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Simulating cold-region hydrology in an intensively drained agricultural watershed in Manitoba, Canada, using the Cold Regions Hydrological Model

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Abstract

Eutrophication and flooding are perennial problems in agricultural watersheds of the northern Great Plains. A high proportion of annual runoff and nutrient transport occurs with snowmelt in this region. Extensive surface drainage modification, frozen soils, and frequent backwater or ice damming impacts on flow measurement represent unique challenges to accurately modeling watershed scale hydrological processes. A physically-based, non-calibrated model created using the Cold Regions Hydrological Modelling platform (CRHM) was parameterized to simulate hydrological processes within a low slope, clay soil, and intensively surface drained agricultural watershed. These characteristics are common to most tributaries of the Red River of the North. Analysis of the observed water level records for the study watershed (La Salle River) indicate that ice cover and backwater issues at time of peak flow may impact the accuracy of both modeled and measured stream flows, highlighting the value of evaluating a non-calibrated model in this environment. Simulations best matched the streamflow record in

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years when peak and annual discharges were equal to or above the medians of 6.7 $m^3 s^{-1}$ and 1.25 × 10^7 m^3, respectively, with an average Nash-Sutcliff efficiency (NSE) of 0.76. Simulation of low-flow years (below the medians) was more challenging (average NSE <0) with simulated discharge overestimated by 90% on average. This result indicates the need for improved understanding of hydrological response in the watershed under drier conditions. Improved simulation of dry years was achieved when infiltration was allowed prior to soil thaw indicating the potential importance of preferential flow. Representation of in-channel dynamics and travel time under the flooded or ice-jam conditions should also receive attention in further model development efforts. Despite the complexities of the watershed being modeled, simulations of flow for average to high flow years and other components of the water balance were robust [snow water equivalency (SWE) and soil moisture]. A sensitivity analysis of the flow routing model suggests a need for improved understanding of watershed functions under both dry and flooded conditions due to dynamic routing conditions, but overall CRHM is appropriate for simulation of hydrological processes in agricultural watersheds of the Red River. Falsifications of snow sublimation, snow transport, and infiltration to frozen soils processes in the validated base model indicate that these processes were very influential to stream discharge generation.

KEY WORDS: Prairie hydrology; cold-region; snowmelt; physically-based modelling; agricultural watershed; intensively drained.

1. Introduction

Lake Winnipeg, the 10th largest freshwater lake in the world, has experienced rapid eutrophication in the last century due to increased loading of phosphorus (McCullough et al., 2012). The Red River is the largest source of phosphorus (P) to the lake, responsible for around 70% of the total annual load (Bourne et al., 2002;Schindler et al., 2012). The majority of the export from the river occurs during hydrological events where P concentration in its tributaries increases with discharge (McCullough et al., 2012). Changes in the discharge of the Red River and its tributaries have been suggested as one of the primary drivers of changes in phosphorus loading to Lake Winnipeg since the 1970s (McCullough et al., 2012;Schindler et al., 2012). Therefore, research to improve understanding of those hydrological processes that control transport is of particular regional importance.

Many popular models utilized for the simulation of hydrological processes in agricultural watersheds were initially developed for regions where rainfall driven runoff is the primary contributor to annual water yield. Snowmelt is the main source of stream flow in tributaries of the Red River and accurate representation of hydrological processes in its agricultural tributaries using popular models like the Soil and Water Assessment Tool (SWAT) has proved challenging. While SWAT has been used to estimate water quality targets and beneficial management practices in Canada (Yang et al., 2012), significant modification of the original model is generally required to achieve a good fit with calibration data (Watson et al., 2008;Liu et al., 2012) and improvement of the accuracy of underlying representation of important hydrological processes (e.g. landscape representation, stream routing) is ongoing (Douglas-Mankin et al., 2010).

As a result of the problems associated with adapting hydrological models developed for more temperate conditions, a number of models that incorporate cold-region hydrological process have been developed, such as ARHYTHM, VIC, and the Cold Regions Hydrological Modelling (CRHM) platform (Pomeroy et al., 2007). Of these models, CRHM offers the most complete range of physically-based process representation for the Northern Great Plains, including blowing snow, interception and sublimation of snow, energy balance snowmelt, canopy influence on radiation, and infiltration to frozen soils (Pomeroy et al., 2007;Fang et al., 2013). Although CRHM currently does not feature a module to represent nutrient dynamics in either soil or water, such modules are under development (Roste, 2015) and the platform is a powerful tool for assessing watershed nutrient dynamics because of the well-established relationships between phosphorus concentrations and discharge rate in tributaries of the Red River, including the La Salle River (McCullough et al., 2012), which is the focus of the research presented here.

The CRHM platform has been successfully used to simulate hydrological processes in a number of contrasting catchments in Canada (Dornes et al., 2008;Fang and Pomeroy, 2008;Ellis et al., 2010),globally in China, Patagonia, and France (Rasouli et al., 2014), and in the intensively studied South Tobacco Creek watershed that drains from the more steeply sloped Pembina/Manitoba Escarpment feature into the Red River in Manitoba (Mahmood et al., 2016). However, CRHM has not yet been used to simulate hydrological processes in the intensively managed lowland agricultural tributaries of the Red River such as the La Salle River. Characteristics in these watersheds include extensive artificial surface drainage, channelization of the stream network, historical drainage of wetlands, clay soils, high fertilizer input, high crop yield, high livestock densities, and highly connected drainage areas with little surface storage. Simulation of cold-region hydrological processes in this landscape is particularly challenging because of the combined effect of climate and land use management on water transport. Large volumes of runoff can be produced when snowmelt is routed over frozen soils (Shook and Pomeroy, 2010;Shook and Pomeroy, 2012) and this process is emphasized where surface drainage enhancements and roadside ditches speed transport (Brunet and Westbrook, 2012;Pomeroy et al., 2014). As a result, flow in streams of the Red River watershed tend to exhibit a flashy response to snowmelt with large volumes of runoff from roadside ditches entering into relatively small river channels that are still covered by ice at time of melting. This in-channel ice restricts flow and frequently causes flooding and backwater conditions to develop (Gray and Prowse, 1993). These conditions can lead to error in discharge measurements calculated using stage-rating curves (Mosley and McKerchar, 1993) also invalidate important assumptions of flow routing models (Fread, 1993), thus making accurate prediction of flow more challenging. For this reason, using a non-calibrated, but flexible physically-based model platform is an attractive alternative to models primarily calibrated based on discharge measurements. The application of CRHM will enhance the understanding of the hydrological controls in tributaries of the Red River since concurrent measurements such as SWE and soil moisture can also be utilized to gauge the accuracy of model process representations independent of uncertainties associated with in-stream flow representation or measurement. At the same time, the limitations of existing conceptual models and/or potential problems with discharge measurement should be more apparent in the absence of calibration (Spence et al., 2013).

The objectives of this study were to assess the performance of CRHM to simulate the hydrology of an intensively managed agricultural sub-watershed of the Red River Valley and to gain insight about the dominant hydrological controls of stream flow in this unique landscape. Model simulation was completed in a sub-catchment of the La Salle River watershed for the 1992-2013 time period. Given global concern regarding the eutrophication of Lake Winnipeg and the importance of discharge from the Red River in determining rates of P loading to the lake, emphasis is placed on evaluating the accuracy of the model in representing snowmelt and high flow events. The research presented here also provides insight into whether there are particular periods of time or weather conditions for which there is poor model performance indicating

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either limitations of model input data or the need for improved understanding and representation of watershed hydrology in the region.

2. Material and Methods

2.1 Study site

The study was conducted in a 189 km^2 sub-catchment of the La Salle River watershed (LS-05OG008; Fig. 1a), a tributary of the larger Red River which is located in the central plains region of Manitoba, Canada (Graveline and Larter, 2006). The study watershed is underlain by lacustrine clay deposited in glacial Lake Agassiz; these deposits consist of a lower, dark grey clay and a thinner upper unit of lighter coloured, calcareous silty clay, with surface texture being predominantly clayey (La Salle Redboine Conservation District, 2007). The study area is located in the Prairie Ecozone, with mean annual temperature around 2.5°C, mean summer temperature of 16°C and mean winter temperature of -13°C; the mean annual precipitation is 560 mm, out of which around 25% takes place as snow, while the potential mean annual gross evapotranspiration is about 834 mm (La Salle Redboine Conservation District, 2007).

2.2 Hydrological and meteorological observations

Daily streamflow observations between 1990 and 2013 were obtained from the hydrometric data (HYDAT) database (Environment and Climate Change Canada, 2013) for Water Survey of Canada (WSC) gauging station 05OG008 (La Salle River near Elie; Fig.1b) located at the outlet of the study watershed. Data collection at this location was seasonal from 1990 to 1996, and has been continuous from 2002 to present. The annual monitoring period for this station spans from March 1st to October 31st, with no data available during winter months; thus, analyses were carried out using calendar years rather than water years (i.e. October 1st to September 30th) since the hydrometric data does not span over more than a calendar year. A gap

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in available flow data exists between flooding in 1997 and instrument replacement in 2001. Only flow data is available from HYDAT for the period prior to 1996, while flow and water level were both recorded from 2002 onwards. Notes in the HYDAT metadata pertained to 2004 and 2008 indicated equipment malfunctions resulting in loss of data. For this reason, the periods from 1997-2001, 2004, and 2008 were not used for model assessment.

The gauging station 05OG008 is located 80 meters downstream from a small stop-log dam, which raises concerns about ice jamming and backwater issues. Ice conditions are flagged in the HYDAT daily records, but backwater and flooding conditions are not indicated for the site. Thus, field notes from site visits were acquired from WSC and used to determine potential backwater conditions. The threshold for flagging these conditions in the present analysis was based on the minimum water level for which backwater was recorded by WSC technicians on the field. This level was 239.3 m, observed on May 19, 2011, which is only 0.2 m below the full supply level (FSL) of the stop-log dam (239.5 m). Potential backwater conditions were assumed whenever the water level was above this threshold. Since water levels in the HYDAT database were only available after 2002, this analysis was carried out between 2002 and 2013. These potential backwater periods are noted in figures displaying measured discharge. However, the presence of backwater conditions, although common, were not consistently documented on the WSC field notes to provide verification of occurrence or impact on measurement accuracy; so even where backwater conditions were suspected, all flow data was assumed accurate and utilized in assessment of model performance.

The hourly weather data used to force CRHM was obtained from closest Environment Canada weather station (Environment and Climate Change Canada, 2015) with available data (Fig. 1a). Nearby stations are located at Portage Southport Airport, Winnipeg International

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Airport, and Marquette (26.6, 47.9, and 9.9 km from the geometric centre of the study area, respectively). Temperature, wind speed, and relative humidity were obtained from the Portage Southport Airport, solar radiation was acquired from the station located at the Winnipeg International Airport, and precipitation was acquired from the weather station in Marquette. Precipitation was available in a daily time-step and was disaggregated to an hourly time-step using HyetosR (Kossieris et al., 2013), which is a package for the temporal stochastic simulation of rainfall process at fine time scales based on Bartlett-Lewis rectangular pulses rainfall model (Koutsoyiannis and Onof, 2001).

2.3 Watershed delineation and HRU definition

The soils, topography, and land use datasets used as model inputs in this study were derived according to the principles described by Liu et al. (2013) for prediction in ungauged basins. The sub-basins within the La Salle watershed (Fig. 1a) were defined using the watershed delineation tool in SWAT (Yang et al., 2014) and the 90-m digital elevation model (DEM) derived from the NASA Shuttle Radar Topography Mission (SRTM) data. Soil datasets with scales ranging from 1:20,000 to 1:126,720 were obtained from the Manitoba Land Initiative (MLI) database. The soils textures in sub-catchment were 94% clay, 4% silt clay loam, 1% silt clay, and 1% silt loam. The land use datasets were acquired from MLI for non-agricultural land uses and from Agriculture and Agri-Food Canada (AAFC) for cropping systems. Cropping systems, or typical cropping rotations, were derived from nine years (2001-2009) of records from the Mantioba Agricultural Services Corporation (MASC) crop insurance database, as well as land use defined by the Ag-Capture tool between 2009 and 2012 that included each parcel of land in the study area (Yang et al., 2014). The Ag-Capture tool is a geospatial, agricultural land-use inventory and mapping tool developed by Agriculture and Agri-Food Canada (OECD, 2013)

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that validates remote-sensed land use classification using field surveys. The cropping system assigned to each parcel was based on the dominant or most common crop grown while its representative crop rotation was based on the proportion of the other most common crops grown on the same land parcel over the entire period of record. Cropping systems used in the present model and the crops therein are shown in Table 1.

Using SWAT's watershed delineation tool, the entire La Salle watershed was divided into 38 sub-basins (Fig. 1a) (Yang et al., 2014). The sub-catchment comprised of sub-basins 2, 3, 5 and 33 was used in the present study; they correspond to the gross drainage area draining into the gauging station at the outlet of the overall watershed (05OG008; Fig.1b). The hydrological response units (HRUs) used by CRHM in this study were also based on the HRUs previously defined for the SWAT model (Yang et al., 2014), where HRUs are defined based on unique combinations of land use, soil, and topography. The HRU-definition strategy for applying cropping systems was based on the land-use split method, which divides the land-use type or cropping system into multiple, more specific crop types based on what would be a typical crop rotation for that system. The land-use split method allows for representing crop rotations in the model in a static fashion by distributing the different crops within a cropping system throughout the acreage of the cropping system in a single year (Fig. 2) (Yang et al., 2014). For instance, the "Fall Cereal Cropping System" is comprised of canola, spring wheat, canola, and winter wheat in a four-year rotation (Fig. 2a). Thus, in the four-year rotation, canola is planted 50% of the time (two out of four years), while spring wheat and winter wheat are each planted 25% of the time (one out of four years). The land-use split method distributed this rotation throughout the Fall Cereal cropping system land base within a single year based on the relative percent of each crop (Fig. 2b). Thus, every year, canola, spring wheat, and winter wheat are represented in the model as being planted in 50%, 25%, and 25% of the Fall Cereal acreage, respectively. Once the cropping systems were represented using the land-use split method, the crops were associated to soil types present in the LS-05OG008 sub-catchment. The combination of land use and soil types resulted in the HRUs presented in Table 1. As indicated in this table, agriculture dominates the land use in the study area with urban areas and natural lands occupying only a very small proportion. This is the first time that the land-use split approach has been used in CRHM for simulation of hydrological processes in agricultural watersheds, allowing a more detailed representation of the agricultural land use that included crop types.

Due to the highly altered nature of the drainage network in the watershed and its low relief, data collection was undertaken to ensure accurate delineation of routing. Initially the stream network was defined based on digital water feature data from the Manitoba Land Initiative (MLI) (1:20,000 Designated Drains) with supplemental ephemeral streams digitized based on aerial photograph interpretation. The drainage ditch dataset, mainly comprised of roadside ditches, utilized a culvert inventory along with LiDAR DEM (vertical accuracy ± 0.15 m) analysis to determine flow direction to create ditch line segments that passed through culverts and ultimately connected to the stream network. The stream and drainage ditch datasets were merged together to create the final drainage network for the model.

2.4 CRHM module selection

The Cold Region Hydrological Modelling platform (CRHM) was used to develop a custom hydrological model for LS-05OG008. CRHM is a modular objected-oriented platform that allows the creation of customizable models varying from conceptual to physically-based representations of the study area, according to the data availability and uncertainty in process parameters of the basin (Harder and Pomeroy, 2014). A detailed description of CRHM and its

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modules, which are based on decades of cold-region hydrological research in western and northern Canada, is available in Pomeroy et al. (2007) , with an update for agricultural applications in the Canadian Prairies described by Fang et al. (2010). A set of physically-based modules was defined and arranged sequentially to simulate the dominant hydrological processes in LS-05OG008. Table 2 lists the modules selected, their function, and the sequence in which they were entered into the customized model. Similar model group structures have been successfully used to simulate hydrological processes in the prairie pothole region of the Canadian Prairies (Fang and Pomeroy, 2008;Fang et al., 2010). The same model structure was applied for the four sub-basins of LS-05OG008 (i.e., sub-basins 2, 3, 5 and 33). Each sub-basin was represented in the model by a Group, which is a collection of modules executed in sequence for all HRUs and connected with one another by a Muskingum routing group.

2.5 CRHM module parameterization

The CRHM software does not make provision for calibration utilizing fitted variables; rather, parameters are selected based on the understanding of the hydrological system (Pomeroy et al., 2007) . Since the land-use split approach was used, the HRU distribution was held constant over the simulation period, which allowed for a single set of parameters to be used in the model for each HRU. Sub-basin and HRU physiographic parameters (i.e. area, elevation, slope, aspect, and latitude) were obtained from the DEM and HRU reports generated by SWAT during the watershed delineation and HRU definition for a previous SWAT simulation in the La Salle (Yang et al., 2014) . The parameters of the soil and recharge layers (e.g. soil texture, soil porosity, saturated hydraulic conductivity, and water holding capacity) were obtained or derived from the Soil Survey Reports published by the Province of Manitoba (Michalyna et al.,

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1972;Ehrlich et al., 1953). The pore size distribution index (λ) was defined based on soil textures associated with clay (Brooks and Corey, 1966;Corey, 1994).

Crop seeding dates were defined based on a 10-year average (2000-2009) for each crop based on crop insurance data obtained from MASC. Harvest dates were based on the length of the growing season defined by consultation with farmers in the study area. Leaf area index (LAI), vegetation height, and stalk diameter for the different crops were obtained from the dataset collected by AAFC for the SMAPVEX12 Campaign in 2012 (Kim et al., 2014). The SMAPVEX12 field sites were located between 13 and 45 km south of LS-05OG008 and are located within the Red River watershed and the same or similar ecoregions as the La Salle (Lake Manitoba Plain or Interlake Plain). The Penman–Monteith method was used to calculate evapotranspiration from crop HRUs, while the Priestley-Taylor method was used to calculate evaporation from open-water HRUs (e.g. wetland, river channel).

Although located in the Canadian Prairies, the runoff routing in the LS-05OG008 sub-catchment does not follow the typical sequence of land uses further west in this region described by Fang et al. (2010) (i.e. fallow, stubble, and pasture routed to woodland and then to wetland, open water, and river channel). Rather, the flat and intensively managed characteristic of the La Salle watershed result in a lack of any typical routing sequence based on land use. For this reason, uplands were routed directly to drainage channels in LS-05OG008. For each HRU, the routing length was calculated as the median of the distances from each HRU to the drainage network, as obtained using ‘near’ tool in ArcGIS 10.1 (ESRI, Redlands, California). The distances to the drainage network were estimated from the 2009 land use coverage using the Ag-Capture tool.

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The maximum depression storage of the HRUs was calculated using the methodology described by (Fang et al., 2010) for upland areas, where volume and area were calculated from the same LiDAR DEM used to derive the final drainage network. Briefly, the 'fill' tool was used to level off the original DEM and the 'cut/fill' tool to calculate the area and volume from the difference between the original and the leveled DEMs. Muskingum routing within and between sub-basins of LS-05OG008 was setup according to (Fang et al., 2013). The storage parameter used in the Muskingum routing module was set to zero, based on the typical pattern observed for regional agricultural runoff monitoring where individual diurnal runoff events at edge-of-field begin as soon as melt starts around noon and stops due to refreezing at night (Tiessen et al., 2010a). In-channel storage was calculated as total reach length (calculated in GIS using the drainage network) divided by average flow velocity, which was estimated using measured hydrographs and channel dimensions (i.e. average flow rate in the simulation period divided by cross sectional area). The dimensionless constant that weights inflow and outflow was set to 0.25, which is a common value for natural stream channels (Carter and Godfrey, 1960) .

2.6 Assessment of model simulations

Model simulations were graphically and statistically assessed against streamflow data collected by WSC at station number 05OG008. The statistical metrics used for model assessment in a daily time-step were the Nash-Sutcliffe model efficiency (NSE), model bias (MB), the root mean square difference (RMSD), and the normalized root mean square difference (NMSD) (Fang et al., 2013). Although streamflow simulations were available between 1990 and 2013, some years could not be used for model assessment. Among those are the years of 1990 and 1991, which were used as the model warm-up period, and the years having data quality issues as

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documented in the WSC streamflow database HYDAT (version 10 issued on October 17, 2014). Thus, the years of 1990-1991, 1997-2001, 2004, and 2008 were not used for model assessment.

Key aspects of hydrological cycle influencing streamflow generation in cold regions were also used to assess model performance. Simulated snow water equivalent (SWE) was compared to SWE calculated from the depth of snow on ground measured at the Marquette station using the following relationship (Pomeroy and Gray, 1995):

$$SWE = 0.01 d_s \rho_s , \quad (1)$$

where d_s is the depth of snow (cm), ρ_s is the snow density, which was assumed to be 180 kg m^{-3} based on the typical density range between new and settled snow (Paterson, 1994), and SWE is same as defined above (mm). Simulated yearly cumulative evaporation from open water was compared to gross evaporation values published for Portage La Prairie between 1992 and 2000 (Martin, 2002), which is the closest location with available data corresponding to the time period of model simulations. Since both values were based on evaporation models and not measured, the evaporation comparison was made only to verify that CRHM simulations were in agreement with values expected for the study area. Simulated volumetric soil water content [VWC, expressed in mm of water in the soil profile, i.e. VMC (m^3 m^{-3}) × profile depth (mm)] was compared to VWC simulated across Canada using the National Drought Model (NDM) (Chipanshi et al., 2013). Similarly to evaporation, no direct measurements of soil moisture were available in close proximity to the watershed; thus, the NDM dataset was used to verify only if the VWC simulated by CRHM was within a reasonable range and followed the expected seasonal trend.

2.7 Model falsification

Taking advantage of the flexible structure of the CRHM platform to simulate physically-based hydrological processes, model falsifications were performed to assess the impact of snow sublimation, blowing snow (which includes both snow sublimation and transport), and frozen-soil infiltration on stream discharge in the study area. These processes are typical of the Canadian Prairies and very influential to runoff generation in the region (Pomeroy et al., 2007). A stepwise model falsification was achieved by sequentially removing the following processes from the model: i) snow sublimation, ii) blowing snow, iii) frozen-soil infiltration, and iv) blowing snow and frozen-soil infiltration, which is the combination of cases (ii) and (iii). Different than the model assessment analysis, which used calendar years, the impact of model falsification was assessed for water years, since a complete time series was available from model simulations. However, statistical metrics used for model assessment (i.e., NSE and MB) were only calculated between March and October, which is the period where observed streamflow is available.

3. Results

3.1 Flow characteristics in the study area between 1990 and 2013

As is typical of the cold-region conditions prevailing in the Canadian Prairies, peak stream discharges take place in the spring (Table 3). Thirteen of 15 years exhibited annual peak discharge with snowmelt. The median peak discharge was 6.7 $m^3 s^{-1}$, while the median annual discharge volume was 1.25×10^7 m^3 and the median water yield was 66 mm. Years with peak discharge above the median corresponded to years with annual discharge volume above the median, due to the strong positive correlation between these two variables (r^2=0.90), reflecting that most of the annual discharge occurs during spring and is associated with event runoff rather

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than baseflow. Those years with peak discharge and annual discharge volume equal to or above median values were considered wet years for model assessment purposes and include the years of 1996, 2005, 2006, 2009-2011, and 2013.

Seven out of 15 years had ice conditions at time of peak discharge, while two years had peak discharges one day after the end of the ice period (Table 3). Ice conditions at peak discharge were most common in years with cumulative and peak discharges equal to or below the median. Field observations at the site indicate that the absence of ice in wet years was likely due to faster-moving water at high discharge. However, ice moving downstream still may have impacted the flow regime at the gauging station through the formation of ice jams along the river channel and promotion of backwater conditions, which were relatively common (Table 3).

Seven out of nine years with both upstream and downstream level monitoring exhibited potential backwater effects (Table 3; Fig. 3). Potential backwater events were generally more associated with years of high discharges. Backwater in this reach could be caused by two factors. The first being that the confluence of the Elm River channel and the La Salle River just downstream of the gauging station 05OG008 (Fig. 1b). Given the gentle topographic gradient of the area and the presence of the small dam, the water backs up in the reach of the La Salle River upstream of the confluence of the two channels. The second factor is the occurrence of ice-damming and potential for build-up from the 4-m dam at Starbuck located 28.6 km downstream following an elevation change of 3 m.

3.2 CRHM simulations of stream discharge

The majority of annual stream discharge occurs in spring and in particular with snowmelt, making this the most important period for hydrological simulations to identify nutrient export

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potential (Table 3). However, stream discharge measurements during the spring are also associated with the greatest potential for model and measurement uncertainties related to ice conditions and backwater issues. Given the hydrological importance of stream discharges driven by snowmelt, model assessment was performed without removing questionable spring records from the dataset. The only period removed from analysis was the backwater period in July of 2005 that occurred following an extreme rainfall runoff event (Table 3; Fig. 3) with a high degree of known uncertainty regarding measurement accuracy caused by backwater and debris buildup (according to WSC field notes), and representing disinformation for model assessment (Beven, 2011).

Graphical comparison between observed and simulated stream discharge indicates that the model skill varied for different years (Fig. 4). Records of discharge measurements performed by WSC during site visits were obtained and are also shown in Fig. 4. Simulated time of peak discharge was generally in good agreement with observed values, except for three out of 15 years (i.e. 1993, 2003, and 2007). These three years had peak discharge and annual discharge volume equal to or below the medians for the 1990-2013 period (i.e. 6.7 $m^3 s^{-1}$ for peak discharge and 1.21×10^7 m^3 for annual discharge volume). The magnitude of peak discharges was also reasonably simulated by the model (Fig. 5), although with more variability than timing of peak. Much of this variation was associated with either years of discharge volume below the median (i.e. 1994, 1995, 2002, and 2007) or large peak discharge (i.e. 2006, 2009, and 2011). There was no direct relationship between overestimation of simulated peak discharges (Fig. 5) and overestimation of annual discharge volumes (Fig. 6). However, there was a tendency for simulated annual discharge volumes to be overestimated in low-discharge years (Fig. 6) and to underestimate large peak discharges (Fig. 5).

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Statistical metrics used to assess model performance are shown in Table 4. The results confirm the trends shown in graphical analysis where the model had very good performance for years with peak discharge equal or larger than the median peak discharge. The Nash-Sutcliff efficiency (NSE) was consistently above 0.65 and averaged 0.76 for 1992, 1996, 2005, 2006, 2009, 2011, and 2013. The year 2010 was an exception, with NSE=0.36. For low discharge years, NSE was negative, indicating that the model was no better than utilizing mean discharge as a predictor of stream discharge. For the years with NSE > 0.65, the model bias (MB) was generally negative, although the average model bias was small (i.e. 5%). This was likely due to the overall underestimation of peak discharges during those years. Conversely, MB was generally positive for years with negative NSE, which correspond to years with annual discharge volumes below the 1990-2013 median. This confirms the difficulty in simulating low discharges as was observed in the graphical analysis. The root mean square difference (RMSD) and the normalized root mean square difference (NRMSD) were small to moderate, given the range of discharges comprised between minimum and peak discharges.

3.3 CRHM simulation of SWE, evaporation, and VWC

The annual trend in SWE and time of melt was accurately captured by the model (Fig.7). Differences in peak SWE (e.g. 1992 and 1996) were likely due to inter-annual variation snow density, which was not measured and can vary substantially with space and time (Pomeroy and Gray, 1995). However, the assumed snow density value did not introduce a substantial bias into SWE estimation, as most years had good agreement between simulated and observed peak SWE values. CRHM was also able to simulate cumulative open water evaporation that compared well with gross evaporation estimates for the years when data was available (Fig. 8). The average cumulative gross evaporation estimated by AAFC at Portage La Prairie was 686 mm, while that simulated by CRHM for open water was 682 mm. The soil moisture range and variation trend over the year was also well simulated by CRHM in most years (Fig. 9). Despite some differences, CRHM was generally able to match the soil moisture content at the beginning of each growing season and to capture its depletion and recovery over the course of the summer and fall seasons, respectively. The results above are important since they imply that antecedent conditions were reasonably well predicted with accurate representation of watershed hydrological processes and that soil infiltration, soil freezing, and snowmelt runoff patterns can be modelled with greater confidence.

3.4 Sensitivity analysis using the storage parameter in the Muskingum model

A sensitivity analysis was carried out using the storage parameter in the Muskingum model (K storage) for both overland and drainage network flow routing to investigate the adequacy of average values for both wet and dry years (Fig. 10). For wet years, the plot indicates equifinality (Beven, 2011), where different models have similar performance when K storage is in the range between zero and four days for both upland and drainage network (Fig. 10a). The model bias for peak flows aids model selection by defining a narrow band for which the bias is minimized (Fig. 10c). However, knowledge of the flow characteristics is still necessary to define the K storage parameter. In this case, K storage of 0 and 3 days for upland and drainage network, respectively, seem reasonable to maximize NSE and minimize peak-flow MB. Conversely, the model performance for dry years tends to improve as K storage increases for both upland and drainage network, although NSE is still in the negative range (Fig. 10b). The contour plot of peak-flow model bias for dry years also suggest large K storage values since low bias is only found for higher K storage values (Fig. 10d).

Despite the relative improvement, changing K storage in dry years did not impact model performance appreciably. These results may suggest that the hydrologic controls under dry conditions in this watershed are not strongly topological (i.e. drainage network) but typological (i.e. landscape elements) (Buttle, 2006). In order to asses this possibility, the CRHM option to allow infiltration prior to the major melt event was selected in an attempt to emulate the effect of preferential flow. The NSE and MB for dry years were, respectively, -27.87 and 2.0 (1994), -0.58 and 0.81 (1995), -9.6 and 1.7 (2002), -1.09 and 0.16 (2003), -0.43 and 0.69 (2007), and -0.17 and 0.25 (2012). These results indicate an improvement in model performance in two out of six years (i.e. 2002 and 2012) when compared to the based model (Table 4), which represents better predictions >30% of the time.

3.5 Model falsification

Comparison of the hydrographs between the base model and the falsified models indicates that sublimation, blowing snow, and infiltration to frozen soils are influential processes in the study area (Fig. 11). Turning off snow sublimation and blowing snow (i.e. snow sublimation and transport combined) in the models resulted in increased peak discharges (Fig. 11b-c), while removing frozen-soil infiltration reduced peak discharge with or without blowing snow (Fig. 11d-e). The average change in peak discharge due to sublimation inhibition increased 25.4%, while the change due to blowing snow inhibition was 39.1%; the effect of inhibiting frozen-soil infiltration was the opposite, with reductions around 60% in peak discharge regardless of the blowing snow process (Table 5). Despite the average increase in peak discharge, there were also reductions in peak discharge in particular years when the snow sublimation and blowing snow were removed (i.e. 1993-1994; 1994-1995; 2003-2004; 2006-2007). For frozen-soil infiltration models, removing this process had a very consistent effect on peak discharge with reductions in all but one year (i.e. 2001-2002).

One striking effect of the model falsification was that disruption the snow sublimation, blowing snow, and frozen-soil infiltration caused a disconnection between peak discharge and annual discharge, which was a feature of the observed stream discharge (section 3.1). In some years, reductions in peak discharge were accompanied by increases in total discharge (e.g. 2003-2004 for snow sublimation and blowing snow falsifications; 2002-2003 for frozen-soil infiltration models). In other years, the opposite was true (e.g. 2009-2010 for snow sublimation and blowing snow falsifications; no instances for frozen-soil infiltration models; Table 5).

Models with snow processes disrupted also presented consistent increases in SWE over the entire simulation period (Table 5). Noteworthy, there was no difference in SWE percent change among the models with snow sublimation and blowing snow falsifications, which indicates no influence of snow transport in SWE. No transport of snow out of the watershed was confirmed by assessing the snow loss variable within CRHM, which indicated total losses smaller than 1 mm over the 21 years of simulation (i.e. including the spin-up years) in all cases.

The statistical metrics calculated for the falsified models (Table 6) confirmed the loss of model performance when compared to the base model (Table 4), which highlights the importance of snow sublimation, blowing snow, and infiltration to frozen soils processes for accurately simulating stream discharge in the study area. Models with falsified snow processes (i.e. snow sublimation and blowing snow) generally presented a loss of performance, although in specific years, performance remained comparable (e.g. 2010) or improved slightly (e.g. 2005, 2006). This improvement was likely due to the increased peak discharge that offset the trend of the model to underestimate large peak discharges in wet years (Fig. 5). Similarly to NSE, model bias tended to become more extreme due to falsification of snow processes.

Metrics for falsification of frozen-soil infiltration (including blowing snow falsification or not) were also degraded in relation to the base model. Loss of performance was more severe in wet years due to drastic reduction in peak discharge (Fig. 11). However, performance tended to improve in dry years (e.g. 2005), which was likely due to an offset in the trend of the base model to overestimate discharges in those years. Reduced peak and total discharges due to falsification of frozen-soil infiltration process was due to increased infiltration.

4. Discussion

The assessment of the hydrological records of the La Salle River at the gauging station 05OG008 suggests that ice and backwater pose additional challenges to simulating streamflow in the study area. Peak flows in the river usually took place under ice impacted conditions or directly after clearing of ice (Table 3), which may have impacted both the accuracy of discharge measurements at the site (Environment and Climate Change Canada 2015) and hydrograph pattern. Comments from WSC field notes identified a number of potential sources of uncertainty for discharge measurements. For example, backwater conditions are reported in 2005, 2010 and 2011, which correspond to the period of backwater identified in this study. Overbank flow into the riparian vegetation is reported for 2007, which also corresponds to the backwater period identified in the present analysis.

Backwater during ice conditions may take place because the bottom of the ice cover causes an increase in flow resistance (Gray and Prowse, 1993) and may affect flow magnitudes and timing. Backing up of water from downstream ice jams after breakup may also impact

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hydrograph shape promoting high peak flow after release and may increase uncertainty associated with discharge measurements (ASCE, 1996). Increasing flows at the confluence of the La Salle River and the Elm River channel, located downstream of 05OG008 may also create backwater conditions where channel capacity is exceeded. According to the WSC field notes, this seems to be the reason for the backwater in 2011, which was caused by the discharge from a controlled breech in dikes of the Assiniboine River being routed through the Elm River Channel. Overall, backwater conditions seem to be quite frequent in the sub-catchment LS-05OG008 according to the present analysis and based on field observations. Due to changes in flow conditions, discharge measurements are recommended on a regular basis after high flow events or ice break-up; if a shift in the rating curve is necessary to accommodate the new flow conditions, a complete new set of discharge measurements must be made (Coulson, 1991). Thus, the peak flows in the observed records could have been exacerbated due to ice conditions and backwater.

Model performance may also be reduced during backwater periods. Flow routing was calculated in CRHM using the Muskingum model, which is not accurate for rapidly raising hydrographs routed through flat sloping rivers and neglects backwater effects due to tributary inflows and presence of dams (Fread, 1993). These features are characteristic of the study area and may have influenced the model simulations. Alternative distributed flow models such as the Kinematic wave model and the Muskingum-Cunge model are also impacted by backwater effect, which limits the selection of alternative methods for flood routing. Dynamic routing models that solve the Saint-Venant equations are not limited by backwater conditions; however, no analytical solution of the complete set of equations is available for most practical applications (Fread, 1993). Thus, numerical solutions based on finite-element or finite-difference schemes are usually

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required. Computational inefficiency, numerical instability, and convergence are among the drawbacks of such solutions, which explain the adoption of simpler routing methods in many hydrological models. This remains a major challenge for application of most hydrological models to basins such as the La Salle River basin.

Ice covered and backwater conditions create added uncertainty in evaluation of model performance, making evaluation for LS-05OG008 more challenging, but this problem is likely to be characteristics of other rivers in the Red River Valley given the relatively flat topography, the presence of dams along the river channels, presence of ice during peak flows, and frequent backwater at the confluence of different streams. It has been suggested that input errors in precipitation datasets are the dominant source of error in hydrological modelling, while errors in streamflow data are much smaller (Kavetski et al., 2006). While this premise is generally accepted, the results shown in the present study suggest that uncertainty regarding streamflow records of agricultural cold regions can be particularly complex.

Despite uncertainty associated with representation of in-stream dynamics during ice and backwater conditions, CRHM was able to capture the overall trend in streamflow with satisfactory simulation of the timing and magnitude of wet years (when peak flows were above the median). However, even in those years, the peak flows were underestimated by the model. Such contrast could be due to different routing conditions taking place during dry and wet years. The contour plots of NSE and peak-flow MB for both wet and dry years suggest that average K storage values are not adequate to represent both hydrological regimes and that dynamical storage might be present in the basin (Fig. 10). Constant values of the Muskingum parameters make them dependent of the hydrological flow data used to derive them, while it has been suggested that a more physically realistic approach is to allow the parameters to vary in time and

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space according to flow variability (Guang-Te and Singh, 1992). Due to this limitation, methodologies have been devised for application of the Muskingum model with variable parameters (Guang-Te and Singh, 1992;Song et al., 2011). In the present study, the K storage parameter was adequate to represent wet conditions only, since good model performance was achieved by the model for those conditions. However, K storage alone was not enough to explain the poor performance during dry years since the NSE was consistently negative even for large K storage values. Trends towards large K storage (i.e. slow movement of overland runoff and channel routing) and overestimation of discharge for dry years (Figs. 4 and 6) suggest that other physical process such as dynamical macropores affecting infiltration through soil cracks could be underestimated during simulations that were designed to address wet condition flowpaths. In-channel process such as water pooling and natural damming may also explain the large K storage values for drier years.

Poor model performance in dry years is not completely unexpected since low flows are generally more difficult to predict than larger flows (Nicolle et al., 2014), particularly for small catchment areas (Stanfield et al., 2009). This difficulty may also have been aggravated if there was flow under or over ice. The general pattern of flow is represented during drier years and overestimation appears not to be caused by overestimation of baseflow; rather, problems are most evident as overestimation of simulated peaks (e.g. years 1994 and 2002 in Fig. 4). While drought conditions and in-stream flow requirements are important management considerations on the Prairies (Fang and Pomeroy, 2007), the smaller magnitude events account for very little of the overall export of water and phosphorus from the La Salle (Corriveau et al., 2013) and CRHM appears to be a promising tool for physically-based simulation of the impact of management change on watershed hydrology in intensively agricultural tributaries of the Red River where elevated nutrient export is of particular concern.

Emulation of preferential flow by allowing infiltration prior to the major melt event resulted in improved simulations more than 30% of the time in dry years, which suggests that this mechanism is an important hydrologic control under those conditions. While the method chosen does not capture all the complex nuances of preferential flow, it does allow for enhanced infiltration and mimics the same effects of this mechanism. Interestingly, the two years that resulted in improved simulations (i.e. 2002 and 2012), were dry years preceded by years with wet springs and dry summers. In 2001, well-above-normal precipitation in the spring was followed by dry summer and fall (Wheaton et al., 2008). The same was observed in 2011 (Cordeiro et al., 2014). This similar trend highlights the importance of antecedent conditions on preferential flow. In contrast, there was no improvement in dry years followed by dry years (i.e. 1995 and 2003). Maybe the simulation of infiltration prior to melt was not enough to capture the magnitude of preferential flow upon prolonged desiccation of the cracking soils in the study area. Regardless, the physically-based nature of the simulations suggests that preferential flow deserves investigation as one of the major hydrological controls driving stream discharge in dry years.

This application of CHRM has a very high cultivated proportion of watershed land use, (87%), extremely level topography, and modest depressional storage, which is unique and contrasts to other agricultural applications of CRHM in land use proportions and topographic relief (Mahmood et al., 2016;Fang et al., 2010;Pomeroy et al., 2007;Pomeroy et al., 2014). The crops and cropping systems have been represented with an extremely high level of detail. The land-use split method used in other modelling efforts in this watershed (Yang et al., 2014) to represent crop rotations in a static fashion in a multi-year model exercise, seemed to work well for the application in this study given the good simulations in wet years. While the input datasets had a high level of detail, sensitivity analysis for different datasets (e.g. soils, land uses, topography) would help identify critical inputs where detailed information is not necessary. Such analysis would direct research and monitoring efforts to collect the most relevant information for model setup and parameterization (Ahuja et al., 2002) in other regions of the Canadian Prairies having physiography similar to that of this study.

Simulations of SWE, evaporation, and VWC were validated by external datasets, indicating that the model state variables were in good agreement with the major hydrological processed in the agricultural landscape. Small yearly differences in evaporation were likely due to differences in input data, location, and method, where AAFC applies Meyer's revised formula (Martin, 2002) for lakes and CRHM uses the Priestley-Taylor procedure for wetlands and small lakes. Differences in soil moisture values could be due to differences in soil properties used to calculate water holding capacity of the soil. Good simulation of model state variables increase the confidence in the runoff simulations and highlight the value of the physically-based approach used by CRHM to represent these landscapes. These measurements corroborate that the physical description of these hydrological processes are reasonably well understood and represented in the context of the Canadian Prairies, indirectly suggesting that the difficulties found by CRHM in simulating stream flow pertain to runoff routing in the drainage network. The gentle topography, ice-jammed channels at time of snowmelt, and river confluences make it a challenge to simulate channel routing. Thus, research efforts should focus on better understanding river dynamics in these landscapes.

Given the good performance in wet years, the present model can also potentially be used for impact assessment of land-use and climate change on nutrient transport dynamics in the study area. Trustworthy representation of the hydrology in the sub-catchment could be used to estimate nutrient transport through fitting of different concentration-discharge (C-Q) models available in the literature (Hall, 1970, 1971;Wilson et al., 2013;Helsel and Hirsch, 2002). Water-quality datasets used for calibration and validation of previous model exercises (Yang et al., 2014) are available to this end in adequate spatial-temporal frequency. This analysis would also allow for a comparison between models in terms of water yield and nutrient export simulations. Such comparisons will be the object of future research in the study area to identify how differing modelling approaches (i.e. calibrated versus non-calibrated simulations) complement each other in simulating flow and nutrient dynamics for future scenarios assessment.

The analysis of model falsification indicates that snow sublimation and blowing snow, as well as infiltration to frozen soils, are crucial for accurate simulations of stream discharge in the flat, intensively-managed agricultural watershed of the La Salle River. The prominence of snow sublimation effects over snow transport contrasts with results observed for mountain environments where greater importance of snow transport has been identified (Zhou et al., 2014). However, snow transport within our watershed was still of importance, despite no loss of snow from the watershed. Inclusion of snow transport affected peak and total discharge, with a more pronounced effect on the latter (Table 5). Inhibition of snow sublimation caused a reduction in total discharge in two out of 21 years (9% of the time) when compared to the base model, while inhibition of both snow sublimation and transport caused a reduction of this variable in eight out of 21 years (38% of the time). Accumulation of snow within watersheds tends to occur in association with steep hills and valley slopes (Pomeroy and Goodison, 1997). In the lower slope

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landscape of the La Salle watershed, snow accumulates in deep drainage ditches and stream channels. If snow transport is inhibited, the simulated accumulation of snow in these topographic features decreases and greater snow melt is simulated for upstream areas. This increases potential for infiltration, which could explain the reduction in total discharge associated with inhibition of snow transport. This pattern stresses the importance of internal snow transport within the watershed to stream discharge generation despite snow transport not impacting peak discharge to the same extent as snow sublimation. The pattern also provides some insight into the potential to site wind barriers such as shelterbelts to retain snow in upstream areas (Steyn et al., 1997) to encourage infiltration and reduce runoff generation with melt.

Regarding infiltration into frozen soils, falsifying this process had an overriding effect over falsification of blowing snow since peak discharge was consistently reduced in these models, despite the trend of increased peak and total discharge arising from falsification of snow processes (Table 5). These results emphasize the importance of infiltration to stream discharge generation. This process has been indirectly discussed by van der Kamp et al. (2003), who observed reduced runoff for land uses with enhanced infiltration. Since runoff is the primary source of stream discharge in the Canadian Prairies (Shook and Pomeroy, 2012;Shook and Pomeroy, 2010), it was expected that its relative importance would be more pronounced than that of blowing snow processes. The model falsification indicates that peak discharges would be reduced, on average, by 61% due to inhibition of frozen-soil infiltration, while inhibition of snow processes would increase peak discharges by 39% on average.

5. Summary and conclusions

Simulation of streamflow in an intensively managed agricultural tributary of the Red River (the La Salle River) with the CRHM platform revealed a number of topics for which knowledge

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of hydrological processes in the region and model representation might be improved. 1) Ice and backwater issues are likely to contribute to increased uncertainty in both input hydrometric data and model representations for tributaries of the Red River. Among the drivers of these issues are the low relief of topography of the region, the presence of dams along the river channel, presence of ice during peak flows, and frequent confluences of streams and artificial channels. 2) Simulation of low flow years remains challenging in the La Salle, as is commonly reported for other hydrological models. In low flow years, discharge was overestimated by 90% and a sensitivity analysis of the storage parameter of the Muskingum routing model indicated that averaging this parameter is not adequate for the study area. Also, improved simulations in dry years through emulation of preferential flow by allowing infiltration prior to the major melt event suggests that even where frozen soil predominates, preferential flow may be an important hydrological feature under dry conditions for the high clay content soils of the Red River Valley. As such, dynamical representation of processes such as infiltration through macrospores may require revision for drier conditions in the Red River Valley.

Despite the potential to improve model representation identified through this research, it is also evident that performance metrics for the CRHM platform indicate very good simulation of peak and yearly cumulative flows in the La Salle River where flows were equal to or above median values (under normal to wet conditions). On average, discharge was underestimated by only 5% in wet years. The good performance of the model in average or above-average flow years indicate that CRHM simulations are likely appropriate for use in regional nutrient-transport assessments where export is largely determined by hydrological drivers in the study area and for assessment of land-use and climate change impacts on streamflow.

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Falsifications of snow sublimation, snow transport, and infiltration to frozen soils processes in the validated base model indicate that these processes were very influential to stream discharge generation. Inhibition of snow sublimation would represented an average increase in peak discharge around 25%, while inhibition of blowing snow, which includes both snow sublimation and transport, would cause an increase in peak discharge around 39%. Simulation of infiltration without changes to model structure to account for frozen-soils would cause a reduction in peak discharge around 61%.

7. Team list

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9. Code availability

CRHM codes are available through model developers. Details can be found at http://www.usask.ca/hydrology/CRHM.php.

10. Data availability

The weather and hydrometric datasets used in this research are publicly accessible through the Environment and Climate Change Canada.

Weather Data: Environment and Climate Change Canada. 2015. Historical Climate Data. Available at: http://climate.weather.gc.ca/. Access: February 22, 2016.

Hydrometric data: Environment and Climate Change Canada. 2015. HYDAT Database-National Water Data Archive. Available at: https://ec.gc.ca/rhc-wsc/default.asp?lang=En&n=9018B5EC-1. Access: February 22, 2016.

11. Appendices

The manuscript has no appendices

12. Supplement link

Plot data to be uploaded and link to be generated.

13. Author contribution

M.R.C. Cordeiro, H.F. Wilson, and J. Vanrobaeys conceived the modelling objectives, scope, and strategy; M.R.C. Cordeiro and J. Vanrobaeys acquired the input data; M.R.C. Cordeiro, J.P. Pomeroy, and X. Fang developed the custom model for analysis; M.R.C. Cordeiro, H.F. Wilson performed data analysis; M.R.C. prepared manuscript with contribution from all co-authors.

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Table 1. List of hydrologic response units (HRUs) used in the LS-05OG008 watershed.

HRU ID	HRU acronym†	Cropping system/Land use	Crop	Soil texture	Occurrence			
					SB 2	SB 3	SB 5	SB 33
1	IVPO/SICL	Irrigated Vegetable	Potato	Silty clay loam	Yes	Yes	No	Yes
2	IVPO/C	Irrigated Vegetable	Potato	Clay	No	Yes	No	No
3	IVCR/SICL	Irrigated Vegetable	Carrot	Silty clay loam	Yes	Yes	No	Yes
4	IVCR/C	Irrigated Vegetable	Carrot	Clay	No	Yes	No	No
5	PRSB/SIC	Pulse Non-Row	Soybean	Silty clay	No	Yes	No	No
6	PRSB/C	Pulse Non-Row	Soybean	Clay	No	Yes	No	No
7	PFAF/C	Perennial Forage	Alfalfa	Clay	Yes	Yes	No	Yes
8	PRSW/SIC	Pulse Non-Row	Spring wheat	Silty clay	No	Yes	No	No
9	PRSW/C	Pulse Non-Row	Spring wheat	Clay	No	Yes	No	No
10	PFSW/C	Perennial Forage	Spring wheat	Clay	Yes	Yes	No	Yes
11	OSSW/C	Oilseed - Spring Cereal	Spring wheat	Clay	Yes	Yes	Yes	Yes
12	FCSW/C	Fall Cereal	Spring wheat	Clay	Yes	Yes	Yes	No
13	FCWW/C	Fall Cereal	Winter wheat	Clay	Yes	Yes	Yes	No
14	PRCA/SIC	Pulse Non-Row	Canola	Silty clay	No	Yes	No	No
15	PRCA/C	Pulse Non-Row	Canola	Clay	No	Yes	No	No
16	OSCA/C	Oilseed - Spring Cereal	Canola	Clay	Yes	Yes	Yes	Yes
17	FCCA/C	Fall Cereal	Canola	Clay	Yes	Yes	Yes	No
18	FYDL/SICL	Feedlot	–	Silty clay loam	No	No	No	Yes
19	FYDL/C	Feedlot	–	Clay	Yes	No	No	No
20	URLD/SICL	Urban (low density)	–	Silty clay loam	Yes	Yes	No	Yes
21	URLD/C	Urban (low density)	–	Clay	Yes	Yes	Yes	Yes
22	URMD/SIL	Urban (medium density)	–	Silt loam	No	No	Yes	No
23	URMD/SICL	Urban (medium density)	–	Silty clay loam	Yes	No	No	No
24	URMD/SIC	Urban (medium density)	–	Silty clay	No	Yes	No	No
25	URMD/C	Urban (medium density)	–	Clay	Yes	Yes	Yes	No
26	WETL/WA	Wetand/water	–	–	Yes	No	No	No
27	River Channel	River	–	–	Yes	Yes	Yes	Yes

† First two letters indicate cropping system/land use; third and fourth letters indicate crop; letter(s) after the slash indicate soil texture.

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946 Table 2. Modules used in the customized CRHM model to simulate hydrological process in the LS-05OG008 watershed.

Sequence[†]	Module	Description
1	Basin	Holds commonly used physical and control parameters
2	Global radiation	Calculates theoretical global radiation, direct and diffuse solar radiation, as well as maximum sunshine hours based on latitude, elevation, ground slope, and azimuth (Garnier and Ohmura, 1970). This module provides radiation input to modules 3, 8, and 13
3	Observation	Adjusts the temperature and precipitation variables in the input weather data to variations in environmental lapse rate, elevation, and wind-induced under-catch
4	Crop growth	Simulates a linear crop development over the growing season
5	Sunshine hours	Estimates sunshine hours from incoming shortwave radiation and provide input to modules 8 and 13
6	Walmsley's windflow	A parametric version of the wind flow model (Walmsley et al., 1989) that adjusts the wind speed change due to local topographic features and provides input to module 11
7	Incoming long-wave radiation	Estimates incoming long-wave radiation from the air temperature and the atmospheric transmittance, which is estimated from measured short-wave radiation and theoretical global radiation and provides input to module 13 (Sicart et al., 2006)
8	All-wave radiation	Estimates the snow-free net all-wave radiation from the calculated short-wave radiation by Garnier and Ohmura (1970) and the caculated net long-wave radiation (Brunt, 1932) using sunshine hours, air temperature and humidity (Granger and Gray, 1990) and provides inputs to module 9
9	Evaporation	Estimates actual evapotranspiration from unsaturated surfaces (Monteith, 1965) and evaporation from saturated surfaces such as stream channels (Priestley and Taylor, 1972). These algorithms modify the moisture content in the interception, ponded surface water, and soil column stores, as well as in the stream channel
10	Canopy	Estimates the snowfall and rainfall intercepted by the forest canopy and updates the under-canopy snowfall and rainfall and calculates short-wave and long-wave sub-canopy radiation (Ellis et al., 2010) with options for open environment (no canopy adjustment of snow mass and energy) and forest environment (adjustment of snow mass and energy from forest canopy)
11	Prairie Blowing Snow Model	Simulates snow sublimation and transport between HRUs (Pomeroy and Li, 2000)
12	Albedo	Estimates the snow albedo during the winter and the melt period (Gray and Landine, 1987). This module indicates the beginning of melt for module 13
13	Energy-Budget Snowmelt Model	Estimates snowmelt for snowpack in the Canadian Prairies (Gray and Landine, 1988) by calculating the energy balance of radiation, sensible heat, latent heat, ground heat, advection from rainfall, and change in internal energy
14	Infiltration	Estimates snowmelt infiltration into frozen soils (Gray et al., 1985) and rainfall into unfrozen soils based on texture and ground cover (Ayers, 1959)
15	Hydraulic conductivity estimator	Darcy's law for unsaturated flow is used to calculate the drainage factors of module 16 utilizing the unsaturated hydraulic conductivity calculated using Brooks and Corey relationship (Fang et al., 2013)
16	Soil	Estimates the soil moisture, groundwater flow, and interactions between ground- and surface-water throughout the year (Leavesley et al., 1983; Dornes et al., 2008; Fang et al., 2010)

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17	Volumetric soil moisture	Converts soil moisture to volumetric equivalent using the variables from module 16 and determines fall status for module 14
18	Muskingum routing	Routes runoff between HRU and sub-basins using the Muskingum method (Chow, 1964)

† Sequence in which the modules were entered into each CRHM Group using the Macro window.

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Table 3. Streamflow characteristics of the study area for the years used in the analysis.

Year	Water Yield (mm)	Discharge					Ice conditions	Backwater
		Annual† (m^3)	Snowmelt (m^3)	Snowmelt Proportion (%)	Peak (m^3 s^{-1})	Peak Date		
1992	64	1.21×10^7	7.27×10^6	60	6.7	April 10th	March 1st – April 12th	No data for analysis
1993	66	1.25×10^7	4.51×10^6	36	5.6	April 07th	March 1st – April 10th	No data for analysis
1994	18	3.33×10^6	9.32×10^5	28	0.7	April 10th	March 1st – April 16th	No data for analysis
1995	61	1.15×10^7	6.56×10^6	57	5.0	March 31st	March 1st – April 15th	No data for analysis
1996	99	1.87×10^7	1.35×10^7	72	13.5	April 29th	March 1st – April 28th	No data for analysis
2002	10	1.94×10^6	1.94×10^6	100	1.6	April 16th	March 1st – April 16th	No backwater
2003	18	3.49×10^6	3.49×10^6	100	2.1	April 2nd	March 1st – April 09th	No backwater
2005‡	83	1.57×10^7	4.54×10^6	29	10.0	April 08th	March 1st – April 04th	April 3rd – April 14th June 29th – July 24th
2006	115	2.18×10^7	2.18×10^7	100	16.5	April 10th	March 1st – April 07th	April 3rd – April 19th
2007	38	7.26×10^6	7.26×10^6	100	4.6	April 12th	March 1st – April 05th	March 31st – April 13th
2009	89	1.69×10^7	1.69×10^7	100	13.3	April 17th	March 1st – April 16th	April 11th – April 26th
2010	110	2.09×10^7	1.04×10^7	50	10.7	June 1st	March 1st – April 05th	May 30th – June 06th September 2nd – September 3rd
2011	150	2.84×10^7	1.59×10^7	56	15.7	April 13th	March 1st – April 13th	April 04th – April 20th May 20th – May 21st
2012	26	4.89×10^6	1.71×10^6	35	2.5	May 29th	March 1st – March 24th	No backwater
2013	76	1.44×10^7	9.38×10^6	65	9.4	May 04th	March 1st – May 1st	April 28th – May 08th

‡ Backwater issues late in the summer; † Total flow from March 1st to October 31st.

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Table 4. Metrics used for model assessment.

Year	NSE	MB	RMSD	NRMSD
1992	0.69	-0.10	0.51	0.89
1993	-0.79	0.31	1.13	1.92
1994	-27.91	2.00	0.68	4.31
1995	-0.58	0.81	1.10	2.02
1996	0.81	0.50	1.00	1.14
2002	-14.04	2.01	0.96	3.92
2003	-1.08	0.16	0.69	1.58
2005	0.85	-0.12	0.93	0.77
2006	0.76	-0.38	2.31	0.84
2007	-0.43	0.69	1.65	1.81
2009	0.65	-0.31	2.18	1.02
2010	0.36	-0.26	1.50	1.52
2011	0.84	-0.29	0.98	0.73
2012	-0.60	0.30	0.27	1.16
2013	0.72	0.36	0.91	1.34

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Table 5. Percent change in peak discharge, total discharge, and snow water equivalent (SWE) between falsified models and base models.

Water Year	Snow sublimation			Blowing snow			Frozen-soil infiltration			Frozen-soil infiltration and blowing snow		
	Peak discharge	Total discharge	SWE	Peak discharge	Total discharge	SWE	Peak discharge	Total discharge	SWE	Peak discharge	Total discharge	SWE
1992-1993	39.4	12.3	23.0	69.5	7.1	23.0	-65.7	-2.8	0.0	-65.0	-5.3	23.0
1993-1994	-3.8	2.1	24.8	-2.0	-2.4	24.8	-34.6	18.4	0.0	-34.4	24.4	24.8
1994-1995	-11.3	-1.9	41.8	-13.1	-1.5	41.8	-77.9	-24.3	0.0	-78.1	-25.3	41.8
1995-1996	24.3	8.7	39.5	47.4	5.3	39.5	-78.5	-29.2	0.0	-82.1	-38.0	39.5
1996-1997	180.1	45.7	39.7	350.5	47.3	39.7	-32.7	8.4	0.0	-43.1	-12.5	39.7
1997-1998	29.5	11.4	19.9	33.6	-1.3	19.9	-75.5	5.4	0.0	-75.4	5.3	19.9
1998-1999	7.3	4.9	62.8	3.1	-2.4	62.8	-42.4	43.4	0.0	-41.8	46.0	62.8
1999-2000	14.3	4.8	30.4	14.6	1.6	30.4	-41.4	8.1	0.0	-41.3	7.2	30.4
2000-2001	19.0	17.0	13.9	16.0	18.4	13.9	-79.7	-12.8	0.0	-79.7	-17.9	13.9
2001-2002	25.1	10.3	22.0	30.5	3.4	22.0	21.9	13.7	0.0	24.0	12.6	22.0
2002-2003	17.0	6.1	151.3	23.8	-1.9	151.3	-72.6	42.7	0.0	-72.2	44.1	151.3
2003-2004	-8.2	9.2	17.3	-1.3	16.3	17.3	-80.1	-21.3	0.0	-79.8	-26.0	17.3
2004-2005	30.4	9.1	19.4	27.5	2.2	19.4	-60.0	-7.1	0.0	-60.0	-12.4	19.4
2005-2006	16.2	8.9	22.3	10.5	1.0	22.3	-89.8	-27.0	0.0	-92.4	-30.8	22.3
2006-2007	-4.0	18.9	28.7	-4.0	9.6	28.7	-84.7	-11.1	0.0	-84.5	-15.0	28.7
2007-2008	99.3	15.4	53.0	89.3	-4.5	53.0	-52.0	14.5	0.0	-62.3	10.0	53.0
2008-2009	36.5	10.7	16.2	49.1	5.2	16.2	-80.4	-4.1	0.0	-76.2	-2.7	16.2
2009-2010	1.7	-0.6	23.6	22.3	-5.8	23.6	-36.1	6.6	0.0	-37.0	5.8	23.6
2010-2011	2.9	6.5	19.6	21.8	5.6	19.6	-80.7	-18.8	0.0	-83.8	-24.7	19.6
2011-2012	16.1	5.0	54.2	4.0	-2.2	54.2	-53.8	36.9	0.0	-53.2	38.9	54.2
2012-2013	2.5	2.3	13.1	28.0	5.6	13.1	-79.5	-29.4	0.0	-82.8	-34.3	13.1
Average	25.4	9.8	35.1	39.1	5.1	35.1	-60.8	0.5	0.0	-62.0	-2.4	35.1

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955 Table 6. Selected statistical metrics (i.e. NSE and Model Bias) for falsified models.

Year	Snow sublimation		Blowing snow		Frozen-soil infiltration		Frozen-soil infiltration and blowing snow	
	NSE	MB	NSE	MB	NSE	MB	NSE	MB
1992	-0.43	0.17	-0.62	0.10	-0.21	-10.80	-0.15	-0.10
1993	-0.80	0.47	-0.59	0.40	-0.02	13.60	0.02	0.09
1994	-29.18	2.09	-28.89	1.91	-11.43	216.00	-11.54	2.22
1995	-0.23	0.77	-0.59	0.79	0.31	26.30	0.34	0.23
1996	0.48	0.64	0.12	0.59	0.22	-6.90	0.22	-0.21
2002	-39.64	2.80	-41.84	2.46	-1.37	85.00	-0.73	0.67
2003	-1.52	0.30	-1.74	0.13	-0.14	9.80	-0.01	0.05
2005	0.89	0.03	0.90	-0.08	-0.05	-40.90	-0.05	-0.50
2006	0.83	-0.29	0.81	-0.35	-0.18	-77.20	-0.19	-0.81
2007	-0.86	1.13	-0.88	0.96	-0.10	-30.10	0.00	-0.44
2009	0.68	-0.16	0.66	-0.16	-0.07	-64.50	0.02	-0.63
2010	0.35	-0.26	0.33	-0.30	0.30	-28.80	0.31	-0.31
2011	0.89	-0.23	0.86	-0.24	0.10	-47.30	0.10	-0.53
2012	-1.16	0.38	-0.64	0.26	-0.14	63.40	-0.29	0.68
2013	0.67	0.39	0.09	0.44	0.01	-12.00	0.05	-0.19
Average	-4.60	0.55	-4.80	0.46	-0.85	6.37	-0.79	0.02

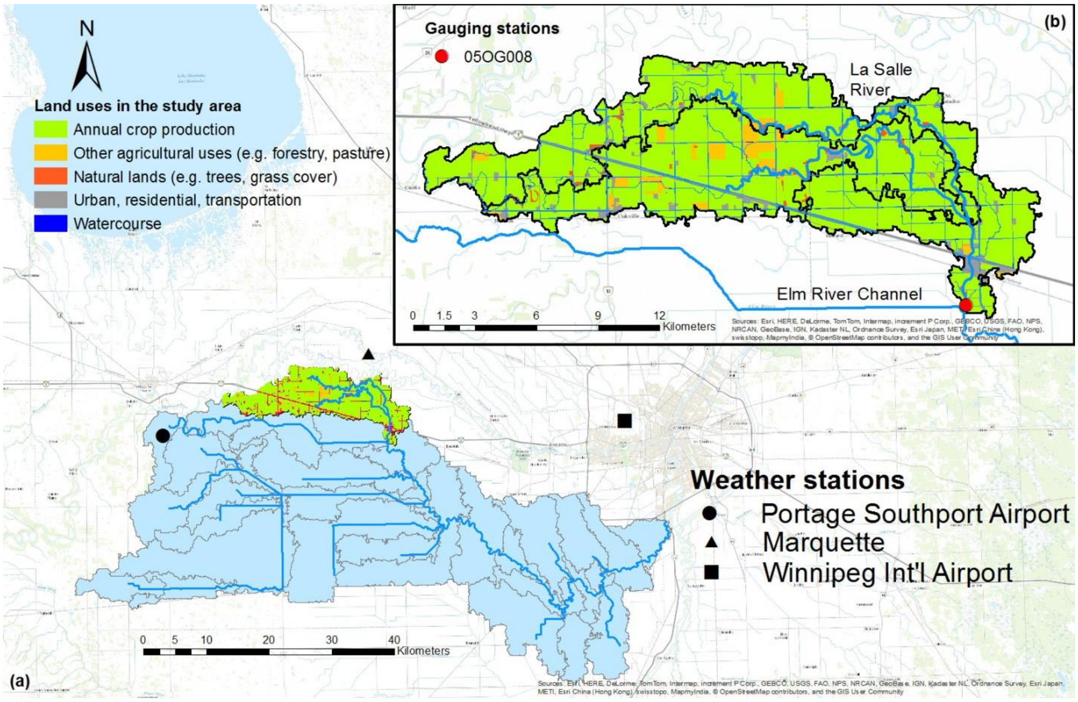

Figure 1. The La Salle watershed (a) and the sub-watershed used in the study, which drains into Water Survey Canada gauging station 05OG008 (b).

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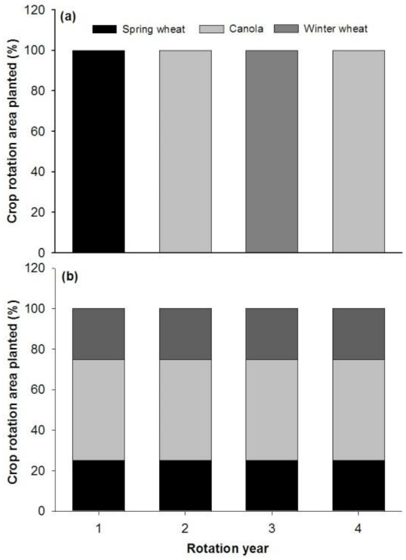
961 

962 Figure 2. Example of how the Fall Cereal Cropping System rotation 4-year rotation (a) was represented every
963 year in the model using the land-use split method (b).

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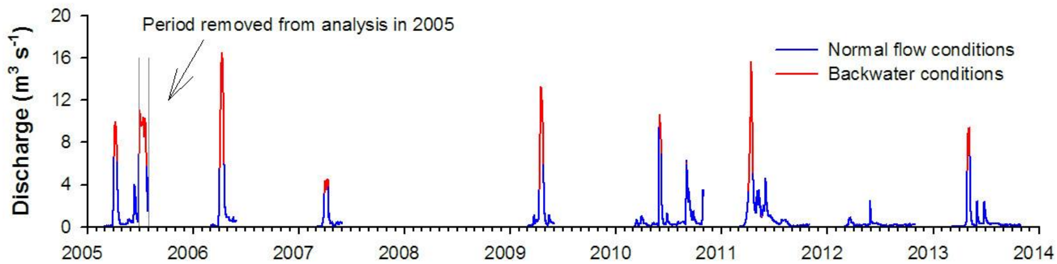

Figure 3. Yearly hydrographs indicating periods of potential backwater issues. Years of 2002, and 2003 not presented since these years did not have backwater issues. Years of 2004 and 2008 were not included in the analysis since quality issues were identified in the metadata of the records. The period between lines in 2005 indicate the records removed from the dataset during model assessment.

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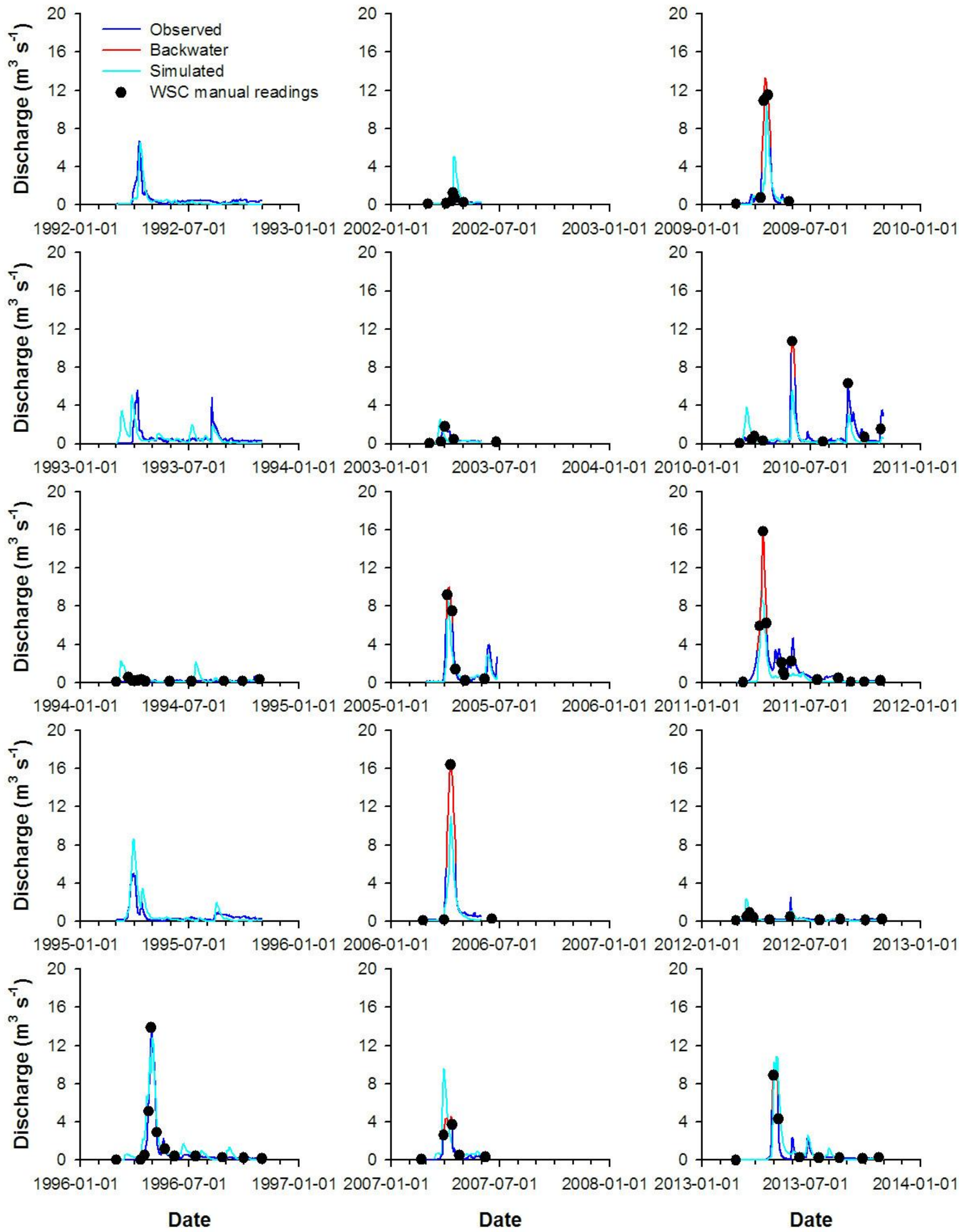

Figure 4. Comparison of observed and simulated stream discharge between 1992 and 2013 for years with good records in the HYDAT database.

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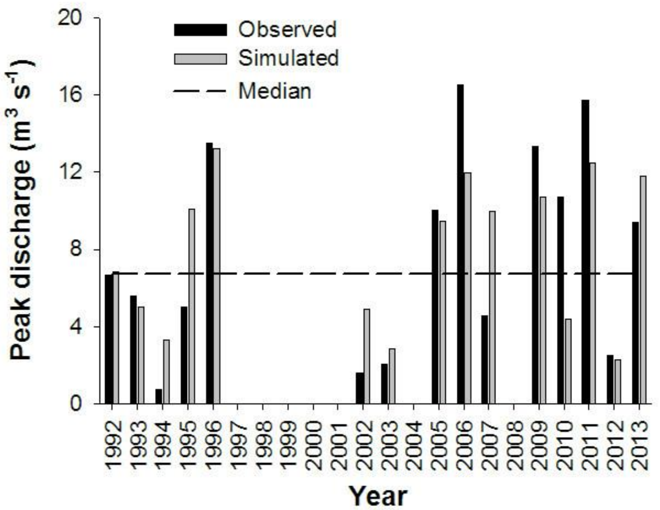
975 

976 Figure 5. Comparison of observed and simulated peak discharge between 1992 and 2013 for years with good
977 records in the HYDAT database. No data available in the HYDAT database between 1997 and 2001. Years of 2004
978 and 2008 were not included in the analysis since quality issues were identified in the metadata of the records.

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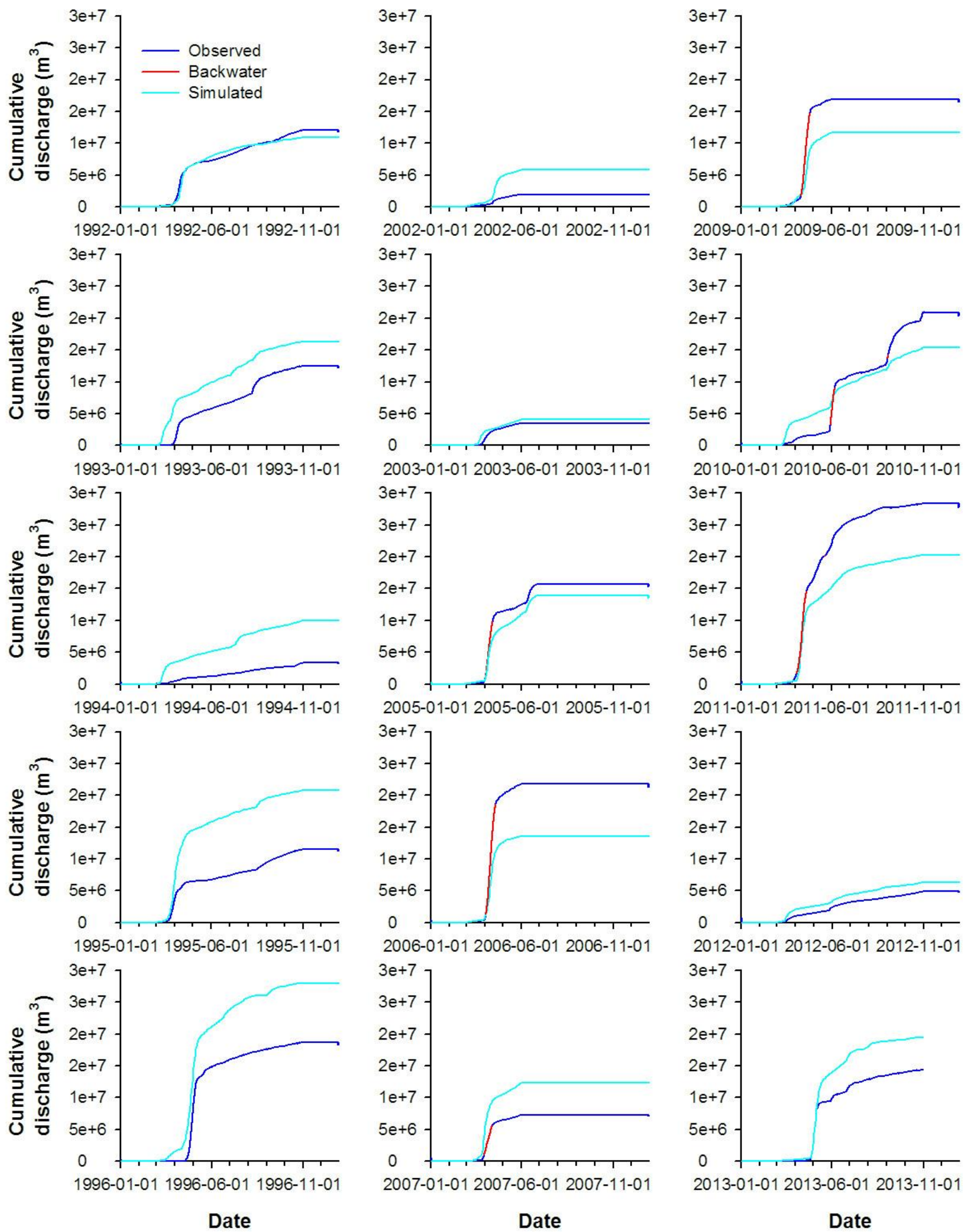
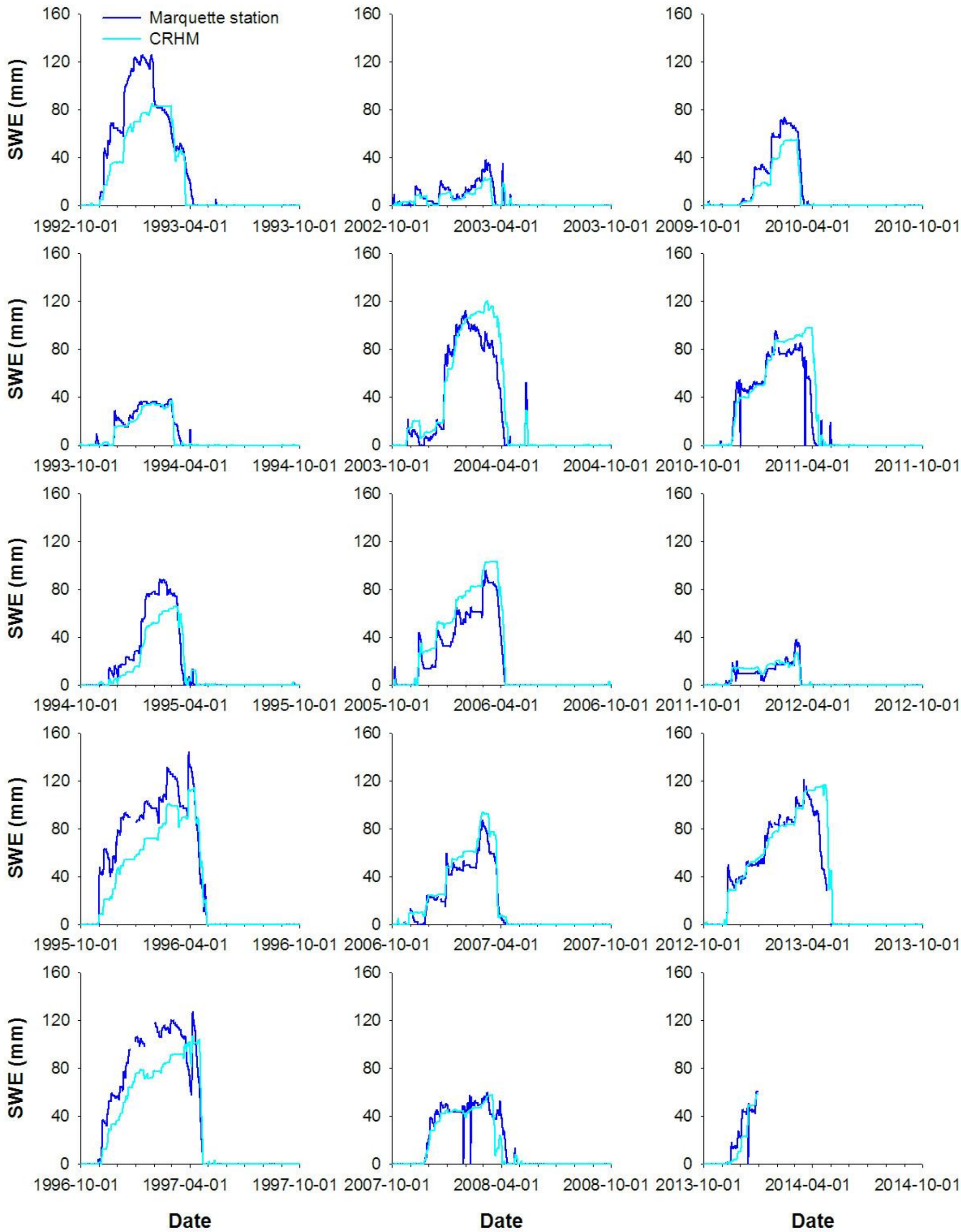


Figure 6. Comparison of observed and simulated annual cumulative discharge between 1992 and 2013 for years with good records in the HYDAT database.

984 

985 Figure 7. Comparison of observed and simulated snow water equivalent (SWE) between 1992 and 2013 for
986 years with good records in the HYDAT database. SWE was calculated assuming a snow density of 180 kg m^{-3}.

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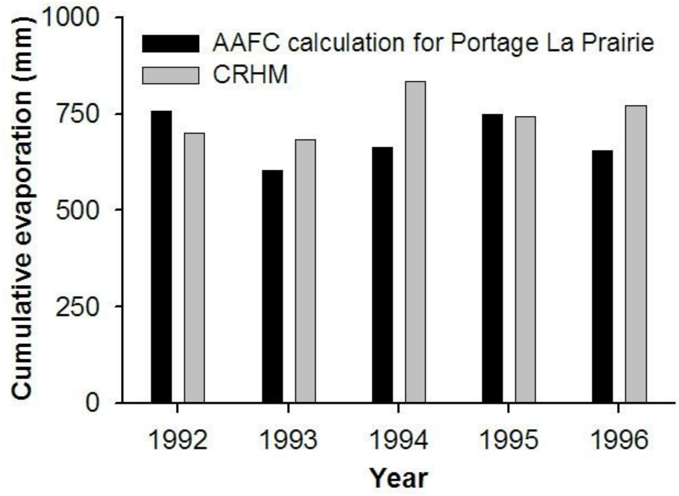

Figure 8. Comparison of evaporation estimates produced by the Agriculture and Agri-Food Canada (AAFC) and CRHM between 1992 and 1996.

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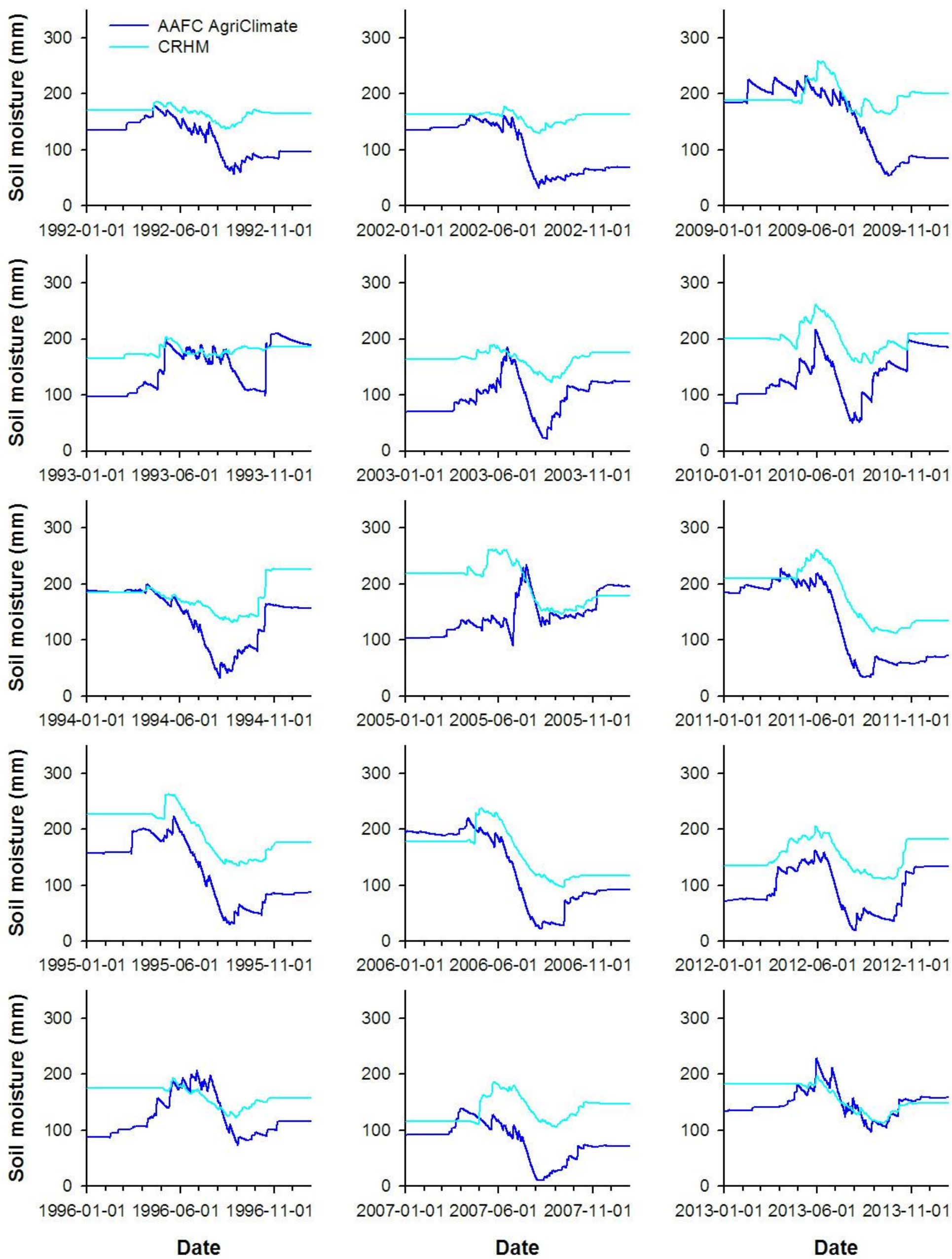

Figure 9. Comparison between simulated volumetric soil water content (VWC; expressed in mm of water in the soil profile) produced by the National Drought Model (NDM) and CRHM between 1992 and 2013 for years with good records in the HYDAT database.

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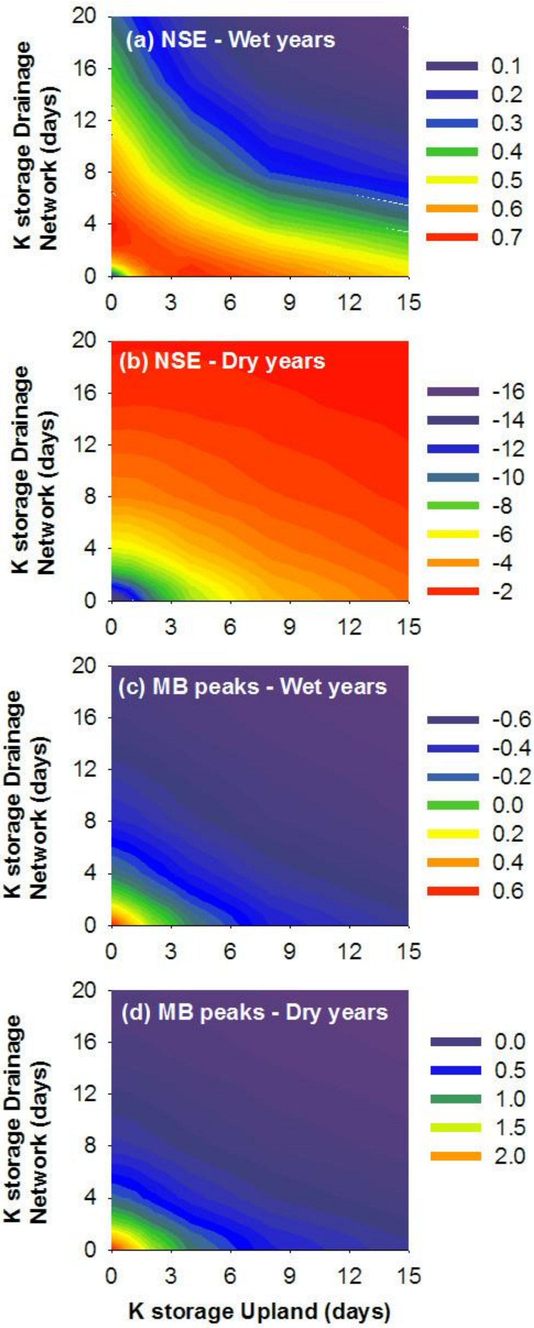

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998 Figure 10. Sensitivity analysis of the K storage parameter in the Muskingum model for upland and drainage
999 network using Nash-Sutcliff efficiency (NSE) and peak-flow model bias (MB) as objective functions.

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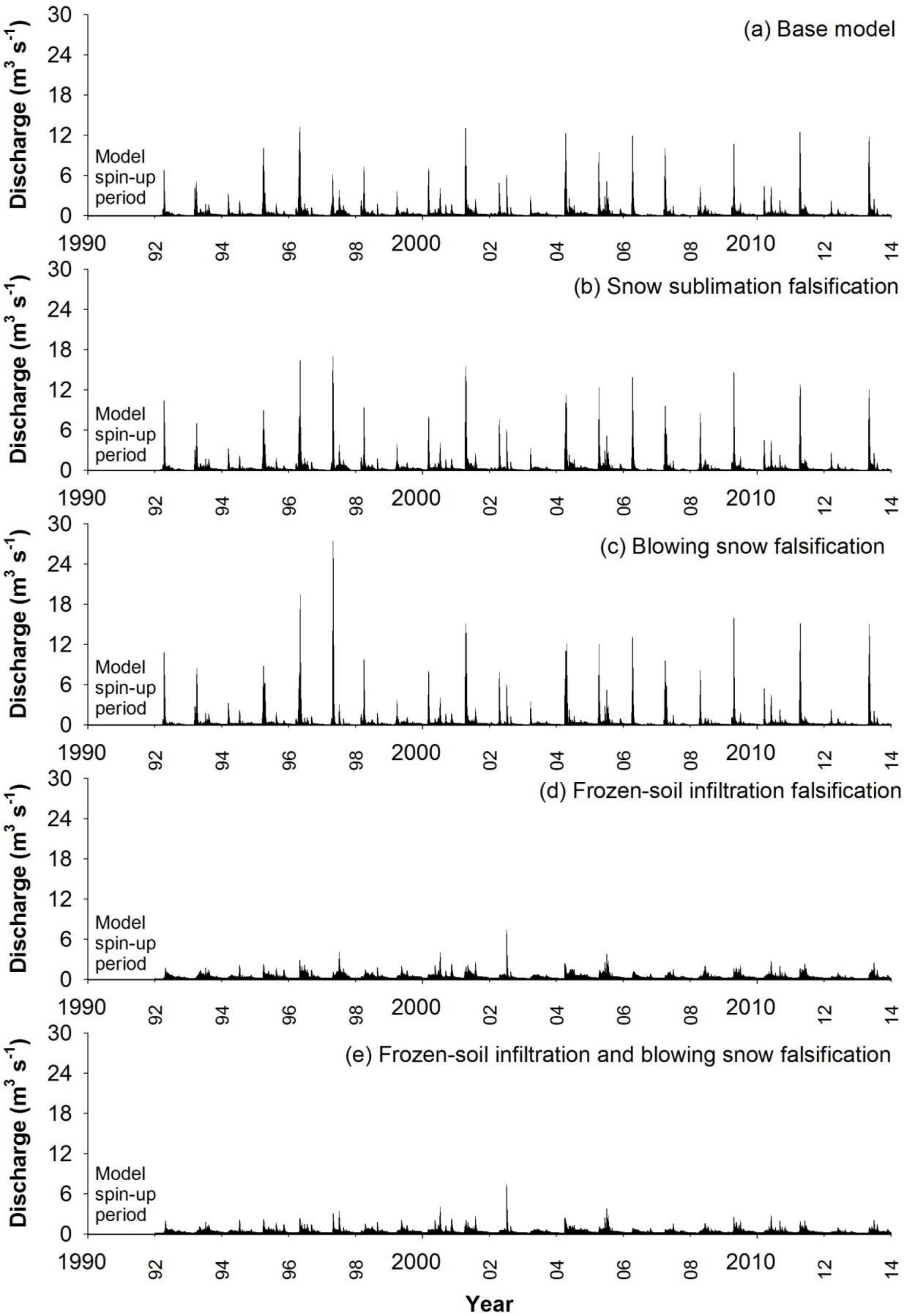

Figure 11. Hydrographs of the entire simulation period (1992-2013) for the base model (a) and the different model falsifications, which include inhibition of snow sublimation (b), blowing snow (c), frozen-soil infiltration (d) and frozen-soil infiltration combined with blowing snow (e).