Upland Watershed Management and Global Change – Canada's Rocky Mountains and Western Plains

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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: 1). So has an explicit assumption that "the hydrological regime is stationary and will continue to be stationary in the future" (Whitfield *et al.* 2004: 89). There is "limited availability of freshwater in Canada at different times and places" (Quinn *et al.* 2004: 1). The place and time of least freshwater is the western plains during recurrent drought. This paper is about the hydroclimate of this region (**Figure 1**) and specifically how water policy and management might be adjusted to compensate for a long view of the surface hydrology. We examine the hydroclimatic variability from 1600-2100 as a context for records from the 20th century, the conventional scientific basis for formulating water policy and management strategies.

Insert: **Figure 1 - The North and South Saskatchewan River Basin shed runoff from the southern Rocky Mountains and across the subhumid to semiarid Prairie Ecozone of southern Alberta and southwestern Saskatchewan.**

Western water policy and management practices reflect the dry climate. In contrast to the accessible surface water and riparian laws of eastern Canada and US, the principles of first appropriation and apportionment developed 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, implying the question: what is the potential for future low flows resulting in conflicts between users and jurisdictions? (Quinn *et al*. 2004). In a recent empirical study of the determinants of water-related international relations, Stahl (2005: 270) concluded that "hydroclimatic variability and population density are most influential in arid to sub-humid basins, while socioeconomic and political factors seem to be more important in … humid basins".

In the southern prairies (**Figure 1**), first appropriation and apportionment, 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% to 50%, in terms of the shortfall of precipitation (P) relative to potential evapotranspiration (PET). The extent of this Canadian drybelt increases by approximately 50% when P/PET is mapped using output from the Canadian GCM ver2 (emission scenario B2) for the 2050s (Sauchyn, *et al*. 2002). While drought could be more severe and frequent under global warming (Kharin and Zwiers 2000), the expansion of subhumid climate is not outside the geographic range of natural variability since in drought years (e.g. 1937, '61, '88, 2001) a large part of the prairies has a P/PET < 0.65, although with devastating consequences (Wheaton *et al*. 2005). Most adjustments to water policy and management practices have occurred in response to these droughts.

Immediately following the driest two years on record, Alberta released its ground breaking Water for Life Strategy (Alberta Environment 2003). The rationale for a provincial water strategy included (p.5):

> "Alberta has been able to manage our water supply while maintaining a healthy aquatic environment because there has been a relatively abundant, clean supply to meet the needs of communities and the economy. However, fluctuating and unpredictable water supply in recent years has stressed the need to make some major shifts in our approach to managing this renewable, but finite, resource."

A "clear set of principles" emerged from consultations to develop the provincial water strategy. They include (p.6):

- 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 available water supply and capacities of individual watersheds. Knowledge of Alberta's water supply is incomplete without data on trends, variability and extremes, and thereby limits and capacities, derived from observation and modeling of hydroclimate over time frames that extend before and beyond our short experience with hydrologic systems.

Most sectors, agencies and communities are aware of and concerned about the potential impacts of climate change on water resources but few are making decisions based on scenarios of trends and variably generated from climate models or from records that extend beyond the length of instrumental records. 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 (Pagano *et al*. 2005, Chiew *et al*. 2003). This standard forecasting methodology has limited application to long-term water planning and policy making, because most instrumental records generally are too short to capture the decadal and longer-term variation in regional climate and hydrology.

Whereas water policy tends to reflect mean hydroclimatic conditions (thus the different philosophies and mechanisms between wet and dry climates), water management overcomes differences in water supply between years and places. 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).

If headwaters are managed for water consumption on the plains, key information for long range planning purposes includes the anticipated water supply in the mountains and demand on the plains. This paper describes research on the stream hydrology and paleoclimatology of this region. This work suggests that current perceptions of water scarcity and variability may be skewed by observation and experience of the 20th century which may be unrepresentative of both natural and future hydroclimate. The extensive wastage of glacier ice from the Rocky Mountains will have 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 Holocene minima (Demuth and Pietroniro 2001). 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, should increase the drought sensitivity of water supplies. According to records and models of pre- and post-20th century climate as described below, the 21st century will almost certainly include droughts of greater severity and duration than those previously observed and experienced by Euro-Canadians in western Canada.

Recent Trends and Future Projections

A recent study by Alberta Environment (Pietroniro *et al*. 2006a) comprises three major investigations of recent and potential future trends in water resources within the headwater catchments of the Nelson River basin. The first focuses on cataloguing glacial extents within the North and South Saskatchewan River Basins (NSRB & SSRB) utilizing legacy Earth Observation data (Demuth and Pietroniro 2001). A second component examines streamflow records for evidence of trends and variability related to changes in glacial extent. The third component involves hydrological modeling of change in flow regime under future climate/glacier-cover 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 paper, we summarize the results of these investigations. For a description of the methods of analysis, the reader should consult 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. **Figure 2** illustrates the basins used in the various analyses. It highlights the North and South Saskatchewan drainages (NSRB & SSRB) and all existing and historic Water Survey of Canada Gauges locations up to the year 2001.

Insert: **Figure 2 – The Nelson Drainage Headwaters including the North and South Saskatchewan River Basins.**

A changing glacier landscape

Documenting land ice influences on the vulnerability of 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 (Demuth *et al.* in progress). 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**. Total glacier area change as a ratio of 1975 glacier extent was approximately 50% in the South Saskatchewan River basin and 23% in the North basin.

Insert: **Figure 3– Delineation of the extent of the Saskatchewan glacier. Note the substantial changes in the tongue of the Saskatchewan glacier between 1975 and 2001.**

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 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 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 4** illustrates the yield from the Mistaya catchment for the period of study. The trend line shown includes all data and depicts declining yields for the TBF period despite evidence that precipitation in the montane is increasing for the same period (Aug 1 – Oct 31). The coefficient of variation (standard deviation/mean) for the streamflow (**Figure 4**) is increasing over the available record suggesting that the ability of the glacier cover to regulate streamflow may have been in decline since the mid-1900s.

Insert: **Figure 4 - Yield, precipitation and streamflow coefficient of variation (C) for the Mistaya River catchment at gauge 05DA007 over the TBF period.**

The stream flow regime was also examined using the minimum, mean and maximum daily discharge data available from the Water Survey of Canada (Environment Canada, 2000). The TBF change for the Mistaya basin (1950-1998) is quantified using a simple linear regression analysis depicted in **Figure 5**. There 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 5**).

Insert: **Figure 5 - Regression analysis for TBF flow period showing trends in minimum, mean and maximum flows for the Mistaya Basin.**

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 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. Selection criteria centered primarily on the length and the completeness of discharge records. Discharge data were obtained from the HYDAT 2003 CD (Environment Canada 2003). Analyses of annual trends were further limited to those stations which contained discharge data for all months of the year; those stations that contained data for a lesser number of months (*e.g.* April – October) 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 18 stations show that the majority of trends detected are negative, indicating decreasing streamflow patterns. In particular, for the North Ram, Siffleur and Mistaya stations of the NSRB, whose percent glacier covers increase from 0% to 2.5% to 8.5%, respectively, there is a decreasing trend in TBF as the percent glacierisation increases. Unfortunately, there is no equivalent comparison for basins with differing glacier 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% of the stations analysed exhibited no trends in discharge over the periods of record. Interestingly, and perhaps predictably, of those 50% where no trend was detected, 78% were for non-glacierised basins.

Modelling Headwater Catchments

Hydrological modeling methodology described by Pietroniro *et al*. (2006a) was used to assess both the impacts of future climate variability of flows in the Nelson headwaters and also to assess 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 Rivers. Sensitivity analysis showed the important contribution of glacier flow to the headwater catchments and its diminishing influence further downstream. Climate change projections using change fields derived from the analysis of GCM output for this region were used to assess possible future changes to the streamflow regime (Toyra *et al*. 2005). As reported by Toyra *et al*. (2005), the ECHAM4 and NCAR-PCM 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. The GCMs could generally replicate the amount of summer precipitation better than in the other seasons, while the spatial pattern of summer precipitation was represented poorly by all models. Winter and spring precipitation amounts were severely overestimated by most models. Nonetheless, the change fields were applied to the WATFLOOD model and the results indicate lower overall mean annual flows. This analysis was done using the 1998 glacier extent, and no projections of future extent were added to the model.

Model calibration and sensitivity analysis for a subset of years was used to determine optimal parameters for streamflow simulation (Pietroniro *et al.* 2006a). Then the hydrological model was run with a continuous time series for 1961-1990 and 2040-69, standard time slices for constructing climate scenarios (IPCC 2001). The basins used in the continuous simulations are included in **Figure 2.** The only meteorological forcing of the WATFLOOD model is precipitation and temperature. Data for stations with complete daily minimum and maximum temperatures were extracted from Environment Canada archives and gridded based on elevation and a linear interpolation between the daily maxima and minima temperature to provide lapse rate corrected, diurnally varying hourly temperatures. As precipitation is spatially far more variable than temperature, high-resolution spatial precipitation gauging enhances accuracy when modeling channel output (Kouwen, personal communication). Climate stations that have daily precipitation records for more than 5 years during the 30 year period were identified.

Results for monthly hydrographs of 3 headwater catchments in the NSRB showed good agreement between observed and modeled flows (**Figure 6)**. These basins represent varying degrees of glacier cover. In all cases the WATFLOOD simulation provides reasonable simulation results.

Insert: **Figure 6 – Watflood model results for 1980 to 1990 in 3 headwater catchments of the North Saskatchewan River basin. The grey solid portion of the graph represents the observed hydrograph, while the solid black line represents the model output. Model results for the 10 year simulation periods.**

A sensitivity 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 7** the Mistaya River displays gradually decreasing volumes and variability during the TBF period when moving from the 1975 to 1998 extent. The hydrographs highlighted in cyan show the estimated flows with no glacier extent. There is no change shown in the Ram River basin simply because it is non-glaciated and the consequences of removing glacier melt from this region are obvious. What this analysis highlights is that basins such as the Siffleur have already experienced de-glaciation to the point where future changes in glacier mass will have very little impact on the runoff regime.

Insert: **Figure 7 – Analysis of glacier contributions to flow using the WATFLOOD model. The hatched area represents the runoff in the basin with no glacier melt. The darker area represents the model simulation with the 1975 glacier extent.**

A preliminary climate change analysis was based on the method outlined by Pietroniro *et al.* (2006b) and the climate change scenarios described earlier (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. 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 3 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 regime for the Bow river headwaters will likely include early and increased spring melt and decreased late summer flows as show in **Figure 8**.

Insert: **Figure 8 – Comparison of 10-year monthly flow estimates from WATFLOOD for the Bow river at Banff derived from both climate change and glacier change projection**.

Hydroclimatic Variability

Most drivers of hydroclimatic variation have a periodicity that approaches or exceeds the length of gauge records: “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). Low frequency variation and sustained departures from mean conditions are observable only with proxy records. Proxy hydroclimatice data can provide water resource planners and engineers with a context for standard reference hydrology to evaluate baseline conditions and water allocations, and a broader 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. Stream flow records correlate with moisture-sensitive tree-ring chronologies, because stream flow and tree growth have a similar muted response to episodic inputs of rainfall and snow melt water. Hydrological peaks are usually underestimated by tree rings, given a biological limit to the growth response to excess 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 (*e.g.* Case and Macdonald 2003). Researchers at the University of Regina Tree Ring Lab (www.parc.ca/urtreelab) have collected tree rings at 85 sites to enable the inference of long-term moisture and streamflow variability from a pool of predictor chronologies that capture more of the regional climatic variability. 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 one streamflow reconstruction to illustrate four centuries of hydroclimatic variability and to provide context for the gauge record from the 20th century. The mean annual flow of the Oldman River at Waldron's Corner, Alberta (gauge AA023) was derived by Axelson (2006) from tree-ring chronologies from five sites within 50 km of the gauge. The methods of constructing tree-ring models of stream flow can be found in any technical paper in dendrohydrology (*e.g.* St. George and Sauchyn 2006). **Figure 9** is a plot of reconstructed and observed flow for the period of the gauge record, 1951-2004.

Insert: **Figure 9 - Mean annual flow of the Oldman River at Waldron's Corner, Alberta for the period of observation 1951-2004. The blue curve is the record from gauge AA023. The green curve is stream flow reconstructed from a tree-ring model. The model predictors are standardized (Arstan) tree-ring chronologies from five sites within 50 km of the gauge.**

This plot illustrates the similar variability in the response of the stream and trees to precipitation, especially at lower (decadal) frequencies. The tree-ring predictors account for about 50% of the variance in stream flow. 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 10** spanning 1602-2004 gives the timing and duration of drought.

Insert: **Figure 10 - 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 mean of the instrumental record.**

The proxy streamflow data in **Figure 10** are plotted as departures from the mean of the instrumental record. This record reveals the local 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 between 1830 to 1880, and 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 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).

Proxy streamflow records reveal periodic shifts in hydroclimatic regime between intervals of dominantly low frequency variation to intervals of dominantly interannual variation. Large year-to-year variability represents a different challenge for water management than extended wet and dry intervals. 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 20th century.

Discussion

The most serious risk to the Canadian plains from climate change is the potential for water scarcity (Schindler and Donahue 2006). Recent trends and future projections include lower summer stream flows, falling lake levels, retreating glaciers, and increasing soil and surface water deficits, as more water is potentially lost by evapotranspiration. Western Canada is losing the advantage of a cold winter, where the accumulation of snow and ice produces a reliable and predictable supply of spring and summer runoff. Water scarcity would be a significant constraint on economic growth from expanded irrigated lands in the south or oil sands production in the north. Thus water conservation will continue to be a major adaptation to climate change and variability. This includes water-pricing regimes to more accurately reflect the real costs of water treatment and supply and to ensure that an increasingly scarce resource is properly allocated.

The impacts of climate change on resource economies are necessarily adverse because resource management practices have assumed a stationary hydrological regime. The realization that hydroclimates are far from stationary has come with the modeling of global warming (climate change forced by greenhouse gas emissions) and from studies of past climate. The inferred paleosalinity of lakes (Laird *et al*. 2003) and long moisture-sensitive tree-ring chronologies (e.g. Woodhouse and Overpeck 1998) reveal shifts in hydrologic regimes at decadal to century timescales. Water use, policy and management were established during a period of fairly stable and reliable water supplies as compared to the recent past (tree-ring and historical evidence of prolonged drought), recent trends (glacier wastage, declining snowmelt runoff and summer flows), and GCM-based scenarios of precipitation, PET and runoff.

The analysis in this paper 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 glacierised basins, however no discernible trend to this point in non-glacierised catchments. Given the uncertainty associated with GCM predictions, 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 effect water resources in low snowfall years, particularly during the transition base flow period in late summer. However, projected increases in precipitation may very well offset these reducuctions 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. The implications on the prairies will likely be less severe.

According to the Intergovernmental Panel on Climate Change (IPCC 2001), flow contributions from glacier sources should increase in the short to medium term, and decrease in the long term. 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 amongst the strongest signals of the impacts of global warming in western Canada. Underlying this trend is the natural variability in hydroclimate represented here with moisture sensitive tree-ring records from the region. 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 Euro-Canadian 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 stream flow to overcome soil moisture deficits (Alberta Environment n.d., de Loë *et al*. 2001). About 70% of the irrigated farmland in Canada (400,000 hectares) is in southern Alberta (Statistics Canada, Ottawa, www.statcan.ca). This is 4% of the cultivated land in Alberta, yet it produces 18% of the provinces agri-food gross domestic product. In the South Saskatchewan River Basin, about 75% of the allocated water is used for irrigation (Alberta Environment n.d.). This percentage rises to 86 in the Oldman River subbasin. Between 20 and 30 percent of withdrawals are returned to the river system.

Irrigation is an adaptation to climate change and variability and the uncertainty of the natural precipitation regime. There is an elaborate network of canals, diversions and dams to store and redistribute the water and overcome the soil moisture deficit across a large area. Irrigators have considerable adaptive given the history of adaptation to climate variability, mostly adjustments of policy and practices in response to drought, and also responses to increased demand and potential conflicts. There have been major improvements in the efficiency of irrigation and water management systems. Water rights transfers have been recently introduced to permit the transfer of the right to use water from one type of use, irrigation, to another, such as food processing.

Adapting to climate change impacts on water resources requires adjustments to practices, polices and infrastructure to sustain economic development given 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 of a buffer from glacier ice and late lying snow at high elevations. 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 21st century:

> Adaptive management explicitly accepts indeterminacy, ignorance, uncertainly and risk; the inevitability of surprise and turbulence; and the need for flexibility. It supplements traditional approaches characterized by a belief in rational, comprehensive model of thinking and analysis. [It] simply recognizes that planners and mangers have imperfect knowledge and understanding, and that even when trying to be anticipatory and preventive will undoubtedly encounter surprises, and require the modification of policies and activities. … (Mitchell and Shrubsol, 1994: 55)

Knowledge of the current state of the climate system and systematic tracking of the gradual changes occurring in these large systems requires large investments in data collection and science. There are important economic justifications for understanding and monitoring progressive changes in support of adaptation. Past trends are really the only systematic way to understand and validate possible future scenarios.

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List of Figures

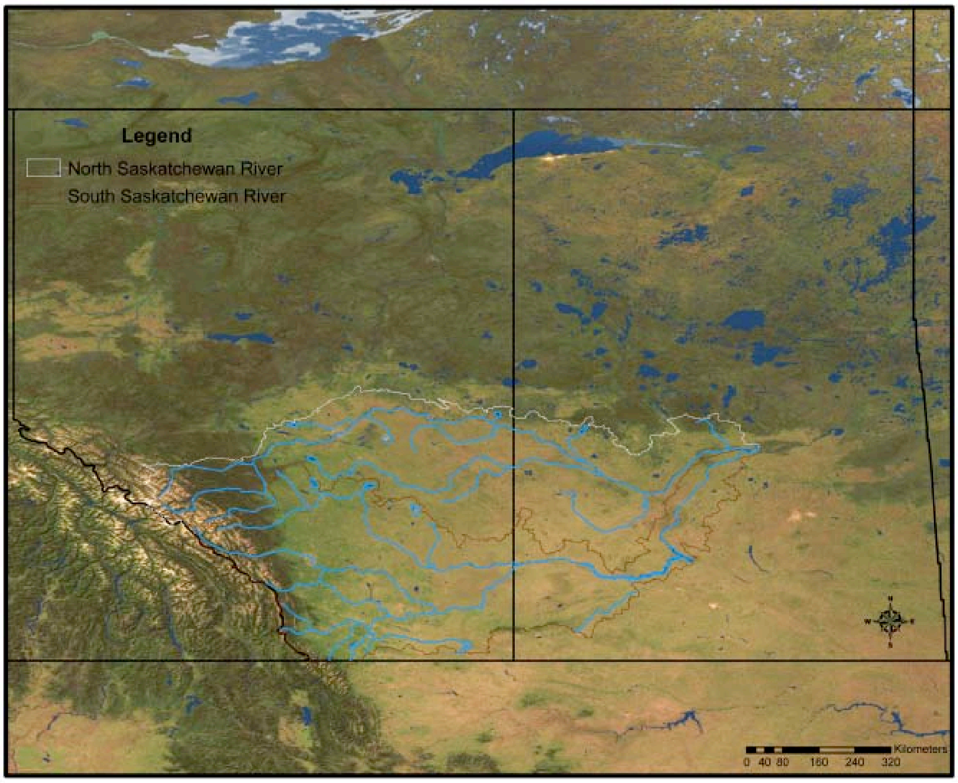


Figure 1 - The North and South Rivers Basin shed runoff from the southern Rocky Mountains and across the subhumid to semiarid Prairie Ecozone of southern Alberta and southwestern Saskatchewan.

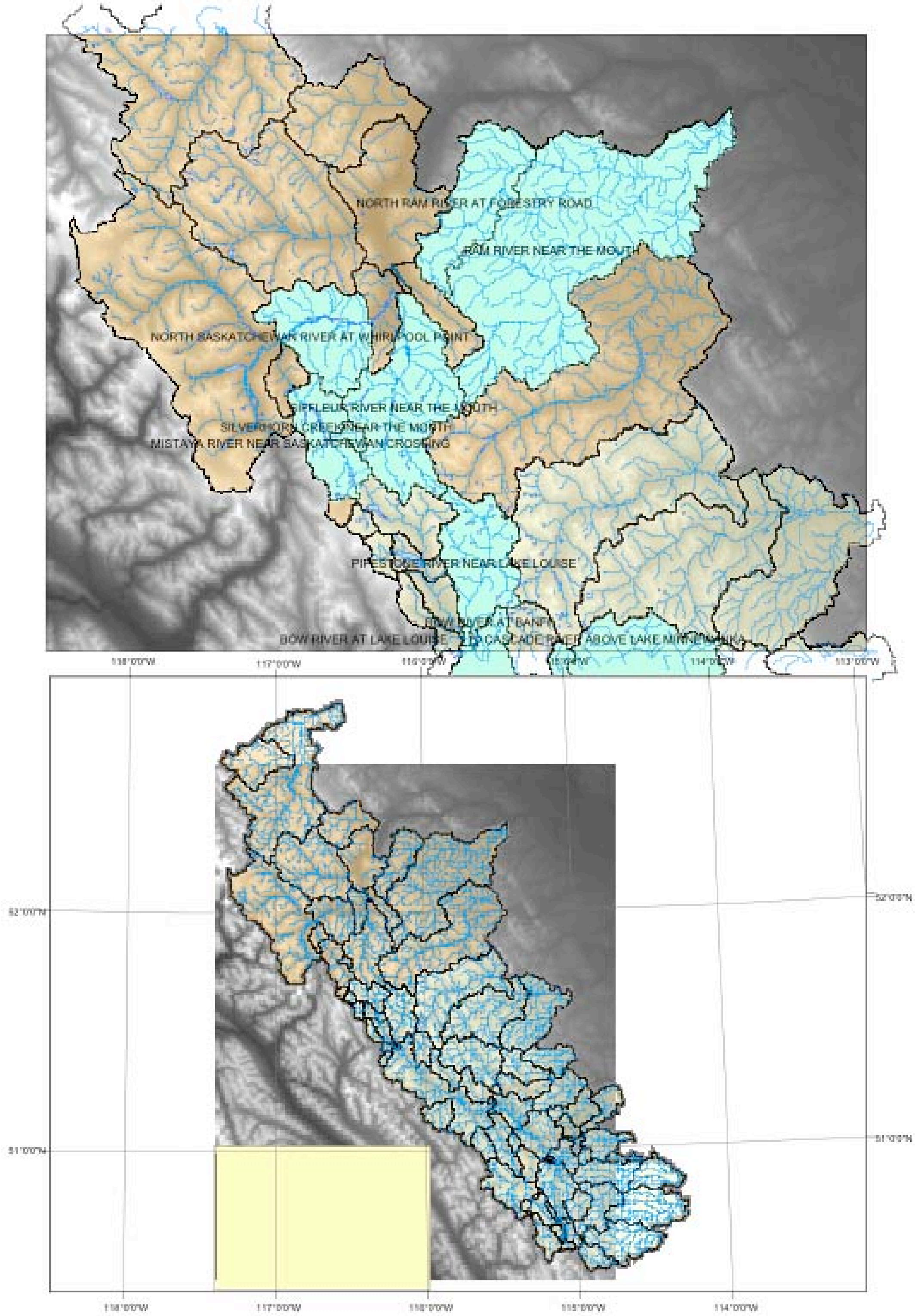

NORTH RAM RIVER AT FORESTRY ROAD
RAM RIVER NEAR THE MOUTH
NORTH SASKATCHEWAN RIVER AT WHIRLPOOL POINT
SIFFLEUR RIVER NEAR THE MOUTH
SILVERHORN CREEK NEAR THE MOUTH
MISTAYA RIVER NEAR SASKATCHEWAN CROSSING
PIPESTONE RIVER NEAR LAKE LOUISE
BOW RIVER AT BANFF
BOW RIVER AT LAKE LOUISE
CASCADE RIVER ABOVE LAKE MINNEWANKA
118°0'0"W
117°0'0"W
116°0'0"W
115°0'0"W
114°0'0"W
113°0'0"W
52°0'0"N
51°0'0"N

Figure 2– The Nelson Drainage Headwaters including the North and South Saskatchewan River Basins and basins used in the modelling analysis.

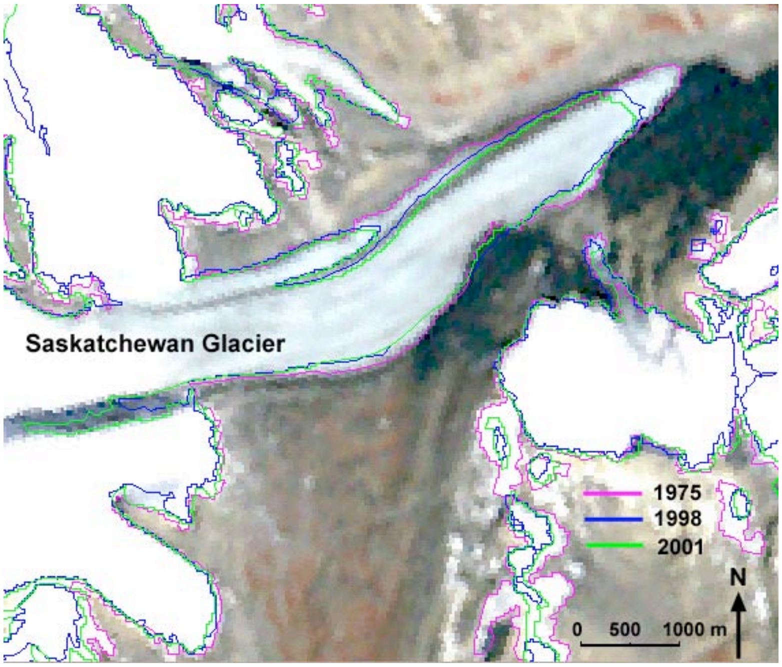


Figure 3– Delineation of the extent of the Saskatchewan. Note the substantial changes in the tongue of the Saskatchewan glacier between 1975 and 2001.

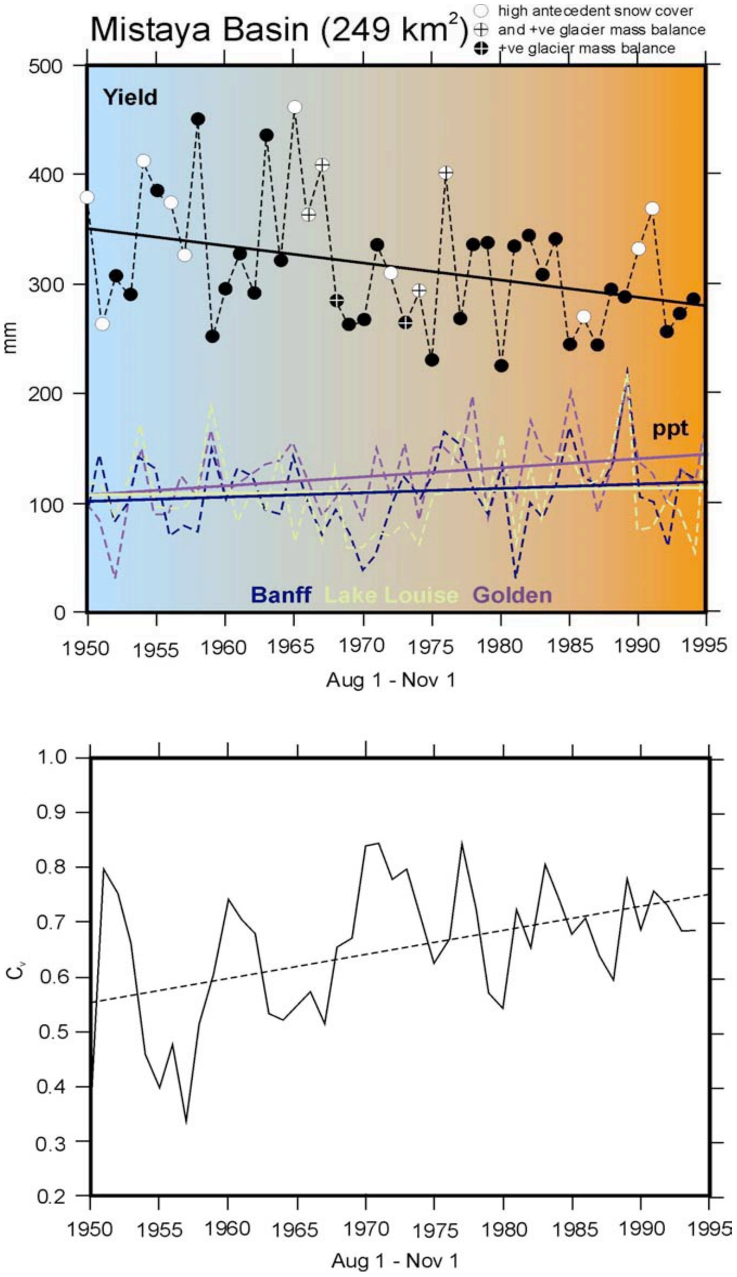


Figure 4- Yield, precipitation and streamflow coefficient of variation (C) for the Mistaya River catchment at gauge 05DA007 over the TBF period.

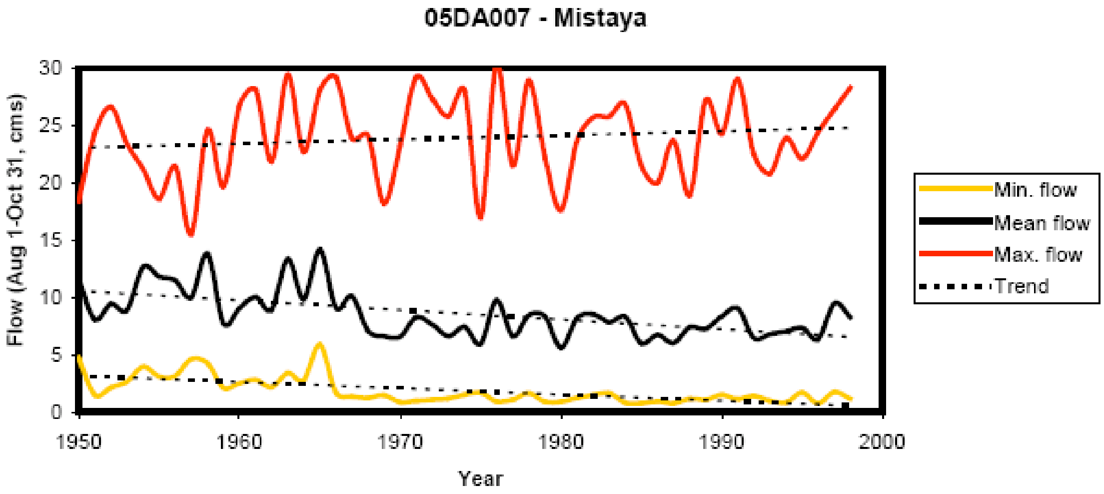


Figure 5- Regression analysis for TBF flow period showing trends in minimum, mean and maximum flows for the Mistaya Basin.

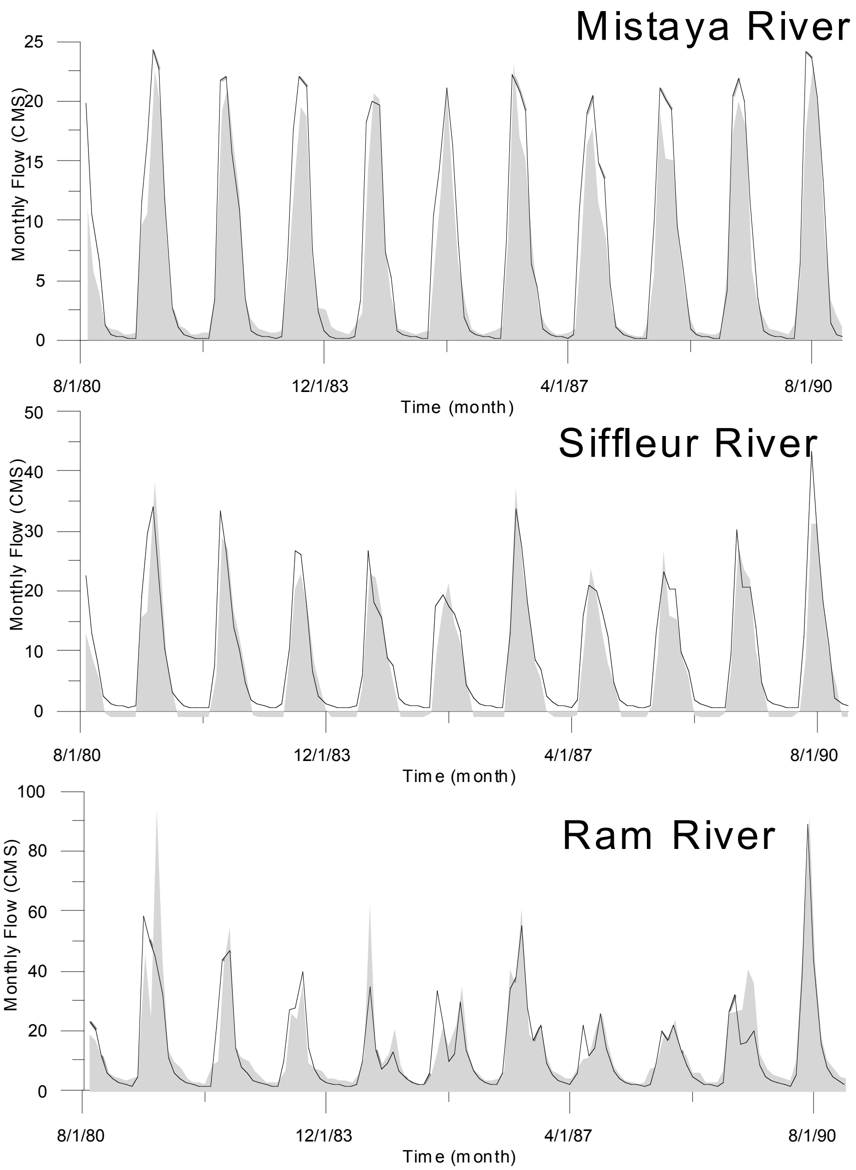
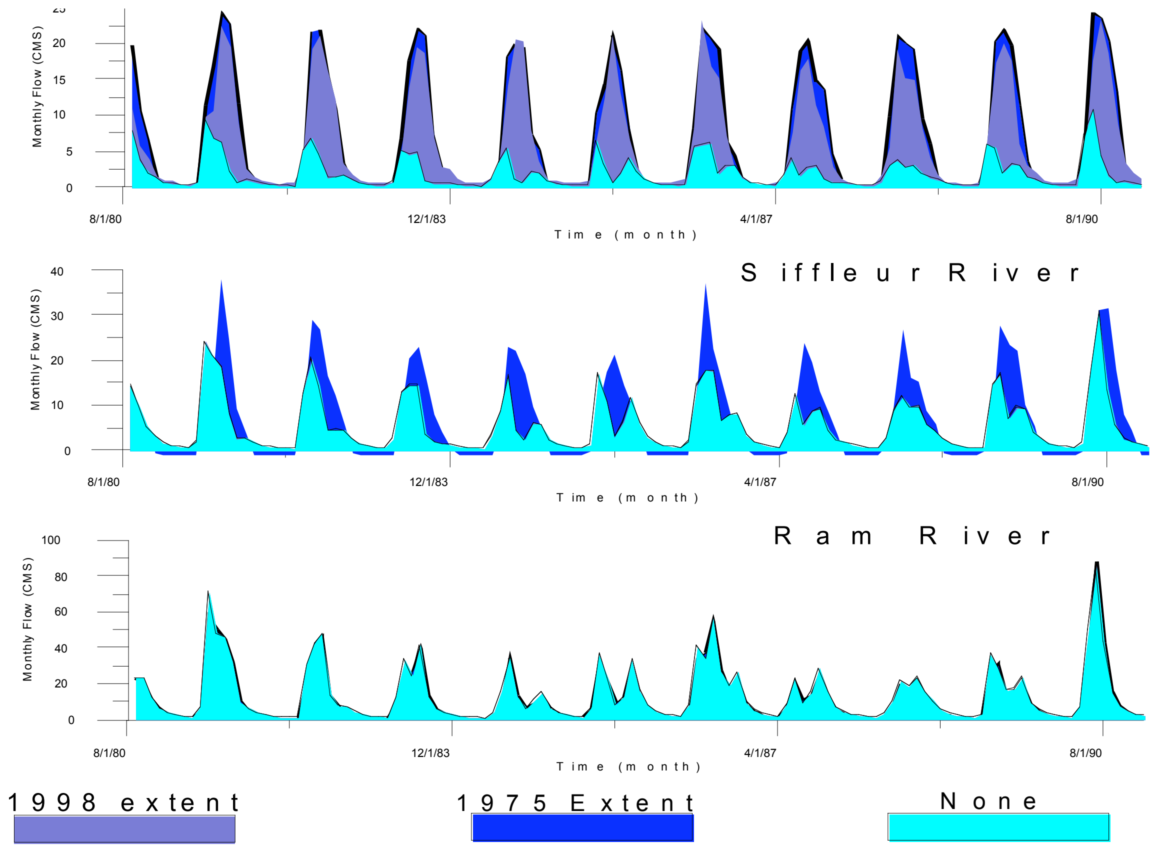


Figure 6 – Watflood model results for 1980 to 1990 in 3 headwater catchments of the North Saskatchewan River basin. The grey solid portion of the graph represents the observed hydrograph, while the solid black line represents the model output. Model results for the 10 year simulation periods.



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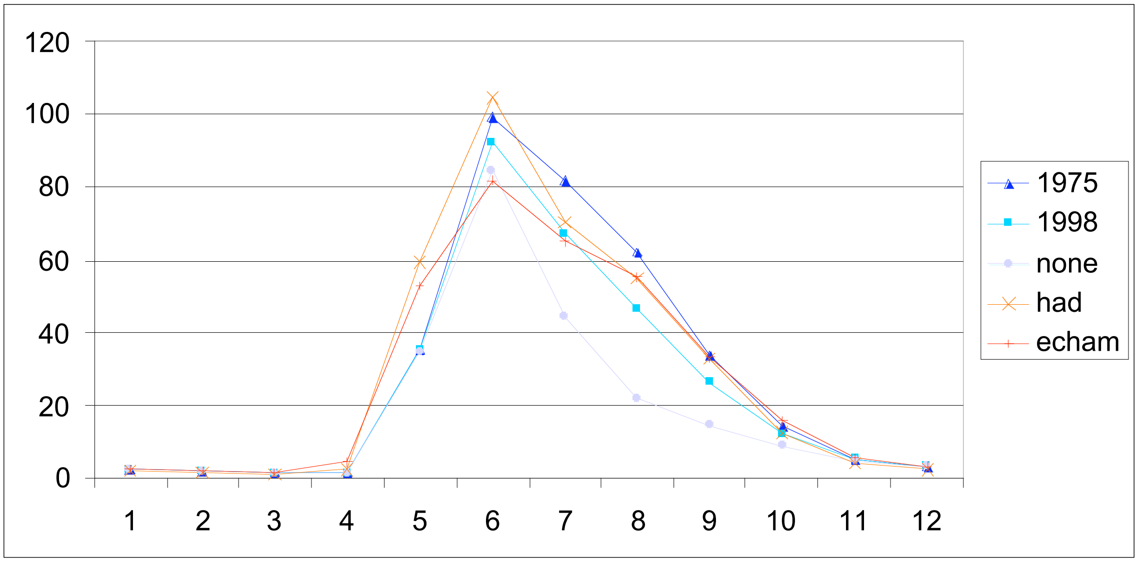

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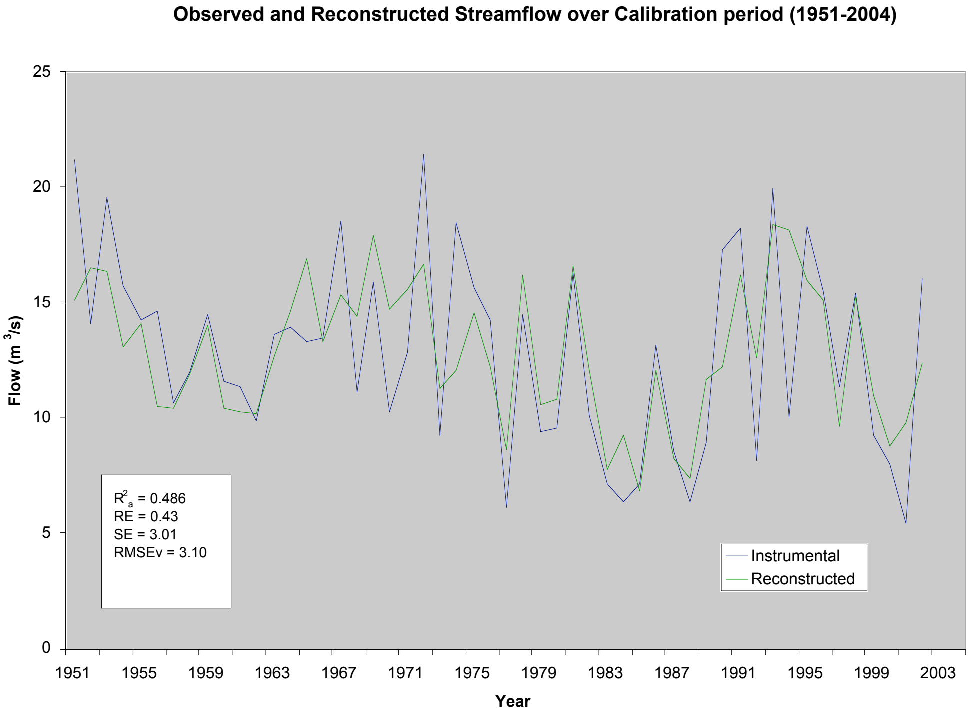

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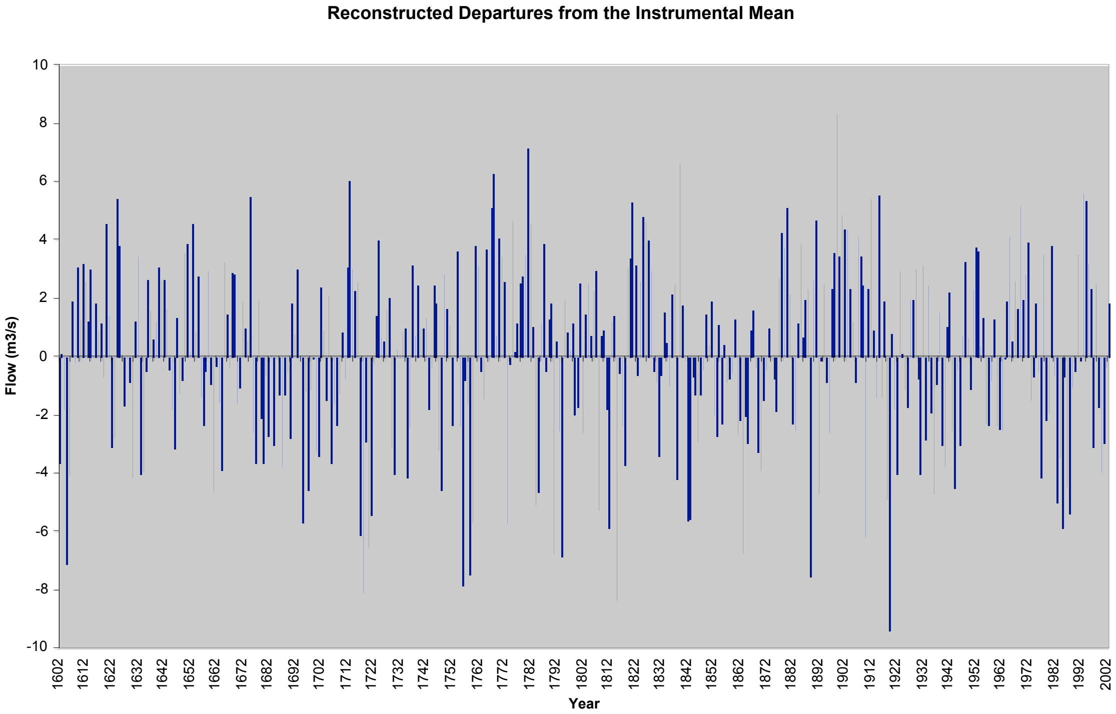

Figure 10 - The full tree-ring reconstruction of mean annual flow of the Oldman River at Waldron's Corner for the period 1602-2004. These proxy streamflow data are plotted as departures from the mean of the instrumental record.