The Impact of Climate Change on the Glaciers of the Canadian Rocky Mountain Eastern Slopes and Implications for Water Resource-related Adaptation in the Canadian Prairies: Phase I

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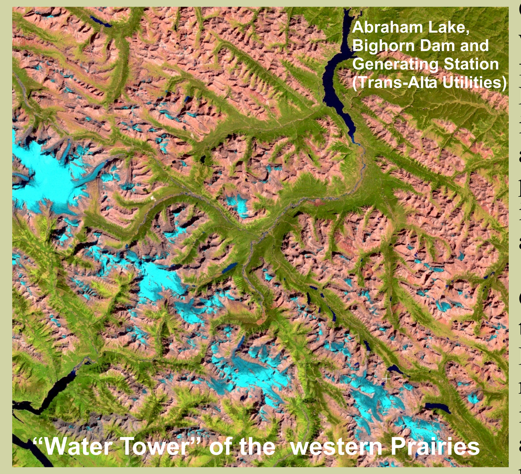
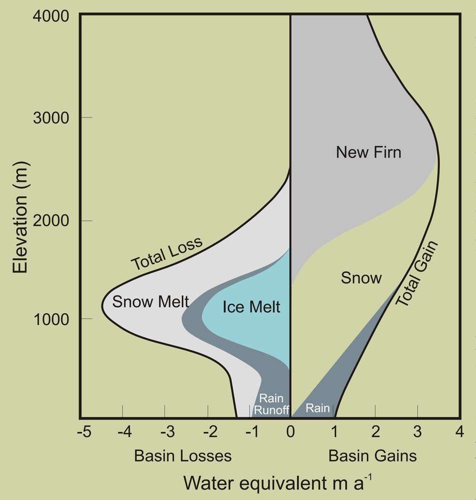
Background

The water-resources in the western Canadian prairies are under increasing pressure from climate change and: i) the need to provide adaptation strategies based on a reduced reliance on fossil fuel energy sources under the Kyoto Protocol; ii) interests outside Alberta and Canada regarding bulk water transfers and flow fragmentation (e.g., Manitoba-North Dakota; iii) evolving concerns amongst the Prairie provinces regarding inter-provincial water allocation.

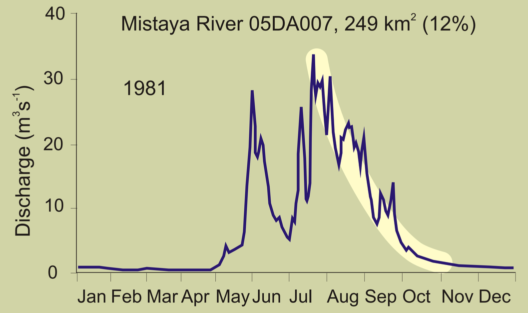


Glacial melt water from the eastern slopes of the Rocky Mountains is recognised as an important factor in adapting to these pressures; the principle question being, **"For how long can such sources reliably regulate streamflow under known and projected variations in climate?"**.

In a mountain watershed, the influence of even small areas of perennial ice on the seasonal variation of runoff is marked. The duration of snowmelt runoff is extended since, in general, glacial catchments extend to higher elevations than those that are solely nival. The major nival/glacial contrast results from the limited life of the snow reservoir.



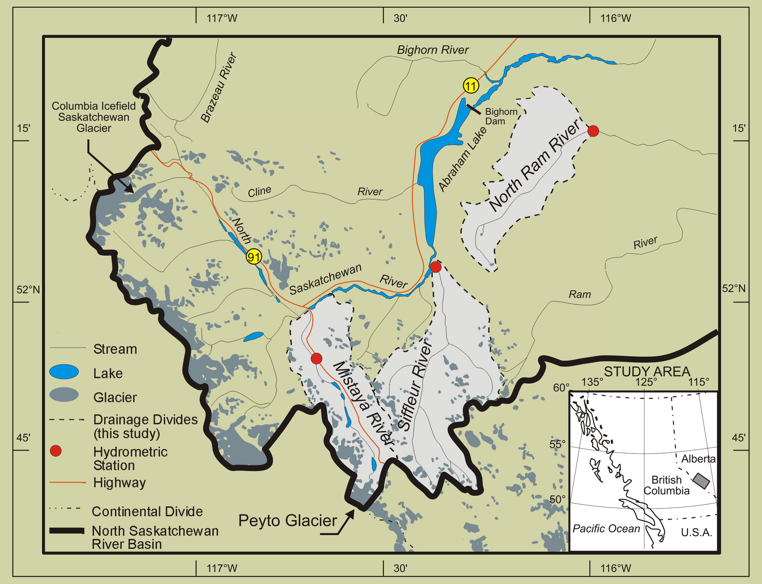
A typical annual hydrograph exhibits base flow augmentation by snowmelt runoff during a period of rising temperature, followed by peak flows resulting from rainfall superimposed upon glacier melt and subsequently, the ***Transition to Base Flow*** **(TBF) period** (nominally August - October inclusive). For the purpose of investigating changing glacier flow contributions, we examine the TBF flow regime in detail:



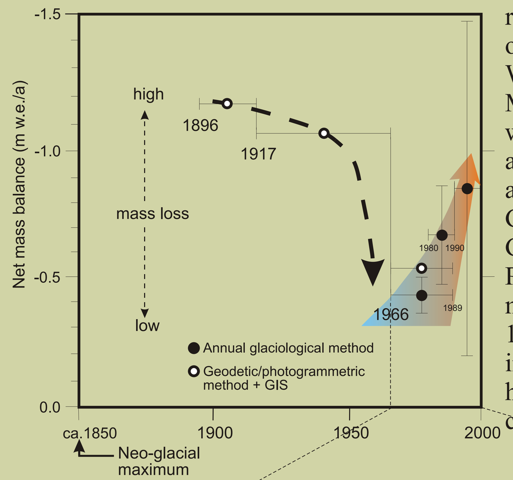
The influence of temperate mountain glaciers:

- Extend period of maximum seasonal flow
- Regulate annual and monthly flow variations
- Provide a source of disturbance

Study area



There are in excess of 1,300 glaciers in the Canadian Rocky Mountain eastern slopes. "Phase I" of this study concerns itself with the influence of 863 glaciers in headwaters of the North Saskatchewan River basin and their past, current and future ability to augment and regulate streams that feed the hydro-electric and irrigation infrastructure of the western Prairies. The streamflow regime of several contributing headwater catchments are considered in detail.



Peyto Glacier is a reference glacier-climate observing site of the World Glacier Monitoring Service, whose observation and assessment is administered by the GSC/NWRI National Glaciology Program. Peyto Glacier has been monitored annually since 1966. It is assessed here in the context of the headwater glacier-climate regime.

Glacier fluctuations

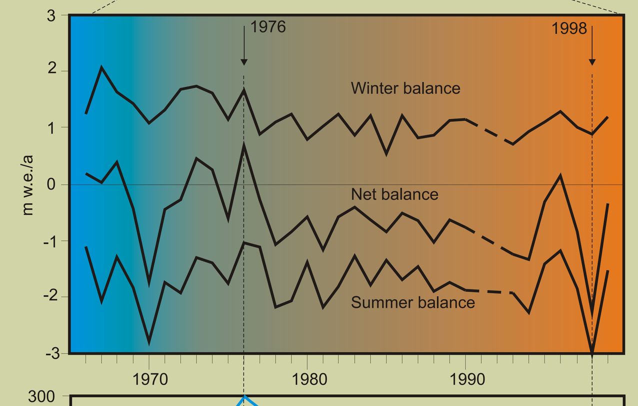
Recent mass balance fluctuations - Peyto Glacier

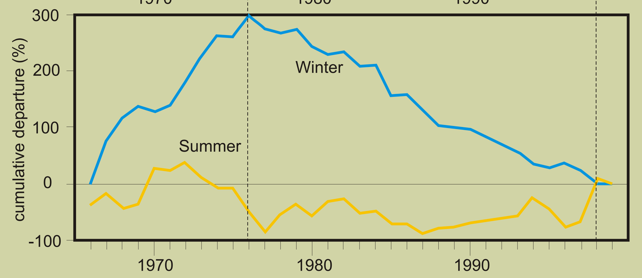
Peyto Glacier exhibits an average net balance of - 0.5 m w.e. a^{-1} for the period 1966-1999. The winter balance played a dominant role in the evolution of the net balance variability with a major shift in the winter balance having taken place after 1976 in association with a regional reduction in the frequency of snow-bearing synoptic weather patterns (Demuth and Keller, 2002). The summer balance, though less important overall, manifested some of the most extreme mass losses for the glacier (e.g., 1998).

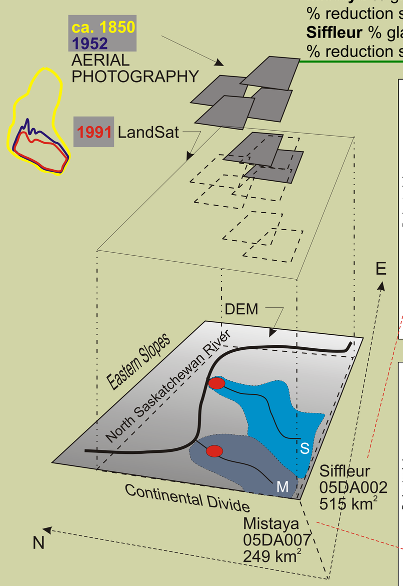
Neo-glacial and past-century fluctuations

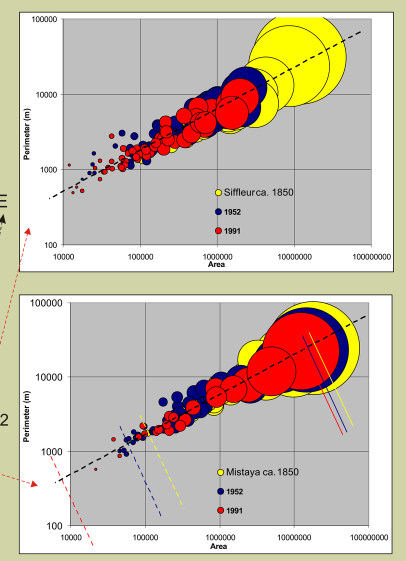
In agreement with the general global pattern, Peyto Glacier undergoes spectacular mass loss after the Neo-glacial maximum (ca. 1850) and through the first half of the 20th Century. This was followed by a pronounced abatement during mid-century. More recently, particularly since the mid-1970's, the rate of mass loss approaches that of the early century, even showing signs of acceleration broadly consistent with estimated man-induced radiative forcing (several W m^{-2}). Morpho-stratigraphic and botanical evidence suggest that Peyto Glacier and other eastern slope glaciers are approaching the warm limit of Holocene variability.

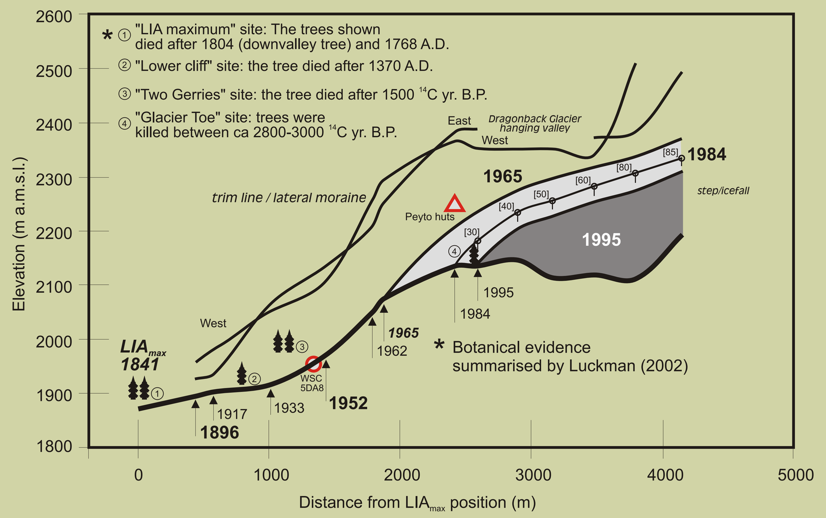
	ca.1850	1952	1991
Mistaya % glacier cover	24.6	14.8	10.3
% reduction since previous epoch		57	27
Siffleur % glacier cover	11.7	5.2	3.3
% reduction since previous epoch		64	51



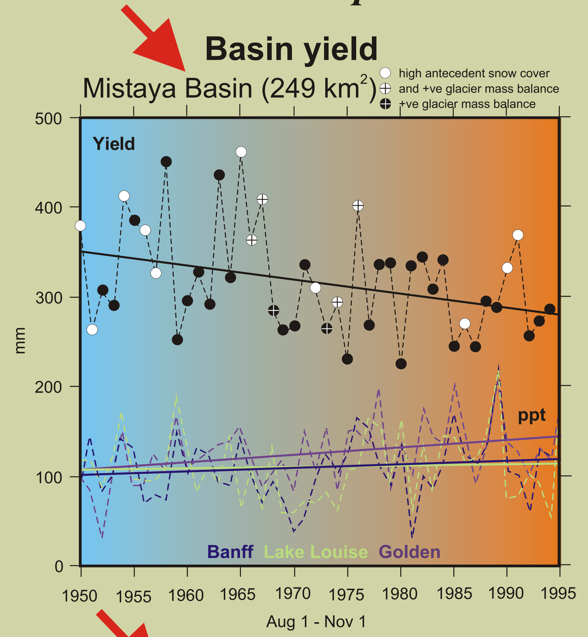


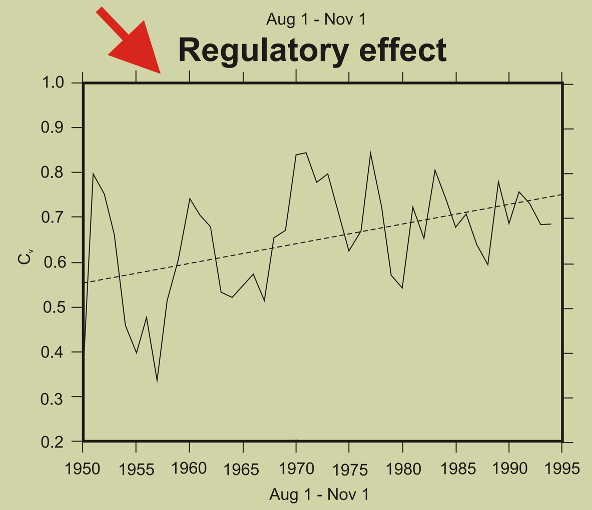


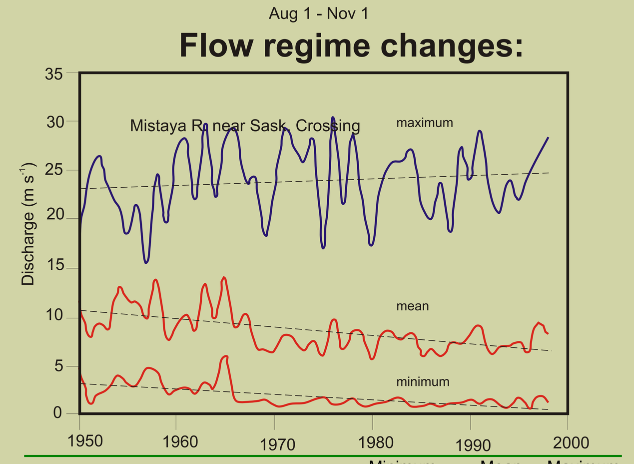




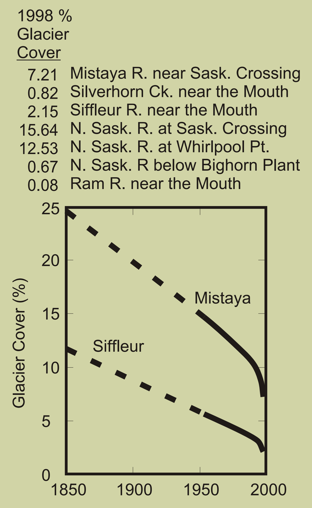
What measurable impacts have we observed in our headwater streams?

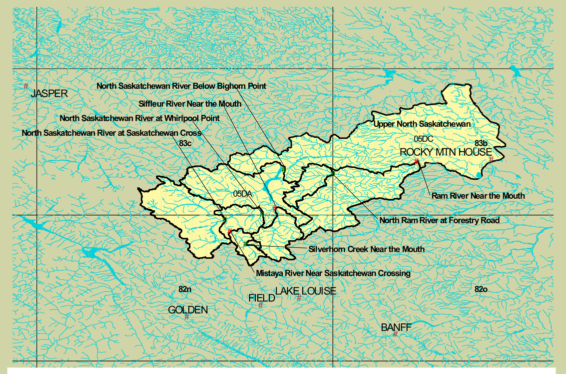


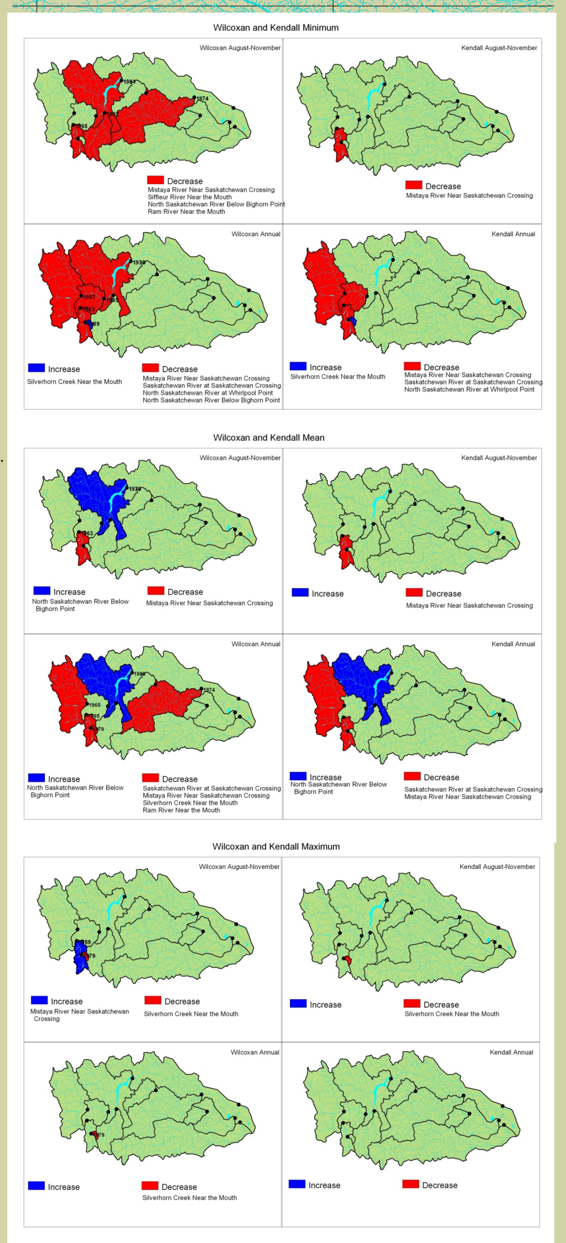




	Minimum	Mean	Maximum
Average streamflow 1950-60 ($m^3 \cdot s^{-1}$)	3.23	10.56	21.37
Average streamflow 1950-98 ($m^3 \cdot s^{-1}$)	1.87	8.59	23.92
Change 1950-1998 ($m^3 \cdot s^{-1}$)	-2.67	-4.12	+1.78
% Change (based on 1950-60 mean)	-82.7	-39.0	+8.3







minimum flows

mean flows

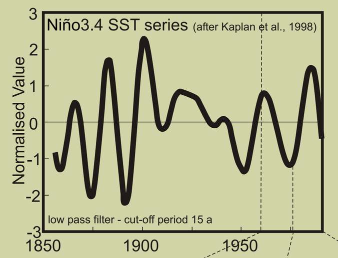
maximum flows

Significance level 5%

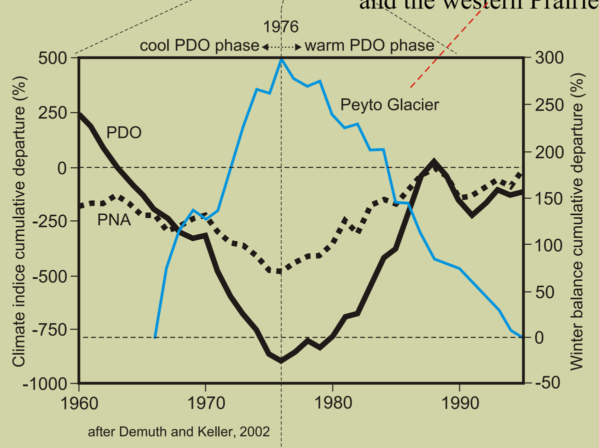
Note: The indicated most-probable date for a shift in the mean (Wilcoxon test) is derived from Bayesian analysis.

How coherent is glacier nourishment/snow cover and climate variability ?

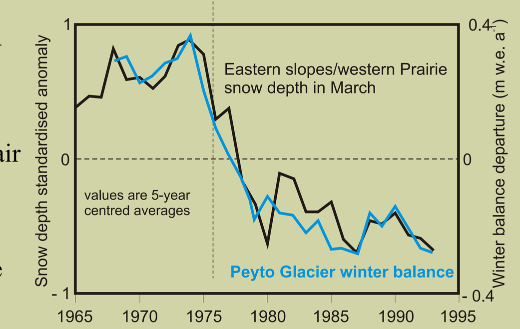
The advection of moisture over the Cordillera is determined, in part, by North Pacific climate variability and the influence of the Pacific Decadal Oscillation (PDO). The PDO is defined by sea surface temperature anomalies for the Pacific Ocean Basin poleward of 20° N. The PDO appears to modulate climate over similar spatial scales as the El-Niño Southern Oscillation (ENSO), but over markedly different temporal scales. It has been described as a "long-lived El Niño-like" pattern with a persistence of some 20-30 years as compared to typical ENSO persistence of 1 +/- .5 a (e.g., Bitz and Battisti, 1999)..



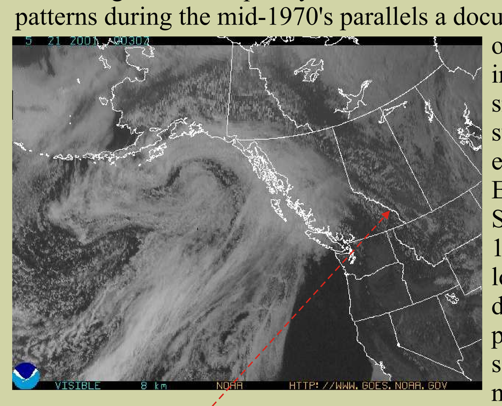
The relationship between the PDO and its capacity to manifest anomalous Pacific North American (PNA) circulation and related Peyto Glacier winter mass balance and regional snow accumulation variability is remarkably clear, with the 1976 breakpoint identifying a shift from a PDO cool phase to the following warm phase.

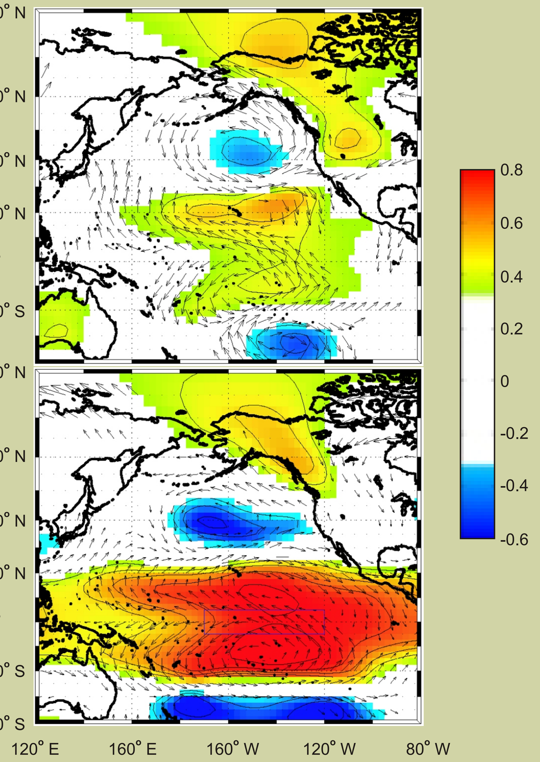


Examining data describing precipitation and temperature anomalies for the Central Canadian Rockies and North Pacific sea surface temperature and windstress, the PDO warm phase appears to manifest meridonal flow of dryer air into the Cordillera in winter and generally warmer Summers. The cold phase appears to correspond with the strong advection moisture over the Cordillera in winter, and summers that are generally cooler.



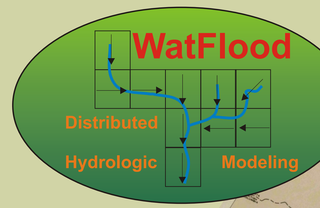
The change in the frequency of snow vs non-snow bearing synoptic patterns during the mid-1970's parallels a documented shift in the position of the Aleutian Low and its influence over the tracking of snow-bearing weather systems. This effect can be especially strong during the E1-Niño phase of the Southern Oscillation . From 1977 to 1988, the Aleutian low-pressure system was deeper and shifted eastward, producing anomalously warm southwesterly flow over the northeastern Pacific. This configuration corresponded to an intensification of the PNA pattern, which tends to produce generally lighter snow packs in the southern Cordillera and the western Prairies.

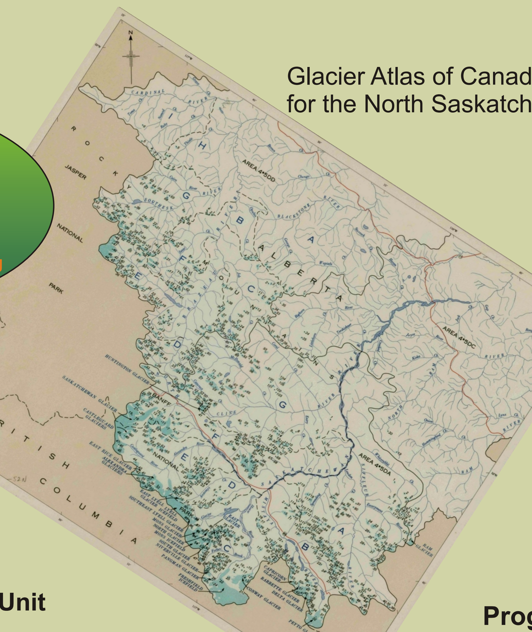




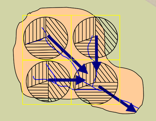
Cross-correlation (95%) of 200 H Pa geo-potential and horizontal wind fields with snow accumulation (top) and El-Nino (bottom). (adapted from Moore et al., 2001)

How vulnerable are our mountain water resources ? Examining basin-wide streamflow regime responses to future climate change - A modeling strategy:

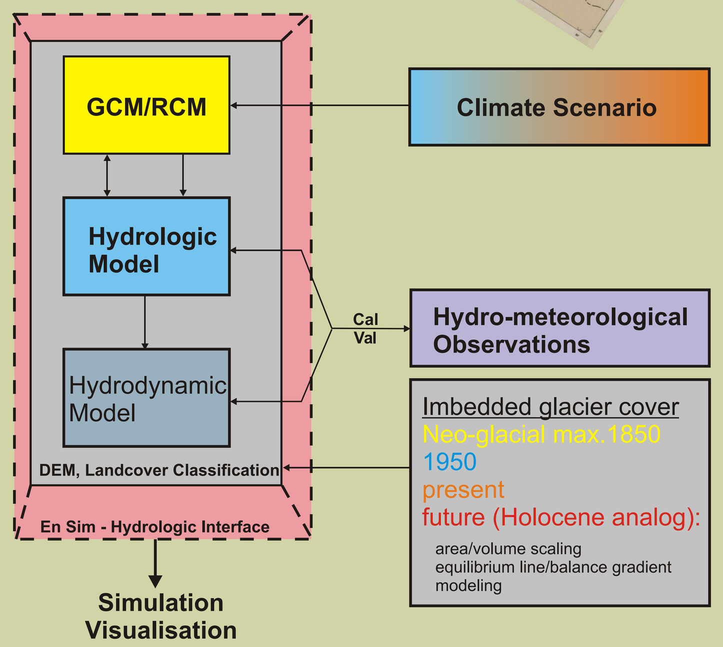




Glacier Atlas of Canada, glacier inventory map for the North Saskatchewan River Basin headwaters.



Grouped Response Unit Approach



Progress to date:

- North Saskatchewan watershed headwater delineation complete.

- DEM and nominal landcover classification complete (1998 glacier cover).

- Neo-glacial maximum and 1950 glacier cover vectors complete for test headwater catchments.

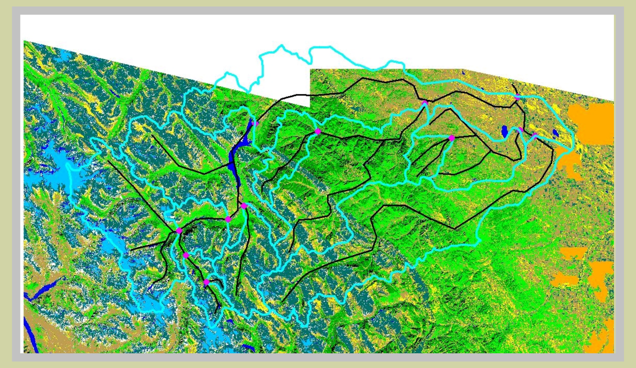
- WatFlood model domain constructed and calibrated with available hydro-meteorological data.

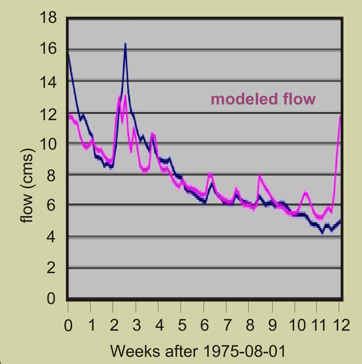
- outputs from GCM/RCM collected and being re-sampled to WatFlood grid.

- Developing improved treatment of glacier cover within WatFlood.

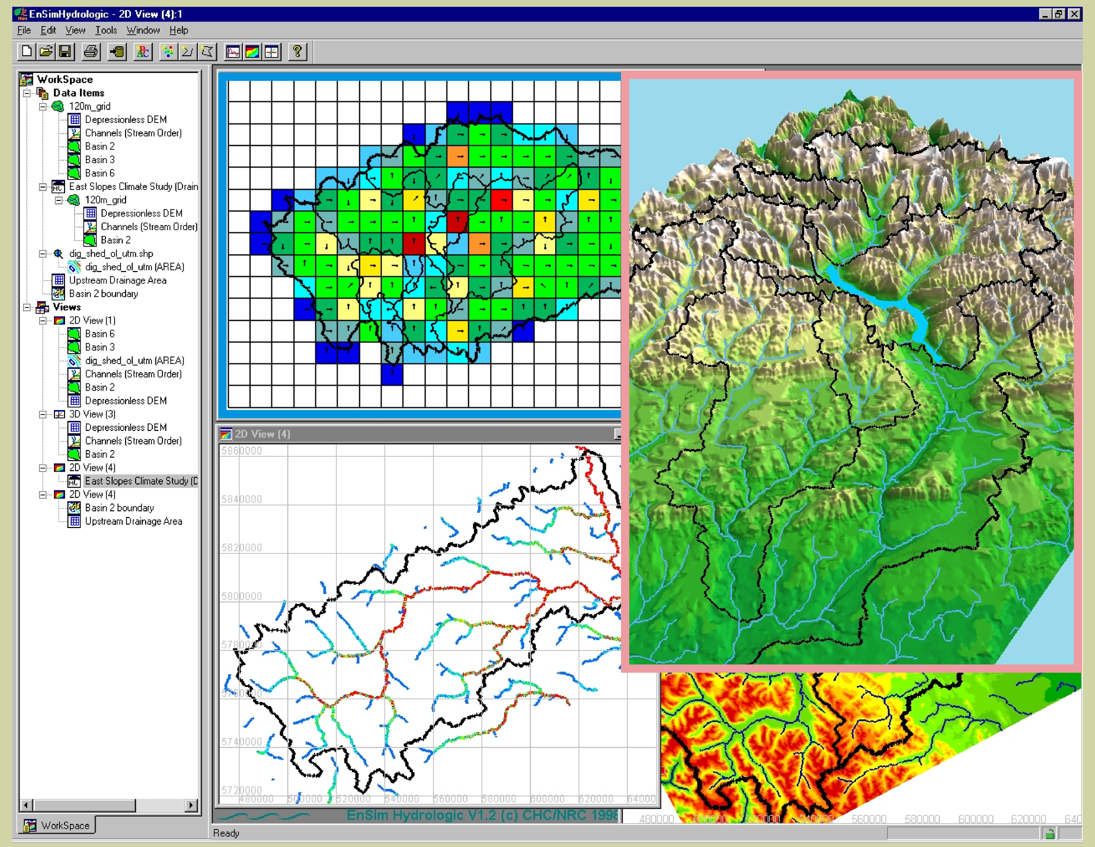
-South Saskatchewan watershed headwater delineation complete.

Supervised land cover classification derived from 1998 LandSat 5 TM data. Study basin delineation and major streams are shown.





Environmental Simulator-Hydrologic interface showing the WatFlood model domain and 2/3-D representations of the stream network and study basin.



Can we adapt to a changing wate supply/demand spectrum?

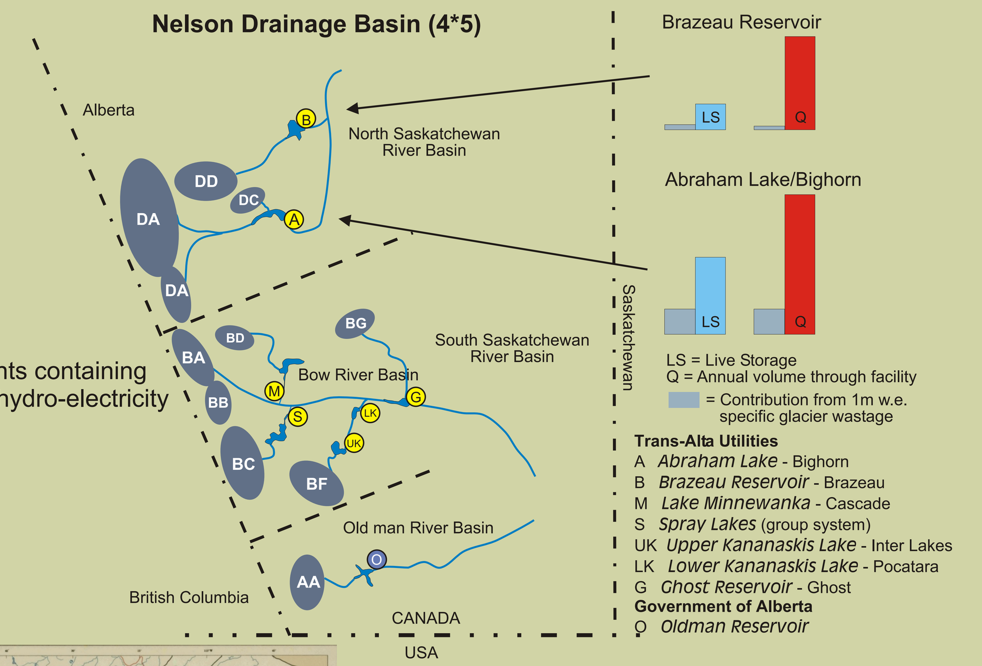
1999 fuel mix for electrical power generation: Coal 69.8%; Natural Gas 13.3%; Hydro 16.9%

?

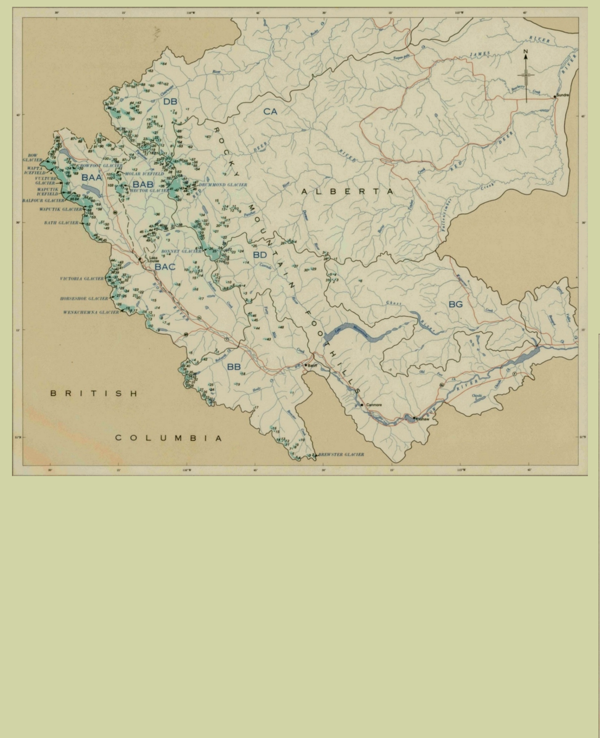
Declining headwater flows will exacerbate water shortages that are already apparent across many areas of Alberta and Saskatchewan owing to drought. Other supply/demand considerations are:

Bull Trout - An Autumnal spawner

- **Inter-provincial water allocation**
- **South Sask is fully allocated at AB/SK border**
- **Other demands: Irrigation, habitat (e.g., Bull Trout), aquifer recharge**
- **North vs South Saskatchewan river basins**



Contributing catchments containing glaciers and relevant hydro-electricity generating reservoirs.



Glacier Atlas of Canada, glacier inventory maps for the Red Deer and Bow River Catchments of the South Saskatchewan River Basin headwaters.

Summary

Glacial meltwater is a key source of water for many Prairie rivers. Along the eastern slopes of the Canadian Rocky Mountains, glacier cover has been decreasing rapidly in recent years, and total cover is now approaching the least extent experienced in the past 10,000 years. As the glacial cover has decreased, so have the downstream flow volumes. While this finding appears to contradict the IPCC projection that warmer temperatures will cause glacial contributions to downstream flow regimes to increase in the short-term, historical stream flow data indicate that this increased flow phase has already past, and that the basins have entered a potentially long-term trend of declining flows.

Acknowledgments

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