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Drought impacts on Canadian prairie wetland snow hydrology

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Abstract:

Droughts affect the Canadian prairies on a regular basis. The drought of 1999–2005 was the most recent one and was the most severe on record for part of the region. It was characterized by lack of precipitation, desiccation of agricultural soils, decline in groundwater tables and depletion of surface water supplies. The effects on wetlands were particularly severe, with many wetlands completely drying out. The physically based cold regions hydrological modelling (CRHM) platform was used to analyse the impacts of this recent drought on water flow to and storage within a small Canadian prairie wetland. Model simulations were conducted for a small closed basin for the drought period of 1999–2005 and the relatively wet period of 2005–2006. The basin consists of a cultivated upland, draining into a glacially formed pothole depression with no outlet. The wetland fills the depression in wet years and is underlain by a heavy glacial till that impedes groundwater exchange. Results from the observations and model outputs showed that much lower precipitation and snow accumulation, shorter snow-covered duration, enhanced winter evaporation, and much lower discharge to the wetland from basin snowmelt runoff developed in the severe drought years of 1999–2002. As a result, there were only 14·9, 3·7, and 14·4 mm of snowmelt runoff for the springs of 2000, 2001, and 2002, respectively. Compared to the 68·2 mm of melt-water discharge in the spring of 2006, discharge to the wetland was 78, 95, and 79% less for these years. This is consistent with the observed water level in the wetland, which shows dramatic decline over this period. CRHM was used to investigate the potential impact of snow management as a tool to enhance runoff to the wetland during droughts. Model runs parameterized with suppressed vegetation in the cultivated land surrounding the wetland showed increased blowing snow transport to the wetland from an area exceeding the basin area that resulted in greater snow accumulation in and melt-water supply to the wetland.

KEY WORDS snowmelt runoff; snowmelt; snow accumulation; infiltration to frozen soil; Canadian prairie; drought; wetland hydrology; cold regions hydrological model; snow management

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INTRODUCTION

Drought is a natural hazard and is a normal part of climate (Wilhite and Buchanan-Smith, 2005), but its impacts can become a disaster when demands for water by humanity and the environment exceed available supply (Maybank *et al*., 1995; Wilhite and Buchanan-Smith, 2005). Drought is a subtle and slowly developed phenomenon, and it is difficult to declare the onset and end of a drought. The common features of a drought are above average air temperature, lack of precipitation, low soil-moisture, and insufficient water supplies from the surface and subsurface (Wheaton *et al*., 1992, 2005; Nkemdirim and Weber, 1999; Wilhite and Buchanan-Smith, 2005).

Droughts are frequent on the Canadian prairies. Over half of the years of the 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 *et al*., 1995). The drought of 1999–2004 was the most recent multi-year drought, with the years 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 south-western section, coinciding with the Palliser Triangle, named after the British explorer Captain John Palliser who when examining the settlement potential of the region in the dry 1850s recommended that the 'triangle' (roughly bounded by Saskatoon, Calgary, and Moose Jaw) never be cultivated or settled for agriculture (Nkemdirim and Weber, 1999). The Palliser Triangle is characterized with dry conditions in the winter especially in the western part 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 (Liu *et al*., 2004; Bonsal and Wheaton, 2005; Shabbar, 2006). Over the prairies, a strong connection developed during the droughts of 1961 and 1988 between warmer and drier conditions in the wintertime and the El Niño/Southern Oscillation (ENSO). ENSO in these droughts 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, north-western United States and south-western Canada (Shabbar *et al*., 1997; Bonsal and Wheaton, 2005; Shabbar, 2006). In contrast, Bonsal and

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Wheaton (2005) showed that the northward extension of persistent drought circulation from the continental United States was the major factor influencing the recent Canadian prairie drought of 1999–2004.

Runoff in the Canadian prairies is over 80% derived from snowmelt despite only about 1/3 of annual precipitation being received as snowfall (Gray, 1970). This relatively high runoff efficiency is due to wind redistribution of snow to streams, wetlands, depressions, and other contributing areas, relatively impermeable frozen soils during snowmelt and low cold season evaporation rates (Gray *et al.*, 1986). The quantity of water in a wetland is governed by both surface and subsurface hydrological processes and is very sensitive to changes in soil and land cover conditions (van der Kamp *et al.*, 2003; Bodhinayake and Si, 2004). Upland wetland recharge is associated with water received from snowmelt and snowmelt runoff to the wetland from its surrounding basin.

Canadian prairie drought has strong effects on wetlands. A first order effect is that drought consistently features below-average winter precipitation. During the drought of 1988, there was only 70–80% of average snowfall east of the Rockies (Lawford, 1992); the agricultural region of prairies received less than 50% of average snowfall (Wheaton *et al.*, 1992). During 1999–2001, part of the prairies experienced the driest condition in a 118 year record (Sauchyn *et al.*, 2003). Above-normal temperature is a summer characteristic of drought in this region, but not always a characteristic of winter. During the drought of 1988, the mean temperature for March, April, and May was 2–4 °C higher than normal in most of Western Canada (Wheaton *et al.*, 1992), while slightly lower temperature anomalies, 0·5–1 °C above normal, existed in the recent drought of 2001–2002, with the highest anomalies found in the climatological winter season of December–February (Bonsal, 2005). Different temperature trends are found depending on the definition of winter; Fang and Pomeroy (2007) found the hydrological winter (November–April) in the recent drought to be colder than normal. In any case, drought winters in the prairies develop fully frozen soils. Many hydrological processes such as blowing snow, sublimation, snowmelt, infiltration, and runoff are sensitive to the cold season meteorological and hydrological conditions found during drought (Fang and Pomeroy, 2007). The combination of low winter soil-moisture with lower snowfall permits little runoff from snowmelt and the drying out of prairie streams and wetlands (Nkemdirim and Weber, 1999; Rannie, 2006; Fang and Pomeroy, 2007).

Prairie upland wetlands cover a vast area of Canada and the northern United States and form an important habitat for the waterfowl and source of water for small wooded areas. These form in small ‘potholes’ formed in glacial deposits and often have no natural outflow under normal flow conditions. With a relatively impermeable glacial till substrate and largely internal drainage, these wetlands fill and then dry in response to drought and pluvial cycles in the region. Under extremely wet conditions they can spill and briefly form a drainage network. With the strong dependence of prairie upland wetland recharge on cold season hydrological processes and the impact of drought on these processes, there is a need to better understand how drought, cold season hydrology and basin characteristics interact to influence prairie wetland recharge. The objective of this study is 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 1999–2005. This objective will be approached by modelling prairie wetland snow hydrology processes during both drought and non-drought periods and analysing drought impacts on these processes by comparing their responses in the drought period to those without drought.

STUDY SITE

The study was conducted at the basin of wetland 109, St Denis National Wildlife Area (SDNWA), Saskatchewan,

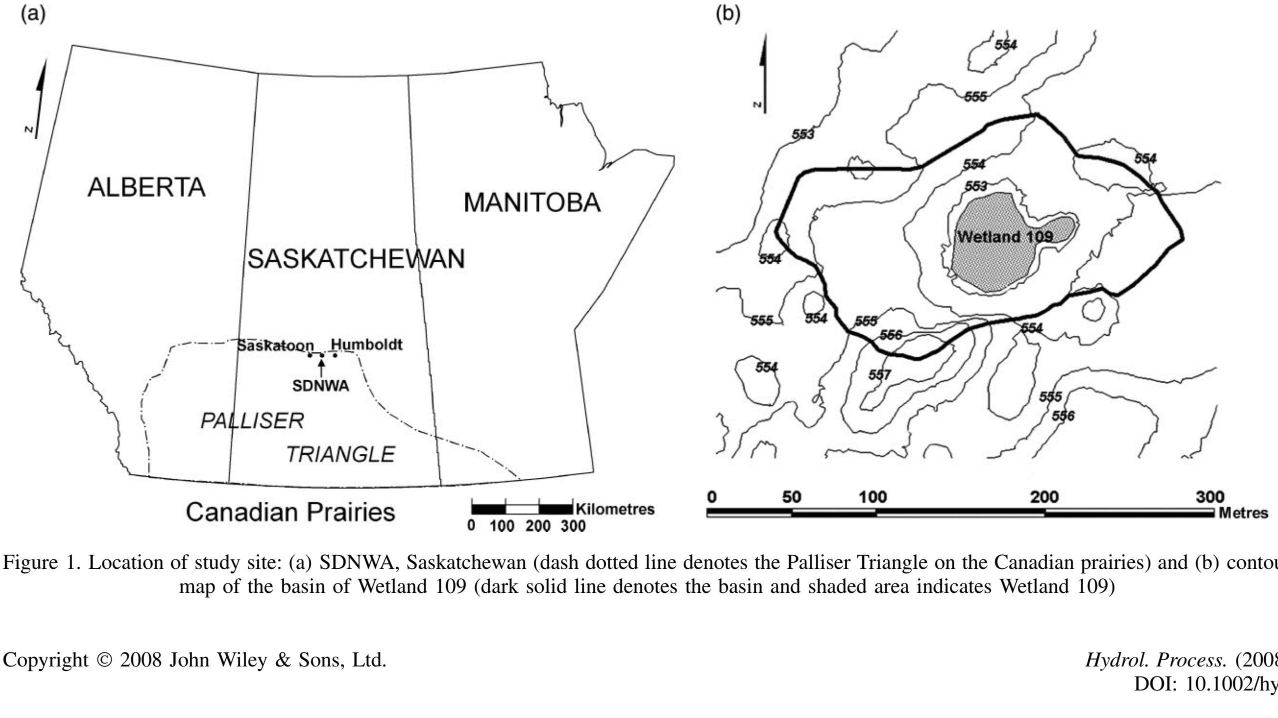

Figure 1. Location of study site: (a) SDNWA, Saskatchewan (dash dotted line denotes the Palliser Triangle on the Canadian prairies) and (b) contour map of the basin of Wetland 109 (dark solid line denotes the basin and shaded area indicates Wetland 109)

Canada (Figure 1). The SDNWA (52°02′N, 106°06′W, 545–560 m a.s.l., 3·85 km^2) is in a moderately rolling agricultural 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). Snowpack accumulation generally starts in November; there are few mid-winter melts, and the melt of the seasonal snowpack and subsequent runoff occurs from March to April (van der Kamp *et al.*, 2003).

The SDNWA is dominated by small depressions, one of which is Wetland 109. Wetland 109 is a small internally drained basin and typifies other depressions in the area. The effective drainage area is that portion of a drainage basin which is expected to contribute runoff in an average runoff season; for Wetland 109 this area is 0·02013 km^2 of which 0·00412 km^2 is the wetland (Hayashi and van der Kamp, 2000; Hayashi *et al.*, 2003). In dry years, only the melt water in the effective area of the basin contributes to the wetland, whereas overflows from other adjacent small depressions can lead to water level rise in Wetland 109 in extremely wet years.

METHODS

Field observations

Extensive field observations at the SDNWA were conducted in the 1990s and the 2000s. Measurements of air temperature, relative humidity, wind speed, and precipitation during 2005 and 2006 were collected from a station operated by the Centre for Hydrology, University of Saskatchewan. Short- and long-wave radiations were measured by a station operated by the Department of Soil Science, University of Saskatchewan over the same time period. Measurements of air temperature, relative humidity, wind speed, and net radiation were made from 1999 to 2006 at a 10-m tower station operated by Environment Canada. Precipitation data from 1999 to 2005 were acquired from a nearby Environment Canada station at Humboldt to assess the missing precipitation periods.

Field surveys of soil properties (volumetric soil-moisture and porosity), vegetation cover (height and type), snow accumulation (depth and density), and wetland water level were conducted by the Centre for Hydrology, Department of Soil Science and Environment Canada. Volumetric soil-moisture was measured using time domain reflectometry (TDR) (Soil Equipment Corp., Trase System) during the autumns of 1999–2004. Gravimetric techniques were used to determine the volumetric soil-moisture and porosity for the fall of 2005. Measured porosities fell within the range for clay loamy soil texture reported by Dingman (1994) and were assumed to remain unchanged through time. The fetch distance for blowing snow was determined from the topographic maps and aerial photographs. Lag and storage coefficients for routing were determined using methods outlined by the Division of Hydrology (1977) based on drainage area size, location, shape and landform type. The routing lag and storage coefficients used here are not for the purpose of fitting the hydrograph, but rather for estimating the progression of snowmelt runoff to the wetland. The observed parameters relevant to modelling for the basin of Wetland 109 during 1999–2006 are summarized in Table I.

Cold regions hydrological modelling platform

The physically based cold regions hydrological modelling (CRHM) platform is capable of simulating the water balance for Canadian prairie basins and has an ability to analyse the sensitivity to drought of prairie snowmelt runoff due 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 (PBSM) (Pomeroy and Li, 2000), the Energy-Budget Snowmelt Model (EBSM) (Gray and Landine, 1988), Gray's parametric 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; Gray and Landine, 1987; Granger and Gray, 1990). 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 that have an internally uniform hydrological response that can be described by a common set of parameters, variables, and fluxes (Pomeroy *et al.*, 2007). For each HRU, model simulations 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 using CRHM.

Within CRHM, PBSM (Pomeroy and Li, 2000) was used to estimate pre-melt snow accumulation (expressed as SWE). Snowmelt rate and cumulative snowmelt (Melt) were calculated by EBSM (Gray and Landine, 1988) using the SWE from PBSM. Cumulative snowmelt infiltration into unsaturated frozen soils (INF) was estimated

Table I. Observed parameters for CRHM simulations at 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 (h)	Routing storage (day)
			1999–2000				
Cultivated (stubbles)	0·01601	0·21	0·48	0·300	300	8	1·0
Wetland	0·00412	0·23	0·54	5·000	300	0	0·5
			2000–2001				
Cultivated (stubbles)	0·01601	0·19(0·09)[a]	0·48	0·100	300	8	1·0
Wetland	0·00412	0·22(0·00)[a]	0·54	5·000	300	0	0·5
			2001–2002				
Cultivated (stubbles)	0·01601	0·19	0·48	0·150	300	8	1·0
Wetland	0·00412	0·22	0·54	5·000	300	0	0·5
			2002–2003				
Cultivated (fallows)	0·01601	0·19	0·48	0·001	300	8	1·0
Wetland	0·00412	0·22	0·54	5·000	300	0	0·5
			2003–2004				
Cultivated (stubbles)	0·01601	0·22	0·48	0·100	300	8	1·0
Wetland	0·00412	0·25	0·54	5·000	300	0	0·5
			2004–2005				
Cultivated (stubbles)	0·01601	0·19	0·48	0·100	300	8	1·0
Wetland	0·00412	0·22	0·54	5·000	300	0	0·5
			2005–2006				
Cultivated (stubbles)	0·01601	0·27	0·48	0·200	300	8	1·0
Wetland	0·00412	0·32	0·54	5·000	300	0	0·5

[a] The values in the brackets are water content levels for the soils with macro-pore development in 2000–2001. These values were used in the CRHM simulations.

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 the 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:

$$R = Melt - INF - Evap \qquad (1)$$

where all terms are in millimetre of water equivalent.

These fluxes were estimated on the spatial units of the HRU. Based on the primary land use of the basin, two HRUs (cultivated and wetland) were defined to calculate the basin runoff. The definition of HRU was based on the major land use within the basin and considered only the area that contributed to the surface runoff. Thus, the estimations of hydrological processes for the basin were made based on HRU area, weighted as:

$$X_{\text{basin}} = X_{\text{cultivated}} \frac{Area_{\text{cultivated}}}{Area_{\text{basin}}} + X_{\text{wetland}} \frac{Area_{\text{wetland}}}{Area_{\text{basin}}} \qquad (2)$$

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

CRHM test

The simulated pre-melt snow accumulation was compared to field observations from the springs of 2000, 2001, 2003, and 2006. Snow accumulation was derived from snow depth and density surveys taken by Environment Canada along two transects (north–south and east–west) across Wetland 109. The simulated cumulative snowmelt runoff in the basin was tested against the observed runoff in the springs of 2000 and 2001 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:

$$MB = \frac{\sum X_{\text{s}}}{\sum X_{\text{o}}} - 1 \qquad (3)$$

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 simulate the water balance during winter and spring periods for the basin of Wetland 109 based on field observations from both the drought period of 1999–2005 and the non-drought period of 2005–2006. Meteorology during the hydrological winter period (1 November to 1 May), soil, land cover conditions, blowing snow fetch distance, and the routing parameters described in Table I were used in CRHM simulations. The simulations were conducted to estimate snow accumulation (SWE) after wind redistribution, sublimation of blowing snow, snow-cover duration, winter actual evaporation, cumulative snowmelt, cumulative rainfall infiltration into unfrozen soils, cumulative snowmelt infiltration into frozen soils, and snowmelt runoff.

Basin land use change scenarios

Two scenarios of land use change were modelled for the severe drought of 1999–2002. CRHM parameters for land cover type and vegetation height in each HRU were altered 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 II:

Scenario 1: Changing the land use of the contributing area (cultivated field) from stubble to summer-fallow while keeping the land use of the wetland area unchanged.

Scenario 2: Changing the land use of the wetland area from tree cover to grass while keeping the land use of the contributing area unchanged.

RESULTS

Air temperature and precipitation anomalies

The seasonal precipitation (rainfall and snowfall) and air temperature for the hydrological winters (1 November to 1 May) during 1999–2006 were observed and acquired from field meteorological stations (Figures 2 and 3). Figure 2 shows that precipitation was consistently low for the winters of 1999–2000, 2000–2001, 2001–2002, 2003–2004, and 2004–2005 with cumulative values of 73·6, 71·2, 58·8, 84·8, and 77·5 mm, respectively. Precipitation in the winter of 2002–2003 was relatively high with a total of 123·8 mm. The highest cumulative precipitation for the period of 1999–2006 was 148·1 mm, in the winter of 2005–2006. Figure 3 shows that air temperatures were relatively cold during the hydrological winters of 2000–2001, 2001–2002, 2002–2003, and 2003–2004 with the average temperature below −8 °C for all these four winters. Average air temperatures during hydrological winters of 1999–2000 and 2004–2005 were somewhat warmer at −6·2 and −7·3 °C, respectively. The highest average temperature for the period 1999–2006 was −5·4 °C, and occurred over the wettest winter, that of 2005–2006.

Figure 4 compares these observations with the longer term average seasonal precipitation and air temperature (Figure 4). Figure 4(a) shows that a 30-year (1975–2005) average precipitation during the hydrological winter was quite similar between Saskatoon and Humboldt, 85·4 and 86·1 mm, respectively (Environment Canada, 2006). Compared to the 30-year average precipitation in Saskatoon, observed precipitation was 14, 17, 31, and 9% lower for the hydrological winters of 1999–2000, 2000–2001, 2001–2002, and 2004–2005 respectively, with similar values for Humboldt. In contrast, precipitation in the hydrological winters of 2002–2003 and 2005–2006 was 45 and 73% higher. The precipitation in the hydrological winter of 2003–2004 was very near to the average of Saskatoon and Humboldt.

Figure 4(b) shows that the 30-year (1975–2005) average air temperatures during hydrological winter was −8·2 and −9·2 °C for Saskatoon and Humboldt, respectively (Environment Canada, 2006). However the 7-year (1999–2006) mean hydrological winter temperature at SDNWA was −7·6 °C. This implies that slightly warmer than average conditions developed during this study period.

CRHM evaluations for prairie snowmelt runoff

The pre-melt snow accumulation from snow depth and density surveys at Wetland 109 were compared to the simulated accumulation for the springs of 2000, 2001, 2003, and 2006 (Figure 5). Figure 5(a) and (b) shows that the simulated 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 also 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 the springs of these years. Figure 5(c) shows that the values of MB were 0·04 and 0·06 for the pre-melt SWE in 2000 and 2003, representing an overestimation of 1·2 and 3·6 mm SWE, respectively. This suggests that CRHM performed well in predicting the redistribution of snow for these 2 years. Values of MB, −0·18 and −0·12 for 2001 and 2006 indicate a more substantial underestimation of 8 and 12 mm pre-melt SWE for 2001 and 2006.

Table II. Vegetation heights for the land use scenarios in the basin of Wetland 109 during the 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	0·30	5	***0·001***	5	0·30	***0·6***
2000–2001	0·10	5	***0·001***	5	0·10	***0·6***
2001–2002	0·15	5	***0·001***	5	0·15	***0·6***

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

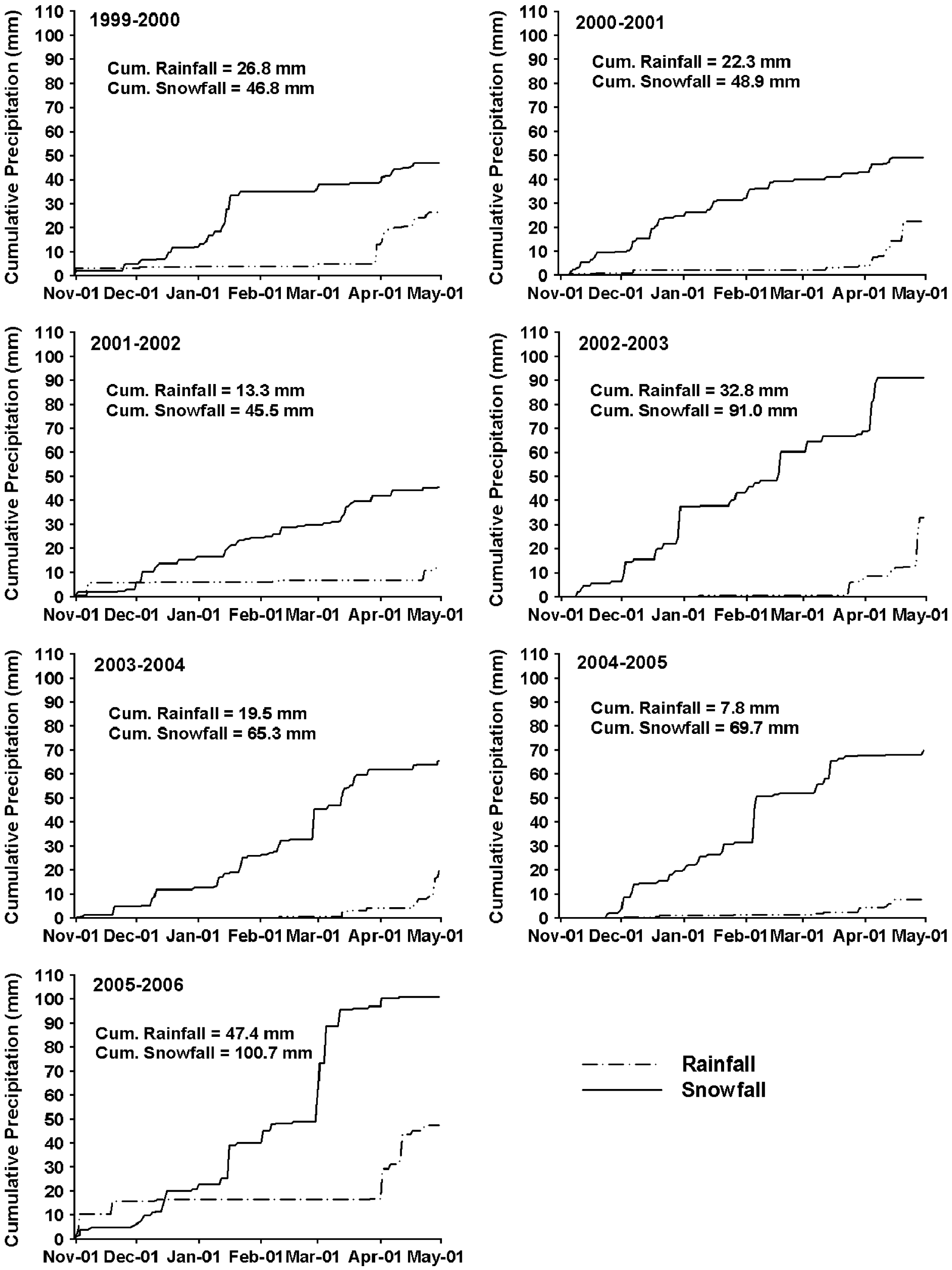

Figure 2. Observed cumulative precipitation for hydrological winters during 1999–2006 at SDNWA

The modelled cumulative snowmelt runoff in the basin was compared with the observed cumulative runoff at the end of March in 2000 and 2001 (Figure 5(d)). In March 2000, 14·9 mm of snowmelt runoff was estimated using CRHM; this underestimates the observed runoff by 3 mm (MB = −0·17). The CRHM simulation estimated 3·6 mm of runoff for March 2001; this was very comparable to the observed melt runoff. Overall, the tests against observed pre-melt snow accumulation and spring snowmelt runoff indicate that CRHM has a reasonable performance in simulating the major water inputs to Wetland 109 for both drought and non-drought periods.

Drought impacts on prairie wetland snowmelt hydrology

Major wetland snowmelt-runoff processes during the hydrological winter were simulated for individual HRU at Wetland 109 during 1999–2006 (Figure 6). The figure shows the combined effects of changing meteorology and changing soil and land cover conditions on the Canadian prairie wetland snowmelt hydrology during

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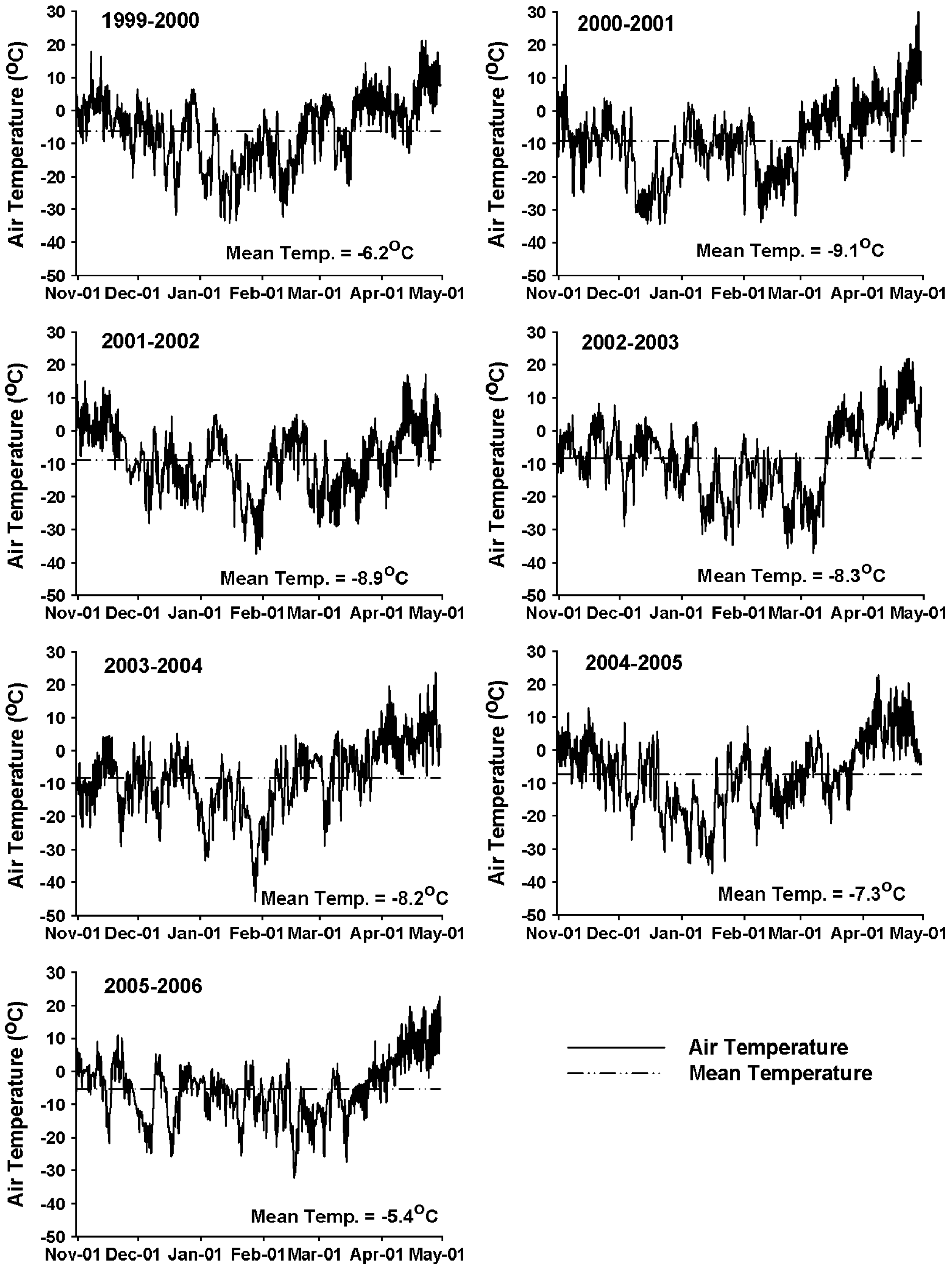

Figure 3. Observed air temperature for hydrological winters during 1999–2006 at SDNWA

the drought. The figure also illustrates how individual HRUs (cultivated field and wetland) respond to these conditions. Figure 6(a) shows that the snow accumulation (SWE) was consistently low for both cultivated field and wetland during the hydrological winters of 1999–2000, 2000–2001, and 2001–2002; all 'severe drought' periods. There was only 46–57% of SWE in the cultivated field and 30–45% of SWE in the wetland compared to the snow accumulations during 2002–2003 and 2005–2006 which were more 'normal' periods. There were only moderate amounts of SWE during the hydrological winters of 2003–2004 and 2004–2005 which were periods of recovery from drought. In contrast, there was substantial snow accumulation in the wetland HRU during 2002–2003 when compared to that during 2005–2006; this is because the summer-fallowed field in 2002 resulted in more blowing snow redistributed to the wetland. Figure 6(b) shows that the snow-covered periods during the severe drought

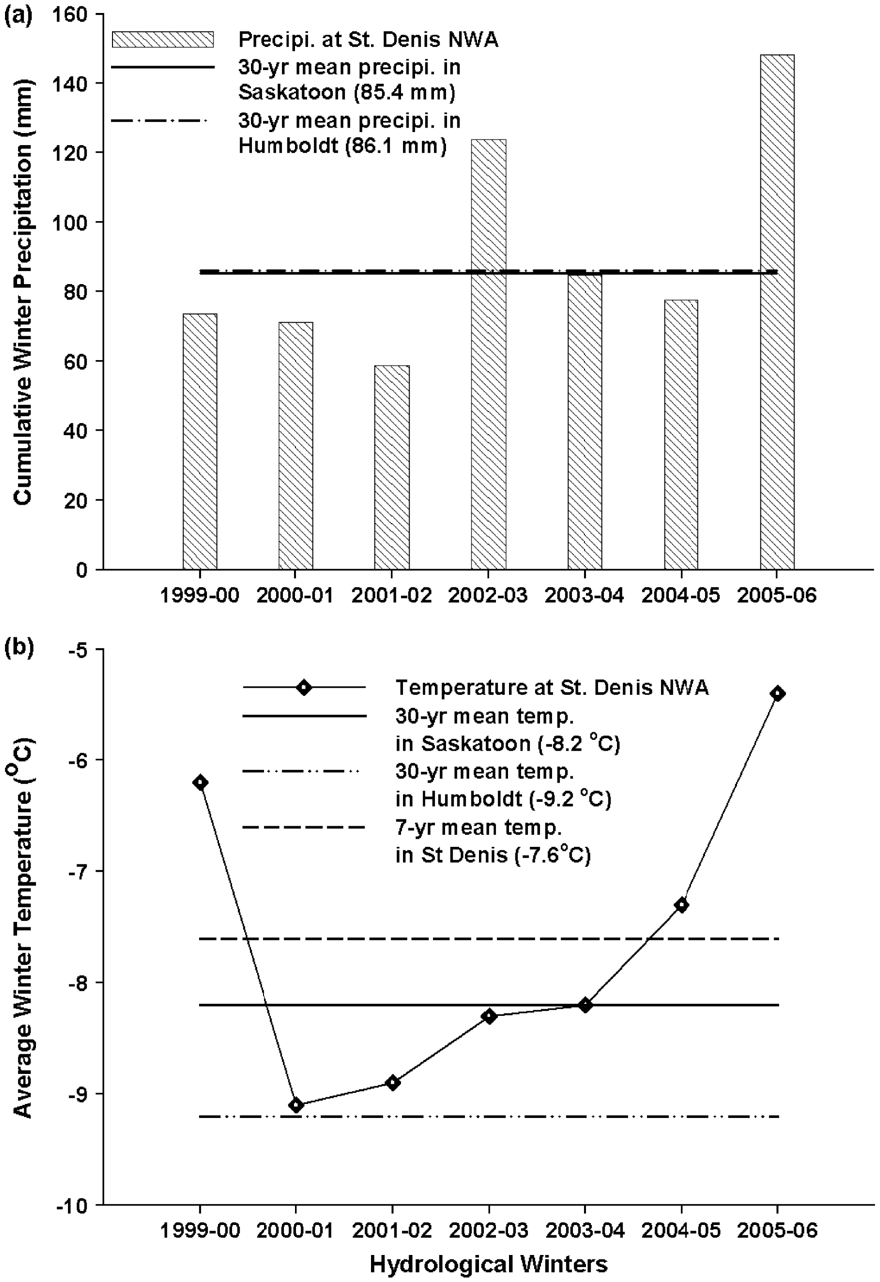

Figure 4. Comparisons of winter precipitation and temperature during hydrological winters of 1999–2006 to 30-year (1975–2005) mean precipitation and temperature

were much shorter than during the recovery and normal years. Figure 6(c) shows that sublimation of blowing snow was persistently low to negligible for the severe drought periods; this is due to suppression of blowing snow transport, as snow depth rarely exceeded the vegetation height in the fields. Figure 6(d) illustrates that winter evaporation in the cultivated field was not very sensitive to drought; however, evaporation in the wetland tended to be higher during the severe drought years of 1999–2000 and 2000–2001, due to shorter snow-covered season and earlier initiation of evaporation in the spring. Figure 6(e) shows that there was no difference in rainfall infiltration into unfrozen soils between HRUs and that infiltration was closely associated with the amount of rainfall. Snowmelt infiltration into frozen soils was very sensitive to the changing soil conditions and increased as the fall soil-moisture decreased (Figure 6(f)). Figure 6(g) demonstrates that compared to the normal periods, there was much lower snowmelt runoff during the severe drought years, with decreases of 35–58 mm and 75–90 mm from normal for the cultivated field and wetland, respectively. This shows that the runoff generation to prairie wetlands is very sensitive to the combined effects of lower snow redistribution by wind, enhanced winter evaporation, and higher infiltrability during drought.

The evolution of some important wetland snowmelt-runoff processes was simulated for the basin of Wetland 109 during 1999–2006 (Figure 7). The cumulative response of these processes to the combined conditions

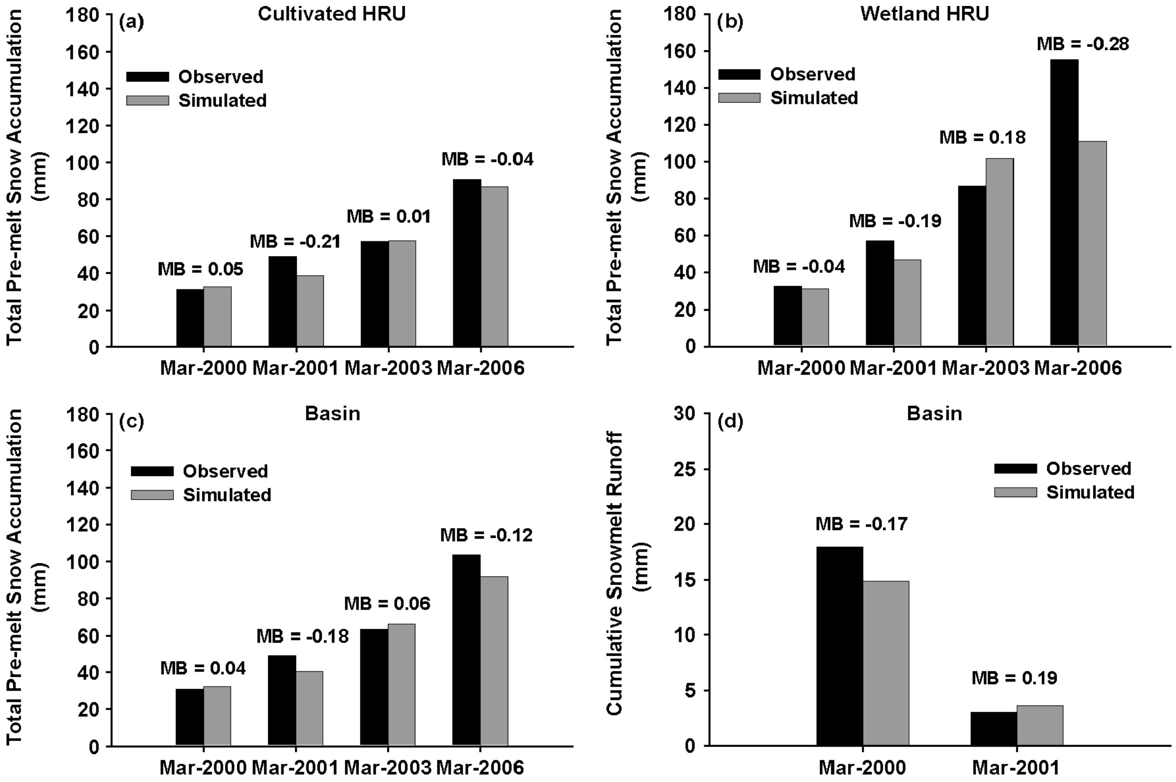

Figure 5. CRHM test of total pre-melt snow accumulation: (a) cultivated HRU, (b) wetland HRU, (c) basin, and (d) CRHM test of cumulative basin snowmelt runoff

of meteorology, soil, and land cover was estimated at end of the winter (Figure 8). Compared to the 'normal' periods, 2002–2003 and 2005–2006, both snowfall and rainfall during hydrological winter were consistently low for the 'severe drought' years, 1999–2002. As a result, compared to the normal years, snow accumulation was 50–55% lower for the basin during severe drought. Snow accumulation was moderate for the hydrological winters of 2003–2004 and 2004–2005, 'recovery' periods. The snow-covered season was 17–63 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 is due to suppressed blowing snow from low snowfall, warm temperatures, relatively tall vegetation cover, and high relative humidity at this upland location. Basin winter evaporation was not very sensitive to the changing conditions during 1999–2006, with increases of 3–8 mm in winter seasonal evaporation during severe drought periods as compared to non-drought. Total winter and spring infiltration was not greatly influenced by the changing conditions during 1999–2006. This is because total infiltration comprises both rainfall infiltration into unfrozen soils and snowmelt infiltration into frozen soils; both are complex processes controlled by combinations of hydrometeorological condition and soil status. Basin snowmelt runoff was much lower during the severe drought periods, approximately 45–65 mm less compared to that in the normal periods. Snowmelt runoff was particularly low in 2000–2001 and this is related to the formation of macro-pores in dry soils (van der Kamp *et al.*, 2003; Bodhinayake and Si, 2004). Macro-pores such as caused by cracks permit unlimited soil infiltrability for frozen soils in the prairie environment (Gray *et al.*, 2001). Similar results to snowmelt runoff were found in the spring wetland 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.

Basin land use change scenarios

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

The results of simulated basin-wide winter and spring hydrological processes corresponding to the hypothetical scenarios of land use change are shown in Figure 11. Figure 11(a) shows that in Scenario 1 for the hydrological winters of 1999–2002, blowing snow sublimation

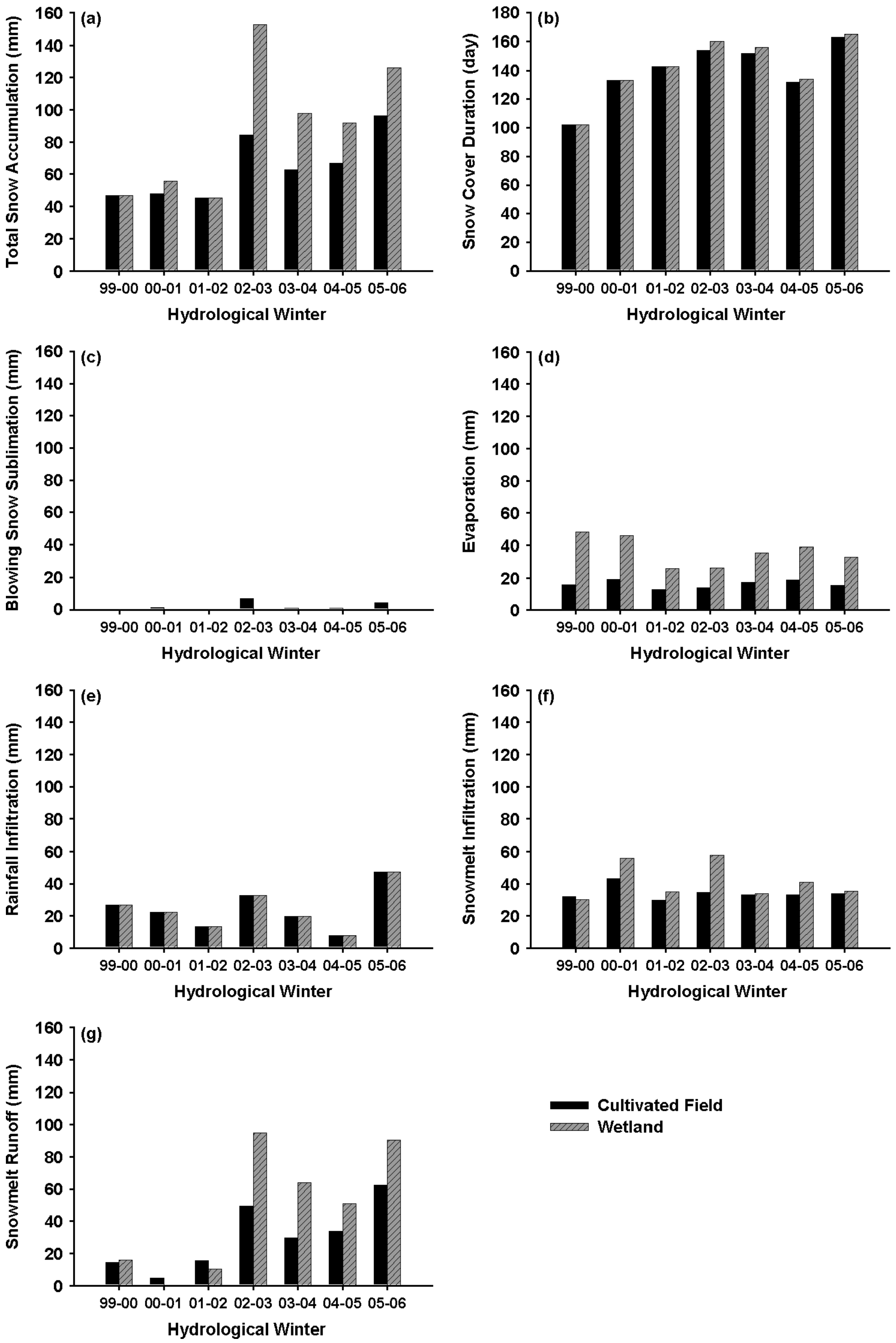

Figure 6. Hydrological processes for individual HRU at Wetland 109 during 1999–2006: (a) total snow accumulation, (b) snow-cover duration, (c) blowing snow sublimation, (d) evaporation, (e) rainfall infiltration, (f) snowmelt infiltration, and (g) snowmelt runoff

and total infiltration increased slightly; winter evaporation decreased slightly, and pre-melt snow accumulation increased by 2–10 mm. The increase in pre-melt snow accumulation was because blowing snow transport was enhanced and more snow was transported from the summer-fallowed field to the wetland, as well as a net gain to the basin by the import of blowing snow from outside of the effective drainage area (Figure 11(b)). Figure 11(a) shows that snowmelt runoff increased as a result of greater basin pre-melt SWE and lower winter evaporation. Figure 11(c) illustrates that in Scenario 2 infiltration increased by 1 mm, winter evaporation decreased by 1 mm, and snowmelt runoff decreased by 1 mm in the winter of 2000–2001, but no notable changes to other processes occurred. The results shown in Figure 11 indicate that reducing the vegetation height in the cultivated field not only enhances blowing snow transport to and snow accumulation in

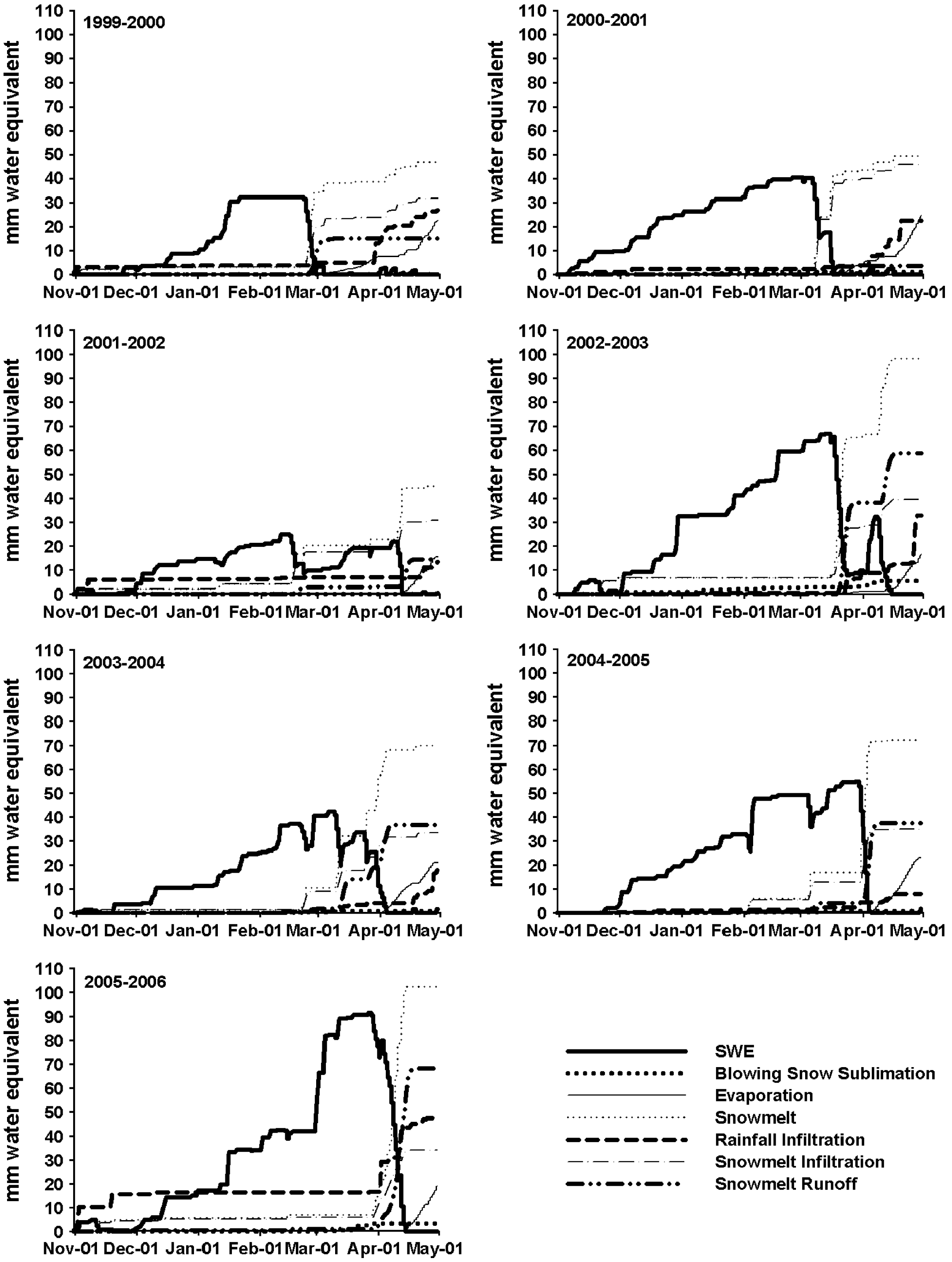

Figure 7. The evolution of wetland snowmelt-runoff processes during the hydrological winter of 1999–2006 at Wetland 109

the wetland, but by increasing overall basin snow accumulation increases basin snowmelt runoff. Reducing the vegetation height in the wetland area had a minimal effect on the winter and spring hydrological processes.

DISCUSSION

Severe winter drought occurred during 1999–2002. It began with an inadequate precipitation during the hydrological winter (1 November 1999 to 1 May 2000) as illustrated in Figure 4(a). This was a meteorological drought characterized by below-average precipitation over an extended period of time (Wilhite and Glantz, 1985). The occurrence of meteorological drought on the Canadian prairie during 1999–2002 was related to large-scale disruptions of atmospheric circulation patterns (Liu *et al.*, 2004; Bonsal and Wheaton, 2005; Shabbar, 2006). 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

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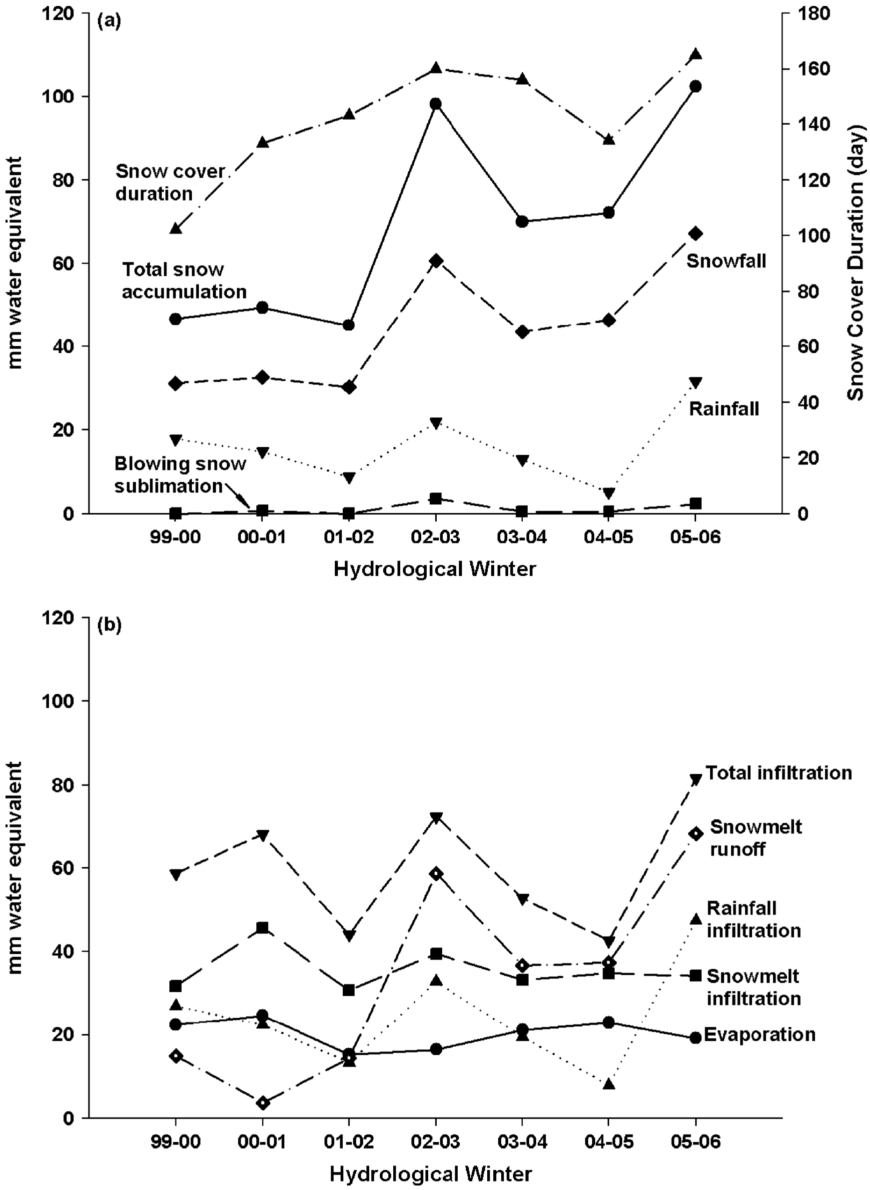

Figure 8. Hydrological processes for the basin of Wetland 109 during 1999–2006: (a) snowfall, rainfall, total snow accumulation, snow-cover duration, blowing snow sublimation and (b) evaporation, rainfall infiltration, snowmelt infiltration, total infiltration, snowmelt runoff

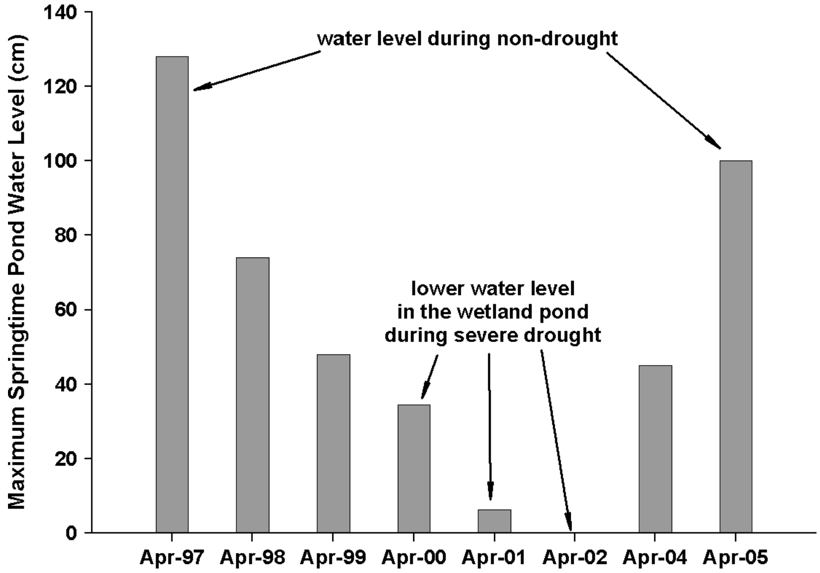

Figure 9. Observed maximum springtime water levels in Wetland 109, St Denis NWA during 1997–2005 (note that water level was not measured in April 2003)

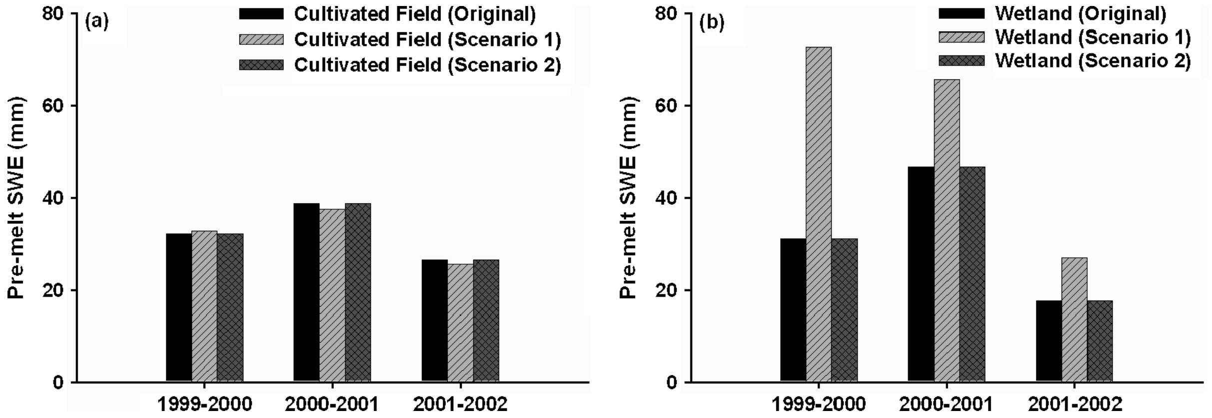

Figure 10. Pre-melt SWE changes corresponding to scenarios of land use change (Table II): (a) cultivated HRU and (b) wetland HRU

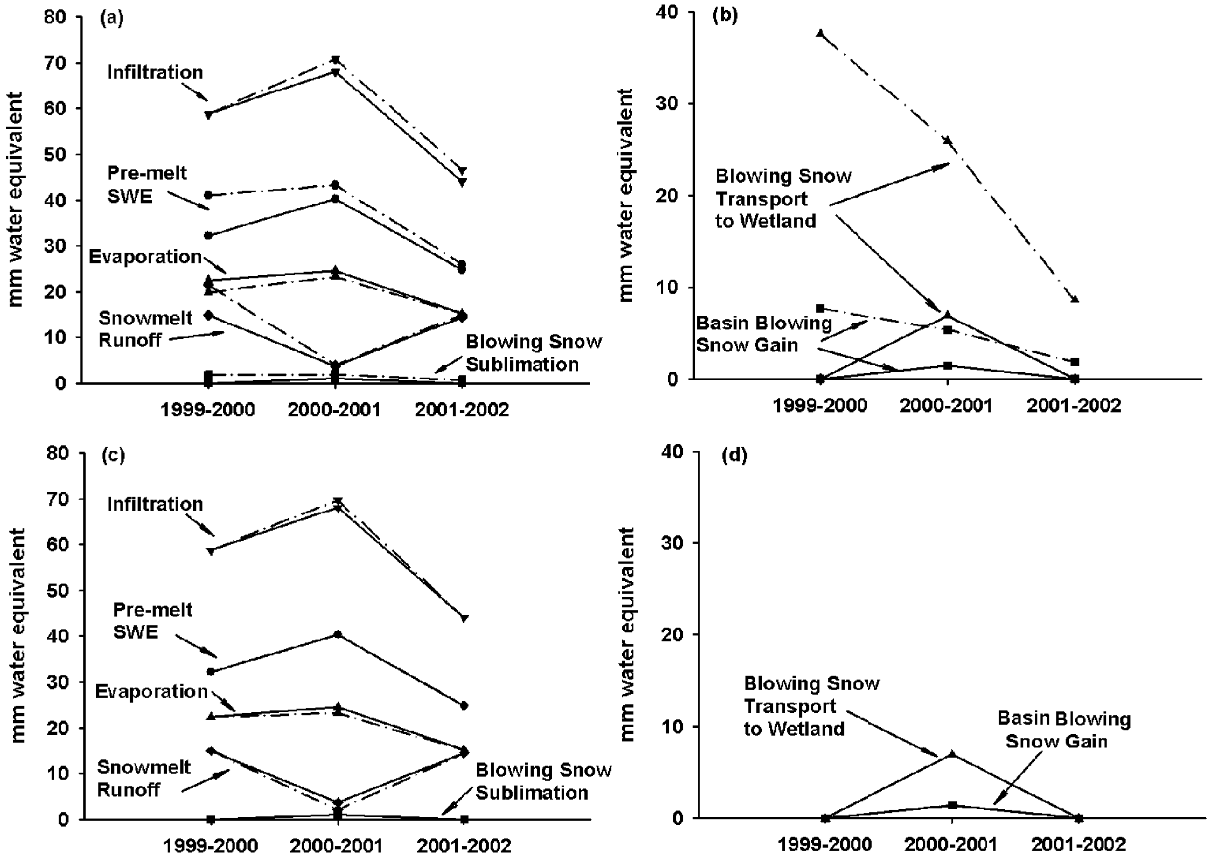

Figure 11. Basin-wide snowmelt runoff-related processes corresponding to (a) and (b) Scenario 1 of land use change (Table II), (c) and (d) Scenario 2 of land use change (Table II) (solid line indicates pre-change and dash dot line indicates post-change)

2001–2002, resulting in much reduced springtime discharge of snowmelt to wetland areas and subsequently in the drying out of wetlands.

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 the major snowmelt-runoff processes that are relevant to the prairie wetland environment. Wetland 109 is typical of small, internally drained headwater prairie depressional basins. The good performance of CRHM in such a basin does not guarantee its performance in larger, more complex basins containing several wetlands. Thus, 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 1999–2005 at the SDNWA has distinctive characteristics. A 3-year (1999–2002) severe winter drought period was followed by a normal year (2002–2003) and then a 2-year (2003–2005) recovery period, with slightly below-average precipitation and notably lower snowmelt runoff and wetland water levels, which then returned to normal in 2005–2006. This observed sequence demonstrates the nature of drought which is a gradual phenomenon, with its beginning and end hard to define (Wilhite and Buchanan-Smith, 2005).

The winter season discussed here is the hydrological winter, extending from October or November to end of April, during which hydrological processes such as snowfall, snowmelt, and snowmelt runoff occur. Different definitions of winter exist, such as the meteorological winter (i.e. December, January, and February). Below-average air temperatures developed during the hydrological winter in drought in the western Canadian prairie (Fang and Pomeroy, 2007) and this central prairie region, whereas positive temperature anomalies were found during the meteorological winter in these regions (Environment Canada, 2007). This suggests that the selection of the definition of winter is important when making comparisons of precipitation and air temperature to long-term averages. In cold regions such as the Canadian prairies, the conventional meteorological definition of winter is not long enough to provide information for the real winter hydrological processes, and in any case real winter in this region is always longer than 3 months. Definitions of seasons in this region should take into account the purpose of the definition rather than following an arbitrary division of the year into four equal seasons—certainly for prairie hydrology a 6-month winter is warranted. Possible mechanisms for colder winters during drought are associated with a persistent upper atmospheric ridge centred near the Rocky Mountains. This leads to mass outbreaks of long, cold arctic air over the northern prairies. The air masses are cold, dry, and stable; very little precipitation occurs during these conditions. Thus, colder temperatures in winter during drought seem reasonable.

Snow accumulation and snowmelt infiltration are two major processes that influence snowmelt runoff and their interaction is important to interpret specific snowmelt-runoff signals. Two hydrological winters: 1999–2000 and 2000–2001 had similar pre-melt snow accumulation, but in the two following springs snowmelt runoff was completely different, with much lower snowmelt runoff in the spring of 2001 compared to that of 2000. This is related to the formation of macro-pores in dry soils as a result of continuous cropping practices following a hot and dry growing season and subsequently low soil-water content (Granger *et al*., 1984; Gray *et al*., 1985). This can lead to unlimited soil infiltrability (Gray *et al*., 2001), which means that moisture content in the soil matrix is no longer a controlling parameter for infiltration. In the unlimited case all melt water infiltrates into soils, leaving negligible water for runoff. Another example is in comparing two hydrological winters: 2001–2002 and 2002–2003 with the same amount of moisture content in the soil matrix, and thus the same snowmelt infiltration. However, there was much less snowmelt runoff in the spring of 2002. This is due to much lower pre-melt snow accumulation in the winter of 2001–2002 compared to 2002–2003.

The scenario of land cover change from stubble to summer-fallow showed that suppressing the surrounding vegetation to permit greater blowing snow transport to the wetland might alleviate shortages of water in wetlands during drought. By suppressing stubble, the wetland and basin can import blowing snow from surrounding fields. However, the 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 were sufficient to trap all possible blowing snow in a dry winter. This second scenario is important in assessing the importance of aspen dieback that occurred in the recent prairie drought.

It should be noted that the SDNWA is a small internally drained basin having many small depressions like Wetland 109. Wetland 109 typifies other small depressions with runoff-contributing area and accumulation area. The connectivity among these small depressions in the SDNWA is poor, and the simulated hydrological processes and drought impacts on Wetland 109 is representative of the SDNWA region. The SDNWA is a representative site of the central Saskatchewan wetland region characterized by rolling topography and small depressions. The results from a variety of simulations (e.g. drought impacts simulation and land use change scenarios simulation) in this study are representative of such a region.

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 1999–2005 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 to 3·7 °C in air temperature during the hydrological winter (1 November to 1 May) when compared to the non-drought period of 2005–2006. The occurrences of colder winter air temperatures during drought are reasonable and are associated with a persistent upper atmospheric ridge centred near the Rocky Mountains.

The drought impacts on snowmelt hydrological processes were simulated in CRHM for a small prairie wetland. Results showed that the 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 snowmelt runoff to the wetland during drought. Infiltration was not much affected by drought 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 the non-drought period of 2005–2006, and this resulted in decreases of more than 50 mm in snowmelt runoff 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 is to suppress the surrounding vegetation in order to allow more blowing snow transport from surrounding fields to the wetland.

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