Canadian Foundation for Climate
and Atmospheric Sciences (CFCAS)
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du climat et de l'atmosphère (FCSCA)

Final Progress Report

Project Title: Canadian Hydrological Drought Processes and Modelling

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1.0 Project Work

1.1 Provide a summary description of a) the objectives of the study, b) the scientific findings and c) the project work undertaken.

a) Objectives

The overall objective is to *better understand, describe and model the evolution of hydrological drought on the prairies, from frozen and unfrozen land surface fluxes, to soil moisture and surface water storage to streamflow generation.* The specific objectives of this study were to better understand and predict three aspects of the hydrological manifestation of prairie drought and its interaction with the atmosphere, specifically,
i) Snowmelt runoff: how snowmelt controls on the rate and amount of runoff to streams and sloughs under conditions of low snowfall, low soil moisture and a short snow-covered season. Runoff components of particular interest are redistribution and sublimation of blowing snow, snowmelt energetics, infiltration into frozen soils and determining the appropriate scales for calculating these terms and aggregating runoff from field to larger scales.
ii) Areal evaporation: how changing moisture content in soils affects the spatial distribution of evaporation from prairie terrain of mixed land use and mild topography. Of particular interest are feedbacks between soil moisture, plant response and atmospheric water vapour deficit near the surface.
iii) Surface water storage in wetlands: how wetland storage capacity and storage dynamics control runoff generation during droughts in basins that are wetland dominated and those that are well drained.
Prediction of these prairie drought processes was accomplished through,
iii) Process based modelling of prairie hydrology in small catchments. Physically based small scale models of the hydrological cycle were developed and evaluated under varying drought conditions across the prairies using the Cold Regions Hydrological Modelling Platform (CRHM). The runoff and soil moisture response of 'ideal' small upland and wetland catchments to drought were developed as a new type of hydrological drought index for Canada.

b) Scientific Findings. These are organised by DRI Theme

Theme 1

Findings included identifying and quantifying the drought variables relevant to generation of spring runoff and summer evapotranspiration from prairie basins. Spring runoff is generated from snowmelt after infiltration is satisfied and snowmelt is controlled by snowfall, blowing snow redistribution, and mid-winter melts. Infiltration is controlled by snowmelt, soil type and frozen soil moisture content. Hence the variables are defined for their use in hydrology and so differ substantially from those traditionally defined in climatology, for instance, 'winter' refers to the period 1 October to 1 May during which the winter snow cover forms, soils freeze, snow melts and most annual runoff is generated.

Variables defined are

i) volumetric soil moisture at the time of fall soil freezing (typically 1 Nov),
ii) winter maximum snow accumulation,
iii) winter vegetation heights (stubble height, land use), densities and winter leaf area index,
iv) winter precipitation (1 Nov to 30 April)
v) winter temperature, humidity, cloudiness and wind speed (1 Nov to 30 April).

An investigation of the 1980s and recent drought showed that hydrological winters do not always behave as expected during prairie droughts. The station shown is Rosetown in the Saskatchewan grainbelt but similar results can be found for adjacent stations. Fig 1b shows the recent 1999-2003 drought and winter precipitation well below average (as low as 60% of mean) as expected during most of the winters (02-03 being a notable exception). However air temperatures were below average by about 1 °C for the core drought years and colder winters are not usually considered characteristics of droughts. It is interesting to note that below average temperatures were also recorded during the 1988-89 period of drought, but not in the winters preceding this.

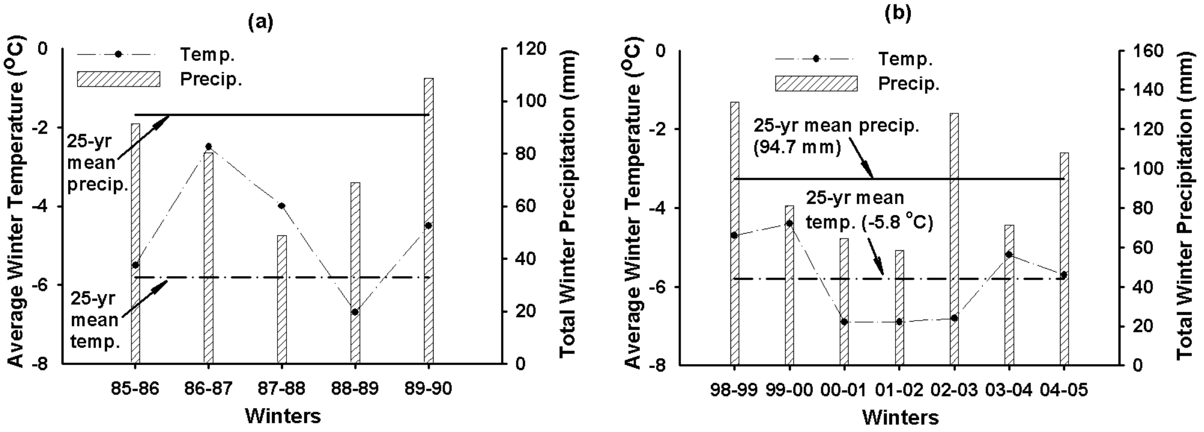

Figure 1: Average winter temperature and total winter precipitation (rainfall and snowfall) observed in Rosetown, Sask. during winters of: (a) 1985-1990, (b) 1998-2005 along with 25-year (1981-2005) winter temperature and precipitation normals.

A detailed description of the drought for a prairie wetland environment was assembled from the St Denis National Wildlife Area, Sask. via collaboration with Dr. Garth van der Kamp. Reliable datasets describing incoming solar radiation, temperature, relative humidity, wind speed, precipitation, soil moisture, snowpack water equivalent and pond level were assembled for St Denis from 1999 to 2006 to show the drought and post-drought recovery period. These data were found in archives of the National Water Research Institute and the Meteorological Service of Canada. Supplementary observations were collected of precipitation, wind speed, air temperature, humidity, soil moisture and snow accumulation for 2005-2006, and latent heat flux, soil moisture, air temperature, humidity and all radiation terms for summers 2006 and 2007 in order to characterize the distinctiveness of the previous drought period.

Hydrological modelling of drought over the Prairies requires hourly values of air temperature, relative humidity, wind speed, and solar radiation, as well as daily or hourly precipitation values. The meteorological variables required were obtained from a number of sources. Gridded datasets were originally proposed for this project, however the poor temporal resolution of gridded measured data (not available hourly) and the very poor quality of NARR and NCEP reanalysis data (particularly of wind speed and precipitation) forced the use of data measured at point locations, and the outputs of the model to be gridded for analysis. The Data Access Initiative (DAI) of Ouranos was able to provide hourly measurements of wind speed, temperature and relative humidity. Unfortunately, the Ouranos hourly precipitation data was limited to rainfall and having both rainfall and snowfall are essential for hydrological modelling. This means we extracted daily snowfall totals from the Environment Canada archive and interpolated these to hourly values. Because the measured snowfall data are known to be strongly affected by wind speed, these data were corrected using Goodison's adjustment for the Nipher wind shield and a recently developed adjustment for Alter wind shields and Geonor gauges (McDonald and Pomeroy, 2008). A positive feature is that the snowfall rate is far less important than is rainfall intensity, so that the effect of any errors in disaggregating daily snowfalls to hourly values is small. The need for hourly solar radiation was obviated by estimating daily incoming shortwave radiation from daily minimum and maximum air temperatures, and then calculating the hourly radiation components from empirical and physically-based equations, as described in Shook and Pomeroy (2009).

Station data from Environment Canada and provincial agencies were fragmented among many locations at each site over the period of simulation, so composite data sets were constructed for each variable for each site. As each hourly variable was comprised of over 400,000 values over the period of the run, the effort was considerable. It is anticipated that the composite data sets will be among the most significant legacies of this project for Theme 1. Composite data sets were constructed for fifteen locations throughout Alberta, Saskatchewan, and Manitoba, all other sites having incomplete series of one or more variable, as shown in Figure 2. Although the Cold Lake and Prince Albert locations are outside of the prairie ecoregion (shown in yellow), they were included in the analyses as they help to define the northern boundary of the simulation region.

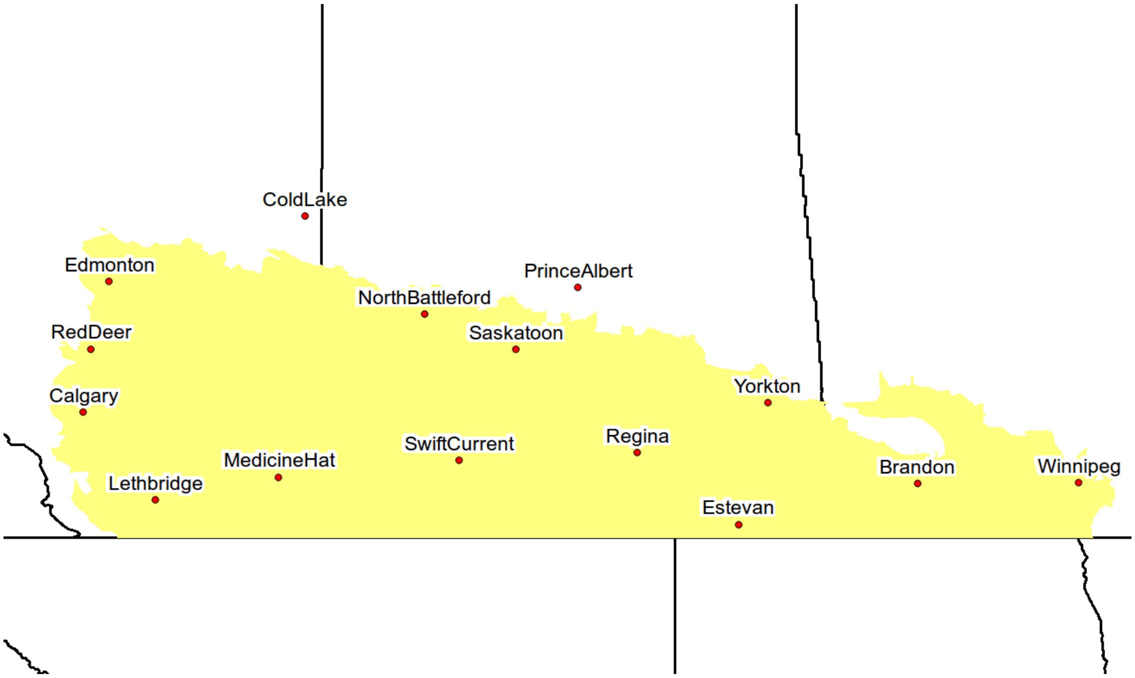

Figure 2: Stations in western Canada having suitable long term datasets for hydrological drought modelling purposes. The prairie ecoregion is shown in yellow.

Theme 2:

A sensitivity study of hydrological processes to drought (Fang and Pomeroy, 2007) showed the extreme sensitivity of prairie spring runoff amongst other hydrological processes to changes in winter air temperature and precipitation. The study used the Cold Regions Hydrological Model (CRHM) developed at the University of Saskatchewan and Environment Canada. Bad Lake, Sask. archival data from 1974-75 was used to define a 'normal' hydrological winter-spring period (1 Oct – 1 May); measured inputs from Bad Lake were then perturbed to show the types of changes expected in prairie droughts (warmer, drier, sparser vegetation) for a small, well drained prairie basin in the grainbelt. The results (Fig. 3) showed that snow accumulation on a stubble field was relatively insensitive to decreases in precipitation and increases in air temperature during drought. This was partly due to the extreme sensitivity shown by blowing snow sublimation loss and the suppression of blowing snow under drought meteorology, which partly compensated for the reduced snowfall. However reduction of stubble vegetation height during multi-year droughts with poor harvests would work to strongly reduce snow accumulation in subsequent winters. Snow cover duration initially dropped when drought meteorology was induced but showed little sensitivity to the onset of severe drought conditions. Soil moisture storage and snowmelt infiltration changed in various directions with increasingly severe drought meteorology but generally increased as fall soil moisture declined. Winter Evaporation increased slightly with the imposition of drought meteorology but any increased losses were more than compensated for by reduced blowing snow sublimation losses. Snowmelt runoff showed a heightened sensitivity to drought meteorology and ceased when precipitation dropped by 50% or air temperatures rose by 5 ºC. The decline in stream discharge in spring resulting from this was magnified in that for every one percentage drop in precipitation, streamflow dropped 1.6% and for every one degree Celsius increase in mean air temperature, streamflow decreased 20%. In contrast, the effect of soil moisture changes on stream discharge were dampened, in that for every one percentage decrease in fall soil moisture content, streamflow declined by only ~0.5%. Vegetation height changes had no effect on stream discharge.

A prairie drought hydrology progression scenario was proposed (Table 1) in which severe winter drought meteorology ensued for the first two years of drought but fall soil moisture and vegetation recovered after the winter meteorology returned to normal. The combination of factors with winter precipitation declining by 15% and air temperatures rising by 2.5 ºC was sufficient to cause the cessation of snowmelt runoff and streamflow discharge. The lingering hydrological impacts of the drought in the winter season subsequent to the end of the winter meteorological drought were enhanced by blowing snow sublimation, and reduced infiltration in response to sparser vegetation and drier soils respectively. The basin contained little surface storage and it is likely that the addition of surface storage terms (such as prairie ponds) to the hydrological system would add a significant additional multi-year memory to the hydrological drought impacts shown here (Fig. 4).

Any one of three factors: lower winter precipitation, warmer winter air temperatures or lower fall soil moisture can cause a dramatic reduction in snowmelt runoff to small streams and sloughs. The results show that spring runoff and streamflow discharge are inherently unstable in the Canadian prairie environment and so magnify the effects of changes in weather patterns typical of drought. This provides an understanding of the rapid depletion of water storage in prairie streams, sloughs and wetlands during drought; in essence the relatively small moderation of the prairie winters during droughts dries the prairie out.

Table 1: Parameters and changes in input variables for a hypothetical 'prairie drought progression'.

Drought Sequence	Fall Volumetric Soil Moisture	Vegetation Height (m)	Winter Precipitation	Winter Temperature (ºC)
Winter 1 'normal'	Normal	normal	normal	normal
Winter 2 'severe'	Normal	normal	-15%	+2.5
Winter 3 'severe'	-45%	-60%	-30%	+2.5
Winter 4 'recovery'	-45%	-60%	normal	normal
Winter 5 'recovery'	Normal	-35%	normal	normal

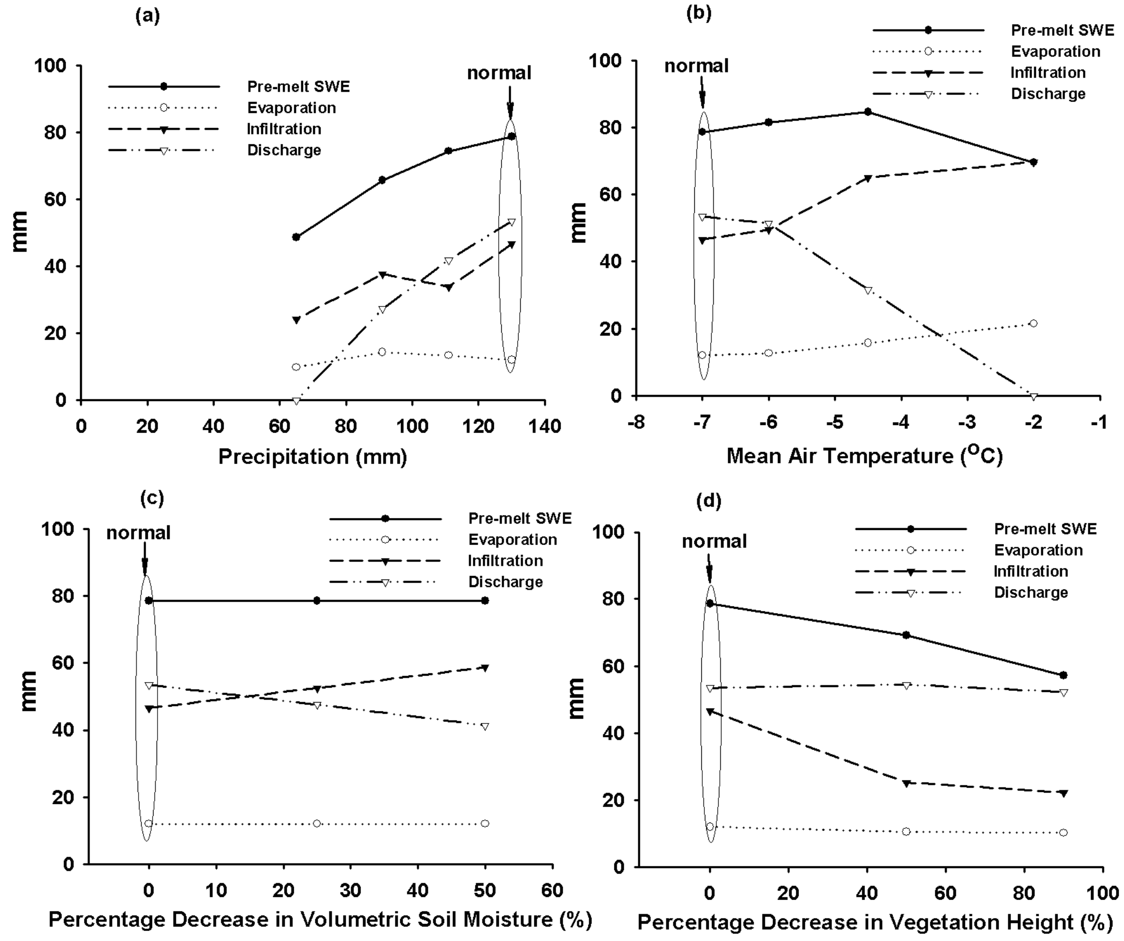

Figure 3: Drought sensitivity of basin-wide snowmelt runoff-related processes to changes in: (a) winter precipitation, (b) mean winter air temperature, (c) initial (fall) volumetric soil moisture content, (d) winter vegetation height (winter = 1 Oct to 1 May). Note ‘premelt SWE’ is maximum snow accumulation, ‘evaporation’ is winter/spring evaporation, ‘infiltration’ is infiltration to frozen soils during winter and spring, ‘discharge’ is the streamflow from a small (11 km^2), well drained basin in SW Saskatchewan.

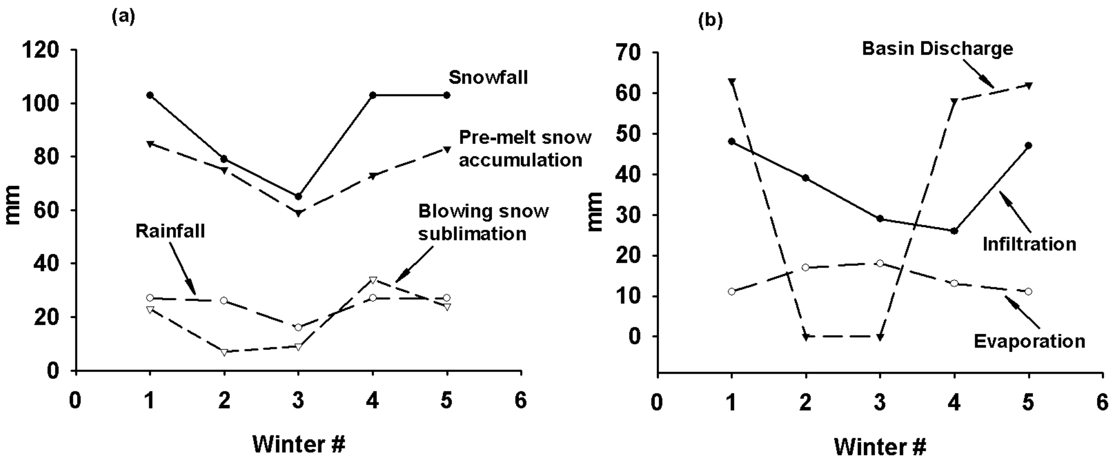

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Figure 4: Prairie winter hydrological drought progression (see Table 1) from normal (winter 1) to severe drought (winter 2, 3) to recovery (winter 4, 5), showing the drought impact on (a)

snowfall, rainfall, pre-melt snow accumulation, blowing snow sublimation and (b) infiltration, evaporation, streamflow discharge (1 October – 1 May).

The data assembled for Theme 1 were used to drive a physically based prairie hydrological model created with CHRM to better describe the evolution of the hydrological drought with respect to spring snowmelt runoff at St Denis (Pond 109). Snowmelt provides the major runoff event of the year. Results showed that much lower precipitation, less snow accumulation, shorter snow-covered duration, enhanced winter evaporation, and much lower discharge to the wetland from snowmelt runoff developed in the severe drought period of 1999-2002. As a result, there was only 14.9 mm, 3.7 mm, and 14.4 mm of snowmelt runoff in the basin for the springs of 2000, 2001, and 2002, respectively. Compared to the discharge in the spring of 2006, 68.2 mm, melt water discharge to the Wetland 109 had decreased by 78%, 95%, and 79% for the springs of 2000, 2001, and 2002, respectively. Hydrological memory working to lengthen the hydrological drought was evident at the cessation of the meteorological drought by a return to normal winter snowfall. Normal snowfall did not result in normal runoff the subsequent spring or a return to normal wetland levels in the first year because of
i) “storage memory” of dry fall soil moisture content which strongly affected spring runoff, and
ii) low water storage in ponds resulting in restricted fill and spill from one pond to the next and hence a small contributing area for runoff generation and rapid infiltration into unsaturated pond soils, both these mechanisms reduced runoff generation dramatically in the subsequent spring.

To understand the dynamics of drought a complete understanding of the evaporation process during drought is necessary. Three physically based actual evaporation models (Penman-Monteith, Granger-Gray, Dalton Bulk Transfer) were examined using energy balance, soil moisture and eddy correlation measurements taken during a drying summer period in a rolling upland prairie landscape (Armstrong et al., 2008). Each has a unique response to changes in atmospheric and surface conditions and so their sensitivity to drying is instructive as to the appropriate modeling approach for drought conditions. Evaporation was measured directly using a eddy correlation system (full corrections applied). All components of net radiation, soil moisture, surface temperature, plant height, air temperature, humidity and wind speed were measured through the summer period for this study. Penman-Monteith relies on net radiation, aerodynamic transfer with strong controls by soil moisture and plant growth (Jarvis type formulation). Granger-Gray is similar but relies on atmospheric humidity as a feedback rather than soil moisture to index soil moisture and plant growth. Dalton Bulk Transfer relies on measured surface temperature and aerodynamic exchange with adjustments for soil moisture and plant growth (Jarvis type formulation). All three models provided reasonable estimates of evaporation (when compared to observations) from time scales of several days to seasonal periods (Fig 5), but provided poor estimates of daily or sub-daily evaporation. The variance compared to observations increased as the time scale decreased. Based on comparisons with observations for several time periods the Penman-Monteith (P-M) method performed the best overall. However, the Granger-Gray (G-D) method also provided results that were close to the P-M method and did so with far fewer parameters (e.g. did not need soil moisture). Over short periods of 2 – 3 days, the G-D method provided the best results overall of the three methods. The poorest agreement between modeled and measured evaporation was provided by the Dalton Bulk Transfer (BT) method. One reason for this may be the purely aerodynamic approach of the BT method itself which lacks consideration of the available energy. Given the large observed scatter at higher temporal resolutions it is unlikely that corrections for stability alone will provide a significant increase in agreement between the modeled estimates and observed evaporation. Rather, other factors influencing evaporation such as, heat storage, and the spatial variability of surface parameters need to be considered explicitly in estimating evaporation.

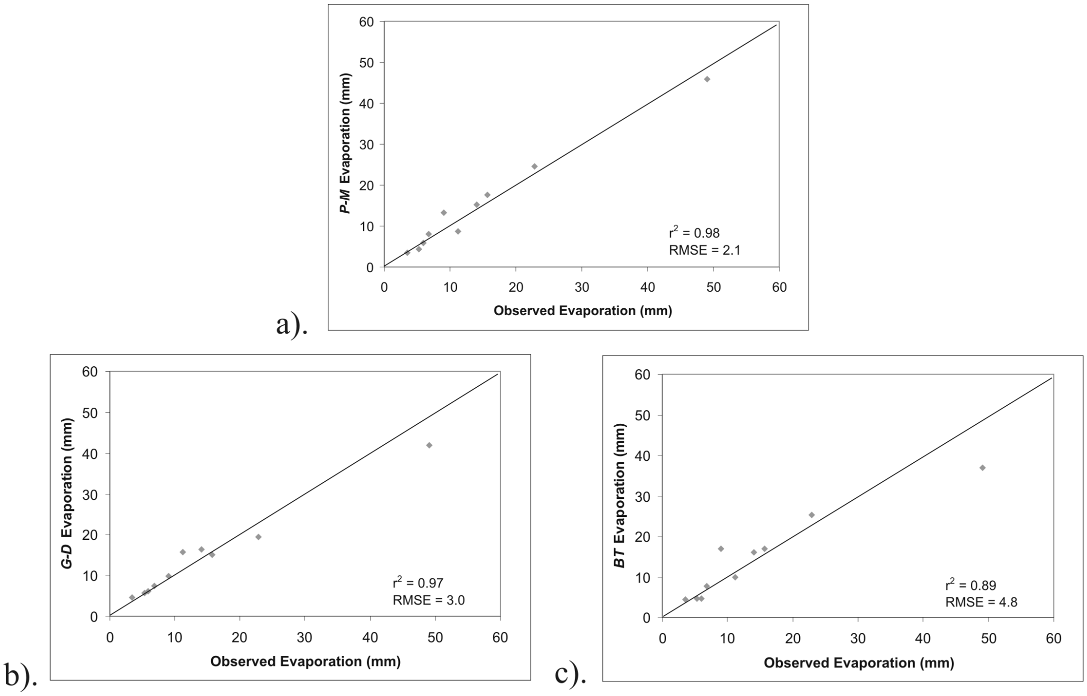


Figure 5: Estimated versus observed evaporation totals for periods of 2 days to 2 weeks in duration and one -to- one line. a) *Penman-Monteith*, b) *Granger–Gray*, c) Dalton *Bulk Transfer*.

Developing techniques from process understanding for characterizing evaporation during drought was a major focus of research. A physically-based hydrological model that considers the interactions of infiltration, evaporation, and soil moisture accounting was assembled using existing modules within the Cold Regions Hydrologic Model (CRHM) platform. Actual evaporation was calculated over the summer period of 2001 at a short grass prairie site located at Lethbridge, Alta (AMERIFLUX) using a resistance-based model (Penman-Montieth) and a complementary feedback model (Granger-Gray). Both models extend the Penman potential evaporation model to the case of a non-saturated surface which has particular relevance during drought. Surface resistances in Penman-Monteith were increased using standard methods (Jarvis) as a function of soil moisture. Granger-Gray evaporation responds solely to atmospheric conditions. The results showed that both the Penman-Montieth, and Granger and Gray models may produce large overestimates of evaporation during a drought period when allowed to run solely as atmospheric models. A coupled soil moisture-precipitation-runoff water balance approach was necessary to further limit evaporation during such periods of severe moisture stress (Armstrong et al., 2010). By restricting evaporation from these atmospheric evaporation models based on enforcement of soil moisture continuity from a hydrological water balance, good performance of both evaporation models could be obtained depending on rooting depth (Fig 6). Evaporation characterisation of drought will require rigorous coupling of existing atmospheric schemes to the soil hydrological system to provide realistic results.

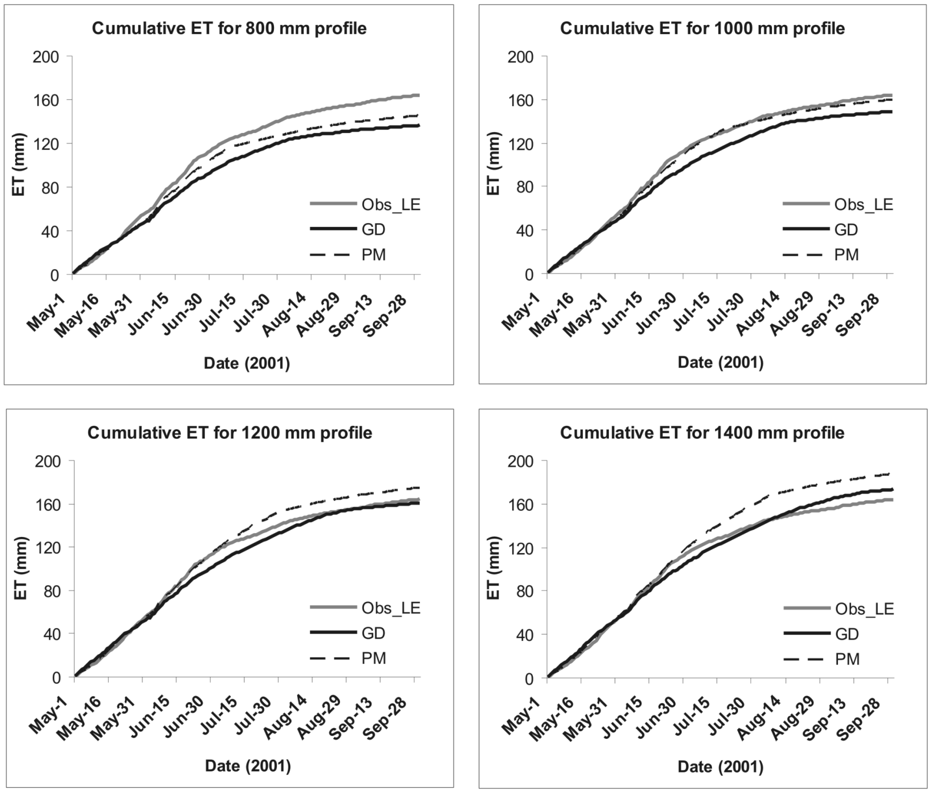


Figure. 6: Cumulative evapotranspiration observed using eddy correlation systems and modelled for varying rooting depths using the Granger-Gray (GD) and Penman Monteith (PM) models.

Evapotranspiration has considerable spatial variability that is not captured by point scale estimates from meteorological station data. Remote sensing can be valuable for deriving key variables needed for distributing point scale evaporation models for direct estimates over large areas. It is possible to obtain distributed estimates of mean daily net radiation over large regions from one-time-of-day (near solar noon) visible and thermal imagery and a single reference value of mean daily net radiation. A new approach has been developed for deriving distributed estimates of the mean daily net radiation balance needed for parameterising energy balance and combination evaporation models. The method has been demonstrated and applied for the calculation of evaporation from a grassed surface at a complex parkland site in central Saskatchewan (Armstrong et al., in preparation). For this purpose, the evaporation model used is that developed by Granger and Gray (G-D model) which extends the Penman combination aerodynamic-energy balance model to non-saturated surfaces. The G-D model is a useful and practical alternative to complex evaporation models in data sparse regions, and can be applied where detailed soil moisture information may not be available. Spatially distributed estimates of the mean daily evaporation (Fig. 7) were obtained by parameterising the G-D model with surface reference measurements of incoming shortwave and longwave radiation, air temperature, humidity, and wind speed. Surface temperature, albedo and aerodynamic roughness height maps were derived from aerial images obtained using hand-held cameras in the thermal and visible wavelengths. This information is used to distributing the outgoing shortwave and longwave radiation, and roughness terms needed for the G-D model. The sensitivity of evaporation to changes in driving factors was examined by considering the ratios of values of key variables to corresponding surface reference values obtained at mid-day. Estimates of daily net radiation were within 5 – 10 % of measured values at two validation sites. The estimated upwind evaporation was found to be 0.5 mm higher than the measured value obtained by the eddy covariance method. The technique is amenable to application using satellite remote sensing information and surface meteorological data. A potential advantage of this approach over that of previous remote sensing methods is that daily evaporation may be estimated directly.

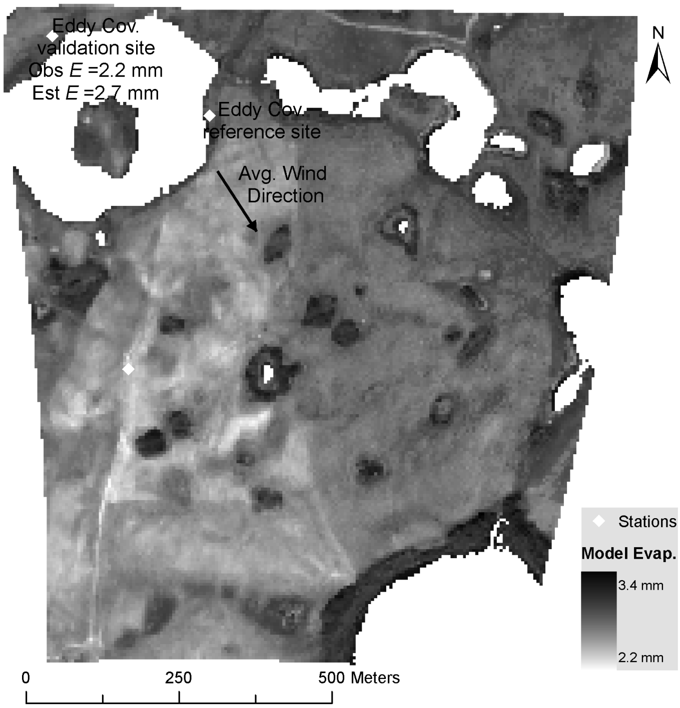


Figure 7: Map of mean daily evaporation estimates. Observed and estimated values indicated along with prevailing wind direction for the day.

Spatial variations of actual evapotranspiration (ET) were then estimated for grass surfaces in the Canadian Prairies using a hydrological cycle model approach. Hydrological processes governing the water balance were modeled for both snow and snow-free periods using the modular Cold Regions Hydrological Model (CRHM) platform. Actual ET was calculated during the snow-free period by the Penman-Monteith method and was limited by available soil moisture. The model was driven by archived observations of hourly temp, RH, wind, rainfall and estimates of incoming solar radiation, and daily snowfall. The general soil texture class for each location were determined from the Soil Landscapes of Canada v3.1.1. The initial soil moisture state at all locations was set to 50% moisture holding capacity based on the initial start date of Jan 1, 1960 during an extensive drought. A minimum canopy resistance of 50 s m^{-1} was set to account for “normal” grass plant conditions; vegetation heights were adjusted for plant growth to a maximum canopy height of 1 m. Growing season analyses were performed for a normal 30 year period extending from 1971 – 2000 and a drought period from 1999 through 2005. In conditions of adequate soil moisture the actual ET rate was found to be relatively insensitive to growing season climate due to several offsetting factors. When soil moisture became low ET rates dropped dramatically. Consequently there is no consistent spatial pattern in actual ET across the region over the drought period. As the drought progressed from 1999 – 2001 there was an increase in the variability of modelled growing seasonal totals of actual ET among the stations, and then a sharp decline ensued from 2002 – 2005 as the moisture conditions progressively became more uniform (Fig. 8).

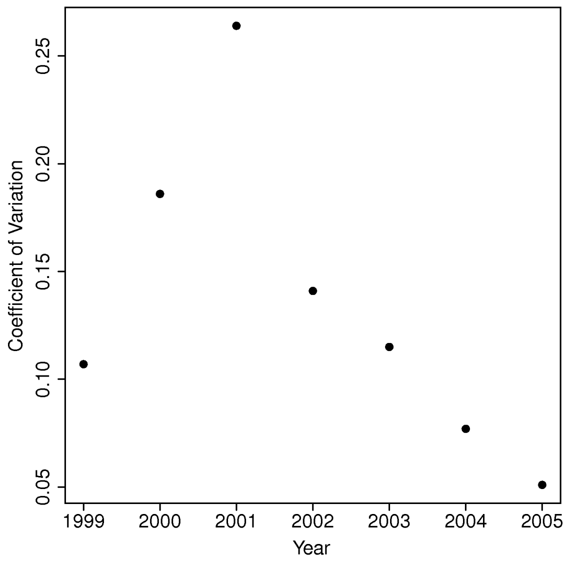


Figure 8: General variability of seasonal estimates of evaporation among the climate stations during the drought period.

Theme 3:
For theme 3 progress consisted of i) Development of the Cold Regions Hydrological Model (CRHM) for application to the prairie environment as a process hydrology model suitable for small basins, ii) evaluation of evaporation calculation procedures for use in hydrological models, land surface schemes and coupled models.

The Cold Regions Hydrological Model was redeveloped for prairie drought situations. This involved extensive testing using the Bad Lake Research Basin archives of the Division of Hydrology (U of Sask), coding revised modules and improvements to the model platform. The methodology for calculating snowmelt runoff using CRHM is shown in Fig. 9.

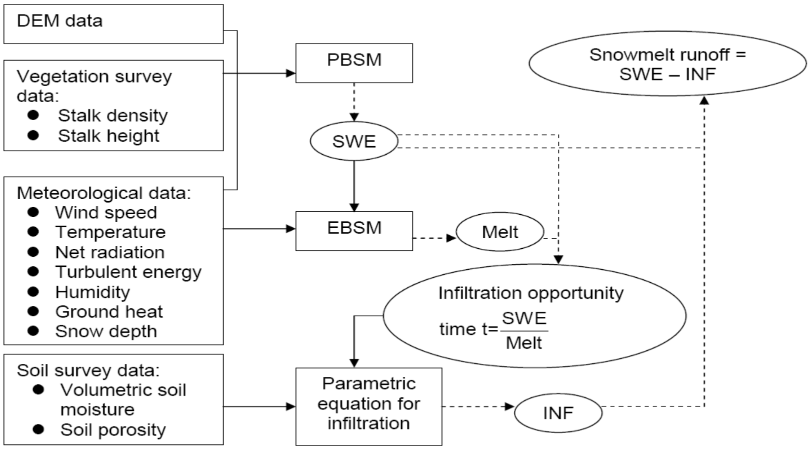


Figure 9: CRHM calculation methodology for calculating snowmelt runoff for drought conditions. PBSM is the Prairie Blowing Snow Model (Pomeroy and Li, 2000), EBSM is the Energy Balance Snowmelt Model (Gray and Landine, 1988), Parametric Equation for Infiltration is described by Gray et al. (2001).

CRHM was assembled to simulate snowcover development, ablation, infiltration to frozen soils and runoff using algorithms developed at the University of Saskatchewan and then tested using data from Bad Lake, an example of which is shown in Fig. 10. The model simulates SWE and Melt well in this uncalibrated test.

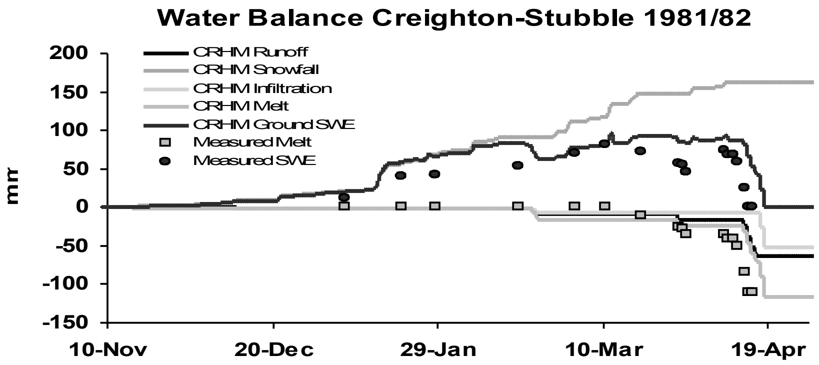


Figure 10: Simulations of SWE, melt, infiltration and runoff using the Cold Regions Hydrology Model with modules for energy balance snowmelt, blowing snow transport and sublimation, infiltration to frozen soils and snowmelt runoff for a stubble field in the Bad Lake Research Basin (Creighton Tributary). Field measurements of *SWE* and snowmelt were derived from extensive snow surveys.

An evaluation of the evaporation, interception and soil moisture balance modules in CRHM was conducted at an open fen site in the former BOREAS study area from the beginning of May until the end of October 2004, part of the drought period. Observations of evaporation were made in two ways, the first by an eddy correlation system (Campbell CSAT sonic anemometer and LI7500 hygrometer, with axis and other corrections by Fluxnet Canada protocols), and the second by energy balance from the net radiation, less sensible heat (estimated by profile method) and heat storage change. These observations were conducted by Raoul Granger of Environment Canada and colleagues. The results are shown in Figure 11 and suggest a good correspondence between evaporation calculated using the Granger-Gray algorithm with an albedo set to 0.1 and to both eddy correlation and energy balance estimates of evaporation. Interestingly, in spring and early summer evaporation is limited by available moisture (cumulative evaporation is roughly equal to cumulative rainfall), whilst in later summer and fall it is no longer limited by precipitation but by energy supply.

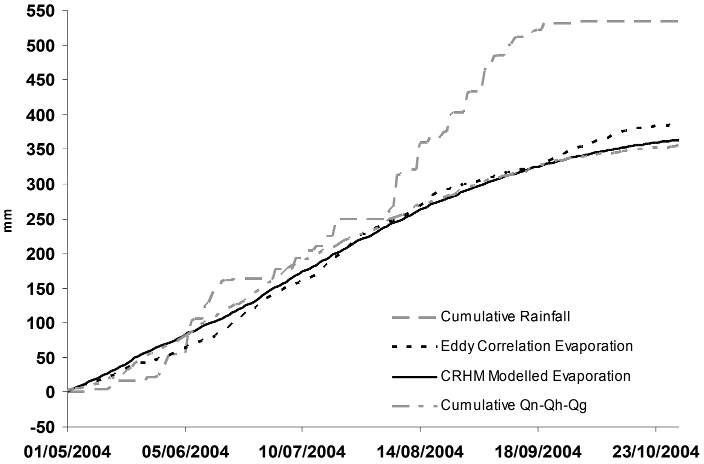


Figure 11: Modelled cumulative evapotranspiration over a fen wetland in the boreal forest of central Saskatchewan from CRHM and evaporation estimated from eddy correlation measurements and as a residual of the energy balance. Also shown is cumulative rainfall in mm

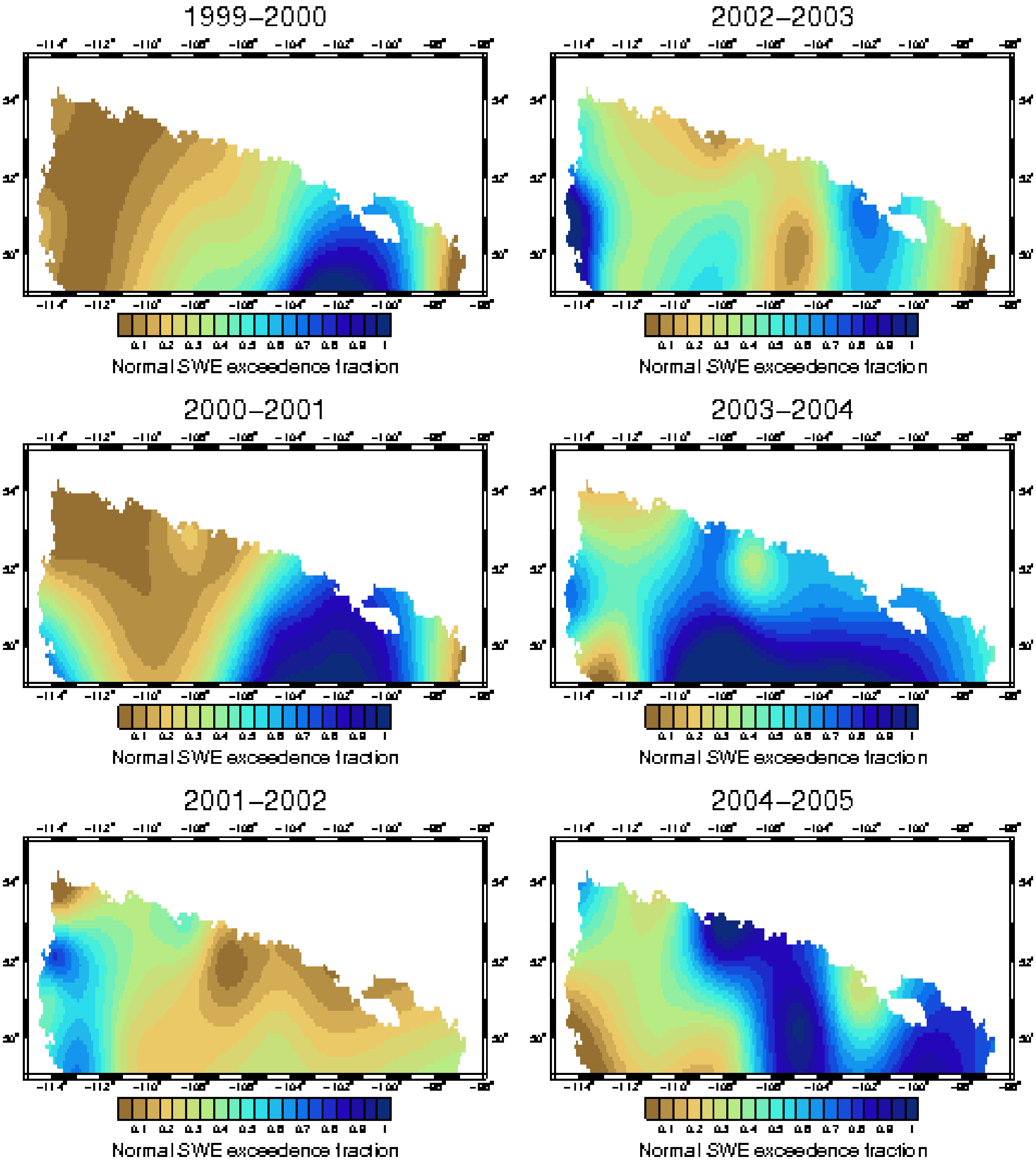
Blowing snow redistribution to runoff producing areas and snowmelt are crucial processes in the spring runoff generation during drought on the prairie. CRHM (spatially aggregated into Hydrological Response Units) and a model of similar physics run on 6 m grid cells (spatially distributed) were used to model blowing snow redistribution and melt at St. Denis. Both the spatially distributed and spatially aggregated scales produced similar end of winter Snow Water Equivalent values. The spatially aggregated scale used by CRHM was sufficiently accurate to estimate the end of winter snow accumulation for a small Prairie basin. This suggests that “tiles” as implemented in Canadian land surface schemes (MESH) will have sufficient spatial resolution but will need to consider redistribution of snow amongst tiles in order to characterize the snow available for melt accurately. After this modelling scale test, CRHM was used to set up a complete hydrological model for prairie snowmelt runoff for both Bad Lake and St. Denis research areas. CRHM generally performed well when compared to observed snow accumulation and streamflow and did not require calibration.

Although the climatological conditions which define a drought are generally well understood, it is more difficult to define and model hydrological drought in a region such as the Canadian Prairies where large non-contributing areas for streamflow generation mean that land surface hydrology is disconnected from the hydrology of major rivers during drought. The response of first order prairie basins is generally unmeasured but critically important to understanding the impact of drought on prairie hydrology. The objective of this component is to determine the responses of typical first order prairie basins to the drought of 1999-2005, and the way in which these responses varied both temporally and spatially, by modelling their hydrological responses to drought and non-drought conditions. The simulation consisted of two CRHM configurations, the first being that of a small well drained watershed containing a first order stream, the second consisting of a internally drained wetland and the adjacent land draining into it. Both are typical of prairie hydrography and contain multiple HRUs. The simulations were carried out over two time periods: 1) the climate normal period of 1961-1990, and 2) the drought period of 1999-2005, allowing comparison of the basins' responses to "normal" and drought conditions.

Although CRHM will compute basin discharges where they exist, other hydrological variables such as soil moisture or snow accumulation are also of interest. CRHM was run during the drought period, and the selected variables were compared with their values during a climate normal period, 1961-1990. The cumulative distribution function (CDF) was computed from the CRHM runs over the normal period for each variable of interest. Annual values (maxima, minima, or means) of the hydrological variables are typically used to establish the normal CDF, but other time scales could also be used. Using the same time step (typically yearly) and aggregation method (maximum, minimum, or mean) as used for the normal period values, exceedence probabilities were computed from the normal period CDF, using the drought period values. As each hydrological variable will have its own CDF, the various types of hydrological drought can be evaluated separately from each other. Because this method explicitly compares the drought conditions to the local normal, it yields a value which is characteristic of a given location, yet can be compared to other locations.

Because the wetland basin model is relatively simple in that all of the blowing snow is redistributed from the upland HRU to the wetland HRUs, only the SWE accumulation in the upland basin model is analyzed here. The cropped SWE is shown in Figure 12 which plots the gridded, interpolated exceedence frequencies for the winters of 1999-2004. Unsurprisingly, the peak SWE accumulations are smallest during the most severe years of the drought. Although the years 1999-2000 and 2000-2001 had the most severe snow accumulation deficits, the droughts of 2001-2002, and 2003-2004 were much more spatially extensive in terms of snow deficit. Interestingly, although the year 2005 produced some of the worst flooding in the history of southern Alberta, the year began as a deficit in accumulated SWE.

When crop rotation is practised, soil moisture in the rooting zone (1.5 m deep in the models) increases during the summer when the land is fallow and decreases when crops are grown. The inter-annual variability in the soil moisture of cropped HRUs is much greater than that of fallow HRUs, because (a) the wetter fallow HRUs are closer to the limiting value of 100% saturation, and (b) the variability of the cropped HRU includes the temporal variability of evapotranspiration. Because of the minimal evapotranspiration during the previous year when the land was fallow, the soil moisture of the cropped HRUs is very close to saturation at the beginning of each year. The gridded exceedence frequencies of the minimum annual soil moisture of the cropped HRUs are plotted in Figure 13. Because the minimum soil moisture tends to occur at the end of the growing season (approximately Sept. 1), it is affected by all of the summer rainfall, as well as the spring snow melt. Therefore the spatial distributions of soil moisture drought bear little resemblance to the spatial distributions of maximum snow accumulation shown in Figure 6.


1999–2000

2002–2003

2000–2001

2003–2004

2001–2002

2004–2005

Figure 12. Hydrological exceedence probabilities of peak annual SWE accumulation on composite cropped HRU compared to climate normals.

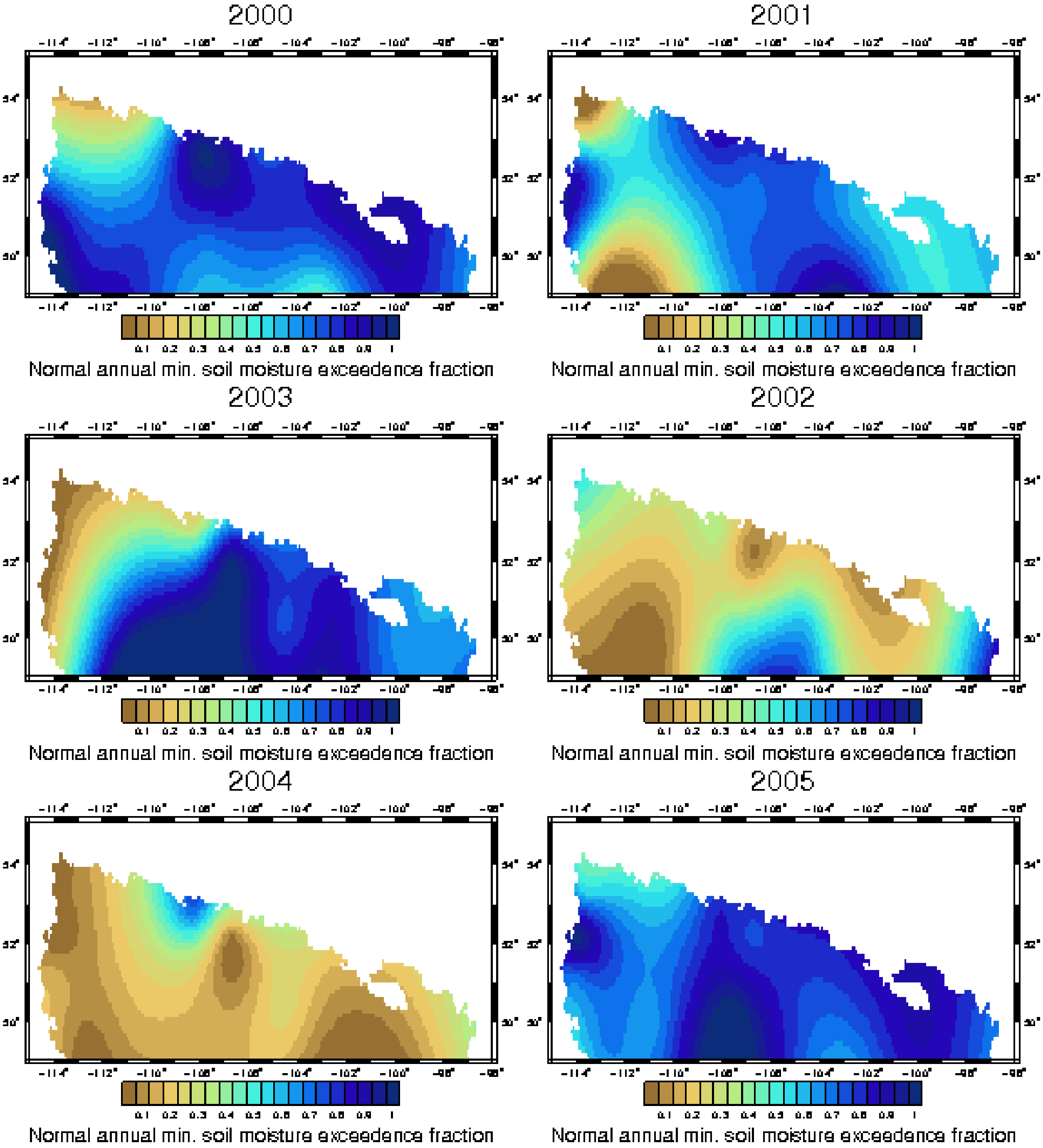
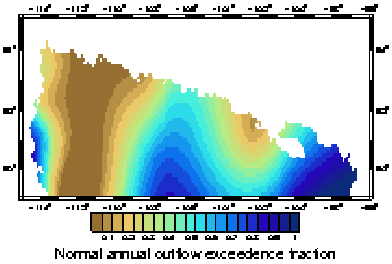


Figure 13. Hydrological normal exceedence probabilities of minimum annual soil moisture on cropped HRUs compared to climatic normals.

The gridded exceedance frequencies of the discharges from the upland and wetland basin models are plotted in Figure 14. As the majority of runoff in the Prairies is caused by the spring melt of the winter snowpack the similarity of the discharge plots, to those of the peak snow accumulation in Figure 12, is expected. When compared year-by-year, the wetland and upland discharge plots show evidence of the memory effects of wetlands on discharge. In the year 2000 the upland discharge deficit occupied much of the westernmost part of the Prairie region. In 2001, the upland discharge deficit deepened and extended further to the west and east, and in 2002, the upland discharge deficit retreated from most of the Prairies. In contrast, the wetland discharge deficit in 2000 began over a smaller region, and expanded more slowly in

2001. In 2002, when the upland discharge deficit was shrinking, the wetland discharge deficit increased.



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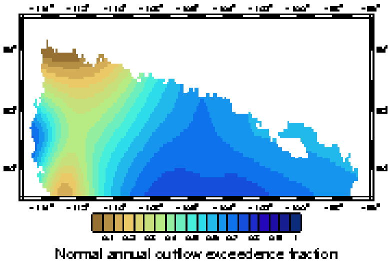

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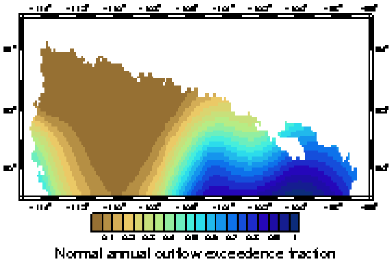

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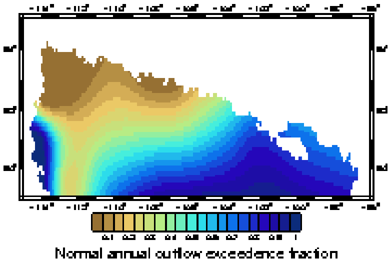

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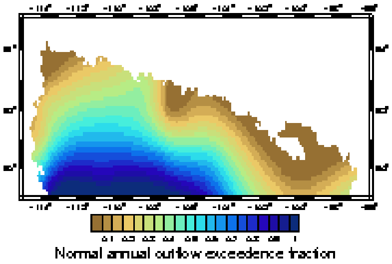

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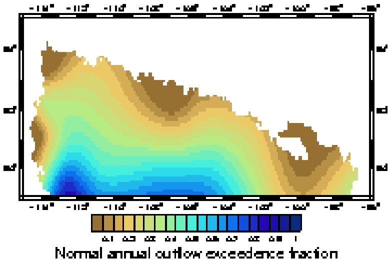
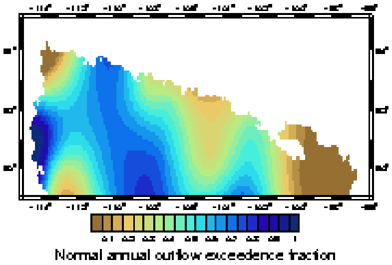
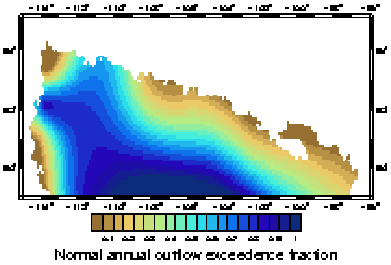


2002



2003



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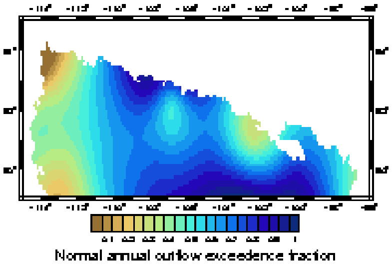

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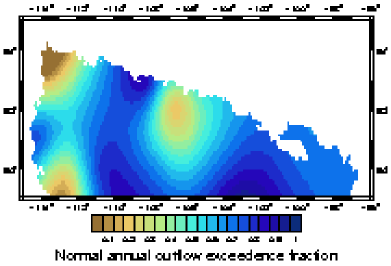

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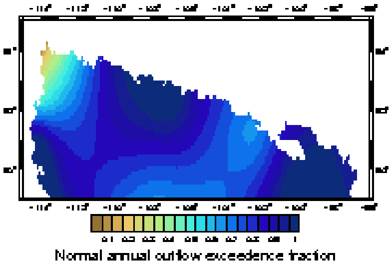
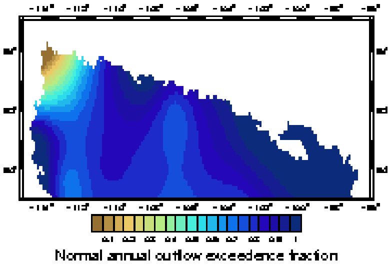


2005



2005

Figure 14. Hydrological exceedence probabilities of annual discharges (2000-2005) compared to the climate normal period. The left column contains outflows from the upland basin model, the right contains the outflows from the wetland basin model.

Similarly, the wetland discharge deficit maps of 2003 and 2004, are similar to the upland discharge deficit maps of 2002, and 2003, respectively. In 2005, both upland and wetland discharge maps are very similar as the large volume of runoff was due to heavy June rainfall which was widely distributed across the region.

Calculation of hydrological normal probabilities for virtual basins is a new methodology for describing hydrological droughts on the Canadian Prairies. The methodology was tested by modelling the extent of hydrological droughts on the Canadian prairies during the period 1999-2005. Because suitable meteorological forcing data are only available at points separated by many hundreds of kilometres, only very large-scale spatial trends are discernible. Nevertheless, plots of interpolated exceedance frequencies were able to demonstrate the following:

1. The differences among snow accumulation, soil moisture and streamflow deficits in defining hydrological drought,
2. The spatial patterns and temporal variation of each of the deficits,
3. The difference between the discharge deficits of small Prairie streams and of wetlands due to the “memory” effects of wetlands.

The persistence of flow in the wetland HRUs slowed the advance of the drought in 2000 and 2001. It is difficult to discern if the wetlands also slowed the retreat of the drought, as the heavy rainfall of 2005 completely ended the drought over the Prairies. Although the behaviour of the wetland model appears to be plausible, further research is required to determine the degree to which the modelled behaviours are found in nature. However the extensive Prairie wetlands have the potential to reduce the severity of short-lived hydrological droughts.

Theme 5

The Cold Regions Hydrological Model platform (CRHM) is a computational toolbox developed by the University of Saskatchewan to set up and run physically based, flexible, object oriented hydrological models. CRHM was used to create the PHM for Smith Creek Research Basin (~400 km^2), Saskatchewan. Two types of PHM runs were performed to estimate the basin hydrology. The non-LiDAR (Light Detection and Ranging) runs used a topographic map based DEM (digital elevation model) to estimate drainage area and hydrograph calibration to determine maximum depressional storage. The LiDAR runs used a fine-scale LiDAR derived DEM to determine drainage area and maximum depressional storage; use of LiDAR information meant that calibration was not required to set any parameter value. In both cases all non-topographic parameters were determined from basin observations, remote sensing and field surveys.

Both LiDAR and non-LiDAR model predictions of winter snow accumulation were very similar and compared quite well with the distributed snow survey results. The simulations were able to effectively capture the natural sequence of snow redistribution and relocate snow from ‘source’ areas (e.g. fallow and stubble fields) to ‘sink’ or ‘drift’ areas (e.g. tall vegetated wetland area and deeply incised channels). This is a vital process in controlling the water balance of prairie basins as most water in wetlands and prairie river channels is the result of redistribution of snow by wind and subsequent snowmelt runoff. Soil moisture status is an important factor in determining the spring surface runoff and in controlling agricultural productivity. Unfrozen soil moisture content at a point during melt was adequately simulated from both modelling approaches.

Both modelling approaches were capable of matching the spring streamflow hydrographs with good accuracy; the non-LiDAR approach performed slightly better than the LiDAR approach because the streamflow hydrograph was calibrated, whereas no calibration was involved in the LiDAR simulation. However, the LiDAR approach to simulation shows promise for application to ungauged basins or to changing basins and demonstrates that prairie hydrology can be simulated based on our current understanding of physical principles and good basin data that provides “real” parameters. The approach uses a LiDAR DEM, SPOT 5 satellite images and involved automated basin parameters delineation techniques and a new wetland depth-area-volume calculation.

The new wetland depth-area-volume calculation used a LiDAR-derived DEM to estimate maximum depressional storage, a substantial improvement over estimates generated from simpler area-volume methods. This was likely due to the inclusion of information on depression morphology when calculating volume. Further, the process to retrieve the coefficients from a LiDAR DEM was automated and wetland storage was estimated at a broad spatial scale. A GIS model was created that can automatically extract the elevation and area data necessary for use in the new depth-area-volume method.

Using the Prairie Hydrological Model, PHM, a series of scenarios on changing land use and wetland and drainage conditions was created from 2007-08 meteorological data. The scenario simulations were used to calculate cumulative spring basin discharge, total winter snow accumulation, blowing snow transport and sublimation, cumulative infiltration, and spring surface depression storage status. From these simulations, spring streamflow volumes decreased by 2% with complete conversion to agriculture and by 79% with complete restoration of wetlands; conversely it increased by 41% with complete conversion to forest cover and by 117% with complete wetland drainage. The greatest sensitivity was to further drainage of wetlands which substantially increased streamflow. Additional sensitivity analysis of scenarios on basin streamflow using historical (29-year periods: 1965-82 and 1993-2005) meteorology and initial conditions and current land use was carried out. Results showed that the effects of land use change and wetland drainage alteration on cumulative basin spring discharge volume and peak daily spring discharge were highly variable from year to year and depended on the flow condition. For both forest conversion and agricultural conversion and wetland drainage scenarios increased the long-term average peak discharge from current conditions, whereas wetland restoration reduced it. Forest conversion, agricultural conversion and wetland drainage scenarios increased the long-term average spring discharge volume by 1%, 19%, and 36% respectively; whilst the wetland restoration scenario reduced volumes by 45%.

Several recommendations were made regarding the modelling challenges facing by this study and value of local meteorological data collection and using a LiDAR generated DEM for Prairie hydrological modelling purposes. It is recommended that similar studies be conducted in other geographic areas of the prairies where climate, soils, wetland configuration and drainage may produce differing results.

c) Project Work Undertaken

All topics used experimental archives to describe processes and support modelling of both cold and warm season hydrological processes and were employed to examine how these processes influence the development, persistence and cessation of water resource drought in the Canadian prairies. Observations and model results from the St Denis National Wildlife Area in the central prairies were compared to archives from the Bad Lake IHD Research Basin and the Lethbridge Ameriflux station in the southern prairies for a range of conditions from wet to extremely dry. Observations from Smith Creek Research Basin in eastern Saskatchewan provided a testbed of for how the hydrology of a wetland basin behaves under wet and dry conditions. Results from snowmelt and evaporation process studies supported the development of the hydrological model. Process-based modelling was at resolutions that define the dynamics within small ‘headwater’ prairie basins and permitted a detailed examination of drought hydrology processes and the scale of their interaction. These results were upscaled to inform the parameterization of larger scale modelling efforts for both hydrology and land surface schemes coupled to atmospheric models.

1.2 Explain how the project milestones and deliverables originally proposed were met.

Original Milestones:

1. Data rescue and review effort of previous and current research basin observational records.
2. Remote sensing imagery will be employed to estimate ET rates using the method of Granger.
3. Supplemental observations will be undertaken for surface snow and exposed frozen soil ET rates using a eddy correlation system.
4. Small-scale Modelling will use a new physically based model of the hydrological cycle, the Cold Regions Hydrological Model (CRHM). New modules suited for drought analysis (surface snow ET, ET from frozen soils) will be developed and tested for CRHM.
5. CRHM module development and verification will be used to suggest and detail improvements to snow, surface and soil processes that can be implemented in the large scale model WATCLASS.

Milestone 1 was met as described in Section 1.1 from Bad Lake and St Denis research sites.

Milestone 2 was used in the spatial variation of ET study at St Denis (Armstrong et al., in preparation)

Milestone 3 was met with a winter and summer field programme at St Denis (Fang, Armstrong theses).

Milestone 4 was met by development of CRHM and its application and testing at Bad Lake, St Denis and Lethbridge.

Milestone 5 was changed when it was realized that CRHM could be run as a large scale model. So CRHM was run across the prairies instead of Watclass as described in Section 1.1

1.3 Describe the tangible results or the measurable outputs generated by the project and how these results have been taken up by user groups for policy development or operational improvements.

A major tangible result of this project is that there is a hydrological memory to drought or non-drought conditions that is enhanced by additional wetland storage volume in a basin. This result has been taken up by Ducks Unlimited Canada and provincial water departments as a reason for wetland conservation. The ability to simulate the streamflow of prairie basins from first principles has been funded by all prairie provinces, and the federal government for a demonstration project on Smith Creek, Sask. This project has for the first time, shown how wetland water storage controls streamflow generation in the Prairie landscape and the implications of wetland drainage on streamflow.

1.6 Describe how the work of co-investigators was integrated or coordinated.

Pomeroy coordinated project co-investigators (Martz, Shook) on this project and it was integrated through joint publications.

Collaborations were maintained with network co-investigators:

-Hayashi in transferring techniques from CRHM to his modelling efforts with the Versatile Soil Moisture Model.

-Pietroniro in transferring techniques from CRHM to his modelling efforts with MESH across the prairies. Particular progress was made in blowing snow algorithms for MESH and in how to characterise wetlands

-van der Kamp – in discussions on how to characterise wetland volume area relationships using LiDAR.

-Woodbury – in plans to couple CRHM to a physically based groundwater model.

1.7 Describe the participation of government (federal, provincial or local), university, industry or foreign researchers in the project.

Collaboration from Environment Canada through data provision from St Denis was crucial for this project. Results were made available to EC.

Collaborations were maintained with the following Environment Canada scientists:

-Pietroniro in transferring techniques from CRHM to his modelling efforts with MESH across the prairies. Particular progress was made in blowing snow algorithms for MESH and in how to characterise wetlands

-van der Kamp – in discussions on how to characterise wetland volume area relationships using LiDAR.

2.0 Impact

2.1 Describe in broad terms how your work has contributed to the overall objectives of DRI and to our scientific understanding of drought.

A hydrological drought sequence was proposed. This sequence lags meteorological drought due to soil moisture and snow accumulation controlling field scale runoff generation and wetland storage of runoff controlling small basin discharge generation. Discharge from small basins is not completely attenuated until wetland water storage, soil moisture and snowpack are all at low levels. Based on field studies and fine scale modelling studies, a comprehensive hydrological model has been developed that contains physically based blowing snow, snowmelt, infiltration to frozen soils, infiltration to non-frozen soils, evapotranspiration, wetland storage and runoff components. It has been applied across the Prairie region during drought and non-drought periods to evaluate the regional differences in the effects of drought on hydrology and the temporal pattern of hydrological drought. This is the first known calculation of small basin streamflow across the Prairies using a physically based model and the first Prairie-wide simulation of evapotranspiration that takes into account the full hydrological inputs to soil moisture. It is the first comprehensive description of local scale hydrological drought across the Canadian Prairies.

2.2 Describe the significance / impact of the results in terms of some or all of the following areas:

- **The impact of the project on government policy development (federal, provincial or municipal);**

The results are being used to develop local and provincial wetland conservation strategies in Saskatchewan, Alberta and Manitoba in light of variability due to drainage and drought.

- **How the project has expanded contacts in partner organizations, or increased cross-disciplinary cooperation;**

Yes, it has resulted in contacts with Ducks Unlimited, the Prairie Habitat Joint Venture Policy Committee and the provincial governments of Saskatchewan, Alberta and Manitoba.

- **Whether and how it has enhanced or improved the reliability of predictive methods related to the science;**

Hydrological models have been improved as a result of DRI such that they can predict prairie hydrology from small basins.

- **The impact of the project on your own institution (e.g. helped attract new students or personnel);**

The study has substantially improved graduate student numbers and training at U of S and has strengthened the Centre for Hydrology and its collaboration with NHRC. It has helped attract a CERC in Water Security whose research focus is hydrology.

- **Whether it has improved or increased the acquisition of funds from other agencies, or led to new partnerships;**

Yes, it has helped in obtaining funding from SWA, MWS, PFRA, DUC, PPWB

- **Any links with international initiatives and the potential impact of these (e.g. profile of Canadian science, influence on international programs);**

It is a Canadian contribution to the International Decade for Prediction in Ungauged Basins (PUB) of IAHS (IUGG).

- **Any commercial or social application the results may have had or could have;**

n/a

- **The anticipated impact of the work on Canadians and their well-being;**

Improved farm and community scale water supply estimation.

4.0 Reverse Impact Statement

4.1 Provide a reverse impact statement, describing what would have happened in terms of the project, the resulting science and the impacts on users/stakeholders, if the work had not been funded by CFCAS.

We would not have a complete understanding of Canadian Prairie hydrology nor a working hydrological model that can describe the hydrology of small prairie basins. We would not understand the dynamics nor the progression of hydrological drought on the Prairies.

5.0 Follow-on Science

5.1. Based on the findings of your research identify any outstanding scientific questions that need to be addressed in future drought studies.

We need to be able to model large scale Prairie hydrology over the major river basins using physically based and hydrologically correct models. This is crucial in order to determine the resiliency of water apportionment agreements during drought.

6.0 Dissemination

6.1 Provide information on the dissemination of the research results (publications, including journal names and whether refereed), conference contributions, seminars, workshops or videos, websites or other methods of transferring the results.

Books

Yilmaz, K., Yucel, I., Gupta, H.V., Wagener, T., Yang, D., Savenijie, H., Neale, C., Kunstmann, H. and J.W. Pomeroy. 2009. *New Approaches to Hydrological Prediction in Data Sparse Regions*. IAHS Publ. No.333. IAHS Press Wallingford. 342 p.

The Expert Panel on Groundwater. 2009. *The Sustainable Management of Groundwater in Canada.* Council of Canadian Academies, Ottawa. 254 p. (Pomeroy member of panel)

Hopkinson, C., Pietroniro, A. and J.W. Pomeroy. 2008 *HYDROSCAN: Airborne Laser Mapping of Hydrological Features and Resources*. Canadian Water Resources Association, Cambridge, Ontario. 376 p.

Spence, C., Pomeroy, J.W. and A. Pietroniro. 2005. *Prediction in Ungauged Basins, Approaches for Canada's Cold Regions*. Canadian Water Resources Association, Cambridge, Ontario. 218 p.

Peer-reviewed journal articles

Armstrong, R.N. Pomeroy, J.W. and Martz, L.W. 2008. Evaluation of three evaporation estimation methods in a Canadian prairie landscape. *Hydrological Processes*, 22(15), 2801-2815.

Armstrong, R.N. Pomeroy, J.W. and Martz, L.W. 2010. Estimating Evaporation in a Prairie Landscape under Drought Conditions. *Canadian Water Resources Journal*, 35(2), 173-186.

Fang, X. and Pomeroy, J.W. 2007. Snowmelt runoff sensitivity analysis to drought on the Canadian prairies. Hydrological Processes 21: 2594-2609.

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King, J.C., Pomeroy, J.W., Gray, D.M., Fierz, C., Föhn, P., Harding, R.J., Jordan, R.E., Martin, E. and C. Plüss. 2008. Snow-atmosphere energy and mass balance. In, (eds. R. Armstrong, E Brun) *Snow and Climate, Physical Processes, Surface Energy Exchange and Modelling*. Cambridge University Press, Cambridge, UK. 70-124.

MacDonald, J. and J.W. Pomeroy. 2008. Gauge undercatch of two common snowfall gauges in a prairie environment. *Proceedings of the Eastern Snow Conference*, 64. 119-126.

Pomeroy, J.W. 2007. Cold regions hydrology, snow and PUB. In, *Predictions in Ungauged Basins: PUB Kick-off*. IAHS Publ. No. 309. IAHS Press, Wallingford, UK. 85-91.

Pomeroy, J.W., de Boer, D. and L. Martz. 2007. Hydrology and water resources. In, (eds. B. Thraves, M. Lewry, J Dale, H. Schlichtmann) *Saskatchewan: Geographic Perspectives*. Canadian Plains Research Centre, Regina, SK. 63-80.

Pomeroy, J.W. R. J. Granger, N. R. Hedstrom, D. M. Gray, J. Elliott, A. Pietroniro and J. R Janowicz. 2005. The process hydrology approach to improving prediction to ungauged basins in Canada. In, (eds. C. Spence, J. Pomeroy and A. Pietroniro) *Prediction in Ungauged Basins, Approaches for Canada's Cold Regions*. Canadian Water Resources Association, Cambridge, 67-95.

Pomeroy, J.W., Gray, DM, Brown, T., Hedstrom, N.H., Quinton, W.L., Granger, R.J. and S.K. Carey. 2007. The cold regions hydrological model: a platform for basing process representation and model structure on physical evidence. *Hydrological Processes*, 21, 2650-2667.

Shook, K.R. and J.W. Pomeroy, 2010. Hydrological effects of the temporal variability of the multiscaling of snowfall on the Canadian prairies, Hydrol. Earth Syst. Sci., 14, 1195–1203, 2010 ,doi:10.5194/hess-14-1195-2010.

Shook, K.R. and J.W. Pomeroy, 2011. Synthesis of Incoming Shortwave Radiation for Hydrological Simulation. Hydrology Research, in press.

Spence, C., J.W. Pomeroy and A. Pietroniro. 2006. Canadian PUB planning and implementation. *Predictions in Ungauged Basins: Promise and Progress* (Proceedings of Symposium S7 held during the Seventh IAHS Scientific Assembly at Foz do Iguaçu, Brazil, April 2005). IAHS Publ. 303, 2006, IAHS Press, Wallingford, UK. 487-491.

Stewart, R., Pomeroy, J.W., and R. Lawford. 2008. A drought research initiative for the Canadian Prairies. *CMOS Bulletin SCMO*, 36(3), 87-96.

The Expert Panel on Groundwater. 2009. *The Sustainable Management of Groundwater in Canada.* Council of Canadian Academies, Ottawa. 254 p. (Pomeroy as member of panel and wrote Prairie chapter and climate change, surface hydrology and drought material)

Yang, J., Yau, M.K., Fang, X. and Pomeroy, J.W. 2010. A triple-moment blowing snow-atmospheric model and its application in computing the seasonal wintertime snow mass budget. Hydrology and Earth System Sciences 14: 1063-1079.

Thesis

Fang, X. 2007. Snow Hydrology of Canadian Prairie Droughts: Model Development and Application. M.Sc. Thesis, University of Saskatchewan, Saskatoon, Saskatchewan. 172pp.

Armstrong, R.N. 2011. Spatial variability of Prairie evapotranspiration in droughts. PhD Thesis, University of Saskatchewan, Saskatoon. in progress.

Reports

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

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Pomeroy, J.W., Fang, X. and B. Williams. 2009. *Impact of Climate Change on Saskatchewan's Water Resources.* Centre for Hydrology Report No. 6. Centre for Hydrology, University of Saskatchewan, Saskatoon. 46 p.

Sauchyn, D., Barrow, E., Fang, X., Henderson, N., Johnston, M., Pomeroy, J.W., Thorpe, J., Wheaton, E. and Williams, B. 2009. Saskatchewan's Natural Capital in a Changing Climate: An Assessment Of Impacts And Adaptation. Report to Saskatchewan Ministry of Environment from the Prairie Adaptation Research Collaborative, 162 pp.

Conference presentations

Armstrong, R., Pomeroy, J.W. and Martz, L. 2008. Examining the Spatial Variability of Actual Evaporation under Clear Skies (oral). Canadian Geophysical Union Meeting, Banff, 2008

Armstrong, R., Pomeroy, J.W. and Martz, L. 2009. Variations in Growing Season Actual Evapotranspiration Across Climatological Gradients in the Prairie Region of Western Canada. AGU Ecohydrology Chapman Conference, Sun Valley, Idaho, Oct. 2009.

Armstrong, R., Pomeroy, J.W. and Martz, L. 2007. Evaluation of Evaporation Estimation Methods During a Summer Drying Period (Poster). Canadian Geophysical Union Meeting, St. John's, NFLD, 2007.

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Fang, X. and Pomeroy, J.W. 2007. Effects of Drought on Canadian Prairie Wetland Snowmelt Hydrology. CMOS-CGU-AMS Congress 2007: Air Ocean, Earth and Ice on the Rock, Canadian Geophysical Union 33rd Annual Meeting, St. John's, NL, May 28 – June 1, 2007.

Fang, X., Pomeroy, J.W., Brown, T., Guo, X. and Westbrook, C. 2009. Hydrological Modelliing of a Canadian Prairie Wetland Basin (Poster). 2009 American Geophysical Union and Canadian Geophysical Union Joint Assembly, Toronto, Canada, May 24-27, 2009.

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Shook, K.R. and J.W. Pomeroy, 2008. Stationarity analyses of historical Canadian prairie weather data. Why do statistical tests give differing answers?, CGU, May 2008

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Invited Presentations

Pomeroy, J.W. 2010. ***Water prescriptions for a dry land – How the West can prepare for drought*. Partnership Group on Sciences and Engineering "Bacon and Eggheads"** Invited talk to MPs and Senators, Parliament of Canada, Ottawa, May 2010.

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Armstrong, R., J.W. Pomeroy and L. Martz, 2007. Problems in Estimating Evaporation in Prairie Environments. DRI Evap Workshop, Saskatoon, 2007

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DRI Prairie Hydrology Workshop
Hilton Garden Inn, Saskatoon, Sask. 18 November 2009

About 80 people from the three Prairie Provinces, British Columbia and Ontario attended this one day workshop in Saskatoon. The workshop was organized by the Centre for Hydrology of the University of Saskatchewan as part of its contribution to the Drought Research Initiative and to promote scientific exchange on aspects of prairie hydrology with various science organizations with an interest in the Prairie region.

The workshop talks were organized around themes of *Drought and Climate Change*, *Distinctive Aspects of Prairie Hydrology* and *Prairie Water Availability* with a total of 17 presentations. Presenters represented scientists, managers, academics and graduate students from Environment Canada, University of Manitoba, University of Saskatchewan, University of Regina, Guelph University, University of Alberta, Agriculture and Agrifood Canada and the Saskatchewan Watershed Authority. The agenda with presenters and their presentation titles is listed at the end of this report.

Three discussion sessions focused on each of the themes. The first discussion on *Drought and Climate Change* centred on three questions:
i) what are the major uncertainties in your understanding that need to be addressed
ii) what are the problems in observation systems that would improve your results
iii) what are the next steps in predicting drought and climate change hydrology in the Prairies?
Areas of uncertainty included meteorological input data, streamflow calibration data, understanding of pothole pond runoff generation, and evapotranspiration. Problems in observing systems included lack of soil moisture and radiation observations, insufficient snowfall, snowpack and rainfall observations, sparse hydrometric network and uneven availability of data that has been collected. Next steps in prediction included linking small scale to large scale hydrology in models in order to estimate contributing area, better incorporation of uncertainty in modelling, better data assimilation in models and including landscape change in long term modelling.

The second discussion on *Distinctive Aspects of Prairie Hydrology* centred on three questions:
i) what are the known deficiencies in your research that are not related to data?
ii) how are you dealing with these problems?
iii) what is holding you back from successfully dealing with these deficiencies?
Known deficiencies in research include difficulty in parameterising fill/spill (including initial states), dealing with spatial variability of parameters, necessity of improvements in modelling, and unknown spatial applicability of precipitation correction equations. Deficiencies were addressed by making assumptions, investigating scales of importance, and by calibration where necessary. Factors holding back progress included personal conflicts, scaling issues (particularly for modelling of medium/large basins), and the difficulty of understanding complex phenomena such as the fill/spill the very large number of wetlands at basin scales.

The third discussion on *Prairie Water Availability* centred on issues of water use and availability from both basin scale studies across the Prairies and Saskatchewan based studies led by the Saskatchewan Watershed Authority. Use of Saskatchewan waters is complex to document and distinctions must be made between allocation, use and actual water removal from the surface hydrological system. The SWA study includes a Water Use Assessment Project with a pilot project on the Swift Current Creek basin. The Groundwater Availability Project will focus on regional aquifer mapping and recharge estimation. The Surface Water Availability Project will focus initially on the Souris River basin in respect to hydroclimatic trend analysis, natural flow trend analysis, and water supply availability for major basins.

6.3 Comment on any outreach or public information activities, including press interviews or other media interest or reports. Has the project helped to popularize science or increase public awareness?

"Whatcha going do when the well runs dry" Western Producer.
Various CBC interviews. Interviews, Saskatoon Star-Phoenix, Ottawa Citizen, Edmonton Journal, Calgary Herald.

7.0 Training

7.1 Quantify student and PDF involvement (indicate the level of each: undergraduate, masters, doctorate or PDF). If possible and within the Federal Privacy Act rules governing the collection of personal information, provide a general indication of their subsequent employment (i.e., university, industry, government, other, etc.), and indicate whether the employment was foreign or domestic.

Dr. Kevin Shook, Research Fellow CRHM modelling. Working for Centre for Hydrology.
Mr. Robert Armstrong, PhD student. Evapotranspiration. Working for AAFC.
Mr. Xing Fang, MSc student. Snow dynamics in drought.. Working for Centre for Hydrology.