Climate Change for the Prairies?

- Highly variable and harsh climate has limited settlement and development possibilities over the last century.

- If weather variability increases, this could degrade the viability of many aspects of ecosystems, human activities and economy.

- However, moderation of some variability (less cold or dry weather) might open up new possibilities for the Prairies.
Prairie Climate is Variable and Extreme

April Average Temperature, Saskatoon

Drought 1999-2004

Current Precipitation Compared to Historical Distribution
(Previously Precipitation Percentiles)
September 1, 2001 to August 31, 2002 (A.M.)

Percentile Classes
- Record Dry
- Extremely Low (0-10)
- Very Low (10-20)
- Low (20-40)
- Mid-Range (40-60)
- High (60-80)
- Very High (80-99)
- Extremely High (90-100)
- Record Wet

Prepared by P.P.A. (Prairie Farm Rehabilitation Administration) using data from the Trinity Climate Monitoring Network and the many federal and provincial agencies and volunteers that support it.
THE DIRTY THIRTIES

"Saskatchewan, Saskatchewan, there's no place like Saskatchewan; we sit and gaze across the plains and wonder why it never rains…"

These words from the song *Saskatchewan* were written during the 1930s.

Prairie Snow
North American Regional Predictions
Climate Difference from 1980-1999 to 2080-2089
A1B – balanced scenario

Prairie Hydrology

- Major river flow is primarily from mountain runoff, but prairie runoff supplies smaller rivers, streams, wetlands, and lakes
- Prairie Runoff
  - forms in internally drained (closed) basins that are locally important but non-contributing to river systems that drain the prairies, OR
  - drains directly to small prairie rivers (Battle, Souris, Assiniboine) >80% of runoff during snowmelt period
- Redistribution of snow to wetlands and stream channels in winter is critical to formation of runoff contributing area
- Drainage of small streams and wetlands ceases completely in summer when actual evaporation* consumes most available water.
- Baseflow from groundwater often nonexistent.
- Prairie streams are almost completely ungauged and often altered by dams, drainage, water transfers, etc

*evaporation used here as transpiration + evaporation + sublimation
Prairie Runoff Generation

Snow Redistribution to Channels

Spring melt and runoff

Dry non-contributing areas to runoff

Water Storage in Wetlands

PRAIRIE HYDROLOGY – Limited Contributing Areas for Streamflow

Localized hydrology affected by poor drainage, storage in small depressions

Non-contributing areas for streamflow extensive in Canadian Prairies
Modelling Prairie Hydrology

- Need a physical basis to calculate the effects of changing climate, land use, drainage
- Need to incorporate key prairie hydrology processes: snow redistribution, frozen soils, spring runoff, wetland fill and spill, non-contributing area
- Frustration that hydrological models developed elsewhere do not have these features
Cold Regions Hydrological Modelling Platform: CRHM

- Modular – purpose built from C++ modules
- Modules based upon +45 years of prairie hydrology research at Univ of Saskatchewan
- Hydrological Response Unit (HRU) basis – natural landscape units with horizontal interaction, ponds, no need for stream
- HRUs assumed to represent one response type, basis for coupled energy and mass balance
- HRUs connected aerodynamically for blowing snow and via dynamic drainage networks for streamflow
- Incorporate wetlands directly using fill and spill algorithm

CRHM Module Development

DATA ASSIMILATION
- Data interpolation to the HRUs

SPATIAL PARAMETERS
- Basin and HRU parameters are set. (area, latitude, elevation, ground slope, aspect)

PROCESSES
- Infiltration into soils (frozen and unfrozen)
- Snowmelt (prairie & forest)
- Radiation – level, slopes
- Evapotranspiration
- Snow transport
- Interception (snow & rain)
- Sublimation (dynamic & static)
- Soil moisture balance
- Pond water balance
- Sub-surface runoff
- Routing (hillslope & channel)
Prairie Hydrology Studies

Bad Lake IHD: semi-arid, well drained

Lethbridge Ameriflux Station: semi-arid

St Denis: sub-humid internally drained non-contributing zone

Smith Creek: sub-humid, wetland dominated, variable contributing area

Drought and Climate Change Studies

- Creighton Tributary of Bad Lake - well drained semi-arid upland
- St. Denis National Wildlife Area - internally drained sub-humid upland
Spatially Distributed Snow Redistribution

Snow mass balance equation

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

St Denis, Saskatchewan

Results – Spatially distributed SWE

Spatially distributed SWE cont’

Mar. 16, 2006

Mar. 17, 2006

Spatially distributed SWE cont’
CRHM HRU Configurations

- Fallow
- Stubble
- Grass Coulee
- Stream
- Cultivated
- Wooded Wetland
- Pond

Creighton Tributary, Bad Lake

Wetland 109, St Denis

Prairie wheat field snow accumulation test

Water Balance Creighton-Stubble 1981/82

- CRHM Runoff
- CRHM Snowfall
- CRHM Infiltration
- CRHM Melt
- CRHM Ground SWE
- Measured Melt
- Measured SWE

mm

10-Nov 20-Dec 29-Jan 10-Mar 19-Apr
Snowmelt Runoff Test at Bad Lake

Snow Accumulation in Drought and Wet Years at Wetland 109, St Denis
Effect of Warmer Winter on Blowing Snow and Snow Accumulation – Bad Lake

Fang and Pomeroy, 2007

Effect of Drier Winter on Blowing Snow and Snow Accumulation – Bad Lake

Fang and Pomeroy, 2007
Cold Season Hydrology – Bad Lake Climate Sensitivity Test

**Drought Factors**
- Winter Precipitation
- Winter Air Temperature
- Fall Soil Moisture
- Summer Vegetation Growth

**Drought Response**
- Winter Evaporation
- Maximum Snowpack
- Spring Infiltration
- Spring Stream Discharge

Fang and Pomeroy, 2007

Snowmelt Runoff over Frozen Soils

Bad Lake: Semi-and SW Saskatchewan

Soil moisture is FALL soil moisture

Snowmelt runoff is Spring

Physically based Infiltration equations (Zhao & Gray, 1999)

Cold Regions Hydrological Model
Prairie Streamflow and Climate Change
First more, then less?

• Toyra et al. 2004: median of three most reliable climate change scenarios suggests increases in annual prairie winter temperature and precipitation from the 1961-1990 average:
  – 2050    +2.6 °C and +11%
  – 2080    +4.7 °C and +15.5%

• Using this scenario in Bad Lake Research Basin (SW Sask) with CRHM results in a 24% rise in 2050 spring runoff, but a 37% drop by 2080, compared to the basin runoff (54 mm) in spring of 1975 (Fang and Pomeroy, 2007).

Climate Change – Winter Snow

![Graph showing winter snow accumulation at Bad Lake, SK in different scenarios.](image-url)
Climate Change – Spring Runoff

Spring Runoff from Creighton Tributary at Bad Lake, SK

- Normal Spring Runoff (Spring of 1975)
- Spring Runoff (Spring of 2050)
- Spring Runoff (Spring of 2080)

Soil Moisture, Evaporation and Runoff

- Should be Easy! If $R = 0$, then $P = E$
- Not that easy…..
  - $E = P - \Delta S$  This is when sub-surface coupling becomes critical to the atmosphere
  - Storage is dynamic during dry periods. Decreasing surface area of open water, increased root depths, increased depth to water table
  - Seasonality –
    - most runoff is from snowmelt (snowfall),
    - most evaporation is from rainfall + snowmelt
    - Precipitation or melt at times of low evaporative energy goes into storage (including soil moisture) or runoff
  - Episodic Events – runoff removes water before it can infiltrate and form storage for evaporation.
    - Snowmelt over frozen soil
    - Intense rainfall rates (convective storms).
Simulation in a Dry Period

CRHM: Cold Regions Hydrological Model

- Rainfall
- Evaporation
- Infiltration
- Interception/Ponding
- Subsurface Runoff
- Surface Runoff
- Groundwater Flow

Energy control on evaporation

P > E
R > 0
S little change

No Drought
P/3
T + 3 °C
R = 0
E > P
S declines

Plant, roots and soil moisture Become important
Early Drought

P/3
T + 3 °C
SI/4
R = 0
E ≈ P
S depleted

Soil moisture critical and limiting
Full Drought
Lethbridge Ameriflux Site (2001)

Synthetic Drought Progression

<table>
<thead>
<tr>
<th></th>
<th>No Drought</th>
<th>1st Summer</th>
<th>Full Drought</th>
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<tbody>
<tr>
<td>Rainfall</td>
<td>222</td>
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<td>75</td>
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<tr>
<td>Evaporation</td>
<td>150</td>
<td>100</td>
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<tr>
<td>Storage Change</td>
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<td>-28</td>
<td>+14</td>
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<tr>
<td>Runoff</td>
<td>90</td>
<td>3</td>
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Smith Creek Hydrology Study

- Problem: Inability to reliably model the basins of the Upper Assiniboine River and other prairie basins where variable contributing area, wetlands, nonsaturated evaporation, frozen soils, snow redistribution and snowmelt play a major role in hydrology.

- Objectives
  - Develop a Prairie Hydrological Model computer program that can simulate the response of streams, wetlands, and soil moisture to weather inputs for various basin types.
  - Evaluate the model performance in Smith Creek by comparing to observations of streamflow, wetland extent, and snowpack.
  - Use the Prairie Hydrological Model to estimate the sensitivity of streamflow, wetland water storage, and soil moisture to changes in drainage and land use.

Instrumentation of Smith Creek

Completed Summer 2007

Hydrometeorological Station
- 11 dual rain gauges
- 7 wetland level recorders
Main Hydrometeorological Station

Temperature, humidity, wind speed, shortwave radiation, longwave radiation, soil moisture, soil temperature, soil heat flux, snow depth, rainfall, snowfall

Telemetry of Hydrometeorological Data to Website – community access

Telemetry to U of Sask website

http://www.usask.ca/hydrology

Daily Climate Values - Smith Creek

<table>
<thead>
<tr>
<th>Yesterday’s Daily Max and Min</th>
<th>Tuesday, April 08, 2009 12:23 PM</th>
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<tbody>
<tr>
<td>Air Temperature (°C)</td>
<td></td>
</tr>
<tr>
<td>max/min of max</td>
<td>5.6</td>
</tr>
<tr>
<td>max/min of min</td>
<td>-6.6</td>
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<tr>
<td>Relative Humidity (%)</td>
<td></td>
</tr>
<tr>
<td>max/min of max</td>
<td>75</td>
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<tr>
<td>max/min of min</td>
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Precipitation

<table>
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<tr>
<th>Daily Total Precipitation (mm)</th>
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<tr>
<th>Yesterday’s Average Values</th>
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<td>Depth</td>
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<tr>
<td>15 cm</td>
<td>16.8</td>
</tr>
<tr>
<td>20 cm</td>
<td>16.8</td>
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<tr>
<td>Soil Temperature</td>
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<tr>
<td>Soil Moisture (%)</td>
<td>32</td>
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<tr>
<td>Air Temperature (°C)</td>
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<tr>
<td>Relative Humidity (%)</td>
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Note: soil moisture is measured when soil temperature <0°C
Snow and Wetland Surveys

Streamflow over Time

Top 4 years for streamflow since 1995
Peak Flow over Time

Maximum Daily Discharge of Smith Creek during 1975-2006

Top 6 peak daily flows since 1995

Changing Climate?

Mean Annual Air Temperature at Yorkton

Warming but high variability

No trend in rainfall and snowfall

Mean Annual Temperature (°C)

Annual Rainfall and Snowfall at Yorkton
Modelling Approach

Smith Creek Basin Characteristics

Drainage Network

Spot Image
CRHM – Prairie Hydrological Model Configuration

Flow Chart in Cold Regions Hydrological Model Platform (CRHM)

HRU Configuration for Smith Creek

Physically-based hydrological modules

- **Group 1**
  - Fallow HRU
  - Shrubland HRU
  - Grassland HRU
  - River Channel HRU
  - Open Water HRU
  - Wetland HRU

- **Group 2**
  - Same seven HRUs

- **Group 3**
  - Same seven HRUs

- **Group 4**
  - Same seven HRUs

- **Group 5**
  - Same seven HRUs

- **Group 6**
  - Muskinglem routing between sub-basins

Sub-basin 1

Sub-basin 2

Sub-basin 3

Sub-basin 4

Sub-basin 5
Parameterisation without Calibration: LiDAR DEM to Calculate Depression Storage

Derivation of Wetland Depressions for Basin

Figure 3. (a) Original 10-m LiDAR DEM, (b) filled depressionless 10-m LiDAR DEM, and (c) “cut/fill” output for Smith Creek basin.
Remote Sensing Supervised Classification

CRHM Tests Smith Creek – No Calibration

Observed SWE vs Simulated SWE at Smith Creek Sub-basin 1

Volumetric Soil Moisture at Smith Creek during Spring Snowmelt Period
Runoff Prediction:
No LiDAR & Calibration = old basin
LiDAR & No Calibration = new basin

Smith Creek Discharge with LiDAR Uncalibrated and No LiDAR Calibrated Parameters

Conclusions

• Possible to model Prairie hydrology without calibration using physically based landscape scale simulations.
• Prairies are expected to become warmer and wetter with an initial increase in spring runoff followed by a substantial decrease in spring runoff generation later in the 21st Century.
• Drought sensitivity is extreme which will lead to magnification of drought-wet cycles in streamflow responses.
• Drainage is increasing streamflow and peak flow in wet and normal years

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<th>New Basin</th>
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<tr>
<td>MR</td>
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<tr>
<td>MW</td>
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<td>0.12</td>
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<tr>
<td>Peak</td>
<td>4.01</td>
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