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Prediction of snowmelt derived streamflow in a wetland dominated prairie basin

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Abstract

The eastern Canadian Prairies are dominated by cropland, pasture, woodland and wetland areas. The region is characterized by many poor and internal drainage systems and large amounts of surface water storage. Consequently, basins here have proven challenging to hydrological model predictions which assume good drainage to stream channels. The Cold Regions Hydrological Modelling platform (CRHM) is an assembly system that can be used to set up physically based, flexible, object oriented models. CRHM was used to create a prairie hydrological model for the externally drained Smith Creek Research Basin (~400 km^2), east-central Saskatchewan. Physically based modules were sequentially linked in CRHM to simulate snow processes, frozen soils, variable contributing area and wetland storage and runoff generation. Five "representative basins" (RBs) were used and each was divided into seven hydrological response units (HRUs): fallow, stubble, grassland, river channel, open water, woodland, and wetland as derived from a supervised classification of SPOT 5 imagery. Two types of modelling approaches calibrated and uncalibrated, were set up for 2007/08 and 2008/09 simulation periods. For the calibrated modelling, only the surface depression capacity of upland area was calibrated in the 2007/08 simulation period by comparing simulated and observed hydrographs; while other model parameters and all parameters in the uncalibrated modelling were estimated from field observations of soils and vegetation cover, SPOT 5 imagery, and analysis of drainage network and wetland GIS datasets as well as topographic map based and LiDAR DEMs. All the parameters except for the initial soil properties and antecedent wetland storage were kept the same in the 2008/09 simulation period. The model performance in predicting snowpack, soil moisture and streamflow was evaluated and comparisons were made between the calibrated and uncalibrated modelling for both simulation periods. Calibrated and uncalibrated predictions of snow accumulation were very similar and compared fairly well with the distributed field observations for the 2007/08 period with slightly poorer results for the 2008/09 period. Soil moisture content at a point during the early spring

was adequately simulated and very comparable between calibrated and uncalibrated results for both simulation periods. The calibrated modelling had somewhat better performance in simulating spring streamflow in both simulation periods, whereas the uncalibrated modelling was still able to capture the streamflow hydrographs with good accuracy. This suggests that prediction of prairie basins without calibration is possible if sufficient data on meteorology, basin landcover and physiography are available.

1 Introduction

The prairie region of Canada (the Prairies) lies in the southern part of provinces of Alberta, Saskatchewan, and Manitoba and is a portion of the vast Prairie Pothole Region of North America (Winter, 1989). The Canadian Prairies are characterized by relatively low precipitation especially in the southwest part and are highly subject to frequent and severe droughts (Nkemdirim and Weber, 1999; Fang and Pomeroy, 2007). Annual precipitation in the prairie region of Saskatchewan ranges from 300 to 400 mm (Pomeroy et al., 2007a), approximately one third of which occurs as snowfall (Gray and Landine, 1988). The Canadian Prairies are a cold region and exhibit typical cold region hydrology typified by continuous snowcover and frozen soils throughout the winter. Great variation in hydrology exists across the prairie region of Saskatchewan, with fairly well-drained, semi-arid basins in the southwest part and with numerous wetlands and lakes development in the sub-humid north central and eastern parts (Pomeroy et al., 2007a).

Important hydrological characteristics of the prairie region of Saskatchewan are long periods of winter (usually four to five months) with occasional mid-winter melts (common in the southwest and rare in the northeast) and a snowcover modified by wind redistribution and sublimation of blowing snow (Pomeroy et al., 1993). The blowing snow process is affected by the interaction of local topography and surficial vegetation cover with regional wind flow patterns (Pomeroy et al., 1993; Fang and Pomeroy, 2009). High surface runoff derives from spring snowmelt, which is 80% or more of annual local surface runoff (Gray and Landine, 1988), and occurs as a result of frozen mineral soils at the time and a relatively rapid release of water from melting snowpacks (Gray et al., 1985). Meltwater infiltration into frozen soils can be restricted, limited, and unlimited depending on soil infiltrability (Gray et al., 1985; Zhao and Gray, 1997). Deep soils are characterized by good water-retaining capacity and high unfrozen infiltration rates (Elliott and Efetha, 1999). Most rainfall occurs in spring and early summer from large frontal systems and the most intense rainfall in summer is associated with convective storms over small areas (Gray, 1970). During summer, most rainfall is consumed by evapotranspiration (Armstrong et al., 2008). Evapotranspiration occurs quickly via wet surfaces such as water bodies, wetted plant canopies and wet soil surfaces and relatively slowly from unsaturated surfaces such as bare soils and plant stomata (Granger and Gray, 1989).

The Canadian Prairies are characterized by numerous small wetlands as known locally as "sloughs" or "potholes"; these depressions formed from previous glaciations of the landscape. Majority of the depressional wetlands do not naturally integrate to any natural drainage system (LaBaugh et al., 1998) and are often internally drained, forming closed basins (Hayashi et al., 2003); in normal hydrological conditions these basins are termed non-contributing areas (Godwin and Martin, 1975). These wetlands occasionally connect to one another during wet conditions through the "fill and spill" mechanism (van der Kamp and Hayashi, 2009). The water balance of these wetlands is influenced by redistribution of snow by wind from adjacent upland areas, precipitation, evapotranspiration, snowmelt runoff, groundwater exchange, and antecedent status of soil and depressional storage (Fang and Pomeroy, 2008; van der Kamp and Hayashi, 2009). Depending on the water balance, these wetlands vary from being shallow and seasonal to deep and permanent. The depressional wetlands are important hydrological elements as they have large storage capacities (Hayashi et al., 2003) which can regulate peak runoff. They are also valuable habitats for migratory waterfowl (Smith et al., 1964). However, hydrology of these wetlands is very sensitive to changes in air temperature, seasonal precipitation and other climatic variability (Poiani et al., 1995; Fang and Pomeroy, 2008; van der Kamp et al., 2008). Land use alteration in surrounding upland areas can produce noticeable impacts on snowpack trapped by wetland vegetation, surface runoff to wetlands, and wetland pond level (van der Kamp et al., 2003; Fang and Pomeroy, 2008). 50 to 75% of the original Prairie wetlands have been filled, levelled, and drained since European settlement (Dahl and Johnson, 1991; Gleason and Euliss, 1998), which has been implicated as a cause for downstream flooding (Rannie, 1980; Hubbard and Linder, 1986).

Substantial efforts have been made to investigate hydrological processes governing prairie wetlands in terms of surface and subsurface hydrological processes, dynamics of wetland storage, and surface runoff (Woo and Rowsell, 1993; Hayashi et al., 1998; Berthold et al., 2004; Spence, 2007; van der Kamp and Hayashi, 2009). Hydrological modelling systems have been developed to focus on predicting water balance for large scale basins with considerable wetland storage (Vining, 2002; St. Laurent and Valeo, 2007; Wang et al., 2008), whereas physically based models integrating more cold regions hydrological processes have been assembled to simulate hydrological processes for the individual closed wetland basins (Su et al., 2000; Pomeroy et al., 2007b; Fang and Pomeroy, 2008). In light of the hydrological and ecological importance of prairie wetlands, the objectives of this paper are to: 1) develop a physically based, modular hydrological model for a Canadian Prairie stream and associated basin that is sensitive to land use, wetland drainage and storage, and other hydrological variables and states; 2) set up calibrated and uncalibrated hydrological modelling approaches, review their information requirements and compare their performance in simulating winter snow accumulation, estimating spring soil moisture, and predicting basin streamflow.

2 Study site and field observations

The study was conducted in the Smith Creek Research Basin (SCRB), which is located between the Rural Municipalities of Churchbridge and Langenburg in the east-central Saskatchewan, Canada approximately 60 km southeast of the City of Yorkton shown in Fig. 1a. The SCRB was initially estimated to have a gross area of about 445 km^2

based on a Ducks Unlimited Canada (DUC) basin delineation shown in Fig. 1b. Agricultural cropland and pasture are the dominant land uses, with a considerable area left to natural wetlands, native grassland and deciduous woodland. Soil textures mainly consist of loam (Saskatchewan Soil Survey, 1991). The basin is characterized by low relief with elevations varying from 490 m above sea level near the basin outlet area at the south end to 548 m in the north end upland; slopes are gentle and range from 2 to 5%. The 30-year (1971–2000) annual average air temperature at Yorkton Airport is 1.6 °C, with monthly means of −17.9 °C in January and +17.8 °C in July; the 30-year mean annual precipitation at Yorkton Airport is 450.9 mm, of which 106.4 mm occurs mostly as snow from November to April (Environment Canada, 2009). Frozen soils and wind redistribution of snow develop over the winter, and snowmelt and meltwater runoff normally occur in the early spring with the peak basin streamflow usually happening in the latter part of April. The spring snowmelt runoff is the main annual streamflow event in the basin and much of this runoff accumulates in the seasonal wetlands and roadside ditches. Many water control structures such as road culvert gates exist in the basin and are operated by local farmers to regulate the runoff in their cropland areas; the gates are closed during extremely high runoff periods (i.e. during fast snowmelts or intense rain storms) but remain open otherwise.

Instrumentation at SCRB consists of a streamflow gauge, main meteorological station, network of 10 rain gauge stations, and network of seven wetland water level transducers shown in Fig. 1b. The main meteorological station (SC-1) was set up in July 2007 and includes the measurements of air temperature, radiation (incoming short, long, outgoing short, and long-wave), relative humidity, wind speed and direction, soil moisture (0–40 cm), soil temperature (0–20 cm), snow depth, rainfall, and snowfall. Snowfall was corrected for wind-undercatch using the algorithm of MacDonald and Pomeroy (2007). These data were collected for two field seasons: 2007/08 and 2008/09. A stream depth gauge located at the basin outlet (05ME007) is operated by Water Survey of Canada at a site with a stable rating curve and has been used to estimate basin streamflow discharge since 1975.

Field surveys of soil properties and vegetation were conducted in the fall of 2007 and 2008. Soil samples were collected from the 18 field transects located nearby the rain gauge and water level stations and were later used to determine the soil moisture and porosity. These transects were selected to represent characteristic basin land uses: summer fallow, grain stubble, grassland, woodland, wetland, and drainage channel. Vegetation height, type, and density were recorded from the same field transects. In addition, snow surveys were taken from the same field transects over the winter of 2007/08 and 2008/09. Each survey was comprised of 420 samples of snow depth and 102 samples of snow density; the depth and density were used to estimate the water equivalent of snowpack.

3 Modelling methods

3.1 Cold Regions Hydrological Modelling Platform

The Cold Regions Hydrological Modelling platform (CRHM) was used to set up a prairie hydrological model to predict water balance for the SCRB. The development of CRHM involved many decades of hydrological research in the cold, semi-arid environment of the Canadian Prairies. CRHM is a state-of-the-art, physically based hydrological model which uses a modular, object-oriented structure (Pomeroy et al., 2007b). Within CRHM, component modules represent basin descriptions, observations or physically based algorithms for calculating hydrological processes, including redistribution of snow by wind, snowmelt, infiltration, evaporation, soil moisture balance, and runoff routing. These processes are simulated on landscape units called hydrological response units (HRU). HRUs are defined as spatial units of mass and energy balance calculation corresponding to biophysical landscape units, within which processes and states are represented by single sets of parameters, state variables, and fluxes. HRUs in the Prairies typically correspond to agricultural fields, grassland, forest woodland, and bodies of water (Fang and Pomeroy, 2008). CRHM has shown good simulations in mountain basins (Dornes et al., 2008), boreal forest and arctic basins (Pomeroy et al., 2007b), a semi-arid, well-drained prairie basin (Fang and Pomeroy, 2007), and a wetland prairie basin (Fang and Pomeroy, 2008).

A set of physically based modules was assembled in a sequential fashion to simulate the hydrological processes relevant to the SCRB (Fig. 2). The key modules include the radiation model of Garnier and Ohmura (1970), Prairie Blowing Snow Model (Pomeroy and Li, 2000), albedo model of Gray and Landine (1987), Energy-Budget Snowmelt Model (Gray and Landine, 1988), Gray's expression for snowmelt infiltration (Gray et al., 1985), Green-Ampt infiltration model (Ogden and Saghafian, 1997), Granger and Gray's (1989) unsaturated surface actual evaporation model, Priestley and Taylor's (1972) evaporation expression for wetlands, and a Muskingum streamflow routing model (Chow, 1964). A new wetland module was developed by modifying a soil moisture balance model, which calculates soil moisture balance and drainage (Dornes et al., 2008) to include depressional storage and pond surface water storage. This model was modified from an original soil moisture balance routine developed by Leavesley et al. (1983). The changes are to make this algorithm more consistent with what is known about prairie water storage and drainage (Pomeroy et al., 2007a). A flowchart of this module is shown in Fig. 3. The soil moisture balance model divides the soil column into two layers; the top layer is called the recharge zone. Inputs to the soil column layers are derived from infiltration of both snowmelt and rainfall. Evaporation only occurs from the recharge zone, and water for transpiration is taken out of the entire soil column. Excess water from both soil column layers satisfies groundwater flow requirements before being discharged to subsurface flow which represents flow in macropores that occurs in cracking clay and very coarse soils. Two components, depression and wetland pond, were added to the soil moisture balance model to simulate wetland drainage. Depressional storage represents small scale (sub-HRU) transient water storage on the surface of upland agricultural fields, pastures and woodlands. Wetland pond storage represents water storage that dominates a HRU in wet to moderate conditions, though the pond can be permitted to dry up in drought conditions. The inputs to depressional storage are from surface runoff and overland flow after the soil column is saturated. After the depressional storage is filled, overland flow is generated via the fill-and-spill process (Spence and Hosler, 2007), in which over-topping of the depression results in runoff but minimal leakage of water from the depression to sub-surface storage is permitted before it overtops. Evaporation is permitted from depressional storage. Wetland pond storage works in a similar manner to depressional storage, except that the pond area does not have a soil column, and inputs are derived from upland surface runoff and subsurface lateral unsaturated flow fed by infiltration.

3.2 Model parameterization

A pre-processing procedure was taken to estimate the values of model parameters. The procedure was essentially a model parameterisation based on field observations, lookup table values, and analysis of remote sensing and GIS. Two types of model parameterisation approaches, one using LiDAR and one substituting calibration for information gained from LiDAR were employed. The non-LiDAR-based calibrated modelling used a coarse topographic map based DEM as input, while the uncalibrated LiDAR-based modelling used a LiDAR derived DEM in the analysis. They had the same methods for setting all parameter values except for surface depression storage capacity. In the non-LiDAR-based modelling, surface depression storage capacity in the upland area was calibrated and surface depression storage capacity in the wetland area was estimated by an area-volume regression equation, whilst the LiDAR-based modelling used an automated GIS procedure with a depth-area-volume relationship (Brooks and Hayashi, 2002; Minke et al., 2010) to estimate surface depression storage capacity in all of the basin.

3.2.1 Basin physiographic parameters

For modelling large basins such as SCRB, CRHM has a new "representative basin" (RB) feature, in which a set of physically based modules are assembled with a specific arrangement of HRUs to represent a sub-basin. The RB can be repeated as necessary in a basin, with each sub-basin having the same modules but differing parameter sets as needed. Streamflow output from a number of RBs is then routed along the main stream through lakes, wetlands and channel. Both calibrated and uncalibrated approaches divided the SCRB into five sub-basins that are represented by five RBs of similar internal structure (Fig. 4). Both modelling approaches attempted the same automated basin delineation technique, "TOPAZ" (Garbrecht and Martz, 1993, 1997), while a 25-m topographic map based DEM and a 1-m LiDAR DEM were used for the calibrated and uncalibrated approaches, respectively. Both DEM inputs were resampled to 50-m for computational efficiency. The calibrated approach failed to delineate the TOPAZ channel and sub-basin segments due to poor quality of the topographic map based DEM, and the five sub-basins were manually defined by examining the Ducks Unlimited Canada (DUC) aerial photography, satellite imagery, and drainage network GIS data. The uncalibrated approach was able to generate TOPAZ channel and sub-basin segments from the LiDAR-based DEM, which were aggregated to five sub-basins.

Within each RB, seven hydrological responses units (HRUs) were derived from the supervised land use classification based on two SPOT 5 10-m multispectral images that were acquired on 5 July 2007 and 1 October 2008. The summer image was used mainly for separating vegetation and non-vegetation features, while the fall image was used to separate cropland and natural vegetation. Areas for fallow, stubble, grassland, open water, woodland, and wetland HRUs were determined from SPOT 5 land use classification; areas for river channel HRU was estimated from DUC drainage network GIS data. The average elevation for HRU at different sub-basins was determined from DEM and HRU classification. The latitude for the basin is the geographic centre of SCRB and was measured from GPS. The average ground slope of HRU was approximated from the reported slope values in Saskatchewan Soil Survey (1991).

3.2.2 Blowing snow and frozen soil parameters

Both calibrated and uncalibrated modelling used the same method for estimating blowing snow and frozen soil parameters. Blowing snow fetch distance is the upwind distance without disruption to the flow of snow. A computer program "FetchR" (Lapen and Martz, 1993) was used to estimate the fetch for the large exposed areas (i.e. fallow, stubble and grassland HRUs) from the DEM and vegetation classification, resulting in fetches of 1000 m, 1000 m, and 500 m, respectively. For river channel, open water, woodland and wetland HRUs, a 300 m fetch length was assigned. The vegetation height, stalk density and stalk diameter were calculated based on vegetation survey measurements. The distribution factor parameterizes the proportional allocation of blowing snow transport from aerodynamically smoother (or windier) HRU to aerodynamically rougher (or calmer) ones and was decided according to observed prairie landscape aerodynamic sequencing to favour deposition in wetland and river channel HRUs (Fang and Pomeroy, 2009). A frozen soil infiltration parameter, initial fall soil saturation, was determined from the soil porosity and volumetric fall soil moisture. The soil porosity was estimated from soil texture, which is predominately loam in the basin. Volumetric fall soil moisture was approximated from gravimetric measurement of soil survey samples.

3.2.3 Wetland and soil module parameters

For the soil column, the maximum water holding capacity was determined from multiplying the rooting zone depth by soil porosity; the initial value of available water in the soil column was estimated by multiplying the maximum water holding capacity by volumetric fall soil moisture content. The soil recharge layer is the shallow top layer of the soil column, approximately 60 mm; the initial value of available water in the soil recharge layer was determined by the product of the maximum water holding capacity and volumetric fall soil moisture content. It should be noted that the model treats river channel, open water, and wetland HRUs as having no soil column, and sustaining permanent surface ponding. Subsurface and groundwater drainage factors control the rate of flow in the subsurface and groundwater domains; these rates are slow in the prairie environment (Hayashi et al., 1998) and were estimated from the saturated hydraulic conductivity based on soil texture. Both modelling approaches used these same methods.

For the calibrated modelling, the maximum surface depression storage in the wetland area (wetland and open water HRUs) was estimated from the average value of individual wetland storage as determined from a simple surface area-volume relation for prairie wetlands (Wiens, 2001). The relationship was slightly modified to derive values in the SI units required by the model:

$$\mathrm{sd}_{\max} = \frac{1000\left[2.85\left(\frac{A}{10\,000}\right)^{1.22}\right]}{A} \quad \text{if} \quad A \leq 700\,000\,\mathrm{m}^2 \tag{1}$$

$$\mathrm{sd}_{\max} = \frac{1000\left[7.1\left(\frac{A}{10\,000}\right)+9.97\right]}{A} \quad \text{if} \quad A > 700\,000\,\mathrm{m}^2 \tag{2}$$

where $\mathrm{sd}_{\max}$ [mm] is the maximum surface depression storage, and A [m^2] is the wetland surface area which was obtained from DUC wetland GIS inventory. The calibrated modelling calibrated the maximum surface depression storage in the upland area (fallow, stubble, grassland, and woodland HRUs) by trial and error comparison of the simulated and observed hydrographs.

For the uncalibrated modelling, an automated procedure involving LiDAR DEM and various ArcGIS tools was used to extract initial depth, area and volume of surface depression which were in turn input into a depth-area-volume relationship, yielding final depth, area and volume of surface depression. The procedure is illustrated in Fig. 5. The basin LiDAR DEM was resampled from its original 1-m spatial resolution to 10-m, and a “fill pits” ArcGIS procedure was used to created a depressionless DEM from the 10-m LiDAR DEM; both were used as inputs in the ArcGIS 3-D spatial analyst “cut/fill”. “Cut/fill” detects changes in the area and volume of a surface between two times due to addition or removal of material. If a surface is characterized as “cut” from erosion, it is categorized into “net loss”, and if a surface is identified as “fill” from deposition, then it is regarded as “net gain”, and “unchanged” is another category if there is no change on the area and volume of a surface. Using both the original DEM and the depressionless DEM in the “cut/fill” created a virtual surface during two periods and generated only one category “net gain”. The DUC sub-basin wetland GIS inventory and the basin “cut/fill” surface depressions were input in the ArcGIS “intersect” tool, producing area and volume of sub-basin “cut/fill” surface depressions in the wetland area. The sub-basin supervised land use classification and the basin “cut/fill” surface depressions were together input in the ArcGIS “intersect” tool, generating the area and volume of sub-basin “cut/fill” depressions for each land use, which were then filtered by DUC sub-basin wetland GIS inventory to “Erase” the wetland portion. The final results were area and volume of sub-basin “cut/fill” surface depressions in the upland area. The volume of “cut/fill” surface depressions ($V_{3\text{-D}_{\text{cut/fill}}}$ [m^3]) results from the product of depth ($d_{3\text{-D}_{\text{cut/fill}}}$ [m]) and area ($A_{3\text{-D}_{\text{cut/fill}}}$ [m^2]), thus the depth of “cut/fill” surface depressions was calculated based on Eq. (3):

$$d_{3\text{-D}_{\text{cut/fill}}} = \frac{V_{3\text{-D}_{\text{cut/fill}}}}{A_{3\text{-D}_{\text{cut/fill}}}} \tag{3}$$

Then, a simplified depth-area-volume relationship (Brooks and Hayashi, 2002) was used to calculate the maximum surface depression volume ($V_{\max}$ [m^3]) according to Eq. (4):

$$V_{\max} = \frac{A_{\max} \cdot d_{\max}}{1+2/p} \tag{4}$$

where $A_{\max}$ [m^2] and $d_{\max}$ [m] are the maximum surface area and depth of depressions, respectively, and p [-] is the shape coefficient of depressions. Rearranging the Eq. (4), the maximum surface depression storage $\text{sd}_{\max}$ [mm] was estimated based on Eq. (5):

$$\text{sd}_{\max} = \frac{V_{\max}}{A_{\max}} \cdot 1000 = \frac{d_{\max}}{1+2/p} \cdot 1000 \tag{5}$$

where d_{max} is estimated from the depth of "cut/fill" surface depressions $d_{3\text{-D}_{cut/fill}}$ calculated by Eq. (3). $d_{3\text{-D}_{cut/fill}}$ was assumed to be the maximum for the depressions in the upland area, but was adjusted for the depressions in the wetland area due to the inability of the LiDAR signal to penetrate water stored in the permanent wetland. The average fall depth from the monitored wetlands shown in Fig. 1b was added to get d_{max} in the wetland area. $A_{3\text{-D}_{cut/fill}}$ was assumed to be the maximum. The shape coefficient p varied with area of each wetland; for the wetland smaller than $10\,000\,m^2$, p=1.72 was used, the average value estimated from Smith Creek wetland volume analysis (Minke et al., 2010). Values for larger wetlands as discussed by Hayashi and van der Kamp (2000) were used. The maximum surface depression storage in the wetland and upland areas was determined from average value of individual "cut/fill" surface depression storage in these areas using Eq. (5). For both modelling approaches, the maximum storage of river channel HRU was estimated from the DUC drainage networks GIS data assuming that the channel has parabolic cross-section. For the river channel, open water and wetland HRUs, the initial surface depression storage was approximated by the product of the maximum storage and the average percentage of fall storage capacity of the monitored wetlands. The initial surface depression storage for the upland area was set as zero due to its ephemeral nature of storage and typical dry antecedent condition in the fall.

3.2.4 Routing parameters

Both modelling approaches used the same method to determine routing parameters. These parameters were used in the Muskingum routing module (Chow, 1964). For the routing within RBs, the routing length is the distance from each HRU to the main channel; for the routing between RBs, the routing length is the main channel length in each sub-basin, and both types of routing length were estimated from DUC drainage networks GIS data. Manning's equation (Chow, 1959) was used to calculate the average flow velocity; the parameters used in the equation include hydraulic radius, longitudinal friction slope, and Manning's roughness coefficient. Hydraulic radius was determined from flow depth based on the channel shape. Longitudinal friction slope was calculated from the average change in elevation over a routing length using the DEM and DUC drainage networks GIS data. Manning's roughness coefficient was estimated based on the channel's condition. From the average flow velocity and routing length, the storage constant was estimated. The dimensionless weighting factor controls the level of attenuation, ranging from 0 (maximum attenuation) to 0.5 (no attenuation), so 0.25 was used for the basin. The routing sequence is illustrated in Fig. 6. For the routing within RBs, runoff in the upland area of fallow, stubble, and grassland is routed to the upland woodland, and then is routed to wetland, open water, and river channel. Runoff from the wetland is accumulated in the open water, which connect to the river channel.

A weighted routing distribution parameter is used to partition amount of runoff between HRUs and the values were determined from a modified Hack's law length-area relationship (Granger et al., 2002). The parameter is multiplied times the outflow from each HRU to distribute this outflow as inflow to the downstream HRU. For each non-river channel HRU, the land use polygons from the supervised classification were used to extract total polygon area and the longest linear length within the polygon. The extracted area and longest length were graphed on a log-log plot to generate the modified Hack's law length-area relationship:

$$L = 1.2815A^{0.5559} \text{ (fallow HRU)} \tag{6}$$

$$L = 1.3486A^{0.5391} \text{ (stubble HRU)} \tag{7}$$

$$L = 1.2965A^{0.5461} \text{ (grassland HRU)} \tag{8}$$

$$L = 1.2947A^{0.542} \text{ (open water HRU)} \tag{9}$$

$$L = 1.3587A^{0.5356} \text{ (woodland HRU)} \tag{10}$$

$$L = 1.2588A^{0.55} \text{ (wetland HRU)} \tag{11}$$

where L (km) is Hack's law length for each HRU and A (km^2) is total area for each HRU. For the river channel HRU, the original Hack's law length-are relationship (Hack, 1957) was used:

$$L = 1.4A^{0.6} \text{ (river channel HRU)} \tag{12}$$

where L (km) is Hack's law length for river channel HRU and A (km^2) is the average sub-basin area. The routing distribution parameter weighting was calculated using the relative estimated Hack's law lengths. For instance, the routing distribution parameters for runoff from fallow HRU to river channel, open water, woodland, and wetland HRUs are:

$$\text{distrib}_{\text{Route}_{\text{fallow}\to\text{river channel}}} = \frac{L_{\text{river channel}}}{L_{\text{river channel}} + L_{\text{open water}} + L_{\text{woodland}} + L_{\text{wetland}}} \tag{13}$$

$$\text{distrib}_{\text{Route}_{\text{fallow}\to\text{open water}}} = \frac{L_{\text{open water}}}{L_{\text{river channel}} + L_{\text{open water}} + L_{\text{woodland}} + L_{\text{wetland}}} \tag{14}$$

$$\text{distrib}_{\text{Route}_{\text{fallow}\to\text{woodland}}} = \frac{L_{\text{woodland}}}{L_{\text{river channel}} + L_{\text{open water}} + L_{\text{woodland}} + L_{\text{wetland}}} \tag{15}$$

$$\text{distrib}_{\text{Route}_{\text{fallow}\to\text{wetland}}} = \frac{L_{\text{wetland}}}{L_{\text{river channel}} + L_{\text{open water}} + L_{\text{woodland}} + L_{\text{wetland}}} \tag{16}$$

3.3 Model performance evaluation

Two simulation periods, 1 November 2007 to 8 May 2008 and 1 November 2008 to 9 May 2009, were carried out for both calibrated and uncalibrated modelling approaches. The maximum surface depression storage of upland area was calibrated for the 2007/08 simulation period, and the calibrated values were retained for the 2008/09 simulation period. For the non-calibrated approach, constant values derived from LiDAR as described previously were used. The model parameters described in Sect. 3.2 were used for calibrated and uncalibrated modelling simulations. The model prediction of snow accumulation, soil moisture, and streamflow was evaluated and comparisons were made between the modelling simulations and observations. To assess the performance of model, two statistical measures: root mean square difference (RMSD) and model bias (MB) were calculated as:

$$\mathrm{RMSD} = \frac{1}{n}\sqrt{\sum (X_\mathrm{s} - X_\mathrm{o})^2} \tag{17}$$

$$\mathrm{MB} = \frac{\sum X_\mathrm{s}}{\sum X_\mathrm{o}} - 1 \tag{18}$$

where n is number of samples, X_o, and X_s are the observed and simulated values, respectively. The RMSD is a weighted measure of the difference between observation and simulation and has the same units as the observed and simulated values. The MB indicates the ability of model to reproduce the water balance; a positive value or a negative value of MB implies model overprediction or underprediction, respectively.

4 Results

4.1 Winter snowpack prediction and comparison

For both calibrated and uncalibrated modelling, the simulations of snow accumulation (SWE) during the February–April of 2008 and 2009 were evaluated against observations. For the 2008 simulation period, three comparisons during the pre-melt period: 7 and 28 February, and 20 March and four comparisons during the melt period: 11–14 April were conducted. Three comparisons during the pre-melt period: 5 February, 3 and 20 March and four comparisons during the melt period: 3–9 April were carried out for the in the 2009 simulation period. Figures 7 and 8 show the comparisons of the observed SWE and the simulated SWE for fallow, stubble, grassland, river channel, open water, woodland and wetland HRUs in sub-basin 1. For the 2008 and 2009 simulation periods, the calibrated and uncalibrated simulations had very similar results and both SWE were generally in good agreement with the observations for most HRUs; except

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for fallow, stubble, grassland and open water HRUs during the melt period of 2008 and the fallow, stubble, and open water HRUs during the melt period of 2009.

Table 1 shows the RMSD for SWE simulations in all five sub-basins. For the 2008 simulation period, values of RMSD were very close between the calibrated and uncalibrated simulations for HRUs in all sub-basins except for the wetland HRU in sub-basin 2 and sub-basin 3. The RMSD ranged from 1.7 to 7.9 mm for fallow, stubble, open water, and woodland HRUs, indicating generally good performance; larger RMSD were found for grassland, river channel, and wetland HRUs, ranging from 7.1 to 25.2 mm. For the 2009 simulation period, values of RMSD were nearly identical between the calibrated and uncalibrated simulations in all sub-basins and were slightly larger than those in the 2008 simulation period. For fallow, stubble, grassland, and woodland HRUs, the RMSD ranged from 4.3 to 8.6 mm, while greater RMSD ranging from 7.8 to 22.4 mm were for river channel, open water, and wetland HRUs. In general, both calibrated and uncalibrated modelling had better simulations in the 2008 simulation period compared to the 2009 simulation period. Nevertheless, both calibrated and uncalibrated modelling simulated the general sequence of wind redistribution of snow well, relocating snow from fallow and stubble fields to river channels and wetlands.

4.2 Spring soil moisture prediction and comparison

After a 12.6 mm rainfall occurred on 22 March 2009, ice layer formation in the cropland, grassland, and shrubby wetland areas was noticed. The snowmelt infiltration into soils was restricted with the ice layer forming above soils, and the initial fall moisture status of soil matrix was no longer valid in this case. To cope with this, the initial fall soil saturation of 2008 for fallow, stubble, and grassland HRUs was adjusted to 80% from their original measured values, and the wetland HRU was set to the restricted case where no infiltration is permitted. With this adjustment, the predicted volumetric spring soil moisture from 14 April to 8 May in both 2008 and 2009 was tested against the observations from the main weather station (Fig. 9). Earlier observations cannot be used because of partially frozen soil. Both calibrated and uncalibrated simulations had identical results; simulated values were somewhat higher than observed in the 2008 simulation and somewhat lower than observed in the 2009 simulation period (Fig. 9). The calibrated and uncalibrated simulations had similar performance, with the RMSD at 0.011 and 0.009 for 2008 and 2009, respectively. This indicates on average, that the difference between the observed and simulated volumetric soil moisture was between 1.1% and 0.9%.

4.3 Spring streamflow prediction and comparison

For both calibrated and uncalibrated modelling, the simulations of spring streamflow were compared to the observations for both 2008 and 2009 simulation periods. Figure 10 shows the comparisons amongst the observed daily mean basin discharge and calibration and uncalibrated simulations. For the 2008 simulation period, both calibrated and uncalibrated simulations showed good timing for estimating the peak daily discharge (Fig. 10a); the peak daily discharge was one day ahead and two days late compared to the observed one. The observed peak daily discharge was 4.65 $m^3 s^{-1}$, which is very comparable to the calibrated (4.47 $m^3 s^{-1}$) and uncalibrated (4.68 $m^3 s^{-1}$) simulations (Table 2). On average, relatively small differences between the observed daily discharge and the simulations were found; Table 2 shows that the RMSD were 0.03 and 0.12 $m^3 s^{-1}$ for the calibrated and uncalibrated simulations, respectively. Both simulations predicted 27 days of spring streamflow, which is three days shorter than the observed streamflow duration. MB listed in Table 2 for the calibrated and uncalibrated simulations was −0.12 and −0.32, suggesting that the calibrated and uncalibrated simulations underestimated the cumulative basin discharge volume by 12% and 32%. The calibrated simulation appears to be better than the uncalibrated one, but the key parameter sd_{max} in the upland area was calibrated by comparing the simulated discharge to the observed one, which without doubt makes the simulation quite close to the observation. On the other hand, uncalibrated simulation used the sd_{max} estimated from entirely automated processes, in which errors may magnify.

For the 2009 simulation period, the calibrated simulation predicted the peak daily discharge two days earlier than the observed one, while the uncalibrated had same timing for peak daily discharge as the observation (Fig. 10b). The calibrated and uncalibrated simulations of peak discharge were 6.85 and 6.29 $m^3 s^{-1}$, respectively, which were quite similar to the observed (i.e. 6.22 $m^3 s^{-1}$; Table 2). RMSD were 0.27 and 0.33 $m^3 s^{-1}$ for the calibrated and uncalibrated simulations, respectively, indicating that on average, the difference between the observation and calibrated simulation was slightly smaller. The simulated duration of spring streamflow was 20 days shorter than the observed one. For the cumulative basin spring discharge, the simulated volume was lower by 30% and 56% for the calibrated and uncalibrated simulations, respectively.

5 Discussion

The calibrated and uncalibrated modelling approaches showed reasonable performance in capturing various components of the Prairie water balance. Both calibrated and uncalibrated predictions of winter snow accumulation were very similar and compared quite well with the distributed field observations. The simulations were able to effectively obtain the prairie blowing snow sequence (Fang and Pomeroy, 2009) and relocate snow from "source" areas (e.g. fallow and stubble fields) and deposit to "sink" or "drift" areas (e.g. tall vegetated wetland area and deeply incised channels). This is a vital process in governing the water balance of prairie basins as the majority of water in the wetlands and prairie river channels has been shown previously to be the result of the redistribution of snow by wind (Fang and Pomeroy, 2008, 2009) and subsequent snowmelt runoff (Gray and Landine, 1988; Pomeroy et al., 2007a).

Soil moisture prediction was also quite adequate for most agricultural management purposes. No difference between two modelling approaches was found because both approaches utilized the same methods (i.e. snowmelt infiltration, Gray et al., 1985, and Green-Ampt infiltration expression, Ogden and Saghafian, 1997) for estimating frozen soil moisture status.

Both modelling approaches were capable of matching the streamflow hydrographs with good accuracy in the 2008 simulation period (Fig. 10a); the calibrated approach performed slightly better than the uncalibrated approach due to trial and error setting of the maximum depressional storage parameter. All parameters were kept the same for both calibrated and uncalibrated simulations in the 2009 simulation period, where the hydrographs were of lower magnitude than observed, particularly in the recession limb of the hydrograph. The relatively large difference in the discharge volume between simulations and observation, especially for the 2009 simulations, is attributed to the representation of wetlands in the model. Only a single type of wetland HRU was set up for the entire basin, and wetlands were aggregated into one HRU for each sub-basin. This is likely an oversimplification as there are other types of wetland (e.g. drained wetland vs. intact wetland) and a wide range of wetland volumes in nature. It is recommended that to model a prairie basin with substantial wetland drainage development, more types of wetland representation are needed, ranging from newly drained wetland, established drained wetland, and intact wetland and that some type of wetland flow sequence be incorporated.

This study demonstrated a model parameterization procedure that does not rely on calibration with streamflow but instead utilizes a LiDAR DEM, SPOT 5 satellite images, stream network, and wetland inventory GIS data. This procedure also involved automated basin parameters delineation techniques and simplified wetland depth-area-volume calculation. Through this procedure, basin physiographic parameters such as basin area and elevation and important hydrological process parameter such as blowing snow fetch distance, wetland surface depression storage, and surface runoff and channel flow routing parameters were derived successfully. Using these parameters, the water balance for a prairie basin dominated by wetlands was reasonably simulated. Other model (e.g., Soil and Water Assessment Tool, SWAT) has a semi-distributed sub-basin and HRU approach to simulate the water cycle in the prairie pothole region (Du et al., 2005; Wang et al., 2008) but relies on streamflow calibration to estimate many parameters (i.e. those governing snowmelt rates and wetland water storage).

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The reason for this is that the SWAT model lacks physically based algorithms for cold region hydrological processes (e.g. snow redistribution by wind, snowmelt, and frozen soil infiltration). The uncalibrated CRHM simulation adequately addressed the major hydrological processes in the cold regions of prairie and did not depend on parameter calibration, suggesting that this uncalibrated modelling approach can be applied to ungauged prairie basins if sufficient meteorology, basin land use, and physiography data are available. In addition, benefits of applying LiDAR derived DEM in prairie hydrology study are high. Canadian prairie basins are characterized by many depressions; it was shown that using a conventional low quality DEM (e.g. topographic map sheet derived) would not be accurate enough to produce prairie channel network and to quantify basin depression storage. A LiDAR derived DEM is therefore highly recommended for investigating prairie hydrology.

6 Conclusions

The Canadian Prairie pothole region is characterized by numerous post-glacial surface depressions. These surface depressions form wetlands which are important factor in controlling the water balance in prairie basins. The ability of wetlands to trap blowing snow in winter and store runoff water is a crucial feature of the hydrology, and this poses a substantial challenge to hydrological modelling. A new wetland module was created in the Cold Regions Hydrological Model platform (CRHM) to deal with wetland water storage. Both the calibrated depressional storage and fully uncalibrated modelling approaches were involved in model parameterization and were used to predict the water balance in Smith Creek Research Basin. Results show that both calibrated and uncalibrated modelling approaches were capable of simulating wind redistribution of snow and snowmelt, updating frozen soil moisture content, and predicting spring basin streamflow. The uncalibrated simulations generated an innovative process to derive model parameters using field survey data, LiDAR DEM, SPOT 5 satellite images, stream network and wetland inventory GIS data. This innovative model parameterization process can be useful for modelling ungauged basins if high resolution information on basin characteristics is available.

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Table 1. Evaluation of snowpack simulations with the root mean square difference (RMSD, mm SWE). The values inside parentheses are for the uncalibrated simulations and the values outside parentheses are for the calibrated simulations.

	2008					2009				
HRU Name	Sub-basin 1	Sub-basin 2	Sub-basin 3	Sub-basin 4	Sub-basin 5	Sub-basin 1	Sub-basin 2	Sub-basin 3	Sub-basin 4	Sub-basin 5
Fallow	2.6	1.8	2.7	2.6	1.7	6.2	6.2	6.2	6.1	5.8
	(2.6)	(2.6)	(1.9)	(1.9)	(1.7)	(6.2)	(6.2)	(6.2)	(6.1)	(5.8)
Stubble	3.3	3.3	7.0	6.8	6.1	4.5	5.2	8.6	8.2	8.1
	(3.3)	(3.3)	(6.9)	(6.8)	(6.1)	(4.3)	(5.2)	(8.6)	(8.2)	(8.1)
Grassland	16.3	16.7	14.9	18.1	15.9	4.5	4.9	4.3	4.9	4.4
	(16.6)	(19.2)	(16.3)	(19.9)	(16.6)	(4.7)	(5.2)	(4.3)	(5.2)	(4.4)
River Channel	17.4	17.4	12.7	13.4	15.4	17.9	17.9	15.1	16.2	17.9
	(17.4)	(17.4)	(10.3)	(17.2)	(10.0)	(17.9)	(17.9)	(10.7)	(17.9)	(9.5)
Open Water	5.4	5.4	5.5	5.5	7.9	15.2	15.2	15.1	15.0	14.9
	(5.4)	(5.4)	(5.5)	(5.5)	(7.9)	(15.2)	(15.2)	(15.1)	(15.0)	(14.9)
Woodland	2.9	3.0	2.9	2.8	2.7	8.4	8.4	8.3	8.3	8.3
	(3.1)	(3.1)	(2.7)	(2.8)	(2.7)	(8.4)	(8.4)	(8.3)	(8.3)	(8.3)
Wetland	6.4	9.6	17.3	17.9	10.8	7.8	10.3	16.0	15.3	10.1
	(7.1)	(25.2)	(12.3)	(16.7)	(11.5)	(8.4)	(22.4)	(13.0)	(14.5)	(11.4)

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Table 2. Evaluation of simulating spring basin discharge with root mean square difference (RMSD, $m^3 s^{-1}$), model bias (MB), peak discharge ($m^3 s^{-1}$), and duration of discharge (day) in 2008 and 2009 simulation periods. CS, US, and Obs are calibrated simulation, uncalibrated simulation, and observation, respectively.

	RMSD (m^3/s)		MB		Peak Discharge (m^3/s)			Duration (Day)		
Year	CS	US	CS	US	Obs	CS	US	Obs	CS	US
2008	0.03	0.12	−0.12	−0.32	4.65	4.47	4.68	30	27	27
2009	0.27	0.33	−0.30	−0.56	6.22	6.85	6.29	40	20	20

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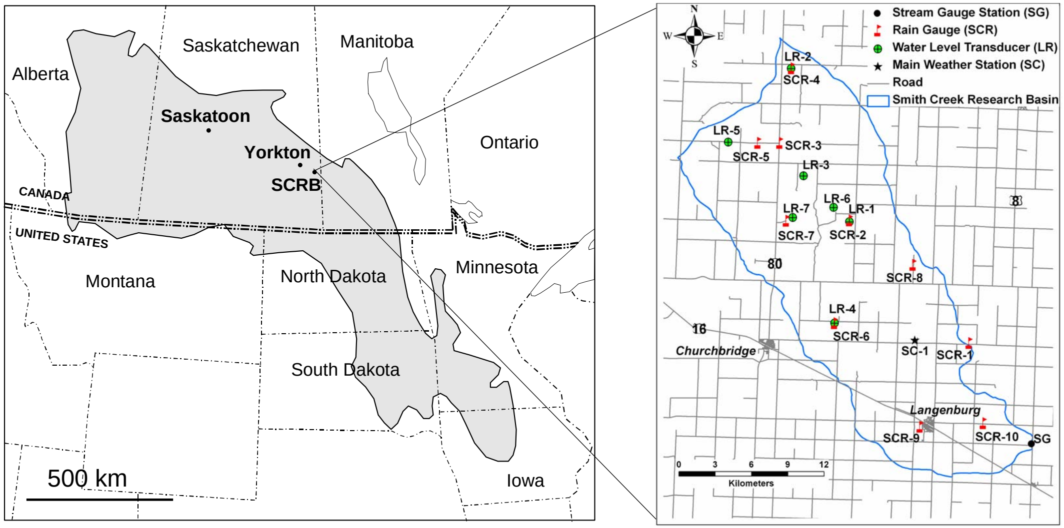

(a) (b)

Fig. 1. **(a)** Extent of the semi-arid glaciated northern prairie wetland region (grey shaded area) in Canada and the United States (Winter, 1989) and the location of Smith Creek Research Basin (SCRB), and **(b)** extent of the SC and field observation stations of rainfall (SCR), water level (LR), hydrometeorology (SC) and streamflow (SG).

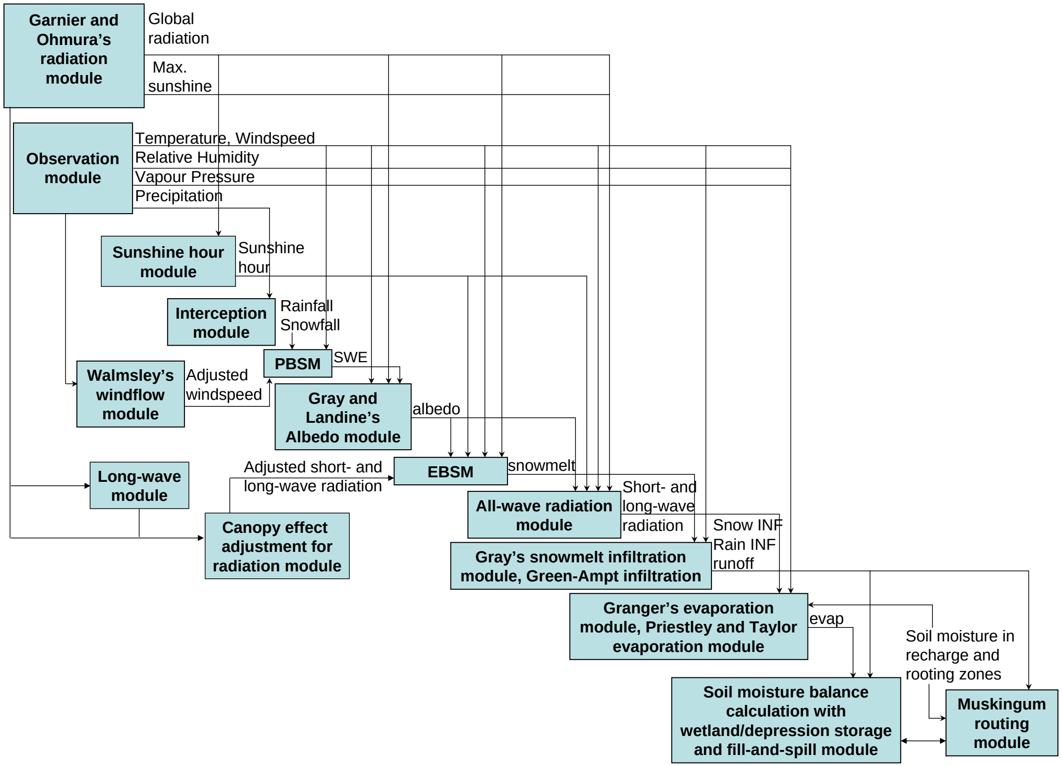

Fig. 2. Flowchart of physically based hydrological modules in CRHM.

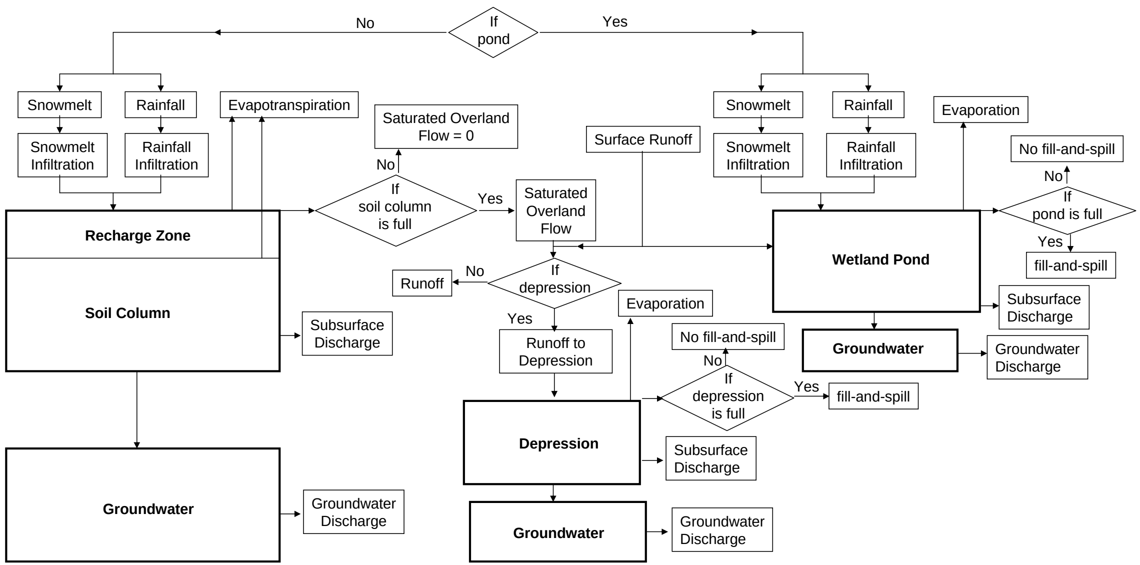

Fig. 3. Flowchart of a wetland module of soil moisture balance calculation with wetland or depression storage and fill-and-spill.

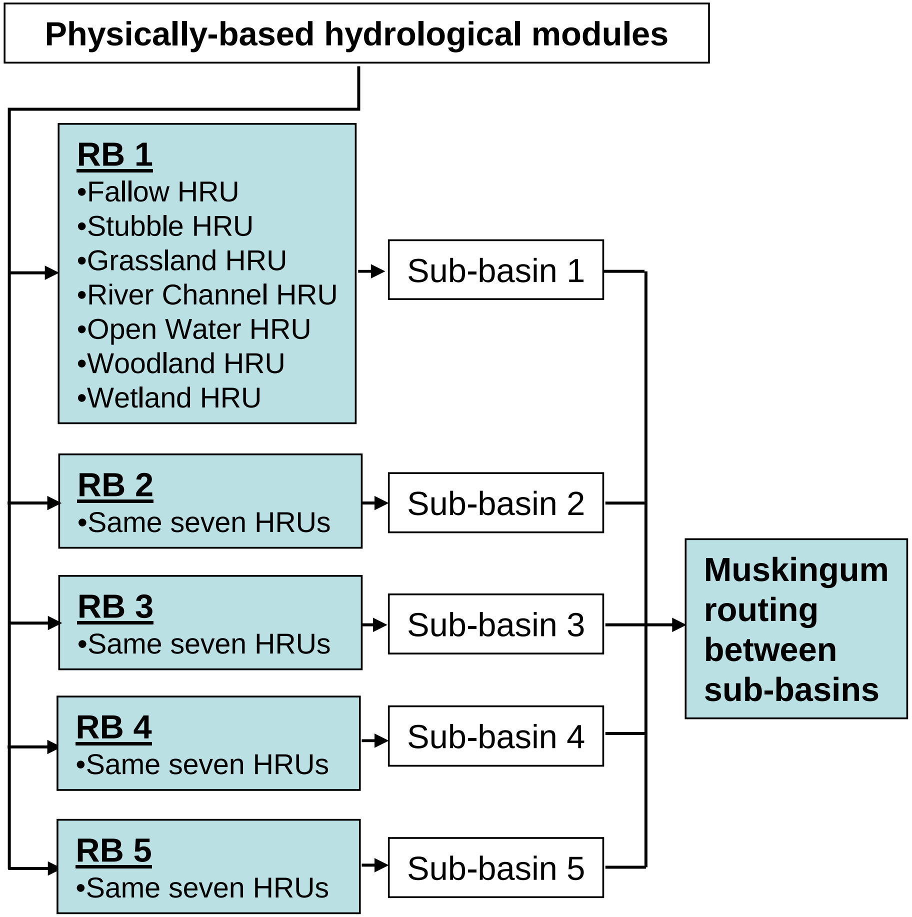

Fig. 4. CRHM modelling structure. Five Sub-basins are simulated by modelling structure "Representative Basin" (RB); same seven hydrological response units (HRUs) exist in each RB. Modelling structure of Muskingum routing connects all five RBs.

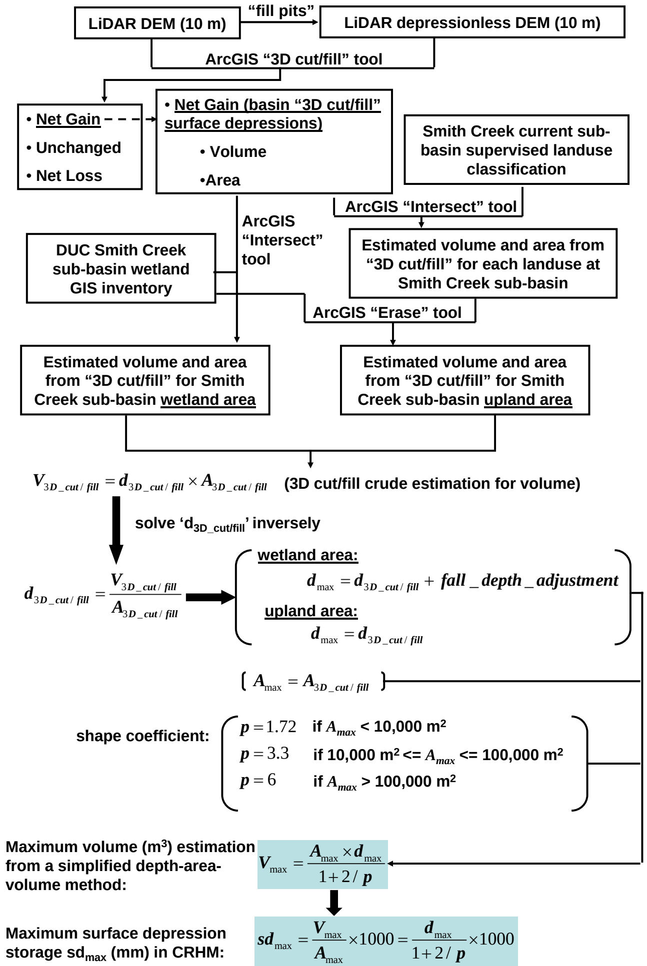

Fig. 5. Flowchart of an automated procedure used by the uncalibrated modelling for estimating maximum surface depression storage.

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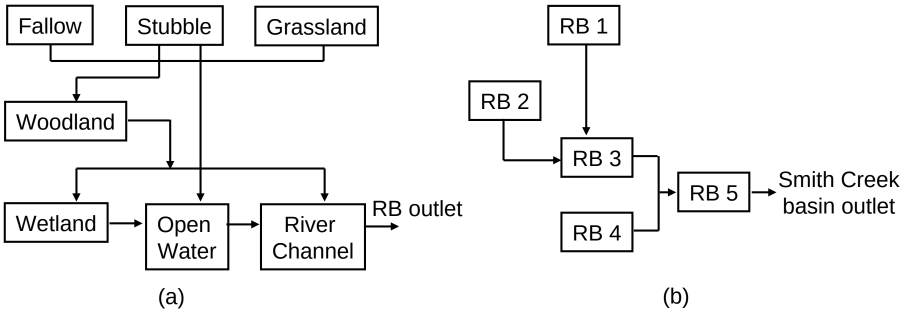

Fig. 6. **(a)** Rouing sequence between HRUs within the sub-basin (RB) and **(b)** routing sequence between RBs.

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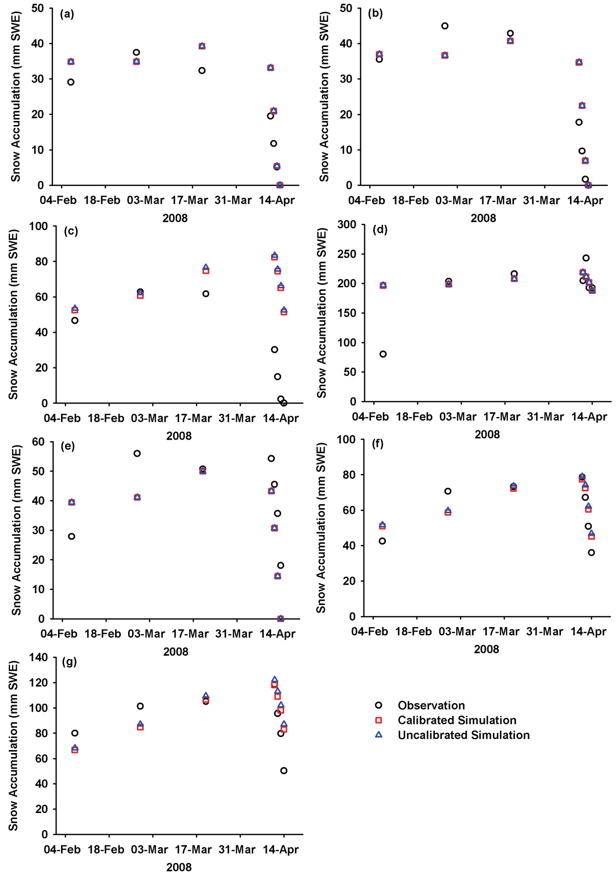

Fig. 7. Comparisons of the observed and simulated snow accumulation (SWE) during 2008 simulation period for seven HRUs in the sub-basin 1 of Smith Creek Research Basin. **(a)** fallow, **(b)** stubble, **(c)** grassland, **(d)** river channel, **(e)** open water, **(f)** woodland, and **(g)** wetland.

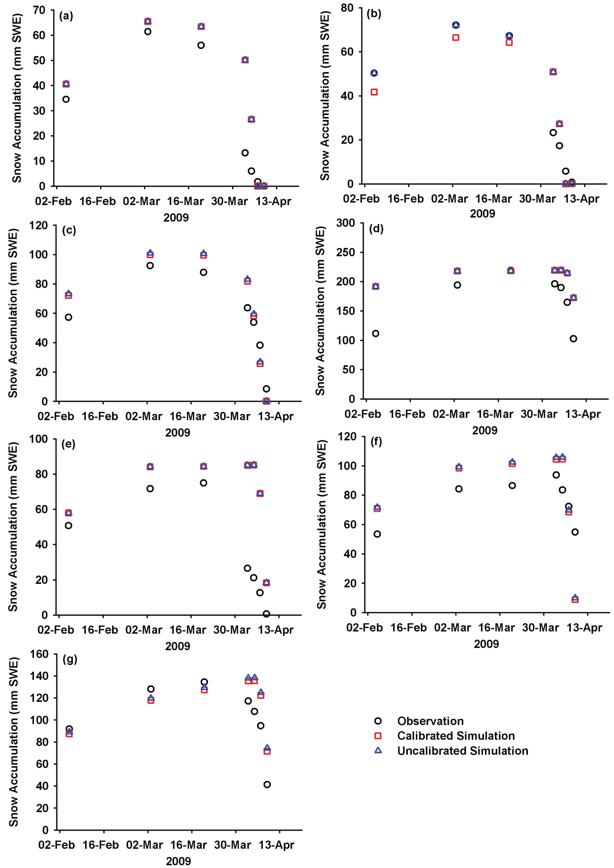

Fig. 8. Comparisons of the observed and simulated snow accumulation (SWE) during 2009 simulation period for seven HRUs in the sub-basin 1 of Smith Creek Research Basin. **(a)** Fallow, **(b)** stubble, **(c)** grassland, **(d)** river channel, **(e)** open water, **(f)** woodland, and **(g)** wetland.

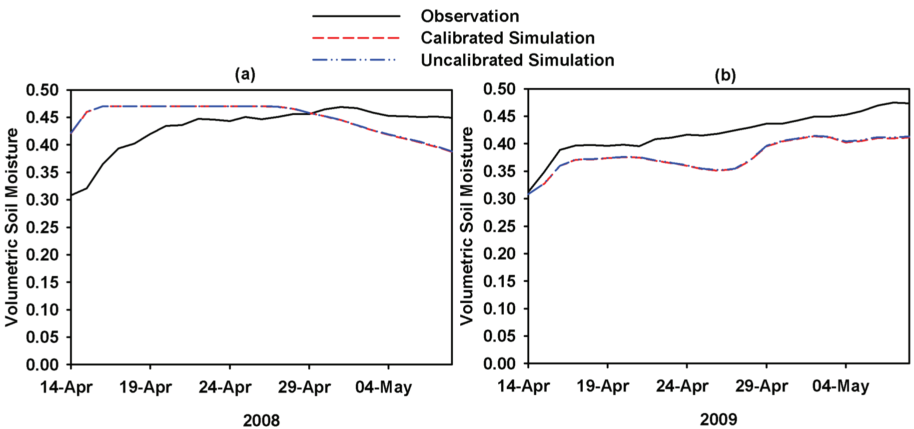

Fig. 9. Comparisons of the observed and simulated volumetric spring soil moisture from the main weather station in the Smith Creek Research Basin. **(a)** 2008 simulation period and **(b)** 2009 simulation period.

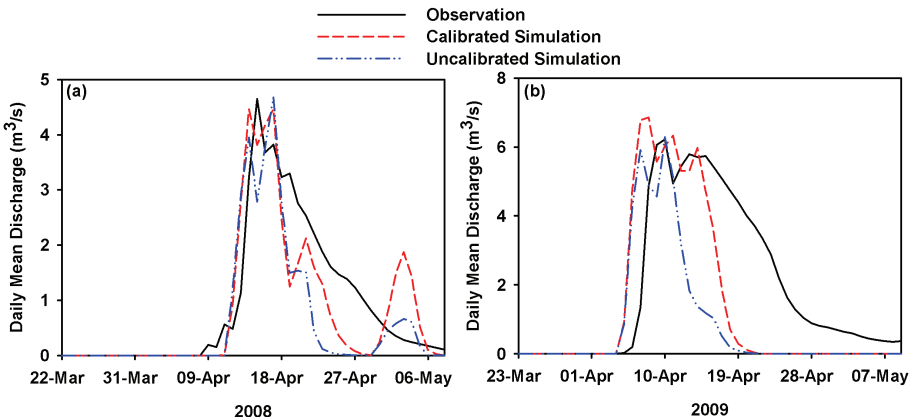

Fig. 10. Comparisons of the observed and simulated spring daily mean discharge in the Smith Creek Research Basin. **(a)** 2008 simulation period and **(b)** 2009 simulation period.