REVIEW OF LAKE DIEFENBAKER OPERATIONS
2010-2011

Centre for Hydrology Final Report to the Saskatchewan Watershed Authority

Centre for Hydrology
University of Saskatchewan
117 Science Place
Saskatoon, Saskatchewan
S7N 5C8

February, 2012

Centre for Hydrology Final Report to the Saskatchewan Watershed Authority

Review of Lake Diefenbaker Operations 2010-2011

University of Saskatchewan,
Saskatoon, Saskatchewan
February, 2012

Outline

Executive Summary

Abstract

Analysis of the Lake Diefenbaker operation and hydrometeorological events of 2010-2011 suggests that minimum reservoir levels have been rising over time and were particularly high in the winter and spring of 2010-2011 resulting in a greater risk of high outflow events if predicted inflows were not accurate. Rules and policies for operating Gardiner Dam based on verified information and priority of operations to minimize cumulative risk were not in place to optimize dam operations after several mid-winter events restricted outflows from the dam. Unfortunately inflows were underpredicted in 2011 due to an underestimation of upstream snowpacks, inability to quantify ungauged inflows from prairie runoff, inadequate available information on upstream and local meteorological conditions, and reliance on statistical forecast procedures based on previous climate conditions. The impact of outflows on downstream areas was difficult to quantify because of an underestimation of outflows from the Coteau Creek hydroelectric station at Gardiner Dam and the lack of sufficient hydrometric stations downstream. Whilst water supply goals for the reservoir were met in the period, and downstream flood extent was cut in half; the acreage duration of flooding between Moon Lake and Saskatoon was not reduced by dam operation and the annual peak flow downstream on the Saskatchewan River was not reduced by dam operation. The overall evaluation of SWA operation of Lake Diefenbaker in light of the operational objectives understood at the time is that SWA forecasting staff did a superb job with the limited tools and resources, complex operating system and unspecified operating rules available to them.

There are various areas for SWA to develop its capabilities in the near future so that the likelihood of repeating the high flow and flooding events of 2011 is diminished and public understanding of the capability of dam operations is improved. Diminishing volumes but undiminished peaks of streamflow into Lake Diefenbaker are making multi-objective operation of the reservoir more difficult and more prone to not meeting both water supply and flood protection purposes. The foremost change needed is to develop formal rules and priorities so that operating procedures for Gardiner Dam can be optimized for accepted goals. If downstream flood protection is one of the primary goals for the reservoir, then the winter minimum level of Lake Diefenbaker should be reduced until improvements in forecast capability are realised. If water supply and hydroelectricity generation are the overriding objectives, then current lake levels are more acceptable, but the reduced flood protection capability should be explained to the public. Operation of the reservoir for any set of goals can be improved by using greater hydrological and meteorological information from Alberta Environment and Water and other agencies in inflow forecasting, improving rating curves, by increasing the number of hydrometric stations measuring the impact of Gardiner Dam outflow, and improving - by automating - data management and distribution, streamflow forecasting and public distribution of forecasts. SWA should start immediately planning how it will develop an integrated hydrological modelling and hydrometeorological observation capability so that quantitative forecasts of prairie streamflow can be issued for ungauged basins, and the uncertainty in forecasts of river flow entering the province can be reduced.

Purpose of Study

The purpose of this study was to conduct a post-event evaluation of the operations of Lake Diefenbaker from August 1, 2010 through to July 31, 2011, namely the decisions made in real-time against the operating objectives understood at the time and in achieving a balance of multi-use objectives, and to address policy needs or gaps to the extent possible. The scope of this project included: technical review of existing documentation and data held by SWA, interviews with SWA staff, interviews with external experts or other participating agencies, and review of hydrometric and meteorological data in the Alberta portion of the drainage basin and forecasting products from Alberta Environment and Water.

Description of Drainage Basin and Lake Diefenbaker

Lake Diefenbaker receives inflows primarily from the Rocky Mountains and a very small proportion from Saskatchewan. Annual streamflow volumes feeding Lake Diefenbaker have declined 40% since the early 20th C.; of this decline 70% is due to upstream consumption, mainly for irrigation, and 30% is due to changes in the natural hydrology and climate of the tributaries. Operation of the reservoir seeks to provide water for irrigation and water supply, hydroelectricity generation, flood protection, recreation, shoreline habitat and to sustain downstream river flows above a minimum threshold whilst keeping reservoir levels below a maximum level. Reservoir levels typically peak in August and are drawn down over the fall and winter to a minimum level in late winter. There are target elevations, but not rules, for irrigation users, Elbow Harbour, recreational use and the piping plover habitat. There is no requirement for downstream flood protection, but it has been found over time that Gardiner Dam operation can reduce downstream flooding to some degree.

Estimating Inflows and Outflows from Lake Diefenbaker

There are deficiencies in estimating inflows and outflows from Lake Diefenbaker that impact on operational decision making in high flow events and attempts to reduce downstream flooding. SWA should formally route and attenuate hourly routed streamflows from Alberta Environment and Water. Estimated ungauged inflows from Saskatchewan were a large component of April 2011 inflows to Lake Diefenbaker, peaking at nearly 600 m^3/s. A method to predict and estimate these inflows is needed to manage the reservoir in high flow years. There is a substantial underestimation of outflows from Gardiner Dam using existing rating curves for the spillway and Coteau Creek hydroelectric plant gauged flows that is most evident at high. During the high flow events in June 2011 this underestimation amounted to 400 m^3/s which meant that SWA staff were not able to correctly estimate the flows at and upstream of Saskatoon resulting from Gardiner Dam operations. The underestimation was not due to runoff into the river between Gardiner Dam and Saskatoon.

Operational Objectives and Trends in Reservoir Elevations

From 2001 to 2011, Saskatchewan has seen both its wettest and driest conditions since records began and this challenges multi-objective reservoir operation. Minimum winter/spring Lake Diefenbaker elevations have been increasing by over 3 m from 1969 to 2011 whilst peak elevations in summer and fall show no trend, but are lower in drought years. The increasing trend in minimum reservoir elevations improves water supply resiliency in times of drought, but reduces the flood protection capability of the reservoir. The trend is likely due to several factors, one being an increased confidence over time by SWA in its ability to predict high flow events from mid-winter mountain snowpacks. This confidence is misplaced as very little predictability is shown until spring. Another factor is the trend in inflows which have dropped by 40% in April and 50% in May since 1960. This drop is far in excess of the decline in natural flows and is also caused by agricultural consumption and the filling of the

Oldman Reservoir. The increase in minimum reservoir elevations has increased the water supply and hydroelectric capability of the reservoir in response to prolonged drought and diminished inflows, but has diminished the flood protection of the reservoir without any evidence of a policy shift or decision. Clear policy direction for reservoir operation is needed in this regard.

Sequence of Events 2010-2011

The sequence of events leading to the high flow of 2011 started in the summer of 2010 with wet conditions in the prairies. Mountain snowpacks in the Oldman River basin were above median levels from December onwards and exceeded 90% of all years by spring. Bow and Red Deer River basin headwaters snowpacks were below median levels until the end of January but exceeded 70% of all years by spring. The heavy accumulations of snow in the Oldman River basin (up to 300% of normal by spring) occurred in the part of the South Saskatchewan River basin headwaters that melts earliest because it is furthest south. Record snowpack accumulated in the Cypress Hills. Exceptionally high snowpacks were measured in the foothills and prairies, meaning that the volume of snowmelt from early prairie melt would be quite high. The large spring inflow ran from 1-26 April 2011 and was poorly estimated by SWA-routed flows derived from Water Survey of Canada data because of errors in this data because of large unmeasured inflows from ungauged prairie streams. A better estimation of inflows could have been obtained by routing Alberta Environment and Water generated flows and estimating the discharge of ungauged basins in Saskatchewan. Mountain snowpacks began to melt at higher elevations in early May 2011 and contributed runoff into June and July. In late May up to 120 mm of precipitation fell on the mountains and foothills resulting in high streamflows in all Alberta tributary rivers to Lake Diefenbaker. These high inflows began to show up on 27 May 2011. Subsequent rains in the Oldman basin and Cypress Hills in June contributed to recession flows from the 27 May peak. The Red Deer River basin received up to 160 mm of rainfall in mid-June which caused a secondary peak inflow to Lake Diefenbaker over 13-17 June 2011. Subsequent rains in the foothills of the Red Deer River basin led to a further peak inflow in late June. While the peak daily inflow was large and earlier than normal it was not exceptional and was well below that experienced in 1995 and 2005. Measured monthly inflows were above median values from March through August, with the June measured inflows exceeded 94% of June inflows after 1965 and averaged 1200 m^3/s.

Downstream Effects

Reservoir levels from August through November 2010 were nearly static with discharges closely matched by inflows. Discharges were intentionally reduced in the fall and winter to assist construction of Circle Drive Bridge in Saskatoon and repairs on two of the Coteau Creek hydroelectric generating units. The spillway was not used to reduce lake levels in winter due to concerns this would cause ice jams on the river. Discharge through all turbines did not increase until late March. As a result, reservoir levels were 2 m higher than normal in the spring. During the large April inflows, discharges from the reservoir were kept low to reduce peaks on the combined Saskatchewan River flow downstream. The long spring peak of the North Saskatchewan River meant that discharges from Lake Diefenbaker were kept relatively small for a long period. As a result, reservoir levels rose in April 2011 by three metres when normally they would rise by ½ m. The reservoir was drawn down in May with higher outflows and rose with the first June inflow event to full storage level. Once this level was reached, subsequent discharges had to remain high through June and early July. However the operation of the dam reduced downstream flows on the South Saskatchewan River for the four largest peak inflow events. Flows over 1750 m^3/s were entirely prevented by dam operation, but flow duration near 1500 m^3/s was increased. The estimated maximum flooded area between Moon Lake and Saskatoon was reduced in half by dam operation. However, flooded acreage duration was unaffected by the dam. The effect of Gardiner Dam operations on the Saskatchewan River system downstream of the confluence was to substantially reduce spring season flow peaks but to not diminish primary flood peak of the year in late June.

Resources Available for Operations

The resources available for river forecasting were limited and this impacted on forecast capability and decision making. Hydrometric station density in inadequate over much of the Saskatchewan River basin and the situation is particularly acute in the Saskatchewan portion of the Saskatchewan River Basin. The lack of a station downstream of the confluence of the North and South Saskatchewan rivers makes assessing the impact of releases from Gardiner Dam on the Saskatchewan River extremely uncertain and is considered to be an extraordinary omission. The paucity of stations for the Saskatchewan portion of the Lake Diefenbaker drainage make this region almost entirely ungauged which resulted in the inability to measure April inflows in to the lake in 2011. Weather station resources were inadequate in the mountain headwaters where precipitation measurement density is 23.5 times less than international standards for mountain regions and extraordinarily inadequate in the Saskatchewan portion of the basin where there were only two usable weather stations near Lake Diefenbaker. Alberta snow survey network data is needed to supplement information from the sparse Alberta snow pillow network. Given the lack of regular local snow measurements in Saskatchewan, there is potential to use snow data assimilation model (SNODAS) products from the US NOAA National Operational Hydrologic Remote Sensing Center in the future.

Streamflow Forecasts

The March 2011 forecast from Alberta Environment and Water for the March through September 2011 cumulative flows for the Bow, Oldman and Red Deer rivers substantially underestimated actual flows on the Oldman and Red Deer rivers but were close to actual volumes for the Bow River. SWA staff should automate flow routing to improve efficiency and accuracy in high flow events. Errors in the Gardiner Dam outflow estimates during high flows resulted in errors in the residual estimates of inflows such that the water balance of the reservoir was very uncertain. The effect of changing head on the spillway should be considered in calculating outflows from Gardiner Dam and a more serious underestimation of high flows from Coteau Creek hydroelectric station should be thoroughly investigated. Because of the paucity of hydrometric stations on the main rivers downstream of Gardiner Dam, methods such as the kinematic wave should be used to route streamflow downstream of Gardiner Dam as substantial translation of the hydrograph is anticipated to occur under high flows and this will affect estimates of flooded areas and inputs to the Saskatchewan River dams.

Data Management

The daily data collection system used by SWA is very inefficient, potentially unreliable and is too slow for the sub-hourly information that is available and is needed by the public and by SWA in a high flow situation. Internal requests for information would be better served by a secure, industrial quality database system designed for hydrological forecasting operations. Raw data downloaded from the Water Survey of Canada is not quality controlled and has substantial missing data. Alberta Environment and Water perform QA/QC on these data and this corrected information can be accessed electronically. SWA should ensure that data collection management systems purchased in the future are compatible not only with WSC but with that of Alberta Environment and Water so that this corrected information can be accessed. Any new system should have a web-page capable reporting system to reduce forecaster time spent in answering outside requests for basic flow data and make hydrological information available to the public in a timely, efficient manner.

SWA Forecasting

SWA forecasts for Lake Diefenbaker underestimated June inflows by a factor of two and did not improve much over the spring despite available reports of rapidly increasing snowpacks. The mountain snowpack information quoted in monthly provincial forecasts and other information suggests that SWA staff did not have an accurate appreciation of the variability of mountain snowpacks and substantially underestimated accumulations because they relied only on sparse snow pillow information. SWA staff had a good appreciation of the potentially high prairie runoff year from high prairie snowpacks and wet frozen soils. However the predictability of inflows to Lake Diefenbaker from available information was overestimated by SWA staff. Early to mid-winter snow accumulation is a poor predictor of peak snow accumulation because of substantial later winter snowfall events in the mountains and foothills. Because spring rainfall also contributes to inflows, forecasts based on peak snowpack alone will also be in error and this effect is more severe in wet years. March forecasts of the Bow, Oldman and Red Deer river flows from Alberta Environment and Water showed errors increasing to from 20% to 60% as discharge increased to higher than mean flows. SWA could improve its forecasts by incorporating probabilistic medium term weather forecasts, accounting for increased climate variability and change in adjusting its probabilistic estimation procedures and developing a hydrological modelling capacity for its prairie drainages. It should be noted that SWA short-term forecasts into Lake Diefenbaker are reasonably accurate, but outflow forecasts are seriously in error and meaningless more than three days after their issue. This creates a perception problem with users of the forecasts and needs remedy either by improvement or better communication of the purpose of these forecasts.

Risk Assessment

SWA staff were aware of high mountain snowpacks by March 2011 and of the potential for high runoff conditions on the prairies, but not that filled depressional storage would cause a dramatic increase in basin runoff contributing area compared to previous years. There was an awareness of the streamflows that would cause flooding between Moon Lake and Saskatoon, but the understood discharges from the dam under high flows underestimated both measured streamflows at Saskatoon and flooded areas between Moon Lake and Saskatoon. Risk assessment was hampered by over-confident forecasting ability, particularly in the ability of winter forecasts to predict peak summer flows and by the incremental accumulation of risk in a period of climate change, increasing upstream consumption, land use changes and non-stationarity. What seemed a series of reasonable decisions on reservoir outflows over the winter led inevitably to higher than desirable summer streamflows. The importance of maintaining low flows for river ice and to reduce April flows to the Saskatchewan River system needs to be carefully reassessed. By not compensating for reduced outflows for bridge construction and hydroelectric generator repair in winter, a substantial additional risk of subsequent high streamflow was undertaken with unquantified reduction to risk from river ice flooding. Rules and policies for operating Gardiner Dam should be based on verified information and priority of operations to minimize cumulative risk for clear priorities for water supply, hydroelectricity generation, recreation, ecosystem protection and/or flood control. Priorities are not clear now which prevents optimisation of reservoir operation.

Potential Improvements to Forecasting

SWA could benefit from deployment of commercially available information technologies and taking advantage of advanced information available from the upstream jurisdiction. By development of a hydraulic routing, hydrological modelling and hydrometeorological observation capability, SWA could reduce uncertainty in forecast flows in the rivers entering the province, better forecast downstream peak flows and flooding, and forecast the local ungauged prairie contribution to reservoir inflows.

Improvements in rating curves and increasing the number of hydrometric stations on the Saskatchewan tributaries and main rivers would further reduce uncertainties in the impact of outflows from Gardiner Dam.

Recommendations for SWA

Immediate needs include

i) Development of formal rules and priorities for operating Gardiner Dam on Lake Diefenbaker instead of the very unclear and *ad hoc* operating regime that is currently in place. Gardiner Dam stands out as one of the few major control structures in North America that is operated for multiple purposes without a formal ranking of the priorities of these purposes and resulting rules of operation. In particular the roles of the dam operation with respect to flood control, hydroelectric generation, water supply, recreation and ecosystem conservation need to be specified, ranked and clarified so that operating rules can specified internally and to outside interests that routinely make requests to modify the operation of Gardiner Dam.

ii) Over time, SWA has increased the winter minimum level of Lake Diefenbaker, thereby reducing its flood attenuation capability whilst maintaining or increasing its hydroelectricity generation and water supply potential. This was partly based on the perception of an improving capability in forecasting spring and early summer high flows whereas in reality there is little mid-winter forecast capability for high flow events. It is also based on declining spring inflows which put the water supply operation of the reservoir at greater risk. There is not sufficient predictability of the system to operate in this manner and achieve all of the current goals for the reservoir. At the first opportunity, SWA must prioritize the water supply and flood protection roles for Lake Diefenbaker. If flood protection remains one of the top priorities for the operation of Lake Diefenbaker, then until such time as SWA can show it has improved its forecast capability, lower winter minimum lake levels should be implemented. If water supply concerns are paramount, then the higher minimum lake levels can be sustained, but the public must be informed of the changing flood risk associated with this operational decision.

iii) SWA could make immediate use of hydraulically routed streamflows and QA/QC'ed streamflow, snow survey, precipitation and meteorological information from Alberta Environment and Water to reduce the uncertainty of forecast and routed inputs to Lake Diefenbaker and thereby increase operating flexibility.

iv) There remains substantial uncertainty at high flows of how releases from Gardiner Dam translate to streamflow downstream. This is due to having only one hydrometric station with a rating curve (Saskatoon) and apparent errors in estimates of discharge from the Coteau Creek hydroelectric station at high flows. A second station with a reliable rating curve, and further improvements to the estimates of discharge from the dam, especially from the Coteau Creek station, would reduce the uncertainty of how releases from the dam impact the downstream environment.

v) SWA forecasters currently operate with little assistance, have non-forecasting duties for data acquisition, data analysis, public consultation and conduct their forecasts with spreadsheet based methods and very little automation of data and information flow or forecast dissemination. SWA should implement a computerized data management system that is compatible with that of its upstream jurisdiction to facilitate and automate sharing of actual and routed flows, meteorology and snow course data. It should further automate public forecasts so that they are distributed widely and efficiently.

Longer term needs include

vi) SWA stands out as one of the few river forecasting operations in North America with no hydrological modelling capability for streamflow prediction. This resulted in an inability to accurately predict the size and timing of inputs to Lake Diefenbaker from prairie basins and to reduce the uncertainty of Alberta forecasts of streamflow from the mountains and foothills. This capability should be developed based on integrated enhanced observations and hydrological modeling of prairie streams arising in Saskatchewan and involvement in improvements to basin-wide snow, meteorology and streamflow observation and modeling systems.

vii) The current hydrometric network in Saskatchewan is sparse. The absence of a hydrometric station on the South Saskatchewan between Saskatoon and the confluence with the North Saskatchewan River increases the difficulty of the management of Saskatchewan River flows. The previously-existing station on the South Saskatchewan River near the forks should be re-activated.

viii) The ice on the South Saskatchewan River requires better monitoring when high flows are anticipated and a better understanding of the impact of winter discharges on ice is needed. The monitoring in 2011 was useful, but internal emails show that it was clearly an ad-hoc program. A more organized inspection program, perhaps supplemented by the high-resolution satellite remote sensing now available, and a rigorous understanding of discharge-ice jam interactions in the river downstream of Gardiner Dam should be developed and instituted.

1 Introduction

Lake Diefenbaker is an important reservoir on the South Saskatchewan River system created by the construction of the Gardiner and Qu'Appelle dams in the 1960's. The reservoir is managed by the Saskatchewan Watershed Authority (SWA) and serves a number of purposes including municipal, industrial, irrigation water supply, hydropower generation, recreation, commercial fishery, and downstream flood control. The reservoir shoreline has become a significant habitat for the endangered Piping Plover. Releases from the reservoir to the South Saskatchewan River provide water supply benefits, allow additional downstream hydropower, enable ferry operations, and provide in-stream aquatic habitat.

Through the fall and winter of 2010/11 a number of factors and decisions led to higher than normal reservoir levels going into the spring 2011 runoff period. Above normal prairie runoff volumes in April further reduced storage available for May/June runoff originating from the Rocky Mountains and foothills. Significant June inflows and the reduced available storage resulted in higher than desired reservoir releases. The high releases resulted in flooding of agricultural land upstream of Saskatoon and claims of mismanagement from agricultural land owners along the river. The lack of available storage also restricted the ability to offset peak flows in the North Saskatchewan River leading to high flows in the Saskatchewan River downstream of the confluence of the North and South Saskatchewan Rivers.

The purpose of this study is to conduct a post-event evaluation of the operations of Lake Diefenbaker from August 1, 2010 through to July 31, 2011, namely the decisions made in real-time against the operating objectives understood at the time and in achieving a balance of multi-use objectives, and to address policy needs or gaps to the extent possible.

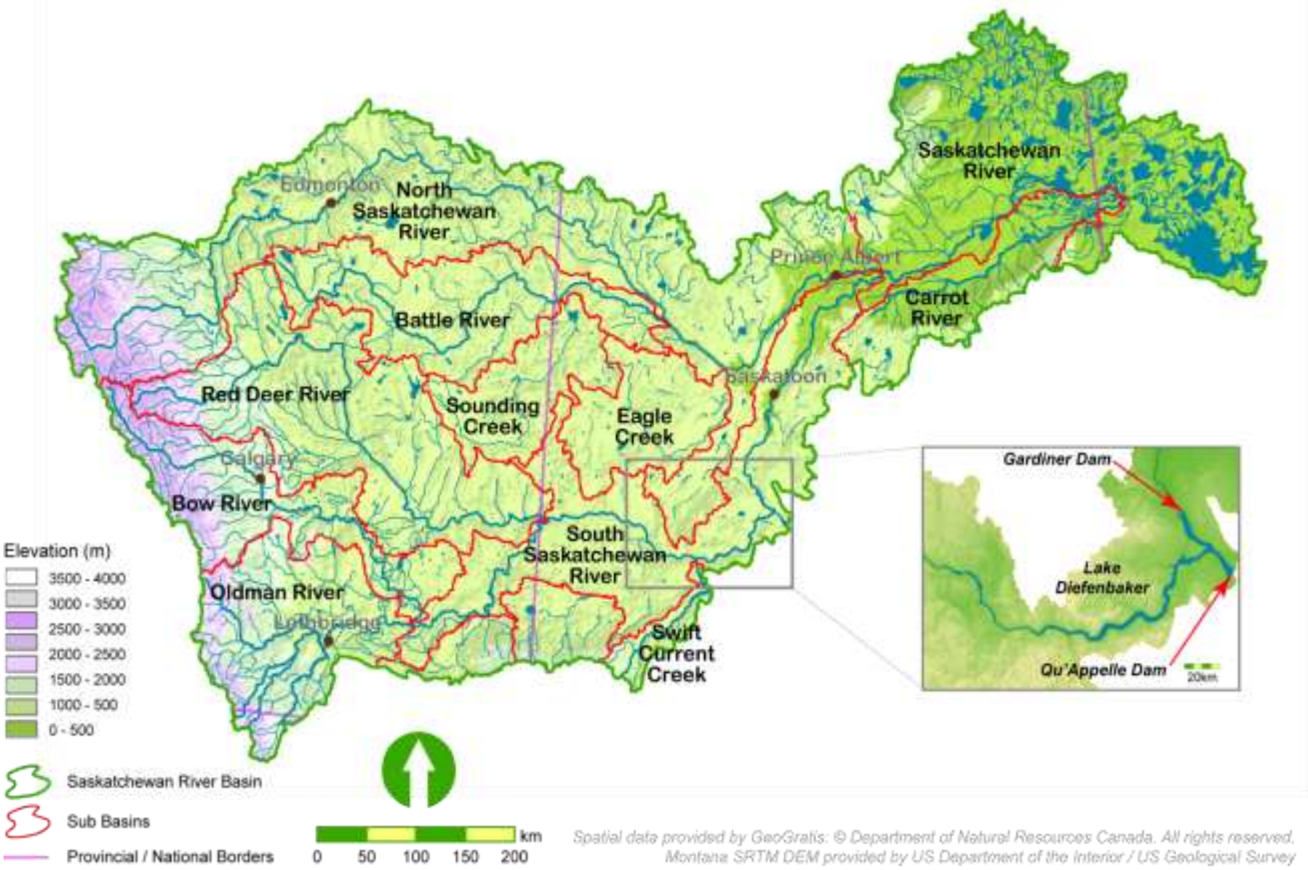
The scope of this study, as established by SWA, included a technical review of existing documentation and data held by SWA, interviews of SWA staff; interviews of external experts or other agencies with a participatory role, review of hydrometric and meteorological data in the Alberta portions of these watershed, as well as forecasting products available from Alberta Environment and Water. The study was confined geographically to the Saskatchewan River Basin in Saskatchewan from the Alberta to the Manitoba borders. The temporal focus of the study was specified as from August 1, 2010 through to July 31, 2011.

2 Events of 2010-2011

2.1 Setting and infrastructure

2.1.1 Basin description

The Saskatchewan River flows east from the continental divide at the crest of the Canadian Rocky Mountains across Alberta and Saskatchewan as the North and South Saskatchewan Rivers which join in Saskatchewan and as the Saskatchewan River flow into Cedar Lake in Manitoba and eventually contribute to the Nelson River which flows to Hudson Bay (Figure 1). The Saskatchewan River system is the fourth longest in North America and drains an area of about 336,900 km^2. The basin is dominated by high mountains covered with glaciers, alpine tundra and coniferous forests in the west, foothills of forest and rangeland just east of the mountains, prairie rangeland and agricultural land in the south and centre, and boreal forest in the north and east. The climate of the Saskatchewan River Basin is extremely continental and varies from a wet, cold mountain climate in the west to a semi-arid climate in the south-west and south-centre, and a sub-humid climate in the north and east. Snow and frozen ground dominate the climate for 4-6 months per year in the prairie and boreal zones and for 7-9 months per year in the mountains.



Spatial data provided by GeoGratis: © Department of Natural Resources Canada. All rights reserved. Montana SRTM DEM provided by US Department of the Interior / US Geological Survey

Figure 1. Saskatchewan River Basin and Lake Diefenbaker. The primary sub-basins, topography, hydrography and major cities of the Saskatchewan River Basin with an inset showing the detail of Lake Diefenbaker, Gardiner Dam on the South Saskatchewan River and the Qu'Appelle Dam linking to the Qu'Appelle River.

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 Canadian Rockies in Alberta with a small portion of the Oldman River draining from Montana. 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 early spring by the melting of snow on the prairies and during the late spring and early summer by snowmelt and rainfall in the mountains. Summer flows may be significant because of major rainstorms on the eastern slopes of the Rocky Mountains. 80% of annual river flow is generated in the Canadian Rocky mountains and foothills; taking typical headwater basin water balances as a guide then approximately 60% of this streamflow is derived from snowmelt, 38% from rainfall runoff and 2% from glacier wastage. Within Saskatchewan, the only significant tributary to the South Saskatchewan River is Swift Current Creek, which contributes less than 1% of the flow. Prairie runoff contributions are normally small because of the semi-arid climate, gentle topography and poorly connected post-glacial drainage system which results in large non-contributing areas. The discharge of the South Saskatchewan River is lowest during the winter months when it has a nearly continuous ice cover. Records from the Water Survey of Canada show that 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. From March to April, the mean monthly discharge increased rapidly to 397 m^3/s, 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 in June as a result of mountain snowmelt. Contrary to popular belief, the wastage of glacier ice in the Canadian Rockies has a minimal effect on the annual flow volume of the South Saskatchewan River entering Saskatchewan – the main effect of glacial melt is to sustain low flows during late summer in the driest years.

The North Saskatchewan River originates at the Saskatchewan Glacier in the Canadian Rocky Mountains. Its main tributary, the Battle River, however, originates in the aspen parkland region of central Alberta. There are no dams on the North Saskatchewan River in Saskatchewan. The North Saskatchewan River at Deer Creek, 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) during the ice-on period (Figure 4b). The monthly mean discharge increases rapidly from March (124 m^3/s) to April (286 m^3/s) due to prairie and parkland snowmelt, and peaks in July (404 m^3/s) as a result of mountain snowmelt. Again, the net effect of glacial ice accumulation and melt in the Rockies on the annual flow of the North Saskatchewan River in Saskatchewan is very small.

The Saskatchewan River is managed and consumed from its headwaters to the lower reaches. Major urban centres, including Calgary and Saskatoon, and numerous smaller communities, use the river for water resources with varying degrees of regulation. The South Saskatchewan River passes through areas of intensive agricultural production; the major consumptive use of water (some 86%) is for irrigation, mainly in Alberta, where the South Saskatchewan River is fully licensed, but also in Saskatchewan. Multipurpose reservoirs in and near the mountain and foothill headwaters store water for local water supply and hydropower. Natural flows of the South Saskatchewan River basin are calculated by Alberta Environment and Water for apportionment purposes from actual flows and take water withdrawal for water management, irrigation, domestic consumption and industrial use into account in adjustment of the actual flows. These natural flows (Fig. 2) show strong cycling between dry and wet periods with low flows in the 1930s, 1980s and early 2000s and high flows in the 1910s, 1920s, 1950s, 1990s and 2005. Though natural variability is high, a gradual decline in natural flows since observations began in the early 20th C is discernible suggesting a slow drying of the basin; this 92 year decline amounts to 12% or 1.2 billion $m^3\ year^{-1}$ drop from the early 20th C flows. Actual flows are calculated from the measured discharge of the South Saskatchewan and Red Deer rivers near their confluence upstream of Lake Diefenbaker and are only shown from 1970 onwards, but natural flows in the early 20th C approximate the actual flows and can be used for comparison. The decline of actual flows is much more severe than for natural flows, amounting to 40% or 4 billion m^3 $year^{-1}$ below the early 20th C flows. Of the decline in actual flows, approximately 70% is due to upstream consumption and 30% is due to changes in the hydrology (natural flows). Most of the hydrological change will have occurred in the mountain headwaters where land use change and abstractions are minimal and so is likely a manifestation of climate change. The climate change interpretation for reduced South Saskatchewan River flows is supported by Centre for Hydrology unpublished results from the Marmot Creek Research Basin MCRB in the Canadian Rockies headwaters of the Bow River. The upper elevations of Marmot Creek have experienced statistically significant warming since the early 1960s with the greatest increases in winter daily minimum air temperatures. This has resulted in an increase in the probability of rainfall and decrease in the probability of snowfall and a shift of precipitation phase of about 1 mm per year over the last 50 years. The warming, and shift in precipitation phase towards rainfall have resulted in decreases in June and July peak streamflow and May through October seasonal streamflow volume. Provisional modelling studies suggest that this is due to a decline in peak snowpack at high elevations, earlier snowmelt, and a longer snow-free season for evapotranspiration losses from the basin.

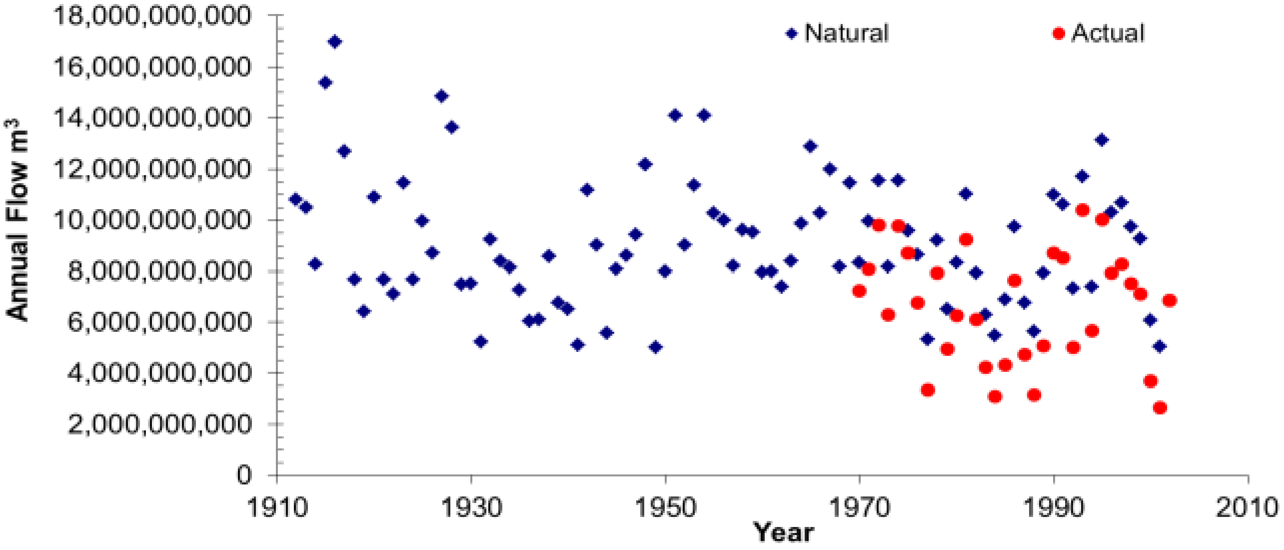


Figure 2. Natural flows and actual annual flows of the South Saskatchewan River draining into Lake Diefenbaker from 1912 to 2004.

Figure 3 shows the relative consumption of South Saskatchewan River water in Alberta from 1970 to 2004 calculated as the difference between natural and actual flows divided by natural flow. There appears to be an increase over time, but the highest relative consumption is associated with droughts in the 1980s and 2001 when both irrigation demand was high and mountain runoff was low. In no years was the consumption above the 50% guideline for water apportionment under the Prairie Provinces Water Apportionment agreement of 1969.

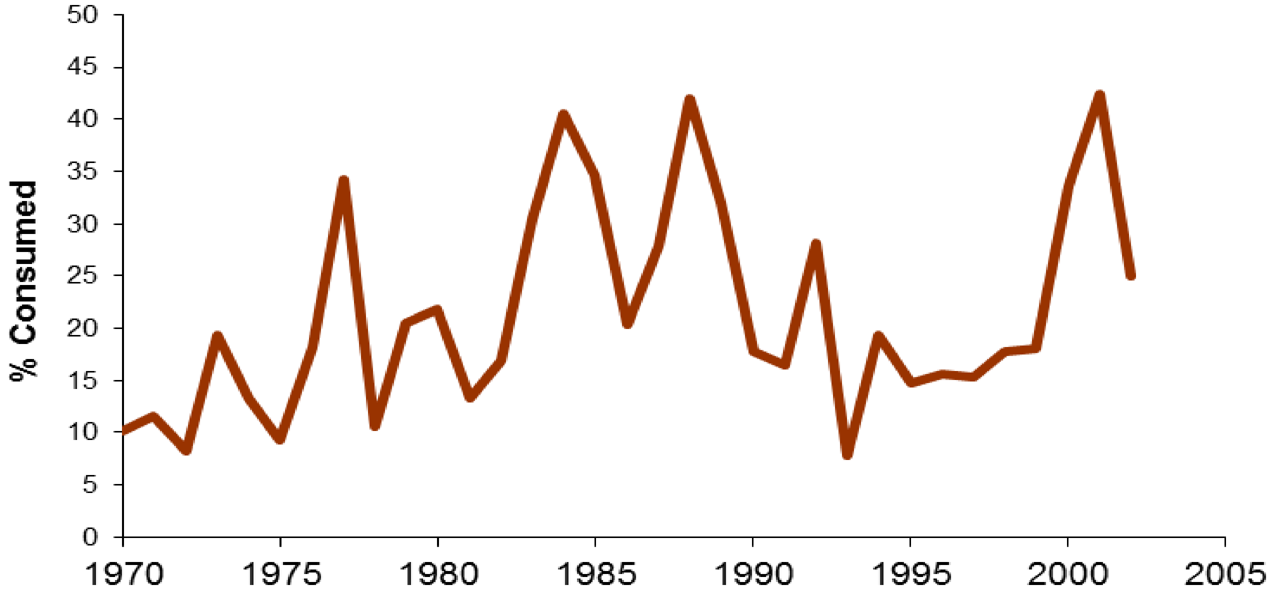


Figure 3. Relative consumption of the South Saskatchewan River upstream of Lake Diefenbaker from 1970-2004 calculated as the difference between natural and actual flows divided by natural flows.

2.1.2 Dam and reservoir

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 (Figure 1). Lake Diefenbaker is operated for irrigation water supply, hydroelectric power, some flood protection, shoreline habitat and recreation as well as to sustain minimum flows in the South Saskatchewan River and the Qu'Appelle River. Its primary mandate was to be a water supply reservoir with some hydroelectric generation potential; other benefits such as flood protection and ecosystem and recreation enhancement have been realised through an informal multiple objective management style.

Electricity is produced by hydroelectric stations at Coteau Creek (Gardiner Dam), and on the Saskatchewan River (E.B. Campbell and Nipawin), and flow through these stations managed by withdrawals from the reservoir. Currently, about 70% of the population of Saskatchewan obtains drinking water that is stored at some point in Lake Diefenbaker. Also, 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. The shoreline habitat of Lake Diefenbaker has become important for the Piping Plover, and so there is an attempt to stabilize changes in reservoir storage during nesting times in the spring and summer. At the maximum water level, the total storage in Lake Diefenbaker is 9.4 billion m^3, of which 4.3 billion m^3 is usable storage between the minimum and the maximum water levels during ordinary operating conditions. The Saskatoon Southeast Water Supply System 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, ultimately to the Lanigan area. 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 million m^3 $year^{-1}$ of water are delivered from Lake Diefenbaker.

Construction and subsequent operation of the Gardiner Dam has radically changed the downstream runoff regime of the South Saskatchewan River as shown in Figure 4. The operating principle is to fill the reservoir with high flows that are expected in spring and deplete this storage for various uses until it can be filled again the next spring. As a result, the seasonal variation in discharge is drastically reduced, and the monthly mean discharge at Saskatoon now (1967-1993 flows) peaks in January (301 m^3/s), with a secondary peak in July (220 m^3/s). The operation guidelines for the dam provide for a minimum flow through Saskatoon of 42.5 m^3/s, though higher minimum flows are preferred.

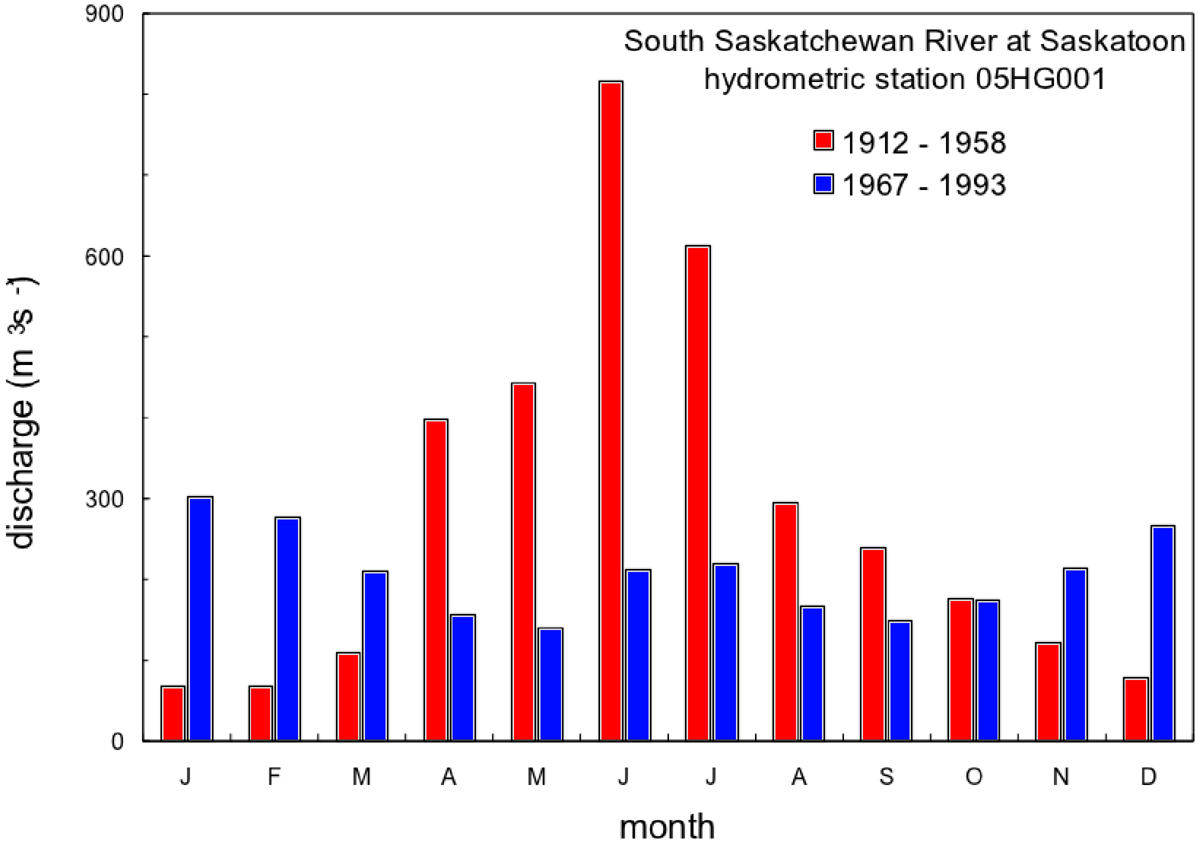


Figure 4. Gauged discharge of the South Saskatchewan River at Saskatoon, downstream of Gardiner Dam, before the dam (1912-1958) and after the dam (1967-1993). Adapted from Pomeroy et al., (2007).

2.1.3 Data and calculations

2.1.3.1 Accuracy and error in streamflow measurement

All measurements have inherent inaccuracy or error. Because streamflows are measured in nature from observations of stream depth that are converted to streamflow using the channel geometry and velocity (rating curve), the error is comparatively large compared to measurements made in laboratories. The magnitude of the error associated with a streamflow measurement depends on the type of measurement, and the conditions under which it was made.

Manual streamflow measurements are usually made by measuring the mean stream velocity at a number of equally-spaced segments at a river cross-section. The streamflow is estimated from the sum of the product of the water velocity and the cross-sectional area of each segment. The error of a manual gauging is affected by many factors including the state of the river channel, the equipment used and the weather, particularly the effects of ice. A good stream gauging is generally considered to be accurate to within about +/-5% (WMO, 2010). Therefore if a good stream gauging indicates a stream flow of 1000 m^3/s, the actual streamflow probably lies between 950 and 1050 m^3/s.

Automatic gauging stations measure a river’s stage, which is the elevation of the water surface above some datum. Streamflow is estimated from the stage measurements using a rating curve, which is determined from a series of manual measurements of velocity and stage. Because river stage is also affected by factors such as changes in the bed, weed growth, and ice, manual adjustments (“shifts”) of the rating curve are frequently required. Therefore, automatic streamflow measurements are inherently less accurate than the manual measurements from which they were derived.

The accuracy of automatic gauges is generally poorest for high streamflows when few measurements are available for constructing rating curves and when channel geometry may be uncertain. Extremely-high streamflows may even require the rating curve to be extrapolated beyond any existing measurements, which increases the error. High streamflows also cause erosion and deposition of sediment in and near the channel, causing further errors in rating curves.

In Canada, Environment Canada’s Water Survey of Canada (WSC) has responsibility for managing the network of gauging stations owned and operated by the Federal Government. The official streamflows computed by WSC meet WMO international standards and are generally considered to be as accurate as is possible, but require considerable time and effort to be determined. At the time of writing, official streamflows are available for the South Saskatchewan River at Saskatoon up to December 2010.

Unofficial real-time streamflows are also available from WSC. These values have not been subjected to the same rigorous quality control as the official data. Because of corrections and changes to the rating curves over time, near real-time streamflows may change from day to day. Because rating curve changes are applied backward in time after they are identified, previously-published streamflow data may also be changed, which is potentially confusing to users. As Alberta Environment and Water does its own Quality Assurance / Quality Control (QA/QC) of data, streamflow values published by Alberta Environment may differ from the WSC real-time data.

SWA needs to improve its communication of the uncertainties of hydrometric data to the public. The current disclaimer on the Sask Flood website (which is very similar to the disclaimer on the WSC website) primarily refers to legal issues:

> ***Disclaimer***
>
> *Users should use the information on this website with caution and do so at their own risk. The Saskatchewan Watershed Authority and the Government of Saskatchewan accepts no liability for the accuracy, availability, suitability, reliability, usability, completeness or timeliness of the data or graphical depictions rendered from the data.*
>
> *This data is preliminary and has been transmitted automatically with limited or no verification and review for quality assurance. Subsequent quality assurance and verification procedures may result in differences between what is currently displayed and what will become the official record.*
>
> *It is the responsibility of all persons who use this site to independently confirm the accuracy of the data, information, or results obtained through its use.*

The Saskatchewan Watershed Authority or the Government of Saskatchewan does not warrant the quality, accuracy, or completeness of any information, data or product from these web pages. It is provided 'AS IS' without warranty or condition of any nature. The Saskatchewan Watershed Authority and the Government of Saskatchewan disclaims all other warranties, either expressed or implied, including but not limited to implied warranties of merchantability and fitness for a particular purpose, with respect to the information, data, product or accompanying materials retrieved from this web site. In no event will the Saskatchewan Watershed Authority or the Government of Saskatchewan or their employees, servants or agents have any obligation to the user for any reason including claims arising from contract or tort, or for loss of revenue or profit, or for indirect, special, incidental or consequential damages arising from the use of this information.

Because the issues affecting streamflow measurements are largely insoluble, it is important that they be also communicated to the public. It is recommended that the issues should be mentioned in the SWA website data disclaimer. As both Alberta Environment and Water, and Environment Canada are currently providing sub-hourly flows on their websites, it is recommended that SWA also begin publishing sub-daily (at least hourly) streamflows as quickly as possible.

2.1.3.2 Routing procedures

As a wave of high streamflow progresses downstream, the value of the peak of the wave is reduced, and the amplitude (width) of the wave stretches in time. This process is illustrated by the plots of the flows of the North Saskatchewan River between Deer Creek and Prince Albert, in Appendix 1. The downstream translation and transformation of the high flow wave is known as routing and its estimation is a standard component of all hydrological models. Flow routing can be estimated by a number of methods including the Muskingum, sum of reservoirs and the kinematic wave methods, all of which can simulate the dependence of the travel time, and the flood wave peak and amplitude on the streamflows.

Currently, all routing is done manually by SWA staff using simple spreadsheets where daily mean values of the upstream flows are shifted in time, to allow for the time of travel between stations. There are several problems with this approach:

1. Most importantly, use of spreadsheets for routine calculations is slow, and error-prone in that a single typo or inadvertent mouse movement can easily damage the formula.
2. Although it is useful for the reservoir stage-storage calculations, the daily time step is very coarse for routing. Significant changes in flow can occur over a day, and the time of travel between river sites is rarely an integer number of days. It is better to route shorter-term (e.g. hourly) flows, which can be aggregated to provide daily values as required.
3. The current method of routing is simply to lag the upstream values by a fixed time step. Because the time lag in this method is not related to the streamflow, as it is in nature, the times of flows are invariably in error. Furthermore, this type of routing does not incorporate the downstream attenuation of the flood wave.

In this study, the only streamflow “routing” done is simply the shifting the flows by a fixed number of days.

2.1.3.3 Calculation of inflows

Inflows to a reservoir cannot be measured directly, only estimated by routing flows gauged upstream or as a residual from measurements of discharge and storage. By conservation of mass,

$$I - O = \Delta S \tag{1}$$

Where,

I = mass of inflow to the reservoir,

O = mass of outflow (discharge) from the reservoir, and

ΔS = change in mass of storage of the reservoir.

As the density of water is fairly constant, Equation 1 is generally assumed to apply for volumes of water.

Thus

$$I=O+\Delta S \quad , \tag{2}$$

allowing inflows to the reservoir to be computed as a the sum of the change in storage and the calculated discharge over some period of time. Being a residual, the computed inflow includes all of the errors in its components. Because the area of the reservoir is very large, the uncertainty in the reservoir elevation strongly affects the uncertainty of the storage. The precision of measurement of the reservoir elevation is approximately 1 mm, or 432,000 m^3 at FSL, which can be a large fraction of the net change in storage over a short period of time.

As the reservoir elevation is only measured at a single location, the uncertainty of inflows is increased over short periods by waves and by surges due to winds, which can result in the estimated inflows fluctuating wildly, even becoming negative, over short periods of time. Figure 5 shows that the use of residual inflows results in exaggerated fluctuations in the estimates of inflows to the reservoir on 17 and 18 June.

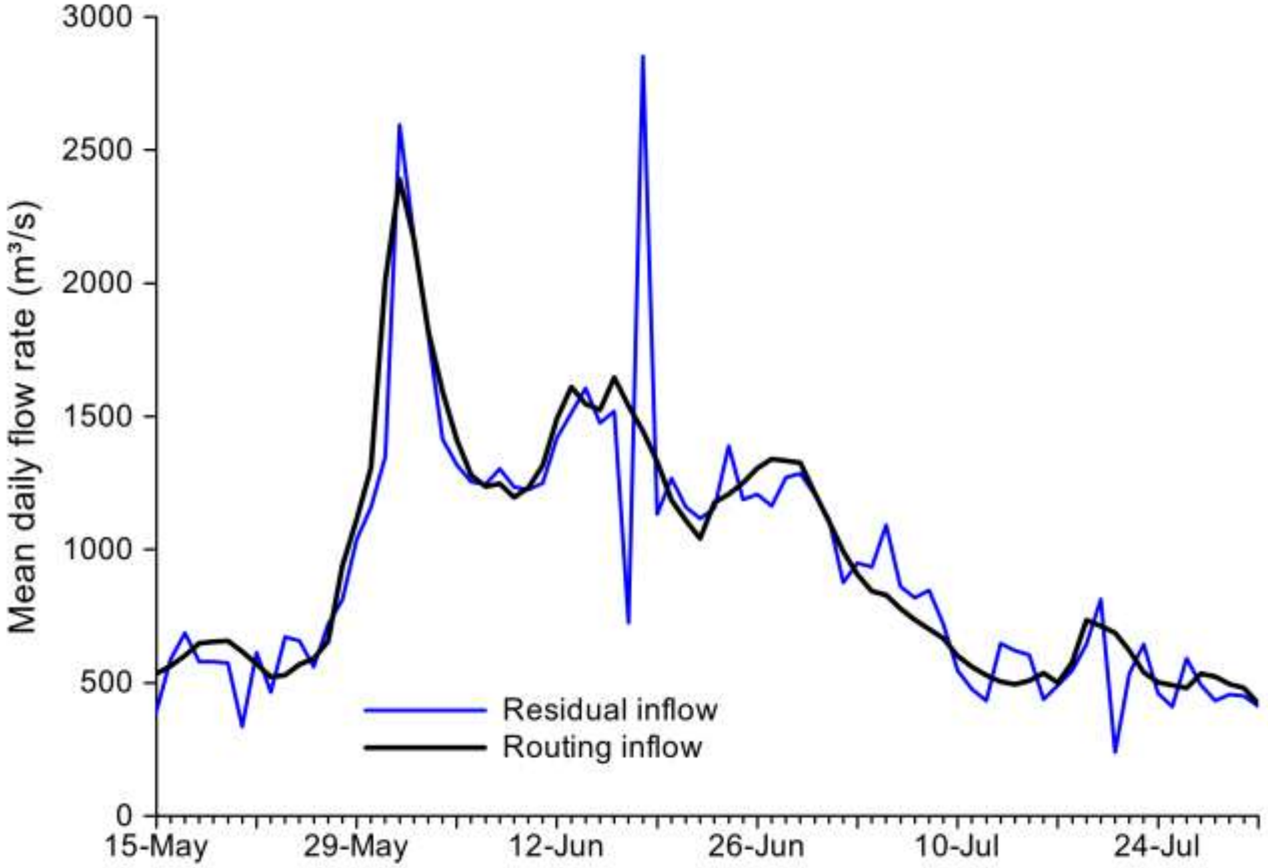


Figure 5. Inflows to Lake Diefenbaker calculated as a residual from outflows and changes in storage, and by routing upstream streamflows over the period May 15 - July 30, 2011.

As shown in Figure 6, the wind speed was high during this period. Importantly, there was an abrupt change in wind direction from the North-East to the South-West beginning 04:00 on June 18. Because the main axis of the reservoir is oriented from South-West to North-East, the initial wind direction caused water to be shifted toward the upstream end of the reservoir, reducing the apparent inflow on June 17. The reversal in wind direction on June 18, caused water to surge downstream toward the dam, thus causing the apparent increase in inflows.

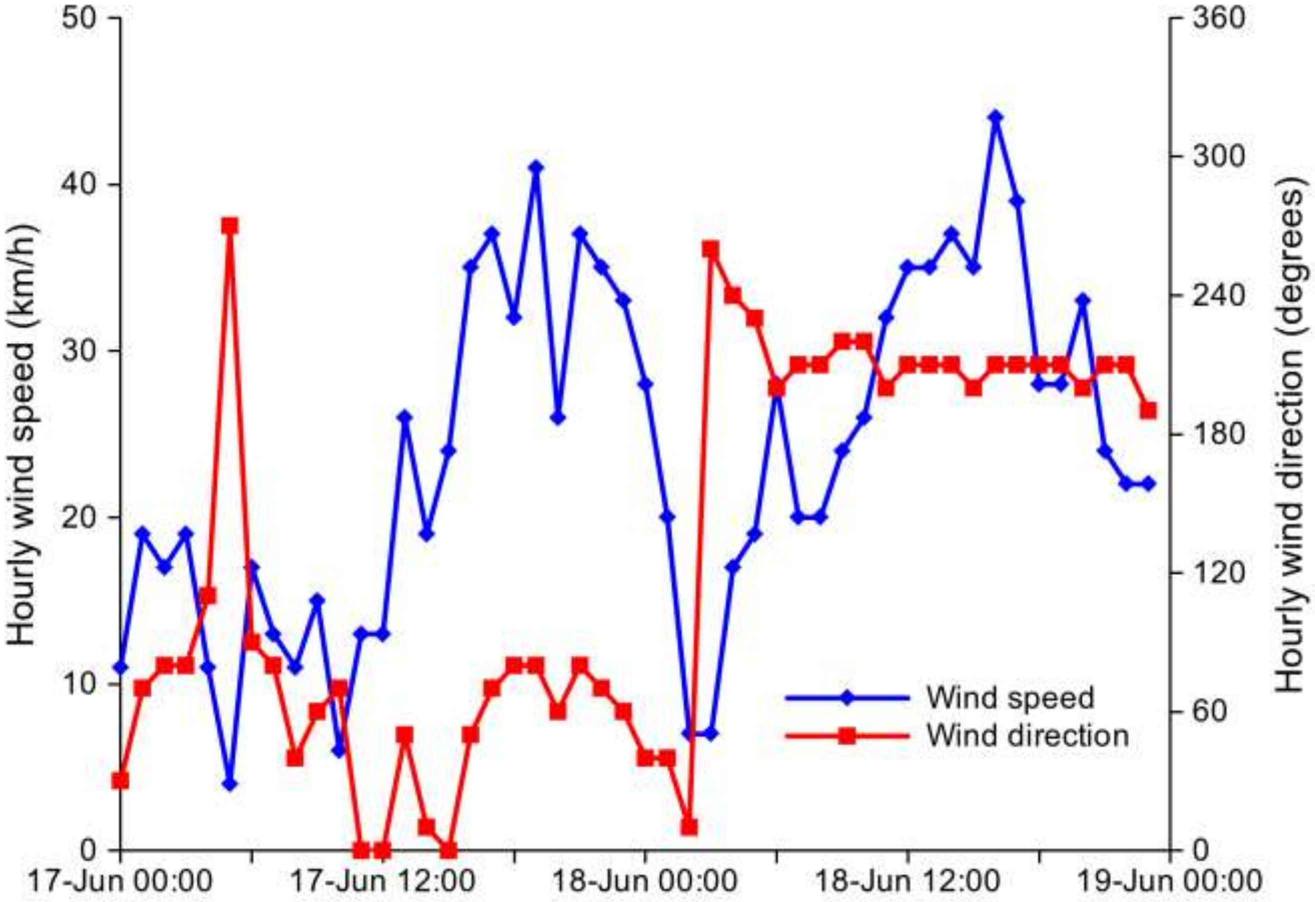


Figure 6. Wind speed and direction at Elbow MSC station, 17-19 June 2011.

Role of ungauged inflows

The previous section shows that there are substantial ungauged and undergauged areas contributing to Lake Diefenbaker. The existence of ungauged (local) inflows is of concern as local inflows cause the reservoir to fill more rapidly than would be anticipated from routed upstream flows. The ungauged region contributing to Lake Diefenbaker is mostly prairie, with some contribution from the Cypress Hills. In the prairie drainage of Lake Diefenbaker, rainfall events rarely produce significant runoff as

a) the region is semi-arid with evapotranspiration generally exceeding rainfall,
b) soils are deep, with considerable capacity to absorb rainfall,
c) slopes are generally mild, and
d) any runoff is generally trapped in the thousands of temporary depressional storages and wetlands (sloughs) present in prairie basins.

Most runoff in the prairies is due to snowmelt, which releases the accumulated winter snowcover over a short period of time. As prairie soils are generally frozen in the spring, the amount of water infiltrating to the soil is reduced, which increases the fraction of melt water running off. The heavy precipitation during the summer and fall of 2010 caused the soils of the region to be very wet before freeze-up, which further reduced the infiltration of melt water in the spring, in many cases completely restricting infiltration. Heavy snowfall was redistributed by wind into channels, depressions and wetlands where it could more easily form runoff when melting. The wet conditions also filled the wetlands, which remained full over the winter and therefore increased the probability that they would overflow and transmit flow to Lake Diefenbaker.

The magnitude of the local inflows was estimated as the difference between the routed upstream flows and the estimated inflows computed as the residual difference between the discharges and change in storage. The routed inflows were those of the South Saskatchewan River at Medicine Hat and the Red Deer River at Bindloss together with the unrouted flows of Swift Current creek near Leiden. The gross areas of the contributing tributaries are listed in Table 1.

During the spring inflow event, the estimated daily local inflows peaked at nearly 600 m^3/s, as shown in Figure 7. The shape of the local inflow hydrograph generally resembles that of Swift Current Creek near Leinen, which is responsible for some of the local inflows, confirming that the overall shape of the hydrograph is probably accurate.

The drainage area of Swift Current Creek near Leinen is largely representative of the ungauged area between the gauges at Medicine Hat and Bindloss and the Dam. Although it is partially controlled, there is still a large region between Reed Lake and gauge which is subject to local inflows, as is shown by the diurnal response of the gauge to snowmelt. Furthermore, the plot of Swift Current Creek below Rock Creek, in the upper part of the basin, which is uncontrolled, shows exactly the same types of response as the lower part. As much of the management of the reservoir occurs in May, the April flows are largely unaffected.

It is concluded that the 2011 spring local inflow was a significant contribution to the April inflow to Lake Diefenbaker. The large magnitudes of the local inflows constitute an unusual event, which has probably not been seen since the large snowpacks of 1974.

Table 1: Areas of major tributaries contributing to Lake Diefenbaker

WSC Code	Station	Gross Basin Area km^2
05CK004	Red Deer at Bindloss	47849
05AJ001	South Saskatchewan at Medicine Hat	56369
05HF003	Lake Diefenbaker at Gardiner Dam	136000
05HD039	Swift Current Creek near Leinen	3730
	Ungauged Local Area	31782
	Reservoir area at FSL	432
	Gross area of Swift Current Creek near Leinen as fraction of ungauged	12%

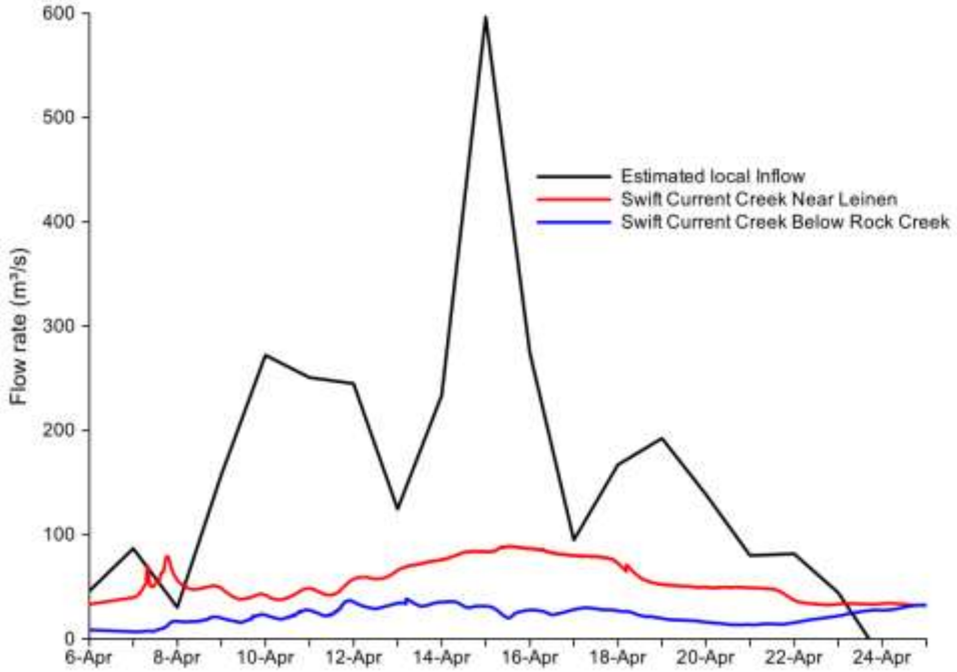


Figure 7. Estimated local inflow (as difference between routed upstream flows and residual inflows) and Swift Current Creek near Leinen and below Rock Creek.

During the summer inflow events, local inflows appear to have been very small, judging from the similarity of the routing and residual inflows plotted in Figure 5.

Evaporation and direct precipitation

As discussed previously, the change in storage of 1 mm of added or removed water at FSL is approximately 432,000 m³, which over one day is equivalent to a flow of 5 m³/s. Ignoring the reduction in contributing area due to the reservoir being below FSL, the contribution of direct precipitation is negligible, as is shown by the plot of inflows calculated with and without direct precipitation in Figure 8.

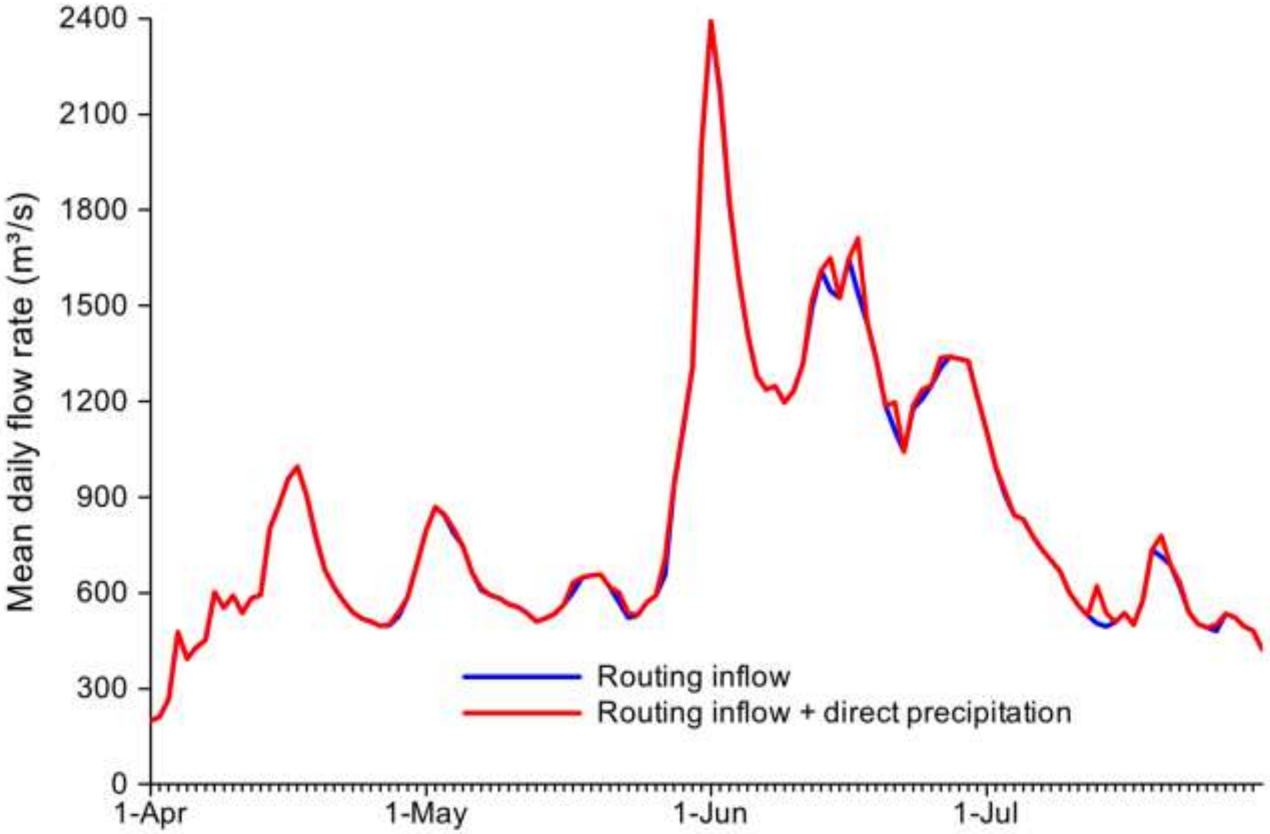


Figure 8. Inflows to reservoir during summer high flow events computed from routing upstream flows and by the addition of direct precipitation with reservoir area set to FSL area. Direct precipitation estimated from the Elbow, Saskatchewan MSC station.

Lake Diefenbaker open water evaporation was estimated using the Meyer evaporation formula for April, May and June using measured temperature and humidity from Elbow, SK, climatological normal wind speed and coefficients recommended for the region by PFRA (2002). Open water evaporation rates varied from 1.47 mm day^{-1} in April to 3.4 mm day^{-1} in May and slightly lower values in June. Although these are not insignificant values, their maximum effect in reducing inflows was 17 m^3/s, which is of little importance given the inflow magnitudes ranging from 600 to 2400 m^3/s during the period of interest. Therefore, the effects of evaporation and direct precipitation on inflows, lake levels and downstream routing are not included in this study.

2.1.3.4 Discharges

During the 2011 high flows, there are differences between the sum of the discharges from Lake Diefenbaker (determined by SWA and Sask Power) and the flows of the South Saskatchewan River at Saskatoon, which are determined by the gauging station near the weir operated by the Water Survey of Canada. The differences between the two sets of measurement, which are shown by their plots in Figure 12, are surprisingly large.

.

As plotted in Figure 9, the difference between dam outflows and measured flows at Saskatoon have also seen during the previous high flow events. The deviation of the Saskatoon gauged flows from the time-shifted Gardiner Dam discharges appears to be roughly linear, and therefore proportional to the flow. It is assumed that the differences in the magnitudes of the flows are not caused by ungauged local inflows. Ungauged local inflows vary substantially from year to year and their magnitude would not be expected to increase with SSR streamflow, as local inflows are generated by snowmelt over frozen soils in early spring and SSR streamflows tend to peak in June. In June runoff generation from the SSR valley is minimal because of unsaturated sandy soils with high infiltration capacities.

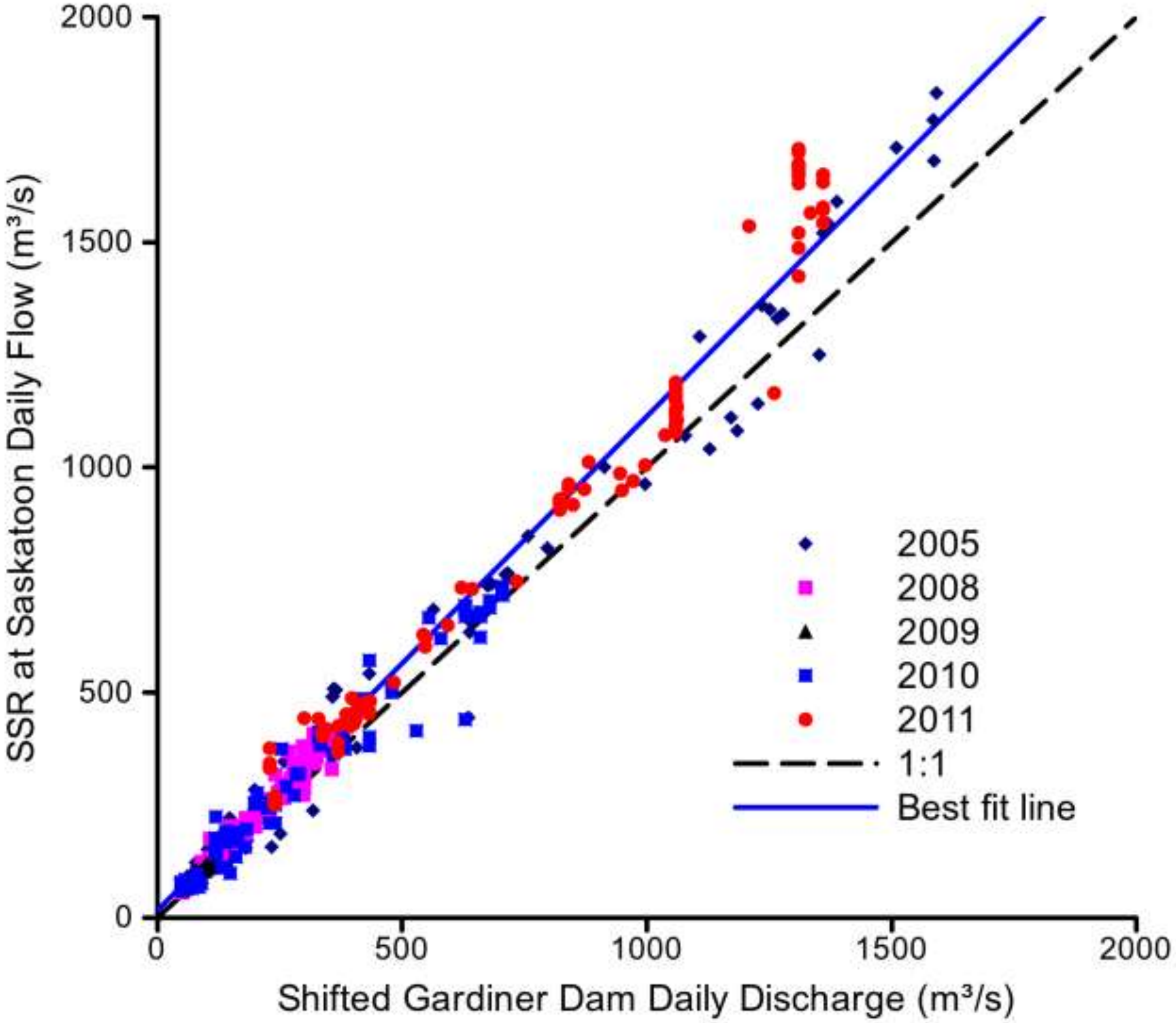
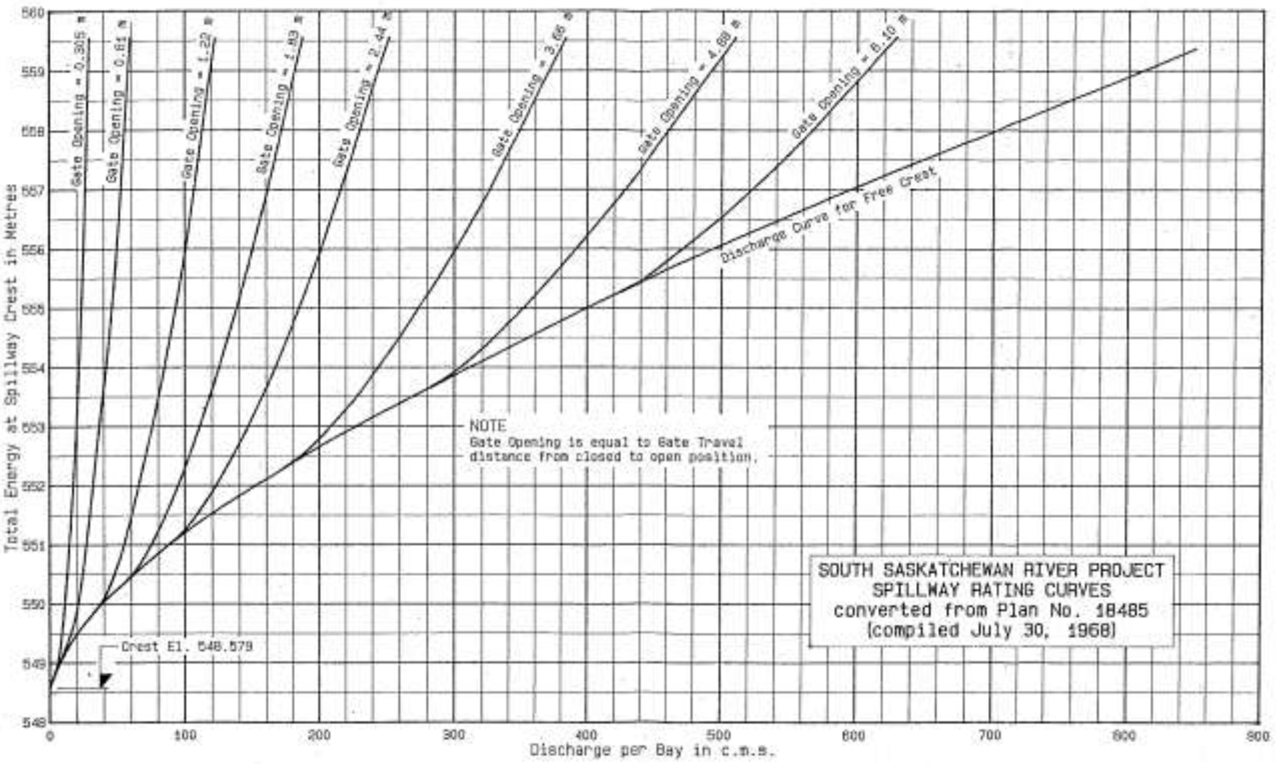


Figure 9. Mean daily flow of South Saskatchewan River and discharges from Gardiner Dam shifted by one day. The best fit line (computed by a linear least-squares fit) and the 1:1 (equal value) line are also plotted.

The method of flow calculation used by SWA staff is one likely cause of the differences between the sets of measurements. During the periods when the spillway is in use, the spillway gates are set to achieve a desired flow, and the discharge is assumed to remain constant until the gate settings are changed. However, as the reservoir elevation (head above gates) changes, the discharge through the gates must also change. The relationships between reservoir elevation and discharge are plotted for several gate openings in Figure 10.



NOTE
Gate Opening is equal to Gate Travel
distance from closed to open position.

SOUTH SASKATCHEWAN RIVER PROJECT
SPILLWAY RATING CURVES
converted from Plan No. 18485
(compiled July 30, 1968)

Figure 10. Rating curve of Gardiner Dam spillway (from SWA).

The effects of variation in head on the spillway gates were tested by fitting second-order polynomial equations to the gate-discharge plots, and then fitting linear regressions to the constants of the polynomials against the gate opening. Using the linear regressions, discharges were computed from the recorded spillway gate elevations and reservoir elevations. As plotted in Figure 11, the revised spillway discharges are generally very similar to the original SWA values. However, the increased outflow due to increased head over the period of June 1 – 7 explains the increase in flows at Saskatoon seen during this period. Although the effects of head changes were generally small, there will probably be increased demand in the future for accurate outflow data over increasingly-short time scales, and it is recommended to plan now for incorporating the effects of head in outflows published in the future.

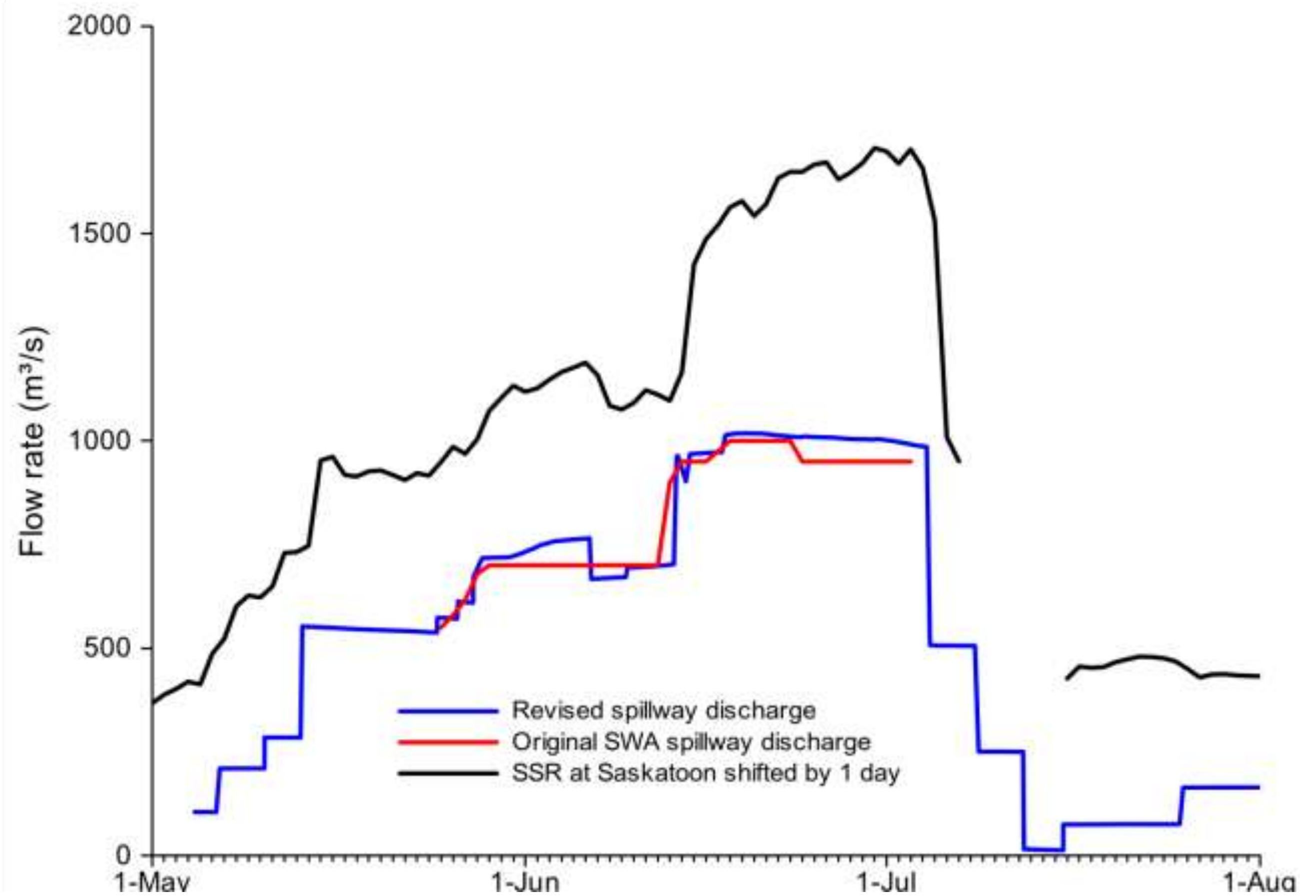


Figure 11. Original (SWA) spillway discharges, revised spillway discharges based on gate adjustments and rating curve, and streamflow of South Saskatchewan River at Saskatoon.

WSC manual gaugings

Adjustment of the spillway discharges does not explain most of the observed differences between the Lake Diefenbaker discharges and the Saskatoon streamflows. During the high flows in the summer of 2011, staff of the Water Survey of Canada manually measured streamflows on the South Saskatchewan River at Saskatoon and downstream of Gardiner Dam, as listed in Table 2. The manual and automatically gauged streamflows are plotted in Figure 12.

WMO standards assume the error for good and poor quality gaugings to be approximately 5% and 8%, respectively. The difference between the June 20 spillway discharge (1000 m³/s) and the WSC gauging (1090 m³/s) is approximately 8%. If the head-adjusted spillway discharge (1018 m³/s) is used, the difference decreases to 7%. On the same day, the manual gauging below the confluence of the spillway and the powerhouse was 1570 m³/s. On this date, the sum of the spillway and powerhouse outflows was estimated to be 1360 m³/s. The difference between the manual gauging and the dam estimates is more than 13%, which is far greater than would be expected for a manual gauging. The increase in relative difference caused by adding the powerhouse outflows indicates that their estimated values are very doubtful.

Streamflow on the South Saskatchewan River at Saskatoon was measured manually on June 9 at 1040 m³/s. Although many of the values from the automatic gauge are unavailable for this day, the automatically gauged streamflow at 02:35 was 1080 m³/s, which is a difference of less than 4% from the manual measurement. The June 21 streamflow at Saskatoon was manually measured by WSC at 1571 m³/s, which was essentially the same as the previous day's manual measurement downstream of the dam and powerhouse of 1570 m³/s and suggests excellent consistency between manual measurements by WSC.

Weather records indicate good conditions for streamflow gauging at these times. According to Environment Canada, on June 9, the maximum and minimum air temperatures recorded at the Saskatoon RCS station (Climate ID 4057165) were 22.2 and 7.9 °C, respectively. No precipitation was recorded. At 10:00 (the closest record to the time of gauging) the wind speed was 17 km/h. On June 20, the Elbow CS station (Climate ID 4022359) showed maximum and minimum air temperatures of 23.6 and 9.9 °C, respectively. There was no precipitation recorded and the wind speeds at 14:00 and 15:00 were 9 and 7 km/h. There were no weather-related reasons why the manual WSC streamflow gaugings would not have been good and the internal consistency between gaugings also suggests minimal uncertainties in these measurements.

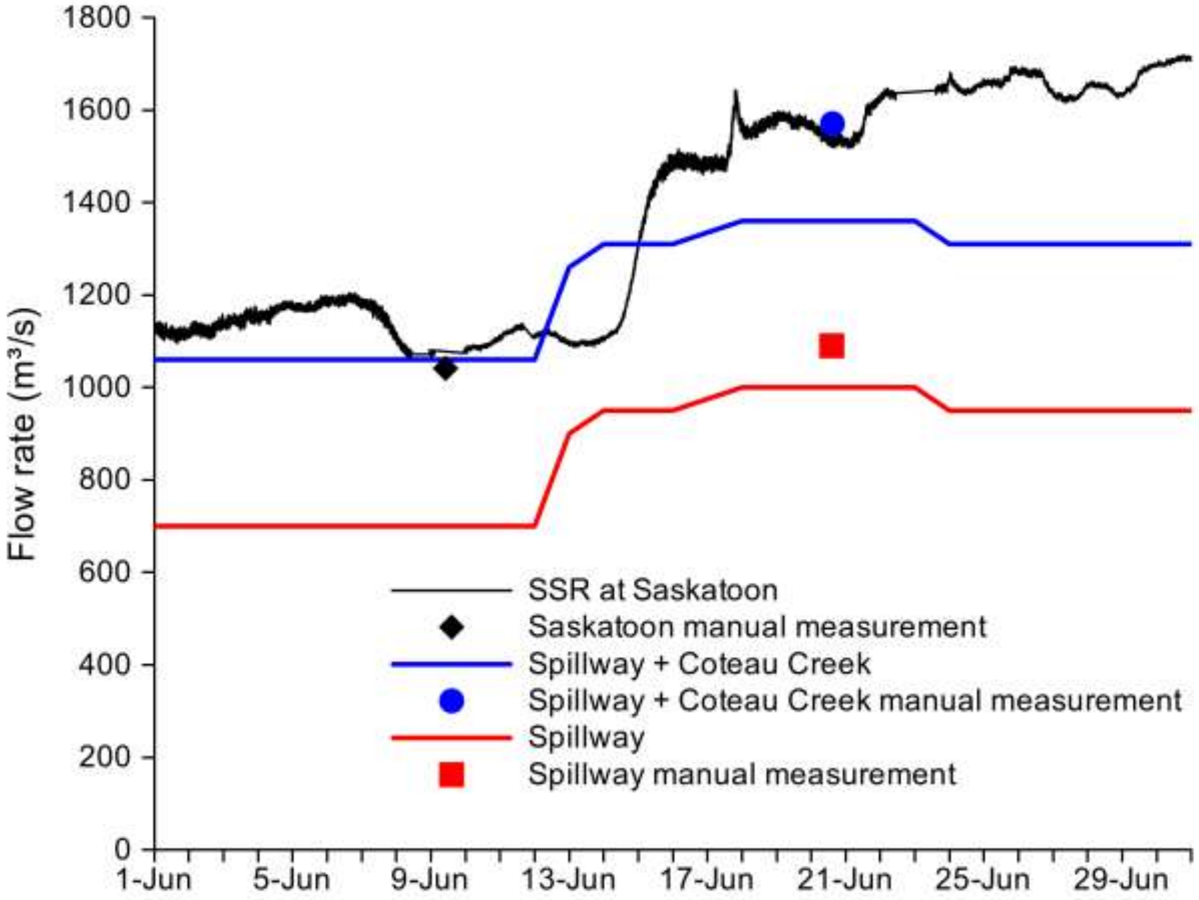


Figure 12. Manual measurements (points) and gauged flows (lines) of the South Saskatchewan River at Saskatoon, at the confluence of the spillway and Coteau Creek, and downstream of the spillway.

Table 2: Manual gaugings of South Saskatchewan River downstream of Gardiner Dam, by Water Survey of Canada (WSC).

Location	Date and Time	Flowrate (m³/s)
Gardiner Dam Flood Spillway, approximately 1.2 km below bottom of spillway	June 20, 2011 14:20	1090
South Sask River below confluence of Gardiner Dam Flood Spillway, approximately 1.1 km below Coteau Creek Hydroelectric Station.	June 20, 2011 15:07	1570
South Saskatchewan River at Saskatoon	June 9, 2011 10:15	1040

Local inflows

The possibility of local inflows causing the differences between the outflows estimated at the dam and the flows measured at Saskatoon was investigated. As described previously, it is rare for prairie rain events to cause significant runoff, except for intense convective storms of hundreds of mm of rainfall - the type which hit Vanguard, Saskatchewan on July 3, 2000. The soils between the dam and Saskatoon are very sandy, which causes rainfall to infiltrate rather than running off. Much of the basin consists of stabilized sand dunes from which overland flow is virtually impossible.

To test for local inflows, streamflows at the Moon Lake gauge between Saskatoon and Lake Diefenbaker were compared to those at Saskatoon and the outflow from the reservoir. SWA operates a river stage station at Moon Lake that is not part of the WSC network. A rating curve does not currently exist for the site, which is subject to a rapidly shifting sand bed. As an alternative, SWA staff created a rating curve for the 2005 flood event from the Moon Lake stage measurements and shifted flow measurements for the South Saskatchewan River at Saskatoon. Figure 13 plots the flow of the South Saskatchewan River estimated from the Moon Lake stage measurements of 2011 and the rating curve derived from 2005, along with the flows determined from the Saskatoon gauge and the sum of the spillway and Coteau Creek discharges. Despite uncertainty in the rating curve due to bed movement, the estimated Moon Lake flows strongly resemble the Saskatoon measurements, suggesting minimal local inflows between Moon Lake and Saskatoon.

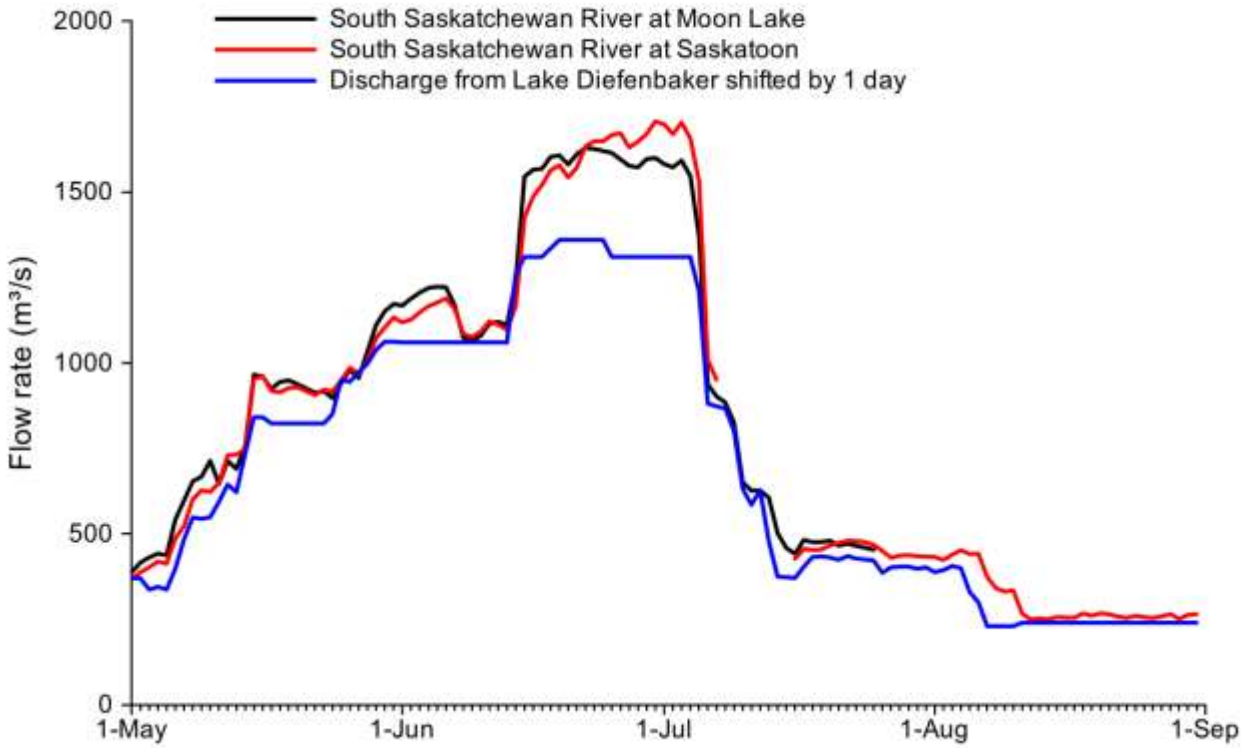


Figure 13. Streamflow of the South Saskatchewan River at Moon Lake in 2011, estimated from 2005 rating curve, the South Saskatchewan River at Saskatoon, and outflows from Gardiner Dam shifted by 1 day.

Summary

The preceding calculations and discussion demonstrate that

1. The manual streamflow gaugings of the South Saskatchewan River downstream of the reservoir are believed to be within the WMO standards of error for good gaugings.
2. The discharges from the spillway computed from its rating curve appear to be slightly smaller than gauged, but are within the WMO standards for poor-quality gaugings.
3. The discharges reported by the Coteau Creek power station are dubious.
4. The automatically gauged flows at Saskatoon were within the WMO standards for manual gauging, when measured directly, and
5. Ungauged local inflows between Gardiner Dam and Saskatoon are not responsible for the discrepancies between the dam’s estimated discharges and the flows gauged in Saskatoon.

Therefore, the automatically gauged flows of the South Saskatchewan River at Saskatoon, during the summer of 2011, are believed to be more accurate than streamflows estimated by lagging discharges from Gardner Dam. This is particularly true for high streamflow events such as developed in late June and early July 2011.

2.2 Reservoir operational objectives

The typical sequence of annual operation is shown by the mean and median reservoir elevations plotted in Figure 14. The sequence over the water year can be defined by several periods.

1. The reservoir generally reaches its greatest elevation in around September 1.
2. Over the late fall to early winter the reservoir elevation declines slowly.
3. Beginning in January, the reservoir elevation decreases rapidly as water is used for electrical generation.
4. The annual minimum generally occurs in March or April and is followed by the melt of the prairie snow pack.
5. June rains in Alberta, along with rapid melt of the high mountain snow pack, cause the reservoir to rise.

The elevation targets that the dam managers try to reach during the summer are listed in Table 2, and are also plotted on Figure 14. These are understood to be targets, not requirements for reservoir operation. The irrigation target and the Elbow Harbour target in May are minimum reservoir levels and the Piping Plover and optimal recreation targets on July 1st are maximum reservoir levels. Whilst the irrigation minimum is exceeded in most years, the Elbow Harbour target is not and the maximums for Piping Plover and recreation are exceeded on the target date about ½ of the time and more frequently later in the summer.

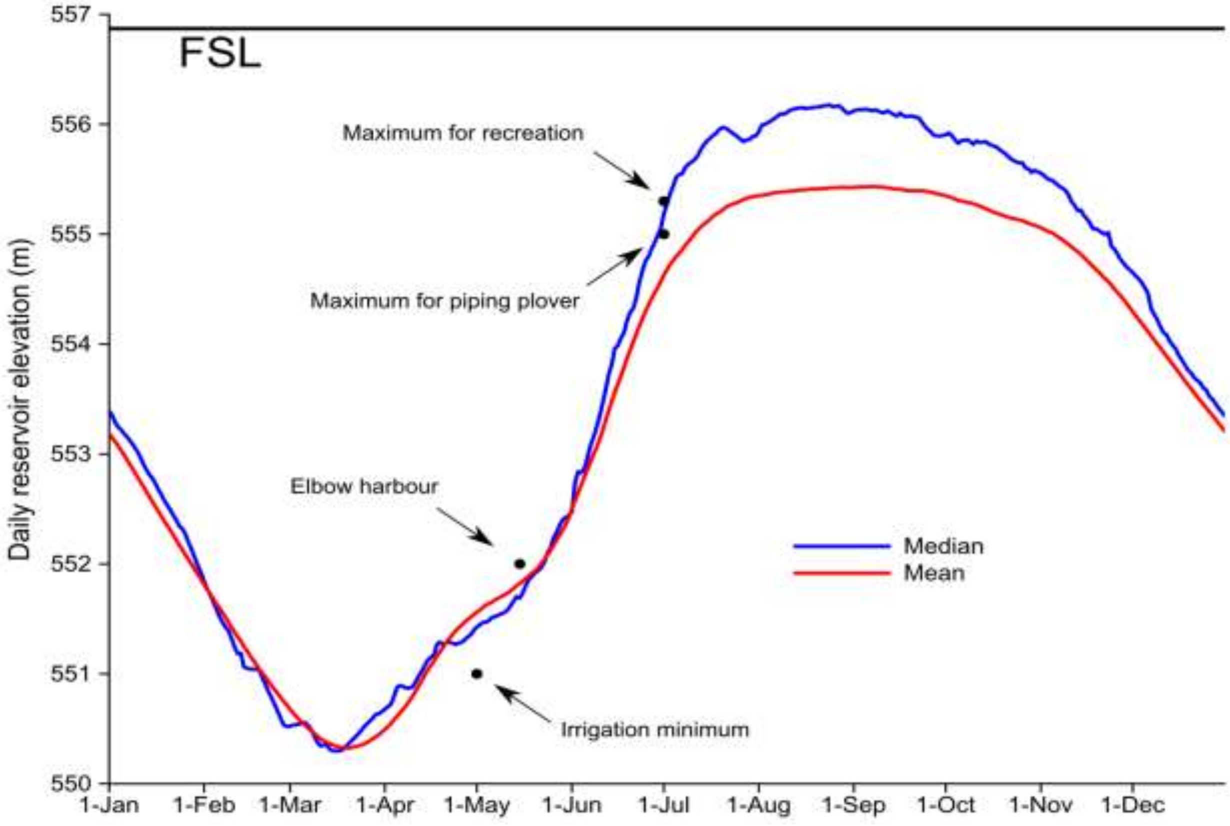


Figure 14. Curves of the mean and median values of the Lake Diefenbaker daily elevation (m). Data from Environment Canada. The plotted points represent typical annual target elevations of the operators of Lake Diefenbaker. Data supplied by SWA.

Table 3: Lake Diefenbaker target elevations

Date	Elevation	Reason
May 1	551.0 m	Minimum acceptable for irrigation users
May 15	552.0 m	Required by Elbow harbor to launch boats
July 1	555.0 to 555.3	Optimal for recreation use
July 1	555.3	Maximum for piping plover. Intended to be achieved on 70% of years

2.2.1 Trends in reservoir elevations

The minimum and maximum reservoir elevations for each year of operation are plotted in Figure 15. The annual maxima display no apparent trend according to a Mann Kendall test (5% significance), although the inability of the reservoir to be filled during droughts, such as in the 1980s and 2001, is apparent. The annual minima display a strong linear trend (Mann-Kendall test, 5% significance), and the best-fit line shows an increase of more than 3 m in the annual minima over the period of 1969-2011.

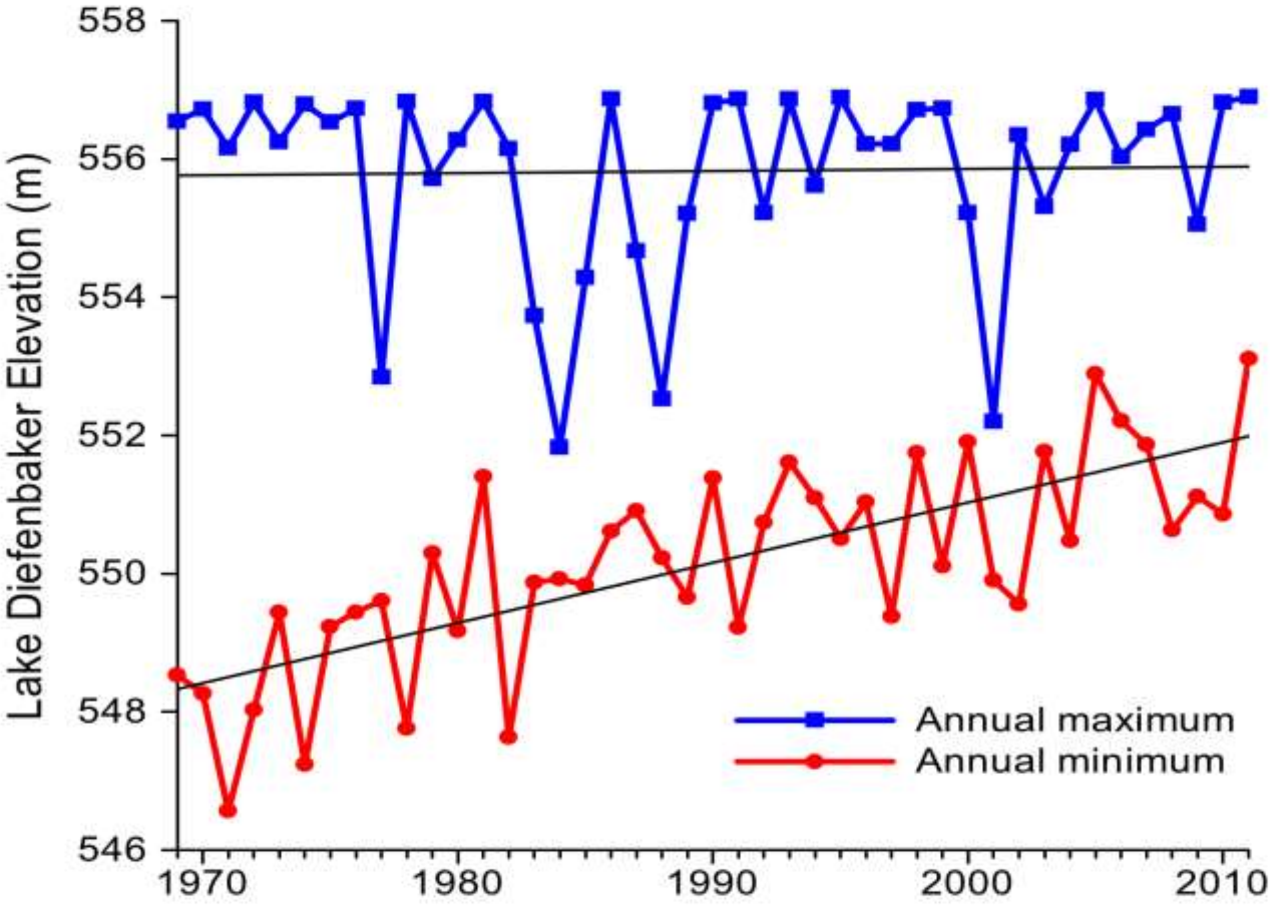
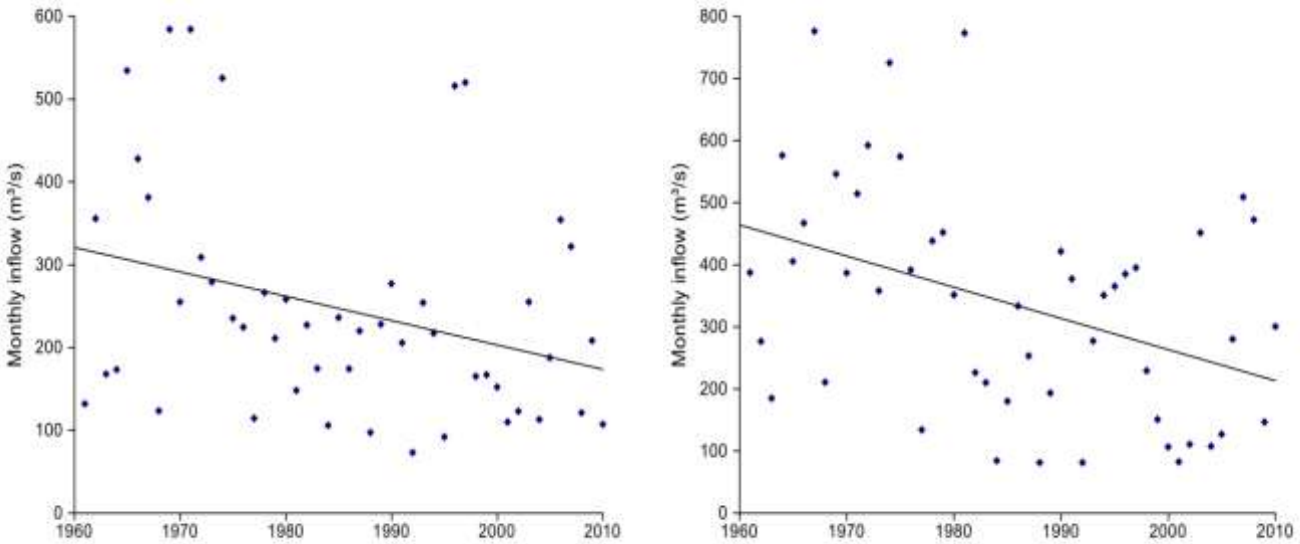


Figure 15. Annual minimum and maximum elevations of Lake Diefenbaker, 1969-2011. Trend lines fitted by least-squares.

The observed trend in the minimum reservoir elevation may be due to trends in inflows, discharges or both. Although, the annual streamflow volumes on the South Saskatchewan River at Medicine Hat have been demonstrated to show strong linear declines over the past century (St Jacques et al., 2010), and the sum of actual flows of the South Saskatchewan River at Medicine Hat and the Red Deer River at Bindloss show a 40% decline over the 20th C, there is no significant trend in inflows to the reservoir over the Lake Diefenbaker period 1961-2010, at either the 5% or 10% levels of significance. It is possible that this is due to the influence of flows from the Red Deer River which currently have very little consumptive use and, being further north than the Bow and Oldman Rivers, may be less subject to reduction in streamflow from climate warming than the more southerly tributaries. For instance, Marmot Creek, which is typical of unregulated front range headwaters feeding the Bow River, has a statistically significant decline in streamflow of 13% from 1962-2007, with the most severe the decline occurring in the month of June. Overall, reductions in naturalized mountain streamflow associated with climate change have been estimated to be less severe or even reversed at higher latitudes in North America (Callaghan et al., 2011). So it is possible that the latitudinal range of the South Saskatchewan River averages out differing climate change signals to result in insignificant trends in annual streamflow volume.

Not only the annual streamflow volumes, but trends in seasonal streamflows must be examined to determine reasons for rising minimum reservoir elevations in Lake Diefenbaker. Monthly inflows were estimated by simply summing the monthly flows of the South Saskatchewan River at Medicine Hat and the Red Deer River at Bindloss. As plotted in Figure 16, the April and May computed inflows to Lake Diefenbaker show statistically-significant trends (Mann-Kendall, 5%) of declining flows over the period 1961-2010. Flows at the end of the period are roughly half of what they were in 1960. The November and December flows show significant (Mann-Kendall, 5%) increasing trends, but the magnitudes of these monthly flows are very small.



a) April inflows b) May inflows

Figure 16. Estimated inflows to Lake Diefenbaker calculated from sum of monthly flows of South Saskatchewan River at Medicine Hat and Red Deer River at Bindloss for a) April and b) May. Lines represent least-squares linear models.

The declining trends in April and May streamflows are partly due to the filling of reservoirs upstream of Lake Diefenbaker in Alberta and may be partly due to climate change. The Bow River at Banff is an excellent example of a natural mountain river with a record from 1910; it shows a statistically significant decrease in annual flow of 11.5% over the last century that is magnified in summer, for instance August flows have dropped 24.5%, but there is not a significant change in April, May and June flows. Marmot Creek streamflows are down substantially in June, but much less in April and May. As shown in Figure 17, the reservoir of the Oldman River dam, which has the greatest maximum storage capacity of all reservoirs in southern Alberta generally begins filling in April and May, contributing to reduced downstream flows during the peak inflow period from this river. More study is required to determine how the filling of upstream reservoirs and changes in the timing and volume of streamflow from the Canadian Rockies interact to cause the dramatic decline in April and May flows to Lake Diefenbaker from Alberta.

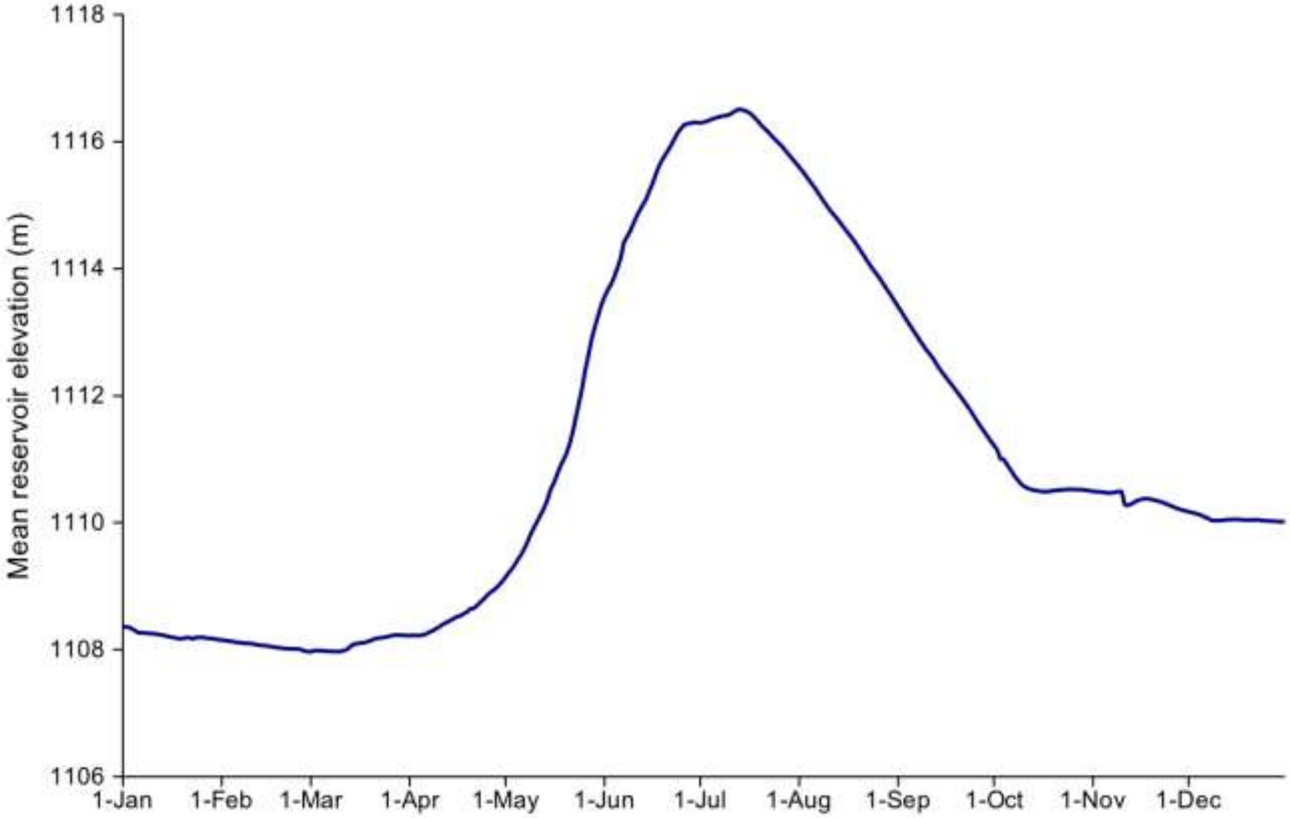


Figure 17. Oldman reservoir mean elevation by day of year, 1992-2009, showing typical filling from April through June.

Peak Inflows

Daily inflows to the reservoir were estimated by lagging and summing the daily streamflows of the South Saskatchewan River at Medicine Hat and the Red Deer River at Bindloss. Over the period of record (1965-2010) the annual peak inflow magnitudes show no significant trends, according to a Mann-Kendall test at the 5% significance level. Neither is there a trend in the day of the year at which the peak inflow occurs. Studies in one of the unmanaged Bow River headwater basins, Marmot Creek, showed no trend in the timing of peak streamflow from 1962 to the present, despite a decrease in peak streamflow and June streamflow. Again, flows from the more northerly Red Deer River may be overwhelming changes in the streamflow coming from the Bow River

2.3 Sequence of events

This summary of the hydrological events is subject to all of the previous caveats concerning measurement errors.

2.3.1 Summer 2010 – Winter 2010/2011

Precipitation

The summer of 2010 was marked by generally heavy precipitation throughout the South Saskatchewan basin upstream of Lake Diefenbaker, particularly in the prairie region, as shown in Figure 18. It is notable that much of the heaviest precipitation (more than 200% of normal) was found immediately adjacent to the South Saskatchewan River immediately upstream of Lake Diefenbaker, and in the Cypress Hills. The greater-than-normal summer precipitation extended into the headwaters of the Oldman River.

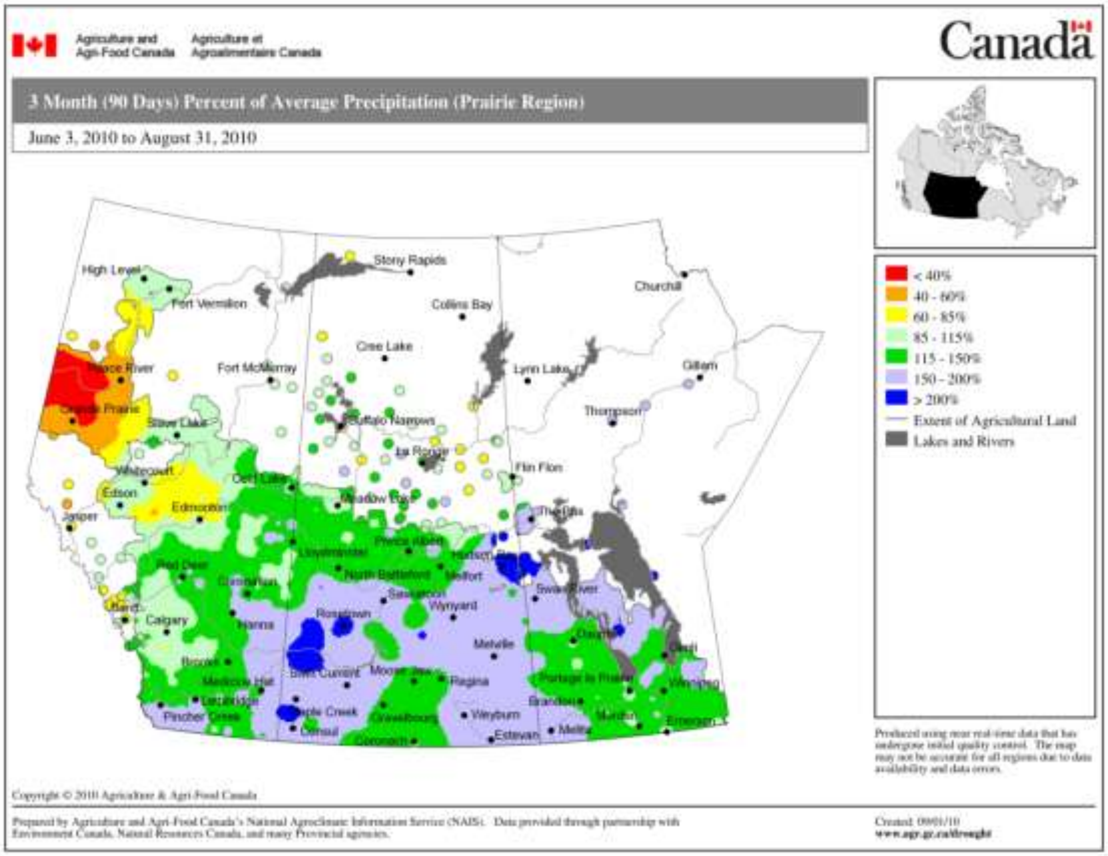


Figure 18. Total precipitation as a percentage of normal for the Canadian prairies between June 3 and August 31, 2010. Figure from Agriculture and Agri-Food Canada, http://www4.agr.gc.ca.

The heavy summer precipitation resulted in widespread agricultural flooding, due to saturated soils and filled wetlands. Figure 19 shows that the fall precipitation was also particularly heavy in the Swift Current Creek Basin, heavy around Lake Diefenbaker and in the mountain and foothill headwaters of the Oldman and Bow Rivers. As described above, heavy rains in the fall can contribute to increased spring runoff by saturating soils. When fall rainfalls occur on frozen soils, there is a tendency for ice layers to form at the soil/snow interface which are preserved over the winter and result in very high runoff efficiencies in the subsequent spring snowmelt period.

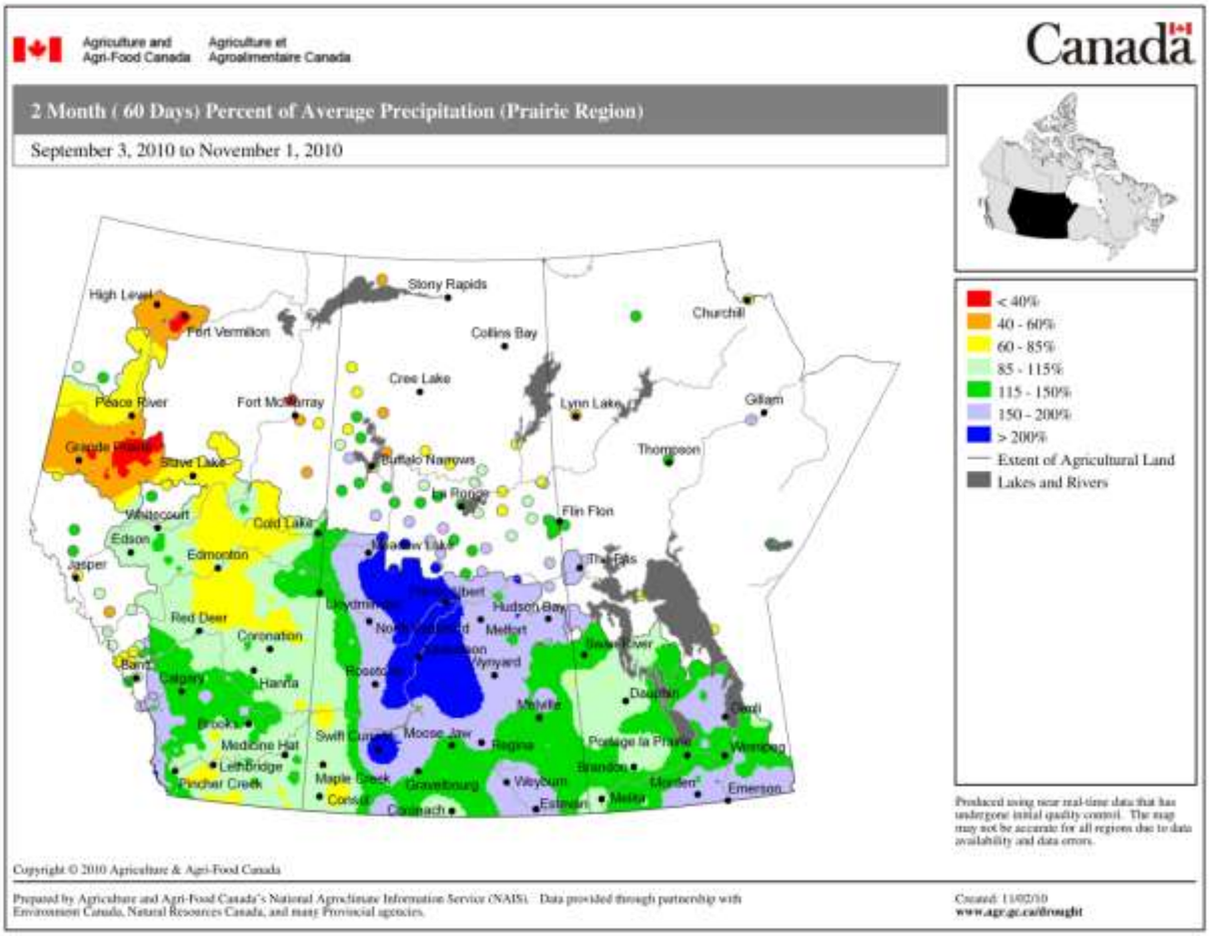


Figure 19. Total precipitation as a percentage of average for the Canadian prairies between September 3 and November 1, 2010. Figure from Agriculture and Agri-Food Canada, http://www4.agr.gc.ca.

Snow surveys

Tributary basin snow accumulation was below normal in the Bow and Red Deer river basins until March and then increasingly above normal from March onwards. Snow accumulation in the Oldman River Basin was above normal all winter. This is demonstrated by Figure 20, which plots the mean monthly snow accumulation over the winter of 2011, as determined by Alberta Environment's snow surveys. The values are plotted as non-exceedence probabilities, which are the probability of a value not being exceeded by historical values. For example, the mean non-exceedence probability of the

December 2010 snow surveys in the Oldman basin was approximately 60%, indicating that approximately 60% of the historical values for December were at or below the values of 2010.

By April, the mountain snow courses were almost all above average with one station over 200% of average. By May, six snow courses were more than 200% of average accumulation with the Many Glacier snow pillow in the Montana portion of the Oldman basin being over 500% of normal.

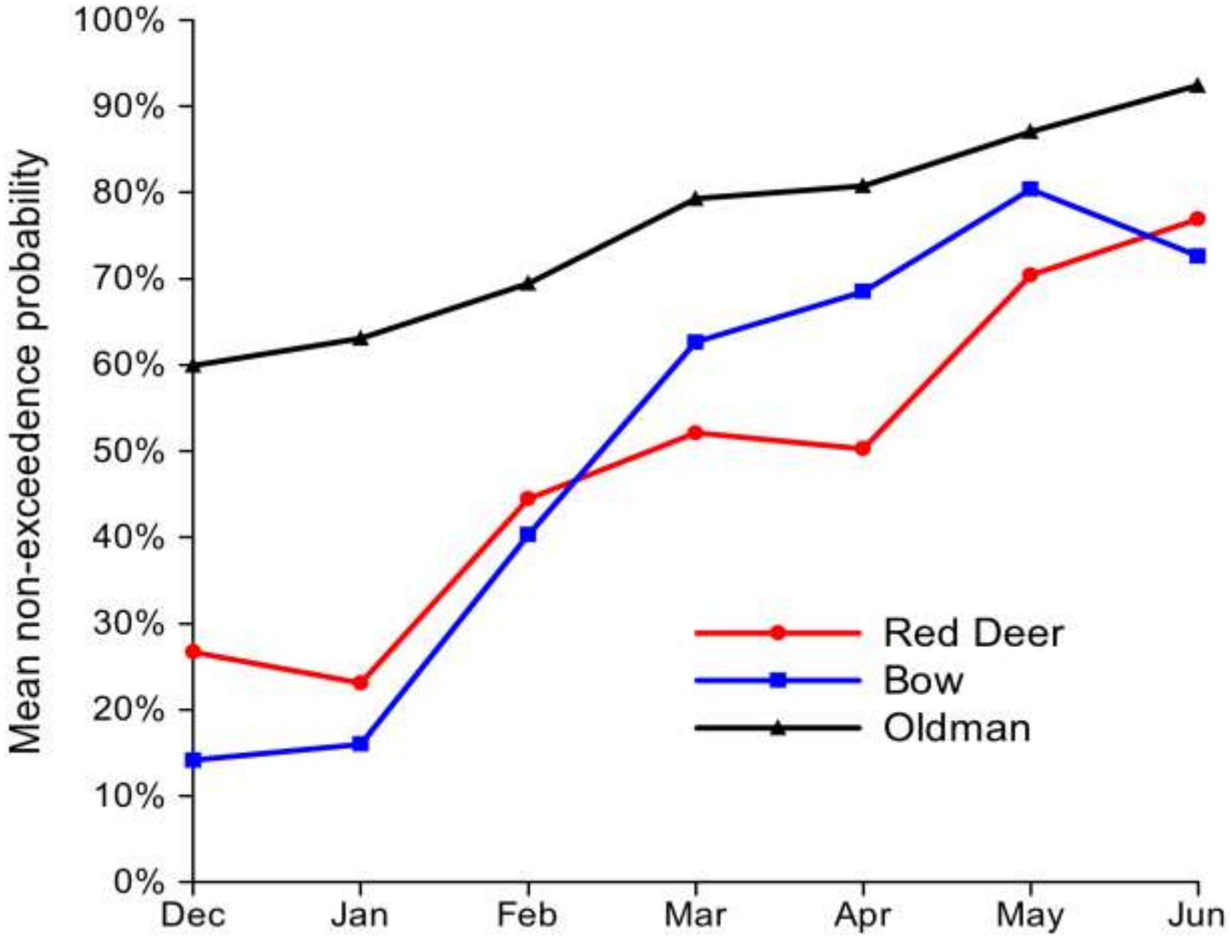


Figure 20. Mean non-exceedence probabilities of the snow surveys in the headwaters of the Oldman, Bow and Red Deer Rivers. Mean values were computed for each month by basin by simple averaging. All data were obtained from the Alberta Environment web site *http://www.environment.alberta.ca/forecasting/WaterSupply/index.html*.

Because air temperatures and solar radiation are higher in the south in spring, the melt of snow in Montana and Alberta tends to proceed from south to north. Therefore, the relatively heavier accumulations of snow in most southerly extent of the upper Oldman basin were an indication of the possibility for the peak snowmelt runoff to occur relatively early and for its magnitude to be large.

Alberta plains snowpacks

In the Red Deer River Basin, Alberta Environment has snow surveys in the forested foothills (James River and Sundre) as well as at more typically prairie locations. Forest snowmelt proceeds much more slowly than does open prairie snowmelt (Pomeroy and Granger, 1997). Because these foothill sites are located well upstream of the Saskatchewan border and melt more slowly than prairie snowpacks, they snowpacks should be included in the "mountain" runoff estimates, rather than the local prairie inflows. The mean non-exceedence probabilities of the Red Deer River Basin plains snowpacks excluding the foothills sites in March and April were 82% and 90%, respectively. Only 1974 had consistently deeper prairie snowpacks than did the spring of 2011 in the Coronation region, which drains into the North Saskatchewan River, but is indicative of the east central region bordering on Saskatchewan. Exceptionally high snowpacks were recorded in the Cypress Hills with average April accumulation of 254 mm SWE – these were the deepest spring snow accumulations recorded in 30 years of snow surveys in the Cypress Hills.

3.2.2 Spring 2011

The large spring inflow event began on approximately April 1 and continued until approximately April 26. Figure 21 plots the daily inflows calculated by SWA as a residual (i.e. based on measurements of discharge and change in storage) and computed by routing streamflows reported by the Water Survey of Canada of the Red Deer River at Bindloss and the South Saskatchewan River at Medicine Hat. The poor agreement between the two methods of estimating inflows is largely due to the existence of gaps in the WSC data, and shows the difficulty of using WSC data early in the season. The inflows estimated using routed Red Deer and South Saskatchewan streamflows provided by Alberta Environment summed with WSC streamflow values for Smith Current Creek near Leiden are also plotted. Because the Alberta Environment data are subjected to daily manual QA/QC, they have fewer gaps than the unofficial WSC data. The difference between the inflows computed as residuals and the inflows computed from the Alberta Environment data is believed to be primarily due to local ungauged inflows between the gauging stations and the reservoir.

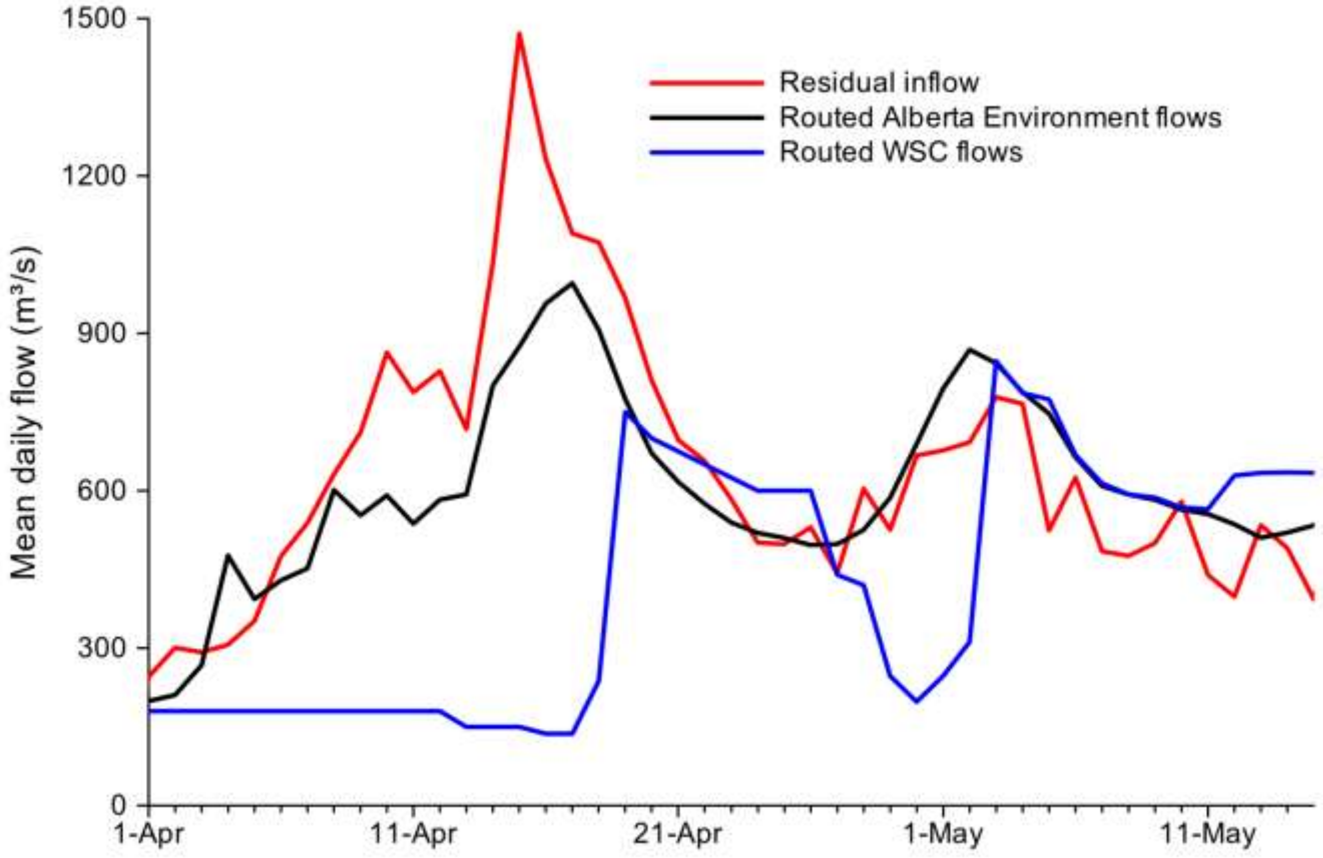


Figure 21. Spring 2011 inflows to Lake Diefenbaker calculated as a residual, from routed WSC data, and from routed Alberta Environment data. Flows of Smith Current Creek near Leiden from WSC were added to the flows of the Red Deer River at Bindloss and the South Saskatchewan River at Medicine Hat obtained from Alberta Environment.

The dearth of precipitation occurring in the South Saskatchewan River basin, except in the mountains and foothills, during the period April 5 to 11 is shown in Figure 22.

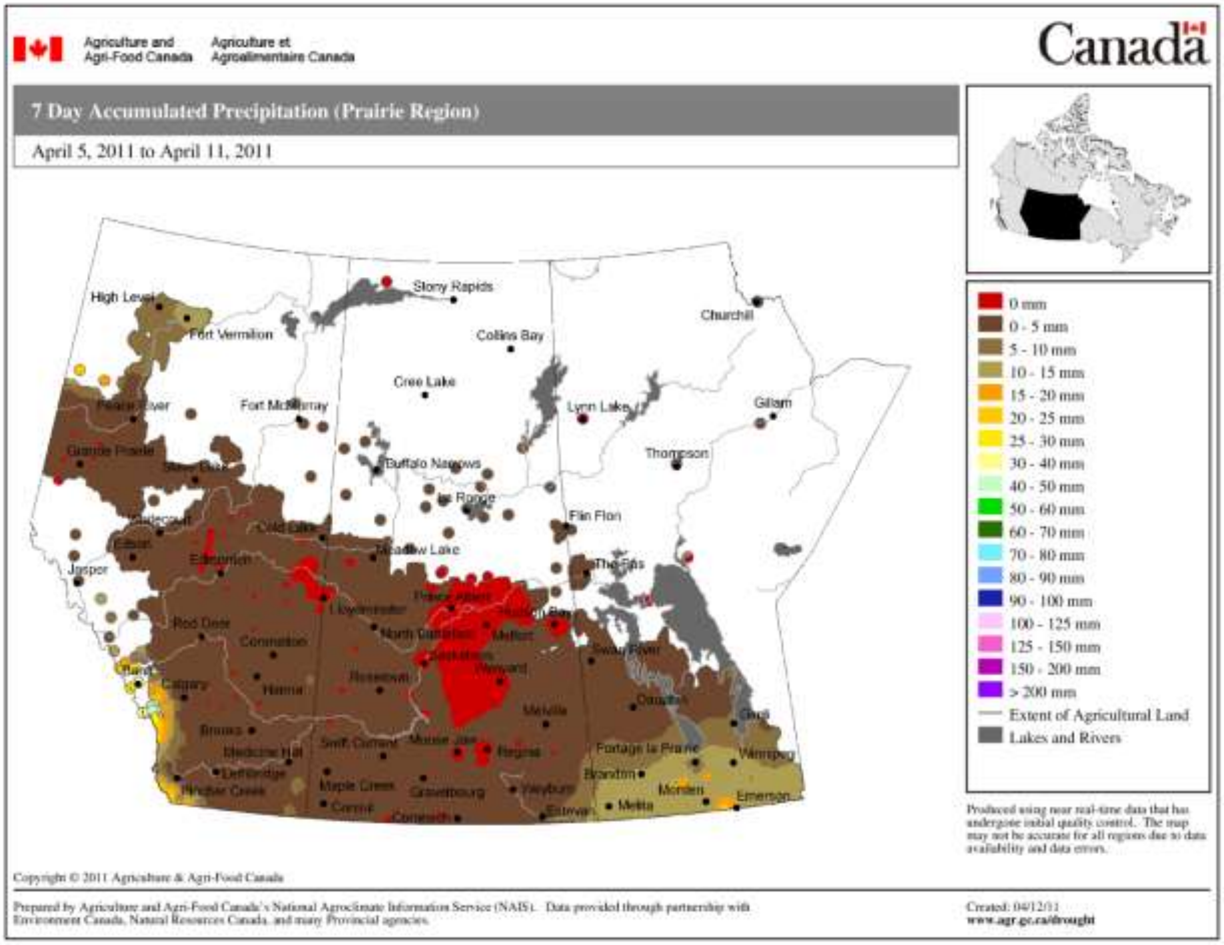


Figure 22. Accumulated precipitation April 5 to 11, 2011.

The spring inflow event had several sub-peaks, as is typical for events primarily driven by snow melt. Figure 23 plots the daily minimum and maximum air temperatures for Medicine Hat, which is located within the region contributing spring snow melt runoff. Because snowmelt in the Canadian Prairies is typically driven by solar radiation (Pomeroy et al., 1998), incoming shortwave solar radiation was estimated from the daily minimum and maximum air temperatures using the method of (Annandale et al., 2002) as described by (Shook and Pomeroy, 2011). Large snowmelt rates occur when the daily incoming shortwave radiation flux is high, and when overnight air temperatures are above zero (preventing the snowpack from refreezing). Warm daily maximum air temperatures also assist with the melt but are generally less important. Conditions were favourable for snowmelt in the first two weeks of April, with the best conditions at Medicine Hat occurring on April 11. The inflow rate to Lake Diefenbaker increased from 1 April onwards peaking on April 15. There was notable precipitation in south-western Alberta (40 mm at Lethbridge), particularly in the Oldman and Bow river basins between the April 12 and 18, as plotted in Figure 24. At higher elevations this would have fallen as snow, but at lower elevations in the prairies as rain on snow. This likely contributed to the peak in the reservoir inflows and certainly contributed to the overall width and volume of the inflow hydrograph.

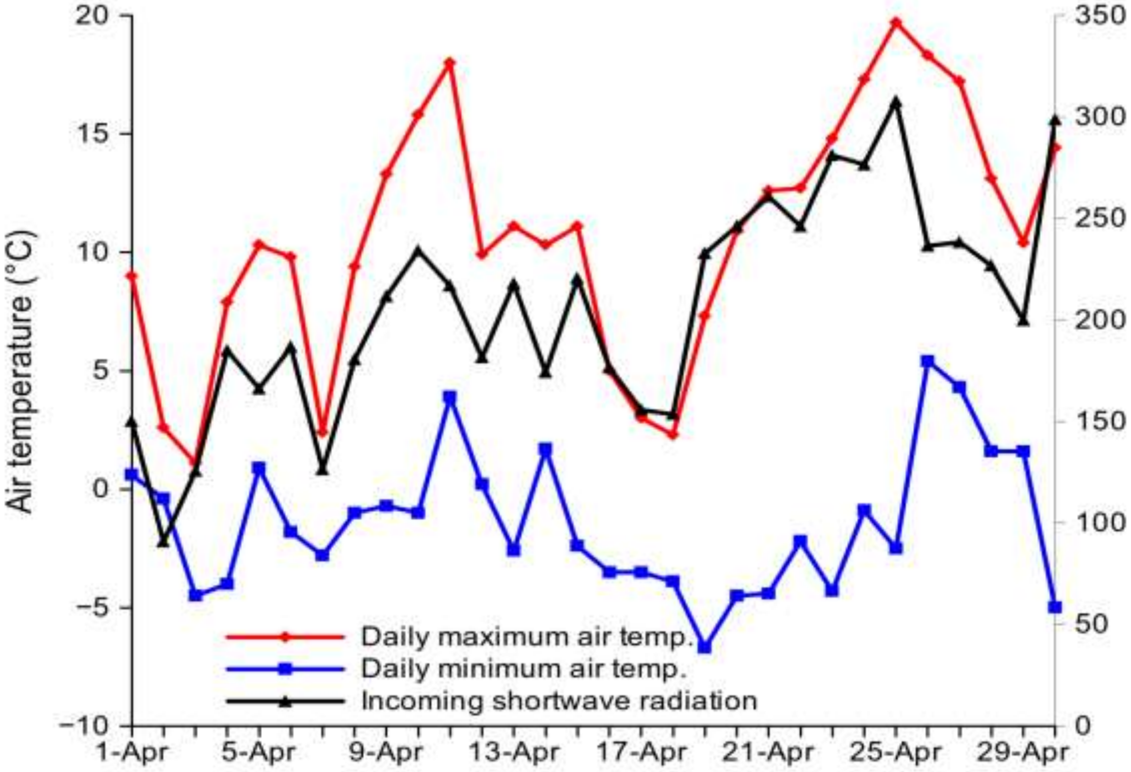


Figure 23. Medicine Hat daily minimum and maximum air temperatures and estimated incoming shortwave solar radiation.

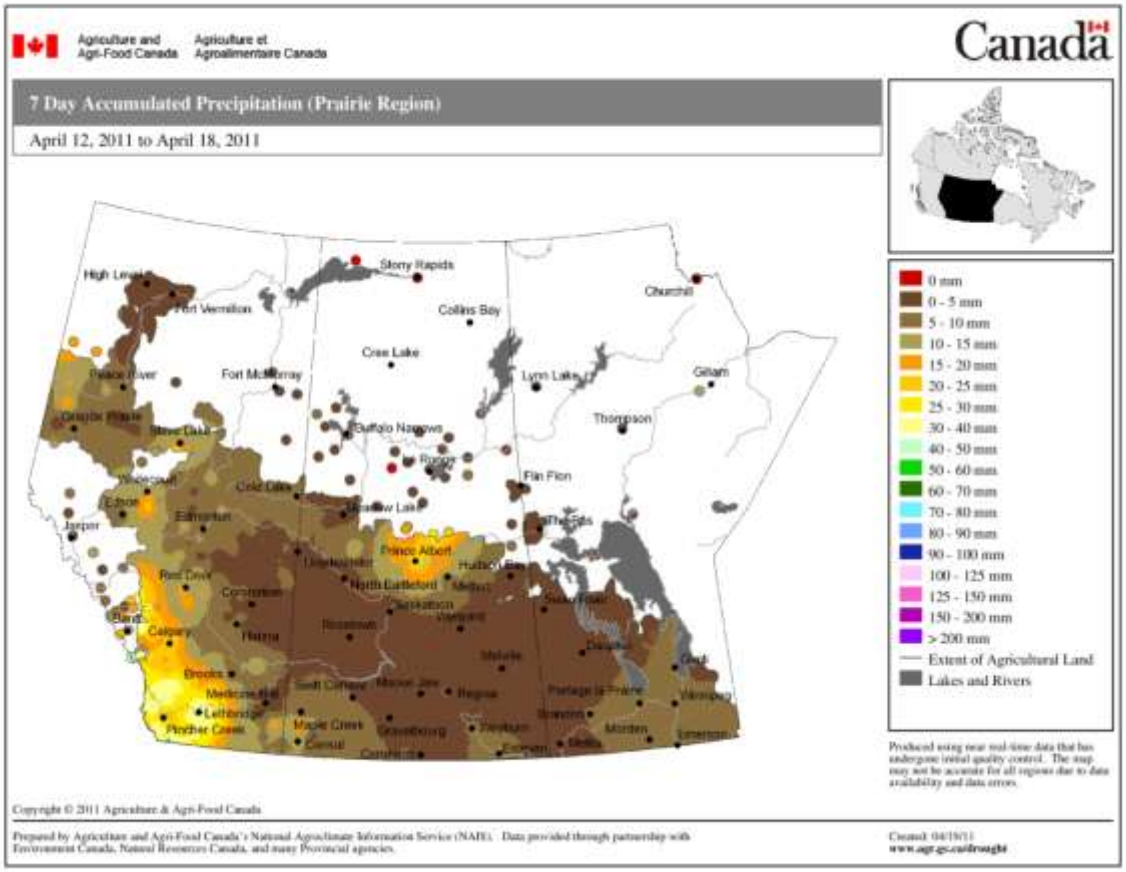


Figure 24. Accumulated precipitation April 12 to 18, 2011.

3.3.3 Summer 2011

By the beginning of May, the mountain snowpacks had begun to melt at altitudes of up to 2000 m as shown by the plots of the Alberta mountain snow pillows in Appendix 3. Runoff from mountain snowmelt generally contributes to streamflow well into June, although the area contributing flow decreases as the snowcover becomes patchy and the mountain snowline retreats upward.

Over the period of 24 – 31 May, up to 120 mm of precipitation fell in southwestern Alberta as mapped in Figure 25a and Figure 26. The plots of the majority of the Alberta mountain snow pillows show increases over this period, indicating that the precipitation fell as snow at elevations exceeding 2000 m, although the heaviest precipitation fell as rain in the foothills. According to Alberta Environment, the precipitation runoff resulted in high stream flows, flood warnings and flood watches in the Oldman, Bow and Red Deer River basins.

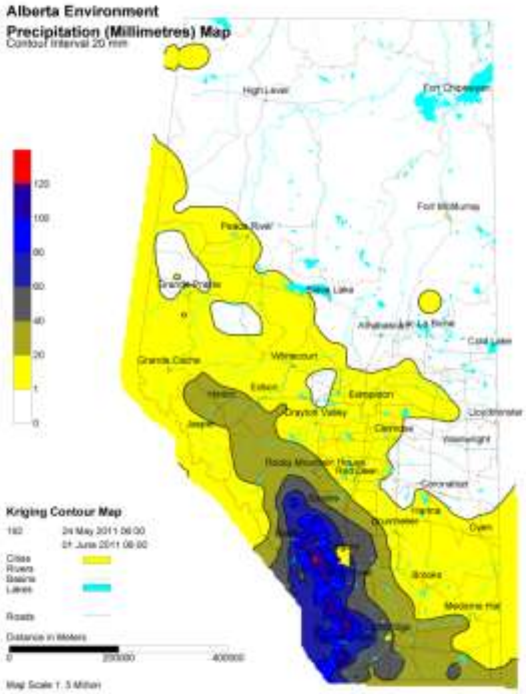
On 27 May inflows to the reservoir began to increase with the peak inflow on 1 June (Figs. 5 & 8). The residual estimate of the June peak daily inflow rate is 2590 m^3/s, while the routing estimate is 2390 m^3/s. The very small difference between the two estimates (~8 %) is probably within the uncertainty of the gauging of the very large upstream flows, but may have had some contribution from heavy rains that fell in Saskatchewan, just north of Lake Diefenbaker, in the last week of May (Fig. 26).

Further precipitation events in the South Saskatchewan River basin in the interval 1-14 June, mapped in Figures 25b and 25c, occurred in the Cypress Hills and immediately upstream of Lake Diefenbaker and then in the headwaters of the Oldman River. These events were fairly small, resulting in Alberta Environment issuing High Streamflow Advisories rather than Flood Watches or Warnings. The prairie events did not cause any notable peaks in inflows to Lake Diefenbaker, but probably contributed to the volume of the recession of the 27 May peak.

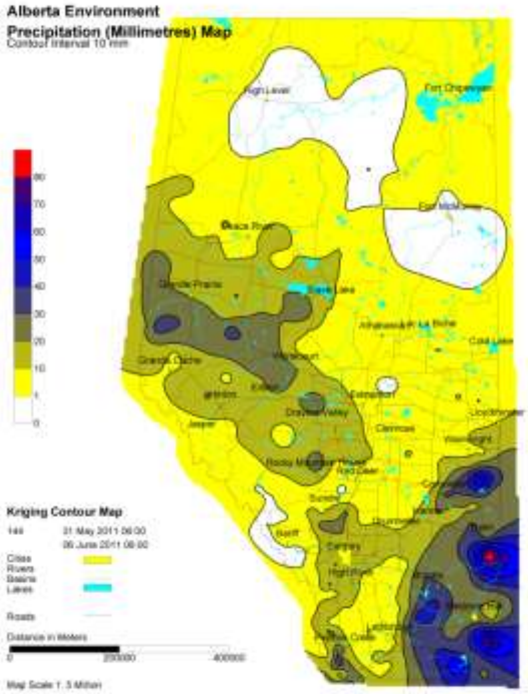
Over the period of 14 – 21 June, up to 160 mm of rain fell in northwestern Alberta as mapped in Figure 25d. Although the heaviest precipitation fell in the Athabasca river basin, there were also strong accumulations in the headwaters of the North Saskatchewan River. The South Saskatchewan River was less affected by the precipitation, which predominantly fell in the Red Deer basin. Alberta Environment issued High Streamflow Advisories and Flood Watches, but did not issue any Flood Warnings, for the North Saskatchewan and Red Deer basins. The high flows on the Red Deer River caused a small, broad secondary peak inflow to Lake Diefenbaker from 13-17 June of approximately 1600 m³/s. The broadness of the peak was probably due to the contribution of the flows from the earlier Oldman headwater event.

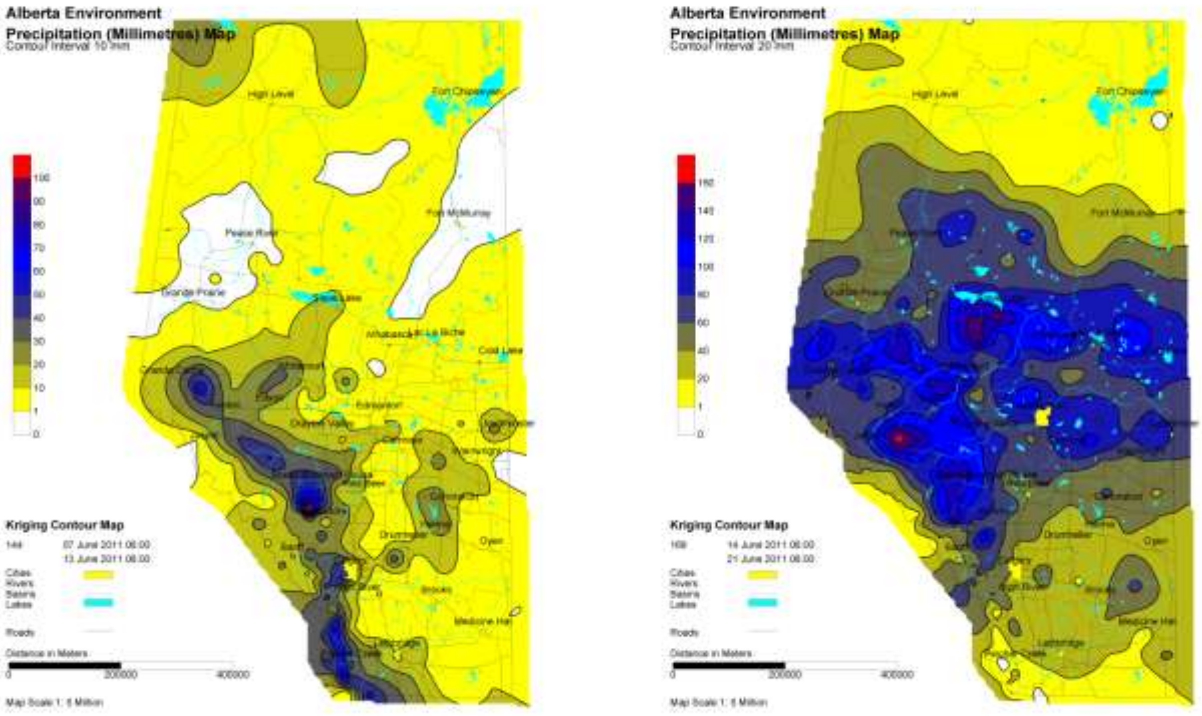
At the end of June, moderate rainfall in the foothills of the North Saskatchewan and Red Deer River basins, led to High Streamflow Advisories and a single Flood Watch by Alberta Environment. The high flows on the Red Deer River Basin caused a broad peak in the inflows to Lake Diefenbaker on 26 – 29 June of approximately 1300 m³/s. The final inflow event to Lake Diefenbaker was also caused by moderate rainfall in the Red Deer River Basin. The inflow peaked at approximately 730 m³/s on 19 July.

a



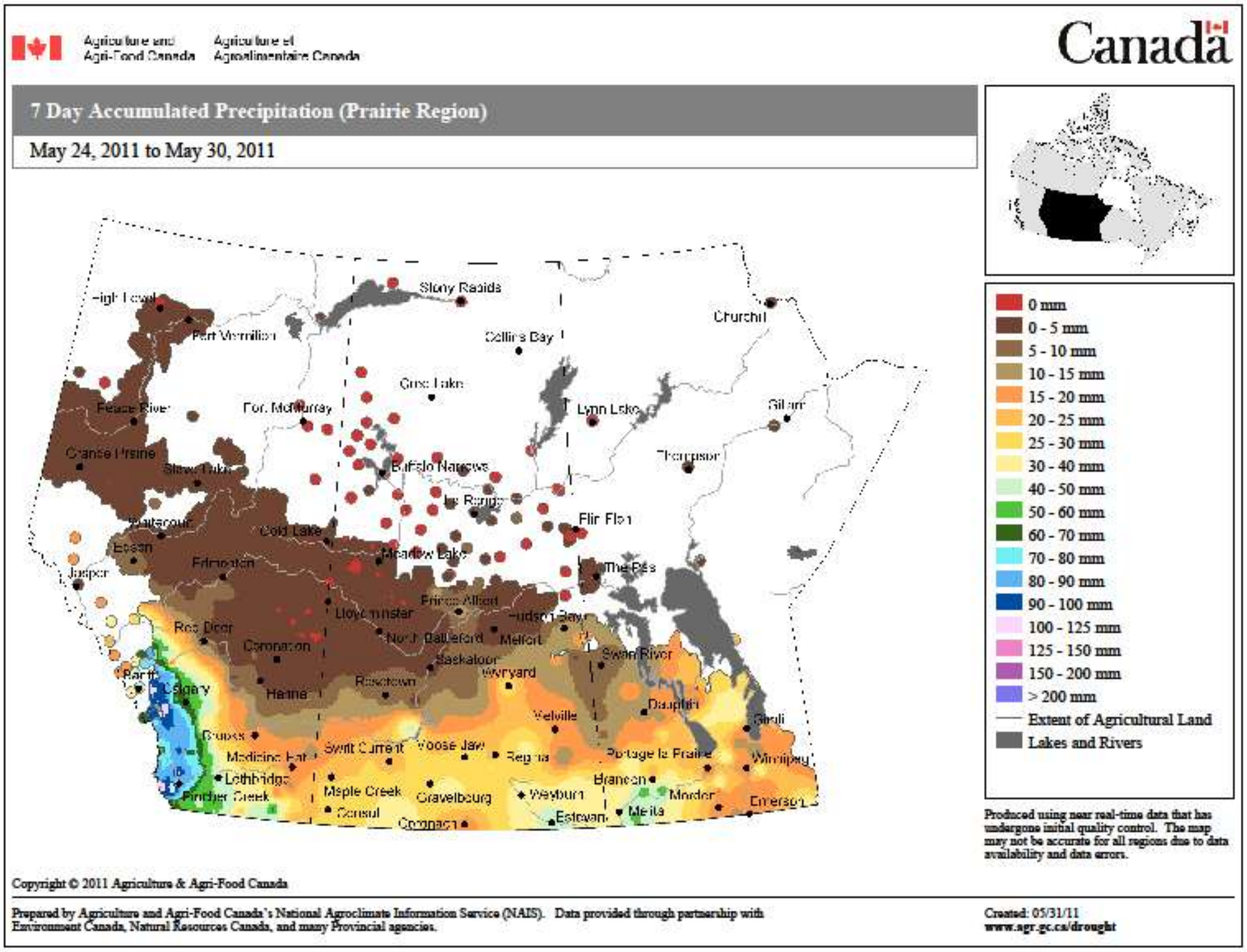
b





c d

Figure 25. Alberta precipitation: a) 24 May – 1 June, b) 31 May – 6 June, c) 7-13 June, d) 14-21 June.



Produced using near real-time data that has undergone initial quality control. The map may not be accurate for all regions due to data availability and data errors.

Prepared by Agriculture and Agri-Food Canada's National Agroclimate Information Service (NAIS). Data provided through partnership with Environment Canada, Natural Resources Canada, and many Provincial agencies.

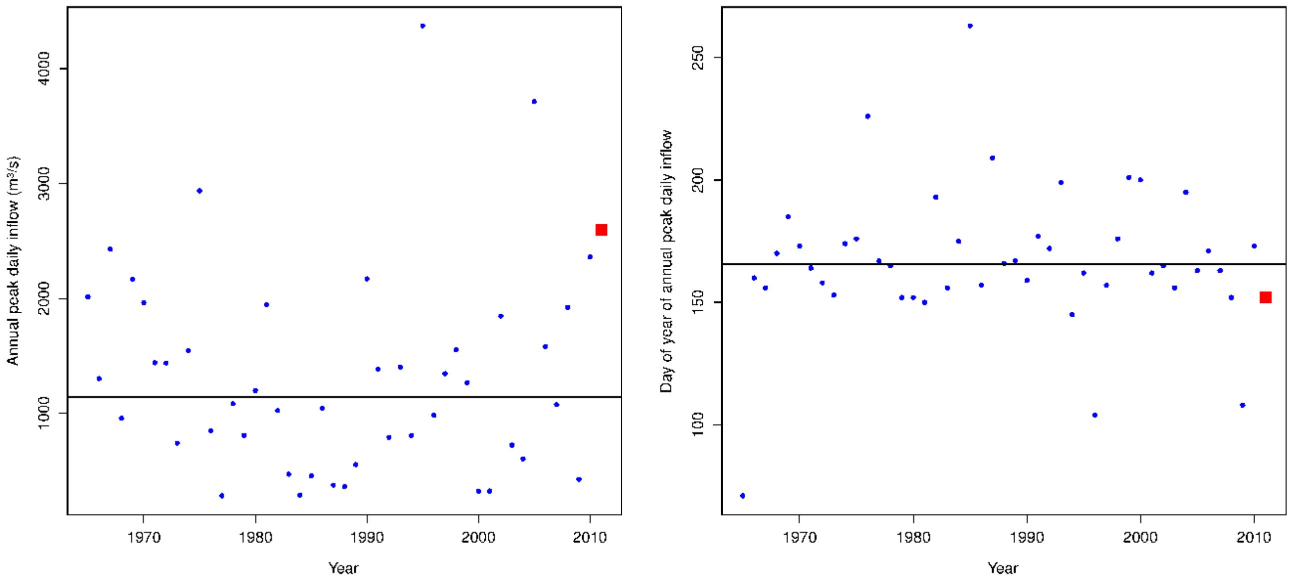
Created: 05/31/11
www.agr.gc.ca/drought

Figure 26. Precipitation from 24-30 May 2011.

2.3.4 Evaluation of inflows

Peak Inflows

As shown in Figure 27a, the 2011 peak daily inflow to Lake Diefenbaker, although of large magnitude was not exceptional. The date of the peak inflow was earlier than usual, as shown in Figure 27b, but also was not exceptional.



a) Annual peak daily reservoir inflow

b) Day number of annual peak daily reservoir inflow

Figure 27. Estimated peak annual daily gauged inflows to Lake Diefenbaker, and the day number of peak flow. Values for 2011 are shown as red squares. Median values shown as horizontal lines.

From the point of managing floods, the magnitude of the peak inflow rate is less important than the total volume of water that is required to be stored. Figure 28 plots the monthly inflows for 2011, along with non-exceedence probabilities of historical inflows expressed as quantiles. A quantile of 95% shows the streamflow which exceeds 95% of all streamflows recorded on this date up to this time and is therefore the 95th percentile of all streamflow on this date. All of the calculated inflows omit the effects of ungauged local inflows. The inflows for 2011 were greater than the historical median for all months after February, with the June inflows ranking between the 90th and 95th percentile flows, demonstrating that the volumes of the monthly inflows were unusually large. As the local ungauged inflows were much greater than usual in 2011, the ranking of the April inflows would actually have been greater than the value plotted in Figure 28 had there been a method to account for local inflow magnitudes.

Summary

There were numerous hydrologically important events in the drainage basin of Lake Diefenbaker over the period of August 1, 2010 - July 31, 2011. Some of the events, such as the spring melt of the prairie snowpack, or the summer rains of 2011, caused substantial inflows, and their effects are easy to identify because of the similar timing of rain or melt event and inflow. Other events, such as the accumulation of heavy mountain snowpacks, or the wetting of prairie soils and filling of prairie wetlands (“sloughs”) in the summer/fall of 2010 did not immediately cause high inflows, but were still important contributors to the large inflows in 2011. On their own, none of the hydrological events were exceptional, although many of them were large in magnitude. The combination of large hydrological events was undoubtedly unusual, although further research would be required to establish the probability of the sequence of events occurring. Part of the difficulty in establishing the probability of events is that prairie inflows were ungauged and there is no modelling capability for these inflows.

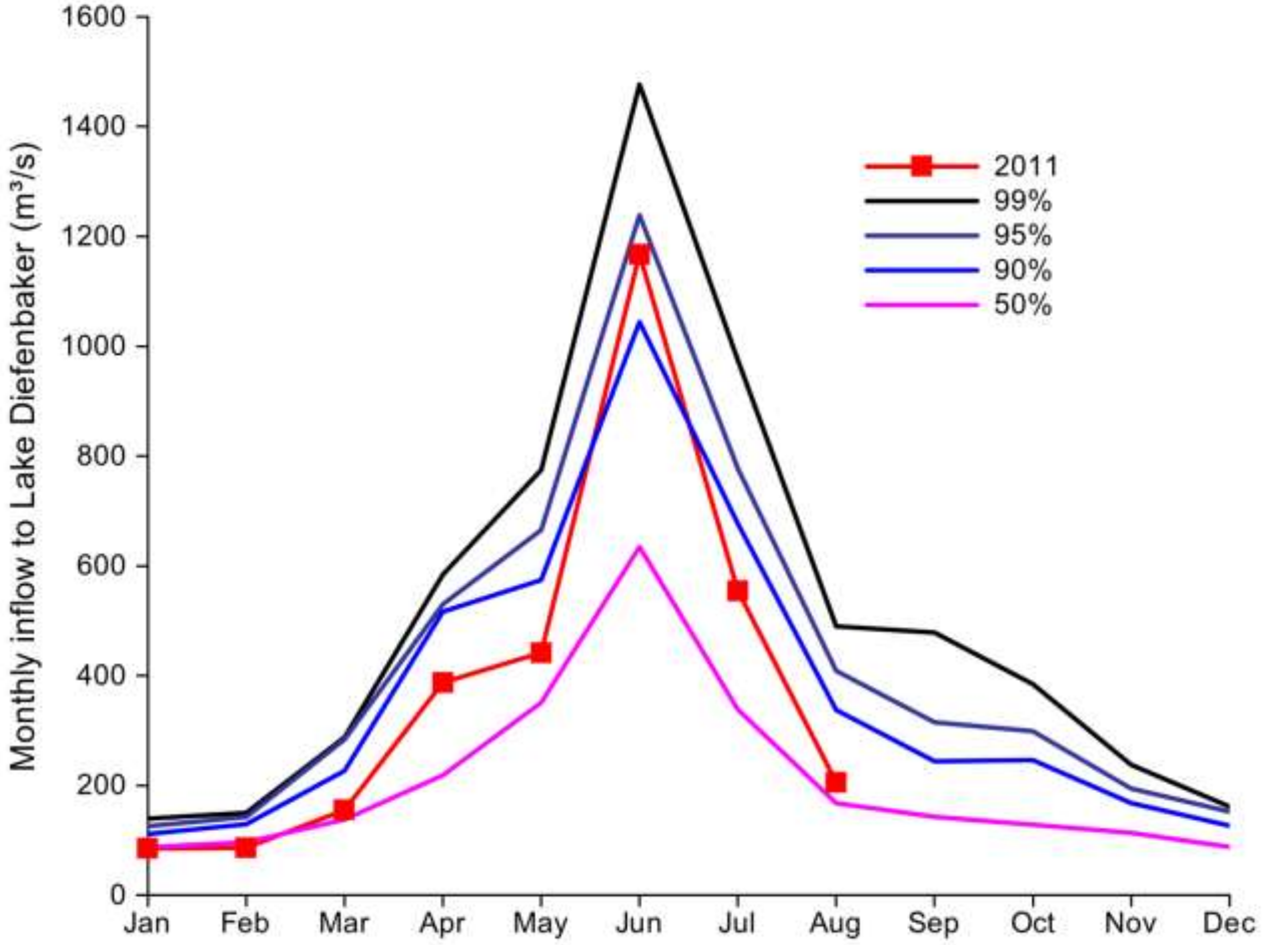


Figure 28. Mean monthly gauged inflows to Lake Diefenbaker for 2011 and historical quantiles (non-exceedence probabilities). All inflows estimated by summing flows of South Saskatchewan River at Medicine Hat and Red Deer River at Bindloss. Inflow quantiles from 1965 - 2010.

2.3.5 Reservoir management

2.3.5.1 Fall-winter 2010-2011

During the period August through mid-November 2010, the reservoir elevation was fairly static, with reservoir discharges generally closely following inflows, as plotted in Figure 29. During this period, the reservoir discharges were smaller in magnitude than usual. According to SWA emails the discharges were reduced in the fall period to assist construction of the Circle Drive south bridge in Saskatoon. Over the fall and winter, repair work on generating units at Coteau Creek restricted the number of turbines in use. As all flows during the period were passed through the turbines at Coteau Creek, with no use being made of the spillway, the reduction in the number of active turbines reduced the outflows from Lake Diefenbaker and therefore contributed to the reservoir being higher than usual in the spring.

During the period of October through mid-March at most two generating units were on-stream.

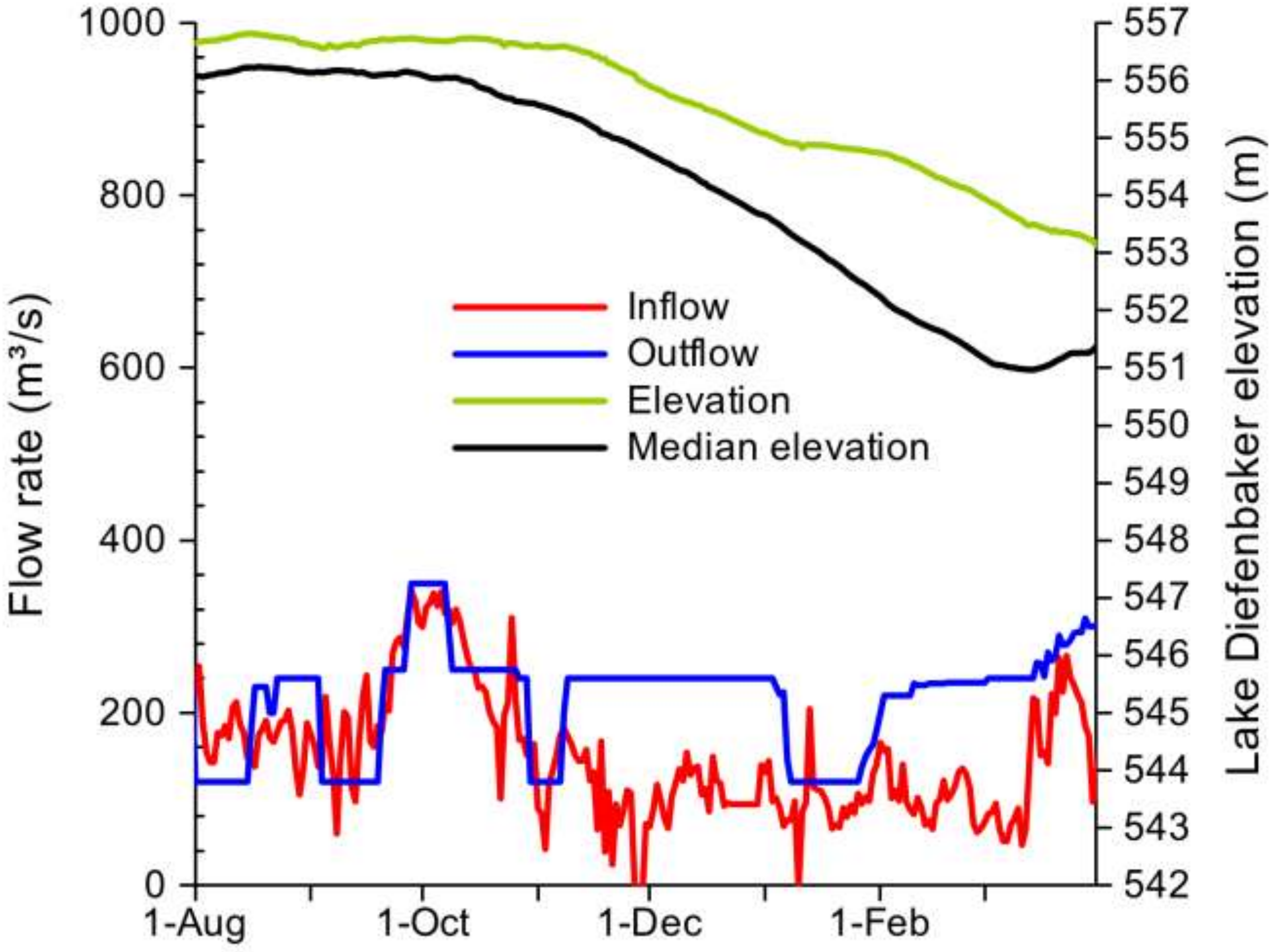


Figure 29. Inflows to Lake Diefenbaker calculated as a residual, discharges from Gardiner Dam, Lake Diefenbaker elevation and median elevation by date. August 1, 2010 – March 31, 2011.

From mid-November through the end of March, outflows exceeded inflows to the reservoir, causing the reservoir elevation to decrease. The abrupt decrease in discharges during January was due to only one generating unit being functional and operating. The increase in flows in the middle of March 2011 was associated with the third generating unit being made functional.

According to internal emails, the reluctance to use the spillway during the winter was largely due to concerns that to do so would fracture the ice cover on the SSR, which could lead to the formation of ice jams which could cause uncontrolled flooding. A report from the 1970s suggests that this is a possibility worthy of investigation but no technical follow-up appears to have occurred. At least one reconnaissance flight was made of the SSR to assess ice conditions in early February.

As shown in Figure 29, the reservoir elevation in early March was more than two metres higher than the median value, which was shown previously to have been affected by the trend to increasing values. The causes of the higher than normal values were:

1. The relatively high reservoir elevations in the summer of 2010,
2. Reservoir elevations being held constant until mid-November, where median elevations show declines beginning in October, due to the bridge construction in Saskatoon,
3. A slightly slower than median rate of decline in December through January, and
4. The slowed rate of decline in January due to only a single generating unit being operational.

Whilst each of these causes by itself would not have led to overly high reservoir levels by spring, and so the perceived risk associated with each factor may be small, their cumulative effect led to high reservoir levels in a winter with extremely wet prairie conditions and increasing mountain snowpacks – these wet conditions and snowpacks guaranteed that relatively low inflows to the reservoir would not occur.

2.3.5.2 Spring 2011

During the spring inflow event the elevation of Lake Diefenbaker increased substantially as shown in Figure 30. The difference between the elevation and the long term median value also increased during this period. According to internal SWA emails, the overriding concern during the spring inflow event was to keep discharges to the South Saskatchewan River low, so that the combined flow of the Saskatchewan River would also be minimized at this time. Outflows actually dropped from 11 to 25 April from ourflows earlier and later in the month. Figure 31 shows that the spring flow on the North Saskatchewan River began to rise in mid-April to a broad peak in late April, and reducing the combined North and South Saskatchewan flows required the discharges from Lake Diefenbaker to be smaller than inflows for a very long period. It is evident that this was very effective as the Saskatchewan River flows below Tobin Lake remained below 1000 m^3/s until early May.

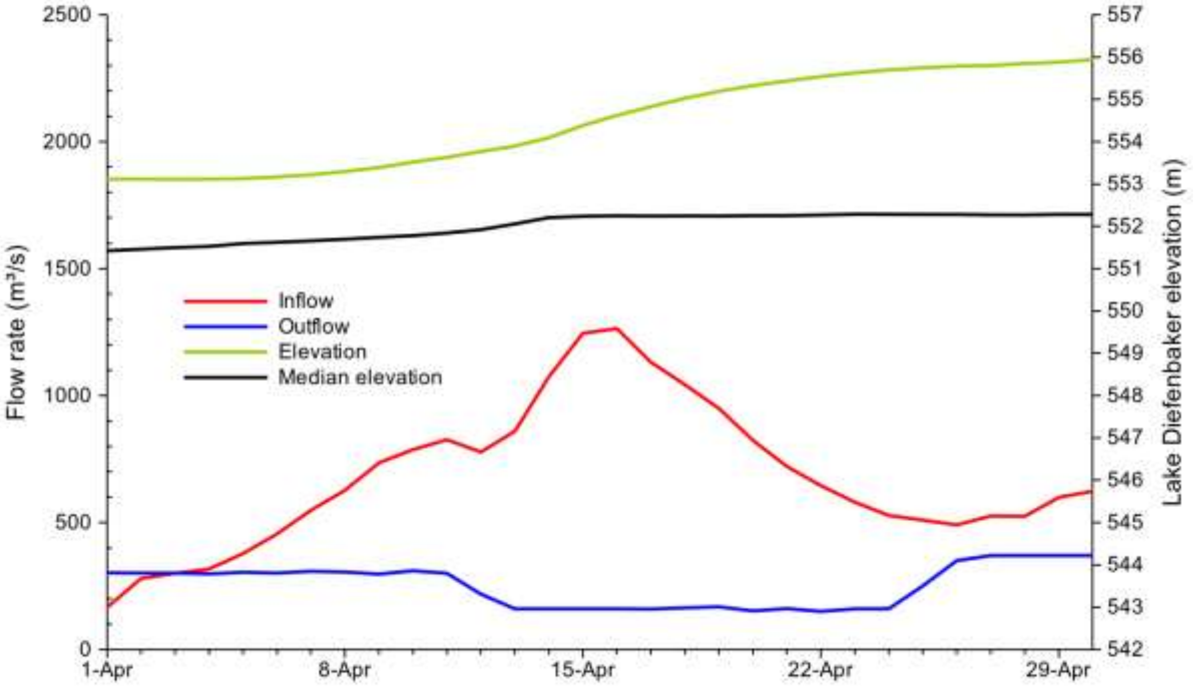


Figure 30. Inflows to Lake Diefenbaker calculated as a residual, discharges from Gardiner Dam, Lake Diefenbaker elevation and median elevation by date. April 1– 30, 2011.

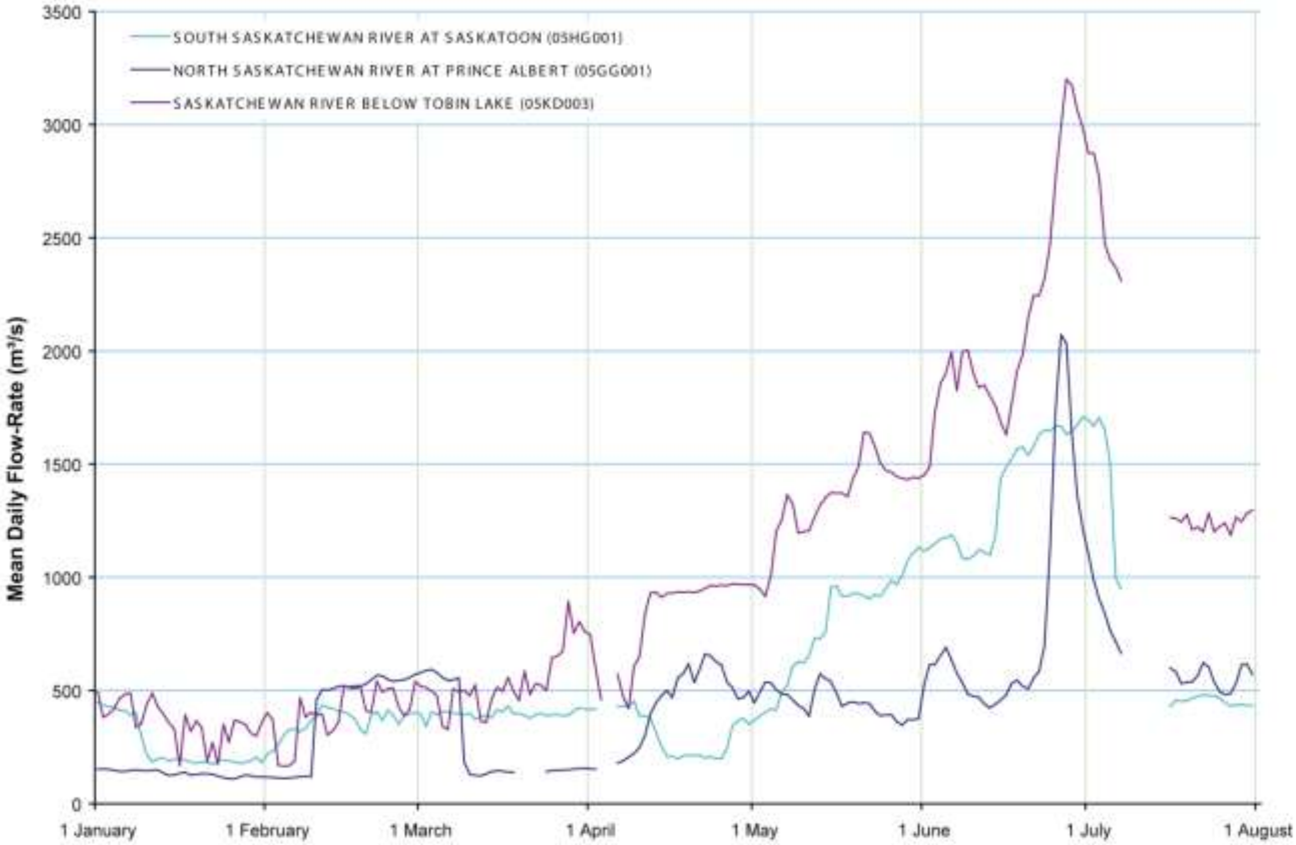


Figure 31. Daily streamflows for the South Saskatchewan River at Saskatoon, the North Saskatchewan River at Prince Alberta and the Saskatchewan River below Tobin Lake in 2011.

As discussed previously, the spring inflows to Lake Diefenbaker were above average, with a much larger than usual contribution from the ungauged local prairie runoff. By the beginning of May, with the elevation of Lake Diefenbaker very close to FSL, the reservoir discharges were increased to reduce the elevation.

2.3.5.3 Summer 2011

Discharges exceeded inflows for the period May 7 - 29 in order to draw down the reservoir in anticipation of the summer peak inflows, as shown in Figure 32. According to internal emails, the intent was to return Lake Diefenbaker to an elevation of 555.0 m by the end of May, which was nearly achieved. However, because the peak summer inflow event occurred relatively early, at the beginning of June, there was not sufficient time for the set discharge rate to achieve the desired reservoir elevation, even with the increases in discharges at the end of May.

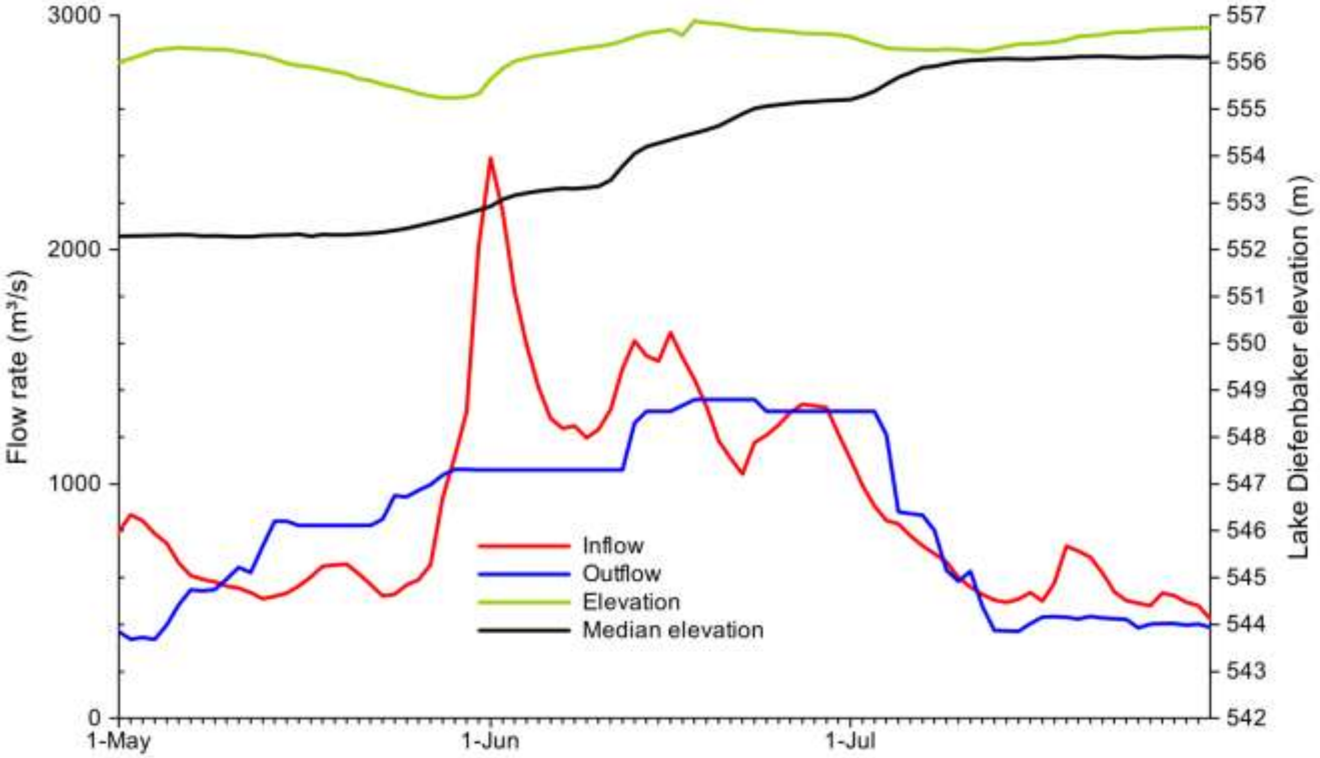


Figure 32. Inflows to Lake Diefenbaker calculated as a residual, discharges from Gardiner Dam, Lake Diefenbaker elevation and median elevation by date. 1 May – 31 July, 2011.

The first summer inflow was managed by storing as much of the event as possible, the intent being to achieve the reservoir's summer target elevations. The internal emails show that numerous scenarios of inflows and discharges were considered at least as early as 3 May. Had the first summer event been the only significant inflows, it is likely that the scenarios which forecasted that the "reservoir would be utilized to minimize the peak releases to 1180 m³/s" (SWA email) would have been fulfilled.

The second summer inflow event began in mid-June when the reservoir was close to FSL, at a time when the discharges were smaller than the inflows. This was a difficult situation for the management of the reservoir and outflows. As discharges were already high, drawing-down the reservoir before the arrival of the flood wave might have caused downstream flooding, particularly as the operators understood at the time that downstream overbank flows began at approximately 1200 m³/s. Once the reservoir elevation reached FSL there was no storage left to manage inflows, and the discharges had to match or exceed inflows for the rest of June and into early July.

2.4 Downstream effects of high flows in summer of 2011

2.4.1 South Saskatchewan River

The daily water balance change for the reservoir (neglecting evaporation and local ungauged inflows), i.e. the differences between the inflows and discharges, is plotted in Figure 33. The positive values indicate a positive water balance for Lake Diefenbaker (increasing storage), the negative values are negative water balances (decreasing storage). Discharges were calculated in two ways, one from the measured discharge of the spillway and power generating station and the second from the lagged measured streamflow of the South Saskatchewan River at Saskatoon. The second method is considered more reliable as discussed earlier. As the total area under the curve above the x-axis is greater than area below for either method of calculation, the dam operations acted to reduce the total volume of discharge and hence streamflow in the South Saskatchewan River over the period 1 April – 31 July.

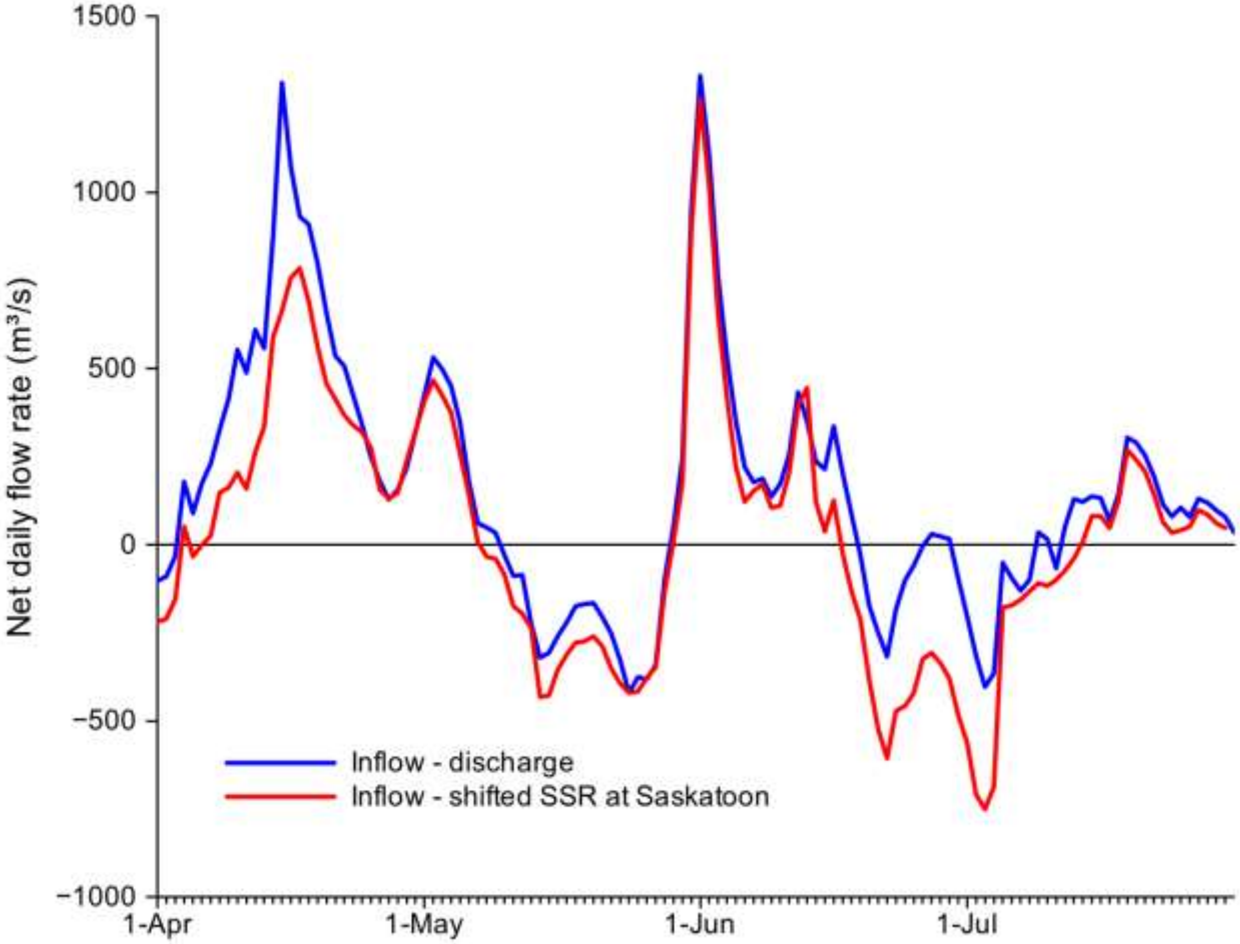


Figure 33. Daily water balance change for Lake Diefenbaker over the period April 1 – July 31, 2011 determined using the discharges estimated for the spillway and Coteau Creek power station and discharges estimated using backward shifted streamflows of the South Saskatchewan River at Saskatoon.

The operation of Gardiner Dam also substantially reduced the downstream streamflows on the South Saskatchewan River of the four largest peak inflow events as shown in Table 4.

Table 4: Peak inflows to Lake Diefenbaker in 2011, same day discharges and next day flows on South Saskatchewan River at Saskatoon. 15 April and 14 June inflows calculated as residuals by SWA. 2 May inflows calculated by routing upstream flows. 1 June inflows as residual/routed values.

Date	Inflow to Lake Diefenbaker (m^3/s)	Same day discharge (m^3/s)	Next day SSR at Saskatoon (m^3/s)
15 April	1471	160	211
2 May	869	337	402
1 June	2391/2594	1060	1118
14 June	1606	1310	1425

Flow duration

The magnitudes of peak streamflows control the areal extent of flooding, but the duration of high streamflows also influences the extent of damage, particularly to agricultural land. Increased duration of inundation restricts access for seeding and tillage and will cause increased mortality for most crops. The same fluvial sediments that cause and increase productivity in the long run when deposited in the floodplain can reduce crop growth immediately after inundation. The duration of inflows, discharges and streamflows of the South Saskatchewan River at Saskatoon are plotted in Figure 34. Durations of streamflows less than 1250 m^3/s were clearly reduced, and streamflows greater than 1750 m^3/s were entirely prevented by the operation of Gardiner Dam. The elimination of streamflows greater than 1750 m^3/s is a significant achievement for the reservoir operation that almost certainly reduced flood damage downstream. Due to the uncertainty of measurement, flows in the vicinity of 1500 m^3/s appeared to have been eliminated when dam discharges understood at the time are considered. However, when the more accurate river flows at Saskatoon are evaluated it is clear that their duration was increased by dam operation.

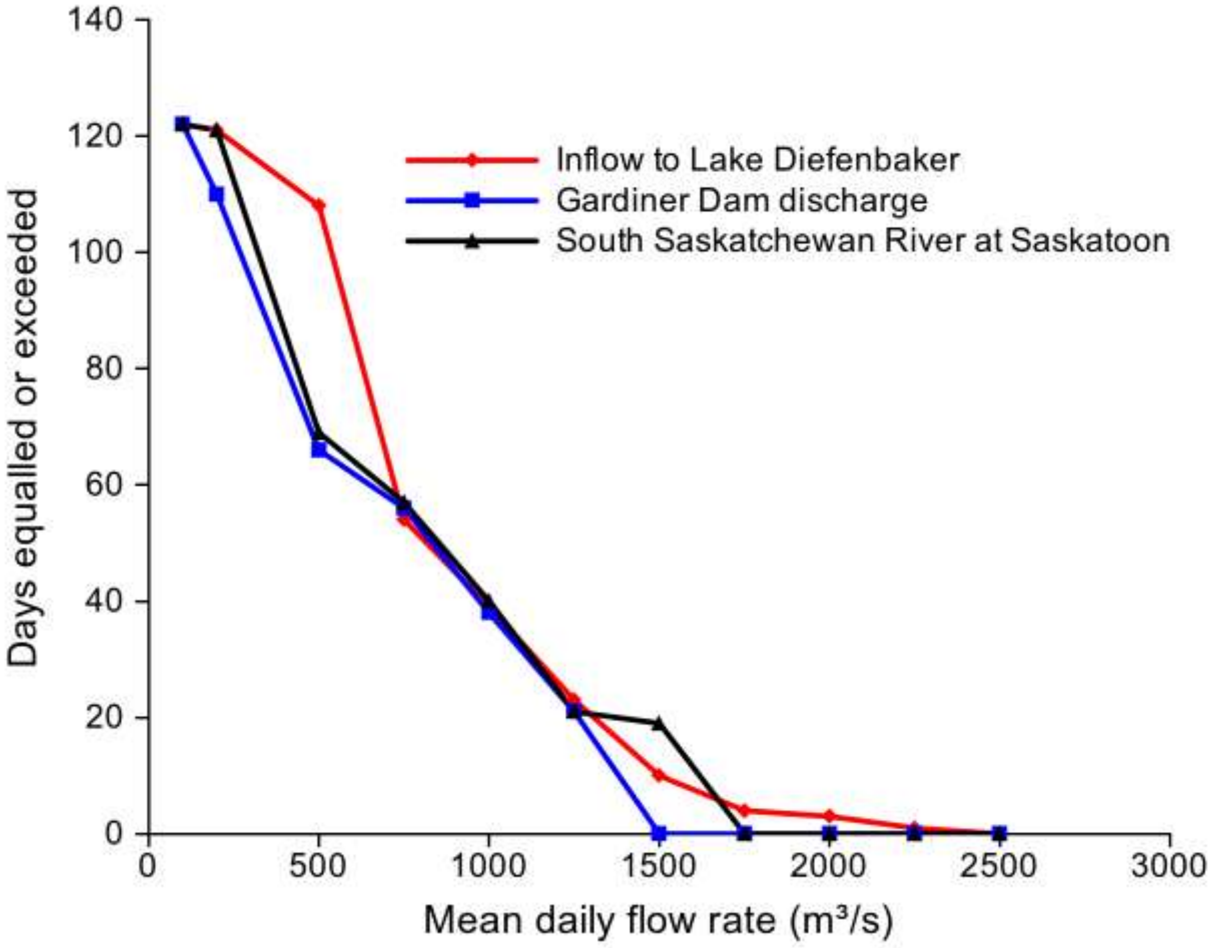


Figure 34. Durations of Lake Diefenbaker daily inflows, discharges estimated from Gardiner Dam and flows of the South Saskatchewan River at Saskatoon.

The difference between the flow duration curves for the dam discharge and the South Saskatchewan River at Saskatoon explains some of the controversy over downstream flows. From the point of view of the dam and dam operators given the understanding available at the time, downstream flooding was greatly reduced. From the point of view of downstream users and the WSC streamflow measurements at Saskatoon, the duration of streamflows of the South Saskatchewan at Saskatoon near 1500 m³/s were increased by dam operations in 2011.

To assess the impact of dam operation on flooded areas downstream of Gardiner Dam as understood by SWA staff, a linear relationship was developed by regression ($r^2 = 0.998$) of SWA data on flooded area between Moon Lake and Saskatoon versus river stage listed in Table 9. The flooded area was established by LiDAR precision altimetry but does not distinguish land use or land value. These areas have not been verified by a formal flood routing study for 2011 which would be required to show precisely which areas would be flooded. Using back-calculated total daily inflows to Lake Diefenbaker which approximate the South Saskatchewan River streamflow without the Gardiner Dam influence, an April flood of almost 2000 acres and a major early June flood of almost 6000 acres would have occurred between Moon Lake and Saskatoon, followed by two more June floods of 2500 acres and 1100 acres with flooding ending in early July (Fig. 35). Without the dam a total of 54,472 acre-days of flooding between Moon Lake and Saskatoon would have occurred. Using the Gardiner Dam discharge numbers available to SWA, the April and early June floods were completely eliminated, and later June flooding was reduced to just over 1000 acres, ending in early July (Fig. 35). Using the Gardiner Dam discharge (spillway plus Coteau Creek) understood to SWA at the time, a total of 24,186 acre-days of flooding occurred, a 56% reduction flooded area duration. As previously discussed, there appear to be large errors in estimated outflows from the Coteau Creek hydroelectric station and small errors in the spillway outflow estimations and it is highly unlikely that any significant local contributions to summer streamflow occur downstream of Gardiner Dam and upstream of Saskatoon. Using the Saskatoon WSC gauging station observations to estimate flooded areas, the April flood was completely eliminated, the early June flood was reduced to just over 500 acres and the mid to late June flood varied between 2000 and 3000 acres and persisted without a break into early July (Fig. 35). Using the Saskatoon WSC gauged data, a total of 54,520 acre-days of flooding occurred, which is not significantly different from that which would have occurred without Gardiner Dam. It should be noted that even using the Saskatoon WSC data the peak flooded area was reduced from 6000 to 3000 acres.

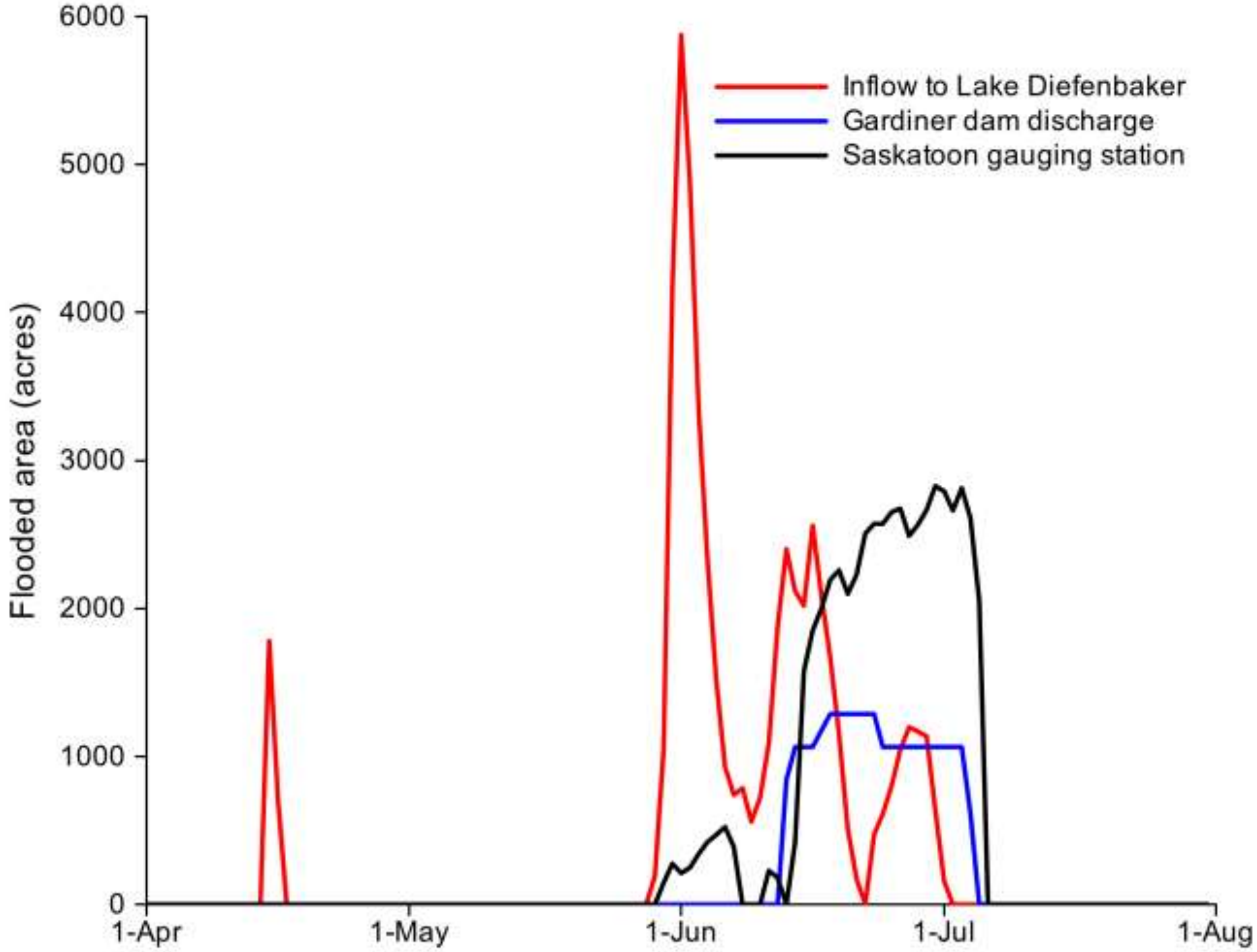


Figure 35. Daily inundated area in 2011 between Moon Lake and Saskatoon estimated using data provided by SWA and back-calculated daily inflows to Lake Diefenbaker, Gardiner Dam discharge values known to SWA and WSC gauged flows at Saskatoon.

2.4.2 Saskatchewan River

As was described previously, and is plotted in Fig. 31, the discharges from Gardiner Dam during the spring inflow event were managed to reduce the effects of coincident peaks on the North and Saskatchewan rivers. During the spring event, the flows on the North Saskatchewan River changed little from Deer Creek to Prince Albert. Unfortunately, due to the current state of the hydrometric network in Saskatchewan, there are no longer any active gauging stations on the South Saskatchewan River downstream of Saskatoon, nor are there any stations immediately downstream of the confluence of the North and South Saskatchewan rivers to help determine the effect of local inflows downstream of Saskatoon and Prince Albert. The only station on the Saskatchewan River is located downstream of Tobin Lake and are subject to management of this reservoir. Therefore, all estimates of the flows at the confluence were made by summing routed flows from Saskatoon and Prince Albert, or could be made by reversing the routing of flows measured at Tobin Lake.

Figure 36 plots the flows at the confluence as estimated from the sum of the measured flows of the North Saskatchewan and routed inflows to Lake Diefenbaker and measured flows of the South Saskatchewan at Saskatoon, as estimated from Gardiner Dam and as measured at Saskatoon. The routing time from Saskatoon was assumed to be one day. The operation of the reservoir clearly reduced some secondary streamflow peaks on the North Saskatchewan River; the events of 17 April, 4 May, and 3 June 2011. However, the operation of the dam may have increased the annual streamflow peak on 26 June. Though the understood discharges from Gardiner Dam were very similar to the inflows, the WSC measured flows at Saskatoon were greater than inflows to the dam and so the high flow event of the year may have been slightly increased by dam operation. The difference between Gardiner Dam discharge and Saskatoon streamflows is almost certainly due to errors in measurement at Gardiner Dam as discussed in Section 1.1.3.4.

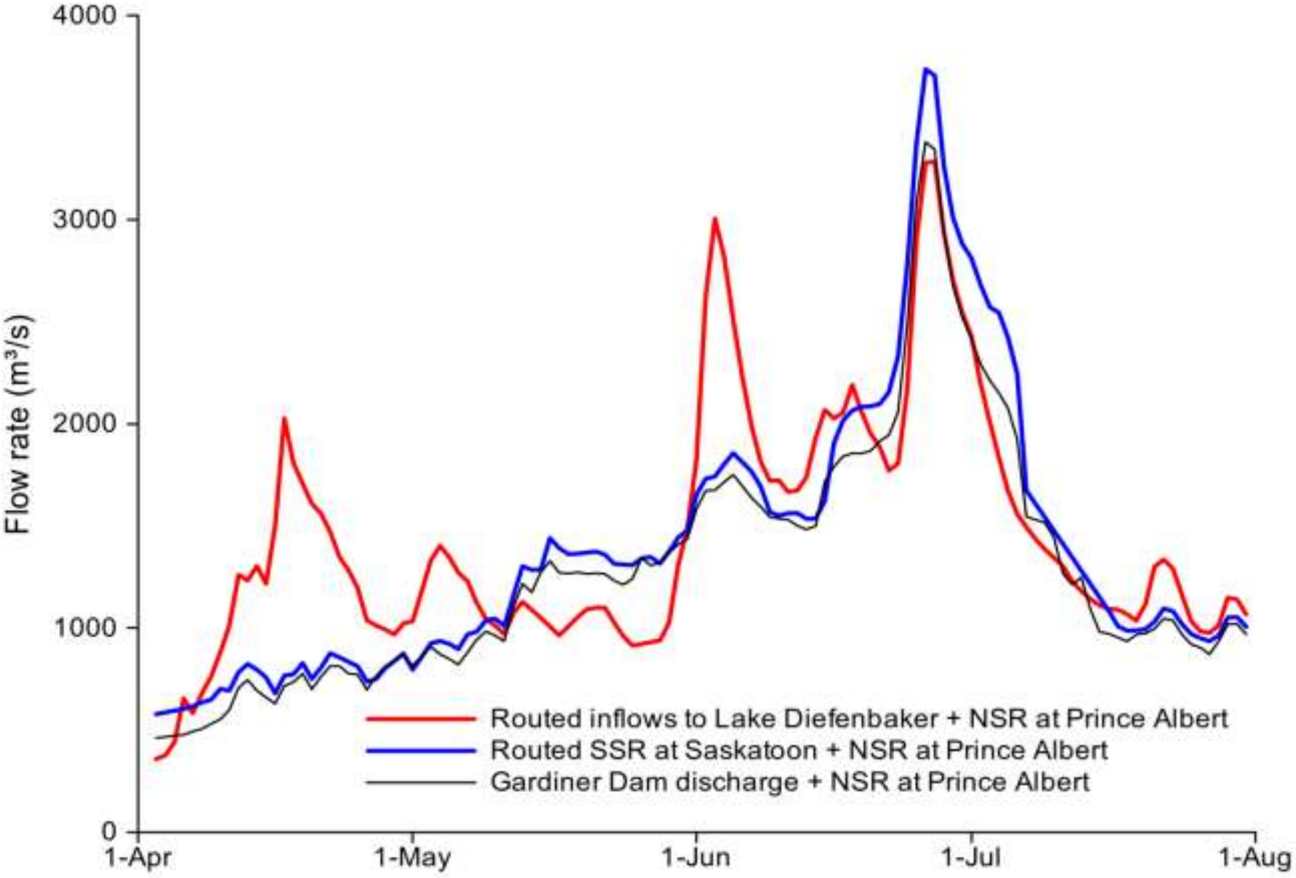


Figure 36. Estimated flow of Saskatchewan River at confluence of North and South Saskatchewan rivers determined adding the North Saskatchewan River at Prince Albert flow to routed inflows to Lake Diefenbaker, routed Gardiner Dam discharge estimates and routed South Saskatchewan River at Saskatoon estimates.

3 Assessment of operations

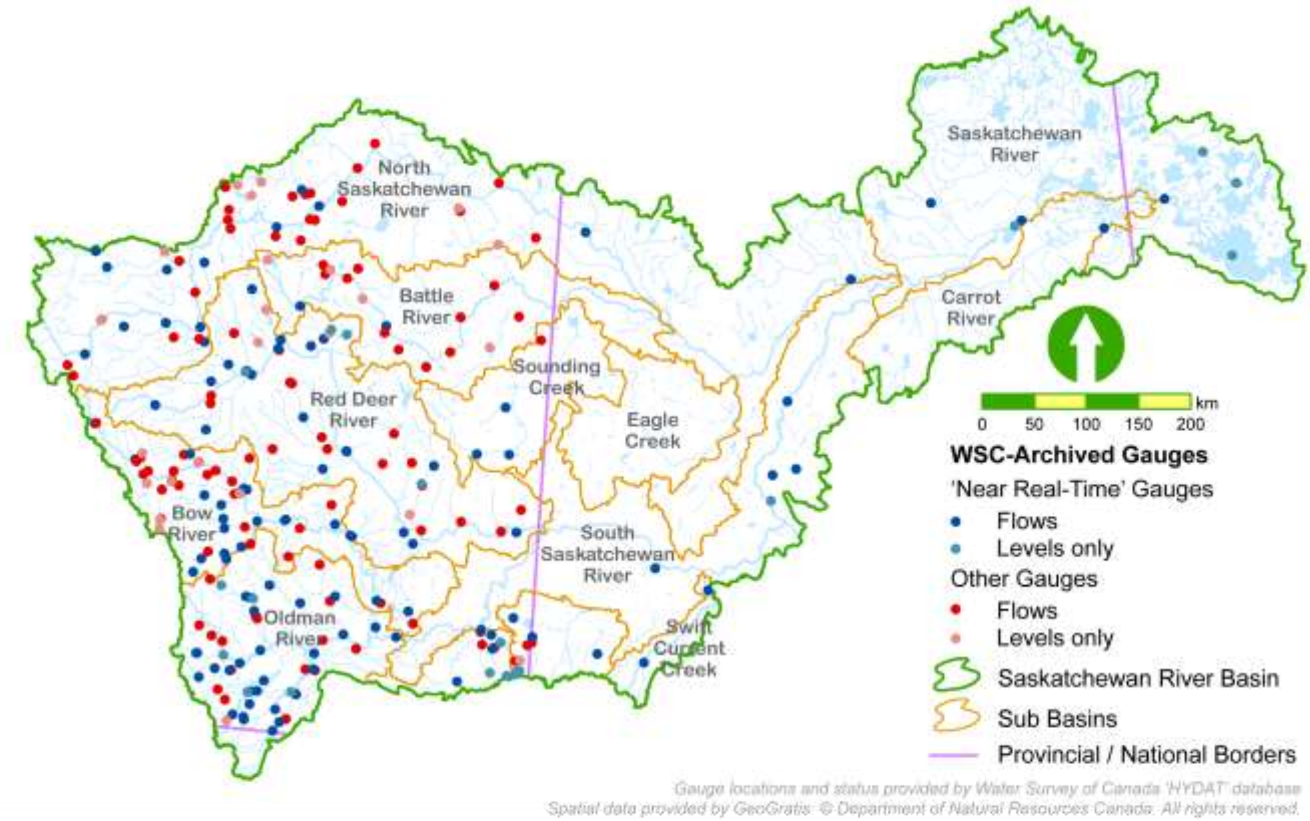
3.1 Available resources

3.1.1 External

3.1.1.1 Hydrological data

The network of currently operating hydrometric stations that are part of the Canadian National Hydrometric Network for streamflow and lake level measurement in the Saskatchewan River Basin is shown in Figure 37. The near-real time hydrometric stations with sub-hourly data are of value in estimating the impact of high runoff events on the river system. SWA has its own internally operated network of hydrometric stations, but the data from these stations do not meet national or international standards, are not publically available, and are not normally available to SWA in near-real time for high streamflow management purposes and so are not considered further in this report. It is evident that the density of hydrometric stations in Alberta is far greater than in Saskatchewan, which is no-doubt due to the Government of Alberta sharing some of the cost with the Government of Canada for the operation of the Canadian National Hydrometric Network in that province. Gauges shown in blue provide near real-time flows using provisional rating curves via the Water Survey of Canada’s website. Gauges shown in red provide data for the WSC archive. Ungauged prairie inflows in April to Lake Diefenbaker were substantial and had a critical impact on managing reservoir levels and outflows in June and July. The underrepresentation of hydrometric stations to measure inflows combined with the lack of a hydrological prediction capacity in SWA to estimate these inflows clearly adds substantial risk to the operation of reservoirs such as Lake Diefenbaker for multiple objectives in wet years.

The state of the current gauging network is due to an erosion of the network through loss of hydrometric gauges from important locations in Saskatchewan over the last 20 years. For example, from 1958-1997 there was a station on the South Saskatchewan at St. Louis (05HH001), immediately upstream of the confluence with the North Saskatchewan. This station would have been invaluable during the high streamflow events of 2011 to establish flows to the confluence of the North and South Saskatchewan River and to calibrate routing to Tobin Lake. A station upstream of Tobin Lake would also be useful in determining the effect of local inflows on the operation of Saskatchewan River reservoirs.



Gauge locations and status provided by Water Survey of Canada 'HYDAT' database
Spatial data provided by GeoGratis © Department of Natural Resources Canada. All rights reserved.

Figure 37. Hydrometric stations in the Saskatchewan River Basin.

In the vicinity of Lake Diefenbaker there is a remarkable paucity of operating stations. Only the WSC stations listed as ‘near real time’ in Figure 38 provide data on local inflows, meaning that the Saskatchewan portion of the Lake Diefenbaker watershed is almost entirely ungauged.

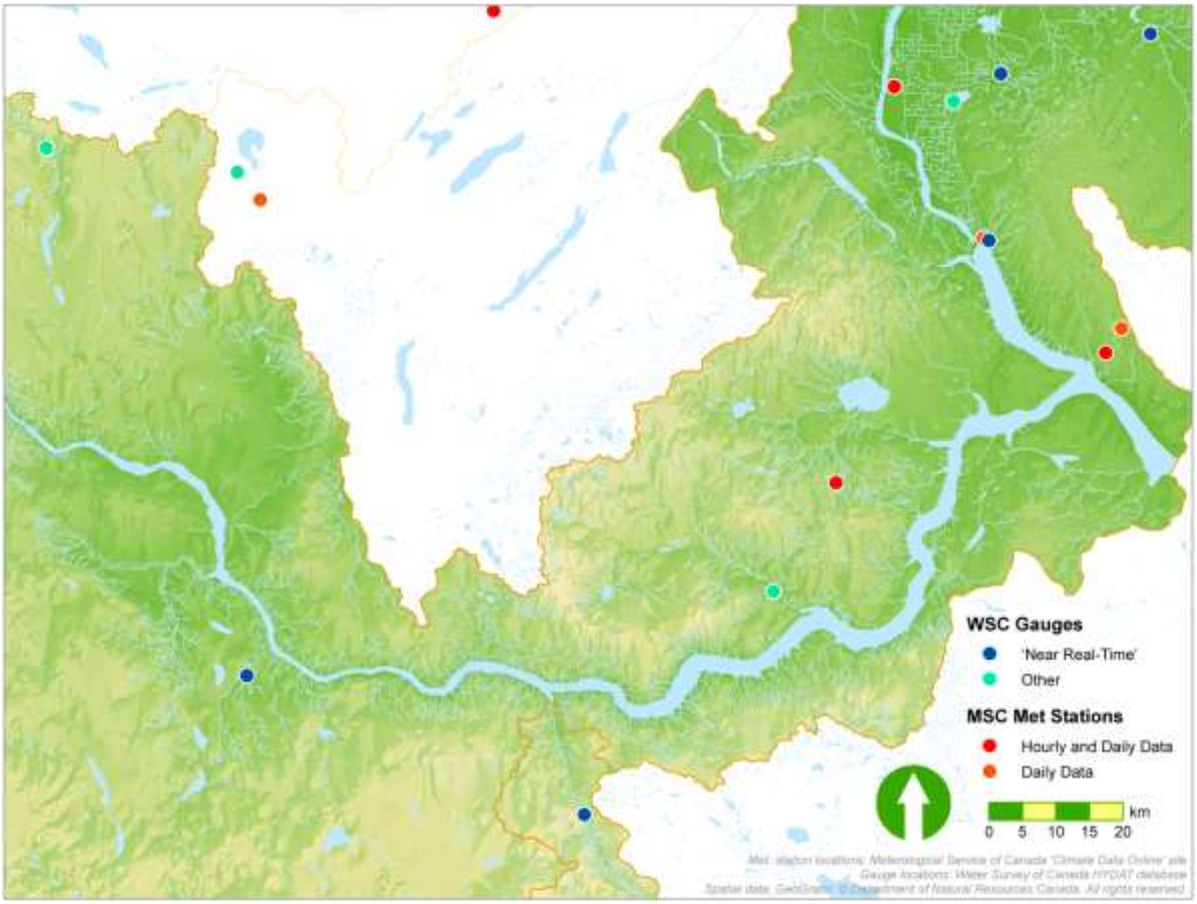


Figure 38. Map of Lake Diefenbaker and local current Water Survey of Canada (WSC) archived hydrometric gauges and Meteorological Service of Canada archived weather stations.

WMO has established standards in its most recent *Guide to Hydrological Practices* (2008), where it provided updated recommendations for minimum network densities based on physiographic units. A recent report by Coulibaly and Samuel (2011) evaluated the Canadian National Hydrometric Network against these standards by ecoregion. For the prairie ecoregion, 224,000 km^2 met WMO network gauge density standards and 157,000 km^2 did not, of which 28% was ungauged and the rest gauged at network densities below WMO standards. Though the report did not break down the numbers by basin or province, it is clear from Figure 39 that much of the Saskatchewan River Basin in eastern Alberta, the Rocky Mountains and southern Saskatchewan is either ungauged or is gauged below WMO standards for network gauge density (Coulibaly and Samuel, 2011). Saskatchewan stands out in Canada for having a large portion of its agricultural zone being ungauged and under-gauged. However, high mountain areas feeding the Saskatchewan River are also undergauged. In a recent unpublished study, Pomeroy and Sinclair (2012) found that the network of hydrometric stations in the Canadian Rocky Mountains does not reflect the frequency distribution of elevations in this region. Each hydrometric station in the Canadian Rocky Mountains samples on average 5½ times more terrain than is recommended by the WMO for mountain regions.

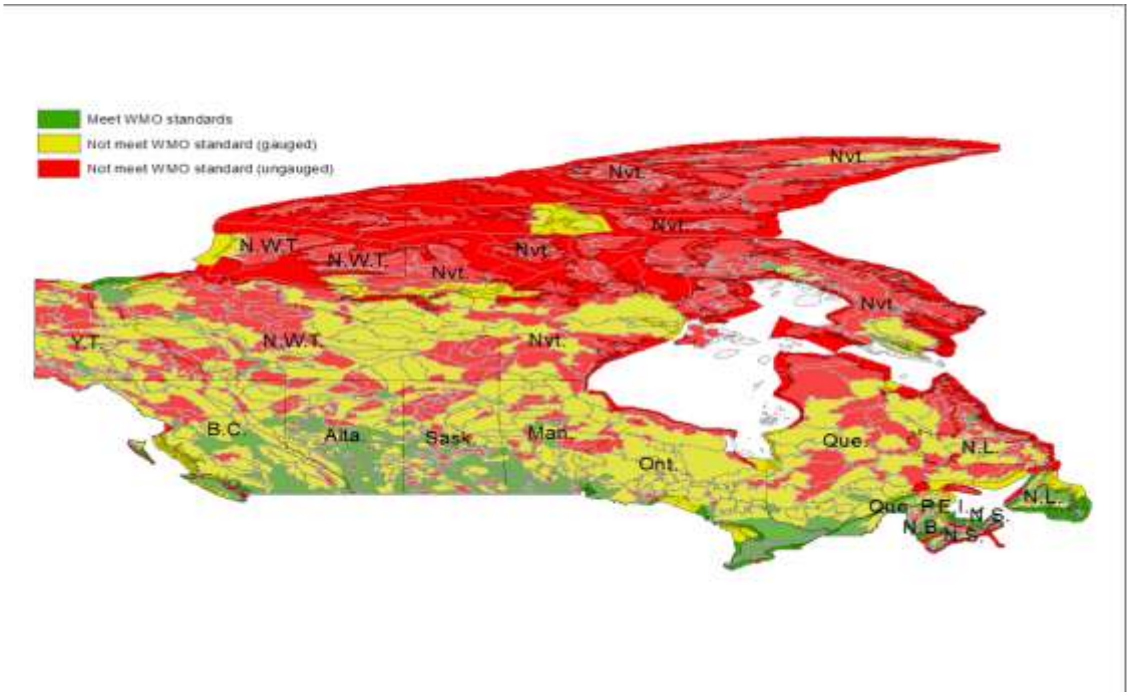
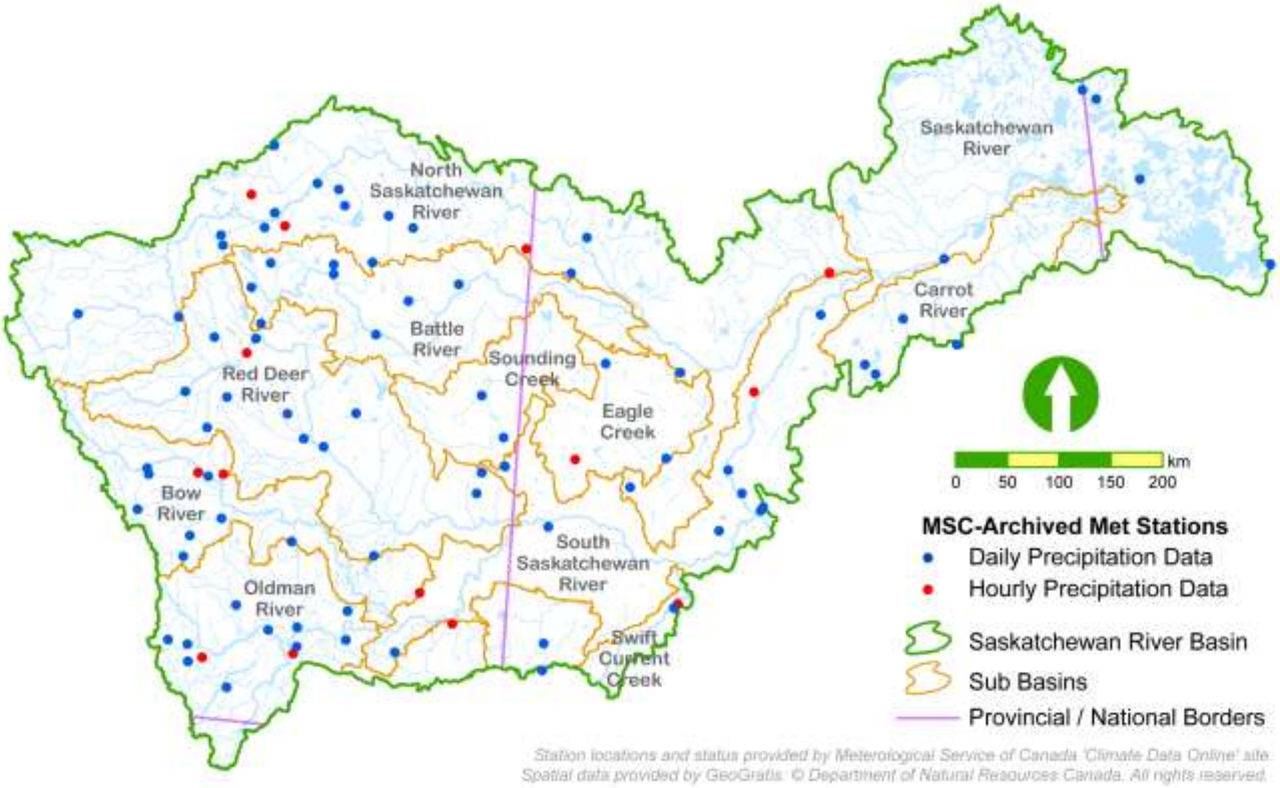


Figure 39. Map of Canada showing hydrometric station density in relation to World Meteorological Organisation (WMO) standards by river basin, from Coulibaly and Samuel, 2011.

3.1.1.2 Weather and snow data

Weather stations are operated by the Meteorological Service of Canada (MSC) in Saskatchewan, Alberta and Manitoba and supplemented by an extensive network of high quality agricultural meteorology stations in Alberta's agricultural regions run by Alberta Agriculture and Rural Development, by a network of forest fire meteorology stations in the Alberta forest regions run by Alberta Sustainable Resource Development and supplementary stations for hydrological and river forecasting by Alberta Environment and Water, mainly in the mountains. Alberta provincial meteorological data is quality controlled and made publically available in near-real time. There are several independent meteorological station networks in Saskatchewan with over 800 stations, but their data is not necessarily shared, assembled in near-real time, or of sufficient quality for hydrological assessments. For instance, Saskatchewan runoff is overwhelmingly produced by snowmelt but there is almost no snow data collected by these independent networks. Weather stations that are archived by MSC and therefore meet World Meteorological Organisation standards are shown in Figure 40. In the United States portion of the Saskatchewan River Basin additional meteorological stations are operated by the US National Weather Service of NOAA and by the Natural Resources Conservation Service of the USDA; these meet international standards but are not archived by MSC and snowfall measurements are conducted with different gauges than those employed by MSC. The weather stations of most interest are those that also measure both snowfall and rainfall and can provide precipitation rates in near real-time. Besides inadequate stations numbers in the mountain headwaters, what is remarkable about Figure 40 is the sharp decline in high quality weather stations east of the Alberta border. With very few weather stations in Saskatchewan it is difficult to impossible to reliably calculate streamflow using normal hydrological techniques. This is especially apparent in Figure 38, where there are only two meteorological stations making hourly observations in the vicinity of the lake. Given that convective storms that are responsible for summer flooding have typical length scales of less than 30 km, having fifty to hundreds of kilometres between stations will mean that hydrologically important precipitation events can be missed.



Station locations and status provided by Meteorological Service of Canada 'Climate Data Online' site. Spatial data provided by GeoGratis. © Department of Natural Resources Canada. All rights reserved.

Figure 40. Meteorological stations in the Saskatchewan River basin that are archived by the Meteorological Service of Canada.

Eleven of the Alberta weather stations and two NRCS stations in Montana also have snow pillows which measure snow water equivalent (SWE) on the ground at a point; these snow pillows are operated at mid to high elevations in the Rocky Mountains as their design is unsuitable for shallow prairie snowpacks (Pomeroy and Gray, 1995). Snow pillows provide near real-time SWE measurements which are invaluable for estimating mountain snowpacks. However their locations are usually restricted to mid-mountain elevations and so they miss low elevation and high elevation snowpack development and ablation. Alberta also has a network of formal snow surveys of snow depth and density starting in December and running through May, mainly in the mountains but also in the foothills and prairie regions and in the Cypress Hills (Figure 41). These snow surveys provide an important supplement to the point snow pillow snow water equivalent estimation as there is a substantial spatial variability that puts much uncertainty on point snow measurements and snow pillows are subject to measurement errors from ice covers, snow bridging and retention of snowmelt water on top of the pillow (Pomeroy and Gray, 1995). We could not find any details on Saskatchewan's snow survey network, but apparently some snow surveys were conducted in 2011.

Reanalysis data sets

Reanalysis data can supplement direct measurement of meteorological variables at stations. Reanalysis data sets are produced by gridding measured variables, which are then loaded into a Regional Circulation Model (RCM), which a program used for simulating weather. The RCM is then run for a single time step and the variables are output, which produces gridded values interpolated using physically-based calculations. Although the quality of reanalysis data needs to be evaluated, the data sets potentially provide a source of meteorological data in regions without meteorological stations. Reanalysis data sets can also be used as sources of variables such as solar radiation which are seldom measured but required for physically-based hydrological modelling.

Locations provided by Alberta Environment
Spatial data provided by GeoGratis:
© Department of Natural Resources Canada. All rights reserved.

Figure 41. Snow survey courses and snow pillow sites in Alberta. There are eleven snow pillow sites in the in Alberta and two sites in the Montana portion of the Saskatchewan River Basin, mainly in the Bow and Oldman River mountain headwaters.

In a recent unpublished study, Pomeroy and Sinclair (2012) found that the network of weather, snowpack and hydrometeorological stations in the Canadian Rocky Mountains does not reflect the frequency distribution of elevations in this region. Furthermore, each precipitation station in the Canadian Rocky Mountains samples on average 23½ times more terrain than is recommended by the WMO as its minimum standard. A precipitation index was used to assess the distribution of the current network in terms of where the majority of precipitation is delivered. While an estimated 77% of precipitation volume is received above 1500 m, only 54% of weather stations are located above this elevation. This situation is exacerbated at higher elevations (>2000 m), highlighting the urgent need for additional observational sites in the Rocky Mountains and reanalysis to improve the applicability of existing data.

There are a few snow depth measurements on the ground made at certain MSC stations in Saskatchewan and remote sensing and model products are available from MSC and from the NOAA National Operational Hydrologic Remote Sensing Center (NOHRSC) in Minnesota to enhance this sparse data. Unfortunately, passive microwave remote sensing maps http://www.socc.ca/CMS%20FTP%20Data/snow/swe/snow_swe.html have serious problems with reliability during the melt period, over unfrozen soils, where there are ice or dust layers, where there is vegetation and for deep snowpacks and so require careful validation and bias adjustment from snow surveys to be a reliable contribution to streamflow forecasting. The Canadian Meteorological Centre produces snow depth maps with 1/3^{o} resolution based on ground based snow depth measurements interpolated over space and time using temperature and precipitation fields from the MSC numerical weather prediction model http://www.weatheroffice.gc.ca/data/analysis/352_50.gif. NOHRSC flies gamma airborne snow surveys over Missouri River and Souris River drainages but not over the Saskatchewan River Basin. It does provide a 1 km resolution SWE product based on an assimilation of available surface and satellite information, numerical weather prediction model outputs into a physically based blowing snow and snowmelt model called SNODAS http://www.nohrsc.noaa.gov/nsa/ that is partly based on snow models developed in Saskatchewan (Pomeroy and Li, 2000). SNODAS model results provided by NOHRSC extend northward into central Saskatchewan and Alberta and are used by flood forecasters in NOAA river forecast regions. Though SNODAS is considered the 'state-of-the-art' for operational SWE products, it has not been evaluated for Saskatchewan, but provides a potentially valuable information resource for river forecasting by SWA.

3.1.1.3 Streamflow forecasts

Alberta Environment and Water

Alberta Environment and Water periodically issues long-term forecasts of cumulative streamflow volumes, which are seasonal totals (March 1 – September 30) rather than monthly values. Figure 42 shows forecasted and measured streamflow volumes as a percentage of the long-term mean. The measured volumes were all above normal; approximately 120% of normal for the Bow River and 150% of normal for the Oldman and Red Deer Rivers. As shown in Figure 42, the 2011 March and May forecasts for Oldman and Red Deer River were for normal to below normal streamflow volumes and therefore substantially underestimated the actual streamflow volumes, while the Bow River estimates were quite close to the actual streamflow volume. August forecasts were for much higher streamflow volumes. The Alberta Environment and Water forecasts are probabilistic in that they include the probability distribution of future precipitation runoff. As the forecast assimilates recorded values, the forecasts converge on the recorded flows for forecasts made later in the prediction period.

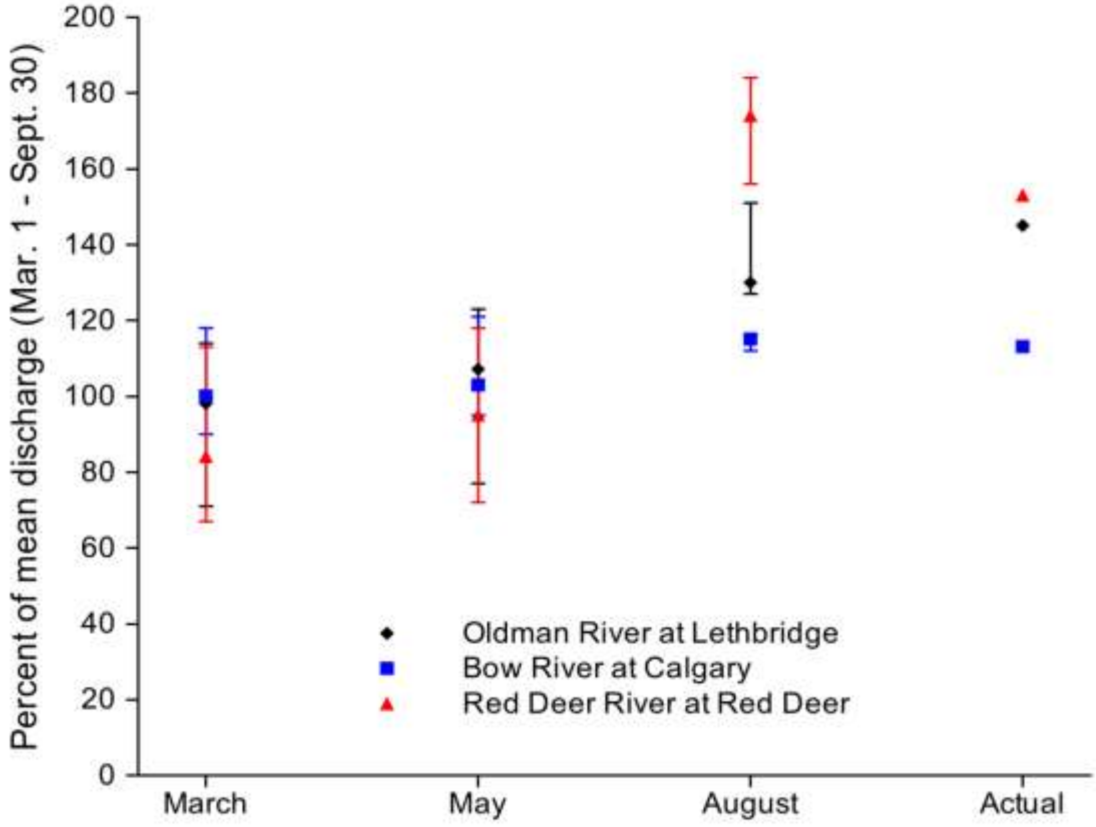


Figure 42. Alberta Environment and Water water supply forecasts for March through September 2011, made in March, May, and August and 2011 actual streamflow volume compared to long-term mean streamflow volumes. The error bars denote the maximum and minimum values of the forecast cumulative flows.

3.1.2 Internal

3.1.2.1 Tools and procedures

The tools and procedures used by SWA staff during the high flows of 2011 were antiquated and contributed to confusion amongst the public in interpreting decisions made by SWA. Because the travel time of flows from the upper basins of the Oldman, Bow and Red Deer River basins is on the order of days, as are the travel times downstream of Gardiner Dam to the Saskatchewan River, SWA has operated on a daily time step. Daily time steps are likely adequate for water supply forecasting, but not for high flow forecasting. The high flow events in 2011 demonstrated that shorter operational time intervals are required, which will require improvements in the tools and procedures used by the SWA staff.

Calculations
Routing of flows is one of the most important tasks carried out by SWA hydrologists. Unfortunately the

tools available to them are limited to spreadsheets, which are used to route daily flows. As described previously, these procedures are slow, laborious and prone to error and should be automated. The small number of streamflow forecasters employed by SWA need to have efficient use of their time made during flood events. Doing routine routing calculations manually is not efficient. Because of the sparse hydrometric network in Saskatchewan, routing of flows is more difficult downstream of Lake Diefenbaker than upstream, and it may be necessary to use fairly sophisticated methods there, such as the kinematic wave method (which can be done without use of measured flows), to compensate for the lack of measured flow data.

As described above, calculation of inflows to Lake Diefenbaker is done by routing inflows and as a residual from changes in storage and computed discharges. Currently the effects of changing head on the spillway gates are not considered when computing either inflows or discharges, reducing the accuracy of both. These calculations should be done automatically.

Data collection

Currently, all external data is gathered by a program developed in house (written in Microsoft Access) which collects data once per day and stores it in a Microsoft Access database. There are many problems associated with the use of this program.

Maintenance and reliability

The use of an in-house developed program is subject to many risks. The collection, management and dissemination of hydrometric and meteorological data are mission-critical for SWA, and reliance on an unsupported program risks SWA operations. The original developer is no longer at SWA, increasing the risk of system outage.

Performance

The current data collection system is very inefficient. Because the system is slow, running as an interpreted script, and only downloads data once per day, it takes a great deal of time to download all of the previous day’s data. A more efficient system of the type typically used by other water management organizations would download the data as they become available, typically every hour. By distributing the data collection over the day, the data more accurately reflect current conditions and the wait for data is reduced.

The use of a modern database will allow the collection of time series datasets having a wide variety of time steps. Hydrometric data are often gauged at 15-minute intervals. Meteorological data are generally reported hourly, although some values are computed daily. Because of the limited resolution, and the effects of wind, residual inflows to Lake Diefenbaker will often be computed daily. The database needs to record the data as they are available and to produce derived products through aggregation, recalculation and interpolation as required by end users and by any models used.

Industrial quality database

Many emails during the events of the spring/summer 2011 are requests for information within SWA. Evidently, a central database which is accessible to all concerned users is required. Such a system needs to be robust, based on reliable servers which provide data to clients. The system needs to be secure, controlling access to the data by job requirement.

Data sources

The current system downloads raw data directly from Environment Canada. As described previously, the EC data are not quality controlled, and may contain gaps. Many of the hydrographs plotted in Appendix 1 display missing values, and the plot of the North Saskatchewan River at Prince Albert in Appendix 1 has a segment from early February through early March 2011 which was obviously erroneously shifted upward, possibly through the effects of icing. Unlike Environment Canada, Alberta Environment and Water does daily QA/QC (more often during flood events) on meteorological and hydrometric data. Currently SWA has access to these data throughout an antiquated program called NewLeaf, whose use by Alberta Environment and Water may not be continued in the future. Unfortunately, the NewLeaf software does not allow the data to be downloaded to the SWA database.

Reporting

The reporting capabilities of the current system are weak. While it is capable of producing simple hydrographs it is not web-capable. During the spring/summer 2011 high flow events, there were many questions from outside clients and agencies regarding basic flow data, which should have been answered by frequently updated graphs and reports and/or realtime queries of the database. Alberta Environment, for example has made tables and plots of flows, stages, and meteorological data available on their website since 2005 at http://www.environment.alberta.ca/apps/basins/. The web data tables are updated hourly; the plots are updated at least daily and more frequently during high flow events.

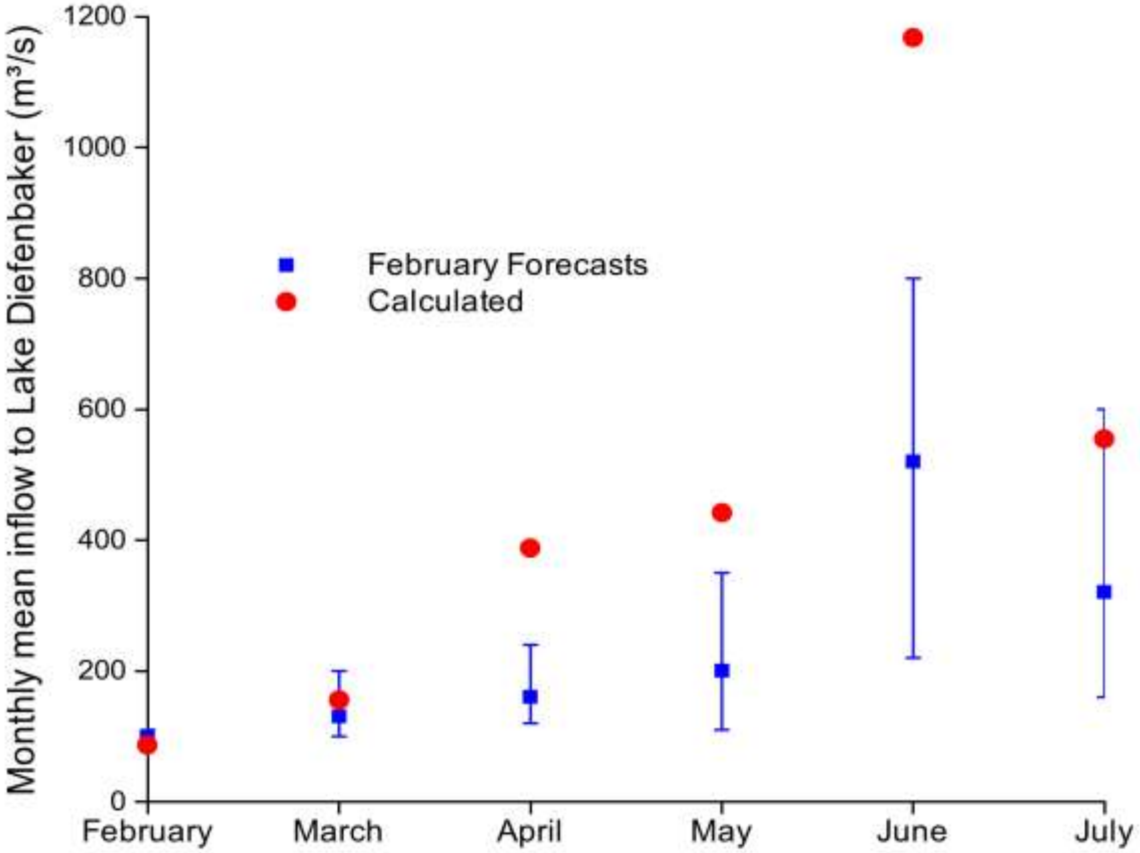
Conversations with SWA staff indicate that they are well aware of the deficiencies of their current data collection and management system. The program Aquarius by Aquatic Informatics Inc. has been purchased to manage the hydrometric and meteorological data of SWA. Unfortunately, the program has not yet been made operational. Although Environment Canada is currently using Aquarius, Alberta Environment and Water uses a competing system, and integration of the two systems will require time and effort. Obviously, full implementation of the Aquarius software, and acquisition of realtime data from Alberta Environment should be a top priority for SWA.

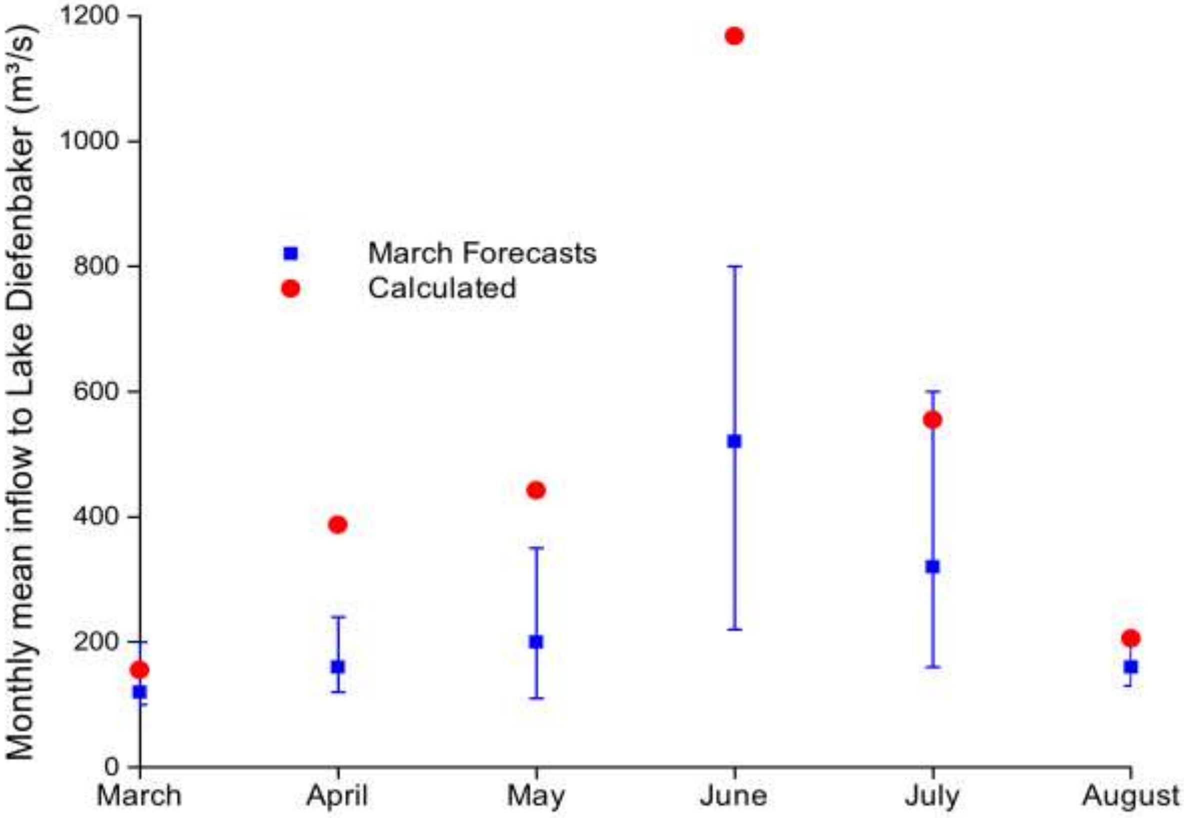
3.1.2.2 Inflow Forecasts

Long-term forecasts of inflows to Lake Diefenbaker

SWA produces long-term forecasts of inflows to Lake Diefenbaker. The method is probabilistic, in that it provides a range of forecasts which represent varying probabilities of future precipitation. The primary purpose of the estimates is to determine if inflows will be sufficient to fill the reservoir.

Monthly inflow forecasts were prepared by SWA in February, March and April of 2011. As shown in Figure 43 all forecasts consistently underestimated the monthly inflows significantly, by a factor of two for June 2011. Surprisingly, the February, March and April forecasts changed very little from month to month, despite reports of rapidly increasing mountain and prairie snowpacks in this period.


Monthly mean inflow to Lake Diefenbaker (m^3/s)
0
200
400
600
800
1000
1200
February
March
April
May
June
July
■ February Forecasts
● Calculated


Monthly mean inflow to Lake Diefenbaker (m^3/s)
0
200
400
600
800
1000
1200
March
April
May
June
July
August
■ March Forecasts
● Calculated

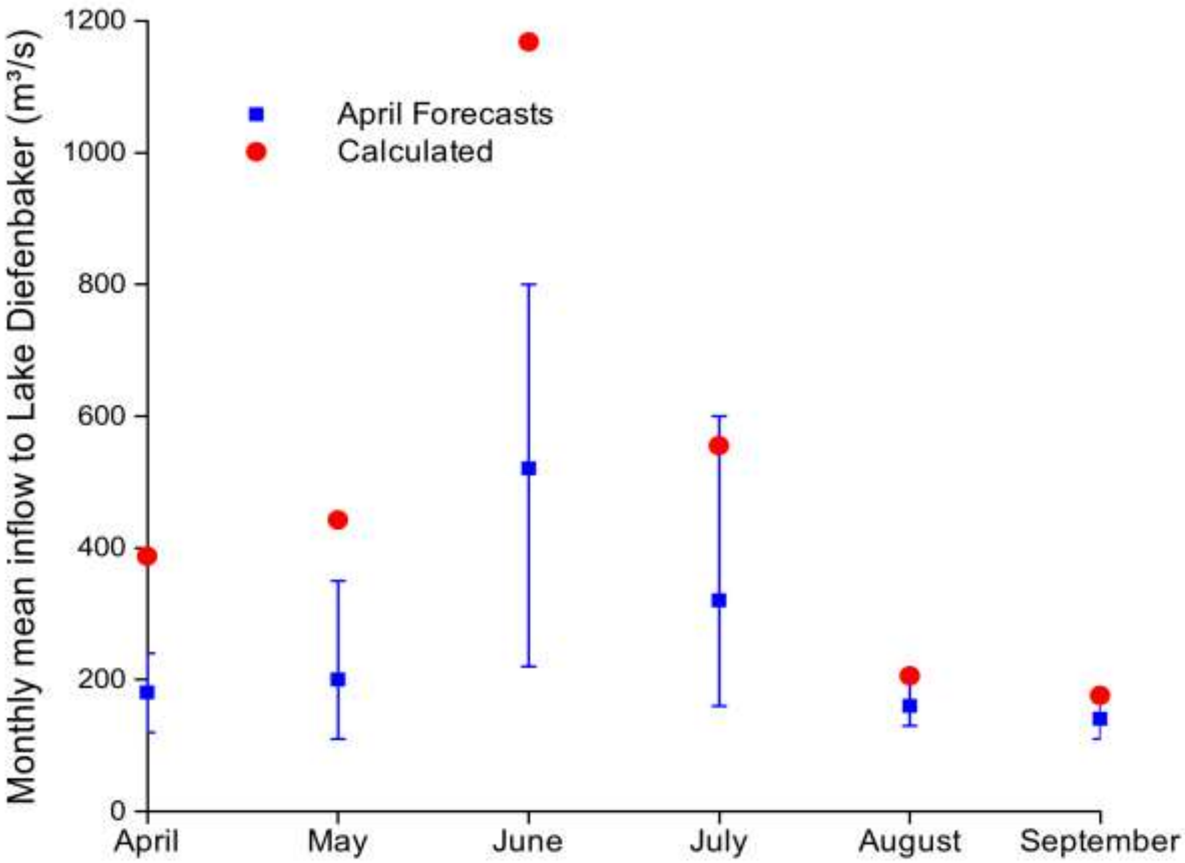


Figure 43. 2011 monthly SWA inflow forecasts and calculated actual inflows for Lake Diefenbaker: a) February, b) March, c) April.

Assessment of Snowpacks
As described above, the state of the mountain snowpack is an important state variable used in the monthly inflow forecasts. The assessed state of the mountain snowpacks in the Monthly Provincial Forecasts from January through April was assessed as:

> “Snowpack accumulations in the mountain headwaters of the North Saskatchewan River basin are below normal. Snowpack accumulations in the mountain headwaters of the South Saskatchewan River basin range from well below normal in the Bow river Basin to above normal in the Oldman River basin.”

It is surprising that the the Monthly Provincial Forecasts did not include the Red Deer River Basin. As shown in Table 5, the mean flow of the Red Deer River at Red Deer is approximately 22% of the total of all three major tributaries of the South Saskatchewan River.

Conversations, official documents and presentations, revealed that the SWA staff were under the impression that mountain snowcovers were at low levels until the spring of 2011. It is believed that this is due to the prevalent use of Alberta Environment Snow Pillow data. Although the snow pillows are useful for their near-real time information, they are well below WMO standards for the spatial density of observations, and operate in a relatively narrow elevation band; it is recommended to supplement them by including snow survey data in all analyses. Also, snow pillows are biased as they are situated in forest clearings, while snow surveys incorporate many sites and can be more representative of a region. Because the frequency distributions of SWE are typically skewed, it is recommended to use evenly-distributed measures such as the non-exceedence frequency when comparing values.

Table 5: Basin areas and mean annual flows for the Red Deer, Bow and Oldman Rivers. The locations were selected to incorporate the headwater tributaries, while being upstream of major irrigation uses.

Basin and Location	Gross area (km^2)	Mean annual flow (m^3/s)	Period of record
Red Deer at Red Deer	11,600	47.7	1912-2010
Bow River at Calgary	7,870	89.9	1911-2010
Oldman River near Lethbridge	17,000	80.2	1911-2010

Plains snowpacks

January

There was awareness as early as January of the potential for heavy runoff due to the snowpack in the western agricultural region being well above normal, and the wet conditions of the soil. The January 15 Map of Runoff Potential clearly shows the region surrounding the main stem of the South Saskatchewan River as having high potential runoff, while the Cypress Hills are shown as having very high potential runoff.

February

In the February report, the majority of the South Saskatchewan River Basin is shown as having “Above Normal” potential runoff. The report also notes the presence of a moderate La Nina in the equatorial Pacific which was had the potential to bring significant annual snowfall, although the report did not specify if this pertained to the mountains or plains.

The report also mentions the difficulty in reconciling the satellite estimates of SWE with accumulated winter precipitation measurements and with snow surveys. The limitations of the satellite passive microwave measurements used by the Environment Canada product are very well known (Brown et al., 2007). Similarly, the effects of blowing snow redistribution on prairie snowcovers in relocating snow and removing snow by sublimation are also very well documented (Pomeroy et al., 1993). These processes have been shown to change the temporal frequency distribution of SWE on the ground to be very different from that of the accumulated snowfall (Shook and Pomeroy, 2010).

March

In the March report, the area shown having “Well Above Average” runoff potential was greatly expanded over the previous month. Snow surveys conducted by SWA were said to demonstrate that the satellite SWE values were greater than the surveyed measurements.

Assessment

The current method for estimating long-term inflows to the reservoir is not necessarily defective. However, it is primarily a method for determining whether spring and summer inflows will be sufficient for water supply needs, rather than a method for predicting high inflow events. A method designed to manage water supplies under drought conditions is not necessarily suited for high flow conditions. As Saskatchewan is anticipated to experience greater extremes of drought and flood under climate change and has experienced both its wettest and driest recorded conditions within the last 10 years then a more robust system is necessary to predict high flow events

Any method for estimating future inflows to the reservoir must deal with the fact that future precipitation is highly uncertain. It must also deal with the fact that the accumulated snow is only a fraction of the total discharge, and that not all of a river's discharge originates in its headwaters.

Limitations of predictability

Use of the long-term predictions is predicated on the assumption that winter snow accumulation is a reliable index of future streamflow. Whilst snowmelt does provide the majority of streamflow in the basin, much snowfall occurs in late winter or early spring. Subsequent to peak snow accumulation, melt rates, surface depressional storage capacity and soil moisture all influence runoff generation from snowpacks. There are several sources of error in arriving at inflow forecasts from the snow accumulation information available from winter snow surveys.

Future snow accumulation

As shown in Figure 44, the fraction of the peak annual snow accumulation of the surveyed sites is quite low in December and January, because nearly 50% of the total of the annual peak accumulations occur in February or later. The effect is more severe at high elevations where we have observed 2/3rd of seasonal snowfall to occur after 1 April in Marmot Creek Research Basin, Alberta in recent years.

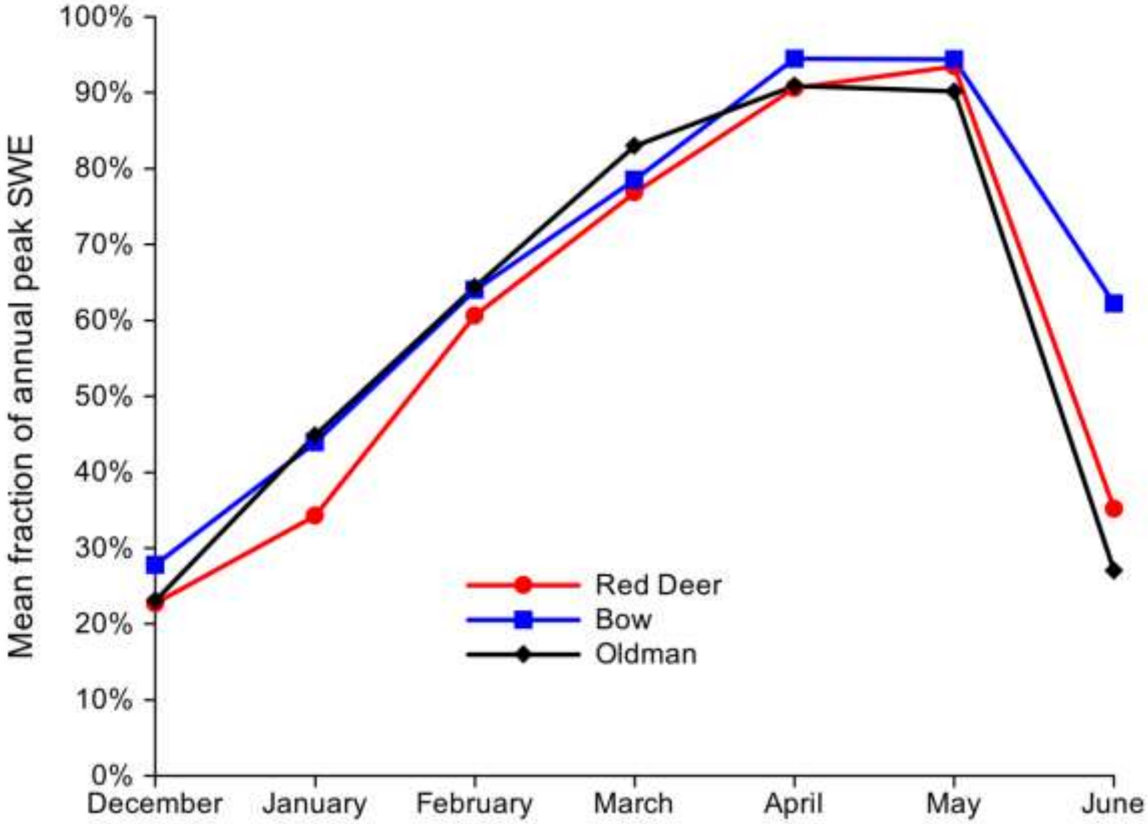


Figure 44. Mean monthly fractions of annual peak SWE accumulation for Oldman, Bow and Red Deer Rivers.

Simple linear regressions were performed for each snow survey in the mountain headwaters of the Oldman, Bow and Red Deer River basins. For each site, the May SWE values were regressed against the SWE values of the months December through April. As shown in Table 6, the magnitude of the mean value of r^2 for the linear models was very small for the months of December and January, only becoming greater than 0.5 in February. This means that early winter snow surveys have very little predictive value for peak snow accumulation in the Canadian Rockies.

Table 6: Mean value of r^2 for regressions of monthly SWE accumulation against peak SWE accumulation. All data from Alberta Environment mountain snow surveys in headwaters of Oldman, Bow and Red Deer Rivers. Only those data sets having more than 10 values were included.

Month	Mean value of r^2
December	0.04
January	0.37
February	0.61
March	0.77
April	0.89

To test whether the relative frequency of SWE was more stable and predictable over time, regressions were also conducted of the exceedence frequencies of monthly SWE accumulations against the exceedence frequency of the May SWE accumulations. Unfortunately, as shown in Table 7, the peak exceedence frequencies are no more predictable as the peak snow accumulations.

Table 7: Mean value of r^2 for regressions of exceedence frequencies of monthly SWE accumulation against exceedence frequencies of peak SWE accumulation. All data from Alberta Environment mountain snow surveys in headwaters of Oldman, Bow and Red Deer Rivers. Only data sets with more than 10 values were included.

Month	Mean value of r^2
December	0.06
January	0.23
February	0.58
March	0.72
April	0.83

Fraction of reservoir inflow due to mid-winter mountain snow accumulation

The difficulty of predicting the spring and summer inflows to Lake Diefenbaker is increased by the fact that a portion of the inflow is due to late winter and early spring snowfall at high elevations and spring rainfall after the forecast is made rather than the winter mountain snowpack which is known when the forecast is made. The Water Supply Outlook reports produced by Alberta Environment are similar to the SWA procedures for producing water supply forecasts in that they are statistical in nature, are intended for the use of water managers and are based in part on the accumulated mountain snowpacks at the time of preparation. Statistical forecasts tend back to normal conditions for the future and are adjusted by known departures from normal at the time of forecast. Although the number of reports, and the months for which forecasts are issued, have declined in recent years, March forecasts for the total streamflows during the period of March through September for the Oldman, Bow and Red Deer basins are available for all years, except for 2005, when only the Oldman forecasts were produced. These forecasts are based on the winter snowpack development, but are not based on information regarding the late winter/early spring high elevation snowfalls or spring rainfall. Quite often what will distinguish a high flow from a low flow year is the occurrence of significant depths of high elevation snowfall and mountain/foothills rain in May and June and of course their occurrence cannot be accurately predicted in March.

To avoid the effects of major consumptive uses on streamflow, the Alberta forecasts for the furthest upstream points on the main stems of the Oldman, Bow and Red Deer basins were selected for analysis. The March forecasts were evaluated over their period of record (November 2001 – November 2011) against the actual flow totals. As shown in Figure 45, the majority of errors are positive indicating that the forecast was smaller than the actual value. The only exception was the Oldman forecast for 2002 when early spring rains were followed by a drought, causing the forecast to greatly overestimate the total flow. That the relative error in the forecasts is greatest for large magnitudes of the flows indicates the importance of late winter snow and spring and summer rains to the annual discharges and that the largest flows, which are most important to forecast for flood management, are the most difficult to forecast.

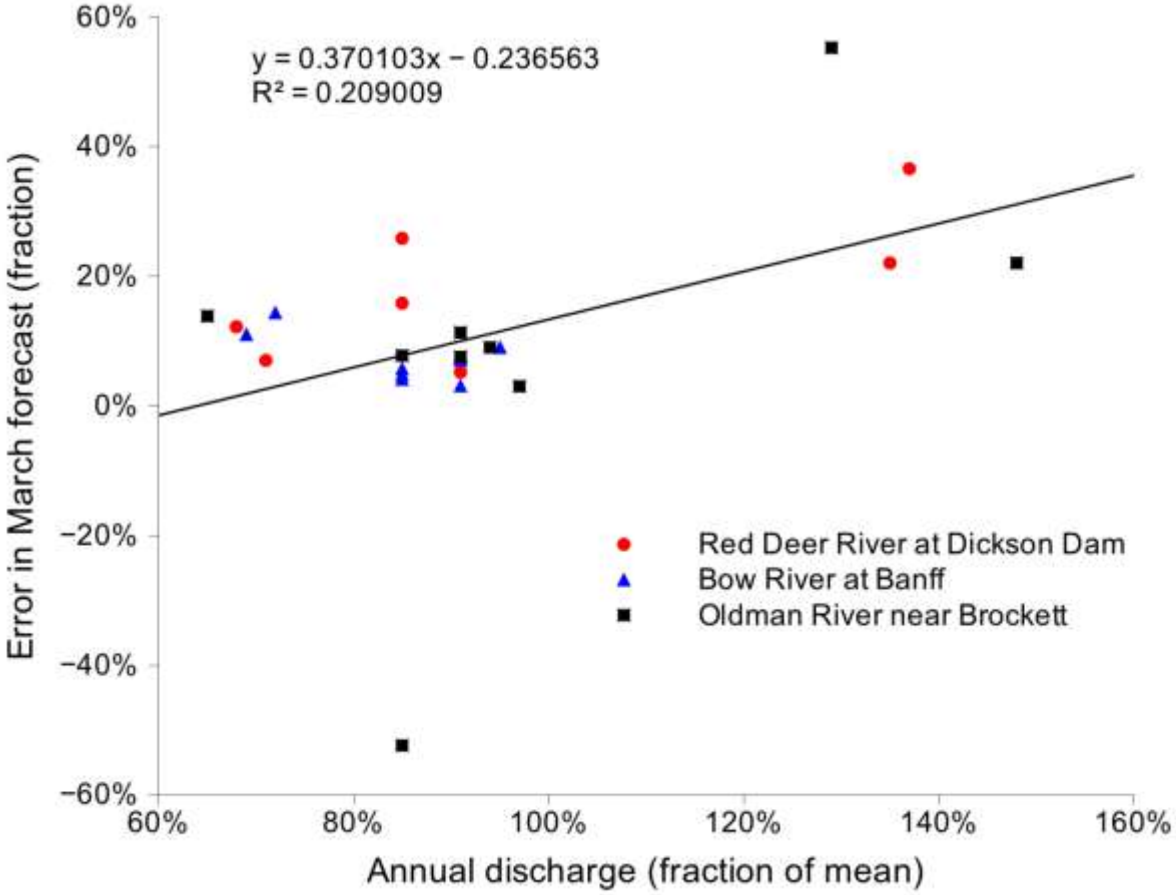


Figure 45. Percentage error in Alberta Environment forecasts of annual discharge of Oldman, Bow and Red Deer Rivers, over the period November 2010 - November 2011.

Short-term forecasts of inflows to Lake Diefenbaker

The short-term inflow forecasts were extracted from the documents titled “SASKATCHEWAN RIVER BASIN FORECAST OF STREAMFLOWS AND RESERVOIR LEVELS” which were produced over the interval of June 13 – July 27, 2011. Although more forecasts are presumed to have been issued, they were not made available. The issued forecasts of inflow are plotted along with inflows estimated by routing upstream flows obtained from Alberta Environment and Water in Figure 46. As both sets of estimates are obtained by simple routing, it is not surprising that they are very similar, with the SWA forecasts tending to divert from reality at their later values.

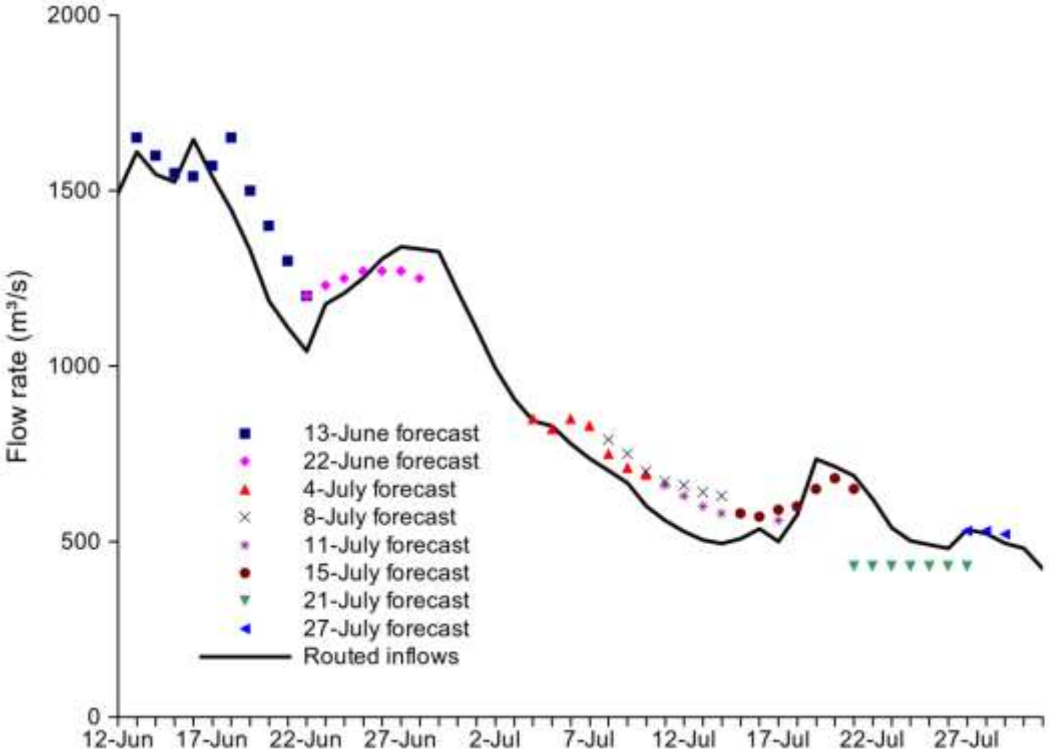


Figure 46. Short-term forecasts of inflows to Lake Diefenbaker issued by SWA, and inflows estimated by routing upstream flows obtained from Alberta Environment.

3.1.2.3 Outflow forecasts

Forecasted discharges from the Gardiner Dam were extracted from the SWA documents as described above, and are plotted along with the SWA estimated discharges in Figure 47. Unlike the inflow forecasts, the discharge forecasts differ greatly from the actual streamflows, particularly when the discharges change rapidly as on the recession limb. By three days, the usefulness of the forecast discharges approaches zero during high flow events, and so the forecasts may be quite misleading. This creates a serious perception problem for SWA with users of these forecasts. Forecasts of outflows need to be rethought, with the forecasts being issued much more frequently and, if their quality cannot be improved, for shorter look-ahead periods.

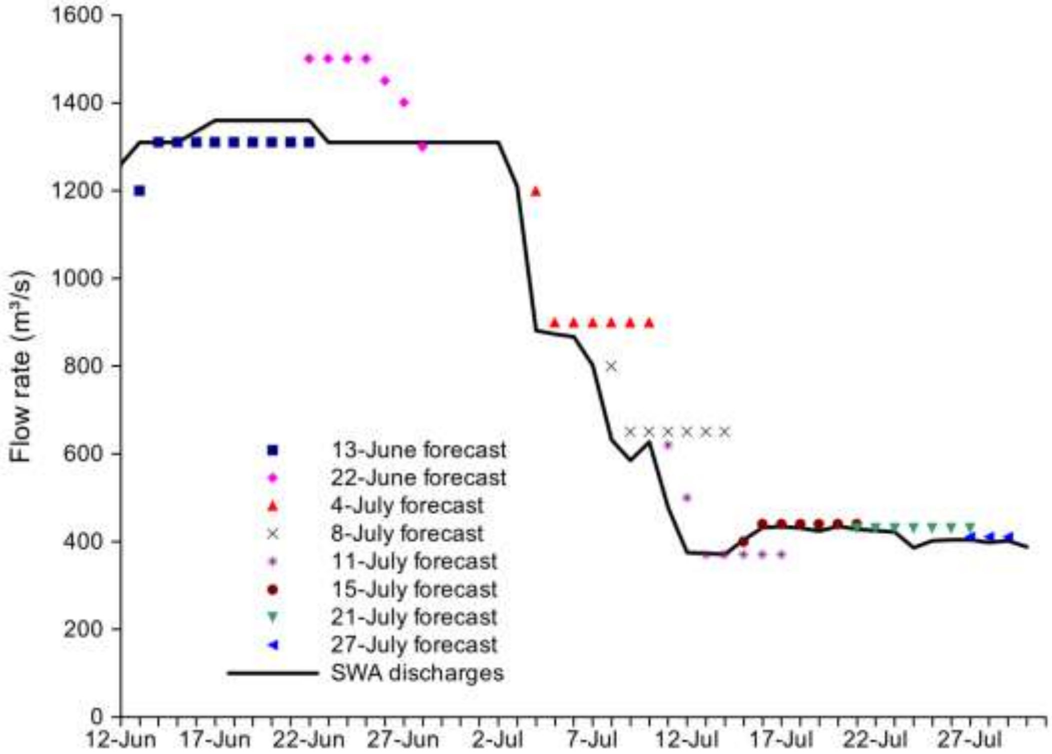


Figure 47. Short-term forecasts of discharges from Lake Diefenbaker and discharges (sum of spillway and powerhouse flows) computed by SWA.

3.1.3 Suggestions for improvement of forecasts

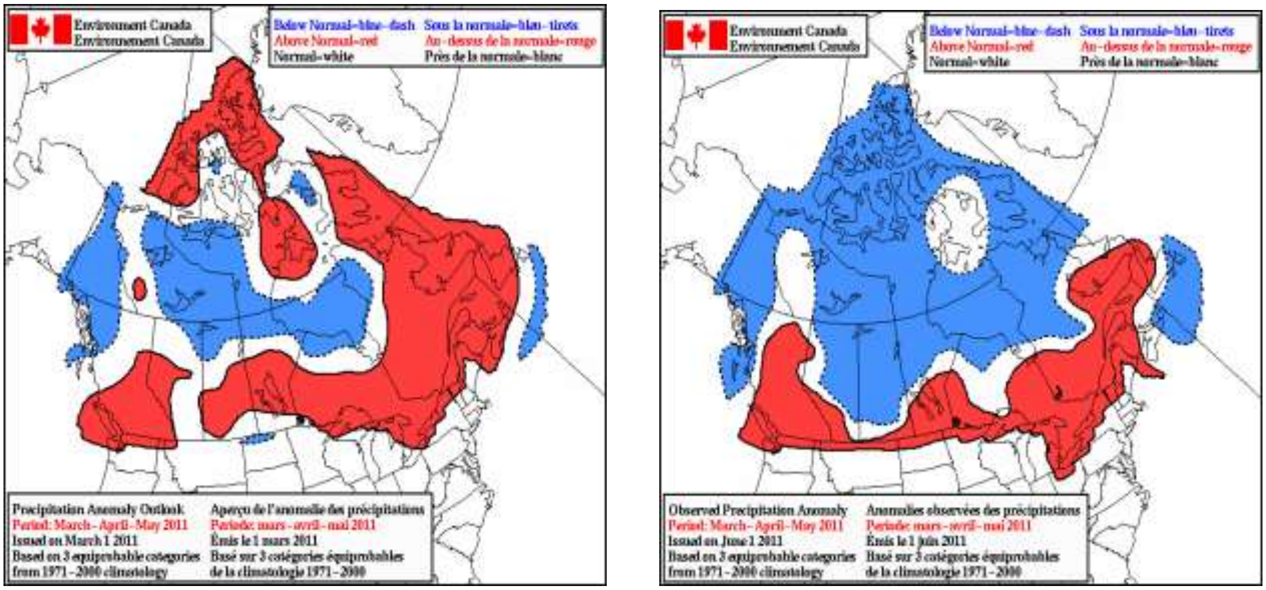
The poor performance of the inflow forecasting models based on the measured snowpack and estimates of future precipitation have not generally been problematic for operations, as they are were intended to indicate the probability of future low flows. However, if forecasts are to be used for managing high inflows, then the forecasting procedures will need to be improved. The degree to which it is possible to create accurate forecasts remains to be investigated; it should at least be possible to assess the risks of various inflow scenarios.

3.1.3.1 Long-term inflow forecasts

Because of the uncertainties associated with long-term weather forecasts, long-term forecasts of inflows to the reservoir will probably be probabilistic (based on statistics) rather than deterministic (forecasts of single values).

Incorporation of long-term weather forecasts
Long-term precipitation forecasts are available from Environment Canada. As shown in Figure 48, the precipitation anomaly forecasts of March through May displayed some skill, although the level of skill was generally low in the South Saskatchewan River basin upstream of Lake Diefenbaker. At the time of writing, the variety of long-term forecasts have been increased and both probabilistic and deterministic forecasts for periods of 1 to 12 months are available. Because it is probable that the shorter-term

forecasts are more accurate than the longer forecasts, the usefulness of the various forecasts will need to be evaluated.



a) Forecast precipitation anomalies for March through May 2011.

b) Observed precipitation anomalies for March through May 2011.

Figure 48. Forecast and observed precipitation anomalies by Environment Canada in late winter and spring 2011.

ENSO and PDO signals

St. Jacques et al. (2010) showed significant relationships between the state of the Pacific Decadal Oscillation (PDO) and annual flow for streams originating in Southern Alberta. As the PDO is also believed to be related to the ENSO, incorporation of these signals may lead to inflow forecasts of greater accuracy. Similar techniques are used for forecasting in Australia, where hydrology is much more strongly coupled to the climate of the ocean.

Non-stationarity

By definition, all regression-based models assume that historical conditions are a guide to future flows. However, as shown by (St. Jacques et al., 2010), there are statistically-significant trends in historical flows that cannot be explained by human use or by short-term climate signals such as ENSO or PDO. Climate change is reducing the reliability of models based on the assumption of stationarity and new flow estimates for new climates will have to be developed, most likely from coupled hydrological and atmospheric models currently under development and assessment by Environment Canada (www.usask.ca/ip3/models.php).

3.1.3.2 Short-term inflow forecasts

It is rare in North America for a river forecasting centre to not possess a capacity to perform hydrological modelling. SWA takes all Alberta-derived snowmelt and rainfall runoff forecasts from

Alberta Environment and Water, but has no ability to confirm or improve these forecasts or to model prairie snowmelt runoff or local inflows to Lake Diefenbaker. The lack of modeling capacity is probably due to the lack of perceived necessity due to Alberta Environment and Water conducting headwater basin modeling, the great importance of routing in long rivers, the lack of data management infrastructure, and the significant labour required to implement a program of hydrological modeling.

Implementing independent modelling of the Saskatchewan River Basin headwaters will allow SWA to be independent of Alberta Environment and Water capabilities, to reduce uncertainty in forecasts and to evaluate the effects on inflows to Lake Diefenbaker of inflow and operational scenarios. Use of the Alberta Environment and Water database system would provide access to their model, which is a component.

The simplest form of inflow forecasting to implement is simply to route gauged upstream flows, as has been described further. As Alberta Environment and Water has already constructed routing models for the South Saskatchewan River, they should be contacted to see if it is possible to obtain these models. The Alberta Model also provides simple ways of estimating rainfall and snowmelt runoff in mountain basins, which can used to extend the period of time. Although the Aquarius software selected by SWA does not contain a modeling package and is therefore not compatible with the model used by Alberta Environment and Water, it may be possible to run the Alberta models remotely or to use the existing routing calibrations in another modeling platform.

Calculation of local (prairie) inflows

As discussed previously, the ungauged inflows to the reservoir were an important component of the inflows in the spring of 2011. Although SWA staff were aware of the potential for heavy local inflows from the prairies, they had no means to estimate what the flows would be.

The unusualness of the 2011 inflows demonstrates that modeling of prairie flows to Lake Diefenbaker will remain of a lower priority than the routing of upstream gauged flows. Furthermore, modeling prairie streamflows is difficult and cannot be done accurately by virtually all hydrological models (Pomeroy et al., 2007). Prairie hydrological processes include accumulation of snow (which is modified by relocation and sublimation due to wind), melt driven by solar radiation, snow internal energy change, infiltration to frozen soils, and rainfall which is typically unable to produce runoff (Gray et al., 1984, 1986; Pomeroy et al., 1998.

Prairie hydrography is unusual in that it is dominated by wetlands. In many prairie “basins” there is no stream, which is a fundamental requirement of almost every hydrological model. Where there is a stream, the wetlands control the fraction of the basin which contributes to flow, as the wetlands fill and spill into their neighbors. The dynamic nature of the contributing area has long been noted by researchers (Stichling and Blackwell, 1957) but has not been incorporated in the majority of hydrological models. Recent research has incorporated wetland effects in prairie hydrological models and found it to be immensely important in predicting streamflow volumes and peaks (Pomeroy et al., 2010). An ability to calculate prairie inflows would permit SWA to assess the importance of wetland drainage, tillage practice and extreme meteorology (for example, freezing rain events) on runoff events and potential inflow to Lake Diefenbaker and other reservoirs.

CRHM (Cold Regions Hydrological Modelling platform) is developed at the Centre for Hydrology at the University of Saskatchewan (Pomeroy et al., 2007). CRHM is uniquely capable of reproducing the cold regions and variable contributing area processes of prairie hydrology. Current work at the Centre for Hydrology is leading to the incorporation of dynamic contributing areas in CRHM models (Shook and Pomeroy, 2011) and application from a few hectares to thousands of km^2.

CRHM is a physically-based deterministic model, but can be used to estimate flows resulting from unknowable future conditions by using multiple future scenarios. The scenarios can be based on long-term forecasts or normal of precipitation and temperature. Unfortunately, CRHM would require substantial investments of human and IT resources to be implemented by SWA. An advantage is that a prairie hydrological modelling capacity would also be useful for rivers, lakes and reservoirs not dominated by mountain runoff, i.e. in most of Saskatchewan.

3.2 Operational decision making

3.2.1 Situational awareness

As discussed previously, internal emails show that SWA staff were aware of the potential for high streamflows due to the accumulation of snow in the Rocky Mountains at least as early as March 2011. Had the snow surveys, rather than the snow pillows, been monitored, SWA staff would have been aware of heavy mountain snow packs earlier.

There was early (at least by January) awareness of the potential for high prairie inflows due to the wetness of soil before freeze up and the heavy snowpack in the prairies. Snow surveys were undertaken by SWA staff to quantify the prairie snowpack as the SWA staff, rightly, were concerned about the accuracy of the remotely sensed SWE maps provided by EC. No mention was made of the likelihood of increased runoff due to prairie wetlands being filled.

By May 2, there were concerns that Lake Diefenbaker spilling would be necessary to manage snowmelt inputs and a concern that spilling to provide flood protection would result in the reservoir being unable to fill to FSL. This outlined a strong understanding of the difficulty of trying to operate a reservoir of limited capacity for water supply, hydroelectricity production and flood protection.

SWA staff were well aware that flooding occurs at high streamflows between Moon Lake and Saskatoon, although there was some internal disagreement concerning the extent of flooding at various streamflows. SWA had available the flooded areas established by LIDAR, which are listed in Table 9 using data from SWA.

Table 9: Rating table of flooded area between Moon Lake and Saskatoon.

Streamflow (m^3s)	Flooded area (acres)
1000	0
1100	0
1200	650
1300	1100
1400	1500
1500	1850
1600	2300
2000	4250
2500	6300

3.2.2 Risk assessment

Risk assessment (or determination) of a reservoir operation is a complex process taking in known risks with varying levels of uncertainty and varying contributions to the accumulation of risk over the annual filling and depleting cycle of the impoundment. It is part of the larger task of risk analysis which contributes to risk control aspects of risk management (Fig. 49). Risk analysis cannot be based on assessment of risk alone, but must be considered in terms of water supply, flood vulnerability and specific hazards. Risks tend to be assessed for and associated with individual decisions regarding the timing, duration and magnitude of releases from a reservoir. Assessment of risk is complicated by unknown risks that cannot easily be factored in to decision making. There are often multiple risks associated with each decision and these risks can be manifested at differing time scales. For instance a high release in mid-winter runs an immediate risk in terms of its impact on river ice and stage, a medium term risk that less hydroelectricity can be generated when desired, and a longer term risk of a high flow event later in the year. The short term risk is clear, immediate and can be assessed in a relatively straightforward procedure. However, longer term risks must be considered as part of the cumulative risk which is influenced by cumulative uncertainty and can be very difficult to assess and analyse because of the incremental change in cumulative risk. The incremental and uncertain nature of a cumulative risk such as summer flooding or insufficient water supply means that it is in danger of being underappreciated in assessing the risk of individual decisions made in winter.

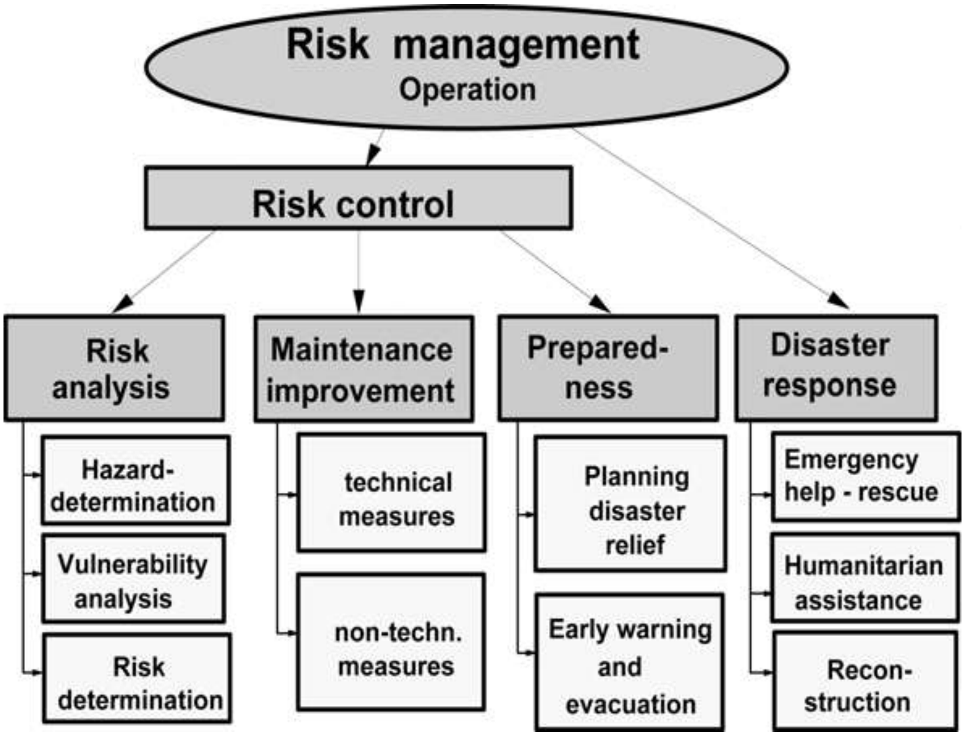


Figure 49. Flood Risk management (from Plate, 2002), showing the role of risk determination (assessment)

For the Lake Diefenbaker operation, there is no clear directive to reduce flooding, only a desire to reduce flooding and (probably) an obligation not to increase it. The main operating objective of the reservoir is to limit the risk to water supply in order to maximize economic benefits to Saskatchewan. Risk assessment of its operations must therefore consider not only spring/summer high flow events downstream, but

i) mid-winter flows and their interaction with river ice,

ii) the risk of not meeting objectives for reservoir elevation with respect to
   a. hydroelectric generation,
   b. water supply for irrigation and water withdrawal,
   c. recreation and
   d. piping plover habitat,

iii) downstream flow events and their interaction with
   a. Saskatchewan River hydroelectric generation,
   b. minimum flow requirements and
   c. high flows in the Saskatchewan River Delta

While there was a clear concern to assess risks in mid-winter, we could not find a formal ranking or list of priorities for risk assessment; it would appear that the dam is managed with an attempt to minimize risk of failure of any of the priorities for the dam. Certainly the email correspondence shows attempts by interest groups to influence the priority for risk management “on the fly”. It seemed inappropriate that flood forecasters had to take valuable time to enter into correspondence on these matters during a high flow event. Being able to refer to a clear set of priorities would permit them to concentrate on minimizing risk according to the set priorities.

Part of risk assessment is assessment of uncertainty in prediction. It is clear in the preceding sections that forecasters had considerable uncertainty in their predictions, but did not always have a good assessment of the level of uncertainty. They were sometimes extremely overconfident in their predictive capability. For instance, Figure 45 shows substantial deficiencies in March forecasts of spring and summer inflows in high flow conditions, and Figure 47 shows that outflow forecasts have little prediction skill after 3 days. Snow pillow information from early winter was used to assess risk in setting reservoir outflows despite very low correlations between early winter snow accumulation and peak snow accumulation in the Canadian Rockies (Table 6). There was no prairie runoff prediction capability, despite the historical record of occasional high April inflows from prairie snowmelt runoff over frozen soils.

There appears to have been insufficient appreciation of the danger of incremental risk accumulation. What seemed to be a series of reasonable decisions on reservoir outflows over the winter led to reservoir levels by late winter that were high enough to entail considerable risk when the uncertainty of predicted inflows and future weather is taken into account. Added to this uncertainty is that in downstream flows as indicated by the mismatch between Gardiner Dam and Saskatoon recorded discharges at high flows.

A final caveat on risk assessment is that risk was assessed using historical information, predictions and an assessment of uncertainty in prediction. Historical hydrological and climate information is becoming less useful under conditions of climate variability and change and upstream water consumption which introduce non-stationarity to statistical measures of historical flows. In response to declining spring inflow, greater risks of high summer flows from the reservoir were taken by increasing minimum winter levels. Lower spring inflows over the last 40 years have caused a perceived need for higher minimum lake levels to achieve water supply objectives, but peak flows into the reservoir have not diminished and so, ironically, reduced spring inflows can lead to greater summer flooding. Extreme conditions in 2010-2011 shattered this increasingly brittle system, starting in 2010 with record high precipitation amounts in many parts of Saskatchewan, which must inevitably lead to new types of hydrological behaviour. In this case it was a dramatic increase in the contributing area of prairie basins flowing into Lake Diefenbaker due to low surface storage capacities leading to high basin connectivity (Phillips et al., 2011; Shook and Pomeroy, 2011), high snowpacks resulting in a high runoff potential (Pomeroy and Gray, 1995) and high fall soil moisture reducing the spring infiltrability of frozen soils (Gray et al., 2001). Non-typical behaviour was also present in the mountains where relatively low early winter snow accumulations were followed by high late winter snowfalls to result in spring snowpacks that were well above normal in the southern Canadian Rockies. The spatial coverage of deep snowpacks in the mountains extended to the valley bottoms in many cases; this exceptional situation made the mid and high elevation snow pillows much less useful as indicators of snow volumes than had been the case in the past and exposes the risk of relying primarily on snow pillows for mountain water supply forecasts. In a changing climate, an over-reliance on historical patterns and information, and reduced flexibility due to diminishing spring inflows introduces a new uncertainty that was not fully appreciated in 2011. This is a general challenge for water resources management in the 21st Century (Milly et al., 2008).

3.2.3 Decision points

Some of the decision points included:

1. The decision to reduce discharges for Saskatoon bridge construction,
2. The decision not to compensate for the reduction in discharge due to the inactive generating units by discharging through the tunnel outlet or the spillway,
3. The selection of the minimum reservoir elevation as a target for 2011,
4. The reduction of discharges on April 10 (during the Spring inflow event) to reduce the combined Saskatchewan flows,
5. Increasing discharges on and after April 25, including drawing-down reservoir elevation,
6. Setting the discharge on May 29 for the second eventually,
7. Increasing the discharge after June 12 to accommodate the next inflow event, and
8. Maintaining discharges greater than inflows to draw down the reservoir elevation below FSL.

The situation faced by the SWA in the operation of Gardiner Dam was complicated by the sequence of inflow events. During the first event, there will always be a tendency to use all available storage, as the probability of occurrence is 100%, and the probability of any future events is always smaller and so is discounted. Failure to use all available storage to mitigate the first flood will inevitably lead to recriminations, particularly if the second event is smaller. However, if the first event is not the largest, its mitigation reduces the storage available to manage the second event, if there is not sufficient time to draw down the reservoir without causing flooding.

It should be noted that SWA forecasting staff did a superb job with the limited tools and resources, complex operating system and unspecified operating rules available to them. At no point was there any indication that forecasting staff did less than the optimum with the procedures, understanding and information available to them.

3.3 Potential impact of modification of operations

A reservoir with a *de facto* multi-objective operation such as Lake Diefenbaker and increasing stresses on its primary water supply function is extremely complex to operate. In 2010-2011 initial low mountain snowpack observations changed to forecasts of high inflow causing SWA to change operational focus from water supply concerns to flood concerns. With greater hydrological extremes expected for the Prairies in the future, SWA should and can take advantage of advanced information and information technologies. If there had been access to routed Alberta Environment and Water streamflows, corrected meteorological information and complete snow survey information then a more realistic assessment of the substantial runoff potential and its uncertainty could have been made. If SWA had some hydrological forecasting capability, enhanced prairie snowpack, soil moisture, depressional storage and meteorological data, and access to seasonal and ensemble 15-day weather forecasts then not only could assessment have been made of potential snowmelt runoff sequences in the mountains and foothills but the Saskatchewan Cypress Hills and prairie runoff could have been forecasted well before the events. Uncertainty could have been assessed much better with access and interpretation of enhanced information and internally generated forecasts. Uncertainty could have been reduced with additional gauged stations on the SSR with known rating curves and correction of the rating curve on the spillway. This would have permitted SWA to have seen the need for rapid drawdown of Lake Diefenbaker before the major inflows occurred and to better assess the flooding caused by their own outflows.

Prairie snow surveys from mid-winter and soil moisture surveys from the fall showed that a major runoff event was highly likely. Even a simple assessment of these indicators would have suggested a large April peak in flows was more likely than normal and could have triggered modified operations before April. With a clearer ranking of operational priorities, then requests for reduction of discharges in the winter and implications of these reductions would have required compensatory increased flows the same winter, if flood protection was deemed a priority for reservoir operation.

4 Policy implications and needs

In developing and reviewing the material for this report it became apparent that there are several policy implications for SWA, some urgent and some relating to long term development of the Authority.

Immediate needs include

ix) Development of formal rules and priorities for operating Gardiner Dam on Lake Diefenbaker instead of the very unclear and *ad hoc* operating regime that is currently in place. Gardiner Dam stands out as one of the few major control structures in North America that is operated for multiple purposes without a formal ranking of the priorities of these purposes and resulting rules of operation. In particular the roles of the dam operation with respect to flood control, hydroelectric generation, water supply, recreation and ecosystem conservation need to be specified, ranked and clarified so that operating rules can specified internally and to outside interests that routinely make requests to modify the operation of Gardiner Dam.

x) Over time, SWA has increased the winter minimum level of Lake Diefenbaker, thereby reducing its flood attenuation capability whilst maintaining or increasing its hydroelectricity generation and water supply potential. This was partly based on the perception of an improving capability in forecasting spring and early summer high flows whereas in reality there is little mid-winter forecast capability for high flow events. It is also based on declining spring inflows which put the water supply operation of the reservoir at greater risk. There is not sufficient predictability of the system to operate in this manner and achieve all of the current goals for the reservoir. At the first opportunity, SWA must prioritize the water supply and flood protection roles for Lake Diefenbaker. If flood protection remains one of the top priorities for the operation of Lake Diefenbaker, then until such time as SWA can show it has improved its forecast capability, lower winter minimum lake levels should be implemented. If water supply concerns are paramount, then the higher minimum lake levels can be sustained, but the public must be informed of the changing flood risk associated with this operational decision.

xi) SWA could make immediate use of hydraulically routed streamflows and QA/QC'ed streamflow, snow survey, precipitation and meteorological information from Alberta Environment and Water to reduce the uncertainty of forecast and routed inputs to Lake Diefenbaker and thereby increase operating flexibility.

xii) There remains substantial uncertainty at high flows of how releases from Gardiner Dam translate to streamflow downstream. This is due to having only one hydrometric station with a rating curve (Saskatoon) and apparent errors in estimates of discharge from the Coteau Creek hydroelectric station at high flows. A second station with a reliable rating curve, and further improvements to the estimates of discharge from the dam, especially from the Coteau Creek station, would reduce the uncertainty of how releases from the dam impact the downstream environment.

xiii) SWA forecasters currently operate with little assistance, have non-forecasting duties for data acquisition, data analysis, public consultation and conduct their forecasts with spreadsheet based methods and very little automation of data and information flow or forecast dissemination. SWA should implement a computerized data management system that is compatible with that of its upstream jurisdiction to facilitate and automate sharing of actual and routed flows, meteorology and snow course data. It should further automate public forecasts so that they are distributed widely and efficiently.

Longer term needs include

xiv) SWA stands out as one of the few river forecasting operations in North America with no hydrological modelling capability for streamflow prediction. This resulted in an inability to accurately predict the size and timing of inputs to Lake Diefenbaker from prairie basins and to reduce the uncertainty of Alberta forecasts of streamflow from the mountains and foothills. This capability should be developed based on integrated enhanced observations and hydrological modeling of prairie streams arising in Saskatchewan and involvement in improvements to basin-wide snow, meteorology and streamflow observation and modeling systems.

xv) The current hydrometric network in Saskatchewan is sparse. The absence of a hydrometric station on the South Saskatchewan between Saskatoon and the confluence with the North Saskatchewan River increases the difficulty of the management of Saskatchewan River flows. The previously-existing station on the South Saskatchewan River near the forks should be re-activated.

xvi) The ice on the South Saskatchewan River requires better monitoring when high flows are anticipated and a better understanding of the impact of winter discharges on ice is needed. The monitoring in 2011 was useful, but internal emails show that it was clearly an ad-hoc program. A more organized inspection program, perhaps supplemented by the high-resolution satellite remote sensing now available, and a rigorous understanding of discharge-ice jam interactions in the river downstream of Gardiner Dam should be developed and instituted.

5 Summary

The purpose of this study was to conduct a post-event evaluation of the operations of Lake Diefenbaker from August 1, 2010 through to July 31, 2011, namely the decisions made in real-time against the operating objectives understood at the time and in achieving a balance of multi-use objectives, and to address policy needs or gaps to the extent possible. The scope of this project included: technical review of existing documentation and data held by SWA, interviews with SWA staff, interviews with external experts or other participating agencies, and review of hydrometric and meteorological data in the Alberta portion of the drainage basin and forecasting products from Alberta Environment and Water. The geographical extent was specified as the Saskatchewan River system from the Alberta to the Manitoba border, and the temporal extent is for operations from 1 August 2010 through 31 July 2011. A stakeholder or public consultation process was excluded.

Lake Diefenbaker receives inflows primarily from the Rocky Mountains via the Bow, Oldman and Red Deer rivers and a very small proportion from Saskatchewan. Annual streamflow volumes in the South Saskatchewan River feeding Lake Diefenbaker have declined by 40% since the early 20th C.; of this decline 70% is due to upstream consumption, mainly for irrigation, and 30% is due to changes in the natural hydrology of the tributaries and is a likely manifestation of climate change. Consumption exceeds 40% of naturalized flows in drought years and 10-20% of naturalized flows in high flow years. Operation of Lake Diefenbaker seeks to provide water for irrigation and water supply, hydroelectricity generation, flood protection, recreation, shoreline habitat and to sustain downstream river flows above a minimum threshold whilst keeping reservoir levels below a maximum level. Discharge from the reservoir often peaks in July with a secondary peak in January, whilst reservoir levels typically peak in August and are drawn down over the fall and winter to a minimum level in late winter. There are target elevations, but not rules, for irrigation users, Elbow Harbour, recreational use and the piping plover habitat. There is no requirement for downstream flood protection, but it has been found over time that Gardiner Dam operation can reduce downstream flooding to some degree.

There are deficiencies in estimating inflows and outflows from Lake Diefenbaker that affect operational decision-making in high flow events and attempts to reduce downstream flooding. Routing of inflows is currently done manually by SWA using simple spreadsheets that shift the timing of daily flows by a fixed time-step. This method is adequate for water supply estimations in low flow periods, but is error-prone, time-consuming and inaccurate and so inadequate for reservoir management in high flow periods. A better method would be to formally route and attenuate hourly routed flows from Alberta Environment and Water. Routing South Saskatchewan River, Swift Current Creek and Red Deer River flows is insufficient to predict the inflow to the reservoir. Estimated ungauged inflows were a large component of April 2011 inflows to Lake Diefenbaker, peaking at nearly 600 m^3/s. There is a substantial underestimation of outflows from Gardiner Dam using existing rating curves for the spillway and Coteau Creek hydroelectric plant gauged flows that is most evident at high flows and is confirmed by manual measurements made of discharge downstream of Gardiner Dam. During the high flow events in June 2011 this underestimation was up to 400 m^3/s which meant that SWA staff were not able to correctly estimate the flows at and upstream of Saskatoon resulting from Gardiner Dam operations. The underestimation was not due to runoff into the river between Gardiner Dam and Saskatoon.

From 2001 to 2011, Saskatchewan has seen both its wettest and driest conditions since records began and this challenges multi-objective reservoir operation. Minimum winter/spring Lake Diefenbaker elevations have been increasing by over 3 m from 1969 to 2011 whilst peak elevations in summer and fall show no trend, but are lower in drought years. The increasing trend in minimum reservoir elevations improves water supply resiliency in times of drought, but reduces the flood protection capability of the reservoir. The trend is likely due to several factors, one being an increased confidence over time by SWA in its ability to predict high flow events from mid-winter mountain snowpacks. This confidence is misplaced as very little predictability is shown until spring. Another factor is the trend in inflows which have dropped by 40% in April and 50% in May since 1960. This drop is far in excess of the decline in natural flows due to changing climate; the magnification of climate change impacts is caused by agricultural consumption and the filling of the Oldman Reservoir in spring and early summer. The increase in minimum reservoir elevations has increased the water supply and hydroelectric capability of the reservoir in response to prolonged drought and diminished inflows, but has diminished the flood protection of the reservoir without any evidence of a policy shift or decision. Clear policy direction for reservoir operation is needed in this regard.

The sequence of hydrological and meteorological events leading to the high flow of 2011 started in the summer of 2010 with precipitation at 200% of normal immediately upstream of Lake Diefenbaker. Subsequent fall precipitation led to soil at or near saturation at the time of freeze-up, which decreased frozen soil infiltrability to minimal levels for the subsequent spring snowmelt runoff. Mountain snowpacks in the Oldman basin were above median levels from December onwards and exceeded 90% of all years by spring. Bow and Red Deer river basin headwaters snowpacks were below median levels until the end of January but exceeded 70% of all years by spring. The heavy accumulations of snow in the Oldman River basin (up to 300% of normal by spring) occurred in the part of the South Saskatchewan River basin headwaters that melts earliest because it is furthest south. Record snowpack accumulated in the Cypress Hills. Exceptionally high snowpacks were measured in the foothills and prairies, meaning that the volume of snowmelt from early prairie melt would be quite high. The large spring inflow ran from 1-26 April 2011 and was poorly estimated by SWA-routed flows derived from Water Survey of Canada data because of errors in WSC data and a large unmeasured inflow from ungauged prairie streams. A better estimation of inflows could have been obtained by i) routing Alberta Environment and Water generated flows and ii) estimating the discharge of ungauged basins in Saskatchewan using an energy balance snowmelt routine in a hydrological model. Mountain snowpacks began to melt at higher elevations in early May 2011 and contributed runoff into June and July. In late May up to 120 mm of precipitation fell on the mountains and foothills resulting in high streamflows in all Alberta tributary rivers to Lake Diefenbaker. These high inflows began to show up on 27 May 2011. Subsequent rains in the Oldman basin and Cypress Hills in June contributed to recession flows from the 27 May peak. The Red Deer River basin received up to 160 mm of rainfall in mid-June which caused a secondary peak inflow to Lake Diefenbaker over 13-17 June 2011. Subsequent rains in the foothills of the Red Deer River basin led to a further peak inflow in late June. While the peak daily inflow was large and earlier than normal it was not exceptional and was well below that experienced in 1995 and 2005. Measured monthly inflows were above median values from March through August, with the June measured inflows exceeded 94% of June inflows after 1965 and averaged 1200 m^3/s.

Reservoir levels from August through November 2010 were static with discharges closely matched by inflows. Discharges were intentionally reduced in the fall to assist construction of Circle Drive Bridge in Saskatoon. Fall and winter repairs on two of the Coteau Creek hydroelectric generating units substantially restricted flow through the turbines and therefore discharge. The spillway was not used to reduce lake levels due to concerns this would disturb ice cover and cause ice jams on the river.

Discharge through all turbines did not increase until late March. As a result, reservoir levels were 2 m higher than normal in the spring. During the large April inflows, discharges from the reservoir were kept low to reduce peaks on the combined Saskatchewan River flow downstream. The long spring peak of the North Saskatchewan River meant that discharges from Lake Diefenbaker were kept relatively small for a long period. As a result, reservoir levels rose in April by three metres when normally they would rise by ½ m. The reservoir was drawn down in May with higher outflows and rose with the first June inflow event to full storage level. Once this level was reached, subsequent discharges had to remain high through June and early July. However the operation of the dam reduced downstream flows on the South Saskatchewan River for the four largest peak inflow events, in the highest inflow event on 1 June 2011, inflows of 2600 m^3/s were reduced to outflows of 1120 m^3/s. Flows over 1750 m^3/s were entirely prevented by dam operation, but flow duration near 1500 m^3/s was increased. The estimated flooded area between Moon Lake and Saskatoon was reduced in half by dam operation, though with the discharge information understood at the time by SWA it would have been estimated to have been reduced to one quarter of natural flood extent. Flooded acreage duration was unaffected by the dam when the streamflow measured at Saskatoon is used to calculate flooded acreage between Moon Lake and Saskatoon, but would have been estimated to be reduced almost in half by dam operations using the discharges from the dam understood at the time. The effect of Gardiner Dam operations on the Saskatchewan River system downstream of the confluence was to substantially reduce the April, May and early June flow peaks but to slightly increase the late June flow peak which was the primary flood peak of the year.

The resources available for river forecasting were limited, which affected the forecasting capability and decision-making. Hydrometric station density in inadequate over much of the Saskatchewan River basin according to World Meteorological Organisation standards and the situation is particularly acute in the Saskatchewan portion of the Saskatchewan River Basin and in high mountain headwaters of the basin where gauging density is 5.5 times less than international standards for mountain regions. The lack of a station downstream of the confluence of the North and South Saskatchewan rivers makes assessing the impact of releases from Gardiner Dam on the Saskatchewan River extremely uncertain and is considered to be an extraordinary omission. The paucity of stations for the Saskatchewan portion of the Lake Diefenbaker drainage make this region almost entirely ungauged which resulted in the inability to measure April inflows in to the lake in 2011. Weather station resources were adequate in the Alberta prairie region but inadequate in the mountain headwaters where precipitation measurement density is 23.5 times less than international standards for mountain regions. Weather station density was extraordinarily inadequate in the Saskatchewan portion of the basin; with only two weather stations near Lake Diefenbaker major spring and summer storms can be entirely missed. There is evidence of other weather stations in Saskatchewan, but their data is of unknown quality and they do not normally collect snow data in near real time. The Alberta snow survey network is needed to supplement information from the sparse Alberta snow pillow network which is restricted to mid-elevations in the mountain headwaters of the Saskatchewan River Basin. No evidence of a formal, regular Saskatchewan snow survey network was found which was very surprising given that over 80% of local prairie runoff is derived from snowmelt. Given the lack of local snow measurements, there is potential to use snow data assimilation model (SNODAS) products from the US NOAA National Operational Hydrologic Remote Sensing Center for estimating snow water equivalent in southern Saskatchewan.

The March 2011 forecast from Alberta Environment and Water for the March through September 2011 cumulative flows for the Bow, Oldman and Red Deer rivers substantially underestimated actual flows on the Oldman and Red Deer rivers but were close to actual volumes for the Bow River. SWA staff routed flows using spreadsheets on a daily time-shift basis or from a residual method based on measured inflows to the lake and estimated outflows from Gardiner Dam. This technique is laborious, slow and prone to error and should be automated to improve efficiency and accuracy in high flow events. Errors in the Gardiner Dam outflow estimates during high flows resulted in errors in the residual estimates of inflows such that the water balance of the reservoir was very uncertain. The effect of changing head on the spillway should be considered in calculating outflows from Gardiner Dam and the more serious underestimation of high flows from Coteau Creek hydroelectric station should be thoroughly investigated. Because of the paucity of hydrometric stations on the main rivers downstream of Gardiner Dam, methods such as the kinematic wave should be used to route streamflow downstream of Gardiner Dam as substantial translation of the hydrograph is anticipated to occur under high flows and this will affect estimates of flooded areas and inputs to the Saskatchewan River dams.

The daily data collection system used by SWA is very inefficient, potentially unreliable and is too slow for the sub-hourly information that becomes available and is needed by the public and by SWA in a high flow situation. Internal requests for information would be better served by a secure, industrial quality database system designed for hydrological forecasting operations. Raw data downloaded from the Water Survey of Canada is not quality controlled and has substantial missing data. Alberta Environment and Water perform QA/QC on these data and this corrected information can be accessed electronically. SWA should ensure that data collection management system purchased in the future is compatible not only with WSC but with that of Alberta Environment and Water so that this corrected information can be shared easily and rapidly. Any new system should have a web-page capable reporting system to reduce forecaster time spent in answering outside requests for basic flow data and make hydrological information available to the public in a timely, efficient manner.

SWA forecasts for Lake Diefenbaker underestimated June inflows by a factor of two and did not improve much over the spring despite available reports of increasing snowpacks. The mountain snowpack information quoted in monthly provincial forecasts and other information suggests that SWA staff did not have an accurate appreciation of the variability of mountain snowpacks and substantially underestimated accumulations because they relied only on sparse snow pillow information rather than the more spatially extensive Alberta Environment and Water snow surveys. SWA staff seemed to have a good appreciation of and concern for a potentially high prairie runoff year from high prairie snowpacks and wet frozen soils. However the predictability of inflows to Lake Diefenbaker from available information was overestimated by SWA staff. Early to mid-winter snow accumulation is a poor predictor of peak snow accumulation because of substantial later winter snowfall events in the mountains and foothills. Because spring rainfall also contributes to inflows, forecasts based on peak snowpack alone will also be in error and this effect is more severe in wet years. March forecasts of the Bow, Oldman and Red Deer river flows from Alberta Environment and Water showed errors increasing to from 20% to 60% as discharge increased to higher than mean flows. SWA could improve its forecasts by incorporating probabilistic medium term weather forecasts, accounting for increased climate variability and change in adjusting its probabilistic estimation procedures and developing a hydrological modelling capacity for the prairie drainages and perhaps the mountain headwaters. It should be noted that SWA short-term forecasts into Lake Diefenbaker are reasonably accurate, but outflow forecasts are seriously in error and meaningless more than three days after their issue. This creates a perception problem with users of the forecasts and needs remedy either by improvement or better communication of the purpose and interpretation of these forecasts.

SWA staff were aware of high mountain snowpacks by March 2011, but could have been aware of these earlier. Staff were very aware of the potential for high runoff conditions on the prairies, but not that filled depressional storage would cause a dramatic increase in basin runoff contributing area compared to previous years or of any impact of wetland drainage on the basin response compared to high snowpack years in the early 1970s. There was an awareness of the streamflows that would cause flooding between Moon Lake and Saskatoon, but the understood discharges from the dam under high flows underestimated measured streamflows at Saskatoon and so flooded areas between Moon Lake and Saskatoon would have been underestimated. Risk assessment was hampered by over-confident forecasting ability, particularly in the ability of winter forecasts to predict peak summer flows and by the incremental accumulation of risk in a period of climate change, increasing upstream consumption, land use changes and non-stationarity. What seemed a series of reasonable decisions on reservoir outflows over the winter led inevitably to higher than desirable summer flows. The importance of maintaining low flows for river ice and to reduce April flows to the Saskatchewan River system needs to be carefully reassessed. By not compensating for reduced outflows for bridge construction and hydroelectric generator repair in winter, a substantial additional risk of subsequent high streamflow was undertaken with unquantified reduction to risk from river ice flooding. Rules and policies for operating Gardiner Dam should be based on verified information and priority of operations to minimize cumulative risk for clear priorities for water supply, hydroelectricity generation, recreation, ecosystem protection and/or flood control. Priorities are not clear now which prevents optimisation of reservoir operation.

SWA could benefit from deployment of commercially available information technologies and taking advantage of advanced information available from the upstream jurisdiction. By development of a hydraulic routing, hydrological modelling and hydrometeorological observation capability SWA could reduce uncertainty in forecast flows in the rivers entering the province, better forecast downstream peak flows and flooding, and forecast the local ungauged prairie contribution to inflows. Improvements in rating curves and numbers of hydrometric stations on the Saskatchewan tributaries and main rivers would further reduce uncertainties in the impact of outflows from Gardiner Dam.

The overall evaluation of SWA operation of Lake Diefenbaker in light of the operational objectives understood at the time is that SWA forecasting staff did a superb job with the limited tools and resources, complex operating system and unspecified operating rules available to them.

6 Conclusions

Analysis of the Lake Diefenbaker operation and hydrometeorological events of 2010-2011 suggests that minimum reservoir levels have been rising over time and were particularly high in the winter and spring of 2010-2011 resulting in a greater risk of high outflow events in the case of above-normal inflows. Rules and policies for operating Gardiner Dam based on verified information and priority of operations to minimize cumulative risk were not in place to optimize dam operations after several mid-winter events restricted outflows from the dam. Unfortunately inflows were underpredicted in 2011 due to an underestimation of upstream snowpacks, inability to quantify ungauged inflows from prairie runoff, inadequate available information on upstream and local meteorological conditions, and reliance on statistical forecast procedures based on previous climate conditions. The impact of outflows on downstream areas was difficult to quantify because of an underestimation of outflows from the Coteau Creek hydroelectric station at Gardiner Dam and the lack of sufficient hydrometric stations downstream. Whilst water supply goals for the reservoir were met in the period, and downstream flood extent was cut in half; the acreage duration of flooding between Moon Lake and Saskatoon was not reduced by dam operation and the annual peak flow downstream on the Saskatchewan River was not reduced by dam operation. The overall evaluation of SWA operation of Lake Diefenbaker in light of the operational objectives understood at the time is that SWA forecasting staff did a superb job with the limited tools and resources, complex operating system and unspecified operating rules available to them.

There are various areas for SWA to develop its capabilities in the near future so that the likelihood of repeating the high flow and flooding events of 2011 is diminished and public understanding of the capability of dam operations is improved. Diminishing volumes but undiminished peaks of streamflow into Lake Diefenbaker are making multi-objective operation of the reservoir more difficult and more prone to not meeting both water supply and flood protection purposes. The foremost change needed is to develop formal rules and priorities so that operating procedures for Gardiner Dam can be optimized for accepted goals. If downstream flood protection is one of the primary goals for the reservoir, then the winter minimum level of Lake Diefenbaker should be reduced until improvements in forecast capability are realised. If water supply and hydroelectricity generation, then current lake levels are more acceptable, but the reduced flood protection capability should be explained to the public. Operation of the reservoir for any goals can be improved by using greater hydrological and meteorological information from Alberta Environment and Water and other agencies in inflow forecasting, improving rating curves and increasing the number of hydrometric stations measuring the impact of Gardiner Dam outflow, and improving - by automating - data management and distribution, streamflow forecasting and public distribution of forecasts. SWA should start immediately planning how it will develop an integrated hydrological modelling and hydrometeorological observation capability so that quantitative forecasts of prairie streamflow can be issued for ungauged basins, and the uncertainty in forecasts of river flow entering the province can be reduced.

7 Selected References

Annandale, J., N. Jovanovic, and N. Benade (2002), Software for missing data error analysis of Penman-Monteith reference evapotranspiration, *Irrigation Science, 21*, 57-67, doi:10.1007/s00271010047.

Brown, R., C. Derksen, and L. Wang (2007), Assessment of spring snow cover duration variability over northern Canada from satellite datasets, *Remote Sensing of Environment*, *111*(2-3), 367-381, doi:10.1016/j.rse.2006.09.035.

Callaghan, T, M. Johansson, R. Brown, P Groisman, N Labba, V Radionov, R Bradley, S Blangey, O Bulgina, T Christensen, J Colman, R Essery, B Forbes, M Forchhammer, V Golubev, R Honrath, G Juday, A Meshcherskaya, G Phoenix, J. Pomeroy, A Rautio, D Robinson, N Schmidt, M Serreze, V Shevchenko, A Shiklomanov, A Shmakin, P Skold, M Sturm, M-k Woo, E Wood (2011) Multiple effects of changes to Arctic snow cover. *Ambio*, 40, 32-45. Doi:10.1007/s13280-011-0213-x

Coulibaly, P. and J. Samuel (2011) Evaluation of Canadian National Hydrometric Network Density vs. WMO 2008 Standards. Final Report Prepared for the Water Survey of Canada, Environment Canada. McMaster University Unpublished Report. 19 p.

Gray, D. M., P. G. Landine, G. E. Dyck, and R. J. Granger (1984), Snowmelt Infiltration to frozen Prairie Soils, *Canadian Journal of Earth Sciences*, *21*(6), 669-677, doi:10.1016/0148-9062(85)92399-X.

Gray, D.M., J.W. Pomeroy and R.J. Granger. 1986. Prairie snowmelt runoff. In, *Proceedings, Water Research Themes, Conference Commemorating the Official Opening of the National Hydrology Research Centre*. Canadian Water Resources Association, Saskatoon. 49-68.

Gray, D. M., Toth, B., Zhao, L., Pomeroy, J. W., and Granger, R. J. (2001). Estimating areal snowmelt infiltration into frozen soils. *Hydrological Processes*, *15*(16), 3095-3111. doi:10.1002/hyp.320

Milly, P., J. Betancourt, M. Falkenmark, R. Hirsch, Z. Kundzewicz, D. Lettenmaier and R. Stouffer. (2008). Stationarity is dead: whither water management? *Science*, 319(5863), 573-574. Doi:10.1126/science.1151915

Phillips, R. W., Spence, C., and Pomeroy, J. W. (2011). Connectivity and runoff dynamics in heterogeneous basins. *Hydrological Processes*, *3075*(May), 3061-3075. doi:10.1002/hyp.8123

Pomeroy, J.W., D.M. Gray and P.G. Landine. 1993. The Prairie Blowing Snow Model: Characteristics, Validation, Operation. *Journal of Hydrology*, 144, 165-192.

Pomeroy, J., Fang, X., Westbrook, C., Minke, A., X. Guo and T. Brown. 2010. *Prairie Hydrological Model Study Final Report.* Centre for Hydrology Report No. 7. Centre for Hydrology, University of Saskatchewan, Saskatoon. 127 p.

Pomeroy, J.W. and R.J. Granger, 1997. Sustainability of the western Canadian boreal forest under changing hydrological conditions - I- snow accumulation and ablation. In (eds. D. Rosjberg, N. Boutayeb, A. Gustard, Z. Kundzewicz and P Rasmussen) Sustainability of Water Resources under Increasing Uncertainty. IAHS Publ No. 240. IAHS Press, Wallingford, UK. 237-242.

Pomeroy, J.W. and D.M. Gray. 1995. *Snow Accumulation, Relocation and Management*. National Hydrology Research Institute Science Report No. 7**.** Environment Canada: Saskatoon. 144 pp.

Pomeroy, J. W., D. M. Gray, K. R. Shook, B. Toth, R. L. H. Essery, A Pietroniro, and N. Hedstrom (1998), An evaluation of snow accumulation and ablation processes for land surface modelling, *Hydrological Processes*, *12*(15), 2339-2367, doi:10.1002/(SICI)1099-1085(199812)12:15

Pomeroy, J.W. and K. Sinclair (2012) Estimation of observational density in the Canadian Rockies in comparison to international standards. Unpublished Report, Centre for Hydrology, University of Saskatchewan, Saskatoon.

PFRA (2002) Gross evaporation for the 30-year period 1971-2000 in the Canadian Prairies. *Hydrology Report #143*, Regina, 114 pp.

Shook, K. R., and J. W. Pomeroy (2010), Hydrological effects of the temporal variability of the multiscaling of snowfall on the Canadian prairies, *Hydrology and Earth System Sciences*, *14*(7), 1195-1203.

Shook, K. R., and J. W. Pomeroy (2011), Memory effects of depressional storage in Northern Prairie hydrology, *Hydrological Processes*, doi:10.1002/hyp.

Shook, K., and J. Pomeroy (2011), Synthesis of incoming shortwave radiation for hydrological simulation, *Hydrology Research*, *42*(6), 433, doi:10.2166/nh.2011.074.

St. Jacques, J.-M., D. J. Sauchyn, and Y. Zhao (2010), Northern Rocky Mountain streamflow records: Global warming trends, human impacts or natural variability?, *Geophysical Research Letters*, *37*(6), doi:10.1029/2009GL042045.

Stichling, W., and S. R. Blackwell (1957), Drainage area as an Hydrologic Factor on the Canadian Prairies, in *IUGG Proceedings, Volume 111*, pp. 365-376

WMO. (2010). *Manual on Stream Gauging Volume I – Fieldwork.* Vol. I, 252 pp. Geneva.

8 Appendices

Appendix 1 Hydrographs

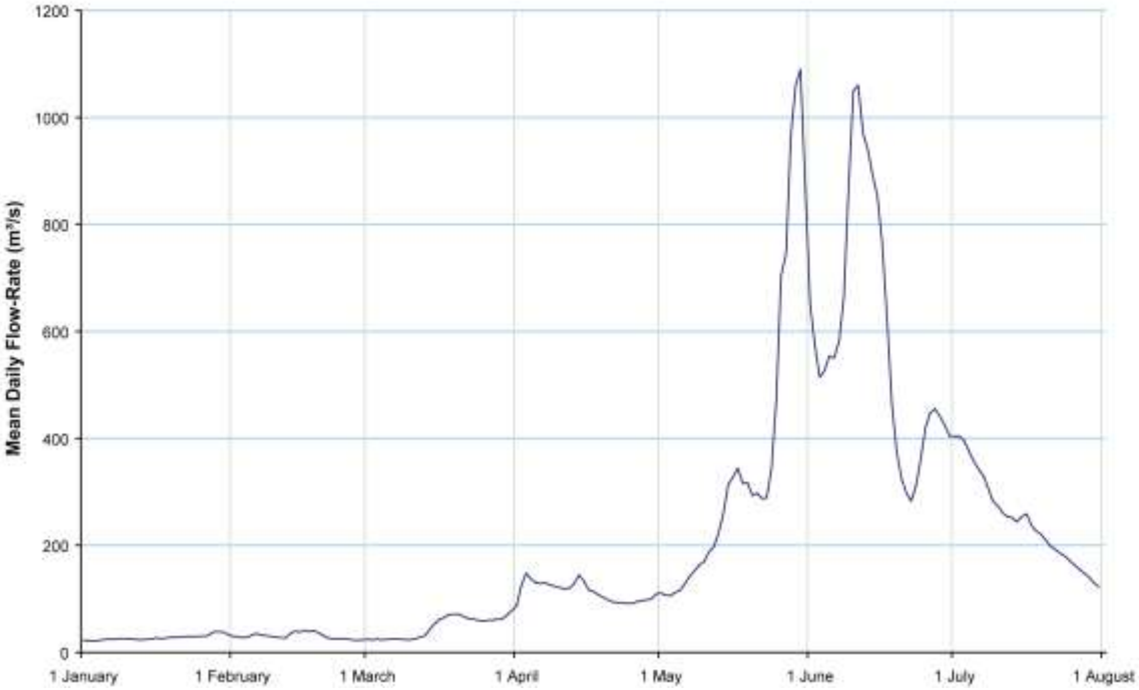


Figure 1: Oldman River near the mouth.

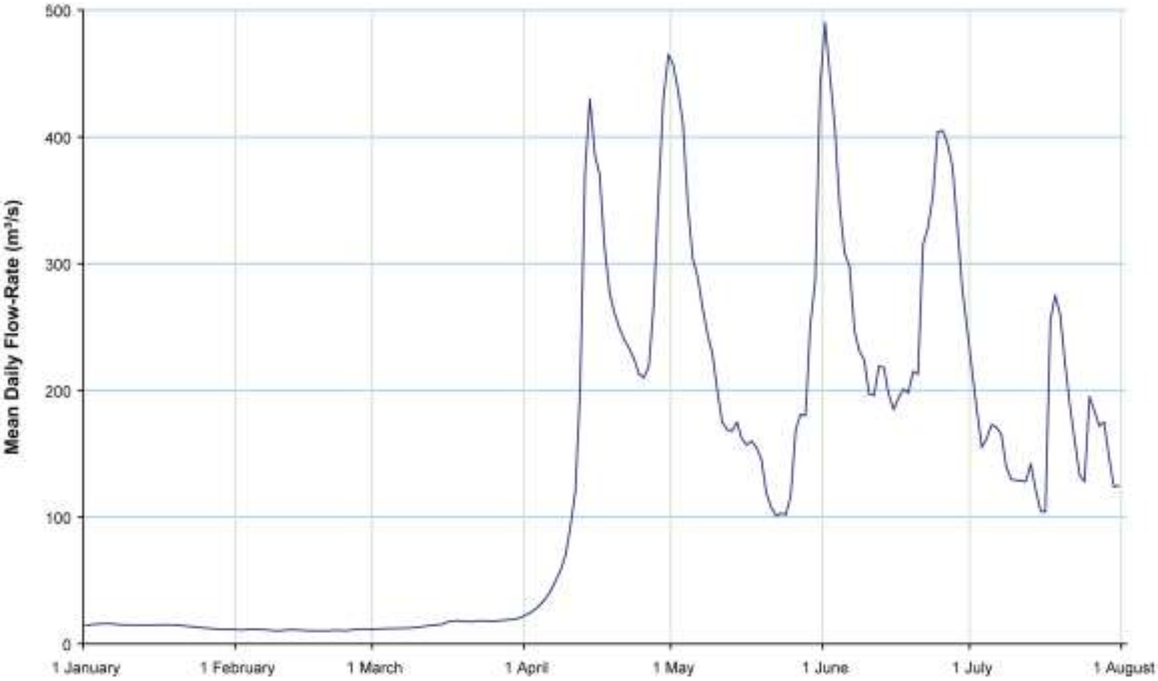


Figure 2: Red Deer River at Bindloss.

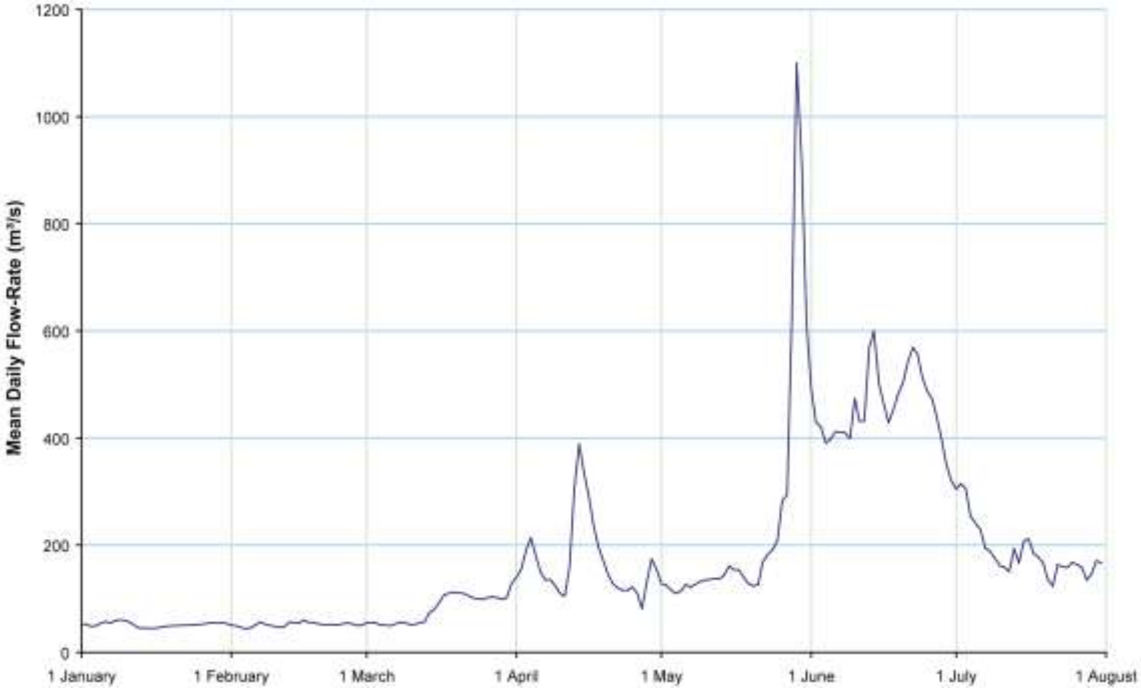


Figure 3: Bow River near the mouth.

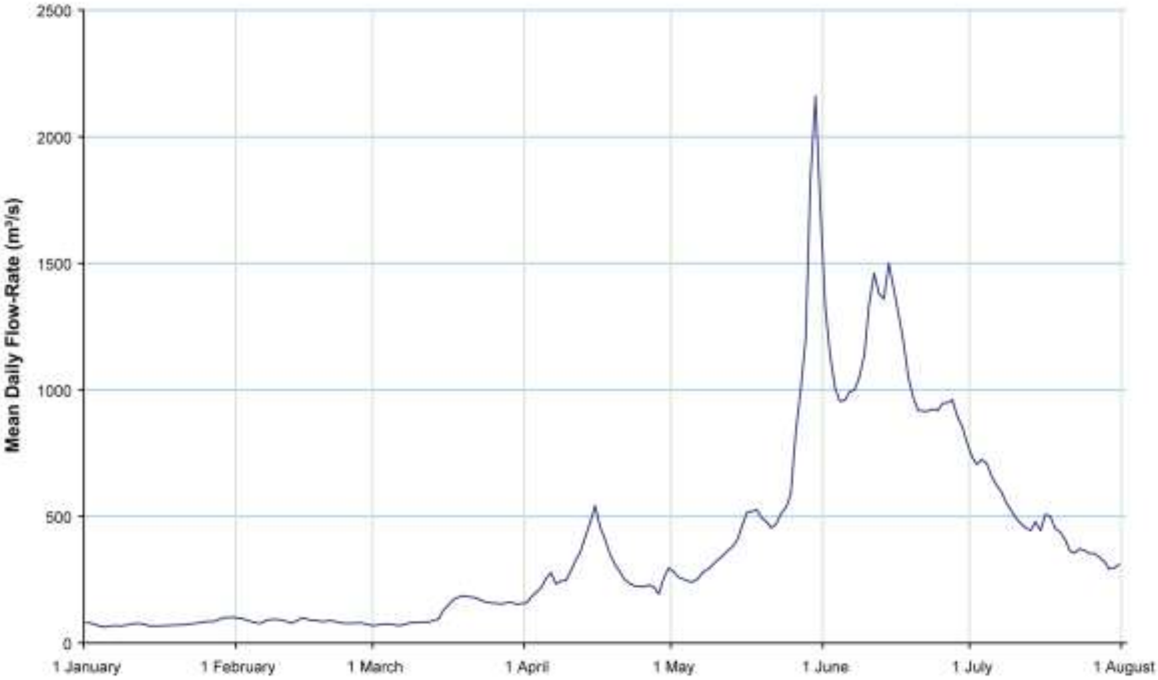


Figure 4: South Saskatchewan River at Medicine Hat.

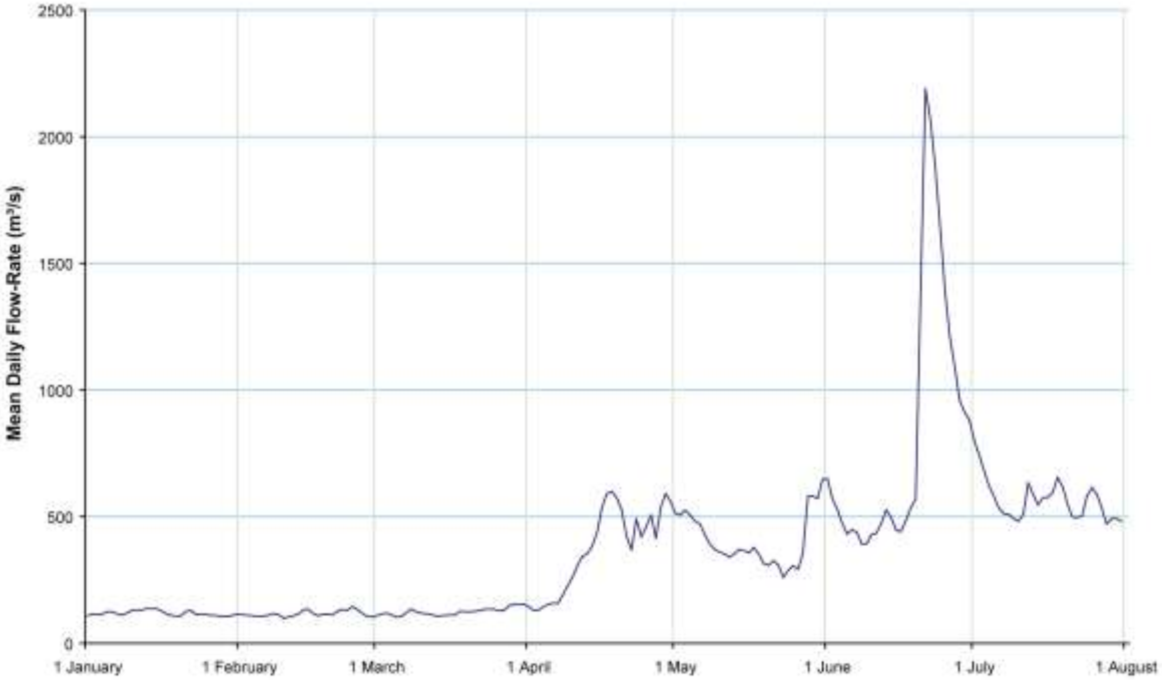


Figure 5: North Saskatchewan River at Deer Creek.

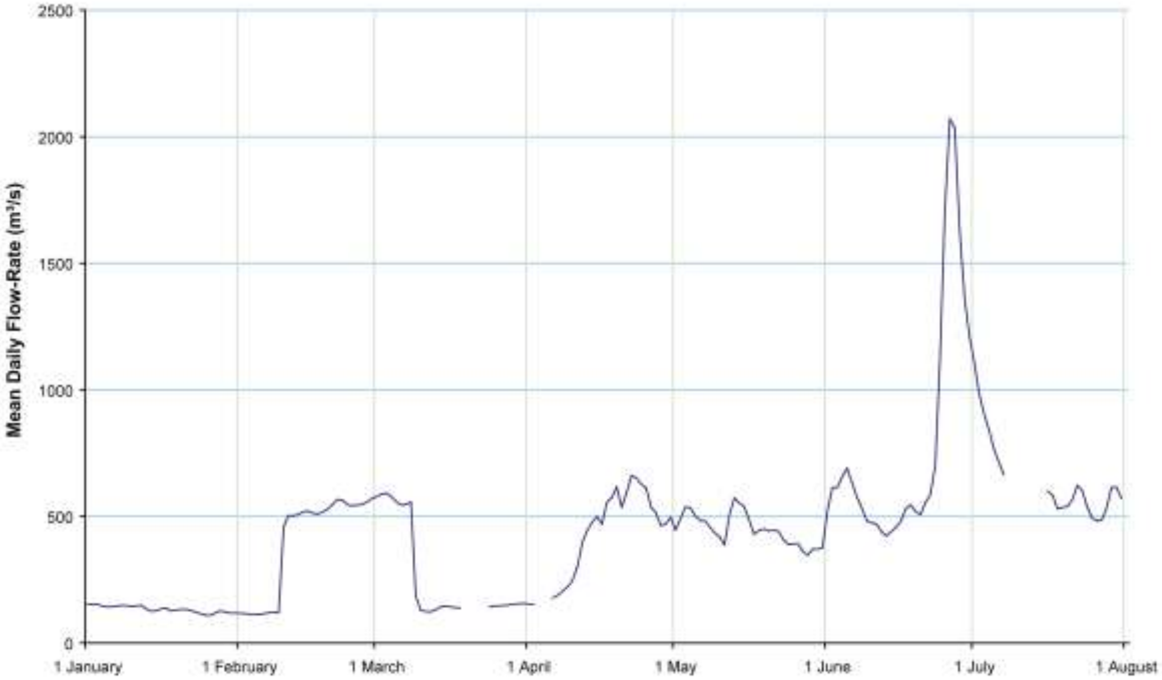


Figure 6: North Saskatchewan River at Prince Albert.

Figure 7: Swift Current Creek near Leinen.

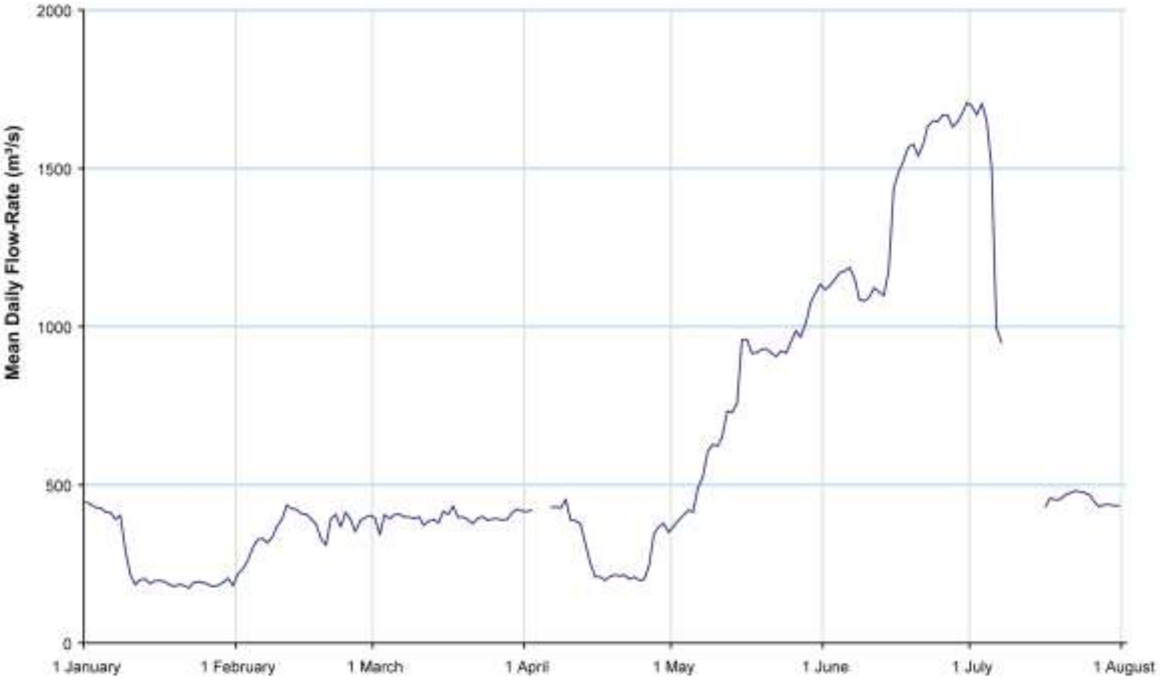


Figure 8: South Saskatchewan River at Saskatoon.

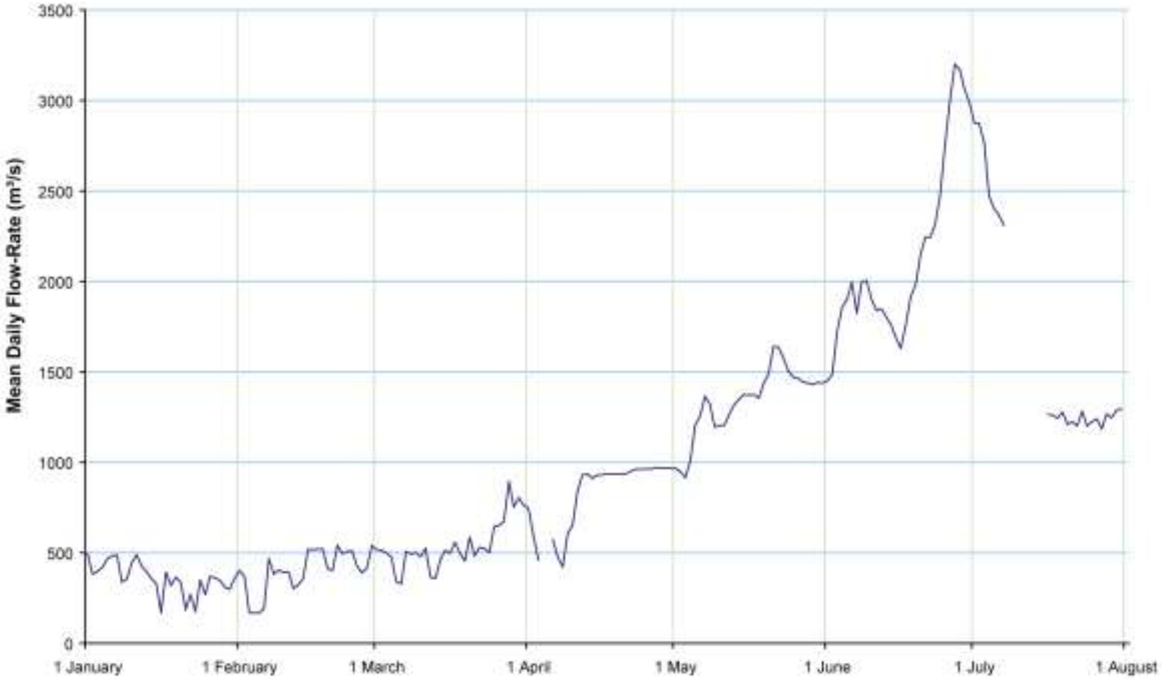


Figure 9: Saskatchewan River below Tobin Lake.

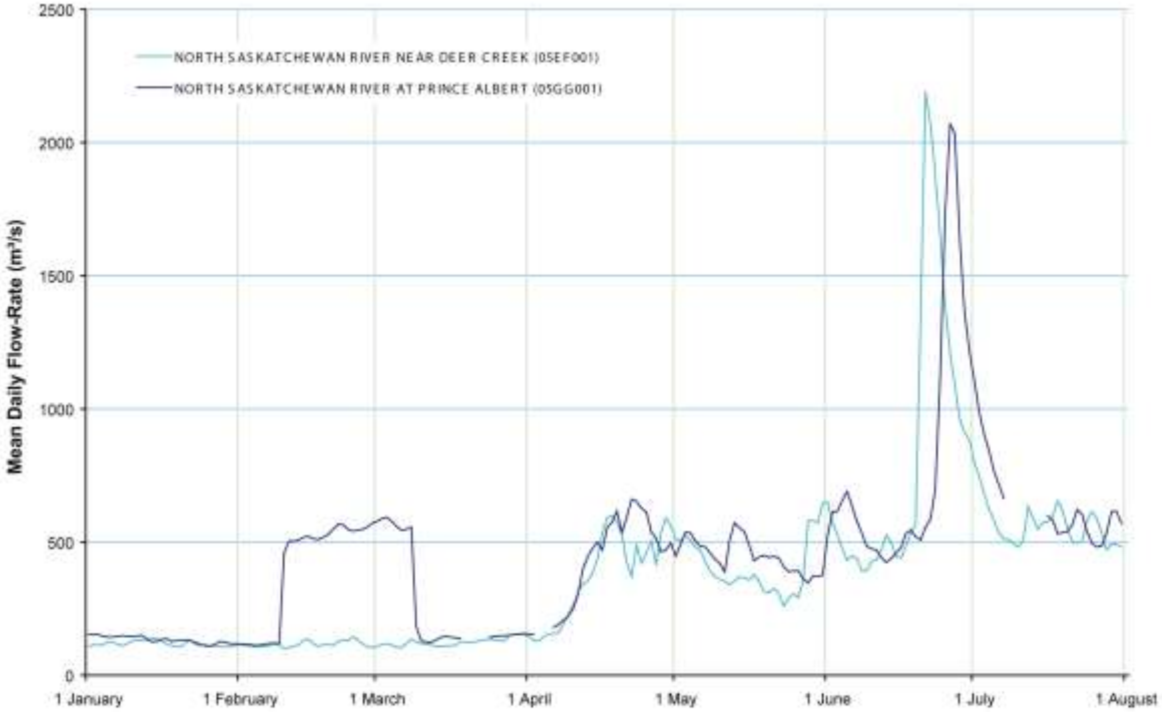


Figure 10: North Saskatchewan River near Deer Creek and at Prince Albert

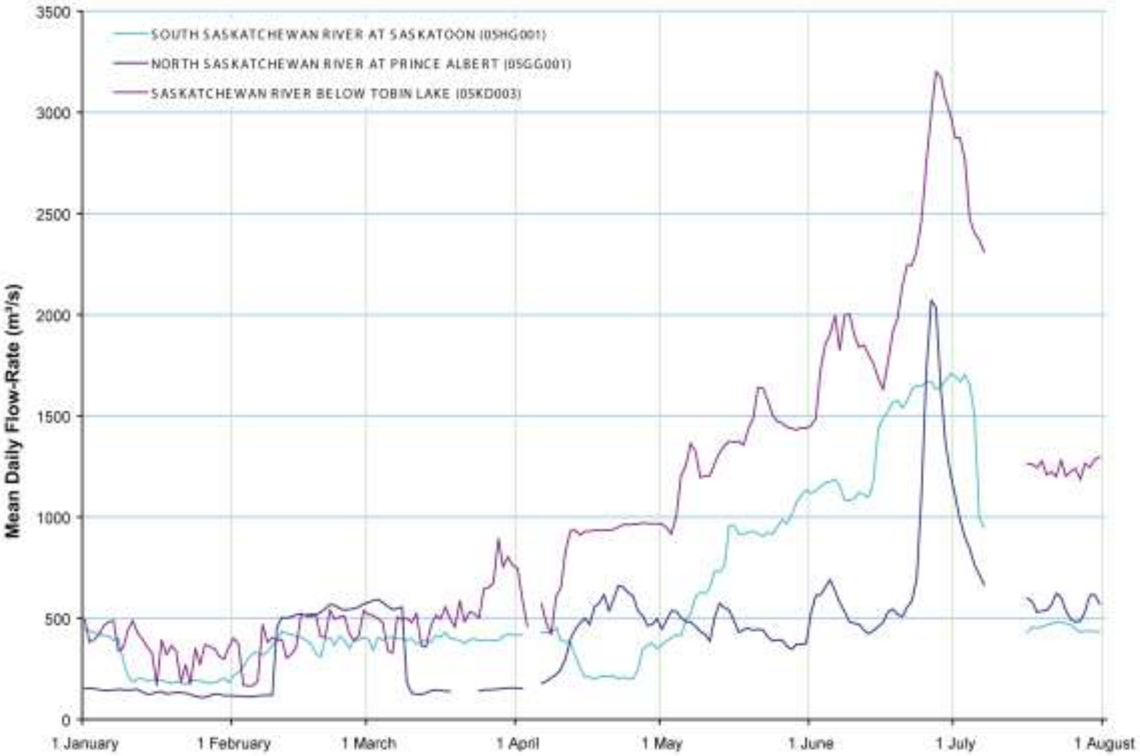


Figure 11: South Saskatchewan River at Saskatoon, North Saskatchewan River at Price Albert and Saskatchewan River below Tobin Lake.

Appendix 2 Peak Flows

Annual Instantaneous Peak Flow Exceedence Probabilities

05AJ001
SOUTH SASKATCHEWAN RIVER AT MEDICINE HAT (05AJ001)

Rank	Year	Peak Q (m^3/s)	Exceedence Probability (%)	Return period (Y)
1	1995	5110	1.5	65.0
2	1953	4300	3.1	32.5
3	1923	4110	4.6	21.7
4	2005	3790	6.2	16.2
5	1929	3450	7.7	13.0
6	1975	3170	9.2	10.8
7	1932	2940	10.8	9.3
8	1942	2650	12.3	8.1
9	1948	2620	13.8	7.2
10	1915	2550	15.4	6.5
11	1967	2360	16.9	5.9
12	**2011**	**2220**	**18.5**	**5.4**
13	2010	2140	20.0	5.0
13	1927	2140	20.0	5.0
15	1969	2010	23.1	4.3
16	2002	1990	24.6	4.1
17	1963	1970	26.2	3.8
18	1964	1950	27.7	3.6
19	1928	1840	29.2	3.4
20	1951	1780	30.8	3.3
21	1981	1720	32.3	3.1
22	1965	1640	33.8	3.0
23	2008	1590	35.4	2.8
24	2006	1560	36.9	2.7
25	1970	1440	38.5	2.6
26	1998	1430	40.0	2.5
27	1990	1380	41.5	2.4
28	1937	1370	43.1	2.3
28	1972	1370	43.1	2.3
30	1974	1320	46.2	2.2
31	1991	1310	47.7	2.1
32	1971	1270	49.2	2.0
33	1966	1150	50.8	2.0
34	1980	1110	52.3	1.9
35	1954	1090	53.8	1.9
36	1997	1080	55.4	1.8
37	1945	1050	56.9	1.8
37	1947	1050	56.9	1.8
39	1959	917	60.0	1.7
40	1986	872	61.5	1.6
41	1978	867	63.1	1.6
42	2007	849	64.6	1.5

05CK004
RED DEER RIVER NEAR BINDLOSS (05CK004)

Rank	Year	Peak Q (m^3/s)	Exceedence Probability (%)	Return period (Y)
1	2005	1050	2.4	42.0
2	1990	997	4.8	21.0
3	1982	981	7.1	14.0
4	1971	869	9.5	10.5
5	1974	756	11.9	8.4
6	1999	715	14.3	7.0
7	1981	661	16.7	6.0
8	1997	642	19.0	5.3
9	2008	584	21.4	4.7
10	1972	558	23.8	4.2
11	1966	544	26.2	3.8
12	1996	543	28.6	3.5
13	1986	538	31.0	3.2
14	2007	536	33.3	3.0
15	1998	517	35.7	2.8
16	**2011**	**509**	**38.1**	**2.6**
17	1967	487	40.5	2.5
18	1995	400	42.9	2.3
19	2003	385	45.2	2.2
20	2010	366	47.6	2.1
21	1992	300	50.0	2.0
22	1973	297	52.4	1.9
23	1980	296	54.8	1.8
24	2004	293	57.1	1.8
25	1991	290	59.5	1.7
26	2000	270	61.9	1.6
27	1985	243	64.3	1.6
28	1989	234	66.7	1.5
29	1978	233	69.0	1.4
30	1987	212	71.4	1.4
30	1976	212	71.4	1.4
32	1961	199	76.2	1.3
33	1983	182	78.6	1.3
34	2002	173	81.0	1.2
35	2001	167	83.3	1.2
36	1977	163	85.7	1.2
37	1962	146	88.1	1.1
38	1968	140	90.5	1.1
39	1988	134	92.9	1.1
40	1979	110	95.2	1.0
41	1984	81	97.6	1.0

43	1976	762	66.2	1.5
44	1994	761	67.7	1.5
45	1996	760	69.2	1.4
46	1979	744	70.8	1.4
47	1957	739	72.3	1.4
48	1992	699	73.8	1.4
49	1936	694	75.4	1.3
50	1982	657	76.9	1.3
51	1958	651	78.5	1.3
52	1999	590	80.0	1.3
53	1973	544	81.5	1.2
54	1989	496	83.1	1.2
55	1985	407	84.6	1.2
56	1983	388	86.2	1.2
57	2004	351	87.7	1.1
58	2009	314	89.2	1.1
58	1987	314	89.2	1.1
60	1988	292	92.3	1.1
61	2001	280	93.8	1.1
62	1984	260	95.4	1.0
63	2000	182	96.9	1.0
64	1977	174	98.5	1.0

05GG001

NORTH SASKATCHEWAN RIVER AT PRINCE ALBERT (05GG001)

Rank	Year	Peak Q (m³/s)	Exceedence Probability (%)	Return period (Y)
1	1915	5660	1.7	60.0
2	1974	4050	3.3	30.0
3	1986	3420	5.0	20.0
4	1954	3060	6.7	15.0
5	1952	3030	8.3	12.0
6	1965	2520	10.0	10.0
7	1972	2380	11.7	8.6
8	1932	2230	13.3	7.5
9	**2011**	**2141**	**15.0**	**6.7**
10	1912	2070	16.7	6.0
11	1990	2050	18.3	5.5
12	2005	1950	20.0	5.0
13	1982	1730	21.7	4.6
14	1925	1670	23.3	4.3
14	1923	1670	23.3	4.3
16	1980	1630	26.7	3.8
17	1969	1590	28.3	3.5
18	1999	1470	30.0	3.3
19	1998	1370	31.7	3.2
20	1997	1349	33.3	3.0
21	1958	1330	35.0	2.9
21	2007	1330	35.0	2.9
23	1966	1310	38.3	2.6
24	1959	1270	40.0	2.5
24	1964	1270	40.0	2.5
24	1970	1270	40.0	2.5
27	1953	1190	45.0	2.2
28	1981	1170	46.7	2.1
29	1963	1160	48.3	2.1
30	1971	1140	50.0	2.0
31	2006	1070	51.7	1.9

05HG001

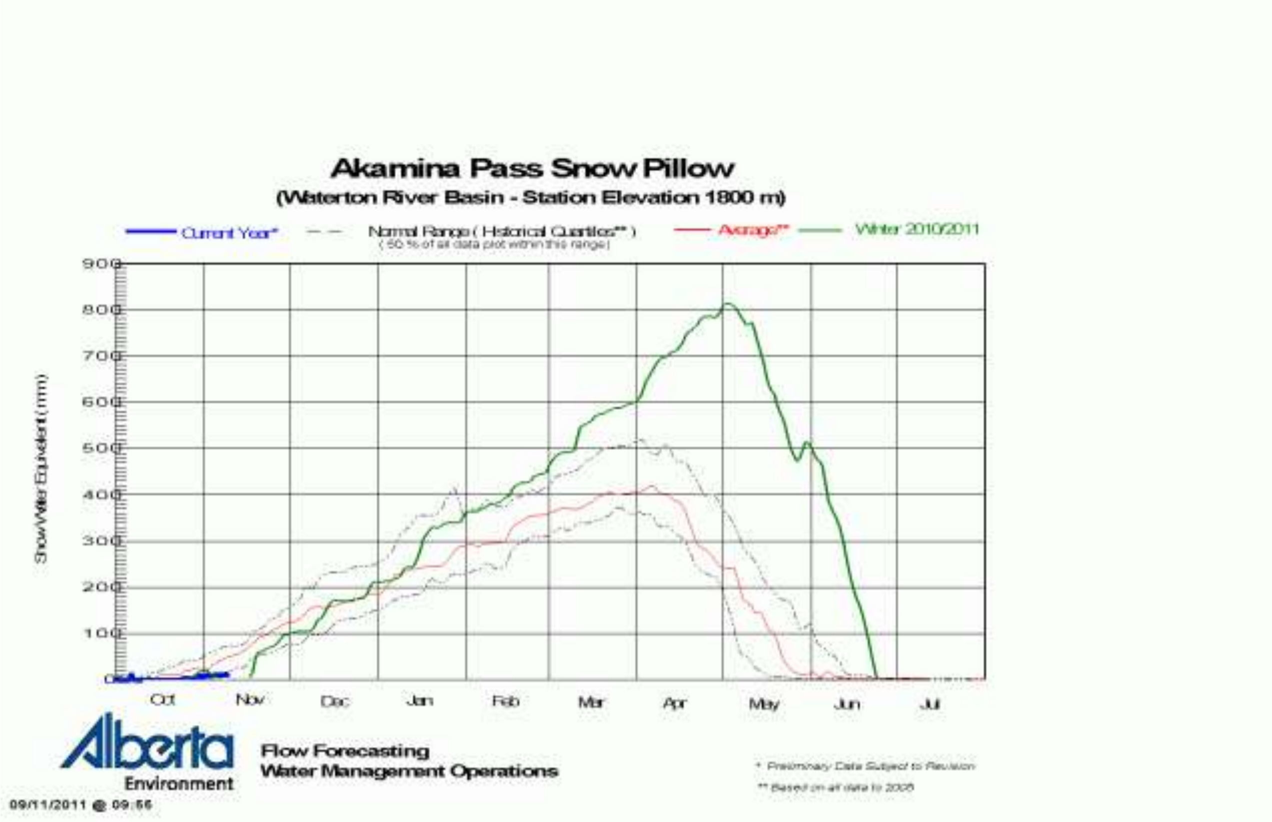
SOUTH SASKATCHEWAN RIVER AT SASKATOON (05HG001)

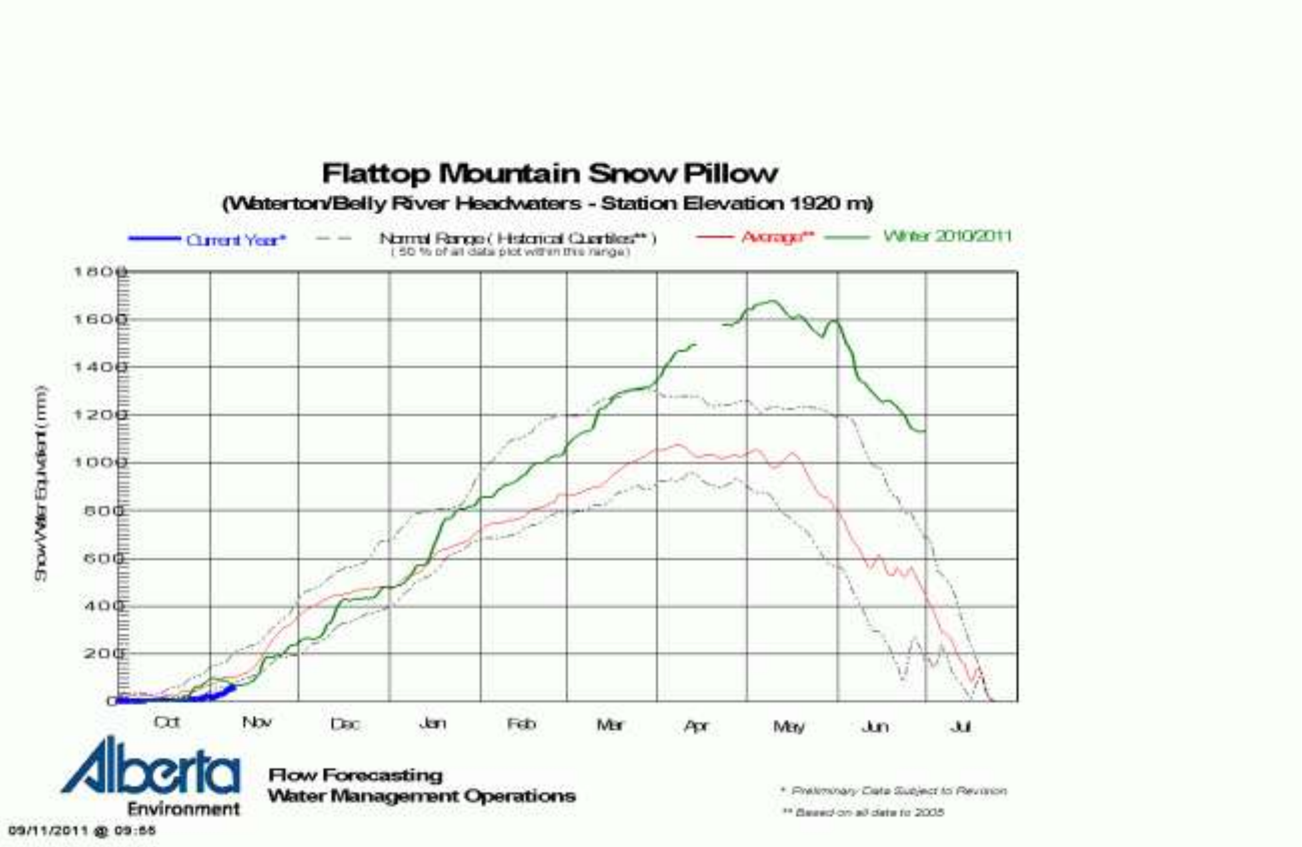
Rank	Year	Peak Q (m³/s)	Exceedence Probability (%)	Return period (Y)
1	1953	4190	1.9	52.0
2	1923	3650	3.8	26.0
3	1929	3260	5.8	17.3
4	1915	3230	7.7	13.0
5	1932	3200	9.6	10.4
6	1917	2040	11.5	8.7
7	1975	1970	13.5	7.4
8	2005	1890	15.4	6.5
9	1942	1840	17.3	5.8
10	1969	1790	19.2	5.2
11	**2011**	**1718**	**21.2**	**4.7**
12	1940	1640	23.1	4.3
13	1951	1610	25.0	4.0
14	1963	1560	26.9	3.7
15	1912	1450	28.8	3.5
16	1964	1430	30.8	3.3
17	1966	1380	32.7	3.1
18	1959	1330	34.6	2.9
19	1995	1290	36.5	2.7
20	1998	1094	38.5	2.6
21	1933	1090	40.4	2.5
22	1922	1080	42.3	2.4
22	1961	1080	42.3	2.4
22	1946	1080	42.3	2.4
25	1993	940	48.1	2.1
26	1962	861	50.0	2.0
27	1974	847	51.9	1.9
28	1972	801	53.8	1.9
29	1990	784	55.8	1.8
30	2010	783	57.7	1.7
31	1981	666	59.6	1.7

32	1991	1020	53.3	1.9
33	1960	1010	55.0	1.8
33	1995	1010	55.0	1.8
33	1985	1010	55.0	1.8
36	2008	982	60.0	1.7
37	1977	929	61.7	1.6
38	1967	883	63.3	1.6
39	2009	859	65.0	1.5
40	1989	849	66.7	1.5
41	1984	835	68.3	1.5
42	2000	829	70.0	1.4
43	1996	817	71.7	1.4
44	2001	809	73.3	1.4
45	2010	801	75.0	1.3
46	1961	799	76.7	1.3
47	1975	790	78.3	1.3
48	1924	767	80.0	1.3
48	1962	767	80.0	1.3
50	2003	744	83.3	1.2
51	1922	719	85.0	1.2
52	1994	716	86.7	1.2
53	1976	668	88.3	1.1
54	1973	646	90.0	1.1
55	1968	603	91.7	1.1
56	1988	529	93.3	1.1
57	1992	520	95.0	1.1
58	2002	501	96.7	1.0
59	1993	477	98.3	1.0

32	1968	603	61.5	1.6
33	1991	597	63.5	1.6
34	2007	510	65.4	1.5
35	1973	493	67.3	1.5
36	1997	464	69.2	1.4
37	1979	446	71.2	1.4
38	2006	443	73.1	1.4
39	1970	439	75.0	1.3
40	1996	432	76.9	1.3
41	2002	428	78.8	1.3
42	1976	425	80.8	1.2
43	2008	418	82.7	1.2
44	2003	416	84.6	1.2
45	1978	405	86.5	1.2
46	1986	402	88.5	1.1
47	1992	360	90.4	1.1
48	2000	344	92.3	1.1
49	2004	327	94.2	1.1
50	2009	292	96.2	1.0
51	2001	289	98.1	1.0

Appendix 3 Snow Pillow Data

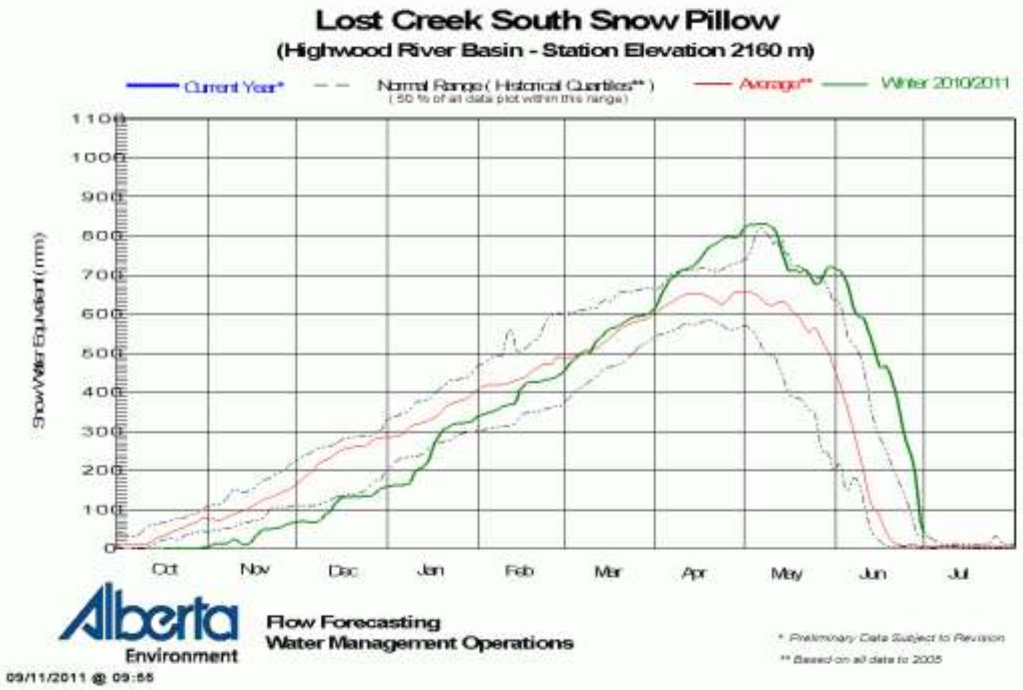


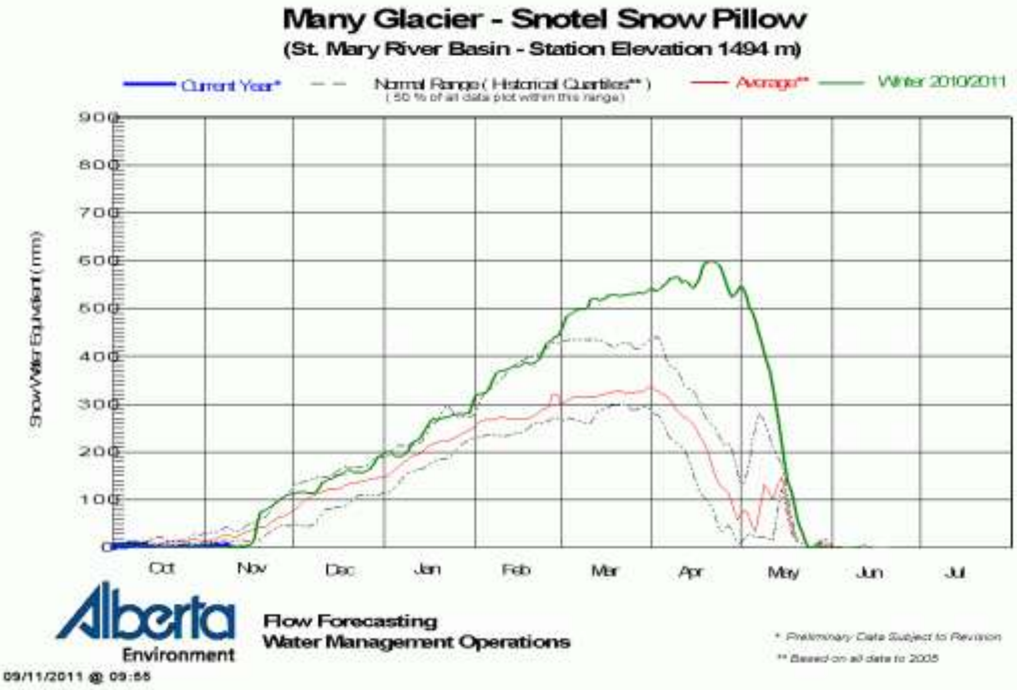

Flattop Mountain Snow Pillow
(Waterton/Belly River Headwaters - Station Elevation 1920 m)
Current Year*
Normal Range (Historical Quartiles**)
(50 % of all data plot within this range)
Average**
Winter 2010/2011
Snow Water Equivalent (mm)
1800
1600
1400
1200
1000
800
600
400
200
0
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Alberta
Environment
Flow Forecasting
Water Management Operations
* Preliminary Data Subject to Revision
** Based on all data to 2005
09/11/2011 @ 09:55

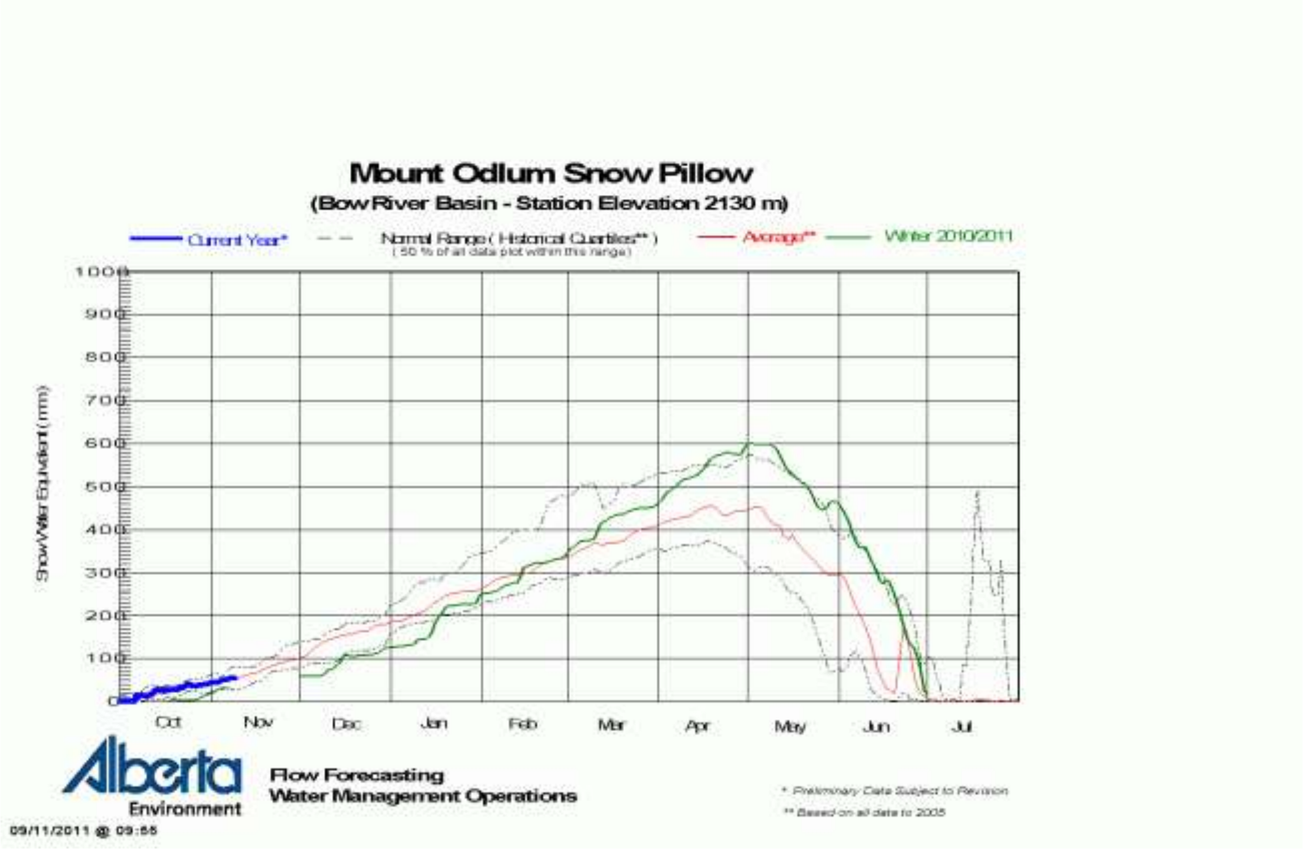

Gardiner Creek Snow Pillow
(Castle River Basin - Station Elevation 1970 m)
Current Year*
Normal Range (Historical Quartiles**)
(50 % of all data plot within this range)
Average**
Winter 2010/2011
Snow Water Equivalent (mm)
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Alberta
Environment
Flow Forecasting
Water Management Operations
* Preliminary Data Subject to Revision
** Based on all data to 2005
09/11/2011 @ 09:55

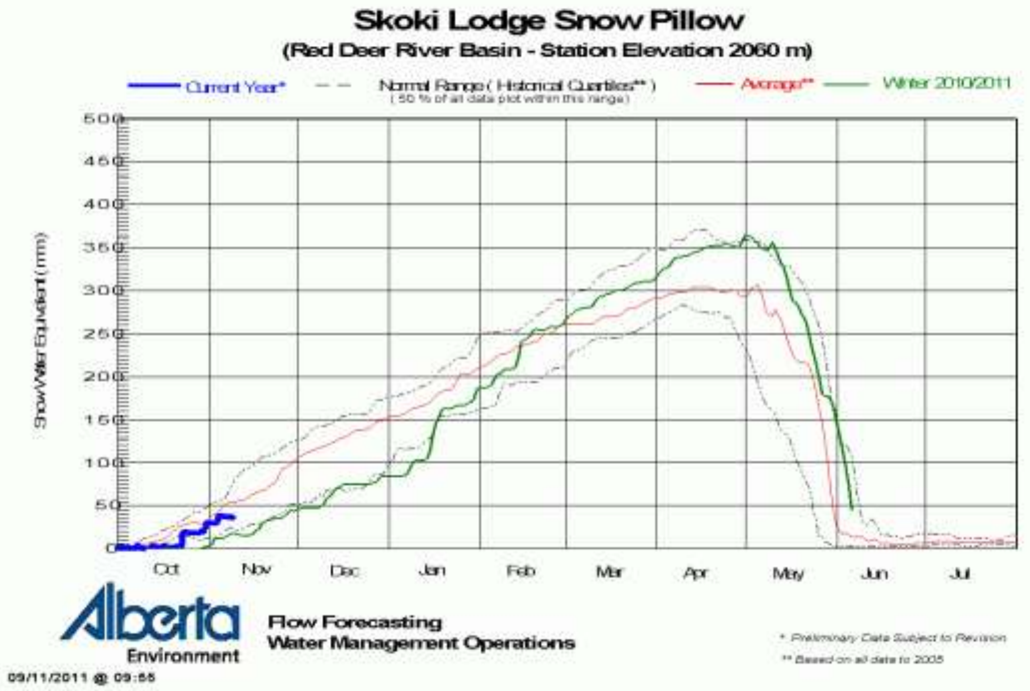

Limestone Ridge Snow Pillow
(Red Deer River Basin - Station Elevation 1950 m)
Current Year*
Normal Range (Historical Quartiles**)
(50 % of all data plot within this range)
Average**
Winter 2010/2011
Snow Water Equivalent (mm)
500
450
400
350
300
250
200
150
100
50
0
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Alberta Environment
Flow Forecasting
Water Management Operations
* Preliminary Data Subject to Revision
** Based on all data to 2005
09/11/2011 @ 09:55

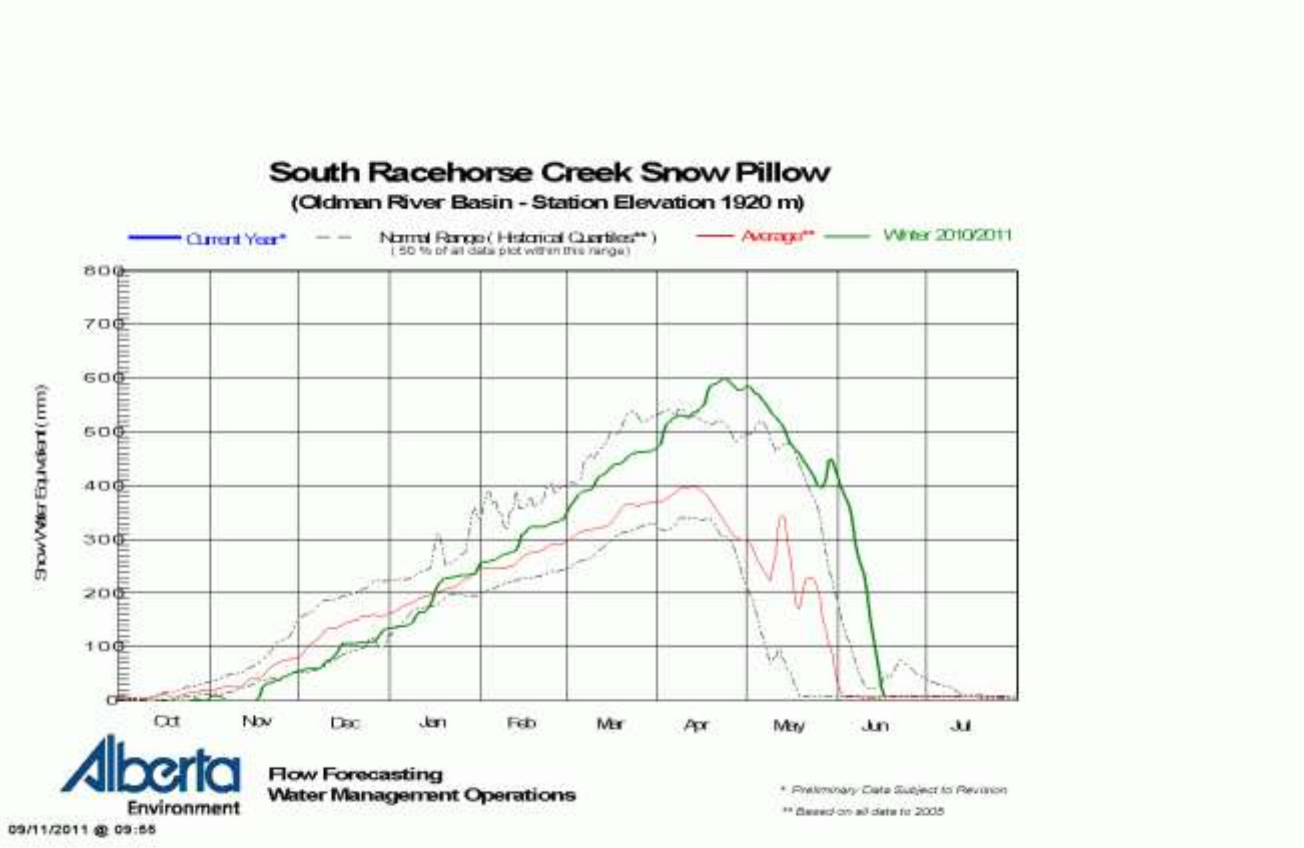

Little Elbow Summit Snow Pillow
(Bow River Basin - Station Elevation 2225 m)
Current Year*
Normal Range (Historical Quartiles**)
(50 % of all data plot within this range)
Average**
Winter 2010/2011
Snow Water Equivalent (mm)
1000
900
800
700
600
500
400
300
200
100
0
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Alberta
Environment
Flow Forecasting
Water Management Operations
* Preliminary Data Subject to Revision
** Based on all data to 2005
09/11/2011 @ 09:55

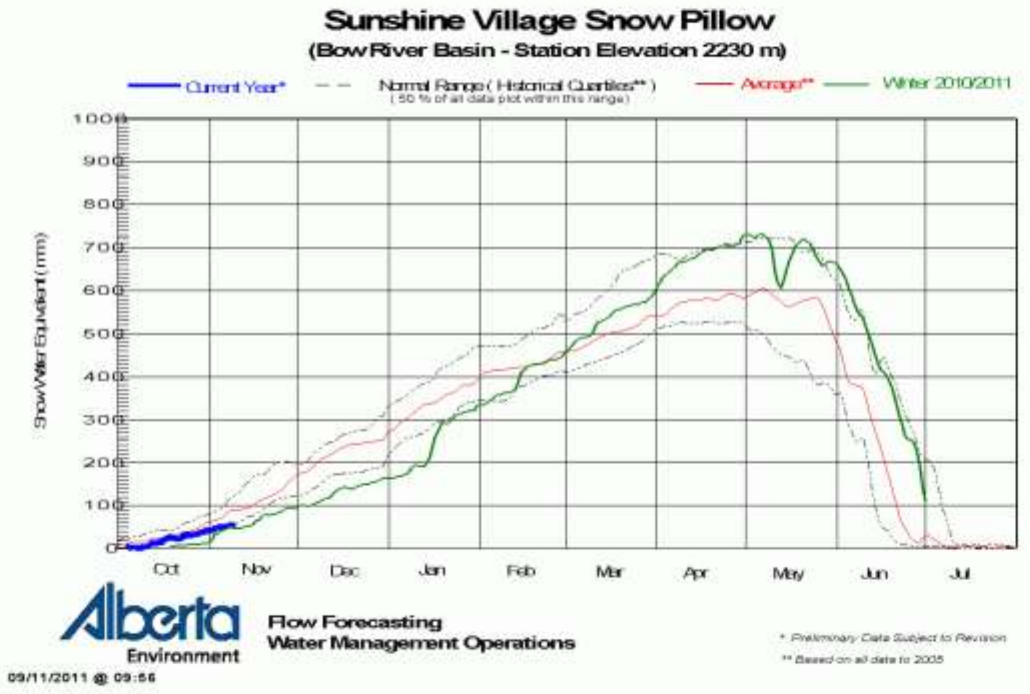

Lost Creek South Snow Pillow
(Highwood River Basin - Station Elevation 2160 m)
Current Year*
Normal Range (Historical Quartiles**)
(50 % of all data plot within this range)
Average**
Winter 2010/2011
Snow Water Equivalent (mm)
1100
1000
900
800
700
600
500
400
300
200
100
0
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Alberta
Environment
Flow Forecasting
Water Management Operations
* Preliminary Data Subject to Revision
** Based on all data to 2005
09/11/2011 @ 09:55


Many Glacier - Snotel Snow Pillow
(St. Mary River Basin - Station Elevation 1494 m)
Current Year*
Normal Range (Historical Quartiles**)
(50 % of all data plot within this range)
Average**
Winter 2010/2011
Snow Water Equivalent (mm)
900
800
700
600
500
400
300
200
100
0
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Alberta
Environment
Flow Forecasting
Water Management Operations
* Preliminary Data Subject to Revision
** Based on all data to 2005
09/11/2011 @ 09:55


Mount Odlum Snow Pillow
(Bow River Basin - Station Elevation 2130 m)
Current Year*
Normal Range (Historical Quartiles**)
(50 % of all data plot within this range)
Average**
Winter 2010/2011
Snow Water Equivalent (mm)
1000
900
800
700
600
500
400
300
200
100
0
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Alberta
Environment
Flow Forecasting
Water Management Operations
* Preliminary Data Subject to Revision
** Based on all data to 2005
09/11/2011 @ 09:55


Skoki Lodge Snow Pillow
(Red Deer River Basin - Station Elevation 2060 m)
Current Year*
Normal Range (Historical Quartiles**)
(50 % of all data plot within this range)
Average**
Winter 2010/2011
Snow Water Equivalent (mm)
500
450
400
350
300
250
200
150
100
50
0
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Alberta
Environment
Flow Forecasting
Water Management Operations
* Preliminary Data Subject to Revision
** Based on all data to 2005
09/11/2011 @ 09:55


South Racehorse Creek Snow Pillow
(Oldman River Basin - Station Elevation 1920 m)
Current Year*
Normal Range (Historical Quartiles**)
(50 % of all data plot within this range)
Average**
Winter 2010/2011
Snow Water Equivalent (mm)
800
700
600
500
400
300
200
100
0
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Alberta
Environment
Flow Forecasting
Water Management Operations
* Preliminary Data Subject to Revision
** Based on all data to 2005
09/11/2011 @ 09:55


Sunshine Village Snow Pillow
(Bow River Basin - Station Elevation 2230 m)
Current Year*
Normal Range (Historical Quartiles**)
(50 % of all data plot within this range)
Average**
Winter 2010/2011
Snow Water Equivalent (mm)
1000
900
800
700
600
500
400
300
200
100
0
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Alberta Environment
Flow Forecasting
Water Management Operations
* Preliminary Data Subject to Revision
** Based on all data to 2005
09/11/2011 @ 09:56


Three Isle Lake Snow Pillow
(Bow River Basin - Station Elevation 2160 m)
Current Year*
Normal Range (Historical Quartiles**)
(50 % of all data plot within this range)
Average**
Winter 2010/2011
Snow Water Equivalent (mm)
800
700
600
500
400
300
200
100
0
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Alberta Environment
Flow Forecasting
Water Management Operations
* Preliminary Data Subject to Revision
** Based on all data to 2005
09/11/2011 @ 09:56