3 Upland watershed management and global change

Canada's Rocky Mountains and western plains

Dave Sauchyn, Michael Demuth, and Alain Pietroniro

Myths of abundant and stationary water resources have influenced water policy and management in western Canada. Data presented in this chapter demonstrate that water use, policy and management were established during a period of fairly stable and reliable water supplies as compared to preceding and projected hydrological regimes. These data include tree-ring and historical evidence of prolonged drought, recent trends (glacier wastage, declining snowmelt runoff and summer flows), and global circulation models (GCM)-based scenarios of precipitation and runoff. We consider how water policy and management might be adjusted to compensate for a long-term view of the surface hydrology that includes more prolonged drought and lower average flows than observed and experienced in the twentieth century.

3.1 Introduction

> No country on Earth has such contrasts of drought and water plenty as Canada. None has so much water ready and available for use. But Canada is learning that national statistics do not begin to portray the complexity of its relationship with its most vital resource. … a new reality is emerging. It is a reality in which water is in increasingly short supply in some places at some times, where water suddenly has a real value rather than being an unlimited resource – and where rivers truly can run dry.
>
> (Pearce 2006)

A "myth of abundance" has historically influenced Canadian water policy and management (Mitchell and Shrubsol 1994; Sprague 2006). An explicit assumption also has been made that "the hydrological regime is stationary and will continue to be stationary in the future" (Whitfield *et al*. 2004: 89). While 25 percent of the world's freshwater is stored within Canada, most of this is underground or in largely inaccessible glaciers and lakes. Sprague (2006) argued that Canada's water supply is the 2.5 percent of annual global precipitation that falls on our populated regions. Thus, there is "limited availability of freshwater in Canada at different times and places" (Quinn *et al*. 2004: 1). The place and time of the least amount of freshwater is the Western Plains during recurrent drought. The hydroclimate of this region (Figure 3.1) is the subject of this chapter. We examined the hydroclimatic

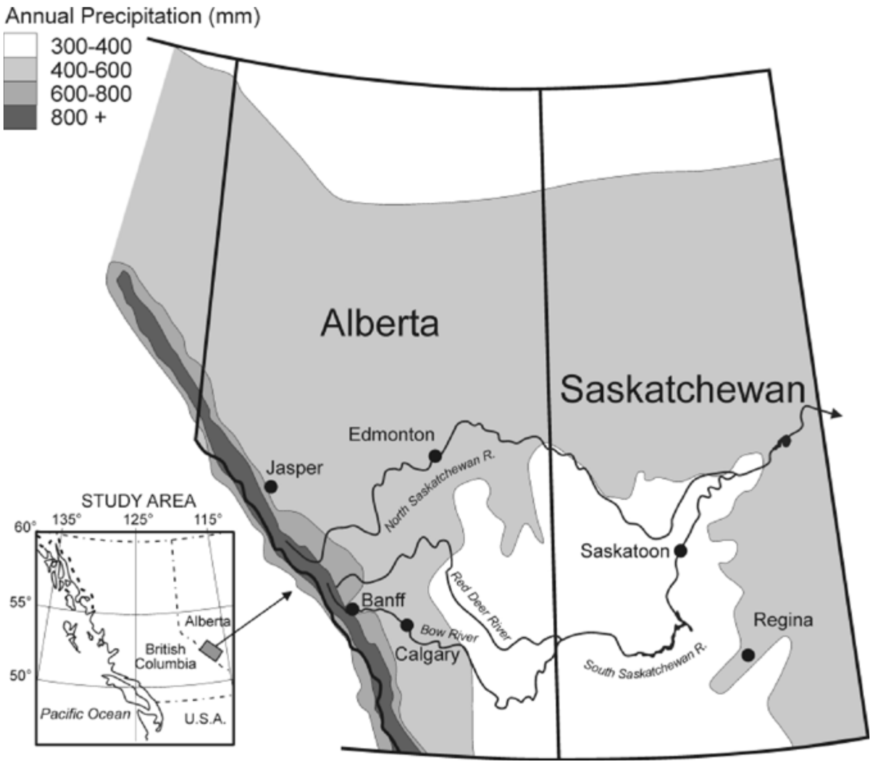

Figure 3.1 The North and South Rivers shed runoff from the southern Rocky Mountains and across the subhumid to semiarid Prairie Ecozone of southern Alberta and southwestern Saskatchewan.

variability from 1600–2100 as a context for the observations and experiences of the twentieth century, upon which water policy and management strategies have been based. We consider how water policy and management might be adjusted to compensate for a long-term view of the surface hydrology.

Western water policy and management practices reflect the dry climate of the continental interior. In contrast to the accessible surface water and riparian laws of eastern Canada and the United States, the principles of first appropriation and apportionment evolved in the west to guarantee access to water for the first users (irrigators) and to allocate water among jurisdictions (Arnold 2005; Quinn *et al*. 2004). Apportionment agreements and guidelines for minimum flows ensure water supplies by jurisdiction and for instream flow needs. If natural flows reach unprecedented levels, the uncertainties and assumptions inherent in the calculation of flows for apportionment agreements and to maintain aquatic ecosystems become more significant. This implies the question: how likely is it future low flows will result in conflicts between users and jurisdictions?

In Canada's southern prairies (Figure 3.1), apportionment and first appropriation of water supplies, and more recently water conservation objectives to protect aquatic systems, are policy responses to a subhumid to semiarid climate. Mean annual water deficits are 35 percent to 50 percent, in terms of the shortfall of precipitation (P) relative to potential evapotranspiration (PET). The extent of this Canadian drybelt increases by approximately 50 percent when P/PET is mapped using output from the CGCM2B2 (Canadian Global Climate Model, version 2, greenhouse gas emission scenario B2) for the 2050s (Sauchyn *et al*. 2002). While more severe and frequent drought is projected under global warming (Kharin and Zwiers 2000), an expanded subhumid climate is not outside the geographic range of natural variability, since in drought years (e.g.1937, 1961, 1988, 2001) a large part of the prairies has a P/PET < 0.65, although with devastating consequences (Wheaton *et al*. 2005). The management of water in the western interior is essentially a process of redistributing the runoff from source areas with excess water (i.e., the Rocky Mountains and prairie uplands; e.g., the Cypress Hills) to the adjacent water-deficient plains that are most of Canada's farmland. In most years, the supply of water from the mountains and uplands is high, relative to the water deficit on the plains. This gap becomes precariously small, however, during years of drought such as 2001, when there were serious economic consequences resulting in adjustments to water policy and management (Alberta Environment n.d.; Wheaton *et al*. 2005).

Immediately following two of the driest years on record, 2001–2, Alberta released its groundbreaking Water for Life Strategy (Alberta Environment 2003). The rationale for a provincial water strategy included the need for major shifts in the approach to managing a water supply that in recent years had been "fluctuating and unpredictable." A "clear set of principles" emerged from consultations to develop the provincial water strategy. They include:

- all Albertans must recognize there are limits to the available water supply.
- Alberta's water resources must be managed within the capacity of individual watersheds.
- knowledge of Alberta's water supply and quality is the foundation for effective decision-making.

Applying these principles to science-based decision making will require estimates of "the limits to the available water supply" and "capacity of individual watersheds." Knowledge of Alberta's water supply is incomplete until data on trends, variability and extremes, and thereby limits and capacities, are derived from the observation and modeling of hydroclimate over time frames that extend before and beyond our short experience with hydrologic systems.

This chapter provides evidence that current perceptions of water supplies and variability may be skewed by the observations and experience of the twentieth century and may be unrepresentative of both natural and future hydroclimate. The extensive wastage of glacier ice from the Rocky Mountains increased local streamflow above the net income of annual precipitation, but it is almost certain that this effect is in decline as the glaciers retreat rapidly towards their least extent in the past 10,000 years (Demuth and Pietroniro 2003). Furthermore climate change scenarios suggest that a significantly larger proportion of winter precipitation will fall as rain, as opposed to snow (Lapp *et al*. 2005). This hydrologic regime, with less natural storage, will tend towards greater extremes, including a higher probability of drought. According to records and models of pre- and post-twentieth century climate, as described in this chapter, the twenty-first century will almost certainly include droughts of greater severity and duration than those previously observed and experienced by western Canadians since European settlement. The results of our research on the hydroclimate and stream hydrology of the Rocky Mountains and western plains suggest that the myths of an abundant and stationary water supply are misconceptions but also based in physical reality.

3.2 Recent trends and future projections

A recent study for Alberta Environment (Pietroniro *et al*. 2006a) comprises three major investigations of recent and potential future trends in water resources within the North and South Saskatchewan River basins (NSRB and SSRB). These studies catalogue glacial extents; examine streamflow records for evidence of trends and variability related to changes in glacial extent; and model changes in flow regime under future climate/glacier configurations. Combined, these analyses provide an assessment of the impacts that climate change may impose on the "water towers" of the Canadian prairies. In this chapter, we summarize the results of these investigations. For a description of the methods of analysis, the reader should consult Demuth (1996), Demuth and Pietroniro (2003) and Pietroniro *et al*. (2006a). The headwater study basins contain historic records of streamflow and climate obtained from Environment Canada Archives, and glacier information from the Geological Survey of Canada.

3.2.1 A changing glacier landscape

Documenting land ice influences on the water resources of the NSRB and SSRB requires periodic mapping of snow and ice extents. These extents can then be incorporated into hydrological modeling- and remote sensing-based glacier-climate scaling frameworks. Landsat satellite images since the 1970s enable repetitive, synoptic, and high-resolution multispectral mapping. Glacier extent in the Nelson headwaters was estimated for 1975 and 1998, and changes in area extent were documented. An example of the delineated glacier extent is shown in Figure 3.2. Total glacier area change as a ratio of 1975 glacier extent was approximately 50 percent in the South Saskatchewan River basin and 23 percent in the North basin.

3.2.2 Streamflow trends in headwater catchments

The influence of changing glacier cover was examined using parametric and non-parametric statistical trend analysis of streamflow and basin yield for several

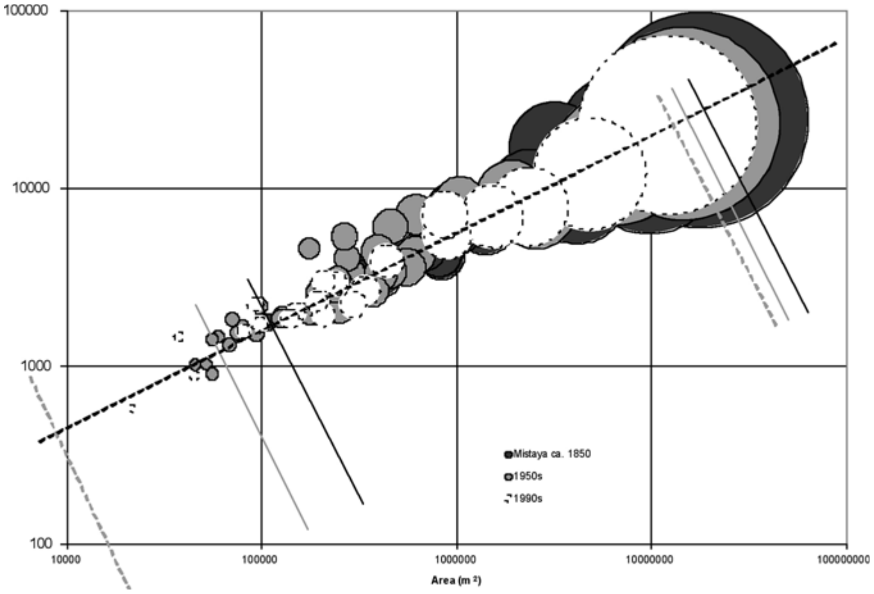

Figure 3.2 Example of recent and past-century glacier cover extent changes for the Saskatchewan River Basin. Top: Mistaya sub-basin depicted as log Perimeter vs. log Area for three epochs. Note the rate of change (fiducial lines) for the largest and smallest glaciers in the sample (after Demuth and Pietroniro 2003). Bottom: Peyto Glacier at the LIA maximum stage (ca. 1850; yellow), 1950s (red) and 1990s (blue).

reference headwater catchments. During periods of precipitation deficit, basin water yield declines and inter-annual flow variability tends to increase with continued glacier shrinkage (Young 1991). The extent to which this situation is evolving in the study area was investigated by analysing longer sequences of historical streamflow data in relation to secular glacier-climate variability (1950–1998) in selected catchments.

The parametric analysis was concentrated on the Mistaya River record (initiated in 1950) and the annual Transition to Base Flow (TBF) period from August to October, when there is maximum contribution from glacier ice melt. Figure 3.3 illustrates the yield from the Mistaya catchment for the period of study. The trend line depicts declining yields for the TBF period, despite evidence that precipitation in the montane is increasing for the same period (August 1–October 31). The coefficient of variation (standard deviation/mean) for the streamflow (Figure 3.3) is increasing over the available record, suggesting that the influence of glacier on streamflow may have been in decline since the mid 1900s.

The streamflow regime was also examined using the minimum, mean and maximum daily discharge data available from the Water Survey of Canada (Environment Canada 2003). The TBF change for the Mistaya basin (1950–98) is quantified using a simple linear regression analysis depicted in Figure 3.4. There

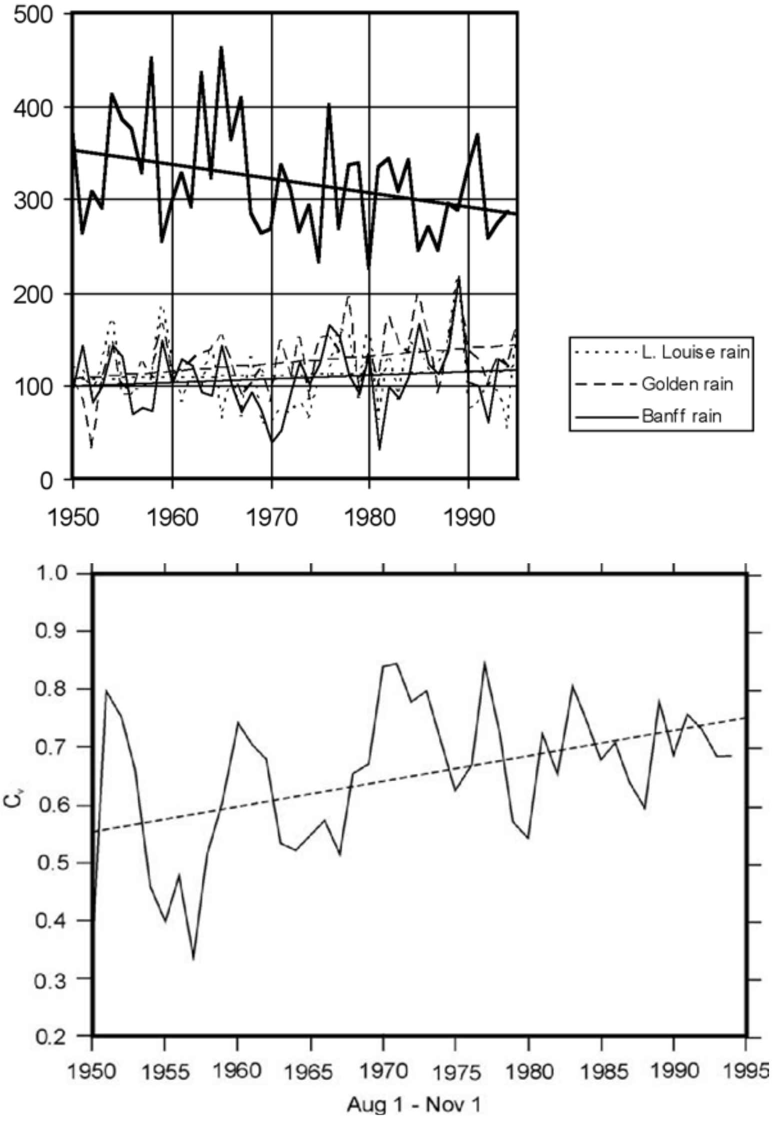

Figure 3.3 Yield (a), precipitation (b) and streamflow (c) coefficient of variation (Cv) for the Mistaya River catchment at gauge 05DA007 over the TBF period (after Demuth and Pietroniro 2003).

is a significant decreasing trend in the mean (R^2=0.33) and minimum (R^2=0.43) TBF time series, and a weaker increasing trend in the maximum (R^2=0.02) TBF time series (Figure 3.4). The initial inference from this analysis is that significant reductions in the mean and minimum flow regimes and increasing flow variability are the result of extensive glacier contraction to the degree that glacier melt

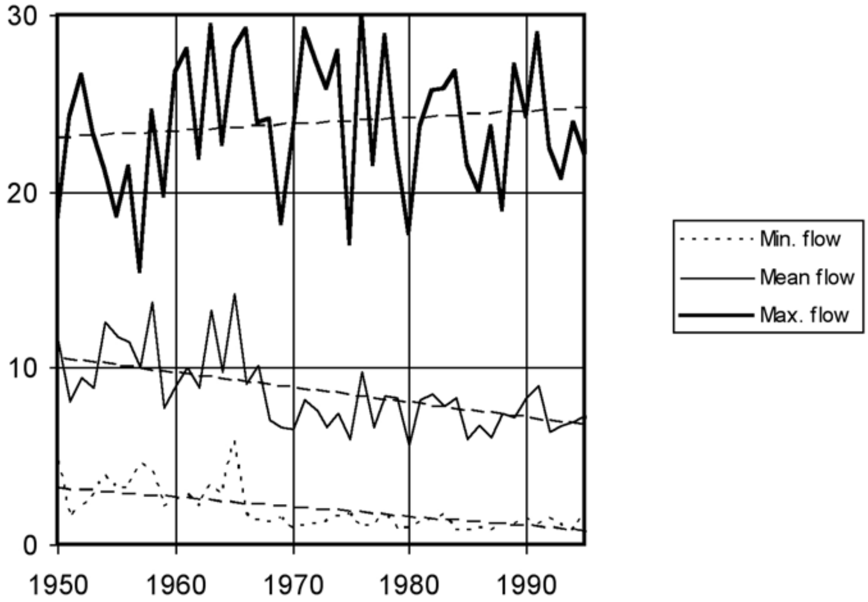

Figure 3.4 Regression analysis for TBF flow period showing trends in minimum, mean and maximum flows for the Mistaya Basin (after Demuth and Pietroniro 2003).

contributions during dry periods, notwithstanding high antecedent snow cover conditions, have been in decline over the period of observation.

All historic records available for the headwater region were examined for use in a non-parametric trend analysis of glaciated and non-glaciated headwaters (Table 3.1). Selection criteria centered primarily on the length and completeness of discharge records obtained from the HYDAT 2003 CD (Environment Canada 2003). Analyses of annual trends were further limited to those stations with discharge data for all months; for a lesser number of months (e.g., April–October) gauge records were used only for analyses of the TBF and/or spring periods and for some observations about changes in monthly trends over the period of record. Spring was defined as March to May, and the TBF period is August to October. Station selection proved exceedingly difficult, since common periods of record of significant duration were never collected. This highlights the importance of systematic and consistent hydrometric data collection. Nonetheless, a total of 18 discharge stations (5 in the NSRB and 13 in the SSRB) were chosen for Mann Kendall (MK) analysis of streamflow trends.

The results for the 14 stations (Table 3.1) show that the majority of trends detected are negative, indicating decreasing streamflow. In particular, for the North Ram, Siffleur and Mistaya sub-basins of the NSRB, whose percent glacier covers increase from 0 percent to 2.5 percent to 8.5 percent, respectively, there is a decreasing trend in TBF as the percentage of glacierization increases. Unfortunately, there is no equivalent comparison for basins with differing glacier

Table 3.1 Results Mann Kendall (MK) analysis of streamflow trends in the NSRB

Station Name	*Station ID*	*Drainage Area*	*Cumulative Area*	*% Glacier Cover*	*Period of Record*	*Total Years*	*Tr/No Tr (Direction)*
NSRB							
Siffleur River Near The Mouth	05DA002	514.74	514.74	2.5	1975–1996 (May–Oct)	22	Jun **Tr** (↑)
Mistaya River Near Saskatchewan Crossing	05DA007	204.31	248.02	8.5	1950–2001 (May–Oct)	52	TBF mean **Tr** (↓) TBF min **Tr** (↓) Jul, Oct **Tr** (↓)
Clearwater River Above Limestone Creek	05DB003	1342.75	1342.75	0.4	1960–1992 (May–Oct)	33	No Tr
North Ram River At Forestry Road	05DC011	347.31	347.31	0	1976–2001 (May–Oct)	26	No Tr
SSRB							
Johnston Creek Near The Mouth	05BA006	122.95	122.95	0	1974–1996 (May–Oct)	22	No Tr
Brewster Creek Near Banff	05BB004	110.15	110.15	0	1971–1996 (May–Oct)	26	No Tr
Redearth Creek Near The Mouth	05BB005	150.61	150.61	1.3	1974–1996 (May–Oct)	23	TBF min **Tr** (↓)
Cascade River Above Lake Minnewanka	05BD005	452.09	452.09	0	1973–1996 (May–Oct)	24	No Tr
Mud Lake Diversion Canal	05BF013	29.00	29.00	4.4	1949–1992 (May–June)	44	TBF mean **Tr** (↑) TBF max **Tr** (↑) Jun, Aug, Sep, Oct **Tr** (↑)
Ghost River Near Black Rock Mountain	05BG002	209.77	209.77	0	1942–1993 (Apr–Nov)	52	No Tr
Jumpingpound Creek Near Cox Hill	05BH013	36.91	36.91	0	1976–2001 (May–Oct)	26	No Tr
Fish Creek Near Priddis	05BK001	260.51	260.51	0	1968–2001 (Mar–Oct)	34	No Tr
Red Deer River Above Panther River	05CA004	941.30	941.30	2.0	1967–2001 (Apr–Oct)	35	Jun **Tr** (↓)

Source: revised from Pietroniro *et al.* 2006.

extent in the SSRB, and thus the pattern with respect to glacier extent and change in streamflow is less clear than for the NSRB. Overall, 50 percent of the stations analyzed exhibited no trends in discharge over the periods of record. Interestingly, and perhaps predictably, of those 50 percent in which no trend was detected, 78 percent were for non-glacierized basins.

3.2.3 Modelling headwater catchments

The methods of hydrological modeling described by Pietroniro *et al.* (2006a) were used to assess both the impacts of projected future climate on flows in the Nelson headwaters and the feasibility of estimating the glacier contributions through simple sensitivity analysis. The WATFLOOD (Kouwen *et al.* 1993) model was used; and calibrated well to conditions in the North and South Saskatchewan River basins. The model was run with a continuous time series for 1961–1990 and 2040–69, standard time slices for constructing climate scenarios (IPCC 2001).

Sensitivity analysis showed the important contribution of glacier runoff to the headwater catchments and its diminishing influence further downstream. This analysis of the impacts of glacier melt on total flow used the 1975 and 1998 glacier extents from the Landsat analysis described earlier. In Figure 3.5, the Mistaya River displays gradually decreasing volumes and variability during the TBF period when moving from the 1975 to 1998 extent. The hydrographs also show the estimated flows with no glacier extent. This analysis demonstrates that basins such as the Siffleur have already been de-glaciated to the point at which future changes in glacier mass will have very little impact on the runoff regime.

Climate change scenarios derived from GCM output for this region were used to assess possible future changes to the streamflow regime. The ECHAM4 (European Centre Hamburg Model) and NCAR-PCM (National Center for Atmospheric Research – Parallel Climate Model) GCMs achieved the lowest errors, highest correlation coefficients and could best model the magnitude of annual and seasonal precipitation and timing of the monthly precipitation in the region (Toyra *et al.* 2005). The potential changes in temperature were applied as offsets, and precipitation was normalized. Spatial gridding of these data produced the anticipated future temperature and precipitation forcing for WATFLOOD. The Hadley Centre and ECHAM models both provided reasonable simulations of the seasonal and annual observed climatology. The WATFLOOD model was re-run using this modified forcing so that current and future streamflow could be compared. This analysis was done using the 1998 glacier extent, and no projections of future extent were added to the model. The results indicate lower overall mean annual flows. Mean monthly flow for the Bow River at Banff shows the influence of changing glacier extent. The 1975, 1998 and "none" hydrographs represent the modelled 10-year monthly flow values using the fixed glacier extents for those years. "None" refers to complete removal of the glaciers from the basin. There is a clear reduction in overall flow volume, and a small reduction in peak magnitude in all three glacier scenarios. The 1998 glacier extent, and climate change forcing from the ECHAM and Hadley Centre models, results in similar patterns with a slight change in peak (increase for Hadley and decrease for ECHAM) and a shift in monthly flows to a higher spring runoff. The TBF period shows very little change resulting from climate change alone, and is more influenced by the glacier extent than by the climate warming. This is simply because the glacier extents are fixed for each grid element in the model at a pre-determined level. Clearly changes in precipitation and temperature will have an influence on the dynamic response of the glacier, and it is likely that glacier recession will continue. The resulting flow

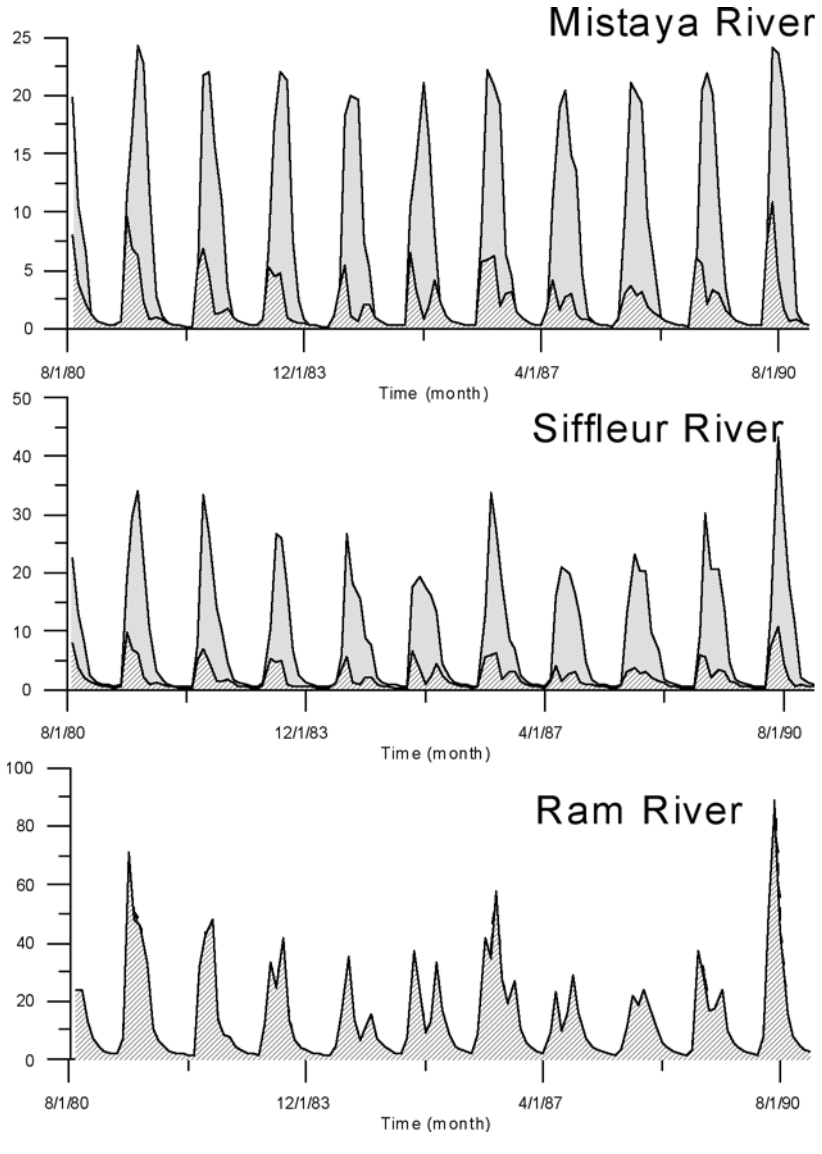

Figure 3.5 Analysis of glacier contributions to flow using the WATFLOOD model. The stippled area represents the model simulation with the 1975 glacier extent. The hatched area represents the runoff in the basin in the absence of glacier contributions (after Pietroniro *et al.* 2006).

regime for the Bow River headwaters will likely include early and increased spring melt and decreased late summer flows as shown in Figure 3.6.

3.2.4 Hydroclimatic variability

The recent and projected streamflow trends described above in part reflect the impact of global warming on a snow-dominated hydrologic regime, but also include a significant component of natural hydroclimatic variability: "many hydroclimate datasets exhibit inter-decadal variability, where some inter-decadal periods are considerably drier or wetter than others. These wet and dry cycles have significant implications for the management of land and water resources systems, where several decades of sufficient water are followed by droughts clustered over the following decades" (Chiew 2006). The length of most hydroclimatic cycles approaches or exceeds the length of gauge records. This low-frequency variability is best observed with proxy hydroclimatic records that provide water resource planners and engineers with a historical context for standard reference hydrology to evaluate baseline conditions and water allocations, and a broad perspective on the variability of water levels to assess the reliability of water supply systems under a wider range of precipitation and flow regimes than recorded by a gauge.

Tree rings are the preferred proxy for records of climate variability at annual to multi-decadal scales spanning centuries to millennia (Briffa 2000). They are the source of both hydroclimate information and a chronology with absolute annual resolution. Annual variations in tree-ring width reflect daily and seasonal growth-limiting processes. Where available soil moisture limits tree growth, standardized tree-ring widths correlate with hydrometric variables. Streamflow records correlate with moisture-sensitive tree-ring chronologies, because streamflow and tree growth have a similar muted response to episodic inputs of rainfall and snow-melt water.

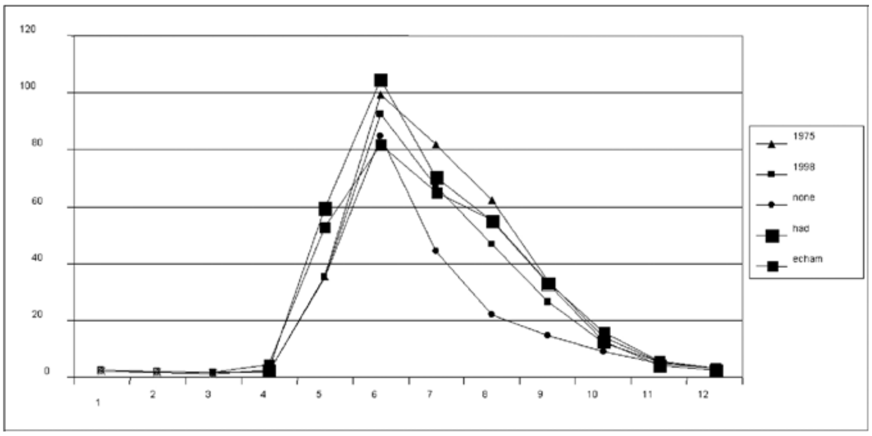

Figure 3.6 Comparison of 10-year monthly flow estimates from WATFLOOD for the Bow River at Banff, derived from both climate change and glacier change project (after Pietroniro *et al.* 2006).

Hydrological peaks are usually underestimated by tree rings, given a physiological limit to the growth response to fluctuations in soil moisture. Therefore, proxy records do not provide precise volumes of streamflow, yet they capture the timing and duration of periods of high and low flow. Tree rings are an especially good indicator of drought; dry years produce narrow rings.

Until recently, networks of moisture-sensitive tree-ring chronologies have been lacking for western Canada, and streamflow has been reconstructed using just a few chronologies (Case and Macdonald 2003). Researchers at the University of Regina Tree Ring Lab (www.parc.ca/urtreelab) have established a network of tree-ring chronologies to infer long-term moisture and streamflow variability from a pool of predictor chronologies that capture a larger range of the regional climatic variability than data from one or a few sites. Nearly all of these collections are from open-canopy forests on ridge crests, south- and west-facing slopes, and/or rapidly drained soils. At these dry sites, tree growth is limited by available soil moisture and therefore our tree-ring chronologies are proxies of summer and annual precipitation, soil moisture and runoff.

Here we present a streamflow reconstruction to illustrate interannual to multi-decadal hydroclimatic variability since 1602 and to provide a historical context for the gauge record from the twentieth century. The mean annual flow of the Oldman River at Waldron's Corner, Alberta (gauge AA023) was reconstructed by Axelson (2007) from tree-ring chronologies from five sites within 50 km of the gauge. The tree-ring model of streamflow was built by entering standardized and lagged tree-ring index data into a stepwise multiple regression. The predictand is the stream gauge record. The best model explains maximum variance in the predictand with the fewest predictors and least standard error. The validity of our tree-ring model for the Oldman River is indicated first by a reduction of error (0.45) that is comparable to the squared correlation coefficient (0.55) (Fritts *et al.* 1990), and secondly by similar values of the standard error (2.9) and root-mean square error of validation (3.07), measures of the uncertainty in predicted values over the calibration and validation periods. When the R^2 is adjusted for the number of predictors (lost degrees of freedom) the explained variance (R^2_a) is 51 percent. Most of the unexplained variance is attributable to the larger amplitude of observed versus reconstructed flows. On the other hand, the tree-ring records capture the timing of low flows and, thus, we are confident that the full reconstruction in Figure 3.7 spanning 1602–2004 gives the timing and duration of drought.

The proxy streamflow data in Figure 3.7 are plotted as departures from the median of the instrumental record. This plot reveals the impact of the droughts of the 1980s on the flow of the upper Oldman River. This sequence of low flows, however, is certainly not the worst streamflow scenario. For almost five decades from the 1830s to 1880s, just before the region was settled by EuroCanadians, there were only nine years of above-average flow. The regional water balance would have been seriously depleted by these sustained dry conditions. Similarly in most years between 1640 and 1720 the tree-rings record below-average flow. Since these droughts are relatively recent, there are historical observations of the water scarcity and its impacts, including evidence of sand dune activity (Wolfe *et*

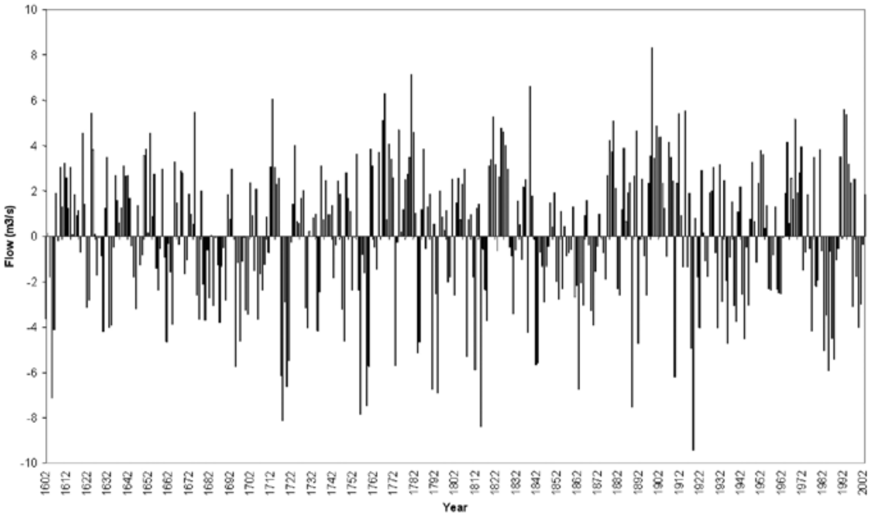

Figure 3.7 The full tree-ring reconstruction of mean annual flow of the Oldman River at Waldron's Corner for the period 1602–2004. These proxy streamflow data are plotted as departures from the median of the reconstruction.

al. 2001) from a lack of soil moisture and flows in the North Saskatchewan River at Edmonton that were so low that furs could not be moved by canoe (Sauchyn *et al*. 2002, 2003).

The proxy streamflow record reveals periodic shifts in the variance of the hydroclimatic regime. Extended wet and dry intervals (low-frequency variability) represents a different challenge for water management than predominately year-to-year (high frequency) variability. In general, natural and socioeconomic systems are able to recover from severe drought of short duration. Sustained drought has cumulative impacts on water balances and ecosystems resulting in significant, sometimes irreversible, impacts. Current water policy and management does not account for sustained dry spells lasting a decade or longer because droughts of this duration did not occur in the twentieth century.

3.3 Discussion

In Canada's western interior, the most serious risk from climate change is a shift in the distribution of water supplies and the potential for water scarcity (Schindler and Donahue 2006; Sauchyn and Kulshreshtha 2008). The region is losing the advantage of a cold winter: snow and ice, the most reliable and predictable source of runoff. The impacts of climate change on economies and communities are necessarily adverse because resource management practices and policies have assumed a stationary hydrological regime. Data presented in this chapter demonstrate that water usage, policy and management were established during a period of fairly stable and reliable water supplies, as compared to preceding and projected hydrological regimes. These data include tree-ring and historical evidence of prolonged drought, recent trends (glacier wastage, declining snowmelt runoff and summer flows), and GCM-based scenarios of precipitation and runoff.

The analysis of recent and future flows in the North and South Saskatchewan River basins showed the important contributions of glacier runoff to the headwater catchments and the diminishing influence downstream and with time. Overall, the evidence indicates large changes in glacier extent with decreasing streamflow in glacierized basins; however, no discernible trend to this point has been found in non-glacierized catchments. Given the uncertainty associated with GCM scenarios, hydrological models and current observation networks, it is difficult to quantify the exact magnitude of change. However, it appears that we are experiencing significant reductions in glacier extent and this is manifest in decreasing streamflow, both annually and in the late summer periods. The changes will likely affect water resources in low-snowfall years, particularly during the transition to base flow (TBF) period of dry late-summer conditions. However, projected increases in precipitation may very well offset these reductions in mean annual flow, resulting in increasing spring snowmelt peak, but less water availability in the TBF period due to the lack of natural storage. These impacts will be particularly acute in mountain headwater basins.

Flow contributions from glacier sources should increase in the short to medium term, and decrease in the long term (IPCC 2001). In the eastern slopes of the Rocky Mountains, there already is evidence during critical periods of a reduction in yield with reduced glacier area. This is among the strongest signals of the impacts of global warming in western Canada. Underlying this trend is the natural variability in hydroclimate represented here with a proxy record of streamflow derived from moisture-sensitive tree-ring records. These data illustrate the significant multi-decadal variability in the hydrologic system and suggest that future surface water supplies very likely will be subject to a drought of longer duration than the most serious droughts experienced since EuroCanadian settlement of the region.

Notwithstanding the uncertainty in climate projection, particularly estimates of precipitation, the science presented here has significant implications for water policy and management in western Canada. Agriculture is particularly sensitive to climate variation and the irrigation sector in southern Alberta and southwestern Saskatchewan is vulnerable given its dependence on streamflow to overcome soil moisture deficits (Alberta Environment n.d., de Loë *et al.* 2001). About 70 percent of the irrigated farmland in Canada (400,000 hectares) is in southern Alberta (Statistics Canada, Ottawa, www.statcan.ca). This is four percent of the cultivated land in Alberta, yet it produces 18 percent of the province's agri-food gross domestic product. In the South Saskatchewan River Basin, about 75 percent of the allocated water is used for irrigation (Alberta Environment n.d.). This percentage rises to 86 in the Oldman River sub-basin. Between 20 and 30 percent of withdrawals are returned to the river system.

3.3.1 Implications for water management

Adapting to the impacts of climate change on water resources requires adjustments to practices, polices and infrastructure so that economic development can be sustained by accommodating shifts in mean hydroclimatic conditions and variability. Management strategies and structures have evolved to limit exposure to a historical range of hydroclimatic variability. Paradigms and practices of water management must be adjusted to manage a hydrological cycle that may be increasingly sensitive to the timing and frequency of rainfall events, with less buffering from glacier ice and late-lying snow at high elevations. Current sensitivity to drought suggests that our communities and institutions are not adequately adapted to climate variability, even in the absence of climate change that could produce shifts in the amplitude and frequency departures from an average climate. The principles of adaptive, anticipatory and integrated water resource management, which include monitoring and scientific discovery, would seem to provide the framework for adapting to the greater range of hydroclimatic variability anticipated for the twenty-first century: "Adaptive management explicitly accepts indeterminacy, ignorance, uncertainly and risk; the inevitability of surprise and turbulence; and the need for flexibility." (Mitchell and Shrubsol 1994: 55)

Establishing trends and variability in past and future hydroclimate is the only systematic way to understand and validate possible future scenarios. Knowledge of the current state of the climate system and systematic tracking of the gradual changes occurring in these large systems requires major investments in data collection and science. There are important economic justifications for understanding and monitoring progressive changes in support of adaptation. Operational decisions about reservoir storage, irrigation, flood and drought mitigation, and hydropower production are based on water supply forecasts from statistical and simulation models that are derived and calibrated using instrumental data from monitoring networks. This standard forecasting methodology has limited application, however, to longer-term water planning and policy making, because most instrumental records generally are too short to capture the decadal and lower-frequency variation in regional climate and hydrology. Some drivers of climate variation have a periodicity that approaches or exceeds the period of instrumental records, during which a stationary climate has or can be assumed. Developing adaptive strategies in anticipation of impacts of climate change requires that current science-based water management and planning be augmented with the types of data and information described in this paper, that is, scenarios of future hydroclimatic variability and proxy (pre-instrumental) sources of hydroclimate data. This provides a much broader perspective on the variability of water levels to assess the reliability of water supply systems under a wider range of flows than recorded by a gauge. It requires, however, that water resource managers and agencies accept and accommodate a lesser degree of determinacy, certainty and stationarity.

The adjustments to water management practices necessary to sustain water use, allocation and apportionment under a changed hydrologic regime represents a knowledge gap that may be constraining the planning of adaptation to climate change in the water resource sector. Institutional adaptive capacity will be enhanced by addressing constraints and opportunities (entry points) for the operational use of scenarios of long-term hydrological variability and by lowering resistance stemming from perceptions of uncertainty and the training required for the application of this new scientific information. Incorporating hydrologic scenarios and paleohydrologic data in the forecasting and managing of water supplies requires 1) moving knowledge from one organizational context to another: from research labs to facilitative research centers to water management agencies, 2) training a subset of water managers (innovators) who then influence decision-making in their organizations, 3) identifying benefits of changes in water management strategy, 4) facilitating change in operational or policy environments by collaborating with practitioners who are willing to move away from the status quo, 5) mainstreaming considerations of hydroclimate change and variability into existing management plans and policy processes, and 6) engaging the end users in the translation, delivery and application of the science.

Acknowledgements

Research described here was funded by the Natural Sciences and Engineering Research Council of Canada, Manitoba Hydro, Alberta Environment, Environment Canada and the Geological Survey of Canada. For assistance and guidance, we thank Jodi Axelson, Antoine Beriault, Jan Mydynski, Nick Kouwen, and Don Burn.

References

Alberta Environment. (2003) *Water for life: Alberta's strategy for sustainability*. Alberta Environment Pub No. I/955. Edmonton: Government of Alberta.

Alberta Environment. (nd) *Background information for public consultation on the South Saskatchewan River Basin draft water management plan*. Edmonton: Government of Alberta.Arnold, P. E. (2005) Managing scarcity: water policy administration in the American West In *The institutional arrangements for water management in the 19th and 20th centuries* (ed.) J. C. N. Raadschelders, Cahier d'Histoire de l'Administration No. 8, Volume 24. International Institute of Administrative Sciences Monographs. Amsterdam: IOS Press, pp. 159–178.

Axelson, J. (2007) *Historical streamflow variability in the south Saskatchewan River Basin inferred from a network of tree-ring chronologies*. M.Sc. thesis, University of Regina.

Briffa, K. R. (2000) Annual climate variability in the Holocene: interpreting the message of ancient trees. *Quaternary Science Reviews*, 19: 87–106.

Case, R. A. and MacDonald, G. M. (2003) Tree ring reconstructions of streamflow for three Canadian rivers. *Journal of the American Water Resources Association*, June 2003: 703–16.

Chiew, F. H. S. (2006) Modelling hydroclimatic variability for water resources management. *Geophysical Research Abstracts*, 8: 1607–7962/gra/EGU06-A-01791.

de Loë, R., Kreutzwiser, R. and Moraru, L. (2001) Adaptation options for the near term: climate change and the Canadian water sector. *Global Environmental Change,* 11: 231–245.

Demuth, M. N. (1996) Effects of short-term and historical glacier variations on cold stream hydro-ecology: a synthesis and case study. *Ecological Monitoring and Assessment Network 2nd National Science Meeting.* January 1996, Halifax, Canada. National Hydrology Research Institute Contribution Series CS-96003.

Demuth, M. N. and Pietroniro, A. (2003) The impact of climate change on the glaciers of the Canadian Rocky Mountain eastern slopes and implications for water resource adaptation in the Canadian prairies. CCAF – Prairie Adaptation Research Collaborative, *Final Report Project P55*, plus Technical Appendices.

Environment Canada. (2003) HyDat for Windows, Canadian Hydrological Data, Environment Canada HyDat CD.

Fritts, H. C., Guiot, J. and Gordon, G. A. (1990) Tree-ring standardization and growth-trend estimation. In Cook, E. R. and Kairiukstis, L. A. (eds.) *Methods of dendrochronology: applications in the environmental sciences*, Dordrecht: Klumer Academic Publishers, pp. 178–185.

IPCC (Intergovernmental Panel on Climate Change). (2001) Climate change 2001: Impacts, adaptation, and vulnerability technical summary. *A Report of Working Group II of the Intergovernmental Panel on Climate Change 2001*, WMO and UNEP.

Kharin, V. V. and Zwiers, F. W. (2000) Changes in the extremes in an ensemble of transient climate simulations with a coupled atmosphere-ocean GCM. *Journal of Climate,* 13: 3760–3788.

Kouwen, N *et al*. (1993) Grouped response units for distributed hydrologic modelling. *Journal of Water Resources Planning and Management*, ASCE, 119 (3): 289–305.

Lapp, S., Byrne, J., Townshend, I. and Kienzle, S. (2005) Climate warming impacts on snowpack accumulation in an alpine watershed. *International Journal of Climatology,* 25(4): 521–536.

Mitchell, B. and Shrubsol, D. (1994) *Canadian water management: visions for sustainability*. Cambridge: Canadian Water Resources Association.

Pearce, F. (2006) *When rivers run dry: journeys into the heart of the world's water crisis*. Key Porter Books.

Pietroniro, A. *et al*. (2006) *Streamflow shifts resulting from past and future glacier fluctuations in the eastern flowing basins of the Rocky Mountains*. NWRI Internal Publication, Contribution Number, 06–026.

Quinn, F. *et al*. (2004) Water allocation, diversion and export. Chapter 1 in *Threats to water availability in Canada*. Burlington, Ontario: National Water Research Institute. NWRI Scientific Assessment Report Series No. 3 and ACSD Science Assessment Series No. 1.

Sauchyn, D. J., Stroich, J. and Beriault, A. (2003) A paleoclimatic context for the drought of 1999–2001 in the northern Great Plains. *The Geographical Journal,* 169(2): 158–167.

Sauchyn, D. J, Barrow, E., Hopkinson, R. F. and Leavitt, P. (2002) Aridity on the Canadian plains. *Géographie physique et Quaternaire*, vol. 56(2–3): 247–259.

Sauchyn, D. and Kulshreshtha, S. (2008) The prairies. Chapter 7 in D.S. Lemmen, F. J. Warren, J. Lacroix and E. Bush (eds.) *From impacts to adaptation: Canada in a changing climate 2007*. Ottawa: Government of Canada.

Schindler, D. W. and Donahue, W. F. (2006) An impending water crisis in Canada's western prairie provinces. *Proceedings of the National Academy of Sciences*, Available online at http://www.pnas.org_cgi_doi_10.1073_pnas.0601568103

Sprague, J. B. (2006) Great wet north? Canada's myth of water abundance. In K. Bakker (ed.), *Eau Canada: The future of Canada's water*. Vancouver: UBC Press. Ch. 2.

Statistics Canada, Ottawa. Available online at http://www.statcan.ca, accesseed September 11, 2008.

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

Wheaton E., Kulshreshtha, S. and Wittrock, V. (2005) *Canadian droughts of 2001 and 2002: climatology, impacts and adaptation.* Volumes I and II. Saskatchewan Research Council Publication No. 11602–1E03.

Whitfield, P. H. *et al*. (2004) Climate variability and change – rivers and streams. Chapter 11 in *Threats to water availability in Canada*. Burlington, Ontario: National Water Research Institute. NWRI Scientific Assessment Report Series No. 3 and ACSD Science Assessment Series No. 1.

Wolfe, S. A. *et al*. (2001) Late 18th century drought-induced sand dune activity, Great Sand Hills, Saskatchewan. *Canadian Journal of Earth Science,* 38: 105–117. Young, G. J. (1991) Hydrological interactions in the Mistaya Basin, Alberta, Canada. In H. Bergmann, H. Lang, W. Frey, D. Issler and B. Salm (eds.) *Snow, hydrology and forests in high alpine areas: proceedings of a symposium held during the XX Assembly of the International Union of Geodesy and Geophysics at Vienna, August 1991*, IAHS-AISH Publication No. 205, 237–244.