Drought Impacts on Canadian Prairie Wetland Snow Hydrology

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ABSTRACT

Droughts frequently strike the Canadian Prairies. The drought of 1999-2004/05 was the most recent one and was the most severe on the record for part of the prairie region. It was characterized by lack of precipitation, shortage of moisture in soils, and insufficient surface water supply. The physically-based Cold Regions Hydrological Modelling platform (CRHM) was used to analyze the impacts of this recent drought on the water supply in a Canadian Prairie wetland. CRHM is based on a modular, object-oriented structure in which component modules represent basin descriptions, observations, or physically-based algorithms for calculating hydrological processes such as wind redistribution of snow, snowmelt, infiltration into unsaturated frozen soils, and snowmelt runoff. To calculate the water balance of a basin, modules are linked into a purpose built model for the basin of interest. The model simulations were conducted for the basin of Wetland 109 at St. Denis National Wildlife Area, Saskatchewan for the drought period of 1999-2004/05 and the non-drought period of 2005/06. 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 decreased by 78%, 95%, and 79% for the springs of 2000, 2001, and 2002, respectively. This is consistent with the observed water level in the Wetland 109, showing a drying out of wetland during the severe drought period of 1999-2002.

Keywords: prairie snowmelt runoff; snowmelt; snow accumulation; infiltration to frozen soil; Canadian prairie; drought; wetland hydrology; Cold Regions Hydrological Model

INTRODUCTION

Drought is a natural hazard and is a normal part of climate (Wilhite and Buchanan-Smith, 2005), but it can come to be a disaster when its impact on human society and environment becomes severe (Maybank *et al.*, 1995; Wilhite and Buchanan-Smith, 2005). Drought is a subtle and slowly-developing phenomenon, and it is difficult to declare its onset and the end (Maybank *et al.*, 1995; Wilhite and Buchanan-Smith, 2005). The common features of drought are: above average air temperature, lack of precipitation, low soil moisture, and insufficient water supplies from the surface and subsurface (Nkemdirim and Weber, 1999; Wheaton *et al.*, 1992; 2005; Wilhite and Buchanan-Smith, 2005).

Droughts are frequent on the Canadian Prairies. Over half the years of three decades, 1910-1920, 1930-1939, and 1980-1989 were in drought (Nkemdirim and Weber, 1999) with the drought of 1961 considered as the most extensive single-year prairie drought in the 20th century (Maybank

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et al., 1995). The drought of 1999-2004 was the most recent multi-year drought and with 1999-2002 being the most severe on record in parts of the Prairies (Bonsal and Wheaton, 2005, Rannie, 2006).

On the Canadian Prairies, severe drought occurs most frequently in the southern parts, coinciding with the Palliser Triangle, named after the British explorer Captain John Palliser (Nkemdirim and Weber, 1999). This region extends from the eastern Rocky Mountains to the southwest corner of Manitoba and is characterized by dry winters due to atmospheric blocking by the Rocky Mountains (Agriculture and Agri-Food Canada, 1998). Drought in this region is usually associated with large-scale disruptions of atmospheric circulation pattern and displacement of air masses (Bonsal and Wheaton, 2005; Liu *et al.*, 2004; Shabbar, 2006). On the Canadian Prairies, a strong connection existed between warmer and drier conditions in the wintertime during the droughts of 1961 and 1988 and the El Niño/Southern Oscillation (ENSO). ENSO caused the jet stream over the North Pacific to split into two branches, one flowing over the Arctic and the other flowing over the Pacific, northwest United States and southwest Canada (Bonsal and Wheaton, 2005; Shabbar *et al.*, 1997; Shabbar, 2006). However, Bonsal and Wheaton (2005) showed that the northward extension of persistent drought circulation from the continental United States was the major factor influencing the recent drought of 1999-2002.

Drought on the Canadian Prairies is featured by below-normal precipitation. During the drought of 1988, there was only 70-80% of normal snowfall east of the Rockies (Lawford, 1992); the agricultural region of prairies received less than 50% of normal snowfall (Wheaton *et al.*, 1992). During 1999-2001, part of the Prairies experienced the driest condition in the 118 year record (Sauchyn *et al.*, 2003). Above-normal temperature is another common characteristic of drought. During the drought of 1988, mean temperatures for March, April and May were 2 to 4 °C higher than normal in most of Western Canada (Wheaton *et al.*, 1992), while slightly lower temperature anomalies, 0.5 to 1 °C above normal, existed in the recent drought of 2001-02, with the highest anomalies found in the winter season (Bonsal, 2005). Different temperature trends were found depending on the definition of winter; Fang and Pomeroy (2007) found the hydrological winter (Nov 1-May 1) to be colder than normal in part of the Prairies during the recent drought. The combination of low soil moisture with drier and warmer atmospheric conditions causes little runoff from snowmelt and the drying out of prairie wetlands and streams (Fang and Pomeroy, 2007; Nkemdirim and Weber, 1999; Rannie, 2006).

The physically-based Cold Regions Hydrological Modelling platform (CRHM) is capable of simulating the water balance for Canadian Prairie basins and has an ability to analyze the sensitivity of prairie snowmelt runoff to drought (Fang and Pomeroy, 2007; Pomeroy *et al*., 2007). CRHM is based on a modular, object-oriented structure in which component modules represent basin descriptions, observations, or algorithms for calculating hydrological processes. Full details of CRHM are described by Pomeroy *et al.* (2007). Relevant modules for simulation of wetland snowmelt hydrological processes include the Prairie Blowing Snow Model (Pomeroy and Li, 2000), the Energy-Budget Snowmelt Model (Gray and Landine, 1988), Gray's expression for snowmelt infiltration (Gray *et al.*, 2001), Granger's evaporation expression for estimating actual evaporation from unsaturated surfaces (Granger and Gray, 1989; Granger and Pomeroy, 1997), a soil moisture balance model for calculating soil moisture balance and drainage (Leavesley *et al.*, 1983), and Clark's lag and route runoff timing estimation procedure (Clark, 1945). These modules are assembled along with modules for radiation estimation and albedo changes (Garnier and Ohmura, 1970; Granger and Gray, 1990; Gray and Landine, 1987) using CRHM "projects" which are basin-specific models. To calculate the water balance of a basin, modules are linked into a purpose built model for the basin of interest. Basins are composed of a number of hydrological response units (HRUs). HRUs are spatial landscape units have internally uniform hydrological function (response) that can be described by a unique set of parameters, variables and fluxes (Pomeroy *et al.*, 2007). For each HRU, simulations can estimate snow accumulation, melt rate, cumulative snowmelt infiltration, and snowmelt runoff. For the simulation period, mean snow accumulation, infiltration and snowmelt discharge can be estimated for the basin.

Many hydrological processes: blowing snow, blowing snow sublimation, snowmelt, infiltration, snowmelt runoff are sensitive to the meteorological and hydrological conditions during drought

(Fang and Pomeroy, 2007). Wetlands represent an important water resource for wildlife on the Canadian Prairies. The quantity of water in a wetland is governed by the surface and underground hydrological processes and is sensitive to changes in soil and land cover conditions (Bodhinayake and Si, 2004; van der Kamp *et al*., 2003). The objective of this study is to use CRHM to examine the combined effects of changing meteorology and changing soil and land cover conditions on Canadian Prairie wetland snowmelt hydrology during the recent drought of 1999-2004.

STUDY SITE

The study was conducted at the basin of wetland 109, St. Denis National Wildlife Area (SDNWA) (Figure 1). The SDNWA (52°02'N, 106°06'W, 545-560 m a.s.l., 3.85 km^2) is located in south-central Saskatchewan, Canada and in a moderately rolling landscape with slope ranging from 10 to 15% (van der Kamp *et al.*, 2003). The area is characterized by poorly-developed drainage, clay soils and glacial till substrate (Hayashi *et al.*, 1998). The SDNWA has three major land uses: native grassland, brome grassland, and cultivated land. Saskatoon Airport, located about 40 km west of the SDNWA, has a 2°C annual air temperature, with -19°C as the January mean temperature and 18°C as the July mean temperature; the 30-year (1967-1996) mean annual precipitation in Saskatoon is 358 mm with 74 mm of snowfall occurring from November to April (van der Kamp *et al.*, 2003). Snowfall generally starts in November, and several snowmelt runoff events occur in early spring between March and April in the area (van der Kamp *et al.*, 2003).

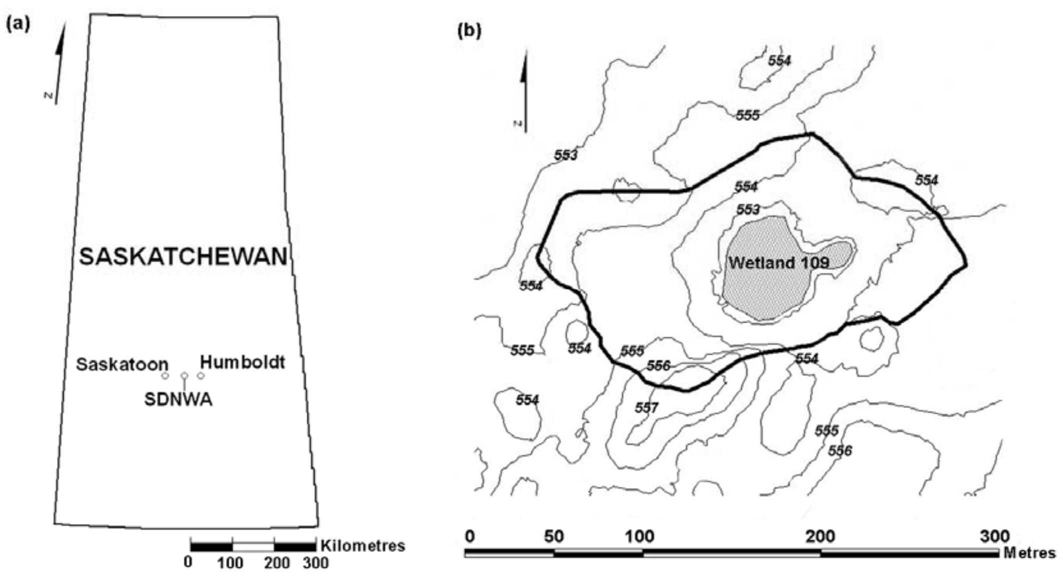

Figure 1. Location of study site: (a) SDNWA, Saskatchewan (b) contour map of the basin of wetland 109 (dark solid line denotes the basin and shaded area indicates Wetland 109).

The SDNWA is dominated by the small depressions, one of which is Wetland 109. It is a small internally-drained basin and typifies other depressions in the area. The effective area of basin is 0.02013 km^2 with 0.00412 km^2 comprising the wetland (Hayashi and van der Kamp, 2000; Hayashi *et al.*, 2003); the effective drainage area is a portion of the drainage basin which are expected to contribute runoff. Four smaller depressions exist in the vicinity of effective area of basin and altogether form the gross drainage of Wetland 109 (Hayashi and van der Kamp, 2000; Hayashi *et al.*, 2003); the gross drainage area is the area enclosed by its drainage divide which are expected to contribute runoff under extremely wet conditions. In dry years, only the melt water in the effective area of basin contributes the water level change in Wetland 109 during early spring period; whereas overflows from other adjacent small depressions can lead to water level rise in Wetland 109 in some wet years.

METHODS

The CRHM was used to simulate the water balance during winter and spring period for the basin based on field observations from both drought period of 1999-2004/05 and non-drought period of 2005-06.

Cold Regions Hydrological Modelling Platform

The Prairie Blowing Snow Model (PBSM) (Pomeroy and Li, 2000) was used to estimate pre-melt snow accumulation (often called SWE). Snowmelt rate and cumulative snowmelt were calculated by Energy-Budget Snowmelt Model (EBSM) (Gray and Landine, 1988) using the SWE from PBSM. Cumulative snowmelt infiltration into unsaturated frozen soils (INF) was estimated by Gray's parametric equation for infiltration (Gray *et al*., 2001), and the method of Granger and Pomeroy (1997), an atmospheric energy balance and feedback approach was used to calculate actual evaporation (Evap). These models were assembled with soil moisture balance model (Leavesley *et al.*, 1983) and Clark's lag and route runoff timing estimation procedure (Clark, 1945) in estimating surface snowmelt runoff (R) based on simple mass balance equation:

$$R = SWE - INF - Evap \tag{1}$$

where all terms are in mm of water equivalent.

Estimations of these processes were carried out on HRUs. Based on the land use of the basin, two HRUs (cultivated and wetland) were built to run the simulations. The definition of HRU was based on the major land uses within the basin and considered only the area that contributes to the surface runoff for the basin. Thus, the estimations of hydrological processes for the basin were made based on HRU area-weighted as:

$$X_{basin} = X_{cultivated} \frac{Area_{cultivated}}{Area_{basin}} + X_{wetland} \frac{Area_{wetland}}{Area_{basin}} \tag{2}$$

where X_{basin}, $X_{cultivated}$, and $X_{wetland}$ are the estimated values of the hydrological processes for the basin, cultivated field, and wetland, respectively; $Area_{basin}$, $Area_{cultivated}$, and $Area_{wetland}$ are area of the basin, cultivated field, and wetland, respectively.

Field Observations

Extensive field observations at the SDNWA were conducted in the 1990s and the 2000s. Measurements of air temperature, relative humidity, two-metre wind speed, and precipitation during 2005 and 2006 were collected from a precipitation gauge station operated by Centre for Hydrology, University of Saskatchewan. Snowfall was corrected for wind undercatch. At the same time measurements of radiation (net short-wave, net long-wave) and vapour pressure were obtained from a station operated by Department of Soil Science, University of Saskatchewan. Measurements of air temperature, relative humidity, ten-metre wind speed, radiation, and vapour pressure from 1999 to 2006 were gathered from a ten-metre tower station operated by Environment Canada. Precipitation data from 1999 to 2005 was acquired from a nearby Meteorological Service of Canada station at Humboldt to assess the missing precipitation periods.

Field surveys of soil properties (volumetric soil moisture and soil porosity), vegetation cover information (height and type), snow accumulation information (depth and density), and wetland water level were conducted by the Centre for Hydrology, the Department of Soil Science and Environment Canada. Volumetric soil moisture was measured by time domain reflectometry (TDR) (Soil Equipment Corp., Trase System) during falls of 1999-2004. Gravimetric techniques were used to determine the volumetric soil moisture and soil porosity for the fall of 2005. The values of porosity fall in the range for the clay loam soil texture reported by Dingman (1994) and were assumed to remain unchanged through time. The fetch distance for blowing snow was determined from the maps and aerial photographs and site and also based on the characteristics of rolling terrain. The method to estimate routing lag and storage was discussed by the Division of Hydrology (1977), the values were selected based on the HRU size, location and shape and landform type. The routing lag and storage used here are not for the purpose of fitting the hydrograph, but rather for estimating the cumulative snowmelt runoff. The information on observed parameters for the basin of Wetland 109 during 1999-2006 is summarized and shown in Table 1.

Table 1. Observed parameters for CRHM simulations at the Wetland 109 during 1999-2006.

HRU	Area (km^2)	Fall Soil Moisture (volumetric ratio)	Porosity (ratio)	Vegetation Height (m)	Blowing Snow Fetch Distance (m)	Routing Lag (hour)	Routing Storage (day)
1999–2000							
Cultivated (stubbles)	0.01601	0.21	0.48	0.3	300	8	1
Wetland	0.00412	0.23	0.54	5	300	0	0.5
2000–2001							
Cultivated (stubbles)	0.01601	0.19(0.09)*	0.48	0.1	300	8	1
Wetland	0.00412	0.22(0.00)*	0.54	5	300	0	0.5
2001–2002							
Cultivated (stubbles)	0.01601	0.19	0.48	0.15	300	8	1
Wetland	0.00412	0.22	0.54	5	300	0	0.5
2002–2003							
Cultivated (fallows)	0.01601	0.19	0.48	0.001	300	8	1
Wetland	0.00412	0.22	0.54	5	300	0	0.5
2003–2004							
Cultivated (stubbles)	0.01601	0.22	0.48	0.1	300	8	1
Wetland	0.00412	0.25	0.54	5	300	0	0.5
2004–2005							
Cultivated (stubbles)	0.01601	0.19	0.48	0.1	300	8	1
Wetland	0.00412	0.22	0.54	5	300	0	0.5
2005–2006							
Cultivated (stubbles)	0.01601	0.27	0.48	0.2	300	8	1
Wetland	0.00412	0.32	0.54	5	300	0	0.5

* The values in the brackets were water content levels for the soils with macropore development in 2000-2001. These values were used in the CRHM simulations.

CRHM Test

The simulated total pre-melt snow accumulation was tested against the field observations in the springs of 2000, 2001, 2003 and 2006. The total snow accumulation was observed by Environment Canada and the value was derived from the snow depth and density surveys along the two transects (north-south and east-west) across the Wetland 109. The simulated cumulative snowmelt runoff in the basin was tested against the observed water runoff in the springs of 2000 and 2001. The observed snowmelt runoff was estimated based on the values reported by Hayashi *et al.* (2003) and van der Kamp *et al.* (2003).

A statistical measure, Model Bias (MB) was used to evaluate the performance of CRHM in estimating the total end of winter snow accumulation and cumulative snowmelt runoff. MB was calculated as:

$$MB = \frac{\sum X_s}{\sum X_o} - 1 \quad (3)$$

where X_o, X_s are the observed and simulated values, respectively. The value of MB assesses the capability of the model in estimating water balance; positive and negative values of MB indicate overestimation and underestimation, respectively.

Drought Impacts on Prairie Wetland Snowmelt Hydrology

CRHM was used to estimate the water balance during winter and spring period for the basin of Wetland 109 during 1999-2006. Meteorology during the hydrological winter period (November 1-May 1) and soil, land cover conditions, blowing snow fetch distance, and routing parameters described in Table I were used in CRHM simulations. The simulations were conducted to analyze the drought impact on the following wetland snowmelt hydrological processes: snow accumulation (SWE) after wind redistribution, sublimation of blowing snow, snow cover duration, winter evaporation, cumulative snowmelt, cumulative rainfall infiltration into unfrozen soils, cumulative snowmelt infiltration into unsaturated frozen soils, and surface snowmelt runoff.

Basin Land Use Change Scenarios

Two scenarios of land use change were carried out for the severe drought of 1999-2002. Land cover and vegetation height in each HRU were altered in CRHM parameters. The corresponding simulations were conducted to examine the effects of these changes on the winter hydrological processes and wetland spring recharge. The scenarios are summarized as follows and fully quantified in Table 2:

Scenario 1: Change the land use of the contributing area (cultivated field) from stubble to summer-fallow and keep the land use of the wetland area unchanged.

Scenario 2: Change the land use of the wetland area from tree cover to grass and keep the land use of the contributing area unchanged.

Table 2. Vegetation height for the scenarios of land use change in basin of Wetland 109 during severe drought of 1999-2002.

Year	Original HRUs Vegetation Height (m)		Scenario 1 HRUs Vegetation Height (m)		Scenario 2 HRUs Vegetation Height (m)	
	Cultivated (Stubble)	Wetland (Tree)	Cultivated (Fallow)	Wetland (Tree)	Cultivated (Stubble)	Wetland (Grass)
1999–2000	0.3	5	***0.001***	5	0.3	***0.6***
2000–2001	0.1	5	***0.001***	5	0.1	***0.6***
2001–2002	0.15	5	***0.001***	5	0.15	***0.6***

Note: The numbers in italic bold are the changed vegetated height for the scenarios.

RESULTS

Air Temperature and Precipitation Anomalies

The cumulative precipitation (rainfall and snowfall) and air temperature for the hydrological winters (Nov 1-May 1) during 1999-2006 were observed and acquired from the field meteorological stations (Figure 2 and Figure 3). Figure 2 shows that precipitation was consistently low for hydrological winters of 1999-2000, 2000-01, 2001-02, 2003-04, and 2004-05 with cumulative values of 73.6 mm, 71.2 mm, 58.8 mm, 84.8 mm, and 77.5 mm, respectively.

Precipitation in the hydrological winter of 2002-03 was high with total of 123.8 mm. The highest cumulative precipitation for the period of 1999-2006 was 148.1 mm, in the winter of 2005-06. Figure 3 shows that air temperatures were cold during the hydrological winters of 2000-01, 2001-02, 2002-03, and 2003-04 with the average temperature below -8 °C for all these 4 winters. While air temperatures during hydrological winters of 1999-2000 and 2004-05 slightly increased, with the average temperature of -6.2 °C and -7.3 °C, respectively. The highest average temperature for the period 1999-2006 was -5.4 °C, in the winter of 2005-06.

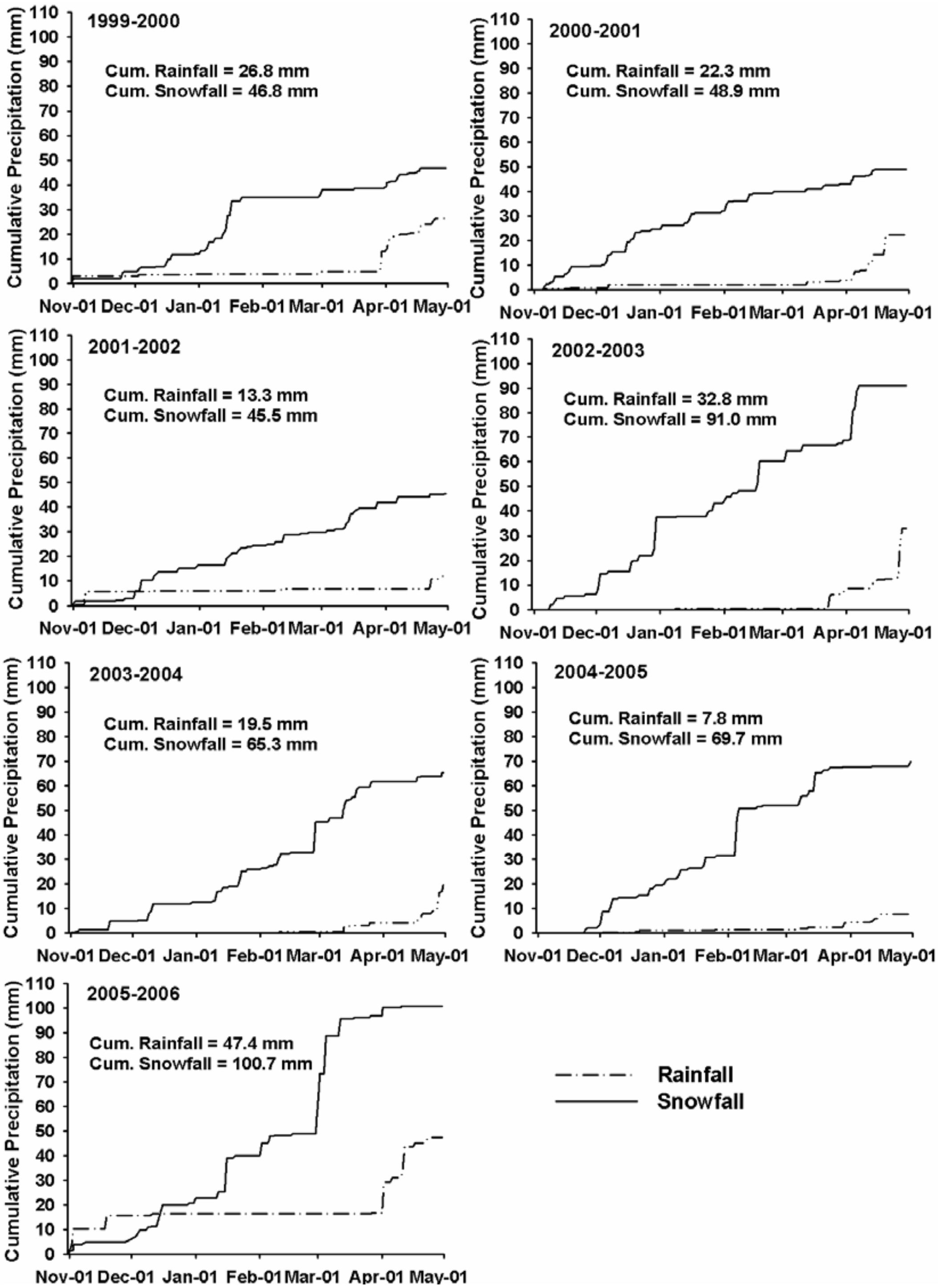

Figure 2. Observed cumulative precipitation for hydrological winters during 1999-2006 at SDNWA.

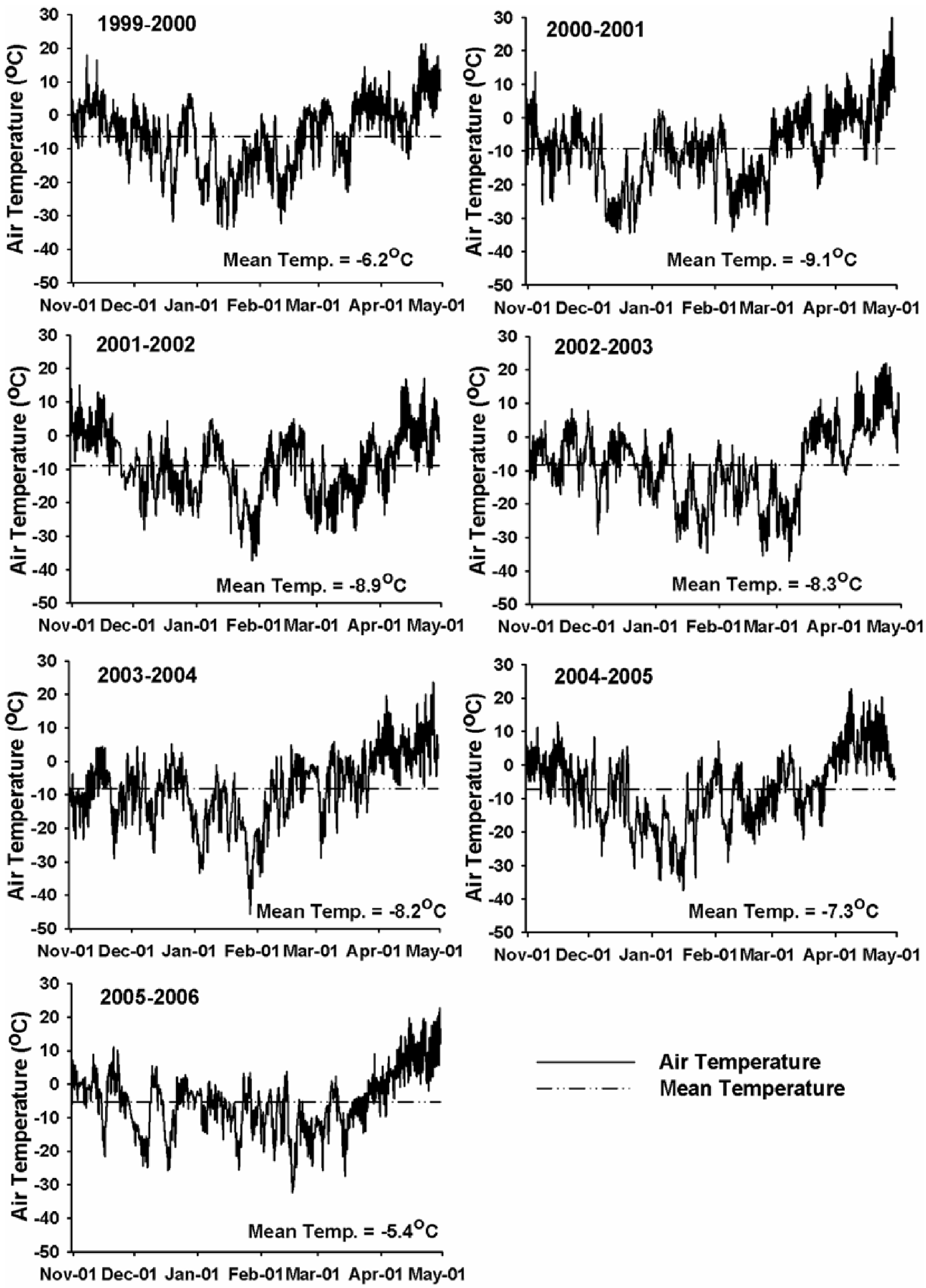

Figure 3. Observed air temperature for hydrological winters during 1999-2006 at SDNWA.

Observed cumulative precipitation and observed air temperature were compared to the long term average precipitation and long term air temperature (Figure 4). Figure 4(a) shows that 30-year (1975-2005) average precipitation during the hydrological winter was very close between Saskatoon and Humboldt, 85.4 mm and 86.1 mm, respectively (Environment Canada, 2006). Compared to the 30-year average precipitation in Saskatoon, the precipitation was 14%, 17%, and

31% lower for the hydrological winters of 1999-2000, 2000-01, and 2001-02, respectively, with similar values for Humboldt. Compared to the 30-year average in Saskatoon, precipitation in the hydrological winters of 2002-03 and 2005-06 was 45% and 73% higher, with similar values for Humboldt. The precipitation in the hydrological winter of 2003-04 was very near the average in Saskatoon and Humboldt. In the hydrological winter of 2004-05, the precipitation was slightly below the average, about 9% less than the 30-year average in Saskatoon and Humboldt.

Figure 4(b) shows that 30-year (1975-2005) average air temperature during hydrological winter was -8.2 °C and -9.2 °C for Saskatoon and Humboldt, respectively (Environment Canada, 2006). The seven-year (1999-2006) mean hydrological winter temperature at SDNWA was -7.6 °C. This implies that slightly warmer than average conditions developed during this seven-year period.

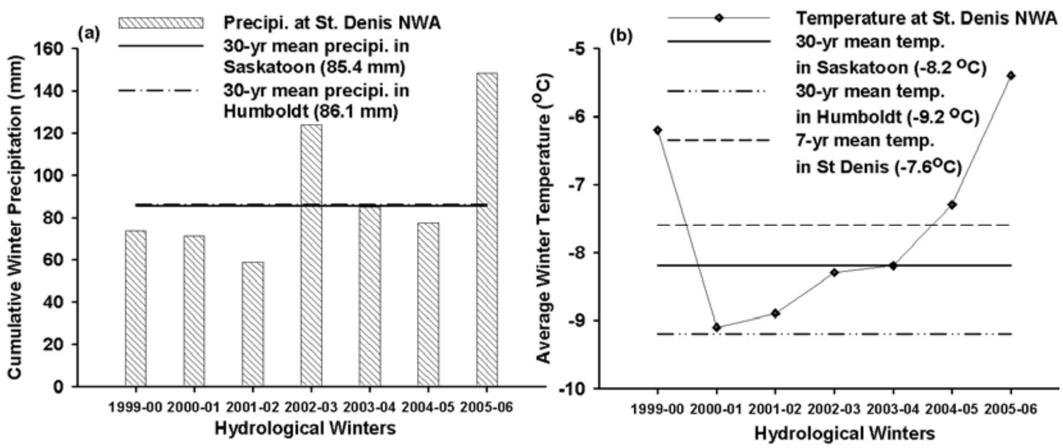

Figure 4. Comparisons of winter precipitation and temperature during hydrological winters of 1999-2006 to 30-year (1975-2005) mean precipitation and temperature.

CRHM Evaluations for Prairie Snowmelt Runoff

The values of observed total pre-melt snow accumulation from snow depth and density surveys at Wetland 109 were compared to the simulated pre-melt snow accumulation for springs of 2000, 2001, 2003 and 2006 (Figure 5). Figure 5(a) and Figure 5(b) show that the simulated pre-melt SWE is close to the observation on the cultivated fields (source area) and wetland (sink area) for the spring of 2000; the simulations of both source and sink areas are generally in accordance with the observations for the springs of 2001, 2003, and 2006. This implies that both transport and sublimation of blowing snow were correctly simulated for springs of these years. The cumulative pre-melt SWE for the basin was estimated from the cultivated field and wetland according to Equation (2) and the statistical indicator Model Bias (MB) was also calculated to quantify the differences between observation and simulation of cumulative basin pre-melt SWE. Figure 5(c) shows that the values of MB are 0.04 and 0.06 for the springs of 2000 and 2003, respectively, representing an overestimation of 1.2 mm and 3.6 mm pre-melt SWE for 2000 and 2003. This suggests that CRHM performed well in predicting the cumulative pre-melt snow accumulation due to wind redistribution for these two years. Values of MB, -0.18 and -0.12 for 2001 and 2006 indicates that an underestimation of 8 mm and 12 mm pre-melt SWE for 2001 and 2006. This suggests only moderate discrepancies to observations of pre-melt SWE for these years.

The cumulative snowmelt runoff to the basin of Wetland 109 was compared the observed total runoff from snowmelt at the end of March in 2000 and 2001 (Figure 5(d)). For the simulation of snowmelt runoff in end of March 2000, 14.9 mm surface runoff was estimated from the snowmelt at the Wetland 109 including the cultivated field (contributing area) and wetland (runoff accumulating area). The moderate value of Model Bias (MB), -0.17, represents an underestimation of surface runoff by 3 mm. The CRHM simulation estimated about 3.6 mm from the contributing area to the wetland at the end of March 2001. Both simulation and observation show that very low snowmelt runoff occurred in March 2001.

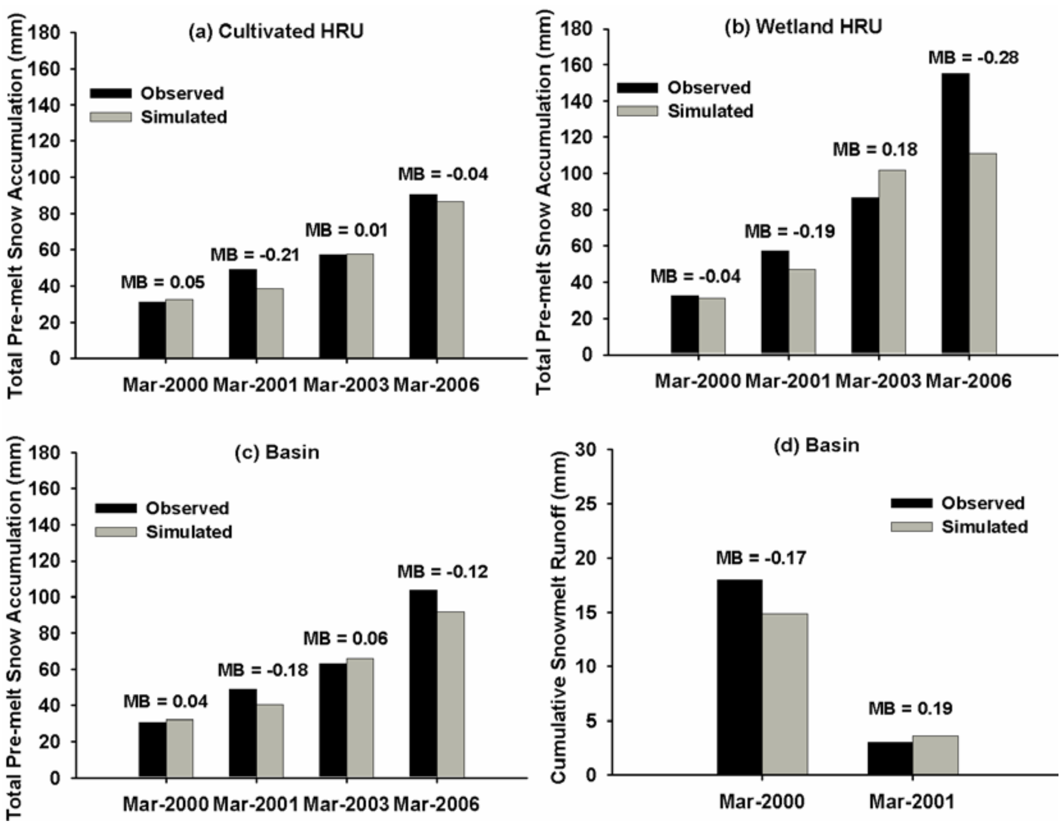

Figure 5. CRHM test of total pre-melt snow accumulation: (a) cultivated HRU, (b) wetland HRU, and (c) basin; (d) CRHM test of cumulative basin snowmelt runoff.

Drought Impacts on Prairie Wetland Snowmelt Hydrology

Major wetland snowmelt-runoff processes during the hydrological winter were simulated for the individual HRU at Wetland 109 during 1999-2006 (Figure 6). Figure 6 shows the combined effects of changing meteorology and changing soil and land cover conditions on the Canadian Prairie wetland snowmelt hydrology during the drought. The figure also illustrates the response of each HRU (cultivated field and wetland) to these conditions.

Figure 6(a) shows that the cumulative snow accumulation (SWE) was consistently low for both cultivated field and wetland during the hydrological winters of 1999-2000, 2000-01, and 2001-02; 'severe drought' periods. There was only 46% to 57% of SWE in the cultivated field and 30% to 45% of SWE in the wetland compared to the snow accumulation during 2002-03 and 2005-06; 'normal' periods. There were moderate amounts of SWE during the hydrological winters of 2003-04 and 2004-05; 'recovery' periods. There was greater snow accumulation in the wetland HRU during 2002-03 when compared to that during 2005-06; this is because summer-fallowed field in 2002 resulted in more blowing snow redistributed to the wetland ('sink'). Figure 6(b) shows that the differences of snow-covered periods of the two HRU are similar during the severe drought periods, with much shorter duration compared to the recovery and normal periods. Figure 6(c) shows that sublimation of blowing snow was persistently low, nearly zero for the severe drought periods; this is due to suppression of blowing snow from low snowfall and tall vegetation cover. Figure 6(d) illustrates that winter evaporation in cultivated field was not very sensitive to the changing conditions during drought; evaporation in the wetland tended to be higher during some severe drought periods, 1999-2000 and 2000-01, due to shorter snow-covered season and earlier occurrence of evaporation in the spring. Figure 6(e) shows that there was no difference in rainfall infiltration into unfrozen soils between HRU and that infiltration was closely associated with the amount of rainfall. Snowmelt infiltration into frozen soils was sensitive to the changing soils conditions; snowmelt infiltration increased as the fall soil moisture decreased (Figure 6(f)). Figure

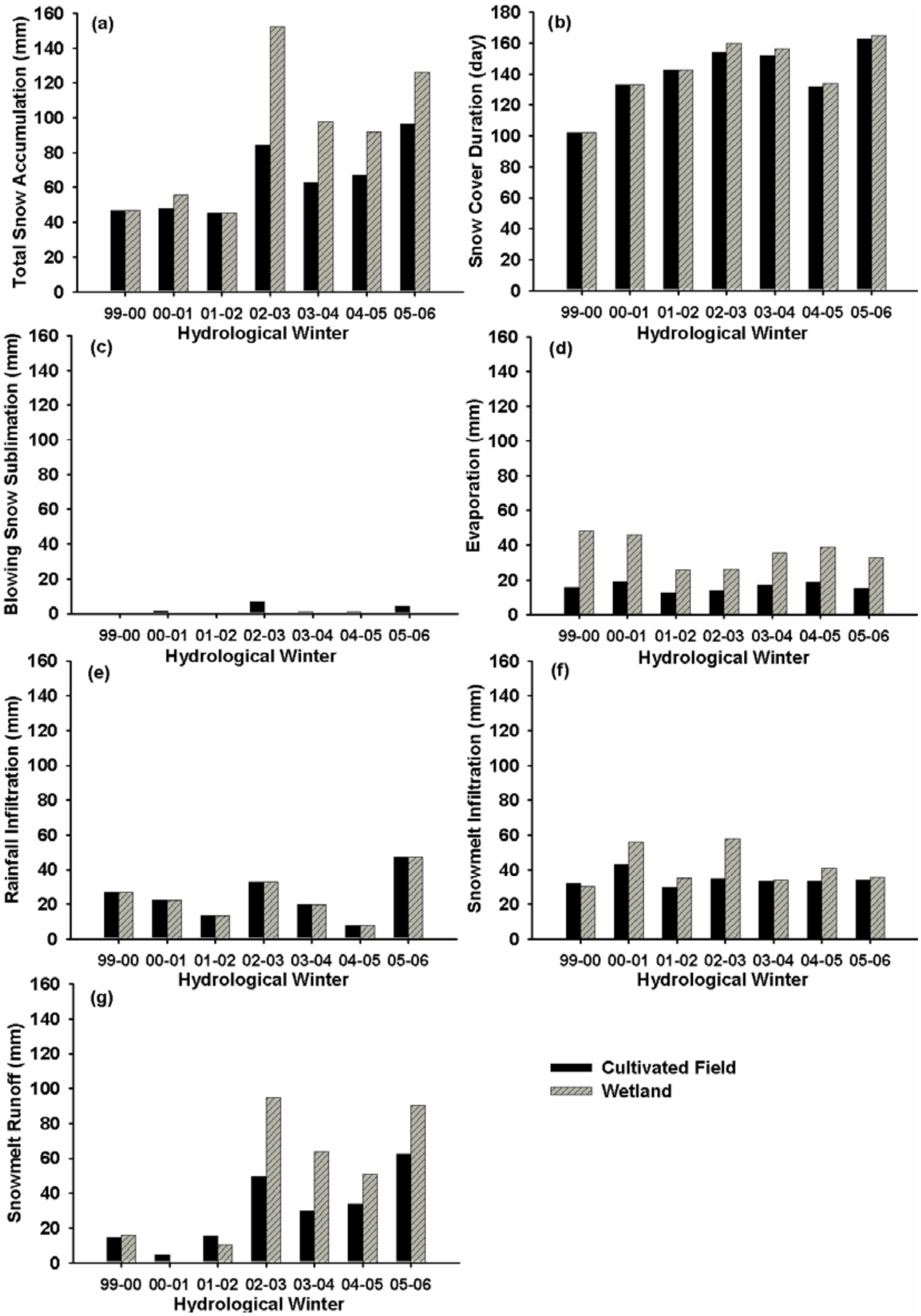

Figure 6. Hydrological processes for individual HRU at Wetland 109 during 1999-2006:
(a) total snow accumulation, (b) snow cover duration, (c) blowing snow sublimation,
(d) evaporation, (e) rainfall infiltration, (f) snowmelt infiltration, (g) snowmelt runoff.

6(g) demonstrates that compared to the normal periods, there was much lower surface runoff from melting snowpacks during the severe drought periods, with decreases of 35 to 58 mm and 75 to 90 mm snowmelt runoff for the cultivated field and wetland, respectively. This shows that the runoff generation in the Canadian Prairie wetland is sensitive to the combined effects of lower snow accumulation, enhanced evaporation, and slightly higher snowmelt infiltration during drought.

The evolution of major wetland snowmelt-runoff related processes during the hydrological winter was simulated for the basin of Wetland 109 during 1999-2006 (Figure 7). The cumulative responses of these hydrological processes to the combined conditions of meteorology, soil, and

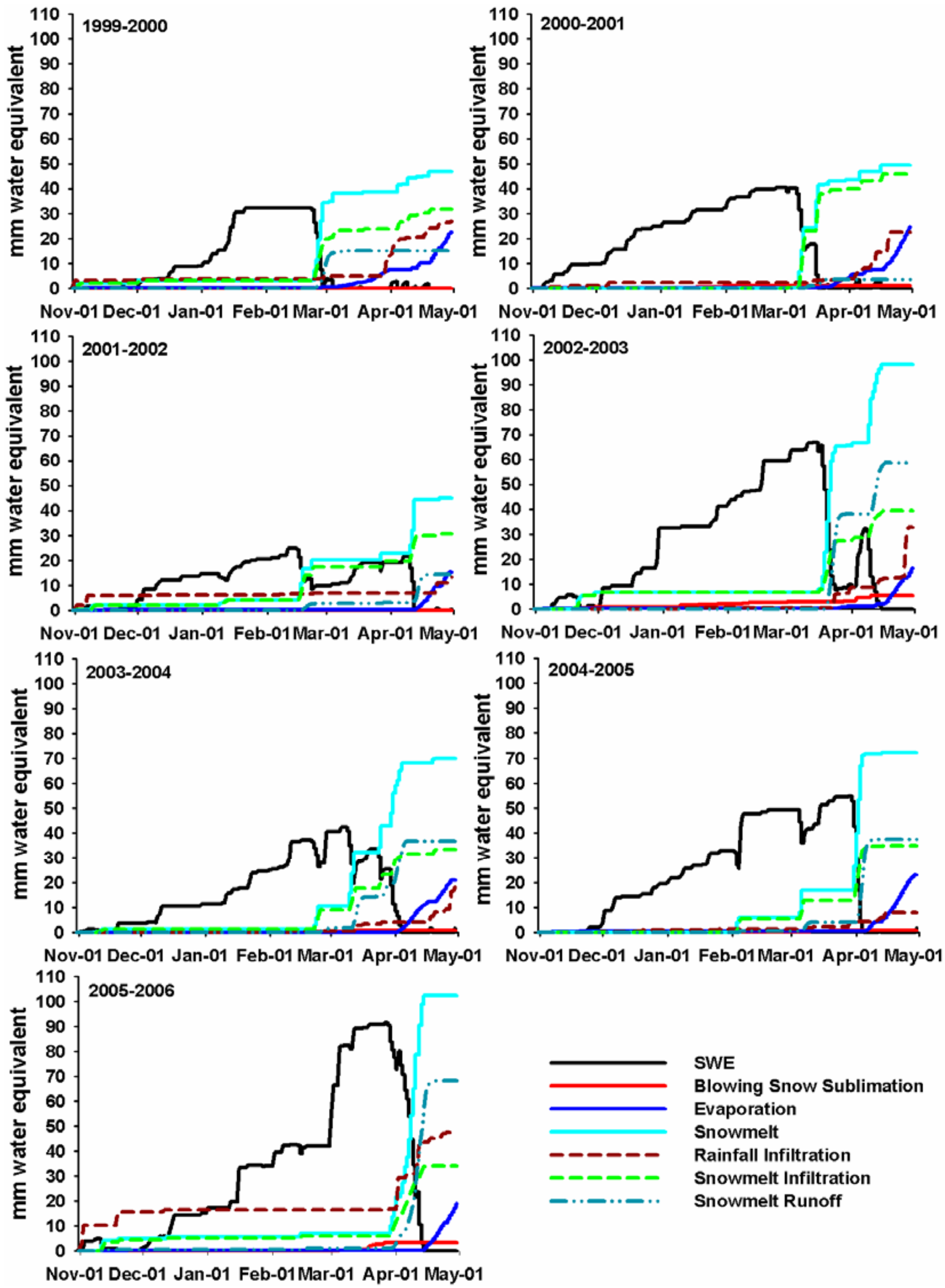

Figure 7. The evolution of wetland snowmelt-runoff processes during the hydrological winter of 1999-2006 at Wetland 109.

land cover were estimated at end of the winter (Figure 8). Compared to the 'normal' periods, 2002-03 and 2005-06, both snowfall and rainfall during hydrological winter were consistently low for the 'severe drought' periods, 1999-2002. As a result, compared to the normal periods, snow accumulation was 50% to 55% lower for the basin during the severe drought periods. Snow accumulation was moderate for the hydrological winters of 2003-04 and 2004-05, 'recovery' periods. The basin snow-cover season was 17 to 63 days shorter during the severe drought periods compared to the normal periods. Sublimation of blowing snow was low for the basin throughout the period of 1999-2006; this owes to lack of blowing snow occurrence from low snowfall, warm

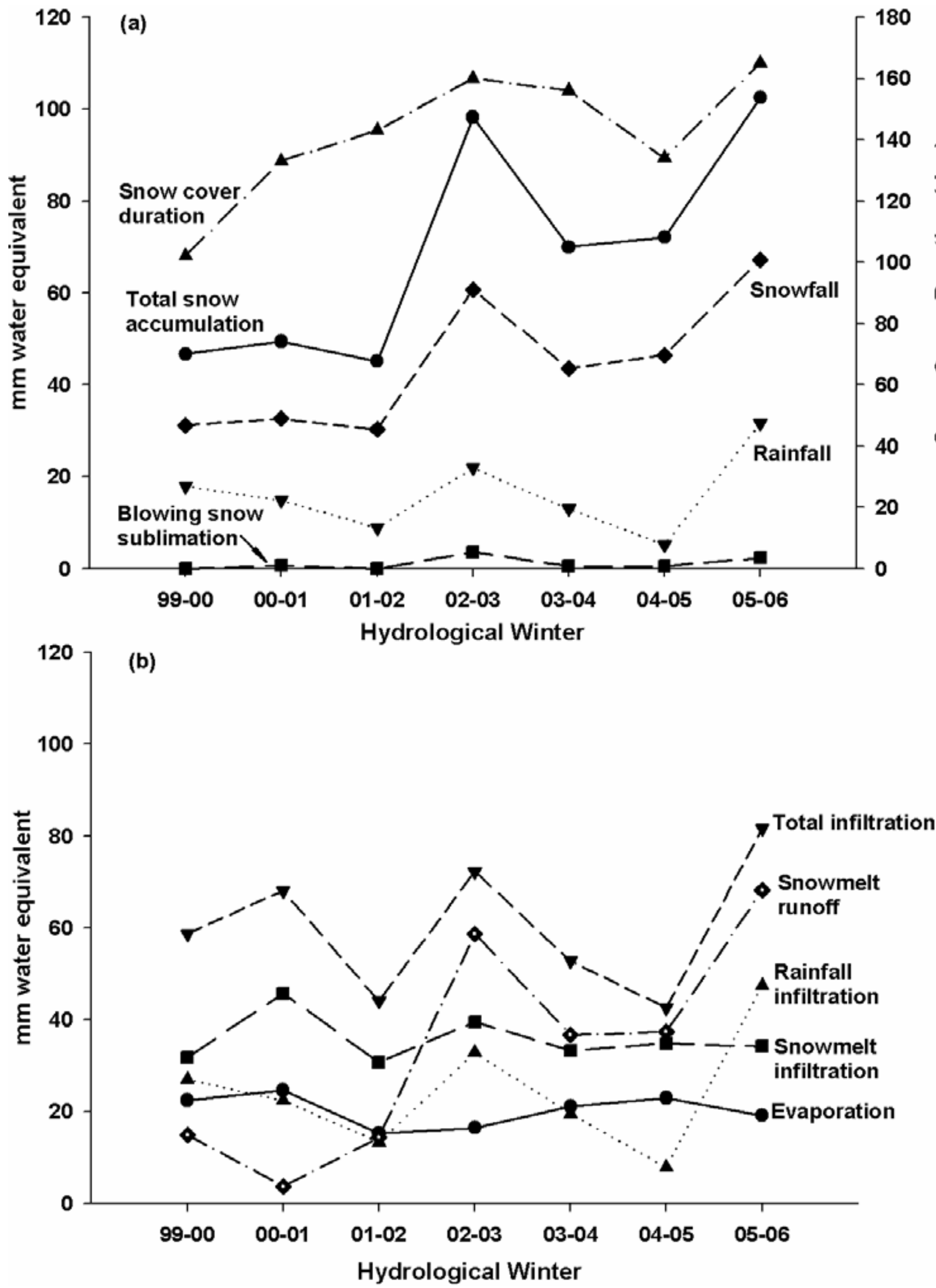

Figure 8. Hydrological processes for the basin of Wetland 109 during 1999-2006:
(a) snowfall, rainfall, total snow accumulation, snow cover duration, blowing snow sublimation and (b) evaporation, rainfall infiltration, snowmelt infiltration, total infiltration, snowmelt runoff.

temperatures and relatively tall vegetation cover and to high relative humidity at this upland location. Basin winter evaporation was not strongly sensitive to the changing conditions during 1999-2006, with increases of 3 to 8 mm in winter seasonal evaporation during severe drought periods as compared to non-drought. Basin infiltration did not show a strong trend with changing conditions during 1999-2006. This is because infiltration comprises both rainfall infiltration into unfrozen soils and snowmelt infiltration into frozen soils; both are complex processes controlled by combinations of hydro-meteorological condition and soil status. Basin surface runoff from snowmelt was much lower during the severe drought periods, approximately 45 to 65 mm less compared to that in the normal periods. Snowmelt runoff was very low in 2000-01 and this is related to the formation of macropores in dry soils (Bodhinayake and Si, 2004; van der Kamp *et al.*, 2003), causing unlimited soil infiltrability (Gray *et al.*, 2001). Similar results were found in the springtime water level during the drought. Figure 9 shows the maximum spring water level observed in Wetland 109 during 1997-2005; the water level was much lower during the severe drought periods compared to the non-drought periods.

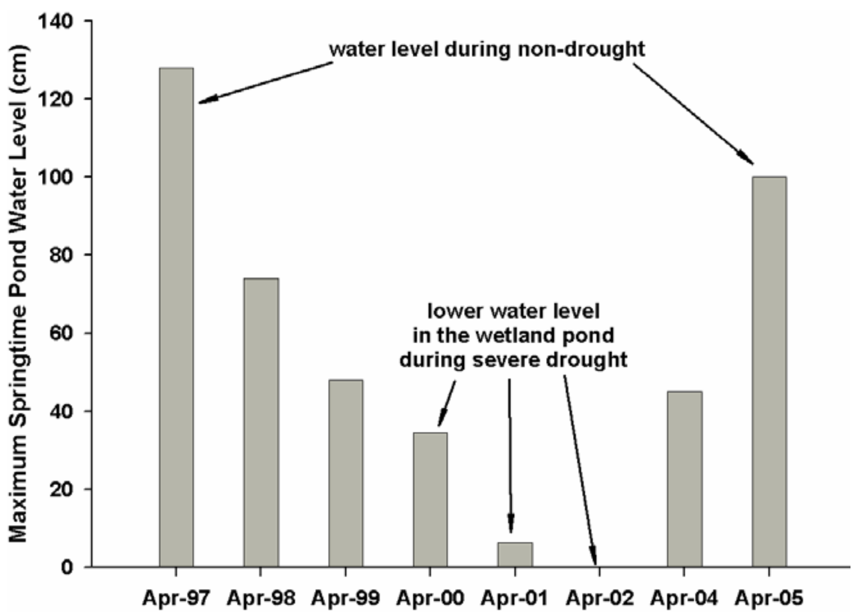

Figure 9. Observed maximum springtime water levels in Wetland 109, St. Denis NWA during 1997-2005 (Note that water level was not measured in April 2003).

Basin Land Use Change Scenarios

The pre-melt SWE on both cultivated HRU and wetland HRU was simulated corresponding to two synthetic scenarios of land use change outlined in Table 2 and the results are shown in Figure 10. Figure 10(a) shows that pre-melt SWE on the cultivated HRU slightly increased in hydrological winter of 1999-2000 and decreased in hydrological winters of 2000-02 as land use in the cultivated field changed from stubble to summer-fallow (Scenario 1). There was no change to pre-melt SWE on the cultivated HRU when land use in the wetland area change from tree to grass (Scenario 2). Figure 10(b) illustrates that pre-melt SWE on the wetland HRU substantially increased by 10 to 40 mm in the hydrological winters of 1999-2002 for the Scenario 1; whereas no change occurred to wetland HRU in the Scenario 2.

The results of simulated basin-wide winter snowmelt processes corresponding to the hypothetical scenarios of land use change are shown in Figure 11. Figure 11(a) shows that in the Scenario 1, infiltration slightly increased; winter evaporation somewhat reduced, and basin pre-melt SWE increased by 2 to 10 mm for the hydrological winters of 1999-2002 with slight increases in blowing snow sublimation. The increase in pre-melt SWE is because blowing snow transport is enhanced and more snow is transported from the cultivated field to the wetland as well

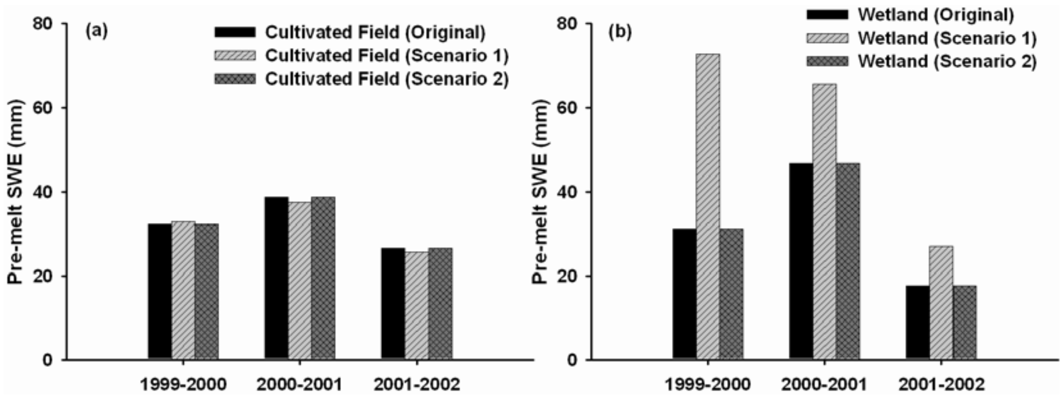

Figure 10. Pre-melt SWE changes corresponding to scenarios of land use change (Table 2): (a) cultivated HRU and (b) wetland HRU.

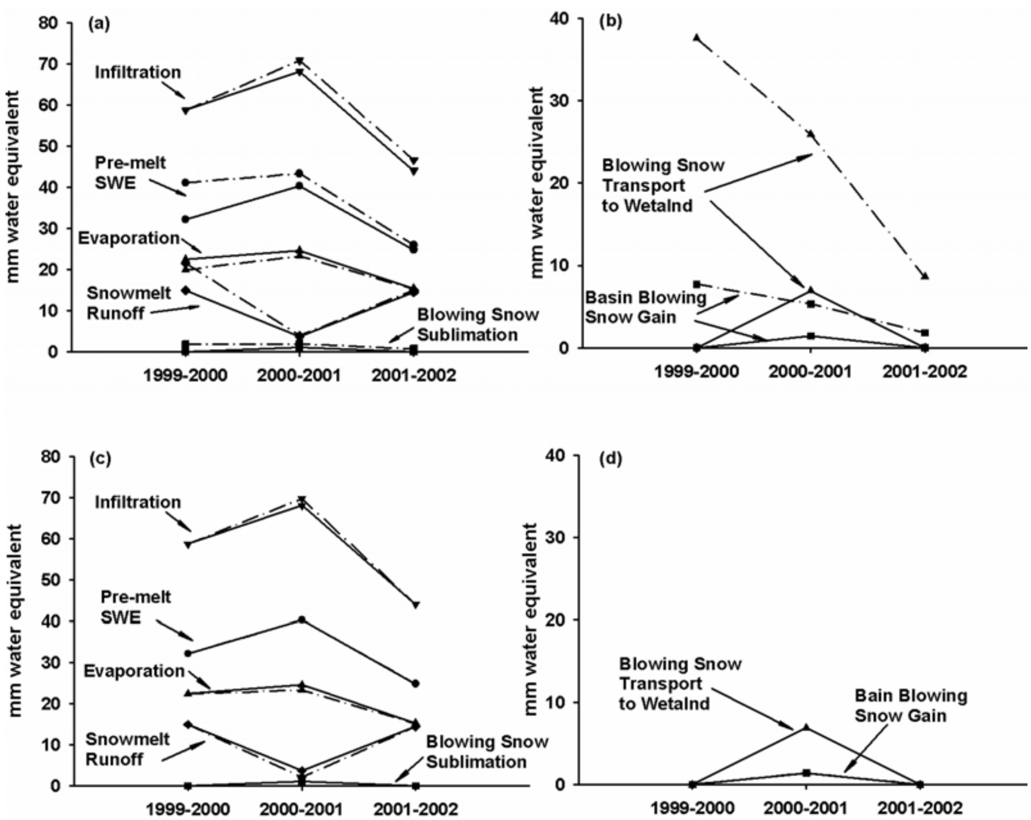

Figure 11. Basin-wide snowmelt runoff-related processes changes corresponding to (a) and (b) Scenario 1 of land use change (Table 2), (c) and (d) Scenario 2 of land use change (Table 2) (solid line indicates pre-change and dash dot line indicates post-change).

as the basin gains more blowing snow from outside of its drainage area (Figure 11(b)). Figure 11(a) shows that snowmelt runoff somewhat increased as a result of more basin pre-melt SWE and less winter evaporation. Figure 11(c) illustrates that in the Scenario 2, infiltration somewhat increased by 1 mm in the hydrological winter of 2000-01, winter evaporation decreased by 1mm and snowmelt runoff reduced by 1mm in the winter of 2000-01; no significant changes to other processes occurred. The results shown in Figure 11 indicate that reducing the vegetation height in the cultivated field does not only enhance the blowing snow transport and subsequently generate more basin snow accumulation, but also increases basin snowmelt runoff, while reducing the vegetation height in the wetland area has minimal effect on the winter hydrological processes.

DISCUSSION

Severe winter drought occurred during 1999-2002. It began with an inadequate precipitation during the hydrological winter (November 1 1999 -May 1 2000) as illustrated in Figure 4(a). This is a meteorological drought characterized by below average precipitation over an extended period of time (Wilhite and Glantz, 1985). As a result, low soil moisture developed during this period, leading to reduced availability of soil water to support crops, an agricultural drought. With these atmospheric and soil conditions, hydrological drought emerged during the hydrological winters of 1999-2000, 2000-2001 and 2001-2002, resulting in much reduced springtime discharge of snowmelt to wetland area and subsequently drying out of wetland.

CRHM showed a reasonable performance in simulating the water balance of Wetland 109 during both drought and non-drought periods when compared to the field observations of pre-melt snow accumulation and springtime surface snowmelt runoff. This is because of the strong physical basis of modules that are key to the water balance; these modules take into consideration all snowmelt runoff processes that are relevant to the prairie wetland environment. However, in order to model a large basin containing several connected wetlands, there is a further need to incorporate surface storage terms (such as depressional storage and pond to pond discharge) into the modelling system.

Compared to the synthetic linear prairie drought progression described by Fang and Pomeroy (2007), the recent multi-year drought of 1999-2004/05 at the SDNWA had distinctive characteristics. A three-year (1999-2002) severe winter drought period was followed by a normal year (2002-03) and then a two-year (2003-05) recovery period, with slightly below average precipitation and notably lower snowmelt runoff and wetland water level, which then returned to normal (2005-06).

The scenario of land cover change from stubble to summer-fallow showed that shortages of water in the wetland during the drought might be alleviated by suppressing the surrounding vegetation to permit greater blowing snow transport to the wetland. By suppressing stubble, the basin can import blowing snow from surrounding fields. However, the second scenario of land cover change in the wetland from trees to grass had no effect on blowing snow or resulting runoff to the wetland because the topographic depression and roughness of the grass was sufficient to trap all possible blowing snow in a dry winter. This second scenario is important because of the aspen dieback that occurred in the recent Prairie drought.

CONCLUSIONS

CRHM showed a reasonable capability for simulating snowmelt runoff-related processes for a Canadian prairie wetland. The winter water balance for a small wetland was successfully simulated for both drought and non-drought periods.

Field observations at St. Denis showed that the recent multi-year drought of 1999-2004/05 was generally characterized by low winter precipitation, low fall soil moisture, and short vegetation cover. The drought period of 1999-2002 was the most severe, with decreases of more than 50% in winter precipitation and decreases of 0.8 °C to 3.7 °C in air temperature during hydrological winter (Nov 1-Apr 30) when compared to the non-drought period of 2005-06. Colder winter air temperatures were not expected for a drought. More research is needed to examine the mechanisms that are responsible for colder air temperature during drought winters.

Drought impact on snowmelt hydrological processes was simulated in CRHM for a small prairie wetland. Results showed that combined effects of soil moisture, vegetation and meteorology caused lower snow accumulation, shorter snow-cover seasons, reduced blowing snow sublimation, somewhat enhanced winter evaporation, and much lower surface snowmelt runoff to a small wetland during drought. Infiltration did not show a trend because it is a complex process containing both rainfall infiltration into unfrozen soils and snowmelt infiltration into unsaturated frozen soils. Snow accumulation and melt are the dominant factors in controlling spring runoff in the prairie regions; the severe drought period of 1999-2002 had only about 50% of total seasonal snow accumulation compared to non-drought period of 2005-06, and this resulted in decreases of more than 50 mm in surface runoff derived from snowmelt in this severe drought period.

Two synthetic scenarios of land use change were proposed and simulated during the severe drought period in CRHM to examine the effects on the wetland hydrological processes and water balance. Results indicated that a possible way to alleviate water shortages in a wetland during drought was to suppress the surrounding vegetation in order to allow more blowing snow transport from surround fields to the wetland.

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