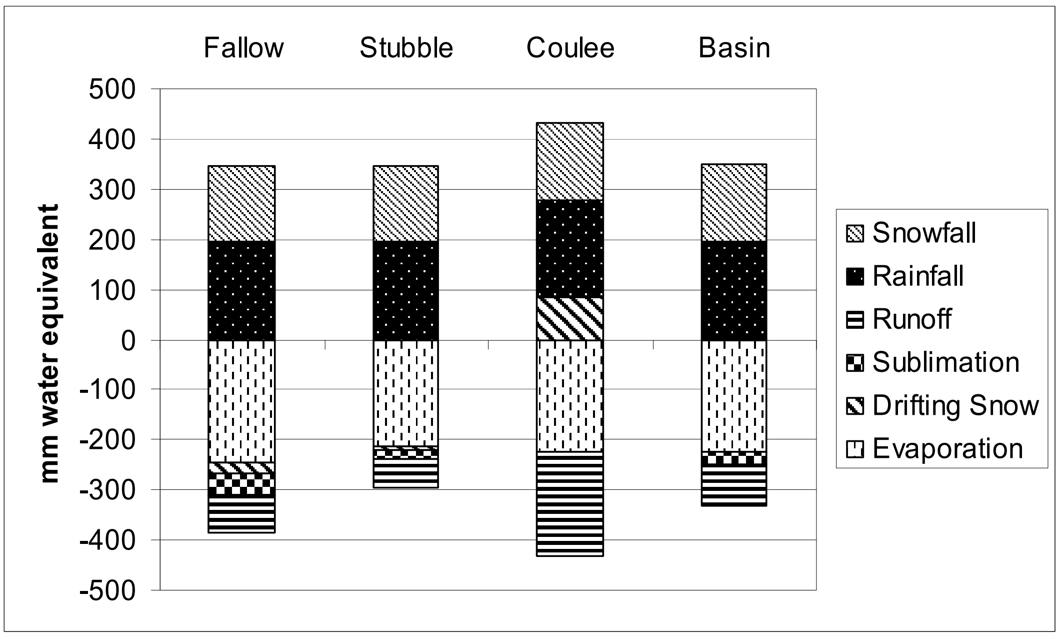
Recharge of groundwater occurs through coarse-textured soils or in topographic depressions with no outflow, such as some pothole lakes. In these situations, infiltrated water is able to percolate below the rooting depth, and unsaturated water moves by gravity drainage to the saturated layer or aquifer (Hayashi et al., 2003). Apart from a few natural springs where groundwater discharges to the surface, runoff occurs when the input of rainfall or snowmelt exceeds the infiltration capacity of the soil. Cultivated and grassland soils in summer have very high infiltration rates, ranging from 3 to 25 mm/hour (Gray, 1970) and so intense rainfall rates are required to generate runoff. These rainfalls are infrequent and of short duration, hence most runoff (80%-90%) occurs during snowmelt when the frozen state of soils reduces infiltration capacity. Gray et al. (1985) showed that frozen Saskatchewan agricultural soils could be grouped into three classes for snowmelt infiltration; unlimited, limited and restricted. Unlimited class soils are extremely porous such as coarse sands and gravels or cracked clays; all snowmelt water infiltrates to these soils so that there is no runoff. Limited class soils are unsaturated soils of moderate texture that can infiltrate 10% - 90% of meltwater with higher quantities for drier soils. Restricted class soils are completely saturated, or are wet heavy clays or have an impeding layer such as an ice lens from a mid-winter melt; as a result they are impermeable so that all snowmelt water goes to runoff. The fall moisture content of soils and the occurrence of major melt events in mid-winter are extremely important in controlling snowmelt runoff rates in the subsequent spring.

The effect of land cover in a prairie water balance for a year with near normal precipitation is shown in **Figure 7** for Creighton Tributary of the Bad Lake basin in southwestern Saskatchewan; the water balance for each land-cover type and a spatially-weighted average for the basin are shown. The units are given as millimetre water equivalent (mm) which is the equivalent depth of liquid water over the land-cover type or basin that rain, runoff, snowfall, melted snow or water vapour would comprise if they were evenly distributed. The water balance was calculated from observations and model output from a prairie hydrological process model (Pomeroy et al., 2005). Over the winter, snow blows from the fallow fields (-22 mm), from the stubble fields (-8 mm), to the coulee (+85 mm). Some blowing snow also sublimates in transit (-24 mm over the basin); as a result only 58% of snowfall is left on the fallow fields, and 82% on the stubble fields, to melt in the spring. In contrast, 55% more snow accumulates and then melts in the coulee than fell there due to this wind redistribution of snow. During snowmelt, runoff is fives times higher than infiltration on the fallow fields due to nearly saturated frozen soils, and six times higher than infiltration in the coulee due to steep slopes and frozen soils, but infiltration is slightly higher than runoff on the stubble fields due to dry soils from the previous year's cropping. At the time of grain germination in early June, the fallow field has lost 85 mm of soil moisture since fall, while the stubble field soil moisture has held steady with infiltration from snowmelt oversetting evaporation in fall, spring and early summer. Almost all runoff is dominated by that from the coulee itself, with the fallow field also making a large contribution. Evaporation through the summer consumes all rainfall and much soil moisture storage from spring infiltration. There is no runoff in the summer.

6. Hydrology of the Boreal Forest

The forested zone of Saskatchewan covers almost two-thirds of the province; most of this forest is boreal forest, and its hydrology is quite different from that of the prairies. The hydrology of the boreal forest is the result of interactions amongst climate, vegetation and soil components of the ecosystem and in turn strongly influences streamflow, water bodies, aquatic habitat, forest vegetation and climate. Precipitation ranges from 400 to 500 mm/year with about 30% as snowfall. Winter persists for about six months and there are few mid-winter thaws. Though the region is sub-humid, summers are cool with frequent convective storms driven by evaporation from lakes and forest. Soils range from well-drained rock, sand and silt with thin organic layers on top in the uplands to thick, poorly drained organic soils (peat) and muskeg that cover extensive wetland areas in lowlands. River systems do not match the dendritic networks of temperate zones as they tend to consist of networks of lakes connected by fast flowing, short stretches of stream (e.g. Churchill River, Otter Rapids). Lake coverage in boreal basins ranges from minimal to more than 50% of basin area.

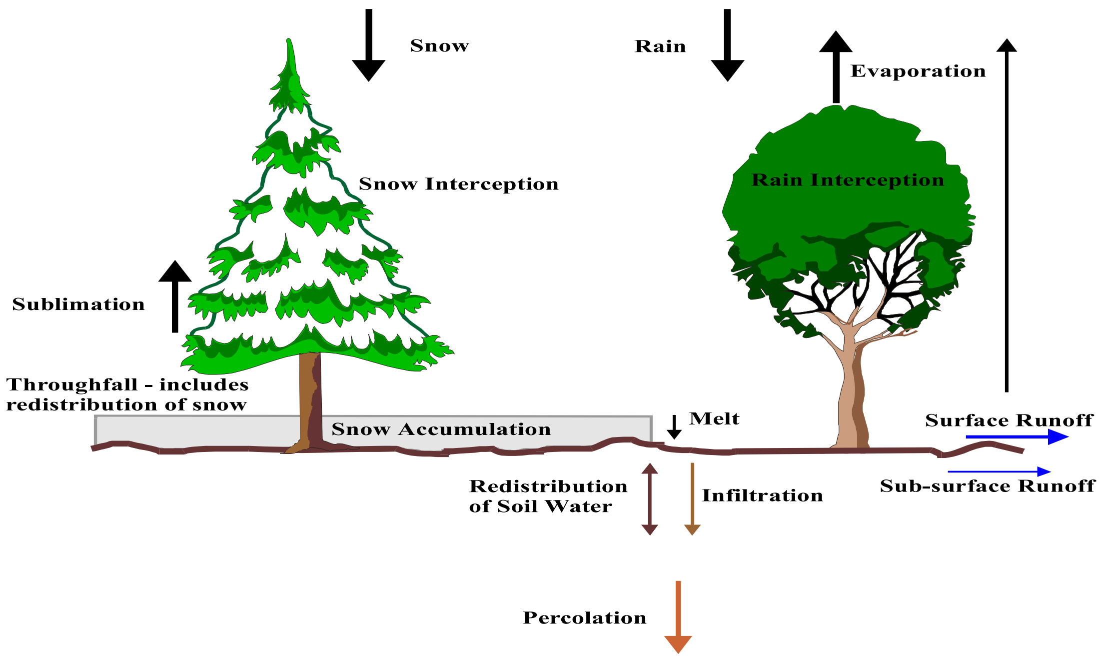
Figure 7. Water balance of a small (12 km^2) basin in the semi-arid prairie region of Saskatchewan; Creighton Tributary of Bad Lake near Bickleigh, Sask. 1 Nov. 1974- 30 Oct. 1975. Basin land cover is 31% summer fallow (fall-spring 1974-75) then grain crop (summer 1975), 54% stubble (fall-spring 1974-75), then grain crop (summer 1975), 15% brush coulee.



Most runoff from mineral soils derives from snowmelt because of the effect of frozen soils, however the streamflow response is greatly delayed because of storage in organic soils in the basin such that peak streamflow is greatly attenuated and may not occur until early summer (Pomeroy et al., 1997). Despite the attenuation of streamflow caused by storage in wetlands and lakes, most parts of the boreal forest drain to a definable drainage basin, and the region sustains a significant density of streams and has a sufficient water surplus to sustain many lakes and for the Churchill River to arise and flow based on local runoff.

Hydrological processes in the boreal forest are intimately connected with the forest canopy as it influences water storage and energy exchange with the surface and the atmosphere. A conceptualisation of hydrological processes in the boreal forest is shown in **Figure 8** where on the left side, winter processes of snowfall, snow interception in the canopy, sublimation (evaporation of snow), throughfall of snow to the ground, snow accumulation, snowmelt and infiltration of snowmelt water into frozen soils are shown. On the right side of Figure 8 are the summer processes of rainfall, rain interception in the canopy, evaporation, drip, surface runoff, sub-surface runoff, infiltration and redistribution of soil water. The schematic shows these processes in their vertical configuration; however, once water reaches the soil it may also move horizontally through the basin as surface or sub-surface runoff, downhill to streams or lakes and then downstream out of the basin.

Figure 8. Major hydrological processes in the boreal forest: left side – winter processes, right side – summer processes.



Snowfall in the boreal forest is intercepted by evergreen canopies and can be held in the canopy for many weeks. In early winter there can be more snow in the canopy than on the ground below. This snow is subject to high net radiation and strong ventilation, and so is subject to sublimation. Seasonal sublimation losses range from 10% (mixed wood of aspen and spruce) to 30% (jack pine) to 45% (dense black spruce) of seasonal snowfall (Pomeroy et al., 1998). Sublimation losses from clear-cut and burned areas are negligible. Pomeroy and Granger (1997) found that snowmelt was three times faster in clearings than under mature forest canopies, despite substantially greater snow accumulation in clear-cut areas. Radiation is the primary energy input to melting snow for both dense forests and clearings, and daily radiation inputs to clearings are 7.5 times greater than to forests during snowmelt.

Interception of rainfall measured in aspen, pine and spruce stands in the boreal forest ranges from 9% to 55% of rainfall, increasing with canopy density. Up to 70% of intercepted rainfall evaporates directly from the canopy. As a result, direct intercepted rain evaporation from the canopy increases with canopy density and amounts to approximately 25% of total evaporation for mature evergreens, declining to negligible amounts for clearings (Elliott et al., 1998). Evaporation in the boreal forest is influenced by interception, soil moisture storage, the albedo (reflectance) of forest canopies, the roughness of canopies and the ability of roots to access water (Granger and Pomeroy, 1997). Aspen canopies reflect twice as much solar radiation as do evergreen canopies and so remain cooler, with lower evaporation over the summer. Forests are rougher and have better developed root systems than do the shrubs, grasses and barren sites in clearings, and so evaporation rates are one-third less in clearings than in mature boreal forests. The development of root and soil systems after disturbance is important in allowing a forest to access water; Pomeroy et al. (1997) showed that evaporation from jack pine stands increased with stand age up to about 90 years, despite the stands achieving a 'mature' canopy density at about 25 years of age.

The major annual runoff events in boreal forests are usually linked to snowmelt because of saturated or frozen soils. Soils are normally frozen at the time of snowmelt, which restricts the infiltration capacity. Relatively high ice-content soils in clearings (because of low evaporation the previous summer) produce the greatest runoff during spring snowmelt (Pomeroy et al., 1997). The effect is magnified because of high snow accumulation and rapid snowmelt in clear-cut areas. In summer, the effect of relatively high soil moisture reserves, and minimal intercepted rain evaporation in clearings is to promote runoff generation from rainfall. In contrast, jack pine stands over sandy soils produce minimal runoff and the other mature forest sites produce little runoff; however, up to one-third of rainfall becomes runoff from clearings.

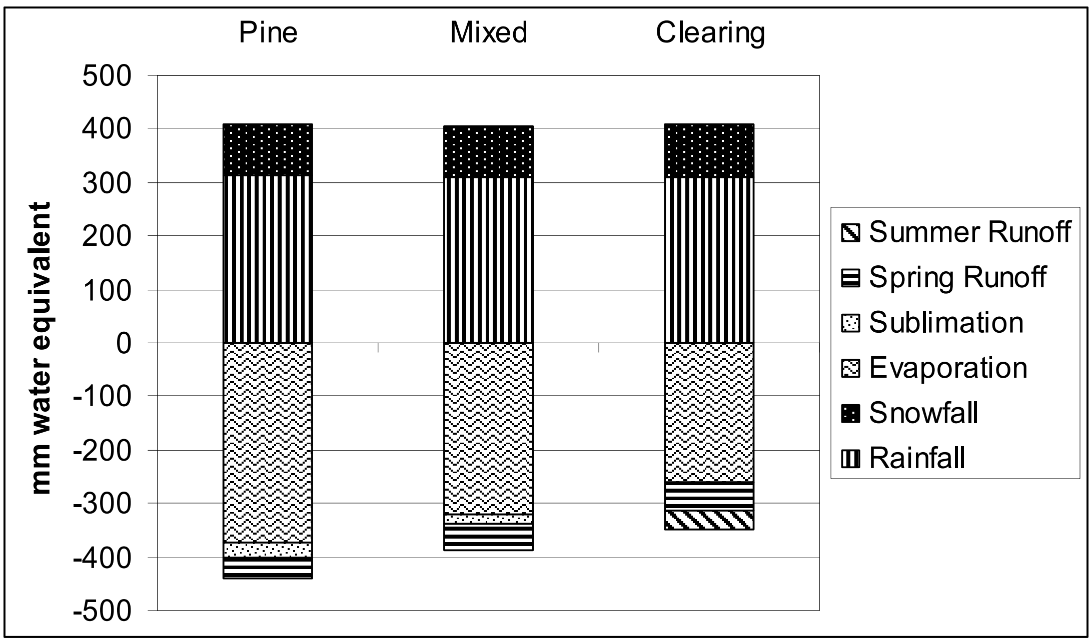
Figure 9 shows an annual water balance for three land covers in the central boreal forest of the Prince Albert Model Forest in a year with near normal precipitation (Pomeroy et al., 1997). The natural stands in Prince Albert National Park (pine, mixed) only produce runoff in the spring during snowmelt over frozen soils. The pine stand loses 29% of winter snowfall to sublimation of intercepted snow, with half this loss occurring from the mixed wood and a negligible loss from the clearing. The large spring runoff from the mixed-wood and clearing is due to high soil moisture reserves at the time of snowmelt and minimal intercepted snow sublimation losses. Evaporation from the clearing is reduced compared to the mixed wood (80% of mixed wood) and even more so compared to the jack pine (69% of pine), a reflection of differences in root systems, soils, albedo and leaf area. The clearing is the only land cover to produce summer runoff. This is because higher evaporation rates from the pine and mixed wood deplete soil moisture over the summer, and interception during rainfall reduces the amount that can reach the ground. Over the example year, the clearing and mixed wood experienced water surpluses, whilst the pine sustained a small water deficit. This suggests that groundwater recharge and discharge might be active and is backed up by a declining water table in the pine site over the summer.

7. Groundwater

Groundwater plays an important role as a water supply due to the limited availability of surface water south of the boreal shield region. Groundwater is precipitation that has infiltrated through the unsaturated soil zone down to a saturated layer from a recharge zone. In the saturated layer it can move horizontally, often over significant distances, to a discharge zone that is at a lower elevation than the original saturated layer.

Groundwater of sufficiently high quality and quantity that it can be used for domestic purposes generally falls into two categories: bedrock and drift aquifers. The distribution of these aquifers across the province is shown in **Figure 10** (H. Maathius, Atlas of Saskatchewan Project, 1999). Bedrock aquifers involve sediments that were laid down before glaciation, while drift aquifers involve material from the top of the bedrock to the surface. Bedrock aquifers include the Cumberland aquifer of limestones and dolomites in east-central Saskatchewan, the Mannville Group of sands near the Canadian Shield, the Judith River Formation sands in south-west and south-central Saskatchewan, and sands and gravels of the Bearpaw, Eastend and Ravenscrag Formations in the south-west.

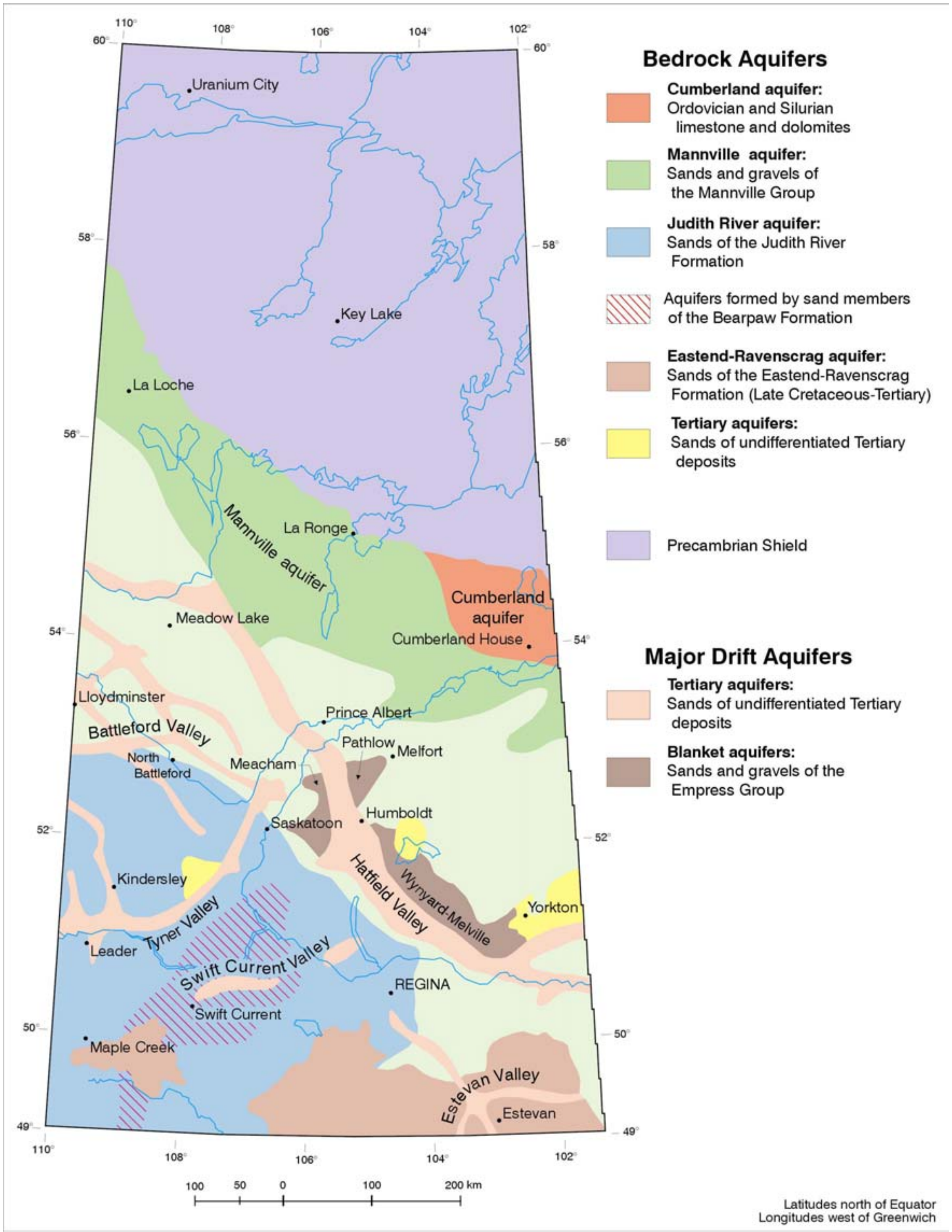
Figure 9. Water balance three land cover types in the central Saskatchewan boreal forest, 1 Oct. 1995- 30 Sept. 1996. 'Pine' is a mature jack pine stand and 'mixed' is a mature mixed-wood of trembling aspen and white spruce in Prince Albert National Park. 'Clearing' is a three-year old clear-cut near to Montreal Lake in the Prince Albert Model Forest.



Drift aquifers form in deep buried valleys now filled with sand and gravel in the Hatfield, Tyner, Battleford and Estevan aquifers. The Hatfield is the major valley aquifer and is up to 30 km wide, and 50 m deep and is buried up to 90 m. The Hatfield aquifer is surrounded by extensive blanket aquifers. Inter-till aquifers are bounded by till layers and are extensive in southern Saskatchewan, and range from large regional aquifers to very small local aquifers. Surface aquifers occur in outwash, alluvial and aeolian sands deposited in the glacial and immediate post-glacial periods.

Groundwater levels show both long-term and seasonal fluctuations, but in all cases these are very slow and quite delayed from surface hydrology water balance changes. Recharge to near-surface aquifers occurs in spring to early summer during snowmelt and spring rainfall in wet years. Consecutive drought years can cause serious decline in the level of surface aquifers. Deep bedrock aquifer levels increase slowly over the winter period but tend not to respond to dry or wet years.

Figure 10. Major drift and bedrock aquifers yielding potable water in Saskatchewan



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In the absence of contamination, groundwater quality is highest in the surface aquifers (ion content < 1000 mg/l). Intertill aquifers have high calcium, magnesium and sulphate concentrations (ion content 1500 to 2500 mg/l) and are perceived as 'hard' water. Surface and near-surface inter-till aquifers are most susceptible to groundwater contamination from human or animal surface wastes. Water in bedrock aquifers is high in sodium (ion content 1000 to 2500 mg/l) and is perceived as 'soft' water. Bedrock aquifers are rarely contaminated from the surface. The major buried valley aquifers have a mixture of bedrock and till water with high calcium, sulphate, magnesium and sodium concentrations (ion content 1500 to 3000 mg/l). Saskatchewan groundwater normally has high concentrations of iron, which can cause taste problems.

8. Conclusions

It has been shown that Saskatchewan's hydrology is characterized by low precipitation, little evaporation or runoff, and relatively large storage. This means that local-scale water resources here 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 throughflow rates in the hydrological cycle. The major rivers of the province arise either outside of its borders or flow in the sparsely populated North and so are not in direct local control.

Nevertheless, the hydrology and water resources of Saskatchewan have been substantially developed and managed since the time of first agricultural settlement and will likely undergo further development and management. Agriculture is now more efficient in its use of water, and further progress with improved crop varieties and tillage systems is expected. Care must be taken so that land management practices that preserve more water for crop use do not result in the drying of small wetlands that are important for wildlife, aesthetics, groundwater recharge and small scale water supplies. More of the provincial population is now located in several large centres which will require secure, high quality and steadily increasing municipal supplies; these centres will also produce more effluent that must be treated. Intensive livestock and food processing industries require large volumes of potable water and can produce significant effluent that must be carefully managed so as to preserve the quality of ground and surface waters.

Most of Saskatchewan's water use is in the south, whilst most of the water is in the north of the province. Drought in the south has shown that many local surface water supplies are unreliable and alternatives are being increasingly explored. The province already redistributes water, for instance from the South Saskatchewan River to the Qu'Appelle River to supply Regina and Moose Jaw. Increasing urban, agricultural and industrial demand must be met by either greater conservation or further redistribution of water in certain localities. The Saskatchewan River system provides a lifeline to much of the population and, because it drains a large portion of the Rocky Mountains, it can be expected to provide reliable, large quantities of water even with a changing climate. The natural flows of the South Saskatchewan River entering the province have not changed significantly since settlement; however, consumptive withdrawals in Alberta are notably reducing the actual flow of this river to currently 75% of its natural flow. Saskatchewan is entitled by interprovincial agreement to receive 50% of the natural flows of this system as it enters the province and to consume 50% of what actually enters the province. Water use in the province is well below this limit and only a dramatic population increase, extensive expansion of irrigation and/or wide-spread development of water-intensive industries could conceivably put stress on the water supplies of the Saskatchewan River system as a whole. With proper planning, innovative water management, and a strong science base to decision making, Saskatchewan should be able to effectively distribute and apportion its water for economic development, but will have to pay particular attention to preserving and restoring aquatic ecosystems and habitats as such development occurs.

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