Improving our Understanding and Prediction of Hydrology and Water Resources in Western Canada

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and students
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www.usask.ca/hydrology
Centre for Hydrology Research

- **Water Resources and Climate Change.** Research on global water and energy cycling, hydrology in climate models, snow and ice, hydrological models.

- **Prairie, Boreal and Arctic Hydrology.** Research on the Saskatchewan River Basin, Mackenzie River Basin, drought, wetlands, groundwater, soil water relationships, hydroecology, forest hydrology, cold regions hydrology.

- **Safe Water.** Research on drinking water toxicology, aquatic biology, agricultural water quality, water pathways, pollutant effects on aquatic ecosystem health, development of software tools to relate changes in water quality and quantity to human development.

- **Effects of the Mining Sector on Water Resources.** Research on mine reclamation with respect to water quality and quantity on uranium mines, tar sands, northern development. Research on the effects of the discharges of mine effluents on aquatic biota and water quality.
Major Issues for Hydrology in Western Canada

- Cold regions hydrology - mountain and northern derived runoff dominates large rivers
- Prairie hydrology – source of soil moisture, groundwater and local streams, lakes and ponds
- Change
  - Climate Change – warming, wetting, drying, extremes
    - Drought
    - Flooding
  - Land Use Change –
    - Agricultural cropping, tillage and drainage
    - Forest clearing and change from harvesting and disease
Critical Problem

Despite +40 years of hydrology research…

increased water use, better defined ecosystem needs and unprecedented changes in water and climate systems mean that the current understanding and predictive capability of western Canadian hydrology is inadequate to answer current and near future water resource management questions.
Overview: CRC Research at Centre for Hydrology

- **OBJECTIVE**
  To better understand, describe and model the hydrological cycle and its underlying processes in the Prairies, Forests and Mountains of Western Canada.

- **FOCUS** – evaluation and sensitivity to variation of climate and land use of:
  - Snow Accumulation and Redistribution
  - Infiltration to Frozen Soils
  - Snowmelt Runoff
  - Evaporation
  - Rainfall
  - Streamflow and water storage
  - Integrated basin response

- **Approach**
  - Physically Based Hydrological Modelling
  - Improved observational methods and instrumentation
  - Intensive field observations of physical processes
Programme Elements

- **IP3 – Improved Processes and Parameterisation for Prediction in Cold Regions**, CFCAS Network for cold regions hydrology and meteorology
- **DRI – Drought Research Initiative**, CFCAS Network for dynamical studies of prairie drought
- **SGI Canada Hydrometeorology Programme** – extreme prairie hydrometeorology and anticipated changes due to a changing climate
- **Prairie Hydrological Model Study** – land use and drainage change in a prairie basin and impacts on streamflow and wetlands
Improved Processes & Parameterisation
for Prediction in Cold Regions

A Research Network of the

Canadian Foundation for Climate and Atmospheric Sciences (CFCAS)
Fondation canadienne pour les sciences du climat et de l’atmosphère (FCSCA)

http://www.usask.ca/ip3

John Pomeroy, (Saskatchewan), Sean Carey (Carleton), Richard Essery (Wales), Raoul Granger (NWRI/EC), Masaki Hayashi (Calgary), Rick Janowicz (Yukon Environment), Phil Marsh (Saskatchewan/EC), Scott Munro (Toronto), Alain Pietroniro (Saskatchewan/EC), William Quinton (Wilfrid Laurier), Ken Snelgrove (Newfoundland), Ric Soulis (Waterloo), Chris Spence (Saskatchewan/EC), Diana Verseghy (Waterloo/EC)

and 16 collaborators from

Environment Canada, Alberta Environment, Indian & Northern Affairs Canada, Natural Resources Canada, Univ Guelph, Univ Idaho, Univ Saskatchewan, Univ Western Ontario, Univ Waterloo, USDA-ARS
IP3 – Goals and Theme Structure

- **Theme 1 Processes:** Advance our understanding of cold regions hydrometeorological processes
- **Theme 2 Parameterisation** Develop mathematical parameterisation of cold regions processes for small to medium scales
- **Theme 3 Prediction** Evaluate and demonstrate improved hydrological and atmospheric prediction at regional and smaller scales in the cold regions of Canada
- **Ultimately** – contribute to multiscale assessment of coupled climate system, weather and water resources in cold regions
Research Basins

- Havikpak Creek, taiga woodland
- Trail Valley Creek, arctic tundra
- Baker Creek, Subarctic shield lakes
- Wolf Creek, subarctic tundra cordillera
- Scotty Creek, permafrost wetlands
- Peyto Creek, glacierized alpine
- Lake O’Hara, wet alpine
- Marmot Creek, Dry subalpine

IP3
IP3 Background

- Declining annual or earlier peak discharge in many cold regions streams and rivers (Rockies and Northern Canada)
- Increasing consumptive use of Rocky Mountain water in Prairie Provinces
- Uncertainty in engineering design for small to medium size ‘ungauged’ basins undergoing resource development and restoration (oil & gas, diamond mines, other mines)
- Opportunity to couple atmospheric-hydrological models with cold regions components for forecasting weather generation, streamflow to Arctic Ocean, flooding, improved climatology
Date of Spring Freshet

Hay River at Hay River
Date of Annual Freshet Peak

Mackenzie River at Fort Simpson
Date of Annual Peak Discharge

Courtesy Derek Faria, INAC
- Hydrology Change: Decline of natural flow by 1.2 billion m³ over 90 years (-12%)
- Consumption of 7%-42% of natural flows during last 15 years
- Combined: Actual decline of 1.1 billion m³ over 30 years (-15%) in actual flow,
- Combined: Actual decline of 4 billion m³ over 90 years (-40%) in actual flow,
- Note 70% of actual decline is due to consumption, 30% of decline is due to hydrology
South Saskatchewan River is most strongly affected by Gardiner Dam.

The graph shows the discharge (m$^3$ s$^{-1}$) of the South Saskatchewan River at Saskatoon hydrometric station 05HG001 from 1912 to 1993. The discharge data is divided into two periods: 1912 - 1958 and 1967 - 1993. The months June and July have the highest discharge for both periods, with peaks of approximately 900 m$^3$ s$^{-1}$.
Marmot Creek Research Basin

- Kananaskis Valley, Alberta 1450-2886 m.a.s.l.
- Headwaters of Bow River
- +600 mm precipitation
- 70% snowfall
- ~50% runoff from snow

Classic mountain water resources
Alpine Blowing Snow: Flow Separation

FOV 24
Trefl=-13 Tatm=-5 Rh=64% Dst=2.4
22/01/06 14:34:40 -40 - +120 e=0.98

°C
Linear simulation of westerly flow over Wolf Creek, Yukon

Essery and Pomeroy, *in preparation*
Simulation of Hillslope Snowdrift

Distributed Blowing Snow Model - Essery, Li & Pomeroy 1999 *Hydrological Processes*
Snow Interception

- Leaf + stem area index (surface to collect snow)
- Air temperature (elasticity of branch, adhesion and cohesion of snow)
- Wind speed (particle trajectory, impact rate, branch bending, scouring)
- Unloading from warm and windy events

Hedstrom and Pomeroy, 1998
Intercepted Snow Sublimation

Pomeroy, Parviainen, Hedstrom, Gray 1998  *Hydrological Processes*
Suggests that 61% of snowfall was sublimated from intercepted snow
Snowmelt

- Improved Methods to Estimate Short and Longwave Radiation
- Terrain Effects on Radiation
- Terrain Effects on Turbulent Transfer
- Forest Canopies – radiation effects
- Combined Forest Canopy and Slope Effects - radiation
Turbulence generation mechanisms in mountains

- Upper level winds
  - Strong shear zone
  - Transported turbulence
  - Valley winds
  - Surface winds (internal B-L)
  - Flux tower in clearing

- Tributary valley winds
Roughness Length ($z_{0m}$)

\[
\frac{U}{u^*} = \frac{1}{k} \left[ \ln \left( \frac{z}{z_{0m}} \right) - \psi_m(\zeta) \right] \quad 0 < \zeta < 0.1
\]

Helgason and Pomeroy, in preparation
Percent increase in longwave irradiance due to terrain emission due to sky view factor ($V_f$) and surface temperature ($T_s$). Air temperature is 0°C and the clear sky emissivity is 0.65.

Sicart et al. 2006 *Hydrological Processes*
Psychrometric Outgoing Longwave Formulation for Snow

\[ T_s = T_a + \frac{\varepsilon (LW \downarrow - \sigma T_a^4) + L [Q_a - Q_{sat}(T_a, P_s)] \rho / r_a}{\varepsilon \sigma T_a^3 + (c_p + L \Delta) \rho / r_a} \]

Pomeroy et al., in preparation
Solar Radiation to Snow beneath Shrubs and Trees

Tall Shrubs

Marmot Creek level forest

Graphs showing solar radiation (SW) in W/m² over days from 2003 and 2005.
Solar Transmission through Sloping Forest Canopies

Transmissivity is a function of LAI, Foliage inclination, Crown coverage, Slope, Aspect, Solar azimuth, Solar elevation

Ellis and Pomeroy, 2007
Hot Canopy and Trunks Increase Forest Longwave Radiation

JD86 Cloudy

JD87 Sunny

Rowlands, Pomeroy, Hardy, Marks, Link, Essery 2002  *Proc. Eastern Snow Conference*
Net Radiation to Snowmelt on 25° Forest Slopes, Marmot Creek Research Basin

Cumulative Net Radiation MJ m⁻²

- Southeast-Facing Forest
- Level Forest
- North-Facing Forest
- Clearing

South Facing Forest Slope

Level & North Facing Forest Slopes

Level Clearing

Ellis, Pomeroy, Essery, Link submission to Canadian Journal of Forest Research
Synchronised Melt – high discharge event

Cumulative Melt Energy (kJ)

Julian Day - 1995

Shrub Tundra

Forest

Alpine
Sequential Melt – low discharge event

Cumulative Melt Energy (kJ)

Shrub Tundra

Alpine

Forest

Julian Days - 1998
Cold Regions Hydrology Model at basin scale
Land surface hydrology model evaluation and development
Evaluation of GEM-LAM and CRCM

Prediction
Cold Regions Hydrology on Complex Terrain

- Figure showing depth and average depth over days for Valley, South facing, North facing, and Plateau.
- Bar chart showing mean energy (W/m²) for Valley Bottom, South Face, and North Face.
- Image indicating 20° slopes on the South Face, Valley Bottom, and North Face.
Scaling

Resolution
- 1 m
- 100 m
- 100 m - 2 km
- 2 - 10 km
- 10 km - 10 km

Landscape type
- Pattern/tile
- Grid/small basin
- Multi-grid/medium basin
- Multi-grid
- Mesoscale
- Regional;

Tile/HRU
- Point
- Hillslope

Prediction
- Terrestrial
- Open Water
- Snow and Ice

Parametrization
- Terrestrial
- Open Water
- Snow and Ice

Process
- Terrestrial
- Open Water
- Snow and Ice

MODELS
- MESH
- CHRM
- MESH
- CHRM
- MESH
- CEOP Hydrology
- CEOP Hydrology

IP3 Scaling Methodology

Previous LSS Scaling Methodology

Integrating the TOP DOWN and BOTTOM UP approaches

Quinton CFCAS Study

MAGS
Modélisation Environnementale Communautaire, MEC

- Atmospheric model (3D) with its own surface scheme (1D)
- Extracted atmospheric model forcings
- Hydrological model (lumped or 2D) with its own LSS
- “On-line” mode
- “Off-line” mode
- Surface scheme (1D)
- Hydrological model (2D)
THE DRI TEAM

- **Co-leads:**
  - Ron Stewart (*McGill*) and John Pomeroy (*Sask*)

- **Network Manager:**
  - Rick Lawford (Manitoba)

- **Information Managers:**
  - Matt Regier (HAL, EC), Patrice Constance (Ouranos)

- **Investigators (13):**

- **Collaborators (14):**
  - Boer (*MSC*), Caya (*Ouranos*), Derome (*McGill*), Derksen (*MSC*), Donaldson (*MSC*), Granger (*NHRC*), Martz (*Sask*), Raddatz (*MSC*), Ritchie (*MSC*), Shabbar (*MSC*), Sills (*MSC*), Smith (*MSC*), Szeto (*MSC*), Walker (*MSC*)

- Research expertise covers critical areas for DRI
- Solid track record of working together as well as being in and leading networks
OBJECTIVE OF DRI

To better understand the physical characteristics of and processes influencing Canadian Prairie droughts, and to contribute to their better prediction, through a focus on the recent severe drought that began in 1999.
1. **Quantify the physical features,**
   - flows of water and energy into and out of the region, and
   - storage and redistribution within the region

2. **Improve the understanding** of processes and feedbacks governing the
   - formation,
   - evolution,
   - cessation and
   - structure of the drought

3. Assess and reduce uncertainties in the prediction of drought

4. Compare the similarities and differences of current drought to previous droughts and those in other regions

5. **Apply our progress to address critical issues of importance to society**
1. QUANTIFY THE DROUGHT

Observational Networks

GRACE satellite

Surface Storage Change

Wells in South Saskatchewan
2. UNDERSTAND THE DROUGHT

Vertical Scale

Storage of Water

Drought

Non-drought

Horizontal Flux of Water

Drought

Non-drought
3. SIMULATE AND PREDICT THE DROUGHT

Global Climate model

AGCM3 200 km

CRCM4 45 km

GEM 15 km

GEM-LAM 2.5 km

CLASS, WATCLASS / MESH 15 km

CPM, CRHM 1 km

Forcings and Initial conditions

Process Parameterizations

LDAS data flow

NWP Model

Cloud-Resolving Model

Global Reanalysis

Regional Climate Model

Land Surface Hydrology Models

Regional Analysis & obs

(for LDAS)

Hydrological Process Models

LDAS
Effect of Blowing Snow Sublimation on Prairie Snow Supply (mm SWE)

<table>
<thead>
<tr>
<th>Location</th>
<th>Stubble-field</th>
<th>Fallow-field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calgary</td>
<td>19.7</td>
<td>37.5</td>
</tr>
<tr>
<td>Peace River</td>
<td>6.6</td>
<td>7.6</td>
</tr>
<tr>
<td>Swift Current</td>
<td>28.2</td>
<td>37.8</td>
</tr>
<tr>
<td>Prince Albert</td>
<td>24.9</td>
<td>29.6</td>
</tr>
<tr>
<td>Regina</td>
<td>39.4</td>
<td>48.1</td>
</tr>
<tr>
<td>Yorkton</td>
<td>18.6</td>
<td>28.6</td>
</tr>
<tr>
<td>Portage</td>
<td>23.5</td>
<td>33.8</td>
</tr>
<tr>
<td>Winnipeg</td>
<td>27.4</td>
<td>36.5</td>
</tr>
</tbody>
</table>

Sensitivity of Blowing Snow Sublimation to Drought

- Drought winters are presumed to have lower snowfall, increased air temperatures, lower vegetation heights (shorter grass or fallow), and drier soils than normal winters.
- Sensitivity of modelled blowing snow to these changes was tested using the Bad Lake archive.
- Note that the 1999-2004 drought sometimes displayed colder winters* than normal.

*winter is Oct-April
Effect of Drier Winter on Blowing Snow Sublimation and Snow Accumulation

- SWE (Normal)
- SWE (50% Decrease in Snowfall)
- Sublimation (Normal)
- Sublimation (50% Decrease in Snowfall)

mm water equivalent

Spatially Distributed Snow Redistribution

Elevation (m)
- 541 - 547
- 547 - 553
- 553 - 558
- 558 - 564
- 564 - 570
- 570 - 575
- 575 - 581
- 581 - 587
- 587 - 593

Vegetation Height (m)
- 0 - 1
- 1 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- 5 - 6
- 6 - 7
- 7 - 8
- 8 - 10

Snow mass balance equation

\[
\frac{\partial S}{\partial t} = S_f - q_s - \nabla \cdot q_t
\]

St Denis, Saskatchewan
Results – Spatially distributed SWE

Jan. 03, 2006

Spatially distributed SWE cont’
Spatially distributed SWE cont’
Spatially distributed SWE cont’
Spatially distributed SWE cont’
Spatially distributed SWE cont’
Spatially distributed SWE cont’
Spatially distributed SWE cont’
Spatially distributed SWE cont’
Spatial Pattern of Blowing Snow Sublimation

Sublimation (mm)

- 0.1 - 1.1
- 1.1 - 2.1
- 2.1 - 3.1
- 3.1 - 4.2
- 4.2 - 5.2
- 5.2 - 6.2
- 6.2 - 7.2
- 7.2 - 8.3
- 8.3 - 9.3
Distributed vs Aggregated Simulation

Cumulative Pre-melt SWE on Mar. 27, 2006

Pre-melt Snow Accumulation (mm)

<table>
<thead>
<tr>
<th>Location</th>
<th>Observed</th>
<th>Distributed Simulated</th>
<th>Aggregated Simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stubble Hilltop</td>
<td></td>
<td></td>
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<tr>
<td>Stubble Slope</td>
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<tr>
<td>Stubble Level</td>
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<tr>
<td>Stubble Valley</td>
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<tr>
<td>Grass Level</td>
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<td></td>
<td></td>
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<tr>
<td>Grass Valley</td>
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<td></td>
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<tr>
<td>Wetland</td>
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</tbody>
</table>

| MB (Distributed) | 0.5     | 0.31                  | 0.26                 |
| MB (Aggregated)  | -0.37   | -0.36                 | -0.11                |
|                  |         |                       | 0.05                 |
|                  |         |                       | -0.02                |
|                  |         |                       | 0.16                 |
|                  |         |                       | 0.07                 |
|                  |         |                       | -0.09                |
Bad Lake – Creighton Tributary Water Balance

With 30% Summer Fallow

Fallow | Stubble | Coulee | Basin

Pomeroy, De Boer, Martz (2007)
Changed to Continuous Grain Cropping

mm water equivalent

% Change

Stubble | Coulee | Basin

-400 -300 -200 -100 0 100 200 300 400 500

Snowfall | Rainfall | Runoff | Sublimation | Drifting Snow | Evaporation

runoff infiltration snowmelt sublimation drift evaporation snowfall rainfall

% Change

-40 -20 0 20 40 60
Snowmelt Runoff over Frozen Soils

Semi-arid SW Saskatchewan

Soil moisture is FALL soil moisture

Snowmelt runoff is Spring

Physically based Infiltration equations (Zhao & Gray, 1999)

Cold Regions Hydrological Model
Wetter and then Drier: Surprise!

- Toyra et al. 2004: median of three most reliable climate change scenarios (ECHAM4, HadCM3 and NCAR-PCM) suggest a rise in annual winter temperature and precipitation from the 1961-1990 average of 2.6 °C and 11% by 2050, and to 4.7 °C and 15.5% by 2080.

- Using this median scenario in Bad Lake Research Basin results in a 24% rise in 2050 and 37% drop in 2080, compared to the basin runoff (54 mm) in spring of 1975.
This was only a sampling of results, other work

- Actual evaporation calculation for complex environments – Armstrong
- Snowmelt infiltration chemistry – Lilbaek
- Acoustic measurement of snow depth and density – Kinar
- Spatial distribution of land surface hydrology models in Arctic mountain basins - Dornes
- Snow covered area depletion in mountains – DeBeer
- Shrub tundra snowmelt - Bewley
- Interception and unloading of mountain snow – MacDonald

- Cold Regions Hydrological Model Development – Brown
- Research Basin Development - Solohub
Conclusions

- Increased requirements for reducing predictive uncertainty and changing conditions of climate and land use are presenting new challenges to hydrological science for water resources prediction.
- A programme to study hydrology in the cold regions of the Rockies and North and the prairie region is focussing on hydrological processes of the greatest uncertainty.
- Physically based hydrological modelling is showing promise as a way to predict with reduced uncertainty where data for calibration are sparse.
- Major research initiatives are underway to develop a predictive system for mountain hydrology and prairie and link this to climate and weather prediction models.
- The next step is to apply this to conditions of changing land use and changing climate.
  - Agricultural drainage and tillage change
  - Climate change