Improving and Testing the Prairie Hydrological Model at Smith Creek Research Basin

J.W. Pomeroy, K. Shook, X. Fang, S. Dumanski, C. Westbrook, T. Brown

Centre for Hydrology Report No. 14

Centre for Hydrology
University of Saskatchewan
117 Science Place,
Saskatoon, Saskatchewan
S7N 5C8

Table of Contents

Executive Summary

The 2010 Prairie Hydrological Model configuration of the Cold Regions Hydrological Model was developed to include improved snowmelt and evaporation physics and a hysteretic relationship between wetland storage and runoff contributing area. The revised model was used to simulate the snow regimes on and the streamflow runoff from the five sub-basins and main basin of Smith Creek, Saskatchewan for six years (2007-2013) with good performance when compared to field observations. Smith Creek measured streamflows over this period included the highest annual flow volume on record (2011) and high flows from heavy summer rains in 2012. Smith Creek basin has undergone substantial drainage from 1958 when it contained 96 km^2 of wetlands covering 24% of the basin area to the existing (2008 measurement) 43 km^2 covering 11% of the basin. The Prairie Hydrological Model was run over the 2007-2013 period for various wetland extent scenarios that included the 1958 historical maximum, measured extents in 2000 and 2008, a minimum extent that excluded drainage of conservation lands and an extreme minimum extent involving complete drainage of all wetlands in Smith Creek basin.

Using the 2008 measurement of wetland extent as the reference scenario for the "current state" of wetlands, the results show that the annual streamflow volume and peak daily discharge have a remarkably strong sensitivity to wetland drainage, both over the historical period (1958-2008) and to the minimum possible wetland extents. Wetland drainage is shown to have a strong impact on floods due to snowmelt (2011) and rainfall (2012). Complete drainage of the current wetland extent results in simulated increases of 32% in the annual flow volume for 2011, the flood of record. The 2011 annual flow volumes simulated with complete wetland drainage are nearly double the streamflow simulated using the 1958 wetland levels. The proportional increase in simulated peak daily discharge in 2011 from drainage of the 2008 wetland extent is 78%, much greater than the increase in annual flow volumes. Restoration of wetlands from the current extent back to that measured in 1958 decreases the simulated 2011 flood peak by 32% and the 2011 yearly volume of streamflow by 29%. 2012 was a unique high flow year in that rainfall-runoff rather than snowmelt generated most streamflow and wetlands still stored large amounts of water after the flood of record in 2012. Despite the wet antecedent conditions and rainfall-runoff generation process operating in 2012, the impact of wetland drainage from 2008 levels on simulated annual flow volumes was similar to that in 2011, but wetland restoration from 2008 to 1958 levels did not cause a decrease flow volumes.

Annual flow volumes in moderate to low flow years increase by very large amounts (200% to 300%) from complete drainage of the 2008 wetlands, and are reduced by smaller amounts (21% to 60%) with restoration of the 2008 wetland extent to 1958 levels. Peak discharges in moderate to low flow years increase substantially (150% to 350%) with complete drainage from the current condition, and decrease by smaller amounts (35% to 70%) with restoration from

current levels to those of 1958. Little differences are found in the annual and peak flows between the completely drained state and the "loss ceiling" due to conservation lands which protect wetlands from drainage in Smith Creek, suggesting that the protected area is inadequate to ameliorate basin hydrological response to further drainage.

Overall, Smith Creek total flow volumes over six years increase 55% due to drainage of wetlands from the current (2008) state, and decrease 26% with restoration to the 1958 state. This sensitivity in flow volume to wetland change is crucially important for the water balance of downstream water bodies such as Lake Winnipeg. Whilst the greatest proportional impacts on the peak daily flows are for dry years, substantial impacts on the peak daily discharge of record (2011) from wetland drainage (+78%) or restoration (-32%) are notable and important for infrastructure in and downstream of Smith Creek. For the flood of record (2011), the annual flow volume and the peak daily discharge are estimated to increase from 57,317 to 81,227 dam^3 and from 19.5 to 27.5 m^3/s, respectively, due to wetland drainage that has already occurred in Smith Creek. Although Smith Creek is already heavily drained and its streamflows have been impacted, the annual flow volumes and peak daily discharge for the flood of record can still be strongly increased by complete drainage from the 2008 wetland state, rising to 103,669 dam^3 and 49 m^3/s respectively. This model simulation exercise shows that wetland drainage can increase annual and peak daily flows substantially, and that notable increases to estimates of the annual volume and peak daily flow of the flood of record have derived from wetland drainage and will proceed with further wetland drainage.

Improving and Testing the Prairie Hydrological Model at Smith Creek Research Basin

1. Introduction

Background

Research at the University of Saskatchewan and Environment Canada has resulted in the development of the Cold Regions Hydrological Modelling Platform (CRHM) (Pomeroy et al., 2007a) which is a physically based, spatially distributed, modular object-oriented model development system. The component modules have been developed based on the results of over 50 years of research in prairie, boreal, mountain and arctic environments. Recent developments in CRHM based on research at Smith Creek Research Basin, Saskatchewan have produced the Prairie Hydrological Model (PHM) formulation of CRHM (Fang and Pomeroy, 2007; 2008, 2009; Pomeroy et al., 2010; Fang et al., 2010; Guo et al., 2012). The PHM formulation includes a wetland module which has had extensive development and testing at Smith Creek with virtual wetland drainage and restoration simulations and tests for its ability to simulate current conditions. Smith Creek Research Basin was established, instrumented with a high quality meteorological station and had extensive baseline measurements of soil type, wetland hydrography, land cover, precise topographic elevation and drainage over 2007-2009. Tests of the model against observations showed that the PHM can simulate most aspects of the prairie hydrological cycle in a wetland dominated system extremely well, but required improvements in its representation of drained wetlands and of complex wetland sequences (Pomeroy et al., 2010).

The hydrology of the Canadian Prairies has been studied for many decades (Gray, 1970). Since settlement, the region has undergone changes in climate and land use with recent changes including the adoption of minimum tillage and continuous cropping and the draining of wetlands (Council of Canadian Academies, 2013). The eastern portion of the Canadian Prairies experienced one of the wettest periods on record from 2010 to 2012 (Chun and Wheater, 2012), producing 1:500 year flood events through much of the region. The specific causes of these events need to be investigated as they can be affected by both climate extremes and wetland drainage.

In the Saskatchewan portion of the Canadian Prairies, annual precipitation ranges from 300-400 mm (Pomeroy et al., 2007b), and is comprised of one-third snowfall (Gray and Landine, 1988), though the rainfall fraction is increasing with time (Shook and Pomeroy, 2012). Winters last 4-5 months and are characterized by continuous snowcover and frozen soils (Pomeroy et al., 2010). Snowmelt over frozen soils leads to high runoff rates (Gray et al., 1985) and accounts for over 80% of the annual surface runoff in the prairie region (Gray and Landine, 1988). Rainfall in the spring and early summer is most typically from frontal systems over large areas, whereas summer precipitation is usually from convective storms supplying intense rainfalls over small areas (Gray, 1970). Shook and Pomeroy (2012) show that multiple-day rainfall events that are consistent with frontal genesis are increasing in frequency, whilst single-day rainfall that are consistent with convective storms are decreasing in frequency at many Canadian Prairie observation stations. Evaporative demand typically exceeds precipitation during the summer (Winter, 1989) which quickly depletes soil moisture levels and shallow wetlands (Millett et al., 2009). This results in minimal runoff from rainfall-runoff processes under normal soil moisture conditions (Granger and Gray, 1989).

Surface runoff on the Canadian Prairies very often drains internally into topographic depressions, forming wetlands or sloughs that act as closed basins (Hayashi et al., 2003; Fang and Pomeroy, 2008). These depressions store surface water for long time periods (Shook and Pomeroy, 2011) and under normal conditions, internally drained basins are non-contributing to streamflow generation and are called non-contributing areas (Godwin and Martin, 1975). During times of high runoff, the storage capacity of many depressions can be exceeded, causing a fill-and-spill process to occur (van der Kamp and Hayashi, 2009). Temporary streamflow networks can form, resulting in a dynamic increase in the contributing area for runoff (Shaw et al., 2012). In Canada, it is estimated that over 70% of the wetlands have been lost (DUC, 2007). Draining wetlands adds permanent surface connections to the hydrometry, reducing the ability for the depressions to store surface water and permanently increasing the contributing area. Some modeling studies have shown that wetland drainage increases stream flood frequencies and magnitudes (Gleason et al., 2007; Yang et al., 2010).

Purpose and Objectives

The main purpose of this study is to use CRHM to further develop the Prairie Hydrological Model (PHM) from its initial formulation (Pomeroy et al., 2010) so that it can more realistically describe the hydrology of wetland complexes including drained wetlands and to evaluate PHM on multiple years of high quality hydrological data from Smith Creek Research Basin, Saskatchewan. The secondary purpose is the preserve the operation of the Smith Creek Research Basin for hydrological modelling development and testing purposes and to further observe the impact of extreme weather events on drained wetland hydrology.

The specific objectives of this study are to:

1. Develop an improved wetland module that incorporates the dynamics of drained wetland complexes in the physically based, modular PHM.
2. Refine existing PHM results for Smith Creek using advances in an improved wetland module, additional parameter data and other adjustments as necessary.
3. Collect field data at Smith Creek (snow surveys, soil moisture surveys, wetland surveys) in order to run and evaluate PHM.
4. Demonstrate hydrological scenarios/sensitivity of landscape components such as wetlands and uplands under variable weather and climate conditions at Smith Creek to provide information that can underpin watershed management.

2. Study Site and Observations

Smith Creek Research Basin

The study was conducted in the Smith Creek Research Basin (SCRB) located in southeastern Saskatchewan, Canada, approximately 60 km southeast of Yorkton, SK. The basin area is 393.4 km^2, and is relatively flat with slopes fluctuating from 2 % to 5 % and elevation ranging from 490 m to 548 m. The basin and its five sub-basins used for this study are outlined in Figure 1 with wetlands and artificial drainage as it was measured by Ducks Unlimited Canada in 2001. The dominant land use is agriculture (cropland and pasture) which encompasses approximately 48% of the basin (Minke et al., 2010). The remainder of the basin is comprised of native grassland, deciduous woodland and natural wetlands (Fang et al., 2010). Soil texture is predominately loam (Saskatchewan Soil Survey, 1991). The SCRB has been partially drained, with the extent of wetland area estimated to have decreased from 24% to 11% of the basin area from 1958-2008 (Figure 1) (Minke et al., 2010; Personal Communication Lyle Boychuck, 2014). Wetlands in this case are defined as depressional storage with either open water or exposed vegetation that are capable of storing water for at least several days. Interviews with farmers within the basin have reported that a higher than normal amount of drainage occurred in response to 1995 and 2011, years where major floods occurred. Rates of drainage are discussed in more detail later in the report. Many road culverts have been installed within the SCRB and act to help control the flow of water. These gates are managed by the rural municipalities (RM's) and are typically left open, except during periods of high runoff (i.e. intense rainfall events, rapid snowmelt).

Hydrometeorological Observations and Conditions, 2011-2013

Instrumentation used to provide datasets for model runs and evaluation within the SCRB over the full period of study (2007-2013) included a hydrometric gauge at the basin outlet, as well as a meteorological station. The stream gauge (site 05ME007) has been operated by the Water Survey of Canada since 1975. Discharge values displayed are calculated using a rating curve applied to stage measurements entering a culvert. The meteorological station installed in July 2007 by the University of Saskatchewan Centre for Hydrology to measure relative humidity, air temperature, radiation (incoming and outgoing short and long-wave), wind speed, wind direction, snow depth, soil moisture (10 cm and 40 cm depth) and temperature (15 cm and 30 cm depth), rainfall, and snowfall was maintained over the period of study. Fall gravimetric sampling of soil moisture and over-winter surveys of snow depth and density provided auxiliary data to initialize the model and evaluate model performance.

Similar to other small streams in much of the Canadian Prairies (Pomeroy et al., 2007b), the peak annual streamflow within the SCRB is normally caused by runoff from the spring snowmelt, which typically occurs by mid-April and streamflow typically ceases shortly after snowmelt. Throughout the winter, soils freeze and snow is redistributed by wind transport of blowing snow into depressions or areas of relatively tall vegetation. . Intense rainfall events can cause intermittent streamflow throughout the summer, but these events normally tend to be small in volume and of short duration. There is normally no baseflow to sustain streamflow in fall and winter due to the extremely low hydraulic conductivity of the glacial tills that underlie soils, streams and

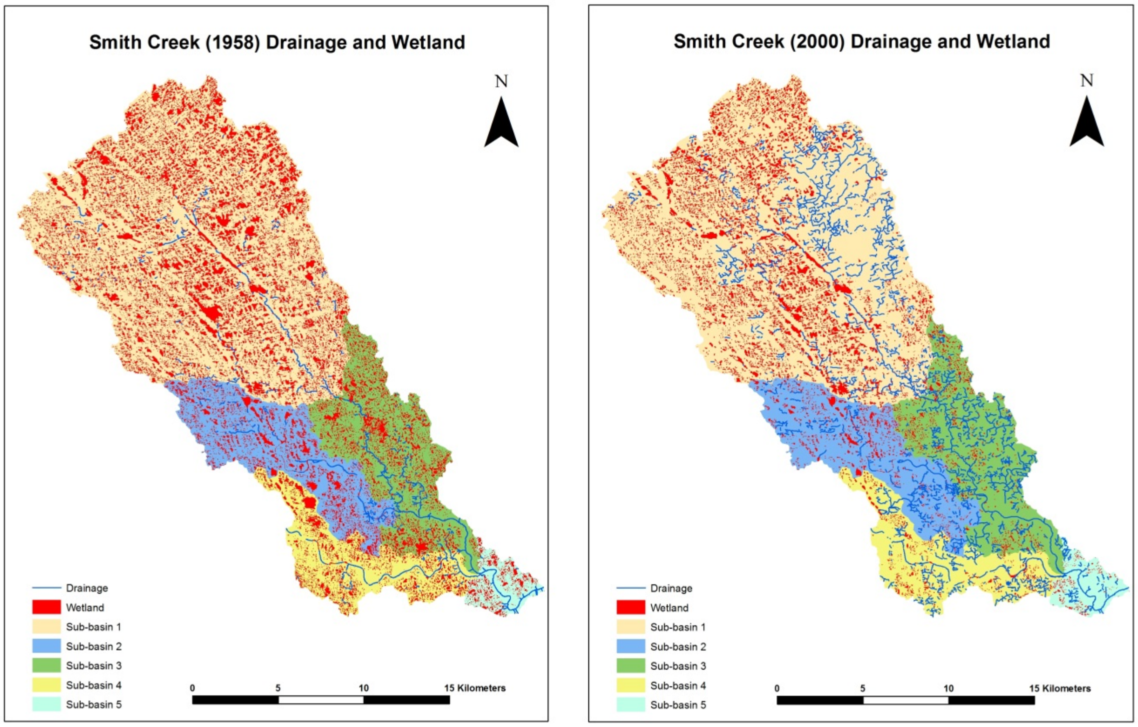

Figure 1. Smith Creek Research Basin wetland areas, sub-basins and drainage network in 1958 and 2000, adapted from data provided by Ducks Unlimited Canada (Lyle Boychuk personal communication).

wetlands. These tills act as aquitards and so any underlying aquifers are deep, confined and poorly connected to surface hydrology. Pomeroy et al. (2010) noted the influence of wetland drainage on increasing the flow volumes in the flood of 1995 in an earlier modelling study of Smith Creek. A major feature of the period of renewed observation at Smith Creek was a very wet period starting in summer 2010 which resulted in flooding in 2011 and 2012. These floods were instructive as the flooding in 1995, 2011 and 2012 were driven by quite different antecedent and concurrent hydroclimatic conditions.

The flood of 1995 was driven by high rainfall in late summer and early fall of 1994, and high snowfall throughout winter. Rainfall depths in August to November 1994 totalled 179 mm, with 130 mm falling in August. Localized runoff and direct precipitation from these summer and fall rains may have acted to increase water storage in wetlands. This large volume of rainfall may have increased the soil moisture content of soils in the basin at the time of fall freeze-up, which has a large influence on reducing infiltration, and therefore increasing runoff, during the subsequent spring melt. For instance, the restricted infiltration to the frozen soils in 1995 may have been enhanced by the formation of an ice lens over frozen ground in November 1994 when 5 mm of rain fell onto the shallow snowpack. The snowfall over the winter of 1994 – 1995 was 180 mm, which was the highest since streamflow records started in 1975. Temperatures warmed in early March 1995 and initiated snowmelt. On March 16th, 1995, mixed precipitation consisting of 7 mm of rain and 10 mm of snow fell. Snow stayed on the ground until April

20th, a week after another mixed precipitation event occurred, consisting of 5 mm of rain and 12 mm of snow. The annual discharge volume in 1995 was 28,140 dam^3, which was the highest on record at the time.

Flooding in the spring of 2011 was caused by more extreme conditions than in 1995. Rainfall in 2010 was 499 mm, 172 mm more than the long-term average and much of this occurred late in 2010, wetting up the basin wetlands and soils going into fall and winter. 2010 was the first year on record where the peak flow in Smith Creek was caused by rainfall and was also the first where streamflow was sustained throughout the summer. This suggests that there were periods in 2010 when the soil moisture and depressional storage capacity within the Smith Creek were nearly full, but may also reflect the enhanced drainage network in 2010 compared to 1994. On October 23-25 2010, two days before the first snowfall, 43 mm of rain fell, saturating the surface layer of soils just before they froze. Snowfall over the winter 2010 - 2011 was close to average, at 130 mm. Snowmelt was initiated by a rain-on-snow event on March 16, 2011, with 8 mm of rain falling; snowmelt was not completed for a further month. Streamflow started on April 8-10th 2011 and culverts began overtopping on April 16th. Many culvert gates were closed in the basin at this time, and many culverts not equipped with gates were boarded up. A flow direction reversal was observed on April 19th, where water flowed through a culvert into the main-stem of Smith Creek. As Smith Creek rose, water was forced back over the road in the opposite direction to the original flow. The SCRB was still partially snow-covered until May 2nd. Peak flow occurred on May 4th and was estimated by WSC to be 19.7 m^3/s but this flow was restricted by the rate of flow from a gridroad-dammed pond through a submerged culvert. Two major rainfall events occurred near the end of snowmelt: 29 mm on April 28th and 35 mm on May 9th. The annual discharge volume in 2011 was 66,746 dam^3, which is by far the largest on record and double that recorded in 1995.

The flood of 2012 in SCRB differed substantially from the floods of 1995 and 2011, which were snowmelt runoff floods occurring in April or May. The 2012 flood occurred in mid-June after the cessation of snowmelt derived streamflow and was the first major flood produced by rainfall-runoff recorded in the basin, following the first high flow due to rainfall-runoff in 2010. Snowfall over the 2011-2012 winter was well below average at 87 mm, and snowmelt occurred early and modestly with a snowmelt derived streamflow peaking at 6.4 m^3/s on March 19th. Streamflow in Smith Creek did not cease until Aug 31st due to 478 mm of rain in the summer of 2012, which was 151 mm above the average. Rainfalls were concentrated in April, May, and June with 50.6 mm, 114.5 mm, and 158.9 mm, respectively. The previous year's heavy snowmelt, and the 2012 spring snowmelt and rainfall filled much of the depressional and soil storage in SCRB early in the summer. The flood in 2012 was triggered by an intense and spatially variable convective storm that was reported by local news to have delivered up to 100 mm of rainfall in parts of the SCRB. The U of S weather station had recorded 74 mm from June 5-15th, which was followed by 52.5 mm of rainfall within the 24-hr convective storm period on June 17-18th. The intense 24 hour storm contributed large amounts of saturation overland flow runoff to the depressions and then by fill-and-spill or direct drainage to the stream. The annual discharge volume in 2012 was 24,965 dam^3, which is the third highest on record.

3. Variable Contributing Area and Wetland Modelling

Contributing Area of the SCRB

The contributing areas of Canadian Prairie basins are dynamic and change with the amount of water in depressional storage (Stichling and Blackwell, 1957; Gray, 1964; Pomeroy et al., 2010; Shaw et al., 2012). Therefore, it is necessary to accurately reproduce the storage of water in the SCRB in order to accurately simulate the fractions of each sub-basin which contribute flow. The depressional storage in the basin has been strongly affected by drainage, and the effects of the drainage must also be included in the simulations.

The initial CRHM simulations of the SCRB (Pomeroy et al., 2010) represented all of the surface water storage within each sub-basin as sub-HRU depressional storage, a single wetland HRU, a single lake HRU and a stream channel HRU. As shown below, this representation, although an advance on earlier models which do not explicitly represent the depressional storage, is not capable of accurately simulating the dynamic nature of depressional storage and contributing area within a Prairie basin.

Models of Prairie Hydrography

Two models, the Wetland DEM Ponding Model (WDPM), and the Pothole Cascade Model (PCM) of prairie wetland complexes described in Shook and Pomeroy (2011) and Shook et al. (2013) have been developed, tested, and improved using information collected from the SCRB drainage network and wetlands. The models have been validated against remote-sensing data from SCRB provided and interpreted by staff from Duck Unlimited Canada as shown by Shook et al. (2013).

The Wetland DEM Ponding Model (WDPM)

The WDPM finds the final spatial distribution of excess water (rainfall or snowmelt) evenly applied over a LiDAR-based DEM, using the iterative algorithm of (Shapiro and Westervelt, 1992). The algorithm and its implementation in the WDPM are described in Shook and Pomeroy (2011) and Shook et al. (2013). Unlike the D8 direction of drainage algorithm used by programs such as TOPAZ Garbrecht and Martz (1997), the Shapiro and Westervelt (SW) algorithm allows drainage in more than one direction, as shown in Figure 2. Given the mild topography of SCRB and uncertainties in flow direction derived from any DEM, it is believed that the SW algorithm is a realistic approach to determining drainage to and from wetlands. The SW algorithm moves simulated water over the landscape. When water is added, it runs into surface depressions. When water is removed, the water levels in the depressions are reduced. Therefore, the WDPM does not require the DEM to be processed to remove pits before it is used. It also means that the landscape drainage changes dynamically, as water is added or removed.

The WDPM applies simulated water to a digital elevation model of a basin using three modules: Add, Subtract and Drain.

Add

This module adds a specified depth of water to the basin. If the DEM is dry prior to the addition of water, a file created containing the water depths for each cell of the DEM. If there is an existing water file, then the specified depth of water is added to the existing water, and the total is redistributed. This module is intended to simulate the addition of excess water to depressional storage by runoff from snowmelt or intense precipitation. It does not consider any infiltration, evaporation or any other abstraction of water. If a stream exists in the DEM, as in the SCRB, then the Add module will route water to the stream channel. Because of the way that the algorithm works, the edges of the DEM act as dams, preventing any the water from leaving the DEM, and causing the modelled stream to 'back up' over the landscape.

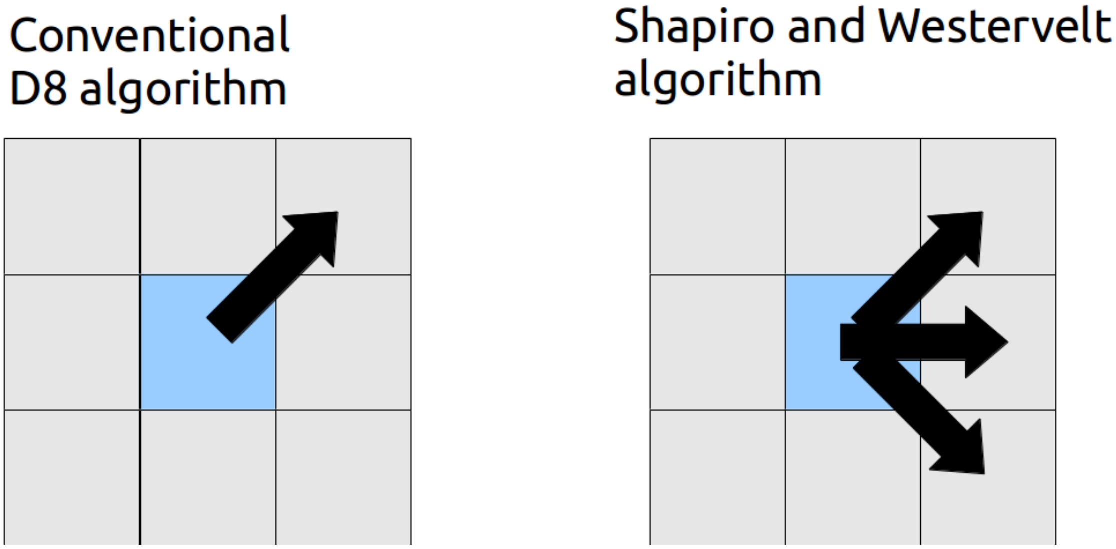

Figure 2. Comparison of D8 and Shapiro and Westervelt algorithms.

Subtract

This module subtracts a specified depth of water from each DEM cell to represent evaporation. No spatial variability is in the evaporation is currently considered. This module generally executes very quickly as very little spatial redistribution of water is usually required.

Drain

This module drains the water on the DEM through the lowest elevational point, assuming that this point is in the drainage system. This module can be the slowest to execute (depending on the resolution and the convergence parameters), as it moves large volumes of water over long distances.

WDPM Execution

The modules may be executed in varying order. For example, it may be desired to add water, to simulate the spring snowmelt runoff to the landscape, followed by draining, and then to remove water to simulate evaporation. This could be followed by the addition of subsequent water to simulate summer rainfall. As was demonstrated by Shook et al. (2013), the addition and removal of water are non-reversible. Each process affects the spatial distribution of water differently.

The WDPM has been extremely slow to execute; a single application of water to sub-basin 5 of the SCRB could require up to 15 hours of simulation run time. The WDPM has other serious limitations. As it uses a DEM, the model cannot reproduce water levels below the elevations present when the DEM data was collected. More importantly for this study, the requirement to use a DEM prevents the WDPM from being used to analyze the effects of historical or future wetland scenarios.

WDPM validation

The WDPM model output was validated at SCRB against a RapidEye image for May 18th, 2011 as classified by Lyle Boychuk and Bill Tedford of DUC. As shown in Figure 3, the frequency distributions of water areas in the remotely-sensed image and the model simulation were very similar. The validation process, together with further validation against remotely-sensed data at St. Denis, SK, is described in more detail by Shook et al. (2013).

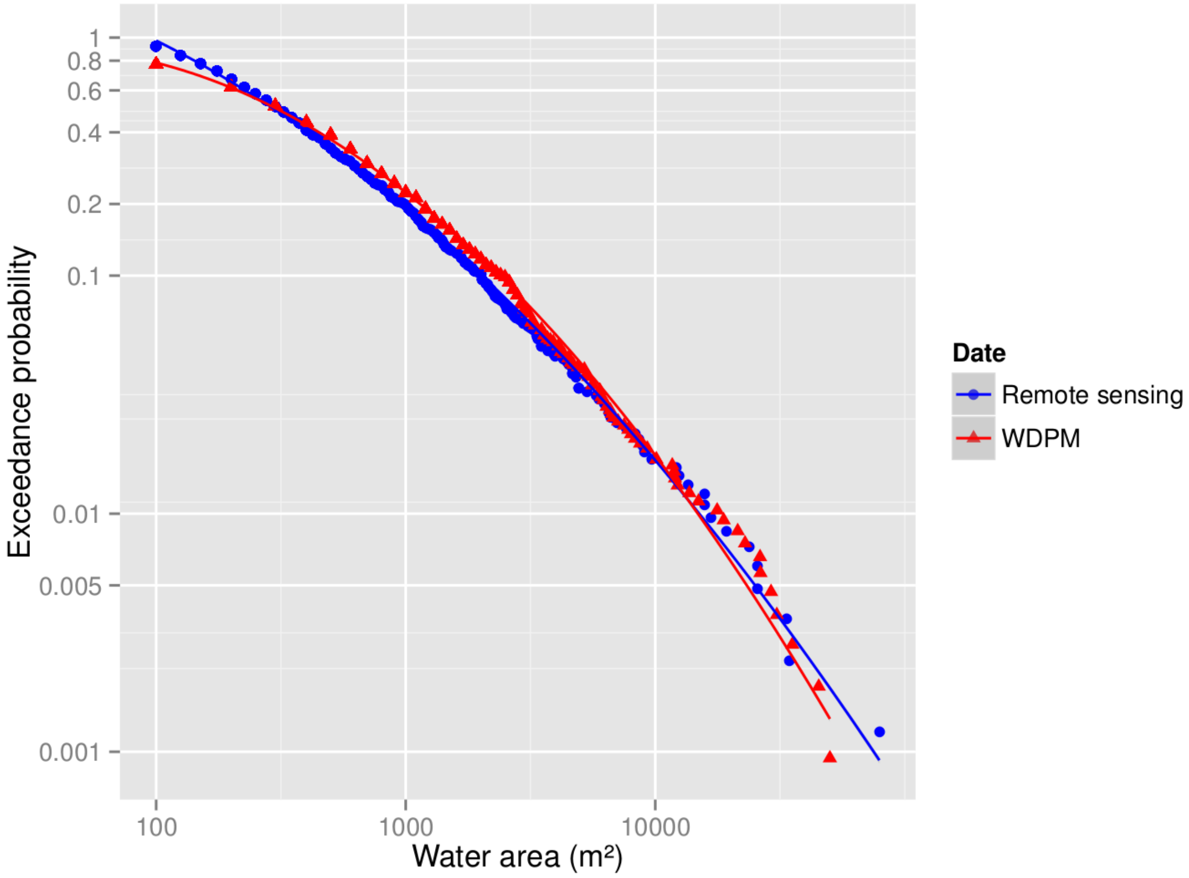

Figure 3. Exceedance probability vs. area for water in RapidEye image and WDPM output for May 18th, 2011.

WDPM Contributing Area Estimation

The WDPM was run for SCRB sub-basin 5, using a wide variety of inputs (additions and removals of water) and initial water storage states. The contributing area fraction of the basin was determined at each stage by adding a small quantity of water (usually 1 mm) and determining the fraction removed when the DEM was drained. As shown in Figures 4 and 5, the relationships between the volume of water stored in the sub-basin and the area of water and the contributing area fraction, are hysteretic. Hysteresis cannot be reproduced by the lumped representation of the depressional storage, as used by the original CRHM simulations of the SCRB.

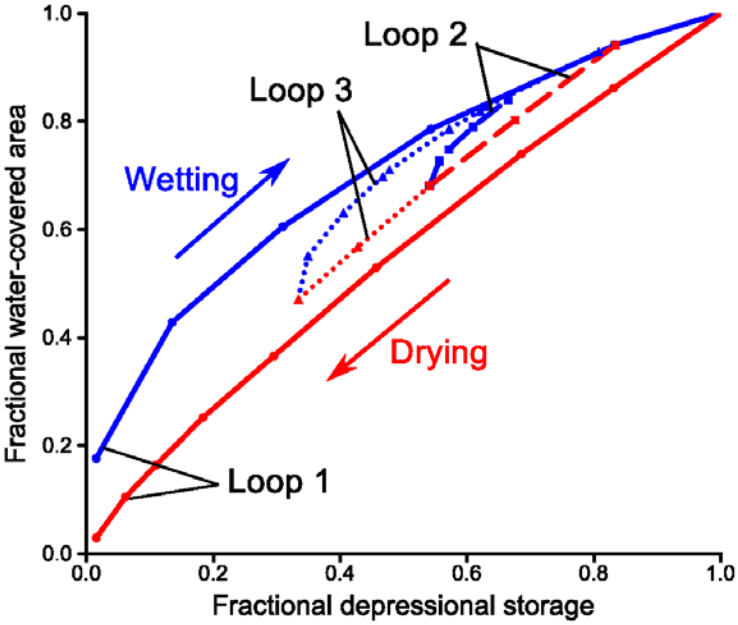

Figure 4. Hysteresis loops of fractional water-covered area vs. fractional depressional storage. All points calculated from the WDPM, Smith Creek sub-basin 5.

The hysteresis in the WDPM simulations is due to the differences in the spatial distribution of ponded water caused by the addition and removal of water. Figure 6 clearly shows that adding and removing water shifts the water area frequency distributions in differing directions. This effect was also validated by remote sensing at St. Denis, SK, as described by Shook et al. (2013). It is imperative that models of the hydrological responses of Canadian Prairie wetland basins, such as SCRB, incorporate the hysteresis in water area and contributing fraction as demonstrated by the WDPM and subsequently validated by remote sensing.

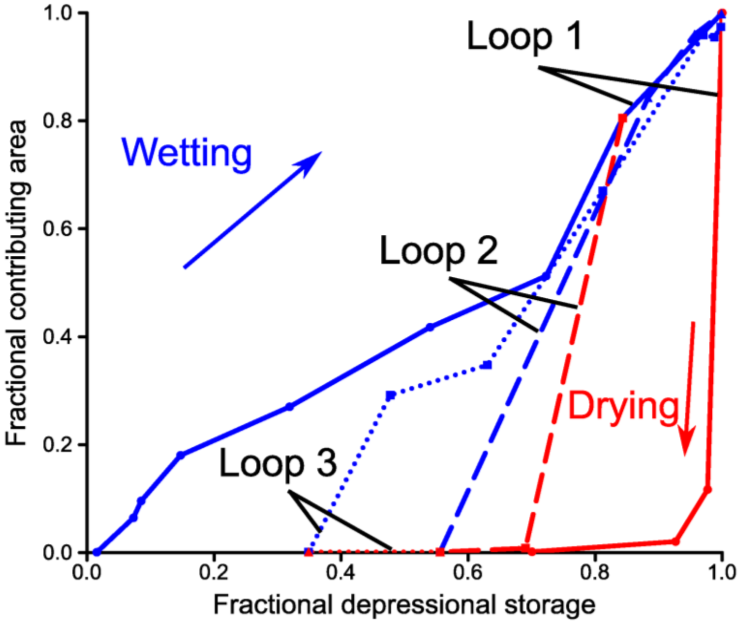

Figure 5. Hysteresis loops of fractional contributing area vs. fractional depressional storage. All points calculated from the WDPM, Smith Creek sub-basin 5.

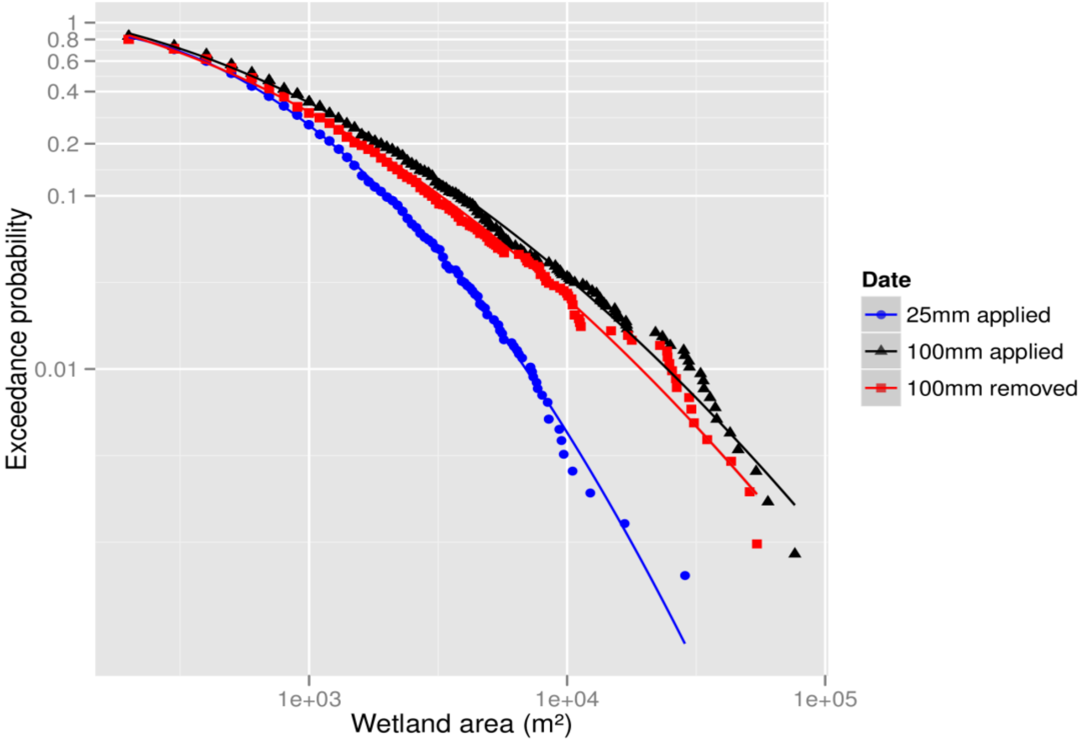

Figure 6. Frequency distributions of water areas modelled by WDPM for additions and removals of water at SCRB sub-basin 5. All simulations were drained.

4. Revised Prairie Hydrological Model Setup and Evaluation

Model Description

Revisions to modules

The original Prairie Hydrological Model (PHM) formulation from the Cold Regions Hydrological Modelling platform (CRHM) was constructed in previous Prairie Hydrological Model Study in 2010, and detailed descriptions of model structure and setup are provided by Pomeroy et al. (2010). Revisions have been made to several modules since then to represent prairie hydrological processes in more realistic way and to generate better simulations under the exceptional hydrometeorological conditions that have ensued since 2009. The following describes the revisions in detail.

1. Longwave module: the longwave module used in the original PHM was updated using longwave estimation algorithm by Sicart et al. (2006). The revised longwave module uses observed shortwave radiation to estimate atmospheric transmittance which then is used to adjust a calculation by Brutsaert (1975) to provide incoming longwave radiation for the canopy and energy-balance snowmelt modules.
2. Canopy module: the original canopy adjustment for radiation module (Sicart et al., 2004) and interception module were combined into a new module canopy module (Ellis et al., 2010). There are both coniferous and deciduous forests in Smith Creek, and the new canopy module has a better representation for calculating the snowfall and rainfall intercepted by forest canopies and updating the sub-canopy snowfall and rainfall as well as sub-canopy shortwave and longwave radiation and turbulent transfer to melting snow.
3. Energy-balance snowmelt module (EBSM): in the original PHM, EBSM used functions developed by Brunt (1932) to estimate net radiation with relationships between sunshine hours in a day, daily clear-sky shortwave radiation, and daily mean air temperature and daily mean vapor pressure. The revised version of EBSM deployed in the PHM uses observed incoming shortwave radiation and estimated longwave radiation from the longwave module to estimate net radiation. Adjustments are made by canopy module to the sub-canopy shortwave and longwave radiation.
4. Infiltration module: the original PHM-CRHM included Gray's snowmelt infiltration (Gray et al., 1985) to estimate snowmelt infiltration into frozen soils and Green-Ampt infiltration and redistribution expression (Ogden and Saghafian, 1997) to estimate rainfall infiltration into unfrozen soils. Green-Ampt infiltration was found to underestimate rainfall infiltration rates in prairie soils as it neglected macropores and preferential flow into porous media and thus was replaced by Ayers' infiltration algorithm (Ayers, 1959), which specifies the maximum unfrozen infiltration rate based on surface ground cover and soil texture characteristics from a wide range of field measurements across Canada. This provides a simple parametric solution but still captures the landscape variability of the rainfall infiltration process. Infiltration is still restricted in the Soil module by air-filled pore space availability – an important feature for wet soils.

5. Evaporation module: the original PHM used Granger's evapotranspiration expression (Granger and Gray, 1989) to estimate actual evaporation from unsaturated surfaces (agricultural surfaces) and the Priestley and Taylor evaporation expression (Priestley and Taylor, 1972) to estimate evaporation from saturated surfaces (wetlands, lakes, and streams). Our recent studies in Manitoba show that Granger's evaporation expression underestimates evapotranspiration in extremely wet conditions and therefore the Granger algorithm was replaced by the Penman-Monteith (P-M) evapotranspiration algorithm (Monteith, 1965) with a Jarvis-style resistance formulation (Verseghy, 1991). The P-M method includes stomatal and aerodynamic resistances which control water vapour transfer to the atmosphere, representing the diffusion path lengths through vegetation and the boundary layer, respectively. Stomatal resistance varies with the biophysical properties of vegetation (i.e. leaf area index, plant height, rooting zone) and is affected by four environmental stress factors: light limitation, vapour pressure deficit, soil moisture tension or air entry pressure, and air temperature. The revised evaporation module is run using measurements of the vegetation biophysical property parameters and simulates all four environmental stress factors, enabling a more realistic representation of the evaporation process in a wide range of conditions from wet to dry (Armstrong et al., 2010).

Prairie Hydrological Model - 2013

A revised PHM was created incorporating all of the updated modules described above and which consists of a set of physically based modules linked in a sequential fashion to simulate the hydrological processes for the Smith Creek Research Basin (SCRB). Figure 7 shows the schematic arrangement of these modules including:

1). Observation module: reads the forcing meteorological data (temperature, wind speed, relative humidity, vapour pressure, precipitation, and solar radiation), adjusting temperature with environmental lapse rate and precipitation with elevation and wind-induced undercatch, and providing these inputs to other modules.

2). Radiation module (Garnier and Ohmura, 1970): calculates the theoretical global radiation, direct and diffuse solar radiation, as well as maximum sunshine hours based on latitude, elevation, ground slope, and azimuth, providing radiation inputs to the sunshine hour module, the energy-budget snowmelt module, and the net all-wave radiation module.

3). Sunshine hour module: estimates sunshine hours from incoming short-wave radiation and maximum sunshine hours, generating inputs to the energy-balance snowmelt module and the net all-wave radiation module.

4). Long-wave radiation module (Sicart et al., 2006): 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. This is input to the energy-balance snowmelt module.

5). Albedo module (Gray and Landine, 1987): estimates snow albedo throughout the winter and into the melt period and also indicates the beginning of melt for the energy-budget snowmelt module.

6). Canopy module (Ellis et al., 2010): 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. This module has options for open environment (no canopy adjustment of snow mass and energy) and forest environment (adjustment of snow mass and energy from forest canopy).

7). Blowing snow module (Pomeroy and Li, 2000): simulates the inter-HRU wind redistribution of snow by wind transport and including the effect of blowing snow sublimation losses throughout the winter period.

8). Windflow module (Walmsley et al., 1989): adjusts the wind speed due to local topographic features and provides topographically-adjusted wind speed to the blowing snow module.

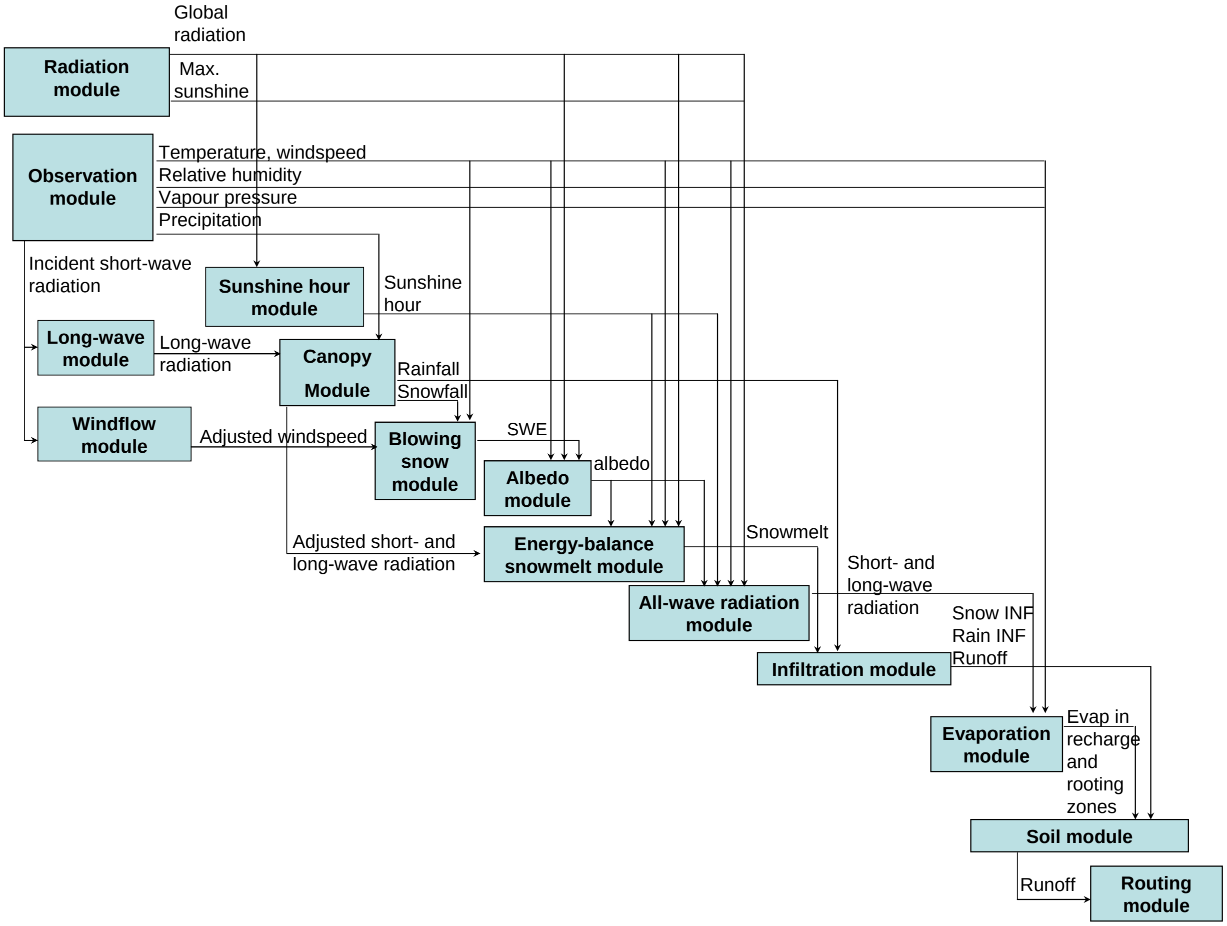

Figure 7. Flowchart of physically based hydrological modules for the revised PHM used in this study.

9). Energy-balance snowmelt module (Gray and Landine, 1988): estimates snowmelt by calculating the energy balance of net radiation, sensible heat, latent heat, ground heat, advection from rainfall, and change in internal energy.

10). All-wave radiation module (Granger and Gray, 1990): calculates the snow-free net radiation from incoming short-wave radiation for input to the evaporation module for snow-free conditions.

11). Infiltration module: Gray's snowmelt infiltration (Gray et al., 1985) estimates snowmelt infiltration into frozen soils based on the preceding fall soil moisture status; Ayers' infiltration (Ayers, 1959) estimates rainfall infiltration into unfrozen soils based on soil texture, tillage and ground cover. Both infiltration algorithms link to the soil moisture content from the Soil module. Infiltration-excess surface runoff forms when the rate of snowmelt or rainfall exceeds the infiltration rate.

12). Evaporation module: The Penman-Monteith method (Monteith, 1965) estimates actual evapotranspiration from unsaturated surfaces using an energy balance and including both stomata and aerodynamic resistances in the estimation; the Priestley and Taylor evaporation expression (Priestley and Taylor, 1972) estimates evaporation from saturated surfaces such as wetlands and stream channels. Both evaporation algorithms withdraw moisture first from the canopy interception store, then ponded surface water and then soil moisture and are restricted by water availability to ensure continuity of mass. The Priestley and Taylor evaporation also withdraws water from water bodies such as wetlands, lakes and stream channels.

13). Soil module: this module was revised from an original soil moisture balance routine developed by Leavesley et al. (1983) and modified by Pomeroy et al. (2007a), Dornes et al. (2008) and Fang et al. (2010) and now calculates the soil moisture balance, groundwater storage, subsurface and groundwater discharge, depressional storage, pond storage and runoff for control volumes of two soil layers, a groundwater layer and surface depressions. The top soil layer is called the recharge layer, which obtains inputs from infiltration of ponded surface water, snowmelt, rainfall or sub-canopy rainfall. Evaporation first extracts water from canopy interception and depressional/pond storage and then can withdraw moisture via transpiration from only the recharge soil layer or from both soil column layers depending on the specified root zone characteristics, and is restricted to plant available soil moisture (Armstrong et al., 2010). Evaporation does not withdraw soil moisture until canopy interception and depressional or pond storage are exhausted. Groundwater recharge occurs via percolation from the soil layers. Subsurface discharge occurs via horizontal drainage from either soil layer; groundwater discharge takes place through horizontal drainage in the groundwater layer. Each soil layer and the groundwater layer have distinct hydraulic conductivities, based on substrate textural characteristics. Depressional storage represents small scale (sub-HRU) transient water storage on the surface of fields, pastures and woodlands. Pond storage replaces depressional storage when a semi-permanent wetland occurs on an HRU and represents water storage that dominates a HRU in wet conditions, though the pond can be permitted to dry up in drought conditions. The inputs to depressional/pond storage are from infiltration excess surface runoff and saturation overland flow. After depressional or pond storage is filled, overland flow is generated via the fill-and-spill process, in which over-topping of the depression results in runoff. Very small rates of leakage of water from the depression/pond to sub-surface storage are permitted before spilling. Surface runoff occurs as saturation overland flow if snowmelt or rainfall inputs exceed subsurface withdrawals from saturated soils or as infiltration excess overland flow if the rate of snowmelt or rainfall exceeds the infiltration rate.

14). Routing module: the Muskingum method is based on a variable discharge-storage relationship (Chow, 1964) and is used to route runoff between HRUs in the sub-basins. The routing storage constant is estimated from the average distance from the HRU to the main channel and average flow velocity; the average flow velocity is calculated by Manning's equation (Chow, 1959) based on the average HRU distance to the main channel, average change in HRU elevation, overland flow depth and HRU roughness. For the subsurface and ground water flows, Clark's lag and route algorithm (Clark, 1945) was used with velocities informed by substrate hydraulic conductivities.

Parameters for the PHM modules listed above are detailed in the previous modelling study of the basin (Pomeroy et al., 2010; Fang et al., 2010).

Pothole Cascade Model and Dynamical Wetland Network

For the PHM to correctly represent the dynamics of wetlands during the filling and spilling sequences, more than one wetland needs to be represented in every sub-basin (Pomeroy et al., 2010). The number of wetlands and other water-holding depressions in a prairie basin is very large; in SCRB, over 65,000 depressions larger than 100 m² were identified. As it is impossible to simulate all of the depressions in even a small basin, it was decided to simulate a small set of depressions whose frequency distribution matched that of a basin, using the same statistical connectivity. Important characteristics of the prairie wetland depressional storage that need to be simulated by this set of depressions include:

1. the connectivity between wetlands is ephemeral, occurring only when wetlands are full,
2. the magnitudes of the depth, area and volume of water stored in wetlands vary tremendously as the wetlands range from transient puddles to semi-permanent lakes, and
3. area of a wetland exposed to evaporation is a non-linear function of its depth.

The relationships between the contributing area of prairie basins and the storage of water in wetlands has long been known to be complex (Stichling and Blackwell, 1957), and has recently been demonstrated to be nonlinear and hysteretic (Shook and Pomeroy, 2011). As a consequence of the hysteresis between wetland water storage and contributing area, the fraction of water running off from a given rainfall or snowmelt event cannot be predicted by the rainfall-runoff relationships present in conventional hydrological models. Shook and Pomeroy (2011) demonstrated that the cause of the hysteretic relationship between water storage and contributing area is the connection amongst wetlands. The changes in the connections amongst the wetlands are demonstrated by the frequency distribution of water areas, which are different and change differently for wetting (formation of connections) and drying (breaking of connections and breakup of ponds). The changing connections among the wetlands can be simulated using a set of synthetic wetlands in a Pothole Cascade Model (PCM) developed by Shook and Pomeroy (2011) and verified using remote sensing imagery by Shook et al. (2013). The PCM was incorporated into the PHM to provide a representation of wetland dynamics that could interact with the upland hydrological fluxes and hydrometeorological processes.

The PCM is a more conceptual wetland model than the WDPM. PCM was initially a simple Fortran 95 model of simulated wetlands and was described in Shook and Pomeroy (2011) where it was denoted as Model 2, and in Shook et al. (2013) where it was denoted by its current name. The PCM is based on the work of Shaw (2010) in that it simulates the filling and spilling of a set of prairie wetlands which are modelled as discrete reservoirs. This method was improved by the discovery that the areas of the drainage basins of individual wetlands are power-law functions of the maximum water areas of the wetlands (Shook et al., 2013). Because of the impossibility of using the WDPM with CRHM for historical simulations, the PCM algorithm was included in CRHM for the SCRB modelling. The flexibility of CRHM's HRU approach meant that no new code was required, but a new configuration was required in that each wetland was modelled as a separate HRU; historical and future scenarios were simulated by adjusting the areas and maximum storage depths of the wetland HRUs.

In Smith Creek, a LiDAR DEM acquired in October 2008 was used to determine the parameters of the PCM synthetic wetlands (areas, volumes, connectivity). The previous study (Fang et al., 2010) delineated all wetlands greater than 100 m² within the sub-basins. These wetlands were overlaid by the conventional drainage network computed from "TOPAZ" program (Garbrecht and Martz, 1993; 1997); the number of wetlands intersecting streams of each Horton-Strahler stream order was calculated, as described by Shook and Pomeroy (2011). Table 1 demonstrates the ratio of wetlands at each order to the next order ranges between 0.99 and 2.69. Accordingly, most of the modelled wetlands were assigned a branching ratio of 2, the only exception being for the first-order wetlands which had branching ratios of 3. Consequently, a 46-wetland network HRU was developed to represent the dynamic wetlands in Smith Creek and is shown in Figure 8. The size of each wetland was determined from the frequency distribution of wetlands at each sub-basin in Smith Creek and was assigned randomly to each wetland HRU (Figures 9 to 13). Detailed descriptions of the dynamical depressional storage network simulation of 46 wetlands and its results are provided by Shook and Pomeroy (2011).

Table 1. Total number of sub-basin 5 wetlands in Smith Creek and bifurcation ratios for each Horton-Strahler stream order.

Horton-Strahler Stream Order	Wetland Count	Bifurcation Ratio
1	2837	1.96
2	1445	1.66
3	868	2.24
4	388	2.69
5	144	0.99
6	145	

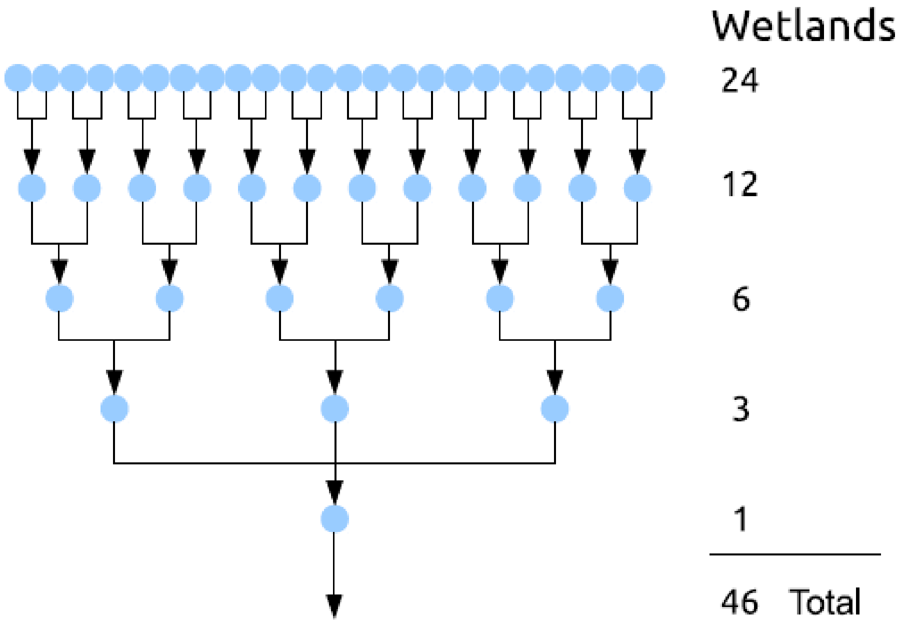

Figure 8. Schematic diagram of arrangement of dynamical wetland network developed from the Pothole Cascade Model (Shook and Pomeroy, 2011).

In the revised PHM, the dynamic 46-wetland HRUs were used to replace the single wetland HRU used in the original PHM setup from 2010 (Pomeroy et al., 2010). A simulated sub-region of upland and dynamical wetland network was used to represent the upland and wetland areas in an actual sub-basin. In order for the sub-region to preserve the inheritance of its corresponding sub-basin, the ratio between the upland and wetland in the sub-region must be same as the one in the actual sub-basin. Streamflow output from the sub-region was scaled via a scaling factor to provide streamflow for the actual sub-basin. Equations [1] to [4] were developed to estimate the streamflow from the simulated sub-region.

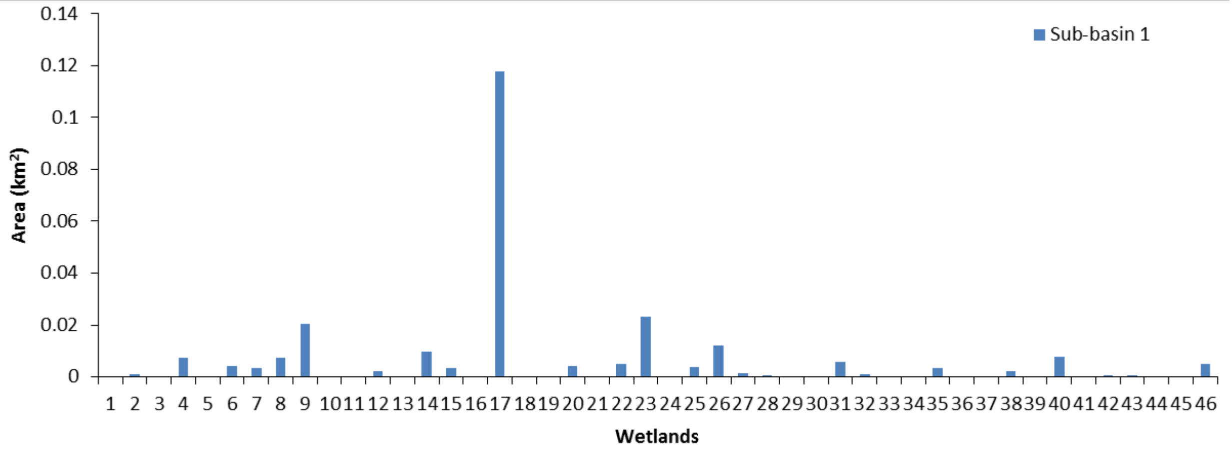

Figure 9. Size distribution of the dynamical wetland network at Smith Creek sub-basin 1.

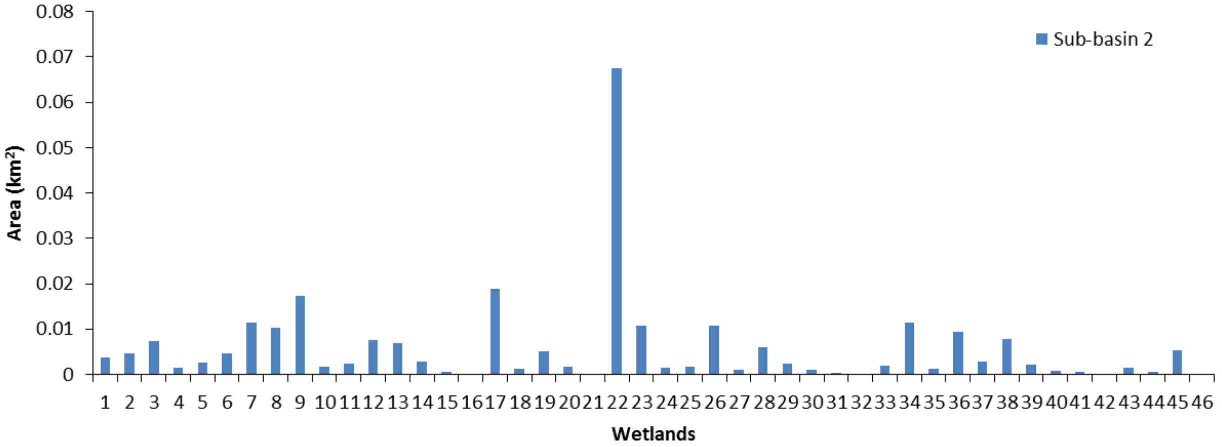

Figure 10. Size distribution of the dynamical wetland network at Smith Creek sub-basin 2.

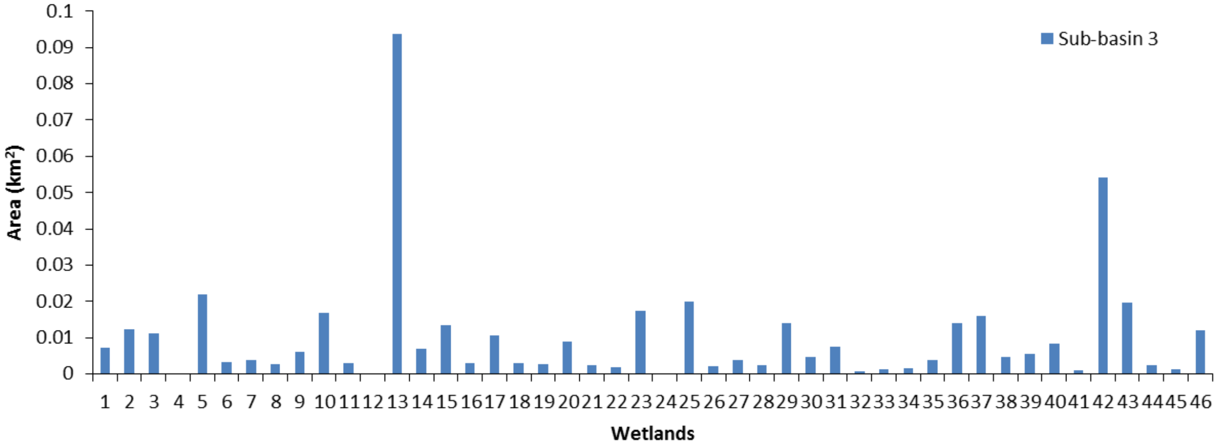

Figure 11. Size distribution of the dynamical wetland network at Smith Creek sub-basin 3.

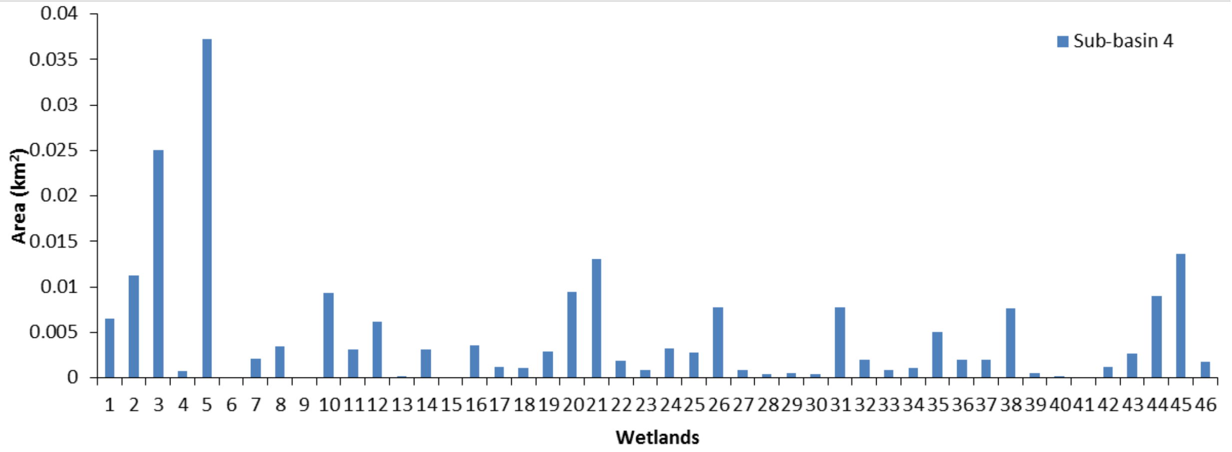

Figure 12. Size distribution of the dynamical wetland network at Smith Creek sub-basin 4.

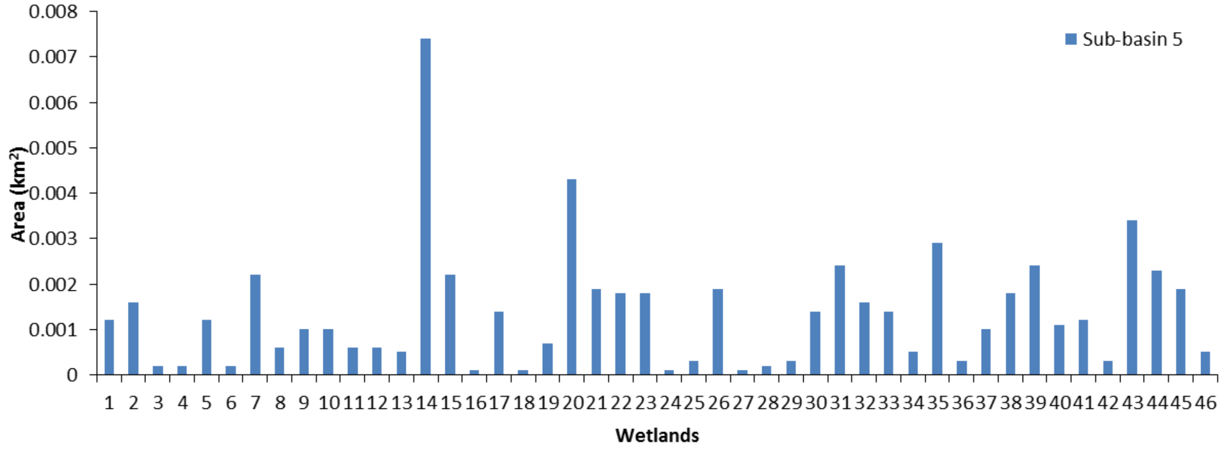

Figure 13. Size distribution of the dynamical wetland network at Smith Creek sub-basin 5.

$$Q_{RWB} = Q_s \; SR_{vs} \quad , \qquad [1]$$

where: Q_{RWB} = streamflow output of the representative wetland sub-basin, Q_S = streamflow output of the simulated sub-region, and SR_{vs} = scaling ratio. The scaling ratio is calculated as:

$$SR_{vs} = \frac{A_{vs}}{A_v} \quad , \qquad [2]$$

where: A_v = the area of a sub-basin, A_{vs} = area of a simulated sub-region in the sub-basin. The area of a sub-basin is the sum of both upland and wetland:

$$A_v = A_{vu} + A_{vw} \quad , \qquad [3]$$

where: A_{vu} = upland area of a sub-basin, A_{vw} = wetland area of a sub-basin. The area of a simulated sub-region in the sub-basin is:

$$A_{vs} = A_{vsu} + A_{vsw} \quad , \qquad [4]$$

where: A_{vsu} = upland area in the simulated sub-region in the sub-basin, and A_{vsw} = wetland area in the simulated sub-region in the sub-basin.

The areas of the sub-basin, the areas of the simulated sub-region in the sub-basin, and the scaling ratios for the Smith Creek sub-basins were estimated using Equations [1] to [4] and are shown in Table 2. In addition to replacing the single wetland HRU in the original PHM setup by the dynamical wetland network of PCM, the routing sequence among HRUs was revised and is illustrated in Figure 14. Values for HRU area, routing length, and depressional storage capacity for the Smith Creek sub-basins in the dynamical wetland network are summarized in Appendix 1.

Table 2. Sub-basin area (km^2), simulated sub-region in the sub-basin (km^2), and scaling ratio for the Smith Creek sub-basins.

	Sub-basin				
	1	2	3	4	5
Total sub-basin (A_v)	234.32	51.67	58.50	37.88	11.00
Total Simulated Sub-region (A_{vs})	1.81	3.84	8.38	3.79	1.33
Scaling Ratio	129.51	13.46	6.98	9.99	8.24

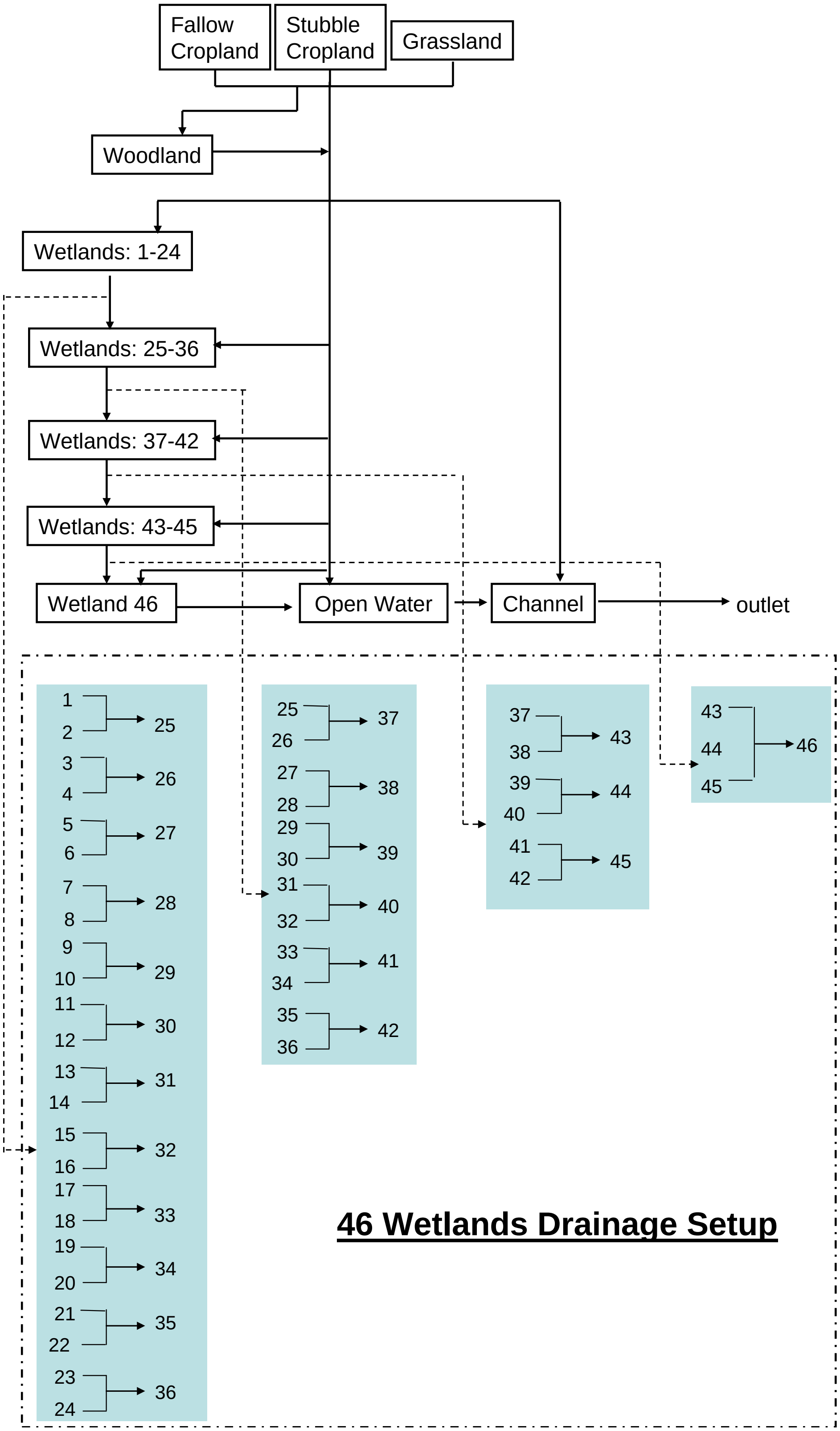

Figure 14. Routing sequence between HRUs within a sub-basin with dynamical 46-wetland network.

Model Evaluation

PCM Evaluation

The effects of using of more than one set of 46 depressions to represent the behaviour of a basin were investigated using the original PCM, outside of CRHM. As simulated water is added to model, the depressions fill and connect, spilling water in a cascade. Figure 15 plots the curves of contributing area vs. total volume of water stored in the depressions for varying numbers of sets of depressions. The use of multiple sets of depressions results in a smoother curve, due to the reduction in the "gatekeeper" effect (Phillips et al., 2011) whereby large wetlands prevent downstream depressions from receiving water until they are filled.

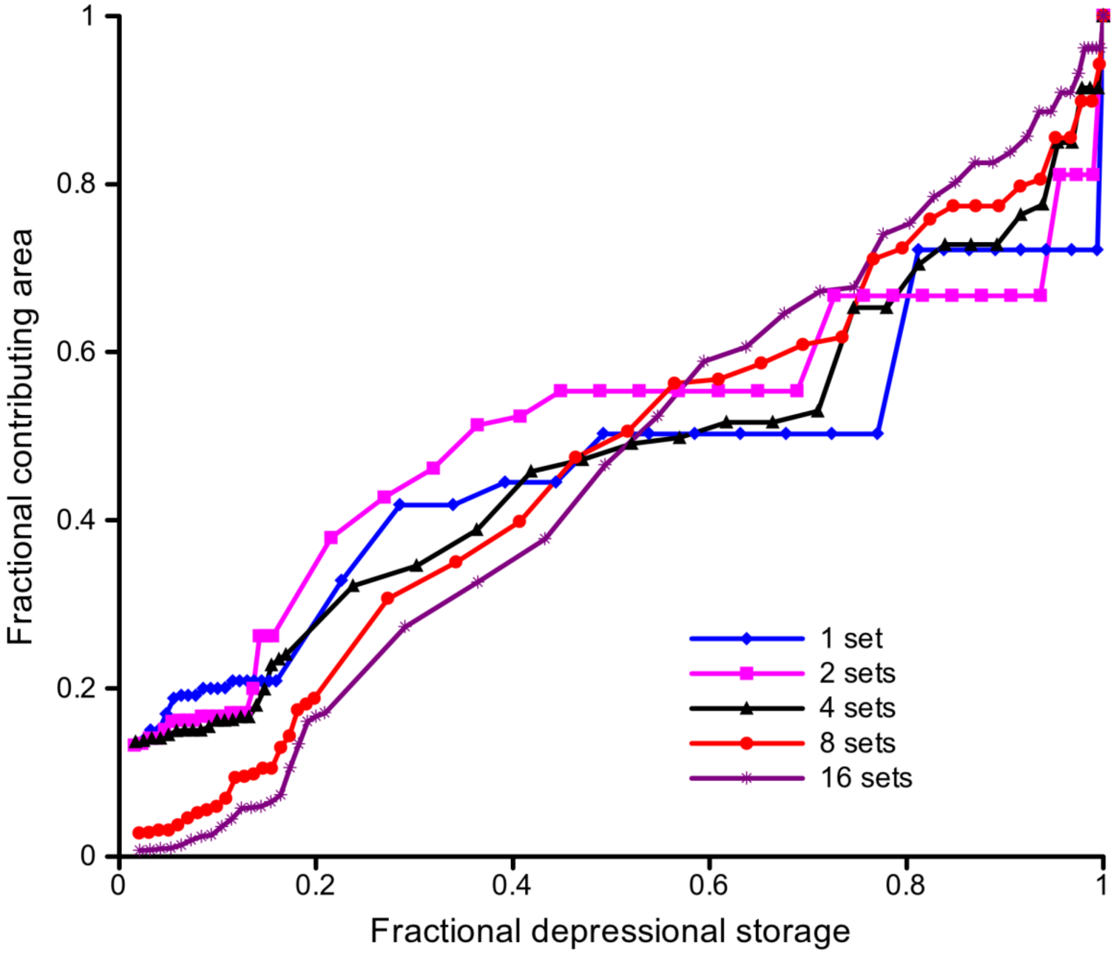

Figure 15: Fraction of simulated basin contributing flow vs. fraction of total water-holding capacity of depressions. All simulations are purely filling.

The contributing-fraction hysteresis loops produced by the PCM with 16 sets of 46 depressions closely resemble those produced by the WDPM, as shown in Figure 16. However, even one set of 46 depressions can adequately represent the hysteresis between contributing area and storage and so it is felt that for multi-year simulations, the PHM as configured for this study can adequately describe wetland dynamics.

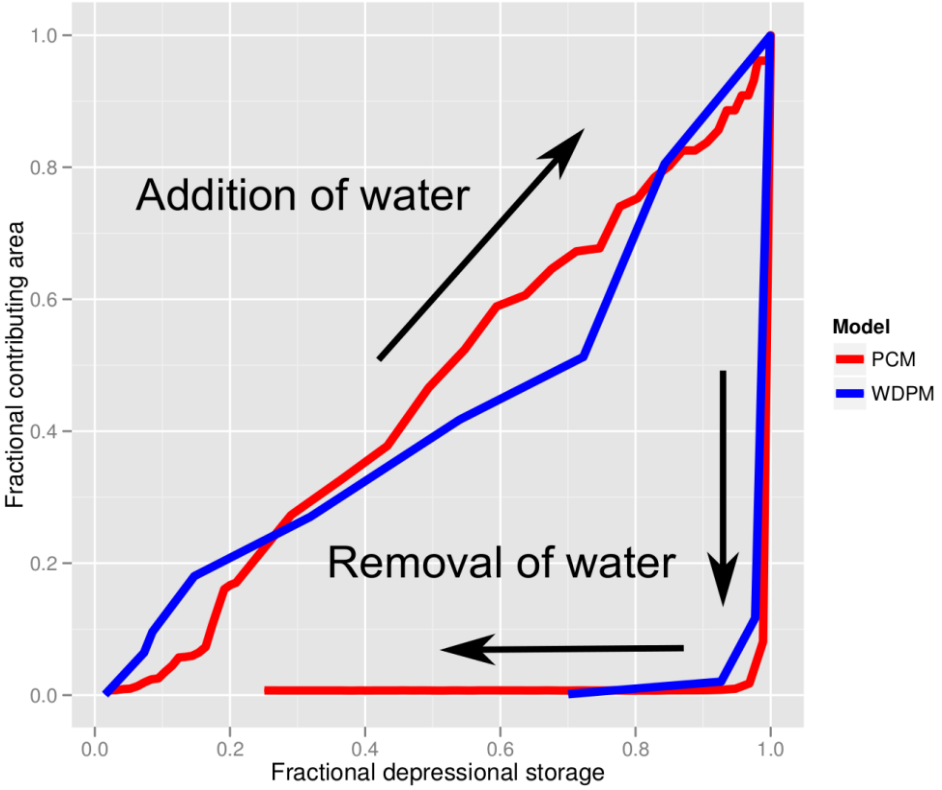

Figure 16: Contributing-area hysteresis loops produced by the WDPM and PCM. All simulations are for SCRB sub-basin 5.

Evaluation of snow accumulation and ablation regime

Simulations using the revised PHM were conducted using meteorological data collected from 31st October 2007 to 29th September 2013 at the University of Saskatchewan main weather station in Smith Creek Research Basin. The model simulated snow accumulation (SWE) was compared to the observed SWE from extensive snow surveys for three seasons (i.e. 2008, 2009, and 2011) and is shown in Figures 17 to 19. These three years span a range from relatively dry to relatively wet winters and had particularly reliable snow surveys for comparison purposes. The primary difference in snow modelling between the original (Pomeroy et al., 2010) model and the current model is a more physically realistic simulation of net longwave radiation for snowmelt and so most differences will occur in the spring snowmelt period. For the snow accumulation period in 2008, both the original and revised PHM estimated nearly the same SWE, as shown in Figure 17. For the snowmelt period of 2008, the revised PHM simulated an earlier snowmelt and the original PHM generated a later snowmelt than the observed occurrence of snowmelt for fallow and cropland HRUs. Compared to the observed snowmelt in 2008, the revised PHM had a closer agreement with snow survey observations for grassland HRU; while original PHM predicted more accurately for open water and wetland HRUs. For the 2009 season, the revised PHM estimated lower SWE than did the original PHM and so performed better when comparing to most observations, except for the wetland HRU snow accumulation period. For winter in the heavy snowfall year of 2011, both the original and revised PHM predicted similar SWE for fallow and open water HRUs, whereas the revised PHM estimated lower and more accurate SWE for grassland, and wetland HRUs than did the original. For the spring snowmelt period in 2011, the revised PHM simulated an earlier onset of snowmelt than did the original, and so was much closer to the observations except for those in the stubble HRU. Table 3 shows the root mean square difference (RMSD) of snow water equivalent on the ground during the combined accumulation and ablation periods for both original and revised PHM. The RMSD for the original PHM ranged from 9 to 88 mm and averaged 39 mm; whilst that of the revised PHM ranged from 8 to 57 mm and averaged 28 mm – these differences occurred for snowpacks that ranged from 30 to 140 mm. With a decrease in mean RMSD of 11 mm, the revised PHM was generally found to have smaller RMSD than the original PHM, except for open water and wetland HRUs in 2008 and the stubble HRU in 2011. What was particularly encouraging is that the timing of snowmelt was improved by the more sophisticated treatment of radiation, and the premelt snow accumulation seemed credible for most HRUs over most years of simulation.

Table 3. Evaluation of snow accumulation with the root mean square difference (RMSD, mm) of model outputs and snow survey transects for both original and revised PHM-CRHM.

	Original PHM-CRHM			Revised PHM-CRHM		
HRU Name	2008	2009	2011	2008	2009	2011
Fallow	23	61	32	10	33	25
Stubble	23	54	11	8.1	26	49
Grassland	39	41	48	13	9.1	31
Open Water	8.6	61	50	32	47	28
Wetland	18	29	88	57	26	30

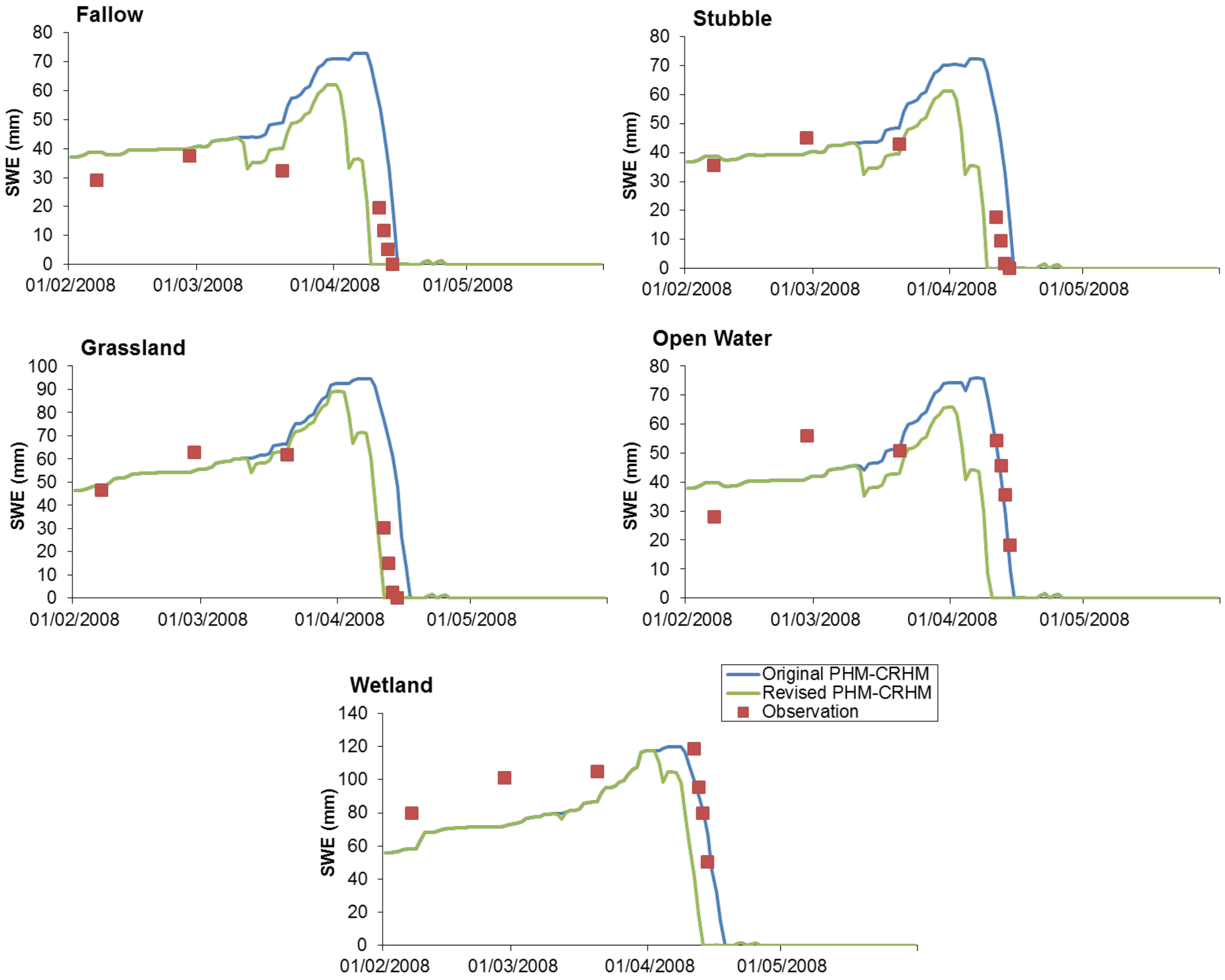

Figure 17. Comparisons of snow regimes between original and revised PHM simulations and observations for the 2008 season.

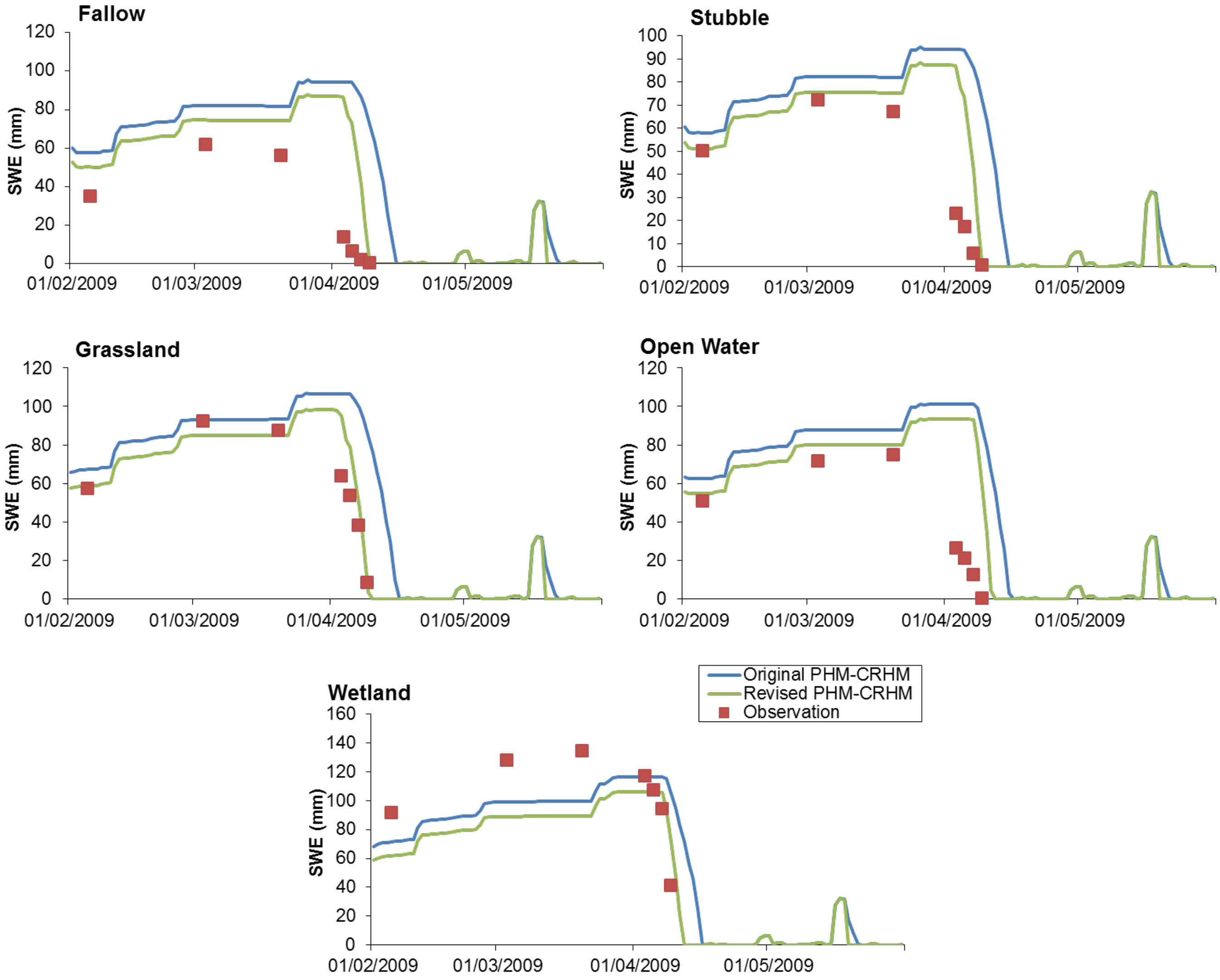

Figure 18. Comparisons of snow regime between original and revised PHM simulations and observations for the 2009 season.

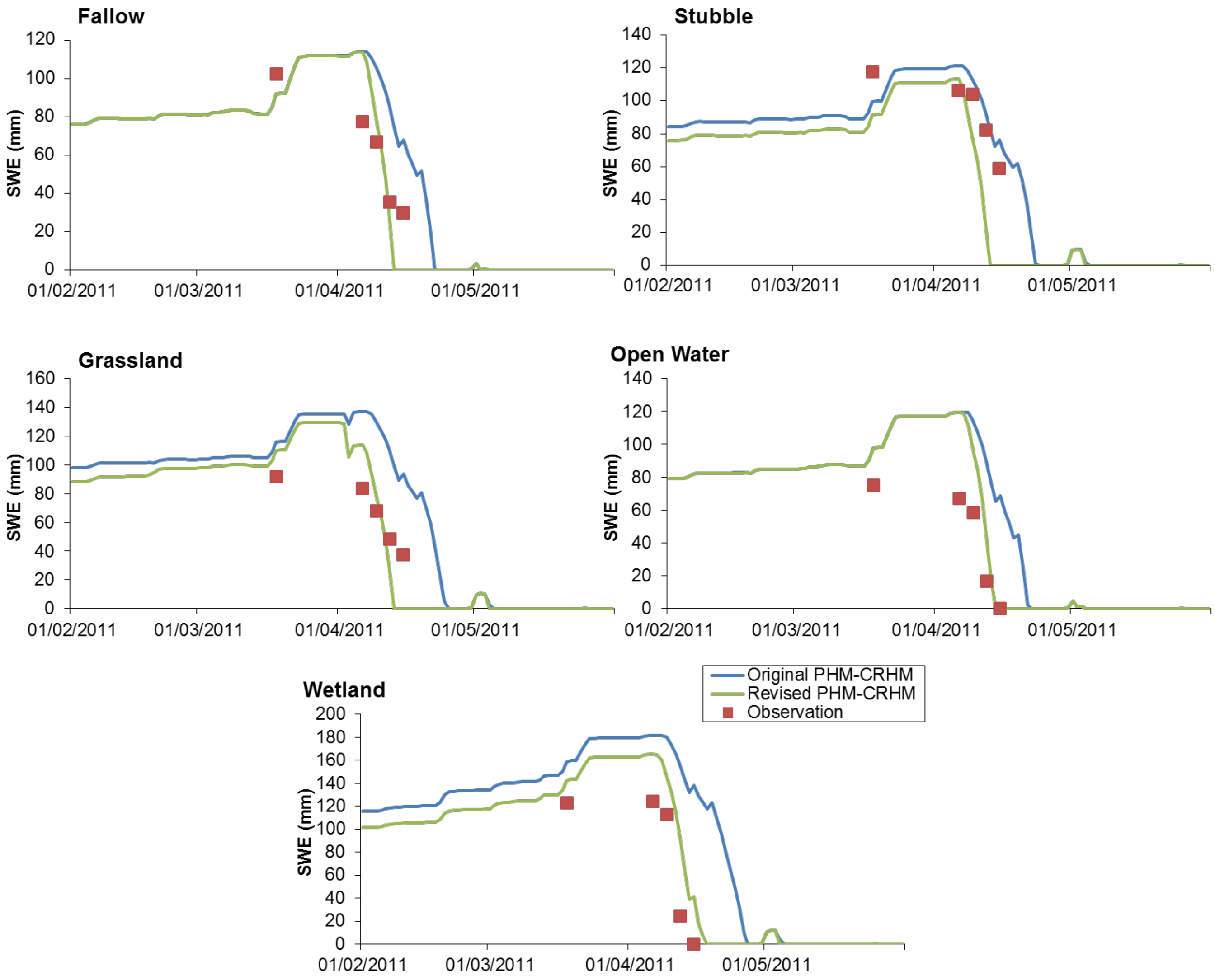

Figure 19. Comparisons of snow regime between original and revised PHM simulations, and observations for the 2011 season

Evaluation of streamflow

Full hydrological simulations using the revised PHM were conducted to predict the streamflow discharge in Smith Creek and were compared with the observed Smith Creek basin discharge at Water Survey of Canada (WSC) gauge station 05ME007 near Marchwell for five seasons from 2008 to 2012. The wetland configuration as measured with LiDAR in October 2008 was used for these simulations and likely became progressively more out of date in for the later years of simulation. The 2013 streamflow was not available from WSC when this report was being prepared. Figure 20 shows the comparisons of the cumulative discharge from the original and revised PHM simulations as well as from observations. In general, the revised PHM was able to better predict the annual increase in cumulative discharge than could the original PHM despite overestimation of summer discharge in 2008 and 2009 and underestimation of summer discharge events in 2010 and 2012. Nevertheless, the revised PHM captured the cumulative discharge regime in a flood year (2011) fairly well, whilst the original PHM failed to estimate the accumulated daily discharge for those five years, especially in summer months.

Table 4 shows the root mean square difference (RMSD) and model bias (MB) of daily streamflow discharge for both original and revised PHM. RMSD for the original PHM averaged 3.19 and ranged from 1.13 to 5.96 m^3/s; compared to this the revised PHM had a much lower RMSD with an average of 1.88 and a range from 0.89 to 4.19 m^3/s. Simulations of daily discharge with the revised model were better in all years except 2009 in which it had a slightly higher RMSD value. The MB values suggest that revised PHM estimated of annual flow volume much more accurately than the original version. For the original PHM, the average MB was 1.9 with a range from 0.53 to 3.92, indicating that it consistently overestimated annual flow volume. In contrast, the revised PHM had an average MB of -0.14 with a range from -0.68 to 0.19, which suggests an overall underestimation. It was encouraging to see that the MB of the major flood year, 2011, was 0.08, suggesting an 8% error in streamflow volume estimation for the flood of record.

Table 4. Evaluation of daily streamflow discharge with root mean square difference (RMSD, m^3/s) and model bias (MB) for both original and revised PHM.

	RMSD (m^3/s)		MB	
	Original PHM	Revised PHM	Original PHM	Revised PHM
2008	1.13	1.10	0.96	0.19
2009	1.25	1.47	0.53	0.13
2010	3.45	0.89	3.92	-0.68
2011	4.18	4.19	0.44	0.08
2012	5.96	1.77	3.65	-0.43

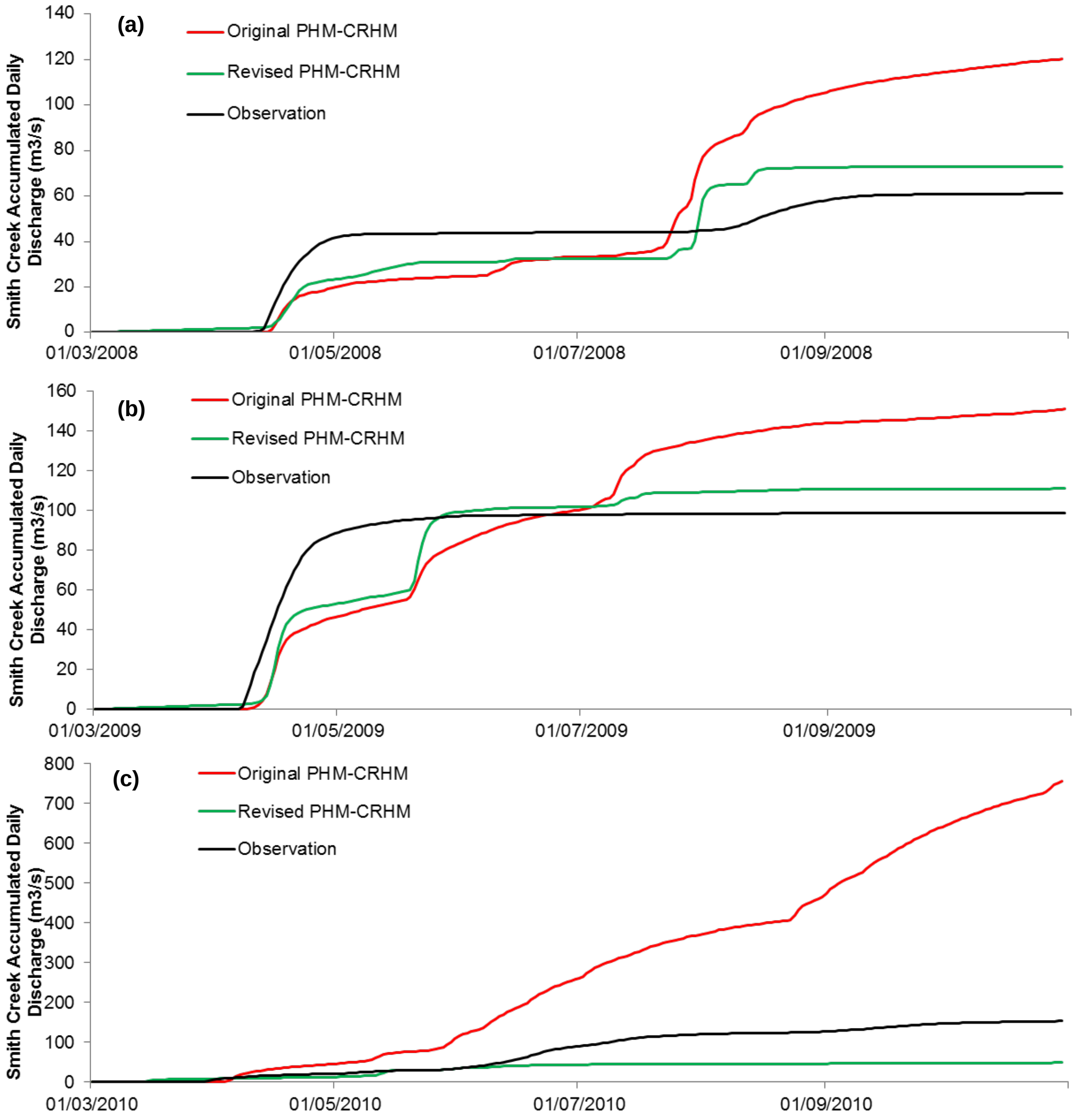

Figure 20. Comparisons of Smith Creek accumulated daily discharge from original and revised PHM-CRHM simulations as well as observation for five seasons: (a) 2008, (b) 2009, (c) 2010, (d) 2011, and (e)

2012.

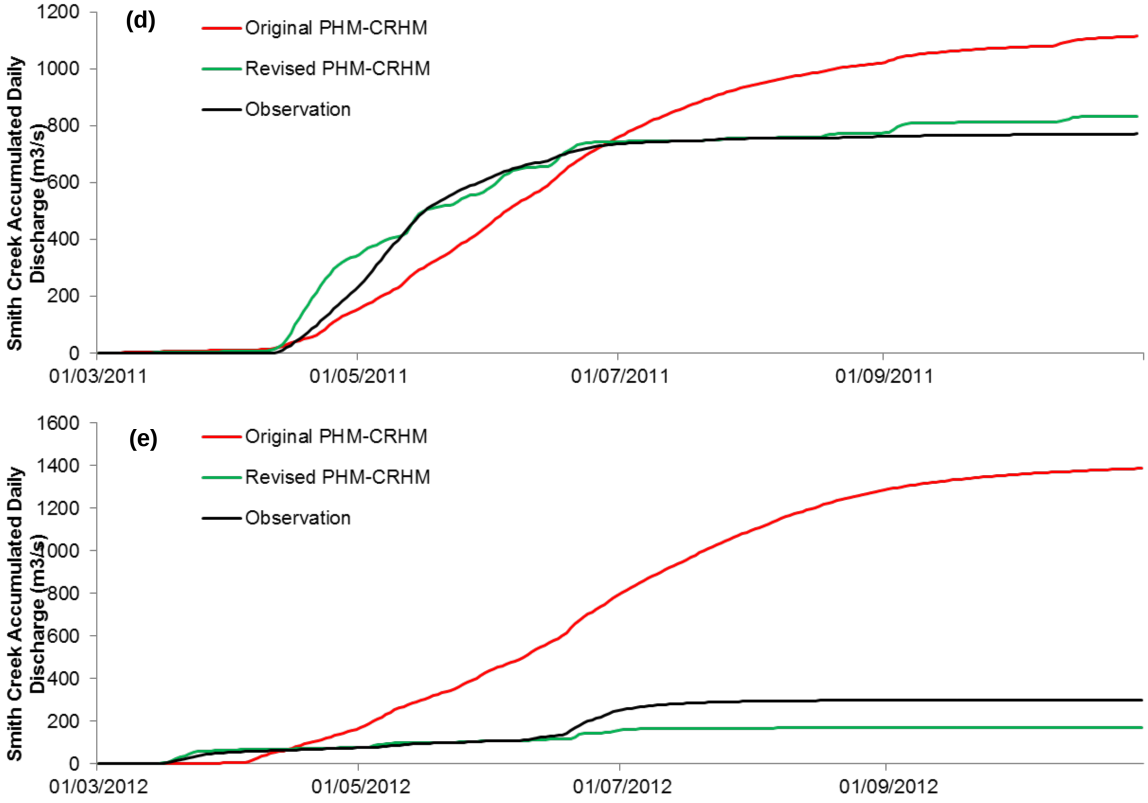

Figure 20. *Concluded*.

5. Modelled Hydrological Sensitivity to Varying Wetland Drainage and Connectivity

Scenario Derivation and Description

The revised PHM with the PCM dynamical cascading wetland network representation was used to simulate both historical and possible wetland scenarios in Smith Creek Research Basin. The dynamical wetland network was manipulated from the maximum known extent (circa 1958) through to a hypothetical highly drained condition to create simulations for scenarios of various wetland storage capacities and connectivities within the range from drained to restored conditions. The first steps in doing this were to determine the historical wetland storage volumes and network using DUC analysis of aerial photographs from 1958 and 2000 to compare with the detailed wetland hydrography analysis possible using the 2008 LiDAR-measured DEM.

The wetland HRU areas needed for PCM in the PHM were determined for 1958 and 2000 by scaling the existing 2008 HRU areas as shown in Eq. 5.

$$Aw_{n,m} = Aw_{2008,m} \frac{At_{n,m}}{At_{2008,m}} \qquad [5]$$

Where, $Aw_{n,m}$ = area of a given wetland HRU in year n, in sub-basin m, $Aw_{2008,m}$ = area of the same wetland HRU in year 2008, in sub-basin m, $At_{n,m}$ = total areas of all wetlands in year n, in sub-basin m, and $At_{2008,m}$ = total area of all wetlands in year 2008, in sub-basin m.

As there was no LiDAR data for 1958 and 2000, the maximum wetland volumes were estimated from the wetland area data for those years, using an equation fitted to the 2008 data by least-squares. Previous research has shown that the relationship between wetland area and volume generally fits a power-law (Hayashi and van der Kamp, 2000, Minke et al., 2010). However, the use of power-law regressions to directly estimate the wetland volumes from their areas was not successful in this case, because different power-law relations would be required for small and large wetlandsAn example of a power-law equation fitted to the wetland volumes versus areas for sub-basin 1 is plotted in Figure 21. Although the value of R^2 is good, the very large number of small wetland areas results in a fitted equation which does not well describe the volumes of large wetlands. The least-squares fit produces a line which both under- and over-estimates the volume compared to the actual values. Figure 22 shows that a polynomial fitted to the area-volume data provides a much more realistic fit. To prevent the spurious regression from underestimating HRU wetland volumes, the following procedure was used.

1. Volumes for the individual wetlands in 1958 and 2000 were calculated by a polynomial regression (see Fig. 22).
2. The total wetland volume was then computed.
3. The adjusted wetland volumes were then computed from Eq. 6:

$$Vw_{n,m} = Vw_{2008,m} \frac{Vt_{n,m}}{Vt_{2008,m}} \qquad [6]$$

where, $Vw_{n,m}$ = volume of a given wetland HRU in year n, in sub-basin m, $Vw_{2008,m}$ = volume of the same wetland HRU in year 2008, in sub-basin m, $Vt_{n,m}$ = total volume of all wetlands in year n, in sub-basin m, and $Vt_{2008,m}$ = total volume of all wetlands in year 2008, in sub-basin m.

The ratios of the total wetland HRU areas for 1958 and 2000, to those for 2008 are shown in Table 5. In all cases, the 1958 total HRU volumes and areas are greater than the 2000 totals, which are greater than the 2008 values. Because of the shape of the regression curves, the volume ratios are generally greater than the area ratios for each year and HRU.

Table 5. Ratios of total wetland HRU areas and volumes to values for 2008 by sub-basin, Smith Creek.

	Sub-basin 1		Sub-basin 2		Sub-basin 3		Sub-basin 4		Sub-basin 5	
	Area	Volume	Area	Volume	Area	Volume	Area	Volume	Area	Volume
1958	1.8	2.3	2.5	3.4	4.4	5.2	2.9	4.2	3.6	3.6
2000	1.4	1.7	1.6	1.8	1.3	1.4	1.1	1.3	1.1	1.2

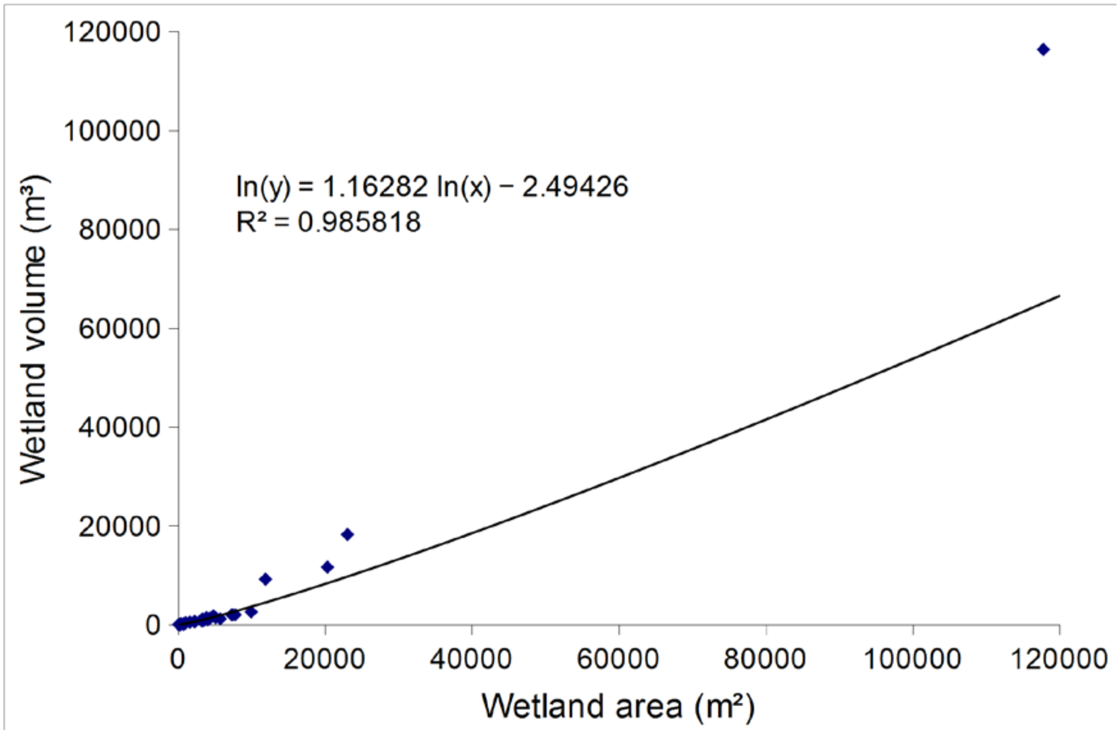

Figure 21. Power-law fit of wetland volume to area for sub-basin 1, 2008.

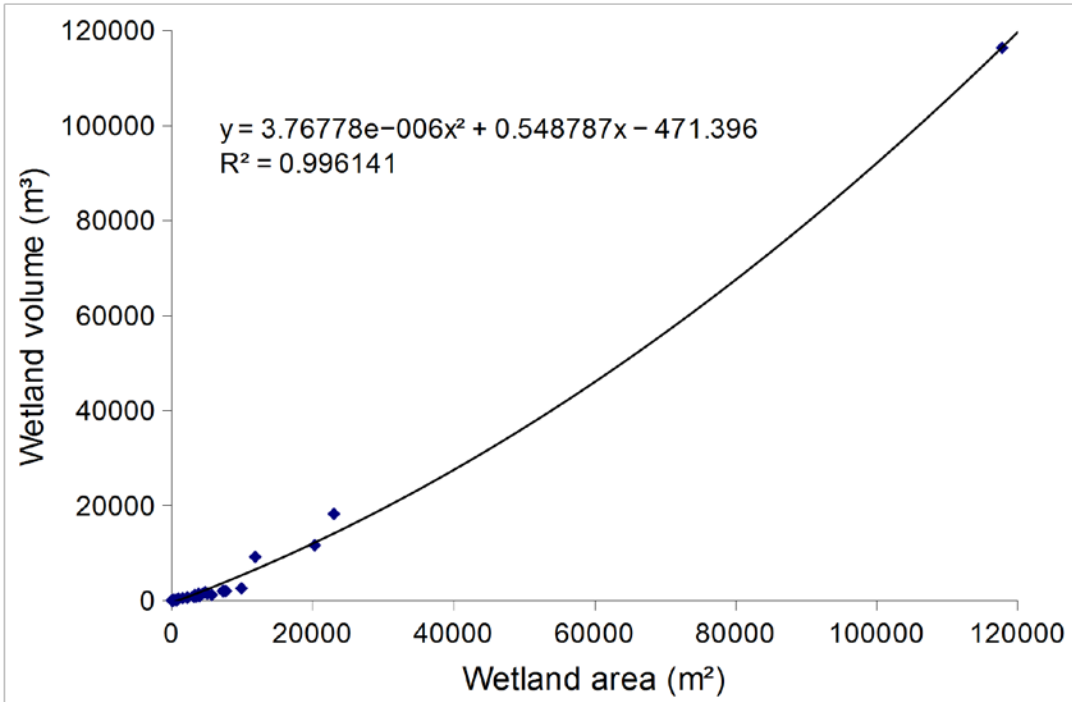

Figure 22. Polynomial fit of wetland volume to wetland area, sub-basin 1, 2008.

The total areas of wetlands for 1958, 2000 and 2008 are plotted for each sub-basin in Figure 23. Sub-basin 1 appears to show the greatest acceleration in the decrease of wetland area over the period of record. The wetland areas and volumes in the years between 1958 and 2000 were found by linear interpolation as shown in Figure 23.

Wetland area estimates were used to create eight different wetland scenarios, which are described in detailed as follows.

1. ***1958* wetland scenario**: The 1958 DUC wetland area extent is considered the “maximum” known wetland extent in each sub-basin for the wetland scenario simulations. Ratios of 1958 to 2008 wetland areas by sub-basin were used along with area-volume polynomials to estimate wetland storage volumes by sub-basin.
2. **1970 wetland scenario**. Derived by linear interpolation of wetland areas between 1958 and 2000 along with area-volume polynomials to estimate wetland storage volumes for each sub-basin.
3. **1980 wetland scenario**. Derived by linear interpolation of wetland areas between 1958 and 2000 along with area-volume polynomials to estimate wetland storage volumes for each sub-basin.
4. **1990 wetland scenario**. Derived by linear interpolation of wetland areas between 1958 and 2000 along with area-volume polynomials to estimate wetland storage volumes for each sub-basin.

5. **2000 wetland scenario**: The 2000 DUC wetland extent was used to generate wetland areas for each sub-basin for 2000 and was used along with area-volume polynomials to estimate wetland storage volumes by sub-basin.
6. **2008 wetland scenario**. The 2008 LiDAR DEM was used to determine the area, storage capacity and connectivity of the dynamical wetland network in the Prairie Cascade Model (PCM) developed by Shook and Pomeroy (2011). The 2008 wetland area extent is considered the "current" wetland extent for the wetland scenario simulations and for PHM model tests against recent obsevations.
7. **"Loss Ceiling" wetland scenario**. All wetlands that occur outside of conservation lands in a sub-basin were drained and only wetlands within the conservation lands were retained. Note that these protected lands are almost entirely in sub-basin 1.
8. **"Fully Drained" wetland scenario**. All wetlands were removed from simulations of the basin and all sub-basins.

Values for HRU area, routing length, and depressional storage capacity in the dynamical wetland network for these eight wetland scenarios are summarized in the Appendix 2. The wetland ratio of area/sub-basin area for each of the scenarios is shown in Figure 24. While the entire basin had more than 18% wetland areal coverage in 1958, by 2008 wetland areas ranged from 5% to 14% of the basin area. Sub-basin 3 had the most rapid drainage, dropping from 28% wetland coverage in 1958 to 5.4% in 2008. Simulations for these eight different wetland scenarios were conducted for six hydrological years from October 31st 2007 to September 29th 2013; there are 48 simulations in total shown in Table 6. A sensitivity analysis of changing wetland network state was conducted on a scenario basis for flows generated within each sub-basin as well as for the whole Smith Creek basin.

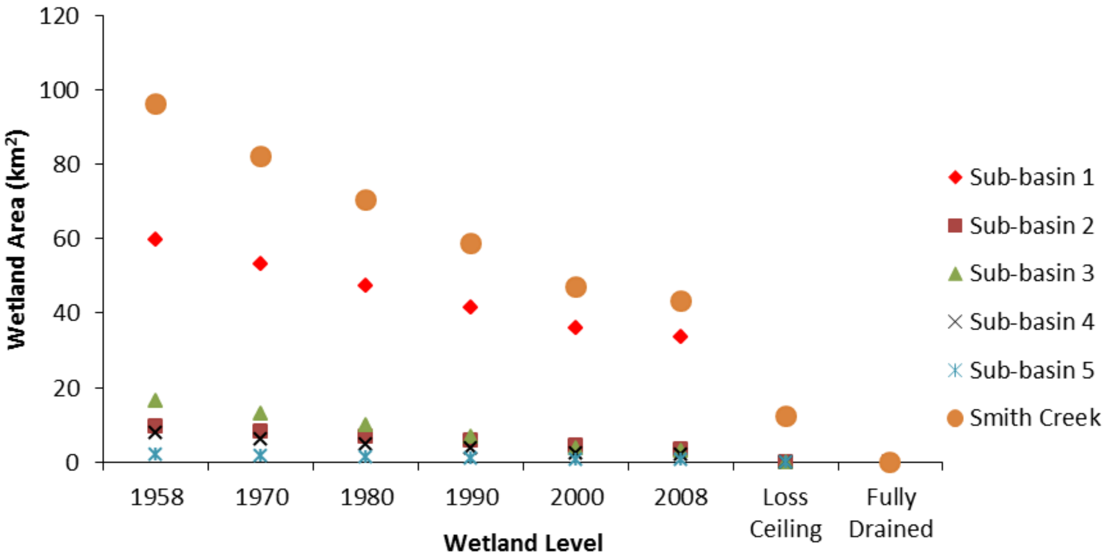

Figure 23. Wetland areas used for the wetland level scenarios by sub-basin and for the Smith Creek basin. Note that 1958 and 2000 are measured from aerial photography, 2008 is measured from LiDAR DEM, 1970, 1980, 1990 are interpolated and the Loss Ceiling is based on the area of conservation lands as provided by Ducks Unlimited Canada.

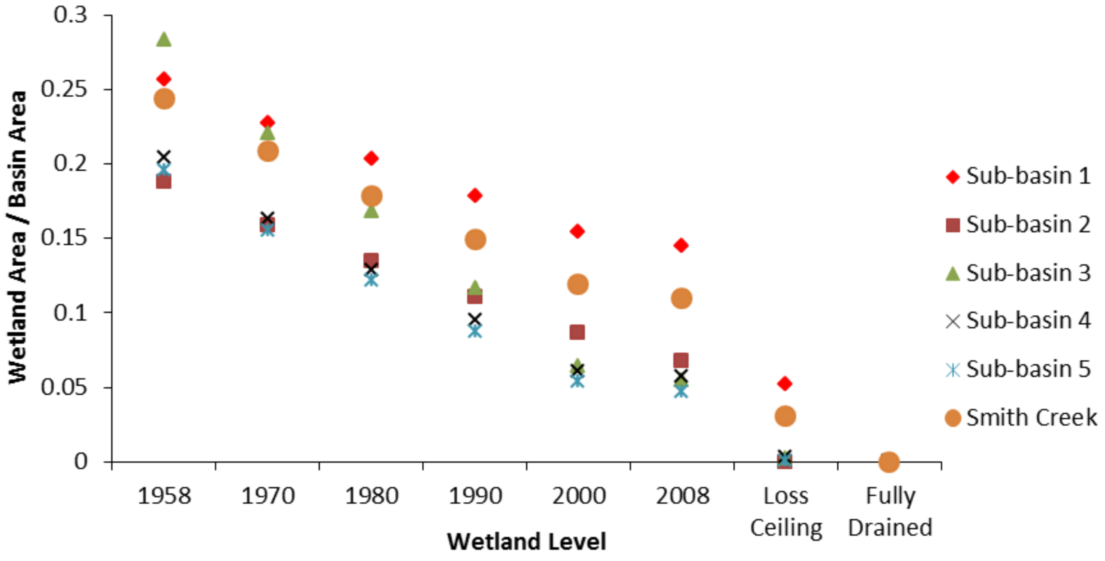

Figure 24. Wetland area to basin (sub-basin) area ratios for the wetland level scenarios by sub-basin and for the Smith Creek basin. Note that wetland areas for 1958 and 2000 are measured from aerial photography, 2008 is measured from LiDAR DEM, 1970, 1980, 1990 are interpolated and the Loss Ceiling is based on the area of conservation lands as provided by Ducks Unlimited Canada. The basin and sub-basin areas are based on a drainage analysis of SCRB using TOPAZ software on the LiDAR DEM.

Wetland Level Scenario Simulation Results

Using the revised PHM, simulated hydrographs for eight wetland scenarios were calculated and are shown in the Appendix 3 for six hydrological years from 2007-2013. A hydrological year in Smith Creek is defined as starting on November 1st. Figures A1 to A48 show these hydrographs are for all five sub-basins as well as the whole Smith Creek basin. The following sections explain the sensitivity of annual flow volume and peak daily discharge to different wetland scenarios for each sub-basin and for the whole Smith Creek basin.

Annual flow volume

The response of sub-basin annual flow volumes to the eight wetland scenarios in each of the six hydrological years (2007-2013) are shown in Figures 25 to 29; the response of the annual flow volume for the whole Smith Creek basin is shown Figure 30. The annual flow volume from the five sub-basins as well as from the Smith Creek basin increased dramatically as wetland extent decreased from that of the maximum extent (in 1958) to the “fully drained” condition. For the Smith Creek basin, flow volumes in the wettest year (2010-2011) almost doubled with complete drainage and in the driest year (2012-2013) flows increased almost six fold. As the wetland extent decreased from 1958 to the current (2008) condition, the annual flow volume increased substantially at the basin scale for all six hydrological years, except for 2011-2012, which was the year after the flood of record.

Table 6. Summary of the wetland scenario simulations.

Simulation Number	Wetland Scenario State	Hydrological Year
1	1958 Wetland	2007-2008
2	1958 Wetland	2008-2009
3	1958 Wetland	2009-2010
4	1958 Wetland	2010-2011
5	1958 Wetland	2011-2012
6	1958 Wetland	2012-2013
7	1970 Wetland	2007-2008
8	1970 Wetland	2008-2009
9	1970 Wetland	2009-2010
10	1970 Wetland	2010-2011
11	1970 Wetland	2011-2012
12	1970 Wetland	2012-2013
13	1980 Wetland	2007-2008
14	1980 Wetland	2008-2009
15	1980 Wetland	2009-2010
16	1980 Wetland	2010-2011
17	1980 Wetland	2011-2012
18	1980 Wetland	2012-2013
19	1990 Wetland	2007-2008
20	1990 Wetland	2008-2009
21	1990 Wetland	2009-2010
22	1990 Wetland	2010-2011
23	1990 Wetland	2011-2012
24	1990 Wetland	2012-2013
25	2000 Wetland	2007-2008
26	2000 Wetland	2008-2009
27	2000 Wetland	2009-2010
28	2000 Wetland	2010-2011
29	2000 Wetland	2011-2012
30	2000 Wetland	2012-2013
31	2008 Wetland	2007-2008
32	2008 Wetland	2008-2009
33	2008 Wetland	2009-2010
34	2008 Wetland	2010-2011
35	2008 Wetland	2011-2012
36	2008 Wetland	2012-2013
37	Fully Drained	2007-2008
38	Fully Drained	2008-2009
39	Fully Drained	2009-2010
40	Fully Drained	2010-2011
41	Fully Drained	2011-2012
42	Fully Drained	2012-2013
43	Loss Ceiling	2007-2008
44	Loss Ceiling	2008-2009
45	Loss Ceiling	2009-2010
46	Loss Ceiling	2010-2011
47	Loss Ceiling	2011-2012
48	Loss Ceiling	2012-2013

In that year, most of the wetland storage was filled from the flood in 2010-2011 and subsequent large rainfalls. With such exceptionally wet antecedent conditions the observed wetland drainage did not increase simulated flow volumes.

As wetlands were drained from the current 2008 state to the “loss ceiling” or “fully drained” states, there were very large increases in annual flow volume suggesting that the basin is sensitive to further drainage. It should be noted that both sub-basins 2, 3, 4 and 5 had few conservation lands, resulting in nearly identical wetland extents and annual flow volume responses for the “loss ceiling” and “fully drained” states. As sub-basin 1 has a large protected wetland area (12.028 km^2), it displayed an increase in the annual flow volume when this was drained. Because sub-basin 1 is 60% of the Smith Creek basin area, it has the greatest share of wetland coverage in Smith Creek, and so changes in its wetland status exert a strong control on the hydrological response of the entire Smith Creek basin. The annual flow volume response of sub-basin 1 shown in Figure 25 dominated the response of Smith Creek basin, as shown in Figure 30

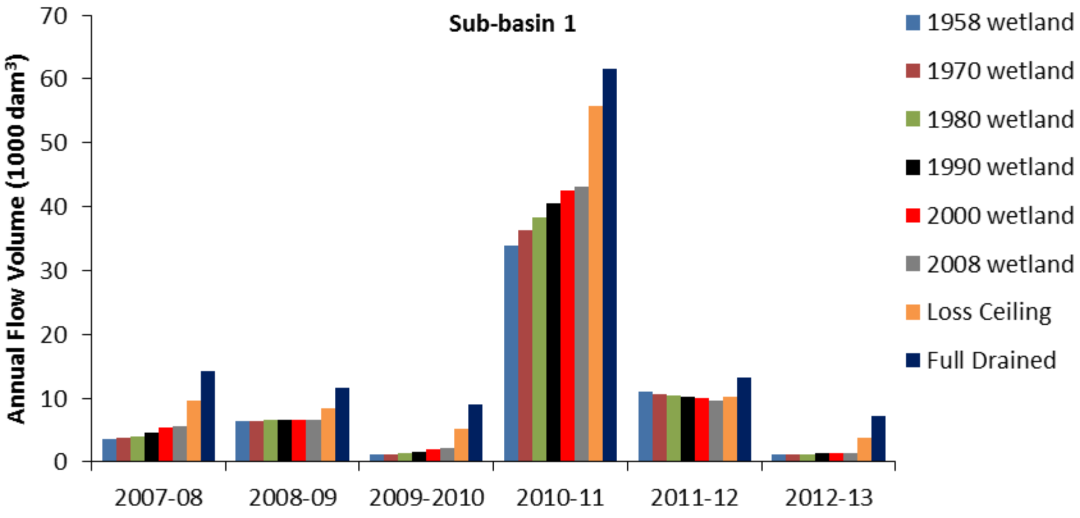

Figure 25. Response of annual flow volume to wetland scenarios for sub-basin 1.

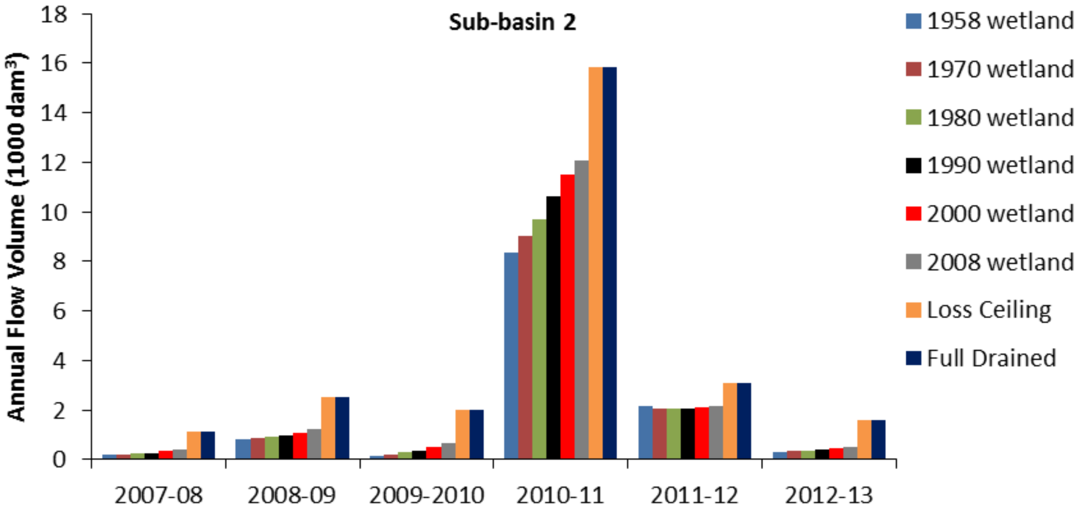

Figure 26. Response of annual flow volume to wetland scenarios for sub-basin 2.

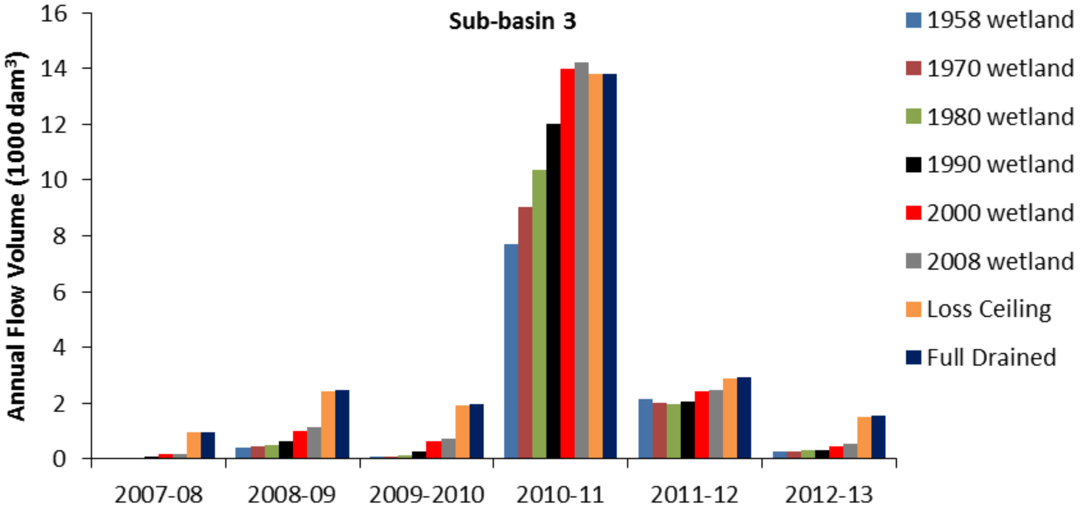

Figure 27. Response of annual flow volume to wetland scenarios for sub-basin 3.

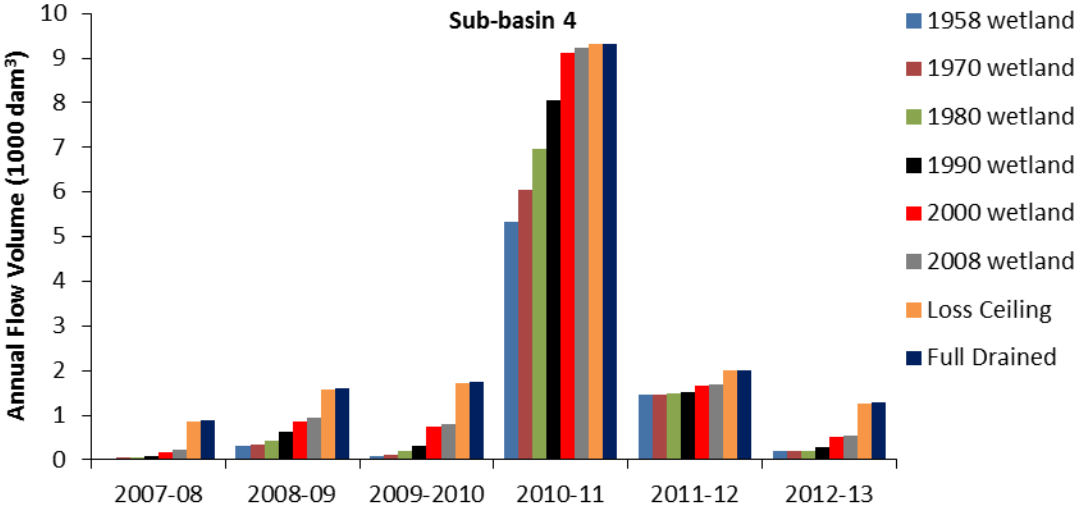

Figure 28. Response of annual flow volume to wetland scenarios for sub-basin 4.

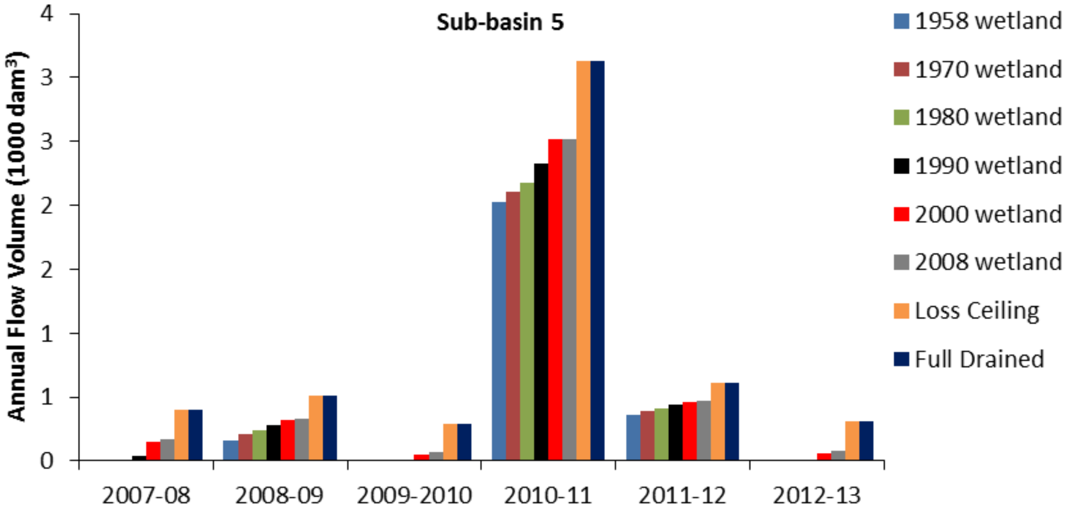

Figure 29. Response of annual flow volume to wetland scenarios for sub-basin 5.

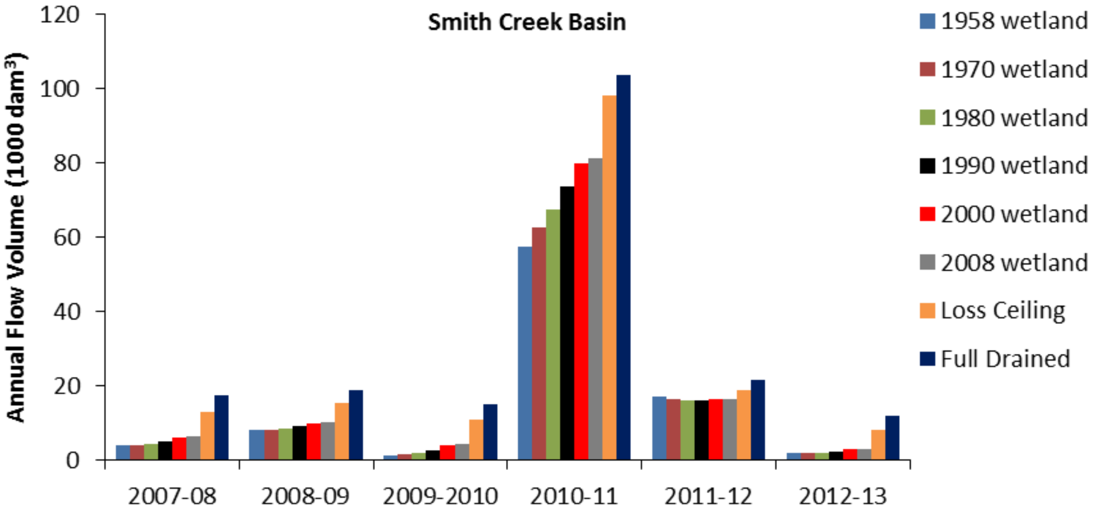

Figure 30. Response of annual flow volume to wetland scenarios for the Smith Creek basin.

The annual flow volume for Smith Creek in each simulation year was plotted against the wetland areas of the drainage scenarios in Fig. 31. The figure shows a nearly-linear decrease in annual flow volume with increasing wetland area for the highest flood year (2010-2011), very little association between flow volume and wetland area for the post-flood year (2011-2012) and substantial declines in flow volume with increasing wetland area for all other years. Much of the decline in annual flow volume occurs as wetland area increases from 0 to about 40 km^2 (about 10% of the basin area). As much of the total streamflow volume from Smith Creek over 2007-2013 occurred in the flood year of 2010-2011,the strong response to drainage in this year has a lasting impact on the long-term response of Smith Creek discharge volumes to drainage.

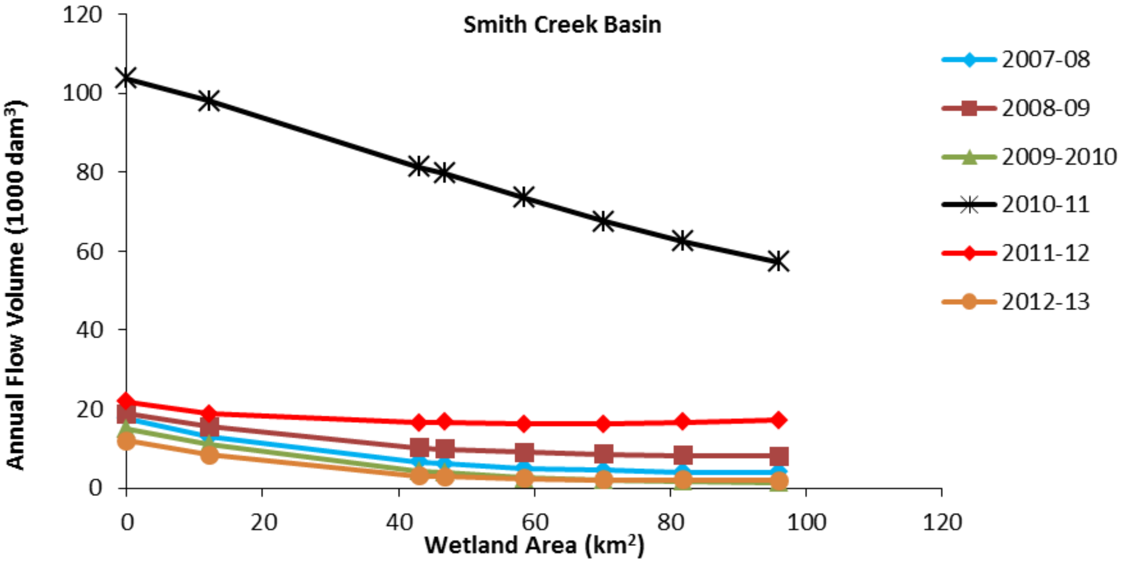

Figure 31. Annual flow volume versus wetland area for Smith Creek basin.

The percentage changes from the current (2008 drainage) in the annual flow volumes from Smith Creek were plotted against the wetland areas of the various drainage scenarios in Figure 32; the plots show how the relative changes in flow volume associated with the drainage or restoration of wetlands can vary strongly with the precipitation and antecedent conditions. Increases in annual flow as result of draining wetlands from the current state caused large percentage changes (up to 200%-300%) in annual flow during relatively moderate to low flow years such as 2009-2010 and 2012-2013. The impacts of wetland drainage were much smaller (but still large) in the flood years 2010-2011 and 2011-2012, when draining all wetlands from the 2008 levels increased annual flow by 32%. Restoring wetlands to 1958 levels had no role in reducing flow volume for 2011-2012 with its filled-storage antecedent condition, but did for all other years including a 29% reduction for the major flood year of 2010-2011 and a 60% reduction for the pre-flood year of 2009-2010. The decrease in the relative change in flow volume with increasing wetness is due to the limited storage capacity of wetlands also being exceeded as flows increase with increasing precipitation. This is evident in 2010-2011 where wet antecedent conditions and very high precipitation inputs caused a relatively small (but still large in absolute terms) response to changes in wetland drainage or restoration. It is also shown very clearly in the post-flood year of 2011-2012, where small depressional storage capacities carried over from 2011 and from the snowmelt event before the main rainfall-driven flood resulted in a relatively small response to wetland drainage and no response to wetland restoration. Clearly the 2012 response was affected by a “memory” of small wetland storage capacities from 2011 as hypothesized by Shook and Pomeroy (2011). It should be noted that this memory was largely erased by 2013 when relative flow volume responses to drainage were very large, as the basin had dried out. Interestingly there are differences in the relative responses to drainage and restoration among the years; 2008-2009 showed a relative modest (but still large) 85% increase in flow volume with drainage of 43 km^2 of wetland, but only a 21% decrease in flow volume with restoration of 53 km^2 of wetland. 2012-2013 was the most sensitive year to drainage but 2009-2010 was the most sensitive to restoration. Clearly there are internally non-linear effects that cause variability in response to wetland area change over time.

The relative response of total basin flow volume over six hydrological years of simulation (2007-2013) shows a non-linear flow response to wetland area change in Fig. 33. This is a useful metric when assessing the effects of wetland change in Smith Creek on the water balance of downstream receiving water bodies such as Lake Winnipeg. Drainage induced decreases in wetland area of 43 km^2 cause an increase in total flow volume of 55%, whilst restoration induced increases in wetland area of 53 km^2 cause a decrease in cumulative flow volume of 26%. Smith Creek is already heavily drained but its flow volumes can still be strongly impacted by further drainage

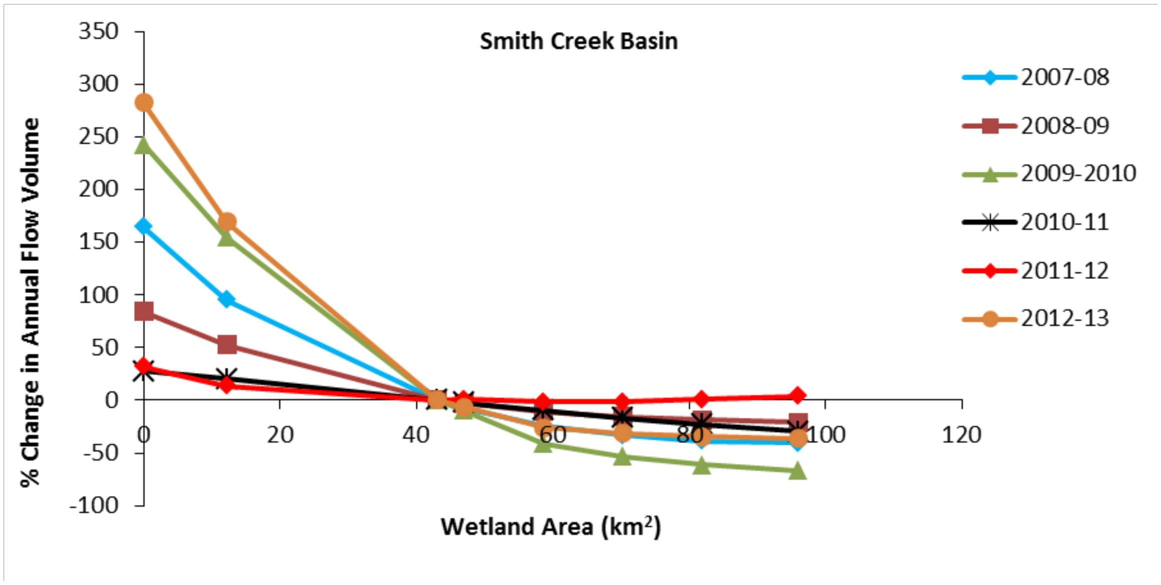

Figure 32. Percentage change in annual flow volume from the "current" (2008) wetland drainage versus wetland area for Smith Creek basin.

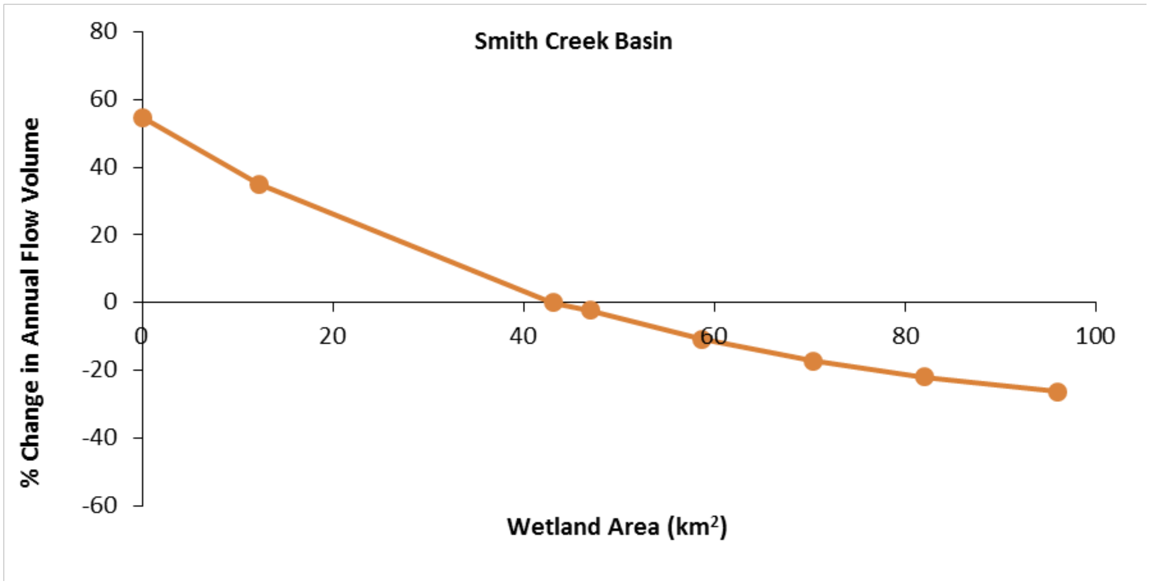

Figure 33. Percentage change in cumulative annual flow volume over six years with wetland area for Smith Creek.

Peak daily discharge

The sub-basin and Smith Creek basin annual peak daily discharges are shown in Figures 34 to 39, for the eight wetland scenarios in each of six hydrological years (2007-2013). The peak discharges increased dramatically with wetland reduction from 1958 levels to complete drainage for all sub-basins, as well as the Smith Creek basin, for all years. When examined only over the historical period (1958-2008), peak discharge increased with drainage for most years of record, with the exception of sub-basin 5 in the record flood year of 2010-2011. Compared to wetland coverage in the historical period, even larger peak daily discharges were estimated for the "loss ceiling" wetland state for all sub-basins, as well as the Smith Creek basin, in all years. Completely draining wetlands resulted in larger peak discharge than for the loss ceiling state for most years in sub-basins 1, 3, and 5 and for the Smith Creek basin for all years.

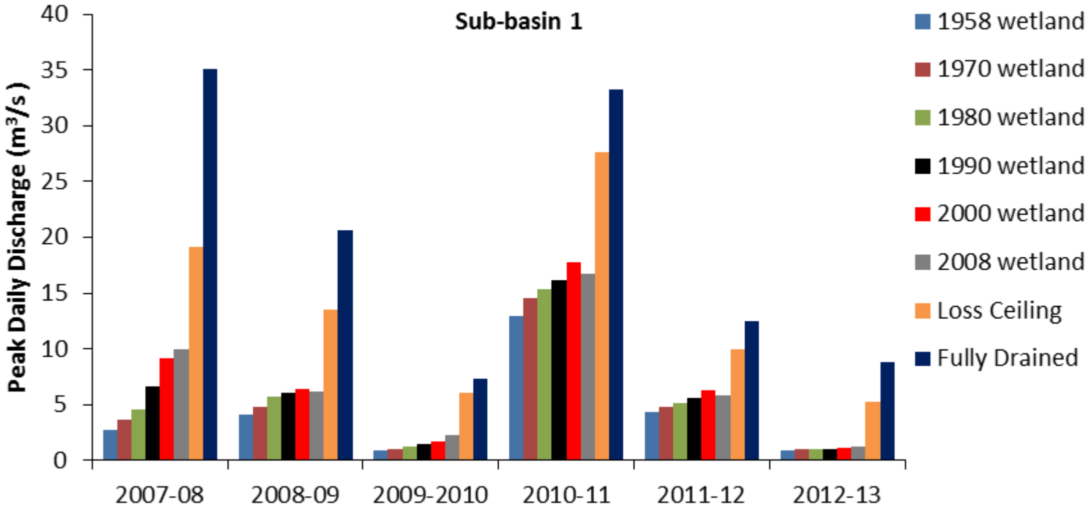

Figure 34. Response of peak daily discharge to wetland scenarios for sub-basin 1.

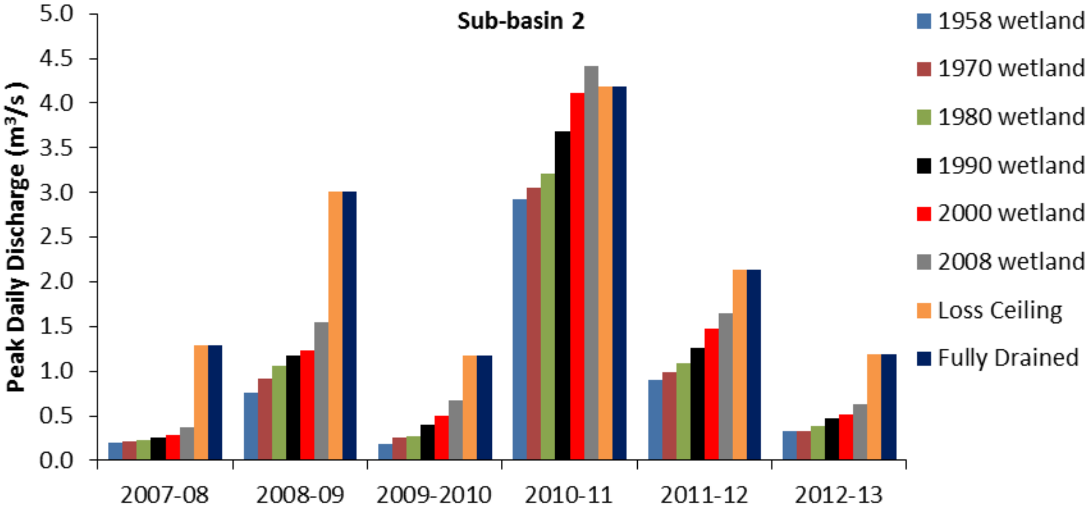

Figure 35. Response of peak daily discharge to wetland scenarios for sub-basin 2.

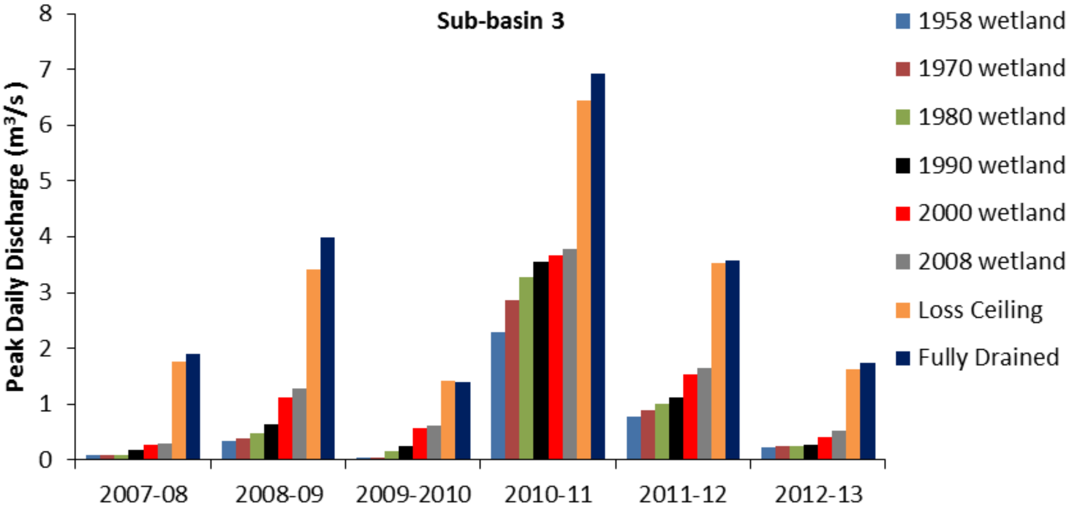

Figure 36. Response of peak daily discharge to wetland scenarios for sub-basin 3.

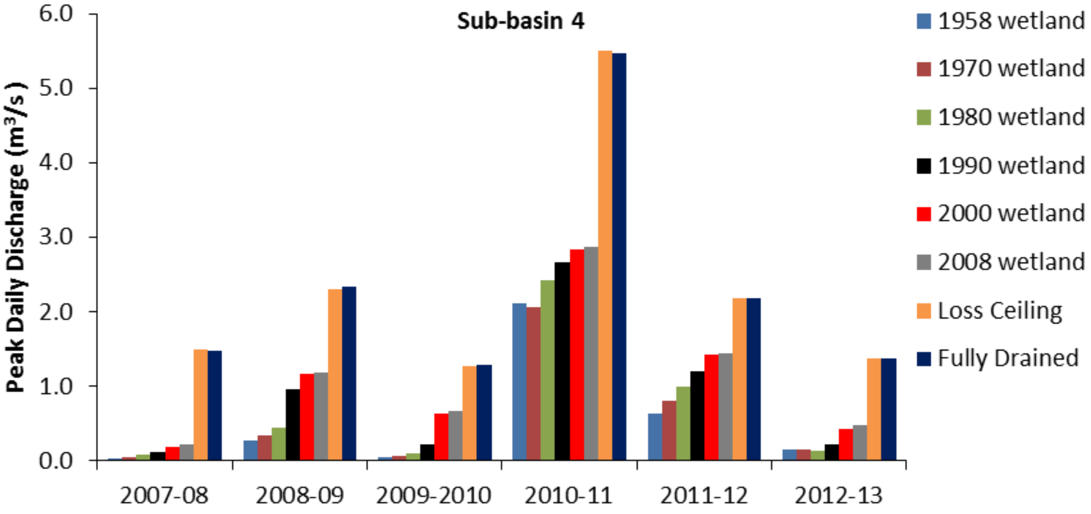

Figure 37. Response of peak daily discharge to wetland scenarios for sub-basin 4.

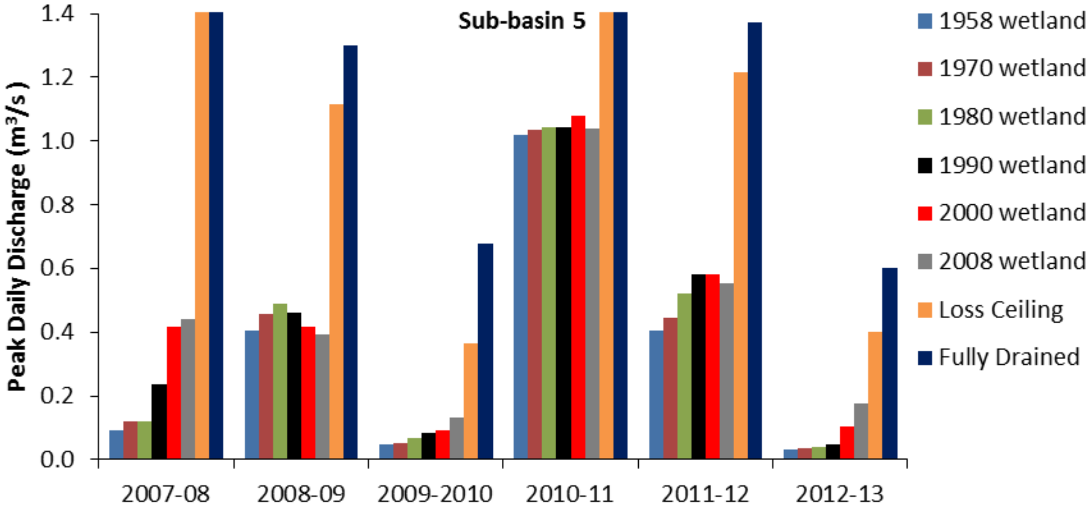

Figure 38. Response of peak daily discharge to wetland scenarios for sub-basin 5.

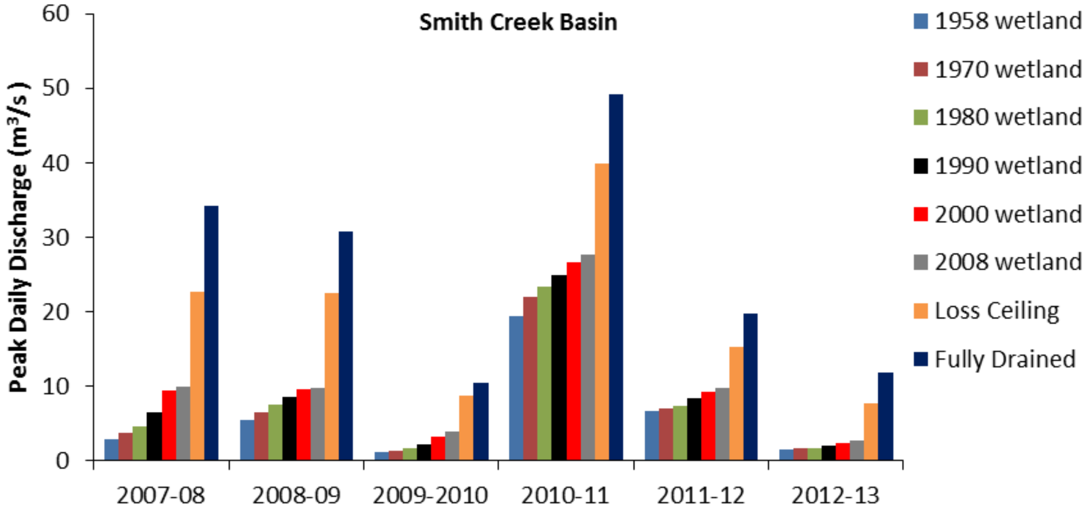

Figure 39. Response of peak daily discharge to wetland scenarios for entire Smith Creek basin.

The annual peak daily discharge for Smith Creek basin is plotted as a function of the scenario wetland area in Fig. 40. Non-linear decreases in peak discharge with wetland area are evident. The weakest association between peak discharge and wetland area is for the flood years of 2010-2011 and 2011-2012 where antecedent low storage conditions might have reduced the effect of wetland storage change on the peak discharge. However, complete drainage from the 1958 wetland state increased the peak daily discharge of record (2011) from 20 to 49 m^3/s which has great bearing on necessary culvert capacity along Smith Creek, operation of downstream reservoirs, downstream flooding and erosional forces when applied to the channel and impeding infrastructure such as roads and buildings.

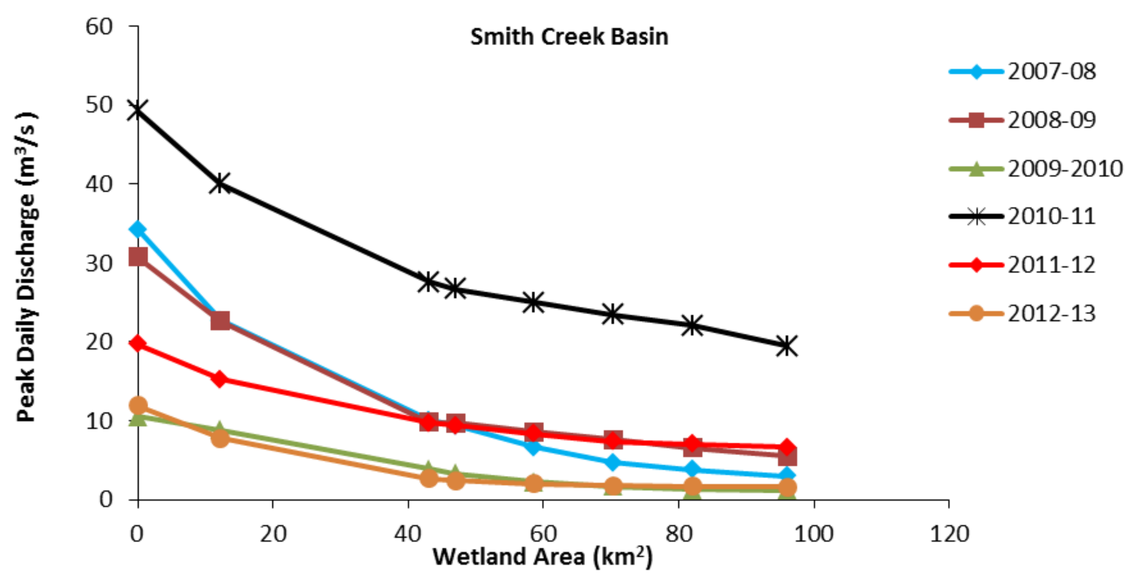

Figure 40. Peak daily discharge plotted against wetland area for Smith Creek basin in various simulation years.

Figure 41 shows the percentage change in peak daily discharge with respect to the discharge for 2008 wetland conditions, for each of the six simulation years. The percentage changes in peak flows are magnified compared to annual flow volumes shown in Fig. 32. In all cases, the relationship is non-linear and the peak discharge increases rapidly with further wetland drainage and decreases moderately with wetland restoration. The percentage change in peak discharge declined with increasing precipitation and antecedent storage in wetlands, as the wetland attenuation of runoff became overwhelmed when storage was small and/or runoff was very high. The most extreme increase, of 350% in peak discharge with complete drainage from 2008 conditions, was for the relatively dry year of 2012-2013 and the less extreme (but still large) increases of 78% and 102% were for the flood years of 2010-2011 and 2011-2012 respectively. Wetland restoration to 1958 conditions caused decreases in peak discharge of 70% in a relatively dry years such as 2007-2008 and 2009-2010 and smaller decreases of 32% for the flood years of 2010-2011 and 2011-2012. Most simulation years indicated increases in peak discharge of between 170% and 241% with complete drainage and decreases of approximately 40% with complete restoration. Whilst the greatest proportional impacts are for dry years, the substantial impacts on the highest peak flow (2011) of wetland drainage (+78%) or restoration (-32%) are notable and important for infrastructure in and downstream of Smith Creek.

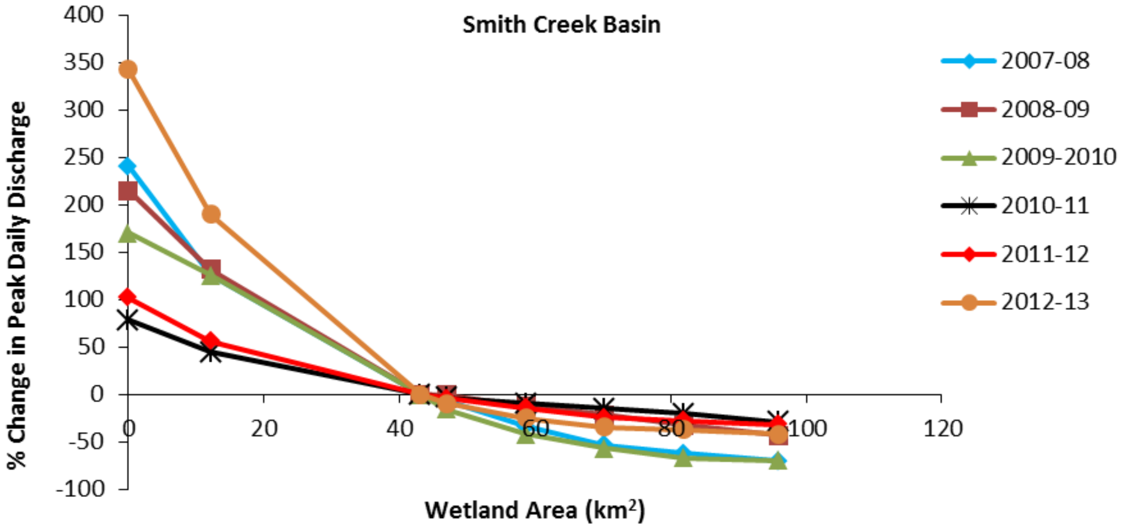

Figure 41. Percentage change in peak daily discharge vs. wetland area for Smith Creek basin.

6. Conclusions

The 2010 Prairie Hydrological Model (PHM) configuration of the Cold Regions Hydrological Model was redeveloped to include improvements to the algorithms for snowmelt, evapotranspiration, networks of dynamic wetlands and variable contributing area. A hysteretic relationship was found between wetland storage and contributing area and the revised model algorithms were capable of simulating this important governing effect on basin hydrological response to precipitation or snowmelt. The PHM was set up without calibration on the five sub-basins and main basin of Smith Creek, Saskatchewan and run using the recorded wetland storage volume of 2008 for six hydrological years (2007-2013) which ranged from normal conditions to the flood of record. Comparisons with measured snowpack and daily and seasonal stream discharge suggest that the model performed sufficiently well for wetland change impact analysis. The PHM was then run for scenarios with wetland extents set to the 1958 historical maximum, recorded extents in 2000 and 2008, interpolated extents between 2000 and 1958, a minimum extent that excluded drainage of wetlands on conservation lands and an extreme minimum extent involving complete drainage of all wetlands in Smith Creek basin.

The results show that the simulated annual streamflow volumes and peak daily discharges in Smith Creek and its sub-basins have a remarkably strong sensitivity to wetland drainage, both to the existing drainage over the historical period (1958-2008) and to further drainage to minimum possible wetland extents. The greatest hydrological sensitivity to wetland drainage was in sub-basin 1 which is by far the largest of all sub-basins, has had substantial wetland coverage and has a large potential for further drainage. Conservation lands in this sub-basin have a notable impact on restricting increases in sub-basin 1 annual flow volumes and peak discharges due to complete wetland drainage, but these effects are much smaller at the scale of Smith Creek.

At the Smith Creek basin scale, the annual flow volume almost doubles for the flood of record (2011) with drainage of the 1958 wetland extent. Drainage from the current 2008 wetland levels increases the 2011 annual flow volume by 32%. The simulated Smith Creek peak daily discharge for the flood of record (2011) increases proportionately more with drainage than does the annual flow volume, more than doubling with complete drainage of the 1958 wetland extent, and increasing by 78% with complete drainage from current (2008) levels. In the secondary flood year (2012) where there was low antecedent depressional storage capacity after the previous year's flood, the impact of drainage from current conditions on annual flow volumes is similar to that in 2011, but, in contrast to all other years, there is no influence on annual flow volumes from restoring wetlands to 1958 conditions. Annual flow volumes in moderate to low flow years increase by very high amounts (200% to 300%) from complete drainage of the 2008 wetlands, and are reduced by smaller amounts (21% to 60%) with restoration of the 2008 wetland extent to 1958 levels. Peak discharges in moderate to low flow years increase substantially (150% to 350%) with complete drainage from the current condition, and decrease by smaller amounts (35% to 70%) with restoration from current levels to those of 1958. Overall, Smith Creek total flow volumes over six years increase 55% due to drainage of wetlands from the current (2008) state, and decrease 26% with restoration to the 1958 state. This sensitivity in flow volume to wetland change is crucially important for the water balance of downstream water bodies such as Lake

Winnipeg. Whilst the greatest proportional impacts on the peak daily flows are for dry years, the substantial impacts on the peak flow of record (2011) from wetland drainage (+78%) or restoration (-32%) are notable and important for infrastructure in and downstream of Smith Creek. The estimated increases in the annual flow volume and the peak flow of the flood of record (2011) due to wetland drainage that has already occurred in Smith Creek are from 57,317 to 81,227 dam^3 and from 19.5 to 27.5 m^3/s. Although Smith Creek is already heavily drained and its streamflows have been impacted, its flow volumes and peak discharges can still be strongly increased by further drainage, rising to 103,669 dam^3 and 49 m^3/s respectively with complete drainage.

It must be noted that these results are from hydrological model simulations, some of which are based on interpolated basin wetland conditions that cannot be verified with field observations. The lack of streamflow observations before wetland drainage commenced and the impossibility of verifying simulations for future drainage make the model results for scenarios impossible to verify independently. The hydrological model simulations only include the wetland drainage components of environmental change in Smith Creek basin and do not include concomitant climate change and other land management change impacts on the basin over the last 50 years. As such they should only be used for assessing the impacts of wetland drainage under conditions of constant climate and agricultural land use.

Smith Creek basin had a very large percentage of its area covered with wetlands in the historical period, 24% in 1958, and has subsequently had substantial drainage to a current coverage of 11%. Therefore the specific results presented here reflect the substantial drainage in Smith Creek and should not be directly extrapolated to other basins. Despite these caveats, the physical basis of the Prairie Hydrological Model, its lack of calibration to current conditions and its detailed representation of wetland dynamics and variable contributing area mean that it is the most reliable and sophisticated estimate now available of the hydrological response to wetland drainage in the Canadian Prairies. This model simulation exercise shows that wetland drainage increases the annual flow volumes and peak daily discharges substantially, with notable increases in the flow volume and the peak discharge of the flood of record due to wetland drainage that has already occurred in Smith Creek. Relative increases in annual flow volumes and peak daily discharge increase with decreasing annual flow volume, showing that the relative hydrological impact of wetland drainage is greatest in moderate to low flow years, but the magnitude of the hydrological impact of wetland drainage is greatest in flood years.

7. Acknowledgements

The authors would like to acknowledge the assistance of Larisa Barber, Rosa Brannen, Nathalie Brunet, Adam Minke, Joni Onclin, Nicole Seitz and Mike Solohub in field data collection, the cooperation of Don Werle for hosting the Centre for Hydrology's Smith Creek Meteorological Station and the information, advice and assistance provided by the Smith Creek Watershed Association, the RMs of Churchbridge and Langenburg and Town of Langenburg throughout this study. Funding for various phases of this study have been provided by NSERC, Canada Research Chairs, University of Saskatchewan, CFCAS-DRI, Environment Canada, Agriculture and Agrifood Canada, Ducks Unlimited Canada, Province of Manitoba, Province of Saskatchewan and the Prairie Habitat Joint Venture Committee. The views expressed in this report are only those of the authors.

8. References

Armstrong, R. N., Pomeroy, J. W., and Martz, L. W. 2010. Estimating evaporation in a Prairie landscape under drought conditions. Canadian Water Resources Journal, 35: 173-186.

Ayers, H. D. 1959. Influence of soil profile and vegetation characteristics on net rainfall supply to runoff, in: Proceedings of Hydrology Symposium No.1: Spillway Design Floods, National Research Council Canada, Ottawa, 198-205.

Brunt, D. 1932. Notes on radiation in the atmosphere. Quarterly Journal of the Royal Meteorological Society, 58: 389-420.

Brutsaert, W. 1975. On a derivable formula for longwave radiation from clear skies. Water Resources Research, 11: 742-744.

Clark, C.O. 1945. Storage and the unit hydrograph. Proceedings of the American Society of Civil Engineering, 69: 1419-1447.

Chow, V. T. 1959. Open Channel Hydraulics. McGraw-Hill, Inc. New York, USA.

Chow, V. T. 1964. Handbook of Applied Hydrology. McGraw-Hill, Inc. New York, USA.

Chun, K. P. and Wheater, H. S. 2012. An extreme analysis for the 2010 precipitation event at the South of Saskatchewan Prairie. Global NEST journal special issue on Hydrology and Water Resources, 14: 311-324.

Council of Canadian Academies. 2013. Water and Agriculture in Canada: Towards Sustainable Management of Water Resources, the Expert Panel on Sustainable Management of Water in the Agricultural Landscapes of Canada. Ottawa: Council of Canadian Academies.

Dornes, P. F., Pomeroy, J. W., Pietroniro, A., Carey, S. K., and Quinton, W. L. 2008. Influence of landscape aggregation in modelling snow-cover ablation and snowmelt runoff in a sub-arctic mountainous environment. Hydrological Sciences Journal, 53: 725-740.

DUC (Ducks Unlimited Canada). 2007. DUC – Dedicated to Wetland and Wildlife Conservation. Available at http://www. ducks.ca/conserve/index.html, Accessed on 26 March 2008.

Ellis, C. R., Pomeroy, J. W., Brown, T., and MacDonald, J. 2010. Simulation of snow accumulation and melt in needleleaf forest environments. Hydrology and Earth System Sciences, 14: 925-940.

Fang, X. and Pomeroy, J. W. 2007. Snowmelt runoff sensitivity analysis to drought on the Canadian Prairies. Hydrological Processes, 21: 2594-2609.

Fang, X. and Pomeroy, J. W. 2008. Drought impacts on Canadian prairie wetland snow Hydrology. Hydrological Processes, 22: 2858-2873.

Fang, X. and Pomeroy, J. W. 2009. Modelling blowing snow redistribution to prairie wetlands. Hydrological Processes, 23: 2557-2569.

Fang, X., Pomeroy, J. W., Westbrook, C. J., Guo, X., Minke, A. G., and Brown, T. 2010. Prediction of snowmelt derived streamflow in a wetland dominated prairie basin. Hydrology and Earth System Sciences, 14: 991-1006.

Garbrecht, J. and Martz, L. W. 1993. Network and subwatershed parameters extracted from digital elevation models: The Bills Creek experience. Water Resource Bulletin, 29: 909-916.

Garbrecht, J. and Martz, L. W. 1997. The assignment of drainage direction over flat surfaces in raster digital elevation models. Journal of Hydrology, 193: 204-213.

Garnier, B. J. and Ohmura, A. 1970. The evaluation of surface variations in solar radiation income. Solar Energy, 13: 21-34.

Gleason, R. A., Tangen, B. A., Laubhan, M. K., Kermes, K. E., and Euliss, N. H. 2007. Estimating water storage capacity of existing and potentially restorable wetland depressions in a subbasin of the Red river of the north. U.S. Geological Survey, U.S. Department of the Interior Open-file report 2007-1159.

Godwin, R. B. and Martin, F. R. J. 1975. Calculation of gross and effective drainage areas for the Prairie Provinces. In: Canadian Hydrology Symposium - 1975 Proceedings, 11-14 August 1975, Winnipeg, Manitoba. Associate Committee on Hydrology, National Research Council of Canada, pp. 219-223.

Granger, R. J. and Gray, D. M. 1989. Evaporation from natural non-saturated surfaces. Journal of Hydrology, 111: 21–29.

Granger, R. J. and Gray, D. M. 1990. A net radiation model for calculating daily snowmelt in open environments. Nordic Hydrology, 21: 217-234.

Gray, D. M. 1964. Physiographic characteristics and the runoff pattern. In: Proceedings of Hydrology Symposium No. 4 Research Watersheds. Subcommittee on Hydrology, Associate Committee on Geodesy and Geophysics, National Research Council of Canada, pp. 147-164.

Gray, D. M. 1970. Handbook on the Principles of Hydrology: with special emphasis directed to Canadian conditions in the discussions, applications and presentation of data. New York: Water Information Center, Inc..

Gray, D. M., Landine, P. G., and Granger, R. J. 1985. Simulating infiltration into frozen Prairie soils in stream flow models. Canadian Journal of Earth Sciences, 22: 464-474.

Gray, D. M. and Landine, P. G. 1987. Albedo model for shallow prairie snow covers. Canadian Journal of Earth Sciences, 24: 1760-1768.

Gray, D. M. and Landine, P. G. 1988. An energy-budget snowmelt model for the Canadian Prairies. Canadian Journal of Earth Sciences, 25: 1292-1303.

Guo, X., Pomeroy, J. W., Fang, X., Lowe, S., Li, Z., Westbrook, C., and Minke, A. 2012. Effects of classification approaches on CRHM model performance. Remote Sensing Letters, 3: 39-47.

Hayashi, M. and van der Kamp, G. 2000. Simple equations to represent the volume-area-depth relations of shallow wetlands in small topographic depressions. Journal of Hydrology, 237: 74-85.

Hayashi, M., van der Kamp, G. and Schmidt, R. 2003. Focused infiltration of snowmelt water in partially frozen soil under small depressions. Journal of Hydrology, 270: 214-229.

Leavesley, G. H., Lichty, R. W., Troutman, B. M., and Saindon, L. G. 1983. Precipitation-runoff modelling system: user's manual. US Geological Survey Water Resources Investigations Report 83-4238. 207 pp.

Millett, B. V., Johnson, W. C., and Guntenspergen, G. R. 2009. Climate trends of the North American prairie pothole region 1906-2000. Climatic Change, 93: 243-267.

Minke, A. G., Westbrook, C. J., and van der Kamp, G. 2010. Simplied volume-area-depth method for estimating water storage of prairie potholes. Wetlands, 30: 541-551.

Monteith, J. L. 1965. Evaporation and environment. Symposia of the Society for Experimental Biology, 19: 205-234.

Ogden, F. L. and Saghafian, B. 1997. Green and Ampt infiltration with redistribution. Journal of Irrigation and Drainage Engineering, 123: 386-393.

Philips, R. W., Spence, C., and Pomeroy, J. W. 2011. Connectivity and runoff dynamics in heterogeneous basins. Hydrological Processes, 25: 3061-3075.

Pomeroy, J. W. and Li, L. 2000. Prairie and Arctic areal snow cover mass balance using a blowing snow model. Journal of Geophysical Research, 105: 26619-26634.

Pomeroy, J. W., Gray, D. M., Brown, T., Hedstrom, N. R., Quinton, W., Granger, R. J., and Carey, S. 2007a. The Cold Regions Hydrological Model, a platform for basing process representation and model structure on physical evidence. Hydrological Processes, 21: 2650-2667.

Pomeroy, J. W., de Boer, D., and Martz, L. W. 2007b. Hydrology and water resources. In Thraves, B., Lewry, M. L., Dale, J. E., and Schlichtmann, H. (Eds.), Saskatchewan: Geographic Perspectives. Regina: CRRC, pp. 63-80.

Pomeroy, J. W., Fang, X., Westbrook, C., Minke, A., Guo, X., and Brown, T. 2010. Prairie Hydrological Model Study Final Report. Centre for Hydrology Report No. 7, University of Saskatchewan, Saskatoon, 113 pp.

Priestley, C. H. B. and Taylor, R. J. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Monthly Weather Review, 100: 81-92.

Saskatchewan Soil Survey. 1991. The soils of Langenburg (181) Fertile Belt (183) Churchbridge (211) Saltcoats (213) rural municipalities, Saskatchewan. Saskatchewan Institute of Pedology, Saskatoon, Saskatchewan, Publication S208.

Shapiro, M. and Westervelt, J. 1992. *R.MAPCALC. An Algebra for GIS and Image Processing*.

Shaw, D. A. 2010. The influence of contributing area on the hydrology of the prairie pothole region of North America, 179 pp., University of Saskatchewan. [online] Available from: http://library2.usask.ca/theses/available/etd-12232009-105101/ (Accessed 31 August 2010).

Shaw, D. A., van der Kamp, G., Conly, F. M., Pietroniro, A., and Martz, L. 2012. The fill-spill hydrology of prairie wetland complexes during drought and deluge. Hydrologocal Processes, 26: 3147-3156.

Shook, K. R. and Pomeroy, J. W. 2011. Memory effects of depressional storage in Northern Prairie hydrology. Hydrological Processes, 25: 3890-3898.

Shook, K. and Pomeroy, J. 2012. Changes in the hydrological character of rainfall on the Canadian prairies. Hydrological Processes, 26: 1752-1766.

Shook, K., Pomeroy, J. W., Spence, C., and Boychuk, L. 2013. Storage dynamics simulations in prairie wetland hydrology models: evaluation and parameterization. Hydrological Processes, 27: 1875–1889, doi:10.1002/hyp.9867.

Sicart, J. E., Pomeroy, J. W., Essery, R. L. H., Hardy, J., Link, T., and Marks, D. 2004. A sensitivity study of daytime net radiation during snowmelt to forest canopy and atmospheric conditions. Journal of Hydrometeorology, 5: 774-784.

Sicart, J. E., Pomeroy, J. W., Essery, R. L. H., and Bewley, D. 2006. Incoming longwave radiation to melting snow: observations, sensitivity and estimation in northern environments. Hydrological Processes, 20: 3697-3708.

Stichling, W. and Blackwell, S. R. 1957. Drainage area as a Hydrologic Factor on the Glaciated Canadian Prairies. IUGG Proceedings, Volume 111, Toronto, Ontario, Canada.

van der Kamp, G. and Hayashi, M. 2009. Groundwater-wetland ecosystem interaction in the semiarid glaciated plains of North America. Hydrogeology Journal, 17: 203-214.

Verseghy, D. L. 1991. CLASS – A Canadian land surface scheme for GCMs. I. Soil model. International Journal of Climatology, 11: 111-133.

Walmsley, J. L., Taylor, P. A., and Salmon, J. R. 1989. Simple guidelines for estimating windspeed variations due to small-scale topographic features – an update. Climatological Bulletin, 23: 3-14.

Winter, T. C. 1989. Hydrologic studies of potholes in the northern prairies. In van der Valk, A. (Ed.), Northern Prairie Wetlands. Iowa: Iowa State University Press, Ames, pp.17-54.

Yang, W., Wang, X., Gabor, S., Boychuk, L., and Badiou, P. H. 2010. Simulated environmental effects of wetland restoration scenarios in a typical Canadian prairie watershed. Wetlands Ecology and Management, 18: 269-279.

Appendices

Appendix 1: HRU area, routing length, and depressional storage capacity in the dynamical wetland network in the revised PHM-CRHM. These values are for the HRUs of the simulated sub-region in the dynamical wetland network. Table A1. HRU area (km^2) in the dynamical wetland network for the Smith Creek sub-basins.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	0.0462	0.1246	0.2932	0.3060	0.0382
2	Stubble	0.9356	2.2922	4.9142	2.1731	0.7581
3	Grassland	0.1743	0.2029	0.7914	0.1371	0.0849
4	River Channel	0.0141	0.0326	0.1010	0.0348	0.0129
5	Open Water	0.0033	0.0000	0.0000	0.0000	0.0000
6	Woodland	0.3787	0.9242	1.8238	0.9241	0.3784
7	Wetland1	0.0001	0.0038	0.0073	0.0065	0.0012
8	Wetland2	0.0009	0.0047	0.0123	0.0112	0.0016
9	Wetland3	0.0002	0.0073	0.0112	0.0251	0.0002
10	Wetland4	0.0073	0.0014	0.0002	0.0007	0.0002
11	Wetland5	0.0001	0.0027	0.0219	0.0372	0.0012
12	Wetland6	0.0040	0.0047	0.0032	0.0001	0.0002
13	Wetland7	0.0033	0.0115	0.0039	0.0021	0.0022
14	Wetland8	0.0074	0.0104	0.0026	0.0034	0.0006
15	Wetland9	0.0203	0.0172	0.0062	0.0001	0.0010
16	Wetland10	0.0003	0.0017	0.0167	0.0093	0.0010
17	Wetland11	0.0003	0.0023	0.0031	0.0031	0.0006
18	Wetland12	0.0023	0.0076	0.0001	0.0062	0.0006
19	Wetland13	0.0001	0.0068	0.0937	0.0002	0.0005
20	Wetland14	0.0099	0.0028	0.0069	0.0031	0.0074
21	Wetland15	0.0032	0.0005	0.0134	0.0001	0.0022
22	Wetland16	0.0003	0.0002	0.0031	0.0036	0.0001
23	Wetland17	0.1178	0.0188	0.0105	0.0012	0.0014
24	Wetland18	0.0001	0.0013	0.0029	0.0011	0.0001
25	Wetland19	0.0002	0.0051	0.0027	0.0029	0.0007
26	Wetland20	0.0043	0.0016	0.0090	0.0095	0.0043
27	Wetland21	0.0003	0.0001	0.0024	0.0131	0.0019
28	Wetland22	0.0051	0.0676	0.0019	0.0019	0.0018
29	Wetland23	0.0230	0.0108	0.0174	0.0009	0.0018
30	Wetland24	0.0001	0.0014	0.0002	0.0032	0.0001
31	Wetland25	0.0038	0.0018	0.0199	0.0028	0.0003
32	Wetland26	0.0119	0.0107	0.0022	0.0077	0.0019
33	Wetland27	0.0016	0.0011	0.0038	0.0008	0.0001
34	Wetland28	0.0007	0.0059	0.0024	0.0004	0.0002
35	Wetland29	0.0001	0.0023	0.0140	0.0005	0.0003
36	Wetland30	0.0002	0.0010	0.0048	0.0004	0.0014
37	Wetland31	0.0057	0.0003	0.0075	0.0078	0.0024
38	Wetland32	0.0010	0.0001	0.0006	0.0020	0.0016
39	Wetland33	0.0001	0.0020	0.0012	0.0008	0.0014
40	Wetland34	0.0002	0.0114	0.0017	0.0011	0.0005
41	Wetland35	0.0035	0.0013	0.0038	0.0050	0.0029
42	Wetland36	0.0003	0.0095	0.0140	0.0020	0.0003
43	Wetland37	0.0001	0.0029	0.0160	0.0020	0.0010
44	Wetland38	0.0022	0.0079	0.0047	0.0076	0.0018
45	Wetland39	0.0003	0.0022	0.0056	0.0005	0.0024
46	Wetland40	0.0077	0.0007	0.0083	0.0002	0.0011
47	Wetland41	0.0001	0.0005	0.0011	0.0001	0.0012
48	Wetland42	0.0007	0.0001	0.0541	0.0012	0.0003
49	Wetland43	0.0007	0.0015	0.0196	0.0027	0.0034
50	Wetland44	0.0004	0.0006	0.0025	0.0090	0.0023
51	Wetland45	0.0001	0.0053	0.0014	0.0136	0.0019
52	Wetland46	0.0048	0.0002	0.0121	0.0018	0.0005

Table A2. Muskingum routing parameter: routing length (m) between HRUs within the sub-basins in the dynamical wetland network for the Smith Creek sub-basins.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	232	403	648	664	209
2	Stubble	1301	2109	3182	2049	1162
3	Grassland	499	543	1141	438	337
4	River Channel	2013	854	1135	742	365
5	Open Water	59	3	3	3	3
6	Woodland	808	1303	1875	1302	807
7	Wetland1	8	59	84	79	31
8	Wetland2	27	66	112	106	36
9	Wetland3	12	84	106	166	12
10	Wetland4	84	34	12	23	12
11	Wetland5	8	49	154	206	31
12	Wetland6	60	66	53	8	12
13	Wetland7	54	108	60	42	43
14	Wetland8	85	102	48	55	21
15	Wetland9	148	135	77	8	28
16	Wetland10	15	38	133	96	28
17	Wetland11	15	45	53	53	21
18	Wetland12	45	86	8	77	21
19	Wetland13	8	81	342	12	19
20	Wetland14	99	50	82	53	85
21	Wetland15	53	19	117	8	43
22	Wetland16	15	12	53	57	8
23	Wetland17	388	141	103	31	34
24	Wetland18	8	33	51	30	8
25	Wetland19	12	69	49	51	23
26	Wetland20	63	36	94	97	63
27	Wetland21	15	8	46	116	40
28	Wetland22	69	286	40	40	39
29	Wetland23	158	104	136	27	39
30	Wetland24	8	34	12	53	8
31	Wetland25	59	39	146	50	15
32	Wetland26	110	104	43	87	40
33	Wetland27	36	30	59	25	8
34	Wetland28	23	75	46	17	12
35	Wetland29	8	45	120	19	15
36	Wetland30	12	28	67	17	34
37	Wetland31	73	15	85	87	46
38	Wetland32	28	8	21	41	36
39	Wetland33	8	41	31	25	34
40	Wetland34	12	107	38	30	19
41	Wetland35	56	33	59	68	51
42	Wetland36	15	97	120	41	15
43	Wetland37	8	51	129	41	28
44	Wetland38	43	88	66	86	39
45	Wetland39	15	43	73	19	46
46	Wetland40	87	23	90	12	30
47	Wetland41	8	19	30	8	31
48	Wetland42	23	8	253	31	15
49	Wetland43	23	35	145	49	55
50	Wetland44	17	21	47	94	45
51	Wetland45	8	71	34	118	40
52	Wetland46	67	12	111	39	19

Table A3. Depressional storage capacity (mm) in the dynamical wetland network for the Smith Creek sub-basins.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	61	67	69	67	69
2	Stubble	61	67	69	67	69
3	Grassland	86	100	95	104	102
4	River Channel	200	200	200	200	200
5	Open Water	317	374	395	386	366
6	Woodland	78	86	90	88	87
7	Wetland1	183	371	325	273	311
8	Wetland2	211	265	752	660	203
9	Wetland3	188	295	682	745	196
10	Wetland4	262	239	267	234	231
11	Wetland5	182	248	805	664	252
12	Wetland6	217	330	261	182	202
13	Wetland7	345	576	198	225	246
14	Wetland8	263	771	311	391	220
15	Wetland9	573	748	317	232	265
16	Wetland10	199	298	690	305	315
17	Wetland11	197	259	266	323	251
18	Wetland12	234	303	201	399	267
19	Wetland13	183	274	830	271	206
20	Wetland14	256	291	296	265	246
21	Wetland15	201	233	814	193	290
22	Wetland16	190	194	420	276	203
23	Wetland17	988	671	747	317	296
24	Wetland18	184	286	252	223	184
25	Wetland19	185	229	403	343	302
26	Wetland20	305	304	361	283	294
27	Wetland21	191	186	309	680	298
28	Wetland22	273	814	235	277	304
29	Wetland23	792	758	911	208	260
30	Wetland24	191	219	333	345	184
31	Wetland25	366	335	763	267	206
32	Wetland26	765	843	353	413	373
33	Wetland27	271	264	325	201	191
34	Wetland28	203	302	293	226	409
35	Wetland29	187	286	830	205	220
36	Wetland30	184	310	329	227	304
37	Wetland31	210	187	462	388	306
38	Wetland32	326	219	260	267	259
39	Wetland33	214	282	269	279	278
40	Wetland34	262	716	393	243	200
41	Wetland35	216	239	237	291	238
42	Wetland36	236	309	933	269	205
43	Wetland37	185	412	721	267	204
44	Wetland38	281	197	337	269	356
45	Wetland39	189	266	308	269	266
46	Wetland40	260	207	279	201	207
47	Wetland41	235	203	250	188	338
48	Wetland42	222	191	802	252	201
49	Wetland43	213	266	906	241	348
50	Wetland44	299	266	354	332	372
51	Wetland45	190	325	272	861	247
52	Wetland46	350	194	755	290	250

Appendix 2: HRU area, routing length, and depressional storage capacity in the dynamical wetland network in the wetland scenario simulations.

Table A4. HRU area (km^2) in the dynamical wetland network for the 1958 wetland scenario.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	0.0371	0.1023	0.1901	0.2410	0.0291
2	Stubble	0.7514	1.8815	3.1857	1.7111	0.5768
3	Grassland	0.1733	0.2029	0.7913	0.1371	0.0849
4	River Channel	0.0009	0.0054	0.0176	0.0071	0.0051
5	Open Water	0.0033	0.0000	0.0000	0.0000	0.0000
6	Woodland	0.3765	0.9242	1.8236	0.9239	0.3784
7	Wetland1	0.0002	0.0105	0.0381	0.0232	0.0050
8	Wetland2	0.0016	0.0130	0.0642	0.0400	0.0067
9	Wetland3	0.0004	0.0201	0.0584	0.0896	0.0008
10	Wetland4	0.0130	0.0039	0.0010	0.0025	0.0008
11	Wetland5	0.0002	0.0074	0.1142	0.1327	0.0050
12	Wetland6	0.0071	0.0130	0.0167	0.0004	0.0008
13	Wetland7	0.0059	0.0317	0.0203	0.0075	0.0092
14	Wetland8	0.0131	0.0287	0.0136	0.0121	0.0025
15	Wetland9	0.0360	0.0474	0.0323	0.0004	0.0042
16	Wetland10	0.0005	0.0047	0.0871	0.0332	0.0042
17	Wetland11	0.0005	0.0063	0.0162	0.0111	0.0025
18	Wetland12	0.0041	0.0210	0.0005	0.0221	0.0025
19	Wetland13	0.0002	0.0188	0.4887	0.0007	0.0021
20	Wetland14	0.0176	0.0077	0.0360	0.0111	0.0310
21	Wetland15	0.0057	0.0014	0.0699	0.0004	0.0092
22	Wetland16	0.0005	0.0006	0.0162	0.0128	0.0004
23	Wetland17	0.2092	0.0519	0.0548	0.0043	0.0059
24	Wetland18	0.0002	0.0036	0.0151	0.0039	0.0004
25	Wetland19	0.0004	0.0141	0.0141	0.0103	0.0029
26	Wetland20	0.0076	0.0044	0.0469	0.0339	0.0180
27	Wetland21	0.0005	0.0003	0.0125	0.0467	0.0080
28	Wetland22	0.0091	0.1865	0.0099	0.0068	0.0075
29	Wetland23	0.0408	0.0298	0.0908	0.0032	0.0075
30	Wetland24	0.0002	0.0039	0.0010	0.0114	0.0004
31	Wetland25	0.0067	0.0050	0.1038	0.0100	0.0013
32	Wetland26	0.0211	0.0295	0.0115	0.0275	0.0080
33	Wetland27	0.0028	0.0030	0.0198	0.0029	0.0004
34	Wetland28	0.0012	0.0163	0.0125	0.0014	0.0008
35	Wetland29	0.0002	0.0063	0.0730	0.0018	0.0013
36	Wetland30	0.0004	0.0028	0.0250	0.0014	0.0059
37	Wetland31	0.0101	0.0008	0.0391	0.0278	0.0101
38	Wetland32	0.0018	0.0003	0.0031	0.0071	0.0067
39	Wetland33	0.0002	0.0055	0.0063	0.0029	0.0059
40	Wetland34	0.0004	0.0314	0.0089	0.0039	0.0021
41	Wetland35	0.0062	0.0036	0.0198	0.0178	0.0122
42	Wetland36	0.0005	0.0262	0.0730	0.0071	0.0013
43	Wetland37	0.0002	0.0080	0.0835	0.0071	0.0042
44	Wetland38	0.0039	0.0218	0.0245	0.0271	0.0075
45	Wetland39	0.0005	0.0061	0.0292	0.0018	0.0101
46	Wetland40	0.0137	0.0019	0.0433	0.0007	0.0046
47	Wetland41	0.0002	0.0014	0.0057	0.0004	0.0050
48	Wetland42	0.0012	0.0003	0.2822	0.0043	0.0013
49	Wetland43	0.0012	0.0041	0.1022	0.0096	0.0143
50	Wetland44	0.0007	0.0017	0.0130	0.0321	0.0096
51	Wetland45	0.0002	0.0146	0.0073	0.0485	0.0080
52	Wetland46	0.0085	0.0006	0.0631	0.0064	0.0021

Table A5. Muskingum routing parameter: routing length (m) between HRUs within the sub-basins in the dynamical wetland network for the 1958 wetland scenario.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	205	361	509	581	179
2	Stubble	1156	1896	2519	1802	1002
3	Grassland	498	543	1141	438	337
4	River Channel	386	291	398	287	209
5	Open Water	59	3	3	3	3
6	Woodland	805	1303	1874	1302	807
7	Wetland1	11	103	209	159	69
8	Wetland2	36	115	278	214	80
9	Wetland3	16	147	264	334	26
10	Wetland4	115	59	29	47	26
11	Wetland5	11	85	382	415	69
12	Wetland6	83	115	133	16	26
13	Wetland7	75	189	148	85	96
14	Wetland8	116	179	118	111	47
15	Wetland9	202	235	191	16	62
16	Wetland10	20	66	329	193	62
17	Wetland11	20	78	130	106	47
18	Wetland12	61	150	20	155	47
19	Wetland13	11	141	849	23	42
20	Wetland14	136	87	202	106	186
21	Wetland15	73	34	291	16	96
22	Wetland16	20	20	130	115	17
23	Wetland17	532	247	255	63	75
24	Wetland18	11	57	126	60	17
25	Wetland19	16	121	121	102	51
26	Wetland20	86	64	234	196	138
27	Wetland21	20	14	113	233	88
28	Wetland22	95	500	99	81	86
29	Wetland23	217	182	336	54	86
30	Wetland24	11	59	29	108	17
31	Wetland25	81	68	362	100	32
32	Wetland26	151	181	108	174	88
33	Wetland27	50	52	146	50	17
34	Wetland28	32	131	113	34	26
35	Wetland29	11	78	298	39	32
36	Wetland30	16	49	166	34	75
37	Wetland31	101	25	212	176	100
38	Wetland32	39	14	53	83	80
39	Wetland33	11	72	77	50	75
40	Wetland34	16	188	94	60	42
41	Wetland35	77	57	146	137	111
42	Wetland36	20	170	298	83	32
43	Wetland37	11	88	321	83	62
44	Wetland38	60	153	164	173	86
45	Wetland39	20	76	180	39	100
46	Wetland40	119	40	224	23	65
47	Wetland41	11	34	74	16	69
48	Wetland42	32	14	628	63	32
49	Wetland43	32	62	359	98	122
50	Wetland44	23	37	116	190	98
51	Wetland45	11	123	84	238	88
52	Wetland46	92	20	275	78	42

Table A6. Depressional storage capacity (mm) in the dynamical wetland network for the 1958 wetland scenario.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	61	67	69	67	69
2	Stubble	61	67	69	67	69
3	Grassland	86	100	95	104	102
4	River Channel	200	200	200	200	200
5	Open Water	317	374	395	386	366
6	Woodland	78	86	90	88	87
7	Wetland1	243	508	382	418	306
8	Wetland2	280	363	883	1011	200
9	Wetland3	250	404	801	1141	193
10	Wetland4	348	327	314	358	228
11	Wetland5	242	340	945	1017	248
12	Wetland6	288	452	307	279	199
13	Wetland7	458	789	233	345	242
14	Wetland8	349	1056	365	599	217
15	Wetland9	761	1024	372	355	261
16	Wetland10	264	408	810	467	310
17	Wetland11	262	355	312	495	247
18	Wetland12	311	415	236	611	263
19	Wetland13	243	375	975	415	203
20	Wetland14	340	398	348	406	242
21	Wetland15	267	319	956	296	286
22	Wetland16	252	266	493	423	200
23	Wetland17	1313	919	877	486	292
24	Wetland18	244	392	296	342	181
25	Wetland19	246	314	473	525	298
26	Wetland20	405	416	424	434	290
27	Wetland21	254	255	363	1042	294
28	Wetland22	363	1114	276	424	300
29	Wetland23	1052	1038	1070	319	256
30	Wetland24	254	300	391	529	181
31	Wetland25	486	459	896	409	203
32	Wetland26	1016	1154	415	633	368
33	Wetland27	360	361	382	308	188
34	Wetland28	270	413	344	346	403
35	Wetland29	248	392	975	314	217
36	Wetland30	244	424	386	348	300
37	Wetland31	279	256	543	594	302
38	Wetland32	433	300	305	409	255
39	Wetland33	284	386	316	427	274
40	Wetland34	348	980	462	372	197
41	Wetland35	287	327	278	446	235
42	Wetland36	314	423	1096	412	202
43	Wetland37	246	564	847	409	201
44	Wetland38	373	270	396	412	351
45	Wetland39	251	364	362	412	262
46	Wetland40	345	283	328	308	204
47	Wetland41	312	278	294	288	333
48	Wetland42	295	261	942	386	198
49	Wetland43	283	364	1064	369	343
50	Wetland44	397	364	416	509	367
51	Wetland45	252	445	319	1319	243
52	Wetland46	465	266	887	444	246

Table A7. HRU area (km^2) in the dynamical wetland network for the 1970 wetland scenario.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	0.0396	0.1079	0.2192	0.2598	0.0317
2	Stubble	0.8017	1.9850	3.6741	1.8446	0.6277
3	Grassland	0.1734	0.2029	0.7913	0.1371	0.0849
4	River Channel	0.0016	0.0072	0.0253	0.0097	0.0059
5	Open Water	0.0033	0.0000	0.0000	0.0000	0.0000
6	Woodland	0.3769	0.9242	1.8236	0.9239	0.3784
7	Wetland1	0.0002	0.0089	0.0296	0.0185	0.0040
8	Wetland2	0.0014	0.0110	0.0499	0.0319	0.0053
9	Wetland3	0.0003	0.0170	0.0455	0.0715	0.0007
10	Wetland4	0.0115	0.0033	0.0008	0.0020	0.0007
11	Wetland5	0.0002	0.0063	0.0889	0.1060	0.0040
12	Wetland6	0.0063	0.0110	0.0130	0.0003	0.0007
13	Wetland7	0.0052	0.0268	0.0158	0.0060	0.0073
14	Wetland8	0.0116	0.0243	0.0106	0.0097	0.0020
15	Wetland9	0.0319	0.0402	0.0252	0.0003	0.0033
16	Wetland10	0.0005	0.0040	0.0678	0.0265	0.0033
17	Wetland11	0.0005	0.0054	0.0126	0.0088	0.0020
18	Wetland12	0.0036	0.0177	0.0004	0.0177	0.0020
19	Wetland13	0.0002	0.0159	0.3803	0.0006	0.0017
20	Wetland14	0.0156	0.0065	0.0280	0.0088	0.0246
21	Wetland15	0.0050	0.0012	0.0544	0.0003	0.0073
22	Wetland16	0.0005	0.0005	0.0126	0.0103	0.0003
23	Wetland17	0.1852	0.0439	0.0426	0.0034	0.0046
24	Wetland18	0.0002	0.0030	0.0118	0.0031	0.0003
25	Wetland19	0.0003	0.0119	0.0110	0.0083	0.0023
26	Wetland20	0.0068	0.0037	0.0365	0.0271	0.0143
27	Wetland21	0.0005	0.0002	0.0097	0.0373	0.0063
28	Wetland22	0.0080	0.1578	0.0077	0.0054	0.0060
29	Wetland23	0.0362	0.0252	0.0706	0.0026	0.0060
30	Wetland24	0.0002	0.0033	0.0008	0.0091	0.0003
31	Wetland25	0.0060	0.0042	0.0808	0.0080	0.0010
32	Wetland26	0.0187	0.0250	0.0089	0.0219	0.0063
33	Wetland27	0.0025	0.0026	0.0154	0.0023	0.0003
34	Wetland28	0.0011	0.0138	0.0097	0.0011	0.0007
35	Wetland29	0.0002	0.0054	0.0568	0.0014	0.0010
36	Wetland30	0.0003	0.0023	0.0195	0.0011	0.0046
37	Wetland31	0.0090	0.0007	0.0304	0.0222	0.0080
38	Wetland32	0.0016	0.0002	0.0024	0.0057	0.0053
39	Wetland33	0.0002	0.0047	0.0049	0.0023	0.0046
40	Wetland34	0.0003	0.0266	0.0069	0.0031	0.0017
41	Wetland35	0.0055	0.0030	0.0154	0.0143	0.0096
42	Wetland36	0.0005	0.0222	0.0568	0.0057	0.0010
43	Wetland37	0.0002	0.0068	0.0649	0.0057	0.0033
44	Wetland38	0.0035	0.0184	0.0191	0.0217	0.0060
45	Wetland39	0.0005	0.0051	0.0227	0.0014	0.0080
46	Wetland40	0.0121	0.0016	0.0337	0.0006	0.0037
47	Wetland41	0.0002	0.0012	0.0045	0.0003	0.0040
48	Wetland42	0.0011	0.0002	0.2196	0.0034	0.0010
49	Wetland43	0.0011	0.0035	0.0796	0.0077	0.0113
50	Wetland44	0.0006	0.0014	0.0101	0.0257	0.0076
51	Wetland45	0.0002	0.0124	0.0057	0.0388	0.0063
52	Wetland46	0.0075	0.0005	0.0491	0.0051	0.0017

Table A8. Muskingum routing parameter: routing length (m) between HRUs within the sub-basins in the dynamical wetland network for the 1970 wetland scenario.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	213	372	551	606	188
2	Stubble	1197	1952	2720	1876	1049
3	Grassland	498	543	1141	438	337
4	River Channel	677	387	572	389	242
5	Open Water	59	3	3	3	3
6	Woodland	806	1303	1874	1302	807
7	Wetland1	10	94	182	140	60
8	Wetland2	34	105	242	189	71
9	Wetland3	15	134	230	295	22
10	Wetland4	108	54	25	41	22
11	Wetland5	10	78	333	366	60
12	Wetland6	77	105	115	14	22
13	Wetland7	70	172	129	75	84
14	Wetland8	109	163	103	98	41
15	Wetland9	189	215	166	14	55
16	Wetland10	19	60	286	171	55
17	Wetland11	19	71	113	93	41
18	Wetland12	57	137	17	137	41
19	Wetland13	10	129	740	21	37
20	Wetland14	128	79	176	93	164
21	Wetland15	69	31	254	14	84
22	Wetland16	19	19	113	101	15
23	Wetland17	498	226	222	55	66
24	Wetland18	10	52	109	53	15
25	Wetland19	15	110	105	90	45
26	Wetland20	81	58	204	173	122
27	Wetland21	19	13	99	206	78
28	Wetland22	89	456	87	71	75
29	Wetland23	203	166	293	47	75
30	Wetland24	10	54	25	95	15
31	Wetland25	75	62	315	88	28
32	Wetland26	141	165	94	154	78
33	Wetland27	47	47	127	44	15
34	Wetland28	30	119	99	30	22
35	Wetland29	10	71	260	34	28
36	Wetland30	15	45	144	30	66
37	Wetland31	94	23	184	155	88
38	Wetland32	36	13	46	73	71
39	Wetland33	10	66	67	44	66
40	Wetland34	15	171	82	53	37
41	Wetland35	72	52	127	122	98
42	Wetland36	19	155	260	73	28
43	Wetland37	10	81	280	73	55
44	Wetland38	56	140	143	153	75
45	Wetland39	19	69	157	34	88
46	Wetland40	111	37	195	21	57
47	Wetland41	10	31	64	14	60
48	Wetland42	30	13	547	55	28
49	Wetland43	30	56	313	87	107
50	Wetland44	22	34	101	168	86
51	Wetland45	10	112	73	211	78
52	Wetland46	86	19	240	69	37

Table A9. Depressional storage capacity (mm) in the dynamical wetland network for the 1970 wetland scenario.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	61	67	69	67	69
2	Stubble	61	67	69	67	69
3	Grassland	86	100	95	104	102
4	River Channel	200	200	200	200	200
5	Open Water	317	374	395	386	366
6	Woodland	78	86	90	88	87
7	Wetland1	235	493	379	407	308
8	Wetland2	271	352	876	983	201
9	Wetland3	242	392	794	1110	194
10	Wetland4	337	318	311	349	228
11	Wetland5	234	330	938	989	249
12	Wetland6	279	439	304	271	200
13	Wetland7	443	766	231	335	243
14	Wetland8	338	1025	362	583	218
15	Wetland9	736	994	369	346	262
16	Wetland10	256	396	804	454	312
17	Wetland11	253	344	310	481	248
18	Wetland12	301	403	234	594	264
19	Wetland13	235	364	967	404	204
20	Wetland14	329	387	345	395	243
21	Wetland15	258	310	948	288	287
22	Wetland16	244	258	489	411	201
23	Wetland17	1270	892	870	472	293
24	Wetland18	236	380	294	332	182
25	Wetland19	238	304	469	511	299
26	Wetland20	392	404	420	422	291
27	Wetland21	245	247	360	1013	295
28	Wetland22	351	1082	274	413	301
29	Wetland23	1018	1007	1061	310	257
30	Wetland24	245	291	388	514	182
31	Wetland25	470	445	889	398	204
32	Wetland26	983	1120	411	615	369
33	Wetland27	348	351	379	299	189
34	Wetland28	261	401	341	337	405
35	Wetland29	240	380	967	305	218
36	Wetland30	236	412	383	338	301
37	Wetland31	270	249	538	578	303
38	Wetland32	419	291	303	398	256
39	Wetland33	275	375	313	416	275
40	Wetland34	337	952	458	362	198
41	Wetland35	278	318	276	434	235
42	Wetland36	303	411	1087	401	203
43	Wetland37	238	548	840	398	202
44	Wetland38	361	262	393	401	352
45	Wetland39	243	354	359	401	263
46	Wetland40	334	275	325	299	205
47	Wetland41	302	270	291	280	334
48	Wetland42	285	254	934	375	199
49	Wetland43	274	354	1055	359	344
50	Wetland44	384	354	412	495	368
51	Wetland45	244	432	317	1283	244
52	Wetland46	450	258	879	432	247

Table A10. HRU area (km^2) in the dynamical wetland network for the 1980 wetland scenario.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	0.0416	0.1126	0.2435	0.2754	0.0338
2	Stubble	0.8437	2.0710	4.0809	1.9557	0.6701
3	Grassland	0.1736	0.2029	0.7913	0.1371	0.0849
4	River Channel	0.0022	0.0090	0.0318	0.0119	0.0066
5	Open Water	0.0033	0.0000	0.0000	0.0000	0.0000
6	Woodland	0.3772	0.9242	1.8236	0.9239	0.3784
7	Wetland1	0.0001	0.0075	0.0226	0.0146	0.0031
8	Wetland2	0.0013	0.0093	0.0381	0.0252	0.0041
9	Wetland3	0.0003	0.0145	0.0347	0.0565	0.0005
10	Wetland4	0.0102	0.0028	0.0006	0.0016	0.0005
11	Wetland5	0.0001	0.0053	0.0678	0.0838	0.0031
12	Wetland6	0.0056	0.0093	0.0099	0.0002	0.0005
13	Wetland7	0.0046	0.0228	0.0121	0.0047	0.0057
14	Wetland8	0.0104	0.0206	0.0080	0.0077	0.0016
15	Wetland9	0.0285	0.0341	0.0192	0.0002	0.0026
16	Wetland10	0.0004	0.0034	0.0517	0.0209	0.0026
17	Wetland11	0.0004	0.0046	0.0096	0.0070	0.0016
18	Wetland12	0.0032	0.0151	0.0003	0.0140	0.0016
19	Wetland13	0.0001	0.0135	0.2900	0.0005	0.0013
20	Wetland14	0.0139	0.0055	0.0214	0.0070	0.0192
21	Wetland15	0.0045	0.0010	0.0415	0.0002	0.0057
22	Wetland16	0.0004	0.0004	0.0096	0.0081	0.0003
23	Wetland17	0.1653	0.0372	0.0325	0.0027	0.0036
24	Wetland18	0.0001	0.0026	0.0090	0.0025	0.0003
25	Wetland19	0.0003	0.0101	0.0084	0.0065	0.0018
26	Wetland20	0.0060	0.0032	0.0279	0.0214	0.0111
27	Wetland21	0.0004	0.0002	0.0074	0.0295	0.0049
28	Wetland22	0.0072	0.1339	0.0059	0.0043	0.0047
29	Wetland23	0.0323	0.0214	0.0539	0.0020	0.0047
30	Wetland24	0.0001	0.0028	0.0006	0.0072	0.0003
31	Wetland25	0.0053	0.0036	0.0616	0.0063	0.0008
32	Wetland26	0.0167	0.0212	0.0068	0.0173	0.0049
33	Wetland27	0.0022	0.0022	0.0118	0.0018	0.0003
34	Wetland28	0.0010	0.0117	0.0074	0.0009	0.0005
35	Wetland29	0.0001	0.0046	0.0433	0.0011	0.0008
36	Wetland30	0.0003	0.0020	0.0149	0.0009	0.0036
37	Wetland31	0.0080	0.0006	0.0232	0.0176	0.0062
38	Wetland32	0.0014	0.0002	0.0019	0.0045	0.0041
39	Wetland33	0.0001	0.0040	0.0037	0.0018	0.0036
40	Wetland34	0.0003	0.0226	0.0053	0.0025	0.0013
41	Wetland35	0.0049	0.0026	0.0118	0.0113	0.0075
42	Wetland36	0.0004	0.0188	0.0433	0.0045	0.0008
43	Wetland37	0.0001	0.0057	0.0495	0.0045	0.0026
44	Wetland38	0.0031	0.0157	0.0145	0.0171	0.0047
45	Wetland39	0.0004	0.0044	0.0173	0.0011	0.0062
46	Wetland40	0.0108	0.0014	0.0257	0.0005	0.0029
47	Wetland41	0.0001	0.0010	0.0034	0.0002	0.0031
48	Wetland42	0.0010	0.0002	0.1675	0.0027	0.0008
49	Wetland43	0.0010	0.0030	0.0607	0.0061	0.0088
50	Wetland44	0.0006	0.0012	0.0077	0.0203	0.0060
51	Wetland45	0.0001	0.0105	0.0043	0.0306	0.0049
52	Wetland46	0.0067	0.0004	0.0375	0.0041	0.0013

Table A11. Muskingum routing parameter: routing length (m) between HRUs within the sub-basins in the dynamical wetland network for the 1980 wetland scenario.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	219	381	584	626	195
2	Stubble	1231	1997	2878	1936	1087
3	Grassland	498	543	1141	438	337
4	River Channel	961	483	719	478	271
5	Open Water	59	3	3	3	3
6	Woodland	806	1303	1874	1302	807
7	Wetland1	10	86	157	123	53
8	Wetland2	32	96	209	166	62
9	Wetland3	14	122	198	259	20
10	Wetland4	101	49	22	36	20
11	Wetland5	10	71	286	322	53
12	Wetland6	73	96	99	12	20
13	Wetland7	65	157	111	66	73
14	Wetland8	102	149	89	86	36
15	Wetland9	178	196	143	12	48
16	Wetland10	18	55	247	150	48
17	Wetland11	18	65	98	82	36
18	Wetland12	54	125	15	120	36
19	Wetland13	10	118	637	18	32
20	Wetland14	120	72	152	82	143
21	Wetland15	64	28	219	12	73
22	Wetland16	18	17	98	89	13
23	Wetland17	468	206	191	49	57
24	Wetland18	10	47	94	46	13
25	Wetland19	14	101	91	79	39
26	Wetland20	76	53	176	152	106
27	Wetland21	18	12	85	181	68
28	Wetland22	83	417	75	63	66
29	Wetland23	190	152	252	42	66
30	Wetland24	10	49	22	84	13
31	Wetland25	71	57	272	78	25
32	Wetland26	133	151	81	135	68
33	Wetland27	44	43	109	39	13
34	Wetland28	28	109	85	27	20
35	Wetland29	10	65	224	30	25
36	Wetland30	14	41	124	27	57
37	Wetland31	88	21	159	136	77
38	Wetland32	34	12	40	64	62
39	Wetland33	10	60	58	39	57
40	Wetland34	14	157	70	46	32
41	Wetland35	68	47	109	107	85
42	Wetland36	18	142	224	64	25
43	Wetland37	10	74	241	64	48
44	Wetland38	52	128	123	134	66
45	Wetland39	18	63	135	30	77
46	Wetland40	104	34	168	18	50
47	Wetland41	10	28	55	12	53
48	Wetland42	28	12	471	49	25
49	Wetland43	28	51	270	76	93
50	Wetland44	21	31	87	147	75
51	Wetland45	10	103	63	185	68
52	Wetland46	80	17	207	61	32

Table A12. Depressional storage capacity (mm) in the dynamical wetland network for the 1980 wetland scenario.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	61	67	69	67	69
2	Stubble	61	67	69	67	69
3	Grassland	86	100	95	104	102
4	River Channel	200	200	200	200	200
5	Open Water	317	374	395	386	366
6	Woodland	78	86	90	88	87
7	Wetland1	227	476	374	392	309
8	Wetland2	262	340	866	947	202
9	Wetland3	233	378	785	1069	195
10	Wetland4	325	307	307	336	230
11	Wetland5	226	318	927	952	250
12	Wetland6	269	423	300	261	201
13	Wetland7	428	739	228	323	244
14	Wetland8	326	989	358	561	219
15	Wetland9	710	960	365	333	263
16	Wetland10	247	382	794	437	313
17	Wetland11	244	332	306	463	249
18	Wetland12	290	389	231	572	265
19	Wetland13	227	351	955	389	205
20	Wetland14	317	373	341	380	244
21	Wetland15	249	299	937	277	288
22	Wetland16	235	249	483	396	202
23	Wetland17	1225	861	860	455	294
24	Wetland18	228	367	290	320	183
25	Wetland19	229	294	464	492	300
26	Wetland20	378	390	416	406	292
27	Wetland21	237	239	356	975	296
28	Wetland22	338	1044	270	397	302
29	Wetland23	982	972	1049	298	258
30	Wetland24	237	281	383	495	183
31	Wetland25	454	430	878	383	205
32	Wetland26	948	1081	406	592	371
33	Wetland27	336	339	374	288	190
34	Wetland28	252	387	337	324	406
35	Wetland29	232	367	955	294	219
36	Wetland30	228	398	379	326	302
37	Wetland31	260	240	532	557	304
38	Wetland32	404	281	299	383	257
39	Wetland33	265	362	310	400	276
40	Wetland34	325	918	452	349	199
41	Wetland35	268	307	273	417	237
42	Wetland36	292	396	1074	386	204
43	Wetland37	229	529	830	383	203
44	Wetland38	348	253	388	386	354
45	Wetland39	234	341	355	386	264
46	Wetland40	322	266	321	288	206
47	Wetland41	291	260	288	270	336
48	Wetland42	275	245	923	361	200
49	Wetland43	264	341	1043	346	346
50	Wetland44	371	341	407	476	370
51	Wetland45	235	417	313	1235	245
52	Wetland46	434	249	869	416	248

Table A13. HRU area (km^2) in the dynamical wetland network for the 1990 wetland scenario.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	0.0437	0.1173	0.2678	0.2911	0.0359
2	Stubble	0.8861	2.1569	4.4878	2.0669	0.7124
3	Grassland	0.1738	0.2029	0.7913	0.1371	0.0849
4	River Channel	0.0029	0.0108	0.0383	0.0141	0.0073
5	Open Water	0.0033	0.0000	0.0000	0.0000	0.0000
6	Woodland	0.3777	0.9242	1.8236	0.9239	0.3784
7	Wetland1	0.0001	0.0062	0.0156	0.0108	0.0022
8	Wetland2	0.0011	0.0077	0.0262	0.0185	0.0030
9	Wetland3	0.0002	0.0119	0.0239	0.0415	0.0004
10	Wetland4	0.0090	0.0023	0.0004	0.0012	0.0004
11	Wetland5	0.0001	0.0044	0.0467	0.0616	0.0022
12	Wetland6	0.0049	0.0077	0.0068	0.0002	0.0004
13	Wetland7	0.0041	0.0187	0.0083	0.0035	0.0041
14	Wetland8	0.0091	0.0169	0.0055	0.0056	0.0011
15	Wetland9	0.0250	0.0280	0.0132	0.0002	0.0019
16	Wetland10	0.0004	0.0028	0.0356	0.0154	0.0019
17	Wetland11	0.0004	0.0037	0.0066	0.0051	0.0011
18	Wetland12	0.0028	0.0124	0.0002	0.0103	0.0011
19	Wetland13	0.0001	0.0111	0.1997	0.0003	0.0009
20	Wetland14	0.0122	0.0046	0.0147	0.0051	0.0138
21	Wetland15	0.0039	0.0008	0.0286	0.0002	0.0041
22	Wetland16	0.0004	0.0003	0.0066	0.0060	0.0002
23	Wetland17	0.1454	0.0306	0.0224	0.0020	0.0026
24	Wetland18	0.0001	0.0021	0.0062	0.0018	0.0002
25	Wetland19	0.0002	0.0083	0.0058	0.0048	0.0013
26	Wetland20	0.0053	0.0026	0.0192	0.0157	0.0080
27	Wetland21	0.0004	0.0002	0.0051	0.0217	0.0035
28	Wetland22	0.0063	0.1100	0.0040	0.0031	0.0034
29	Wetland23	0.0284	0.0176	0.0371	0.0015	0.0034
30	Wetland24	0.0001	0.0023	0.0004	0.0053	0.0002
31	Wetland25	0.0047	0.0029	0.0424	0.0046	0.0006
32	Wetland26	0.0147	0.0174	0.0047	0.0127	0.0035
33	Wetland27	0.0020	0.0018	0.0081	0.0013	0.0002
34	Wetland28	0.0009	0.0096	0.0051	0.0007	0.0004
35	Wetland29	0.0001	0.0037	0.0298	0.0008	0.0006
36	Wetland30	0.0002	0.0016	0.0102	0.0007	0.0026
37	Wetland31	0.0070	0.0005	0.0160	0.0129	0.0045
38	Wetland32	0.0012	0.0002	0.0013	0.0033	0.0030
39	Wetland33	0.0001	0.0033	0.0026	0.0013	0.0026
40	Wetland34	0.0002	0.0186	0.0036	0.0018	0.0009
41	Wetland35	0.0043	0.0021	0.0081	0.0083	0.0054
42	Wetland36	0.0004	0.0155	0.0298	0.0033	0.0006
43	Wetland37	0.0001	0.0047	0.0341	0.0033	0.0019
44	Wetland38	0.0027	0.0129	0.0100	0.0126	0.0034
45	Wetland39	0.0004	0.0036	0.0119	0.0008	0.0045
46	Wetland40	0.0095	0.0011	0.0177	0.0003	0.0020
47	Wetland41	0.0001	0.0008	0.0023	0.0002	0.0022
48	Wetland42	0.0009	0.0002	0.1153	0.0020	0.0006
49	Wetland43	0.0009	0.0024	0.0418	0.0045	0.0063
50	Wetland44	0.0005	0.0010	0.0053	0.0149	0.0043
51	Wetland45	0.0001	0.0086	0.0030	0.0225	0.0035
52	Wetland46	0.0059	0.0003	0.0258	0.0030	0.0009

Table A14. Muskingum routing parameter: routing length (m) between HRUs within the sub-basins in the dynamical wetland network for the 1990 wetland scenario.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	225	389	616	645	202
2	Stubble	1263	2041	3030	1995	1123
3	Grassland	499	543	1141	438	337
4	River Channel	1245	579	865	568	300
5	Open Water	59	3	3	3	3
6	Woodland	807	1303	1874	1302	807
7	Wetland1	9	77	128	104	44
8	Wetland2	30	86	170	140	51
9	Wetland3	13	110	161	219	16
10	Wetland4	94	44	18	31	16
11	Wetland5	9	64	233	272	44
12	Wetland6	68	86	81	10	16
13	Wetland7	61	141	90	56	61
14	Wetland8	95	134	72	73	30
15	Wetland9	166	176	117	10	40
16	Wetland10	16	49	201	127	40
17	Wetland11	16	58	80	69	30
18	Wetland12	50	112	12	101	30
19	Wetland13	9	106	519	15	27
20	Wetland14	112	65	124	69	119
21	Wetland15	60	25	178	10	61
22	Wetland16	16	15	80	75	11
23	Wetland17	436	185	156	41	48
24	Wetland18	9	43	77	39	11
25	Wetland19	13	90	74	67	33
26	Wetland20	71	48	143	128	89
27	Wetland21	16	10	69	153	56
28	Wetland22	78	374	61	53	55
29	Wetland23	177	136	206	35	55
30	Wetland24	9	44	18	70	11
31	Wetland25	66	51	221	65	20
32	Wetland26	124	136	66	114	56
33	Wetland27	41	39	89	33	11
34	Wetland28	26	98	69	22	16
35	Wetland29	9	58	182	25	20
36	Wetland30	13	37	101	22	48
37	Wetland31	82	19	129	115	64
38	Wetland32	32	10	32	54	51
39	Wetland33	9	54	47	33	48
40	Wetland34	13	140	57	39	27
41	Wetland35	63	43	89	90	71
42	Wetland36	16	127	182	54	20
43	Wetland37	9	66	196	54	40
44	Wetland38	49	115	100	113	55
45	Wetland39	16	57	110	25	64
46	Wetland40	97	30	137	15	42
47	Wetland41	9	25	45	10	44
48	Wetland42	26	10	384	41	20
49	Wetland43	26	46	220	64	78
50	Wetland44	19	28	71	124	63
51	Wetland45	9	92	51	156	56
52	Wetland46	75	15	168	51	27

Table A15. Depressional storage capacity (mm) in the dynamical wetland network for the 1990 wetland scenario.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	61	67	69	67	69
2	Stubble	61	67	69	67	69
3	Grassland	86	100	95	104	102
4	River Channel	200	200	200	200	200
5	Open Water	317	374	395	386	366
6	Woodland	78	86	90	88	87
7	Wetland1	216	451	366	365	312
8	Wetland2	249	322	846	883	203
9	Wetland3	222	359	767	997	196
10	Wetland4	309	291	300	313	232
11	Wetland5	215	302	906	889	253
12	Wetland6	256	401	294	244	202
13	Wetland7	407	701	223	301	247
14	Wetland8	311	938	350	523	221
15	Wetland9	677	910	357	311	266
16	Wetland10	235	362	776	408	316
17	Wetland11	233	315	299	432	252
18	Wetland12	276	369	226	534	268
19	Wetland13	216	333	934	363	206
20	Wetland14	302	354	333	355	247
21	Wetland15	237	283	916	258	291
22	Wetland16	224	236	473	369	203
23	Wetland17	1167	816	840	424	297
24	Wetland18	217	348	284	298	184
25	Wetland19	219	279	453	459	303
26	Wetland20	360	370	406	379	295
27	Wetland21	226	226	348	910	299
28	Wetland22	322	990	264	371	305
29	Wetland23	935	922	1025	278	261
30	Wetland24	226	266	375	462	184
31	Wetland25	432	407	858	357	206
32	Wetland26	904	1025	397	553	374
33	Wetland27	320	321	366	269	191
34	Wetland28	240	367	330	303	410
35	Wetland29	221	348	934	274	221
36	Wetland30	217	377	370	304	305
37	Wetland31	248	227	520	519	307
38	Wetland32	385	266	293	357	260
39	Wetland33	253	343	303	373	279
40	Wetland34	309	871	442	325	200
41	Wetland35	255	291	267	390	239
42	Wetland36	279	376	1050	360	205
43	Wetland37	219	501	811	357	204
44	Wetland38	332	240	379	360	357
45	Wetland39	223	324	347	360	267
46	Wetland40	307	252	314	269	207
47	Wetland41	278	247	281	252	339
48	Wetland42	262	232	902	337	201
49	Wetland43	252	324	1019	323	349
50	Wetland44	353	324	398	444	373
51	Wetland45	224	395	306	1152	248
52	Wetland46	413	236	849	388	251

Table A16. HRU area (km^2) in the dynamical wetland network for the 2000 wetland scenario.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	0.0457	0.1218	0.2907	0.3057	0.0380
2	Stubble	0.9265	2.2394	4.8717	2.1708	0.7537
3	Grassland	0.1741	0.2029	0.7913	0.1371	0.0849
4	River Channel	0.0061	0.0164	0.0691	0.0247	0.0091
5	Open Water	0.0033	0.0000	0.0000	0.0000	0.0000
6	Woodland	0.3784	0.9242	1.8236	0.9240	0.3783
7	Wetland1	0.0001	0.0048	0.0085	0.0069	0.0014
8	Wetland2	0.0010	0.0060	0.0144	0.0118	0.0018
9	Wetland3	0.0002	0.0093	0.0131	0.0265	0.0002
10	Wetland4	0.0078	0.0018	0.0002	0.0007	0.0002
11	Wetland5	0.0001	0.0034	0.0256	0.0393	0.0014
12	Wetland6	0.0043	0.0060	0.0037	0.0001	0.0002
13	Wetland7	0.0035	0.0147	0.0046	0.0022	0.0025
14	Wetland8	0.0079	0.0133	0.0030	0.0036	0.0007
15	Wetland9	0.0216	0.0219	0.0072	0.0001	0.0011
16	Wetland10	0.0003	0.0022	0.0195	0.0098	0.0011
17	Wetland11	0.0003	0.0029	0.0036	0.0033	0.0007
18	Wetland12	0.0024	0.0097	0.0001	0.0066	0.0007
19	Wetland13	0.0001	0.0087	0.1094	0.0002	0.0006
20	Wetland14	0.0105	0.0036	0.0081	0.0033	0.0084
21	Wetland15	0.0034	0.0006	0.0156	0.0001	0.0025
22	Wetland16	0.0003	0.0003	0.0036	0.0038	0.0001
23	Wetland17	0.1254	0.0240	0.0123	0.0013	0.0016
24	Wetland18	0.0001	0.0017	0.0034	0.0012	0.0001
25	Wetland19	0.0002	0.0065	0.0032	0.0031	0.0008
26	Wetland20	0.0046	0.0020	0.0105	0.0100	0.0049
27	Wetland21	0.0003	0.0001	0.0028	0.0138	0.0022
28	Wetland22	0.0054	0.0862	0.0022	0.0020	0.0020
29	Wetland23	0.0245	0.0138	0.0203	0.0010	0.0020
30	Wetland24	0.0001	0.0018	0.0002	0.0034	0.0001
31	Wetland25	0.0040	0.0023	0.0232	0.0030	0.0003
32	Wetland26	0.0127	0.0136	0.0026	0.0081	0.0022
33	Wetland27	0.0017	0.0014	0.0044	0.0008	0.0001
34	Wetland28	0.0007	0.0075	0.0028	0.0004	0.0002
35	Wetland29	0.0001	0.0029	0.0163	0.0005	0.0003
36	Wetland30	0.0002	0.0013	0.0056	0.0004	0.0016
37	Wetland31	0.0061	0.0004	0.0088	0.0082	0.0027
38	Wetland32	0.0011	0.0001	0.0007	0.0021	0.0018
39	Wetland33	0.0001	0.0025	0.0014	0.0008	0.0016
40	Wetland34	0.0002	0.0145	0.0020	0.0012	0.0006
41	Wetland35	0.0037	0.0017	0.0044	0.0053	0.0033
42	Wetland36	0.0003	0.0121	0.0163	0.0021	0.0003
43	Wetland37	0.0001	0.0037	0.0187	0.0021	0.0011
44	Wetland38	0.0023	0.0101	0.0055	0.0080	0.0020
45	Wetland39	0.0003	0.0028	0.0065	0.0005	0.0027
46	Wetland40	0.0082	0.0009	0.0097	0.0002	0.0012
47	Wetland41	0.0001	0.0006	0.0013	0.0001	0.0014
48	Wetland42	0.0007	0.0001	0.0632	0.0013	0.0003
49	Wetland43	0.0007	0.0019	0.0229	0.0029	0.0039
50	Wetland44	0.0004	0.0008	0.0029	0.0095	0.0026
51	Wetland45	0.0001	0.0068	0.0016	0.0144	0.0022
52	Wetland46	0.0051	0.0003	0.0141	0.0019	0.0006

Table A17. Muskingum routing parameter: routing length (m) between HRUs within the sub-basins in the dynamical wetland network for the 2000 wetland scenario.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	231	398	645	663	208
2	Stubble	1294	2083	3167	2048	1158
3	Grassland	499	543	1141	438	337
4	River Channel	1219	565	905	605	295
5	Open Water	59	3	3	3	3
6	Woodland	807	1303	1874	1302	807
7	Wetland1	8	67	92	81	33
8	Wetland2	28	75	122	110	39
9	Wetland3	12	96	116	171	12
10	Wetland4	87	39	13	24	12
11	Wetland5	8	56	168	212	33
12	Wetland6	63	75	58	8	12
13	Wetland7	56	123	65	44	47
14	Wetland8	88	117	52	57	23
15	Wetland9	153	154	84	8	30
16	Wetland10	15	43	144	99	30
17	Wetland11	15	51	57	54	23
18	Wetland12	46	98	9	79	23
19	Wetland13	8	92	373	12	21
20	Wetland14	103	57	89	54	91
21	Wetland15	55	22	128	8	47
22	Wetland16	15	13	57	59	9
23	Wetland17	402	162	112	32	36
24	Wetland18	8	37	55	31	9
25	Wetland19	12	79	53	52	25
26	Wetland20	65	42	103	100	67
27	Wetland21	15	9	50	120	43
28	Wetland22	71	327	44	41	42
29	Wetland23	164	119	148	27	42
30	Wetland24	8	39	13	55	9
31	Wetland25	61	44	159	51	16
32	Wetland26	114	119	47	89	43
33	Wetland27	38	34	64	26	9
34	Wetland28	24	85	50	18	12
35	Wetland29	8	51	131	20	16
36	Wetland30	12	32	73	18	36
37	Wetland31	76	17	93	90	49
38	Wetland32	29	9	23	43	39
39	Wetland33	8	47	34	26	36
40	Wetland34	12	123	41	31	21
41	Wetland35	58	37	64	70	54
42	Wetland36	15	111	131	43	16
43	Wetland37	8	58	141	43	30
44	Wetland38	45	100	72	89	42
45	Wetland39	15	50	79	20	49
46	Wetland40	90	26	98	12	32
47	Wetland41	8	22	32	8	33
48	Wetland42	24	9	276	32	16
49	Wetland43	24	40	158	50	59
50	Wetland44	18	24	51	97	48
51	Wetland45	8	81	37	122	43
52	Wetland46	69	13	121	40	21

Table A18. Depressional storage capacity (mm) in the dynamical wetland network for the 2000 wetland scenario.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	61	67	69	67	69
2	Stubble	61	67	69	67	69
3	Grassland	86	100	95	104	102
4	River Channel	200	200	200	200	200
5	Open Water	317	374	395	386	366
6	Woodland	78	86	90	88	87
7	Wetland1	202	413	343	310	318
8	Wetland2	233	295	794	749	207
9	Wetland3	208	328	720	845	200
10	Wetland4	289	266	282	265	236
11	Wetland5	201	276	850	753	258
12	Wetland6	240	367	276	206	206
13	Wetland7	381	641	209	255	251
14	Wetland8	290	858	328	444	225
15	Wetland9	633	833	335	263	271
16	Wetland10	220	332	729	346	322
17	Wetland11	218	288	281	366	256
18	Wetland12	258	337	212	453	273
19	Wetland13	202	305	876	307	211
20	Wetland14	283	324	313	301	251
21	Wetland15	222	259	860	219	296
22	Wetland16	210	216	443	313	207
23	Wetland17	1091	747	789	360	302
24	Wetland18	203	318	266	253	188
25	Wetland19	204	255	426	389	309
26	Wetland20	337	338	381	321	300
27	Wetland21	211	207	326	771	305
28	Wetland22	301	906	248	314	311
29	Wetland23	875	844	962	236	266
30	Wetland24	211	244	352	391	188
31	Wetland25	404	373	806	303	211
32	Wetland26	845	938	373	469	381
33	Wetland27	299	294	343	228	195
34	Wetland28	224	336	309	256	418
35	Wetland29	207	318	876	233	225
36	Wetland30	203	345	347	258	311
37	Wetland31	232	208	488	440	313
38	Wetland32	360	244	275	303	265
39	Wetland33	236	314	284	317	284
40	Wetland34	289	797	415	276	204
41	Wetland35	239	266	250	330	243
42	Wetland36	261	344	985	305	209
43	Wetland37	204	459	761	303	208
44	Wetland38	310	219	356	305	364
45	Wetland39	209	296	325	305	272
46	Wetland40	287	230	295	228	212
47	Wetland41	260	226	264	213	345
48	Wetland42	245	213	847	286	205
49	Wetland43	235	296	957	273	356
50	Wetland44	330	296	374	377	380
51	Wetland45	210	362	287	977	252
52	Wetland46	387	216	797	329	255

Table A19. HRU area (km^2) in the dynamical wetland network for the 2008 wetland scenario.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	0.0462	0.1246	0.2932	0.3060	0.0382
2	Stubble	0.9356	2.2922	4.9142	2.1731	0.7581
3	Grassland	0.1743	0.2029	0.7914	0.1371	0.0849
4	River Channel	0.0141	0.0326	0.1010	0.0348	0.0129
5	Open Water	0.0033	0.0000	0.0000	0.0000	0.0000
6	Woodland	0.3787	0.9242	1.8238	0.9241	0.3784
7	Wetland1	0.0001	0.0038	0.0073	0.0065	0.0012
8	Wetland2	0.0009	0.0047	0.0123	0.0112	0.0016
9	Wetland3	0.0002	0.0073	0.0112	0.0251	0.0002
10	Wetland4	0.0073	0.0014	0.0002	0.0007	0.0002
11	Wetland5	0.0001	0.0027	0.0219	0.0372	0.0012
12	Wetland6	0.0040	0.0047	0.0032	0.0001	0.0002
13	Wetland7	0.0033	0.0115	0.0039	0.0021	0.0022
14	Wetland8	0.0074	0.0104	0.0026	0.0034	0.0006
15	Wetland9	0.0203	0.0172	0.0062	0.0001	0.0010
16	Wetland10	0.0003	0.0017	0.0167	0.0093	0.0010
17	Wetland11	0.0003	0.0023	0.0031	0.0031	0.0006
18	Wetland12	0.0023	0.0076	0.0001	0.0062	0.0006
19	Wetland13	0.0001	0.0068	0.0937	0.0002	0.0005
20	Wetland14	0.0099	0.0028	0.0069	0.0031	0.0074
21	Wetland15	0.0032	0.0005	0.0134	0.0001	0.0022
22	Wetland16	0.0003	0.0002	0.0031	0.0036	0.0001
23	Wetland17	0.1178	0.0188	0.0105	0.0012	0.0014
24	Wetland18	0.0001	0.0013	0.0029	0.0011	0.0001
25	Wetland19	0.0002	0.0051	0.0027	0.0029	0.0007
26	Wetland20	0.0043	0.0016	0.0090	0.0095	0.0043
27	Wetland21	0.0003	0.0001	0.0024	0.0131	0.0019
28	Wetland22	0.0051	0.0676	0.0019	0.0019	0.0018
29	Wetland23	0.0230	0.0108	0.0174	0.0009	0.0018
30	Wetland24	0.0001	0.0014	0.0002	0.0032	0.0001
31	Wetland25	0.0038	0.0018	0.0199	0.0028	0.0003
32	Wetland26	0.0119	0.0107	0.0022	0.0077	0.0019
33	Wetland27	0.0016	0.0011	0.0038	0.0008	0.0001
34	Wetland28	0.0007	0.0059	0.0024	0.0004	0.0002
35	Wetland29	0.0001	0.0023	0.0140	0.0005	0.0003
36	Wetland30	0.0002	0.0010	0.0048	0.0004	0.0014
37	Wetland31	0.0057	0.0003	0.0075	0.0078	0.0024
38	Wetland32	0.0010	0.0001	0.0006	0.0020	0.0016
39	Wetland33	0.0001	0.0020	0.0012	0.0008	0.0014
40	Wetland34	0.0002	0.0114	0.0017	0.0011	0.0005
41	Wetland35	0.0035	0.0013	0.0038	0.0050	0.0029
42	Wetland36	0.0003	0.0095	0.0140	0.0020	0.0003
43	Wetland37	0.0001	0.0029	0.0160	0.0020	0.0010
44	Wetland38	0.0022	0.0079	0.0047	0.0076	0.0018
45	Wetland39	0.0003	0.0022	0.0056	0.0005	0.0024
46	Wetland40	0.0077	0.0007	0.0083	0.0002	0.0011
47	Wetland41	0.0001	0.0005	0.0011	0.0001	0.0012
48	Wetland42	0.0007	0.0001	0.0541	0.0012	0.0003
49	Wetland43	0.0007	0.0015	0.0196	0.0027	0.0034
50	Wetland44	0.0004	0.0006	0.0025	0.0090	0.0023
51	Wetland45	0.0001	0.0053	0.0014	0.0136	0.0019
52	Wetland46	0.0048	0.0002	0.0121	0.0018	0.0005

Table A20. Muskingum routing parameter: routing length (m) between HRUs within the sub-basins in the dynamical wetland network for the 2008 wetland scenario.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	232	403	648	664	209
2	Stubble	1301	2109	3182	2049	1162
3	Grassland	499	543	1141	438	337
4	River Channel	2013	854	1135	742	365
5	Open Water	59	3	3	3	3
6	Woodland	808	1303	1875	1302	807
7	Wetland1	8	59	84	79	31
8	Wetland2	27	66	112	106	36
9	Wetland3	12	84	106	166	12
10	Wetland4	84	34	12	23	12
11	Wetland5	8	49	154	206	31
12	Wetland6	60	66	53	8	12
13	Wetland7	54	108	60	42	43
14	Wetland8	85	102	48	55	21
15	Wetland9	148	135	77	8	28
16	Wetland10	15	38	133	96	28
17	Wetland11	15	45	53	53	21
18	Wetland12	45	86	8	77	21
19	Wetland13	8	81	342	12	19
20	Wetland14	99	50	82	53	85
21	Wetland15	53	19	117	8	43
22	Wetland16	15	12	53	57	8
23	Wetland17	388	141	103	31	34
24	Wetland18	8	33	51	30	8
25	Wetland19	12	69	49	51	23
26	Wetland20	63	36	94	97	63
27	Wetland21	15	8	46	116	40
28	Wetland22	69	286	40	40	39
29	Wetland23	158	104	136	27	39
30	Wetland24	8	34	12	53	8
31	Wetland25	59	39	146	50	15
32	Wetland26	110	104	43	87	40
33	Wetland27	36	30	59	25	8
34	Wetland28	23	75	46	17	12
35	Wetland29	8	45	120	19	15
36	Wetland30	12	28	67	17	34
37	Wetland31	73	15	85	87	46
38	Wetland32	28	8	21	41	36
39	Wetland33	8	41	31	25	34
40	Wetland34	12	107	38	30	19
41	Wetland35	56	33	59	68	51
42	Wetland36	15	97	120	41	15
43	Wetland37	8	51	129	41	28
44	Wetland38	43	88	66	86	39
45	Wetland39	15	43	73	19	46
46	Wetland40	87	23	90	12	30
47	Wetland41	8	19	30	8	31
48	Wetland42	23	8	253	31	15
49	Wetland43	23	35	145	49	55
50	Wetland44	17	21	47	94	45
51	Wetland45	8	71	34	118	40
52	Wetland46	67	12	111	39	19

Table A21. Depressional storage capacity (mm) in the dynamical wetland network for the 2008 wetland scenario.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	61	67	69	67	69
2	Stubble	61	67	69	67	69
3	Grassland	86	100	95	104	102
4	River Channel	200	200	200	200	200
5	Open Water	317	374	395	386	366
6	Woodland	78	86	90	88	87
7	Wetland1	183	371	325	273	311
8	Wetland2	211	265	752	660	203
9	Wetland3	188	295	682	745	196
10	Wetland4	262	239	267	234	231
11	Wetland5	182	248	805	664	252
12	Wetland6	217	330	261	182	202
13	Wetland7	345	576	198	225	246
14	Wetland8	263	771	311	391	220
15	Wetland9	573	748	317	232	265
16	Wetland10	199	298	690	305	315
17	Wetland11	197	259	266	323	251
18	Wetland12	234	303	201	399	267
19	Wetland13	183	274	830	271	206
20	Wetland14	256	291	296	265	246
21	Wetland15	201	233	814	193	290
22	Wetland16	190	194	420	276	203
23	Wetland17	988	671	747	317	296
24	Wetland18	184	286	252	223	184
25	Wetland19	185	229	403	343	302
26	Wetland20	305	304	361	283	294
27	Wetland21	191	186	309	680	298
28	Wetland22	273	814	235	277	304
29	Wetland23	792	758	911	208	260
30	Wetland24	191	219	333	345	184
31	Wetland25	366	335	763	267	206
32	Wetland26	765	843	353	413	373
33	Wetland27	271	264	325	201	191
34	Wetland28	203	302	293	226	409
35	Wetland29	187	286	830	205	220
36	Wetland30	184	310	329	227	304
37	Wetland31	210	187	462	388	306
38	Wetland32	326	219	260	267	259
39	Wetland33	214	282	269	279	278
40	Wetland34	262	716	393	243	200
41	Wetland35	216	239	237	291	238
42	Wetland36	236	309	933	269	205
43	Wetland37	185	412	721	267	204
44	Wetland38	281	197	337	269	356
45	Wetland39	189	266	308	269	266
46	Wetland40	260	207	279	201	207
47	Wetland41	235	203	250	188	338
48	Wetland42	222	191	802	252	201
49	Wetland43	213	266	906	241	348
50	Wetland44	299	266	354	332	372
51	Wetland45	190	325	272	861	247
52	Wetland46	350	194	755	290	250

Table A22. HRU area (km^2) in the dynamical wetland network for the “Loss Ceiling” wetland scenario.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	0.0213	1.8155	0.0442	0.0643	0.3325
2	Stubble	0.4306	33.3914	0.7415	0.4565	6.5916
3	Grassland	0.0688	2.6736	0.1101	0.0266	0.6851
4	River Channel	0.0075	0.5145	0.0147	0.0073	0.1065
5	Open Water	0.0013	0.0000	0.0000	0.0000	0.0000
6	Woodland	0.1495	12.1783	0.2538	0.1794	3.0532
7	Wetland1	0.00001	0.00001	0.00002	0.00005	0.00001
8	Wetland2	0.00012	0.00001	0.00004	0.00009	0.00001
9	Wetland3	0.00003	0.00001	0.00003	0.00021	0.00001
10	Wetland4	0.00100	0.00001	0.00000	0.00001	0.00001
11	Wetland5	0.00001	0.00001	0.00007	0.00031	0.00001
12	Wetland6	0.00055	0.00001	0.00001	0.00000	0.00001
13	Wetland7	0.00045	0.00001	0.00001	0.00002	0.00001
14	Wetland8	0.00102	0.00001	0.00001	0.00003	0.00001
15	Wetland9	0.00279	0.00001	0.00002	0.00000	0.00001
16	Wetland10	0.00004	0.00001	0.00005	0.00008	0.00001
17	Wetland11	0.00004	0.00001	0.00001	0.00003	0.00001
18	Wetland12	0.00032	0.00001	0.00000	0.00005	0.00001
19	Wetland13	0.00001	0.00001	0.00029	0.00000	0.00001
20	Wetland14	0.00136	0.00001	0.00002	0.00003	0.00001
21	Wetland15	0.00044	0.00001	0.00004	0.00000	0.00001
22	Wetland16	0.00004	0.00001	0.00001	0.00003	0.00001
23	Wetland17	0.01619	0.00001	0.00003	0.00001	0.00001
24	Wetland18	0.00001	0.00001	0.00001	0.00001	0.00001
25	Wetland19	0.00003	0.00001	0.00001	0.00002	0.00001
26	Wetland20	0.00059	0.00001	0.00003	0.00008	0.00001
27	Wetland21	0.00004	0.00001	0.00001	0.00011	0.00001
28	Wetland22	0.00070	0.00001	0.00001	0.00002	0.00001
29	Wetland23	0.00316	0.00001	0.00005	0.00001	0.00001
30	Wetland24	0.00001	0.00001	0.00000	0.00003	0.00001
31	Wetland25	0.00052	0.00001	0.00006	0.00002	0.00001
32	Wetland26	0.00164	0.00001	0.00001	0.00006	0.00001
33	Wetland27	0.00022	0.00001	0.00001	0.00001	0.00001
34	Wetland28	0.00010	0.00001	0.00001	0.00000	0.00001
35	Wetland29	0.00001	0.00001	0.00004	0.00000	0.00001
36	Wetland30	0.00003	0.00001	0.00001	0.00000	0.00001
37	Wetland31	0.00078	0.00001	0.00002	0.00006	0.00001
38	Wetland32	0.00014	0.00001	0.00000	0.00002	0.00001
39	Wetland33	0.00001	0.00001	0.00000	0.00001	0.00001
40	Wetland34	0.00003	0.00001	0.00001	0.00001	0.00001
41	Wetland35	0.00048	0.00001	0.00001	0.00004	0.00001
42	Wetland36	0.00004	0.00001	0.00004	0.00002	0.00001
43	Wetland37	0.00001	0.00001	0.00005	0.00002	0.00001
44	Wetland38	0.00030	0.00001	0.00001	0.00006	0.00001
45	Wetland39	0.00004	0.00001	0.00002	0.00000	0.00001
46	Wetland40	0.00106	0.00001	0.00003	0.00000	0.00001
47	Wetland41	0.00001	0.00001	0.00000	0.00000	0.00001
48	Wetland42	0.00010	0.00001	0.00017	0.00001	0.00001
49	Wetland43	0.00010	0.00001	0.00006	0.00002	0.00001
50	Wetland44	0.00005	0.00001	0.00001	0.00007	0.00001
51	Wetland45	0.00001	0.00001	0.00000	0.00011	0.00001
52	Wetland46	0.00066	0.00001	0.00004	0.00001	0.00001

Table A23. Muskingum routing parameter: routing length (m) between HRUs within the sub-basins in the dynamical wetland network for the “Loss Ceiling” wetland scenario.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	151	1785	226	279	695
2	Stubble	856	8939	1148	884	3727
3	Grassland	301	2218	389	179	1055
4	River Channel	2714	1023	1187	808	373
5	Open Water	35	3	3	3	3
6	Woodland	491	5183	652	541	2470
7	Wetland1	3	2	4	6	2
8	Wetland2	9	2	5	8	2
9	Wetland3	4	2	4	12	2
10	Wetland4	28	2	0	2	2
11	Wetland5	3	2	6	15	2
12	Wetland6	20	2	2	1	2
13	Wetland7	18	2	2	3	2
14	Wetland8	28	2	2	4	2
15	Wetland9	50	2	3	1	2
16	Wetland10	5	2	6	7	2
17	Wetland11	5	2	2	4	2
18	Wetland12	15	2	0	6	2
19	Wetland13	3	2	14	1	2
20	Wetland14	33	2	3	4	2
21	Wetland15	18	2	5	1	2
22	Wetland16	5	2	2	4	2
23	Wetland17	130	2	4	2	2
24	Wetland18	3	2	2	2	2
25	Wetland19	4	2	2	4	2
26	Wetland20	21	2	4	7	2
27	Wetland21	5	2	2	8	2
28	Wetland22	23	2	2	3	2
29	Wetland23	53	2	6	2	2
30	Wetland24	3	2	0	4	2
31	Wetland25	20	2	6	4	2
32	Wetland26	37	2	2	6	2
33	Wetland27	12	2	2	2	2
34	Wetland28	8	2	2	1	2
35	Wetland29	3	2	5	1	2
36	Wetland30	4	2	3	1	2
37	Wetland31	25	2	4	6	2
38	Wetland32	9	2	1	3	2
39	Wetland33	3	2	1	2	2
40	Wetland34	4	2	2	2	2
41	Wetland35	19	2	2	5	2
42	Wetland36	5	2	5	3	2
43	Wetland37	3	2	5	3	2
44	Wetland38	15	2	3	6	2
45	Wetland39	5	2	3	1	2
46	Wetland40	29	2	4	1	2
47	Wetland41	3	2	1	1	2
48	Wetland42	8	2	11	2	2
49	Wetland43	8	2	6	3	2
50	Wetland44	6	2	2	7	2
51	Wetland45	3	2	1	8	2
52	Wetland46	22	2	5	3	2

Table A24. Depressional storage capacity (mm) in the dynamical wetland network for the “Loss Ceiling” wetland scenario.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	61	67	69	67	69
2	Stubble	61	67	69	67	69
3	Grassland	86	100	95	104	102
4	River Channel	200	200	200	200	200
5	Open Water	317	374	395	386	366
6	Woodland	78	86	90	88	87
7	Wetland1	109	0	125	127	0
8	Wetland2	125	0	288	307	0
9	Wetland3	112	0	261	347	0
10	Wetland4	156	0	102	109	0
11	Wetland5	108	0	309	309	0
12	Wetland6	129	0	100	85	0
13	Wetland7	205	0	76	105	0
14	Wetland8	156	0	119	182	0
15	Wetland9	341	0	121	108	0
16	Wetland10	118	0	264	142	0
17	Wetland11	117	0	102	150	0
18	Wetland12	139	0	77	186	0
19	Wetland13	109	0	318	126	0
20	Wetland14	152	0	113	123	0
21	Wetland15	120	0	312	90	0
22	Wetland16	113	0	161	128	0
23	Wetland17	588	0	286	147	0
24	Wetland18	109	0	97	104	0
25	Wetland19	110	0	154	160	0
26	Wetland20	181	0	138	132	0
27	Wetland21	114	0	118	316	0
28	Wetland22	162	0	90	129	0
29	Wetland23	471	0	349	97	0
30	Wetland24	114	0	128	160	0
31	Wetland25	218	0	292	124	0
32	Wetland26	455	0	135	192	0
33	Wetland27	161	0	125	93	0
34	Wetland28	121	0	112	105	0
35	Wetland29	111	0	318	95	0
36	Wetland30	109	0	126	106	0
37	Wetland31	125	0	177	180	0
38	Wetland32	194	0	100	124	0
39	Wetland33	127	0	103	130	0
40	Wetland34	156	0	151	113	0
41	Wetland35	128	0	91	135	0
42	Wetland36	140	0	358	125	0
43	Wetland37	110	0	276	124	0
44	Wetland38	167	0	129	125	0
45	Wetland39	112	0	118	125	0
46	Wetland40	155	0	107	93	0
47	Wetland41	140	0	96	87	0
48	Wetland42	132	0	307	117	0
49	Wetland43	127	0	347	112	0
50	Wetland44	178	0	136	154	0
51	Wetland45	113	0	104	400	0
52	Wetland46	208	0	289	135	0

Table A25. HRU area (km^2) in the dynamical wetland network for the “Fully Drained” wetland scenario.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	0.0213	1.8155	0.0442	0.0643	0.3325
2	Stubble	0.4306	33.3914	0.7415	0.4565	6.5916
3	Grassland	0.0688	2.6736	0.1101	0.0266	0.6851
4	River Channel	0.0075	0.5145	0.0147	0.0073	0.1065
5	Open Water	0.0000	0.0000	0.0000	0.0000	0.0000
6	Woodland	0.1495	12.1783	0.2538	0.1794	3.0532
7	Wetland1	0.00001	0.00001	0.00001	0.00001	0.00001
8	Wetland2	0.00001	0.00001	0.00001	0.00001	0.00001
9	Wetland3	0.00001	0.00001	0.00001	0.00001	0.00001
10	Wetland4	0.00001	0.00001	0.00001	0.00001	0.00001
11	Wetland5	0.00001	0.00001	0.00001	0.00001	0.00001
12	Wetland6	0.00001	0.00001	0.00001	0.00001	0.00001
13	Wetland7	0.00001	0.00001	0.00001	0.00001	0.00001
14	Wetland8	0.00001	0.00001	0.00001	0.00001	0.00001
15	Wetland9	0.00001	0.00001	0.00001	0.00001	0.00001
16	Wetland10	0.00001	0.00001	0.00001	0.00001	0.00001
17	Wetland11	0.00001	0.00001	0.00001	0.00001	0.00001
18	Wetland12	0.00001	0.00001	0.00001	0.00001	0.00001
19	Wetland13	0.00001	0.00001	0.00001	0.00001	0.00001
20	Wetland14	0.00001	0.00001	0.00001	0.00001	0.00001
21	Wetland15	0.00001	0.00001	0.00001	0.00001	0.00001
22	Wetland16	0.00001	0.00001	0.00001	0.00001	0.00001
23	Wetland17	0.00001	0.00001	0.00001	0.00001	0.00001
24	Wetland18	0.00001	0.00001	0.00001	0.00001	0.00001
25	Wetland19	0.00001	0.00001	0.00001	0.00001	0.00001
26	Wetland20	0.00001	0.00001	0.00001	0.00001	0.00001
27	Wetland21	0.00001	0.00001	0.00001	0.00001	0.00001
28	Wetland22	0.00001	0.00001	0.00001	0.00001	0.00001
29	Wetland23	0.00001	0.00001	0.00001	0.00001	0.00001
30	Wetland24	0.00001	0.00001	0.00001	0.00001	0.00001
31	Wetland25	0.00001	0.00001	0.00001	0.00001	0.00001
32	Wetland26	0.00001	0.00001	0.00001	0.00001	0.00001
33	Wetland27	0.00001	0.00001	0.00001	0.00001	0.00001
34	Wetland28	0.00001	0.00001	0.00001	0.00001	0.00001
35	Wetland29	0.00001	0.00001	0.00001	0.00001	0.00001
36	Wetland30	0.00001	0.00001	0.00001	0.00001	0.00001
37	Wetland31	0.00001	0.00001	0.00001	0.00001	0.00001
38	Wetland32	0.00001	0.00001	0.00001	0.00001	0.00001
39	Wetland33	0.00001	0.00001	0.00001	0.00001	0.00001
40	Wetland34	0.00001	0.00001	0.00001	0.00001	0.00001
41	Wetland35	0.00001	0.00001	0.00001	0.00001	0.00001
42	Wetland36	0.00001	0.00001	0.00001	0.00001	0.00001
43	Wetland37	0.00001	0.00001	0.00001	0.00001	0.00001
44	Wetland38	0.00001	0.00001	0.00001	0.00001	0.00001
45	Wetland39	0.00001	0.00001	0.00001	0.00001	0.00001
46	Wetland40	0.00001	0.00001	0.00001	0.00001	0.00001
47	Wetland41	0.00001	0.00001	0.00001	0.00001	0.00001
48	Wetland42	0.00001	0.00001	0.00001	0.00001	0.00001
49	Wetland43	0.00001	0.00001	0.00001	0.00001	0.00001
50	Wetland44	0.00001	0.00001	0.00001	0.00001	0.00001
51	Wetland45	0.00001	0.00001	0.00001	0.00001	0.00001
52	Wetland46	0.00001	0.00001	0.00001	0.00001	0.00001

Table A26. Muskingum routing parameter: routing length (m) between HRUs within the sub-basins in the dynamical wetland network for the “Fully Drained” wetland scenario.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	151	1785	226	279	695
2	Stubble	856	8939	1148	884	3727
3	Grassland	301	2218	389	179	1055
4	River Channel	3311	1023	1190	814	373
5	Open Water	3	3	3	3	3
6	Woodland	491	5183	652	541	2470
7	Wetland1	2	2	2	2	2
8	Wetland2	2	2	2	2	2
9	Wetland3	2	2	2	2	2
10	Wetland4	2	2	2	2	2
11	Wetland5	2	2	2	2	2
12	Wetland6	2	2	2	2	2
13	Wetland7	2	2	2	2	2
14	Wetland8	2	2	2	2	2
15	Wetland9	2	2	2	2	2
16	Wetland10	2	2	2	2	2
17	Wetland11	2	2	2	2	2
18	Wetland12	2	2	2	2	2
19	Wetland13	2	2	2	2	2
20	Wetland14	2	2	2	2	2
21	Wetland15	2	2	2	2	2
22	Wetland16	2	2	2	2	2
23	Wetland17	2	2	2	2	2
24	Wetland18	2	2	2	2	2
25	Wetland19	2	2	2	2	2
26	Wetland20	2	2	2	2	2
27	Wetland21	2	2	2	2	2
28	Wetland22	2	2	2	2	2
29	Wetland23	2	2	2	2	2
30	Wetland24	2	2	2	2	2
31	Wetland25	2	2	2	2	2
32	Wetland26	2	2	2	2	2
33	Wetland27	2	2	2	2	2
34	Wetland28	2	2	2	2	2
35	Wetland29	2	2	2	2	2
36	Wetland30	2	2	2	2	2
37	Wetland31	2	2	2	2	2
38	Wetland32	2	2	2	2	2
39	Wetland33	2	2	2	2	2
40	Wetland34	2	2	2	2	2
41	Wetland35	2	2	2	2	2
42	Wetland36	2	2	2	2	2
43	Wetland37	2	2	2	2	2
44	Wetland38	2	2	2	2	2
45	Wetland39	2	2	2	2	2
46	Wetland40	2	2	2	2	2
47	Wetland41	2	2	2	2	2
48	Wetland42	2	2	2	2	2
49	Wetland43	2	2	2	2	2
50	Wetland44	2	2	2	2	2
51	Wetland45	2	2	2	2	2
52	Wetland46	2	2	2	2	2

Table A27. Depressional storage capacity (mm) in the dynamical wetland network for the “Fully Drained” wetland scenario.

		Sub-basin				
HRU #	HRU Name	1	2	3	4	5
1	Fallow	61	67	69	67	69
2	Stubble	61	67	69	67	69
3	Grassland	86	100	95	104	102
4	River Channel	200	200	200	200	200
5	Open Water	317	374	395	386	366
6	Woodland	78	86	90	88	87
7	Wetland1	0	0	0	0	0
8	Wetland2	0	0	0	0	0
9	Wetland3	0	0	0	0	0
10	Wetland4	0	0	0	0	0
11	Wetland5	0	0	0	0	0
12	Wetland6	0	0	0	0	0
13	Wetland7	0	0	0	0	0
14	Wetland8	0	0	0	0	0
15	Wetland9	0	0	0	0	0
16	Wetland10	0	0	0	0	0
17	Wetland11	0	0	0	0	0
18	Wetland12	0	0	0	0	0
19	Wetland13	0	0	0	0	0
20	Wetland14	0	0	0	0	0
21	Wetland15	0	0	0	0	0
22	Wetland16	0	0	0	0	0
23	Wetland17	0	0	0	0	0
24	Wetland18	0	0	0	0	0
25	Wetland19	0	0	0	0	0
26	Wetland20	0	0	0	0	0
27	Wetland21	0	0	0	0	0
28	Wetland22	0	0	0	0	0
29	Wetland23	0	0	0	0	0
30	Wetland24	0	0	0	0	0
31	Wetland25	0	0	0	0	0
32	Wetland26	0	0	0	0	0
33	Wetland27	0	0	0	0	0
34	Wetland28	0	0	0	0	0
35	Wetland29	0	0	0	0	0
36	Wetland30	0	0	0	0	0
37	Wetland31	0	0	0	0	0
38	Wetland32	0	0	0	0	0
39	Wetland33	0	0	0	0	0
40	Wetland34	0	0	0	0	0
41	Wetland35	0	0	0	0	0
42	Wetland36	0	0	0	0	0
43	Wetland37	0	0	0	0	0
44	Wetland38	0	0	0	0	0
45	Wetland39	0	0	0	0	0
46	Wetland40	0	0	0	0	0
47	Wetland41	0	0	0	0	0
48	Wetland42	0	0	0	0	0
49	Wetland43	0	0	0	0	0
50	Wetland44	0	0	0	0	0
51	Wetland45	0	0	0	0	0
52	Wetland46	0	0	0	0	0

Appendix 3: Revised PHM-CRHM simulated hydrographs for the wetland scenarios in Smith Creek.

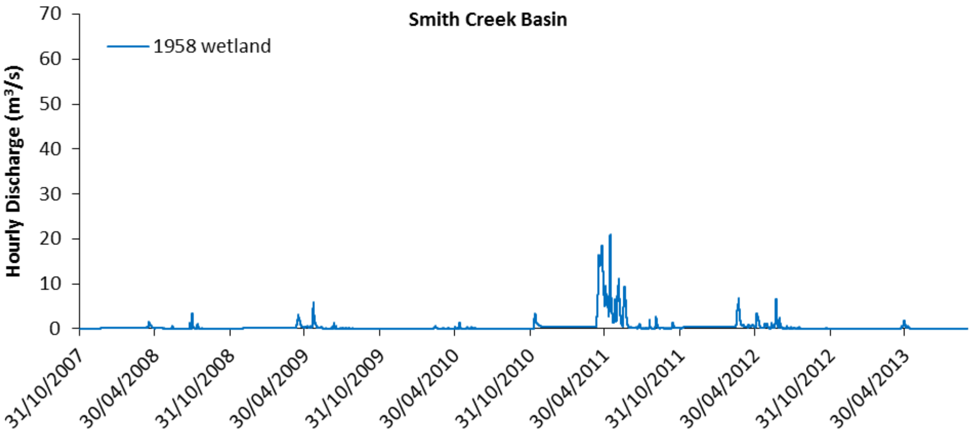

Figure A1. Simulated hydrograph for the 1958 wetland scenario in Smith Creek sub-basin 1.

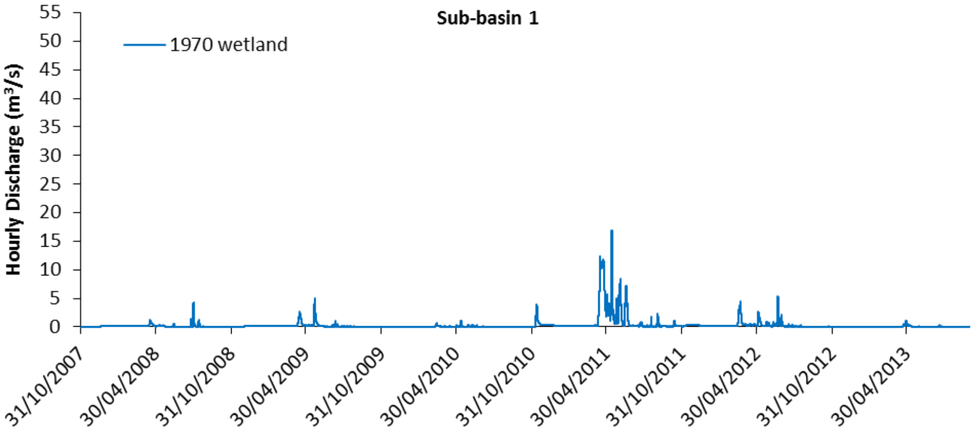

Figure A2. Simulated hydrograph for the 1970 wetland scenario in Smith Creek sub-basin 1.

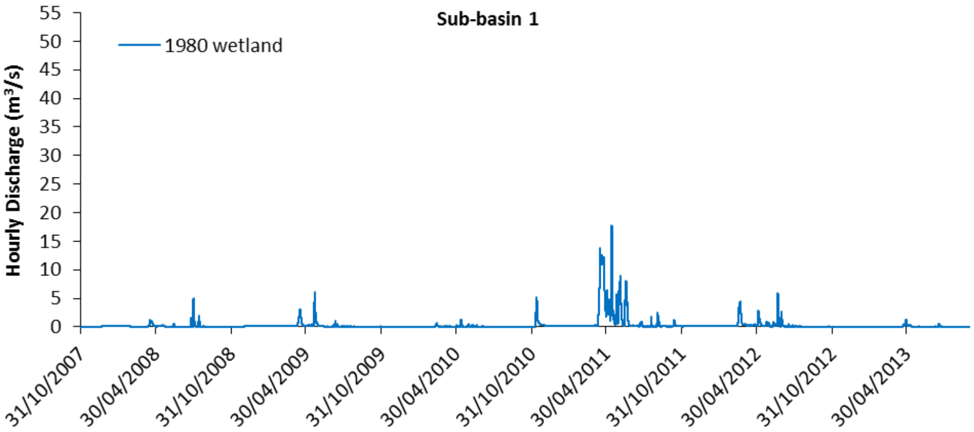

Figure A3. Simulated hydrograph for the 1980 wetland scenario in Smith Creek sub-basin 1.

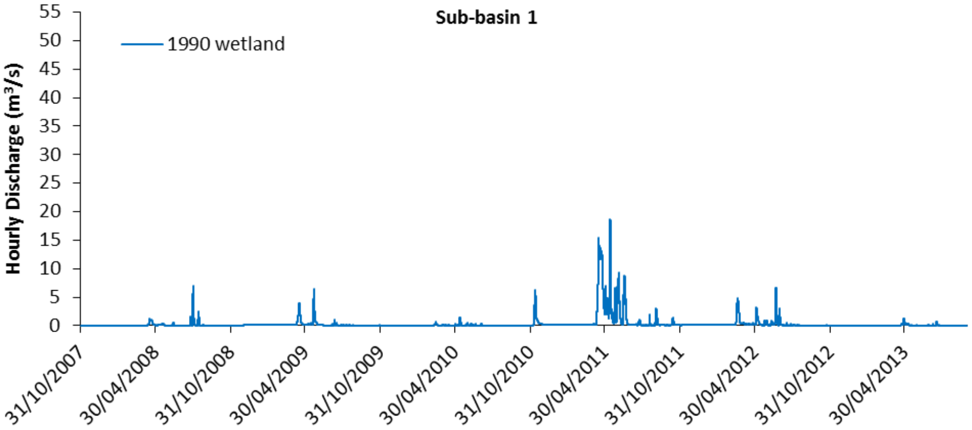

Figure A4. Simulated hydrograph for the 1990 wetland scenario in Smith Creek sub-basin 1.

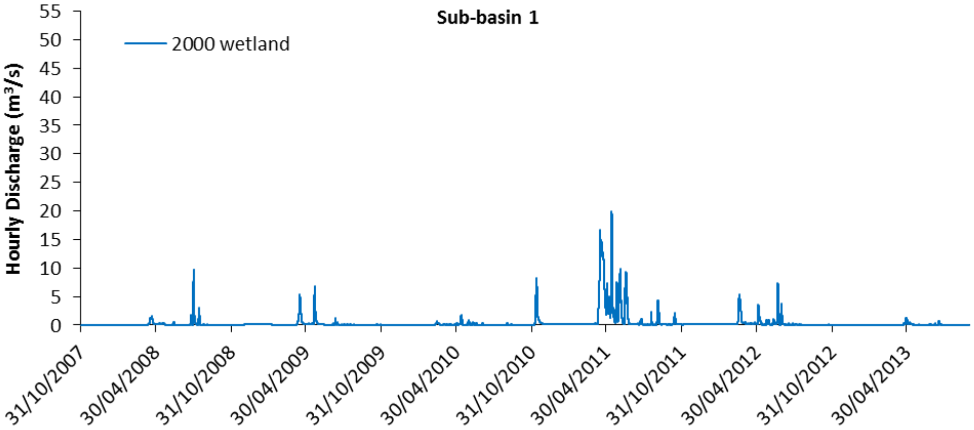

Figure A5. Simulated hydrograph for the 2000 wetland scenario in Smith Creek sub-basin 1.

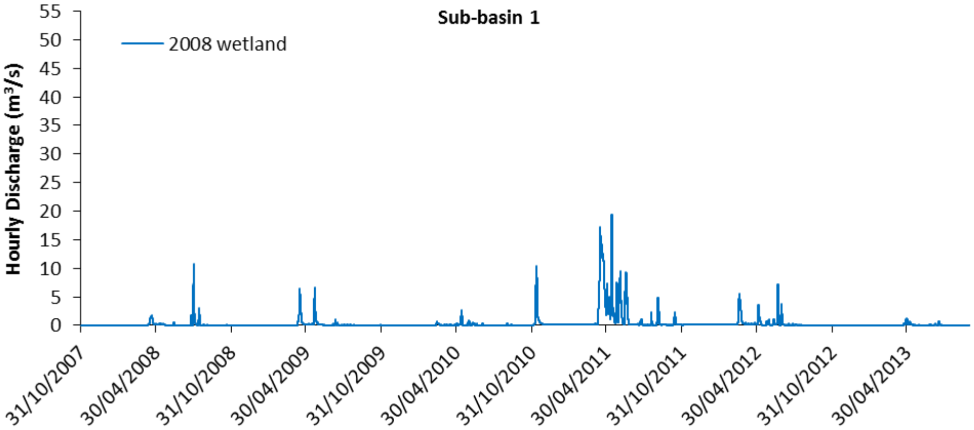

Figure A6. Simulated hydrograph for the 2008 wetland scenario in Smith Creek sub-basin 1.

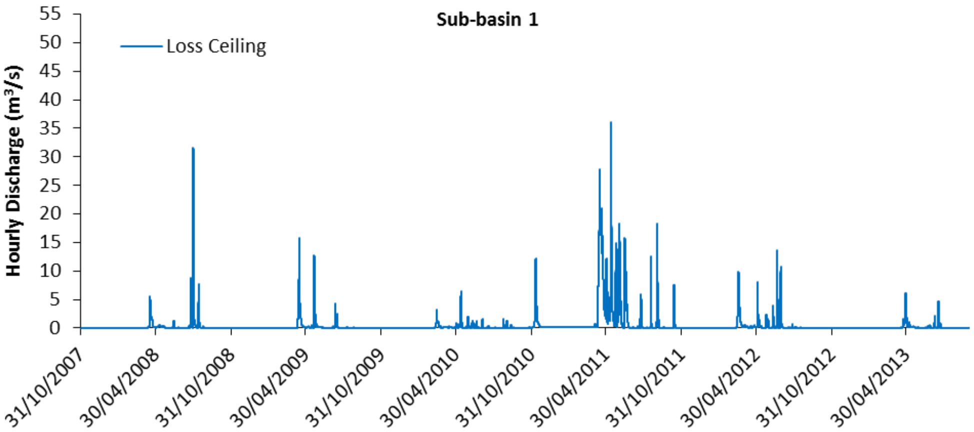

Figure A7. Simulated hydrograph for the “Loss Celing” wetland scenario in Smith Creek sub-basin 1.

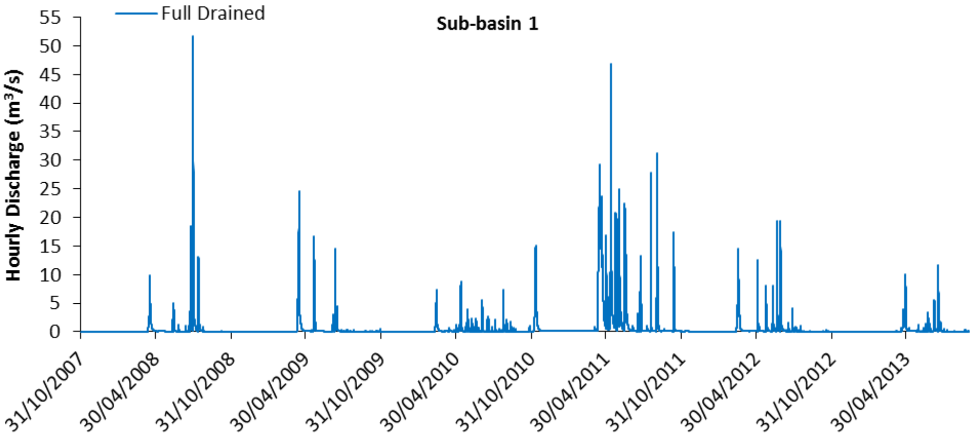

Figure A8. Simulated hydrograph for the “Full Drained” wetland scenario in Smith Creek sub-basin 1.

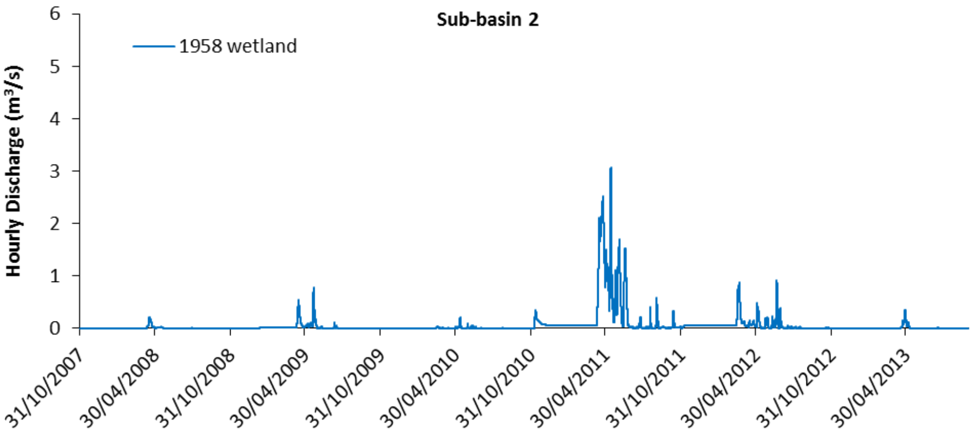

Figure A9. Simulated hydrograph for the 1958 wetland scenario in Smith Creek sub-basin 2.

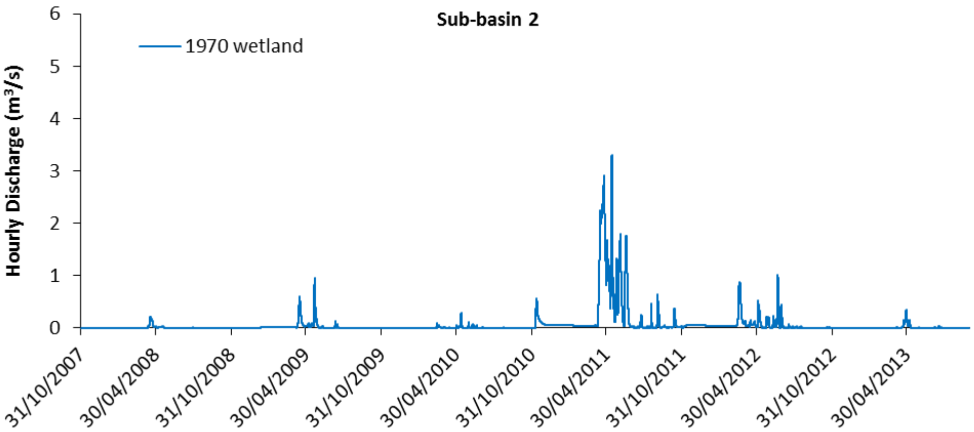

Figure A10. Simulated hydrograph for the 1970 wetland scenario in Smith Creek sub-basin 2.

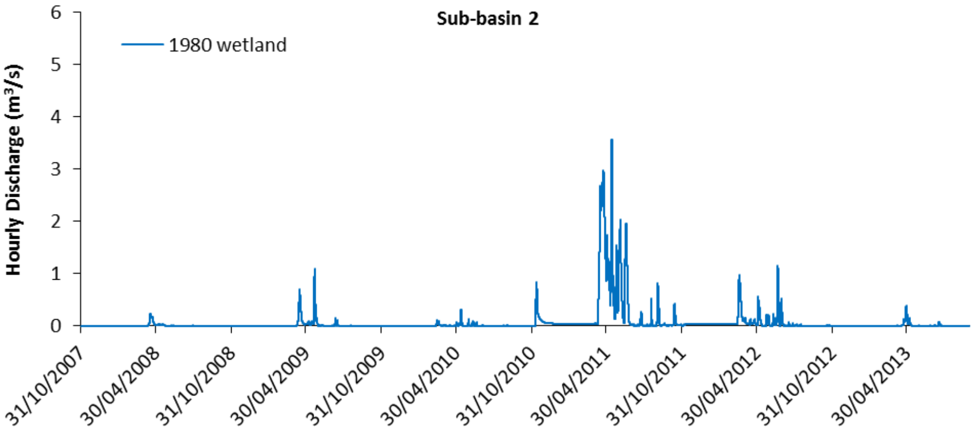

Figure A11. Simulated hydrograph for the 1980 wetland scenario in Smith Creek sub-basin 2.

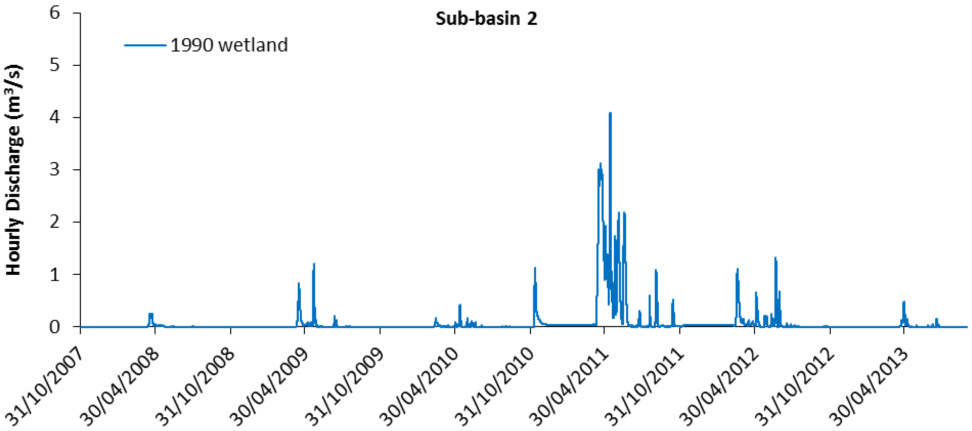

Figure A12. Simulated hydrograph for the 1990 wetland scenario in Smith Creek sub-basin 2.

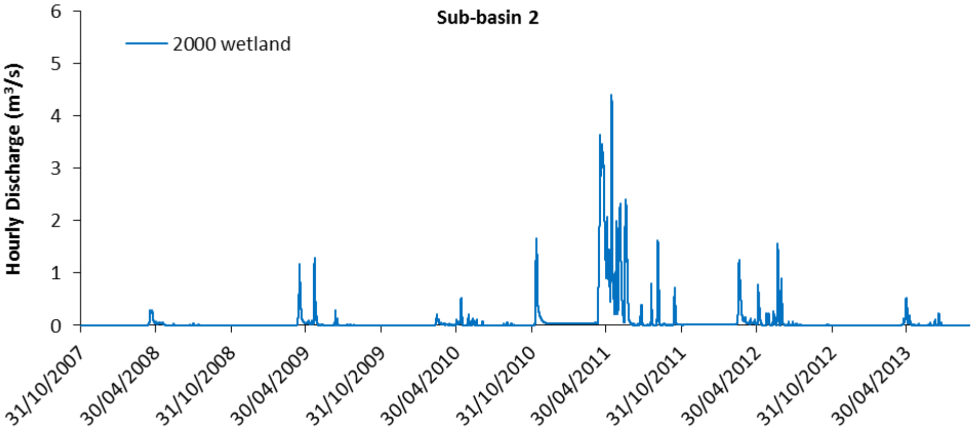

Figure A13. Simulated hydrograph for the 2000 wetland scenario in Smith Creek sub-basin 2.

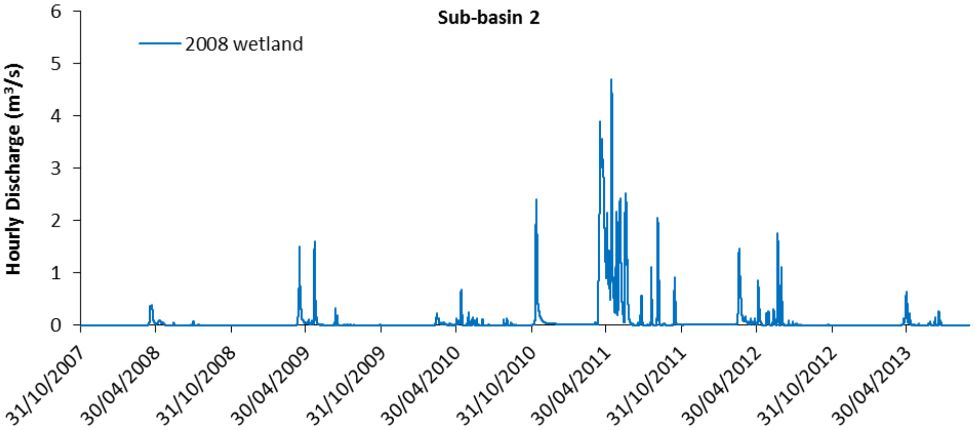

Figure A14. Simulated hydrograph for the 2008 wetland scenario in Smith Creek sub-basin 2.

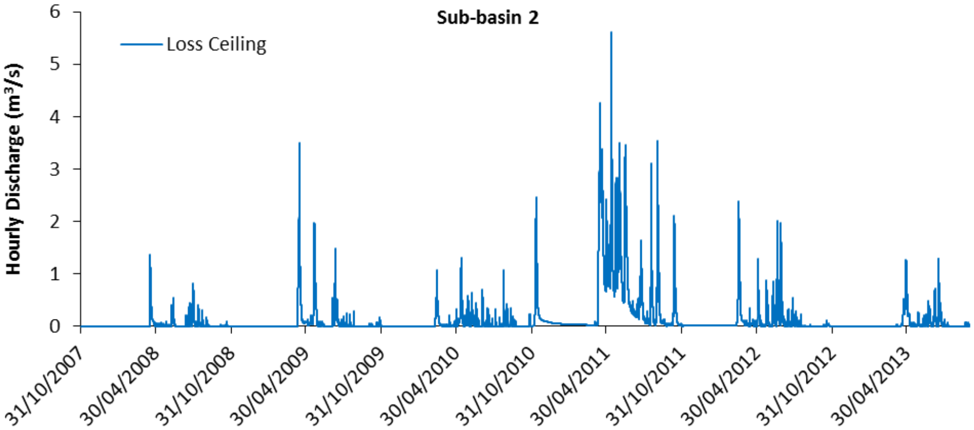

Figure A15. Simulated hydrograph for the “Loss Ceiling” wetland scenario in Smith Creek sub-basin 2.

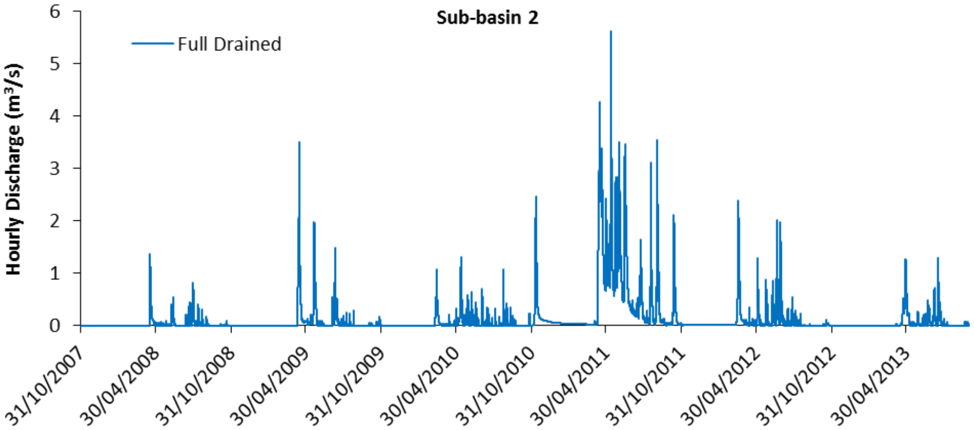

Figure A16. Simulated hydrograph for the “Full Drained” wetland scenario in Smith Creek sub-basin 2.

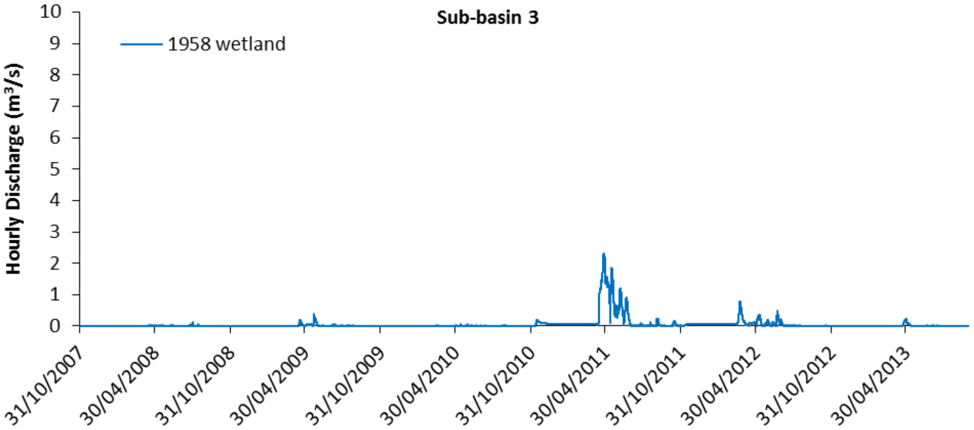

Figure A17. Simulated hydrograph for the 1958 wetland scenario in Smith Creek sub-basin 3.

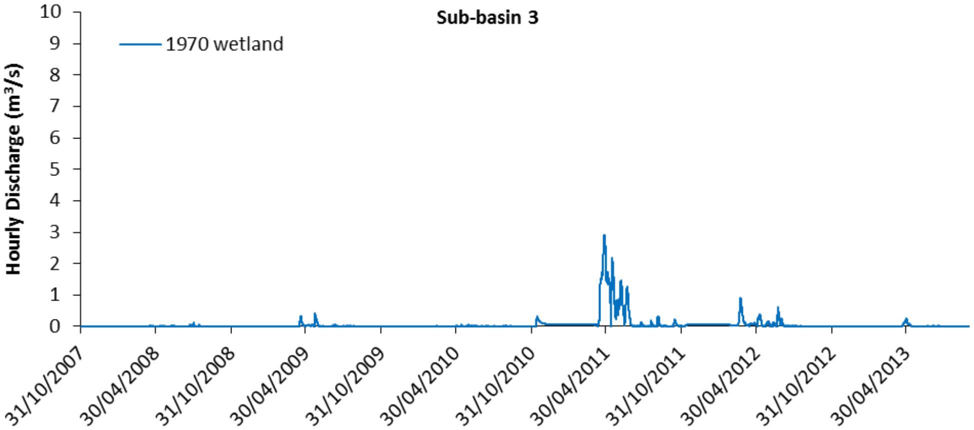

Figure A18. Simulated hydrograph for the 1970 wetland scenario in Smith Creek sub-basin 3.

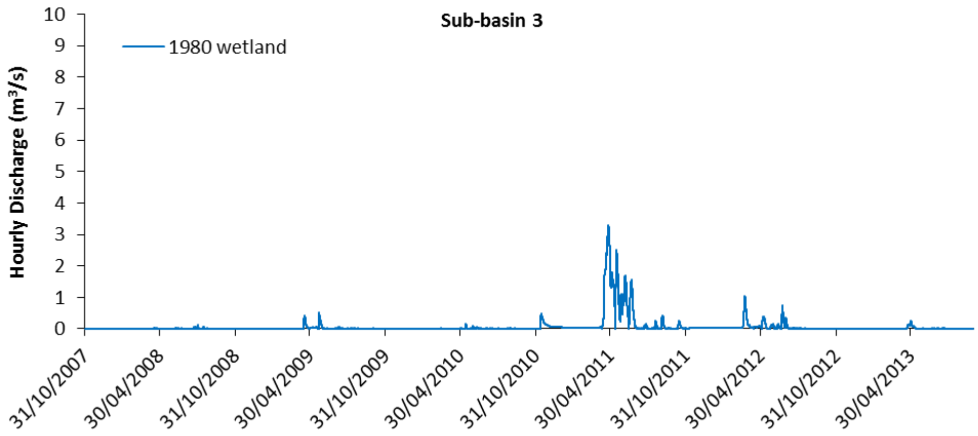

Figure A19. Simulated hydrograph for the 1980 wetland scenario in Smith Creek sub-basin 3.

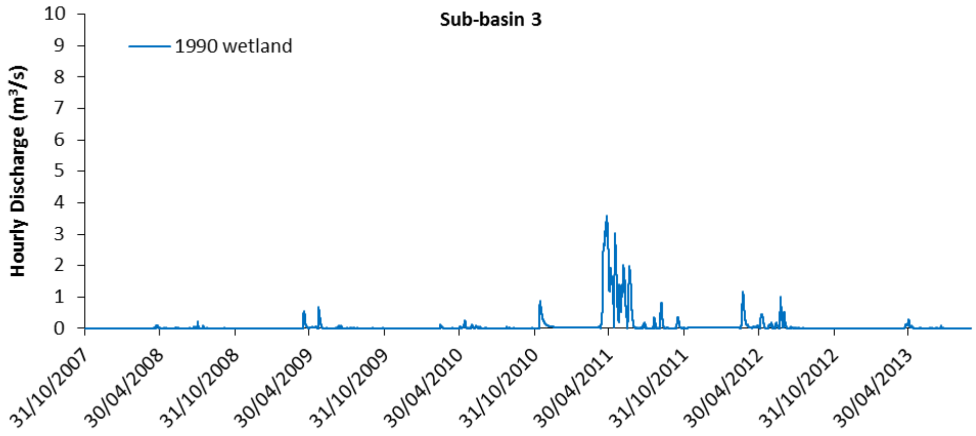

Figure A20. Simulated hydrograph for the 1990 wetland scenario in Smith Creek sub-basin 3.

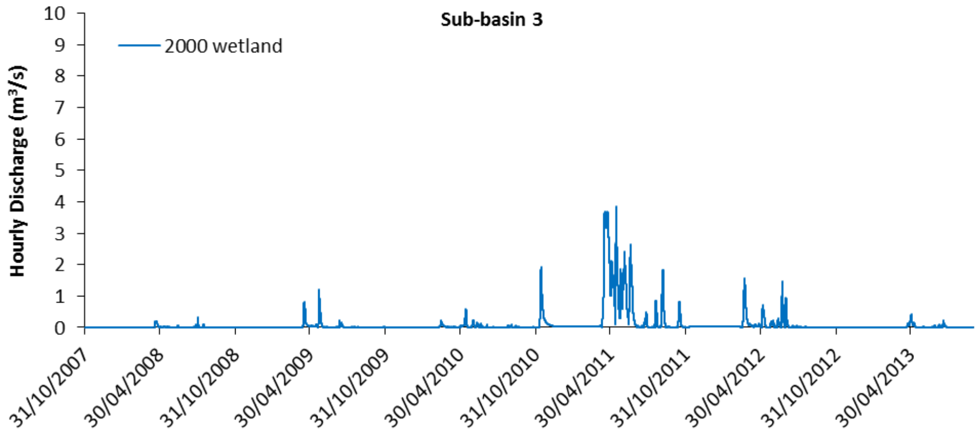

Figure A21. Simulated hydrograph for the 2000 wetland scenario in Smith Creek sub-basin 3.

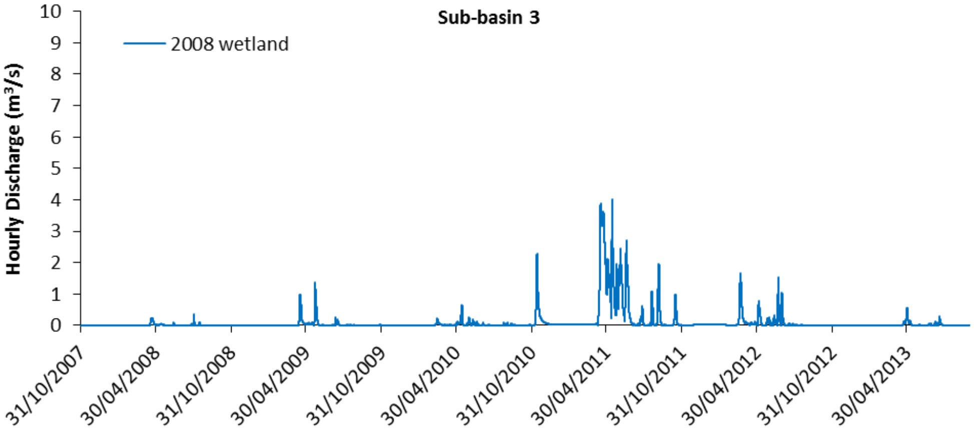

Figure A22. Simulated hydrograph for the 2008 wetland scenario in Smith Creek sub-basin 3.

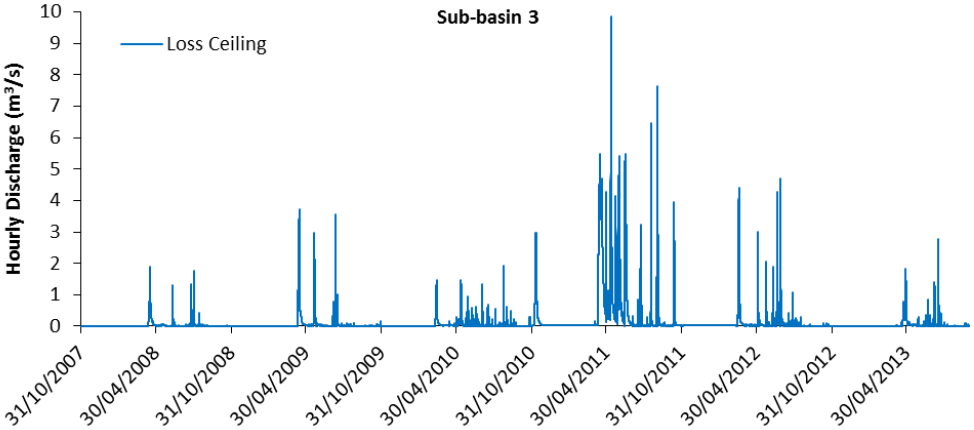

Figure A23. Simulated hydrograph for the “Loss Ceiling” wetland scenario in Smith Creek sub-basin 3.

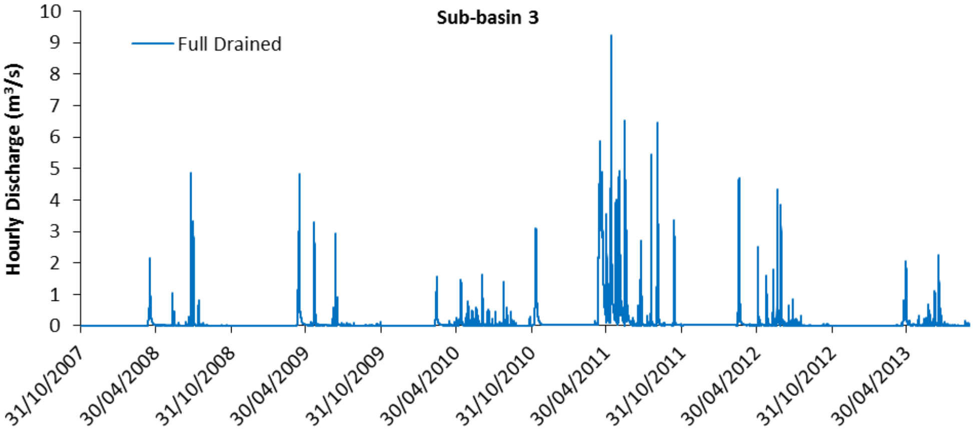

Figure A24. Simulated hydrograph for the “Full Drained” wetland scenario in Smith Creek sub-basin 3.

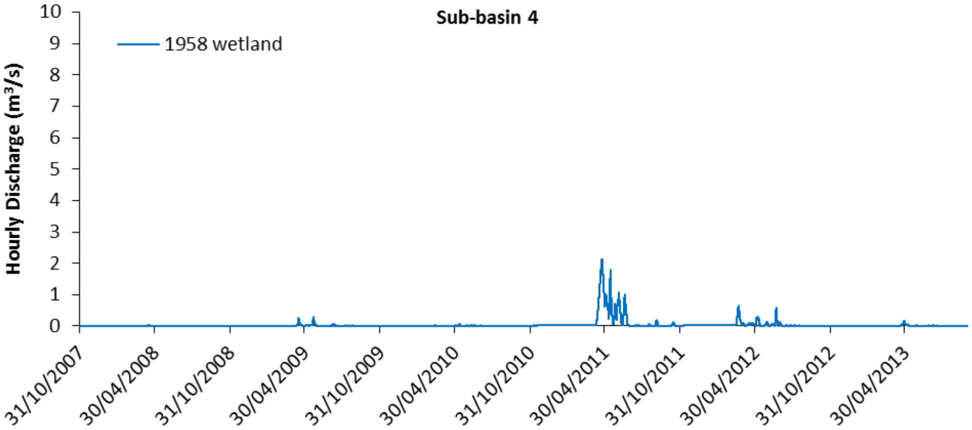

Figure A25. Simulated hydrograph for the 1958 wetland scenario in Smith Creek sub-basin 4.

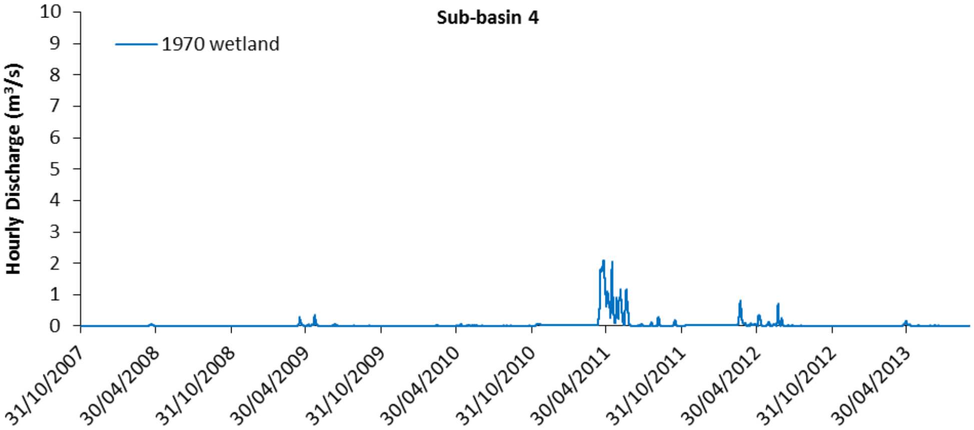

Figure A26. Simulated hydrograph for the 1970 wetland scenario in Smith Creek sub-basin 4.

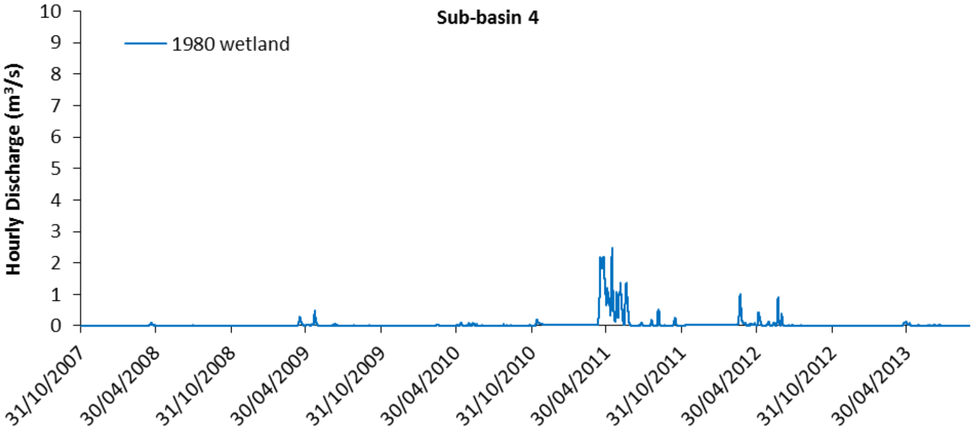

Figure A27. Simulated hydrograph for the 1980 wetland scenario in Smith Creek sub-basin 4.

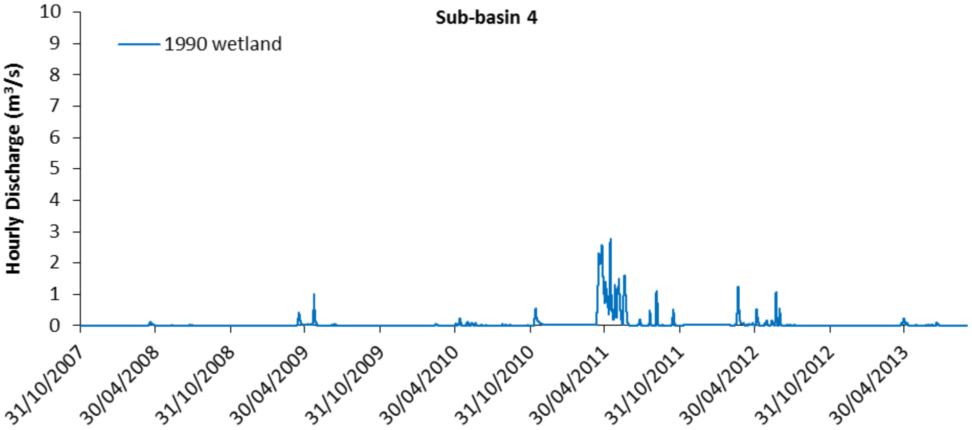

Figure A28. Simulated hydrograph for the 1990 wetland scenario in Smith Creek sub-basin 4.

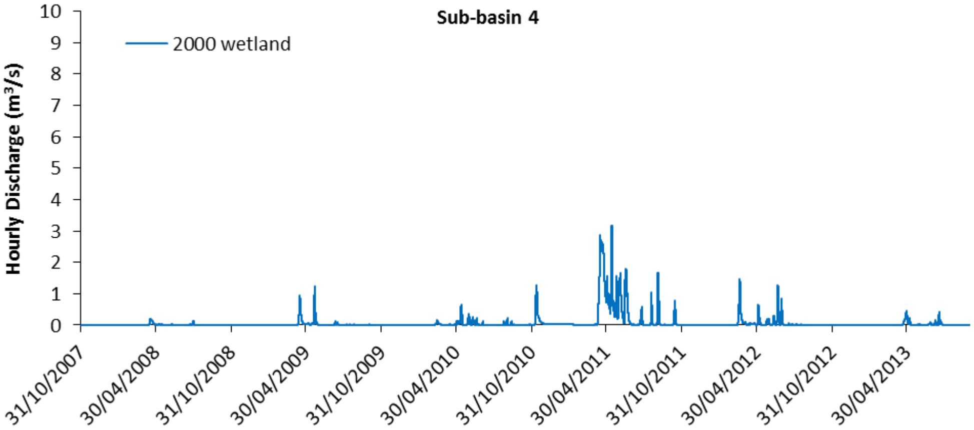

Figure A29. Simulated hydrograph for the 2000 wetland scenario in Smith Creek sub-basin 4.

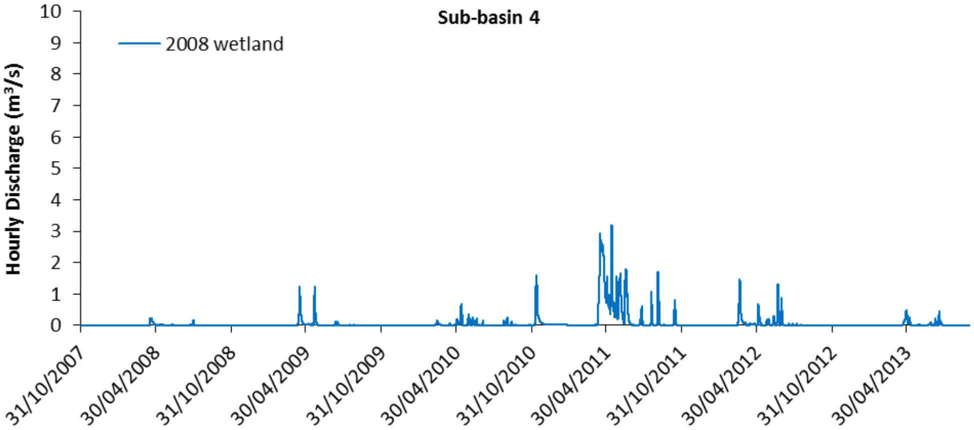

Figure A30. Simulated hydrograph for the 2008 wetland scenario in Smith Creek sub-basin 4.

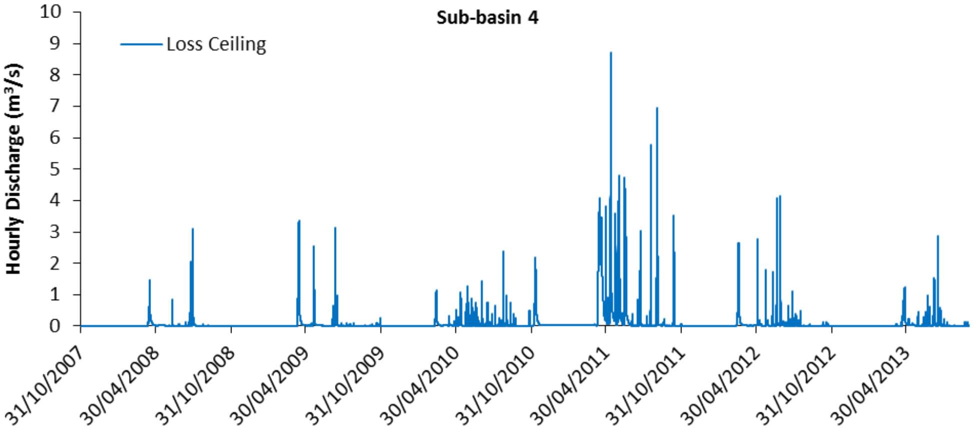

Figure A31. Simulated hydrograph for the “Loss Ceiling” wetland scenario in Smith Creek sub-basin 4.

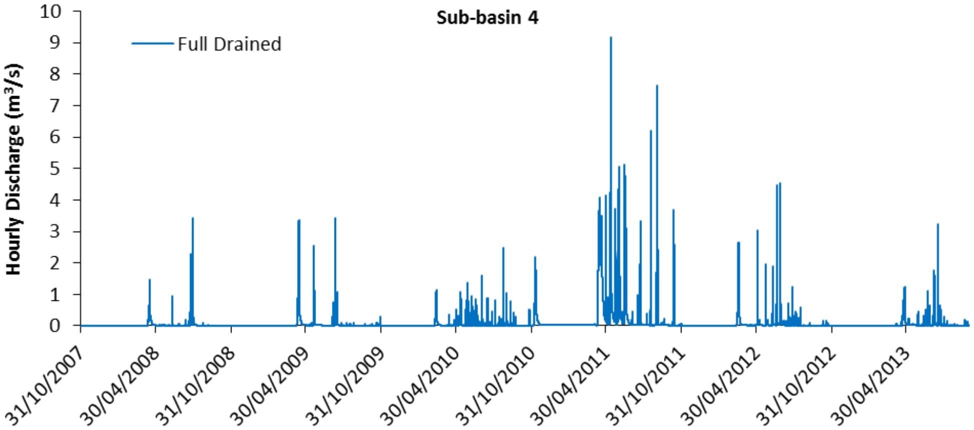

Figure A32. Simulated hydrograph for the “Full Drained” wetland scenario in Smith Creek sub-basin 4.

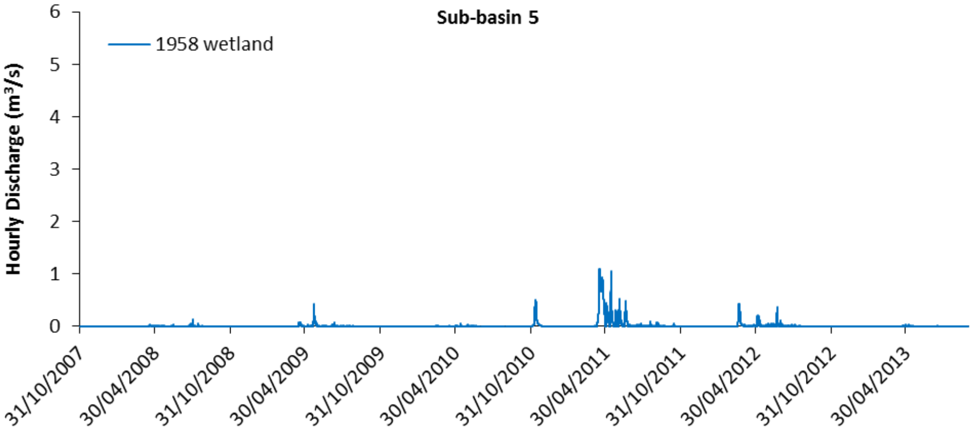

Figure A33. Simulated hydrograph for the 1958 wetland scenario in Smith Creek sub-basin 5.

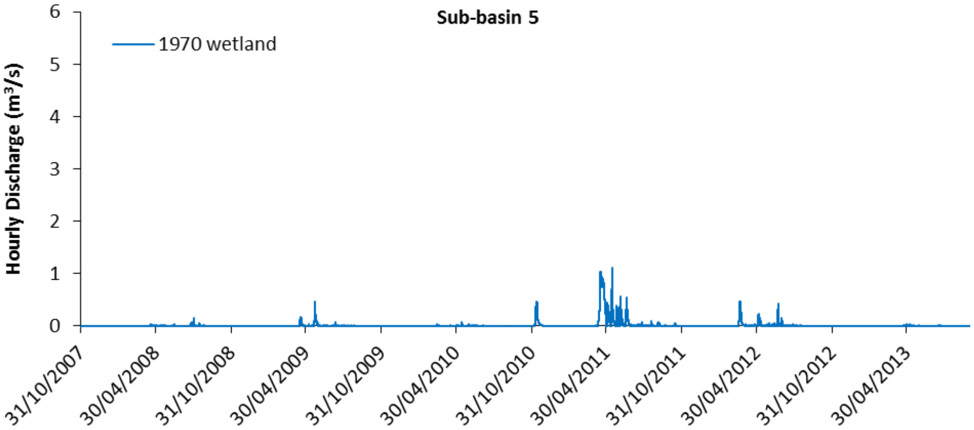

Figure A34. Simulated hydrograph for the 1970 wetland scenario in Smith Creek sub-basin 5.

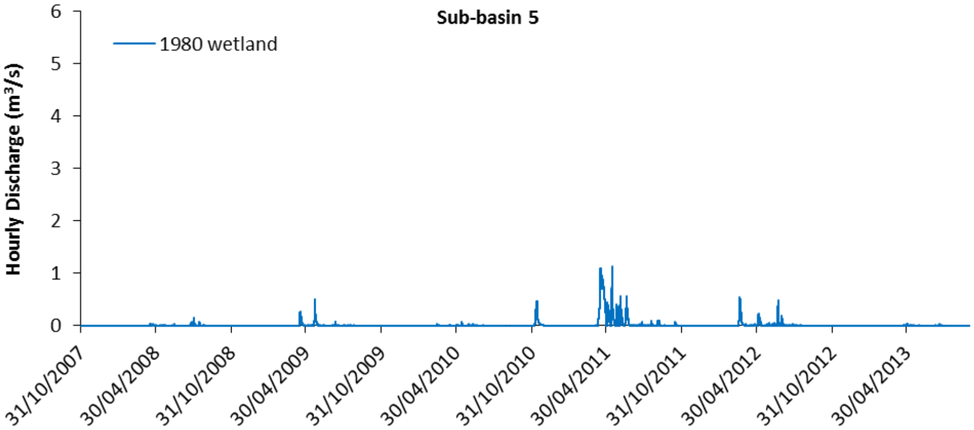

Figure A35. Simulated hydrograph for the 1980 wetland scenario in Smith Creek sub-basin 5.

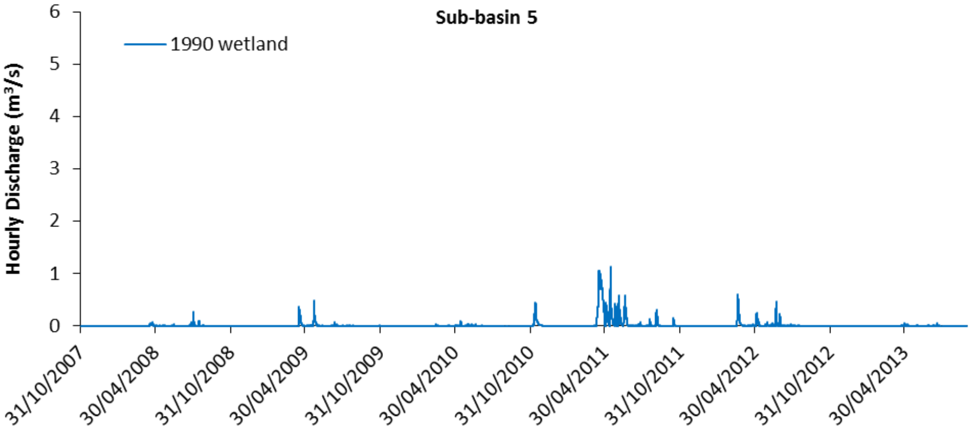

Figure A36. Simulated hydrograph for the 1990 wetland scenario in Smith Creek sub-basin 5.

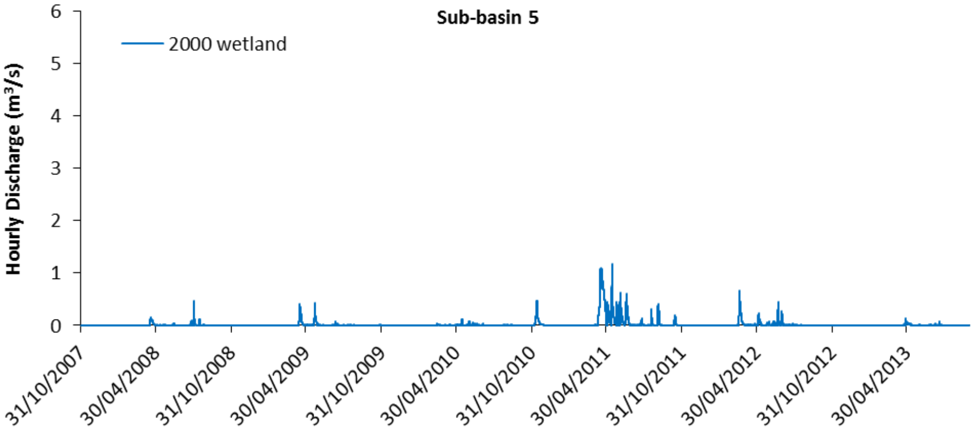

Figure A37. Simulated hydrograph for the 2000 wetland scenario in Smith Creek sub-basin 5.

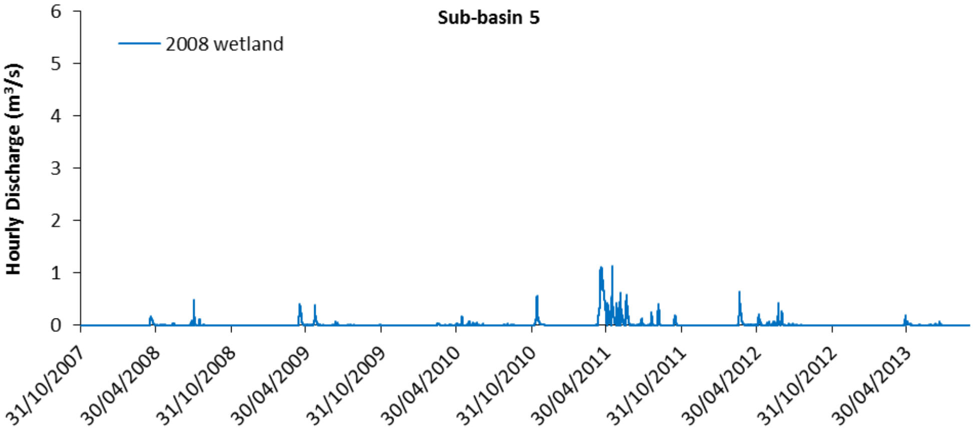

Figure A38. Simulated hydrograph for the 2008 wetland scenario in Smith Creek sub-basin 5.

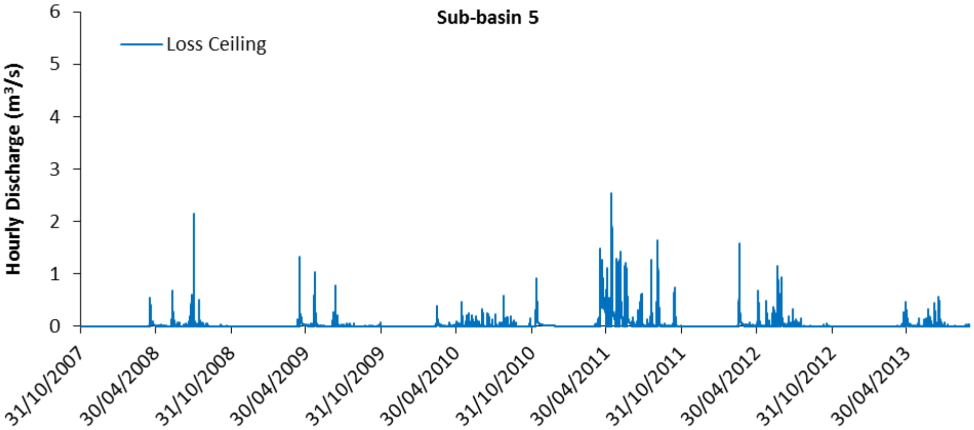

Figure A39. Simulated hydrograph for the “Loss Ceiling” wetland scenario in Smith Creek sub-basin 5.

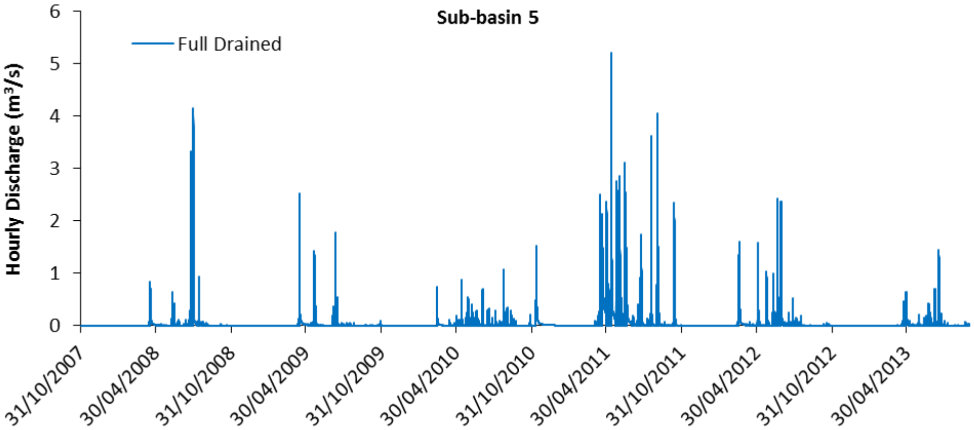

Figure A40. Simulated hydrograph for the "Full Drained" wetland scenario in Smith Creek sub-basin 5.

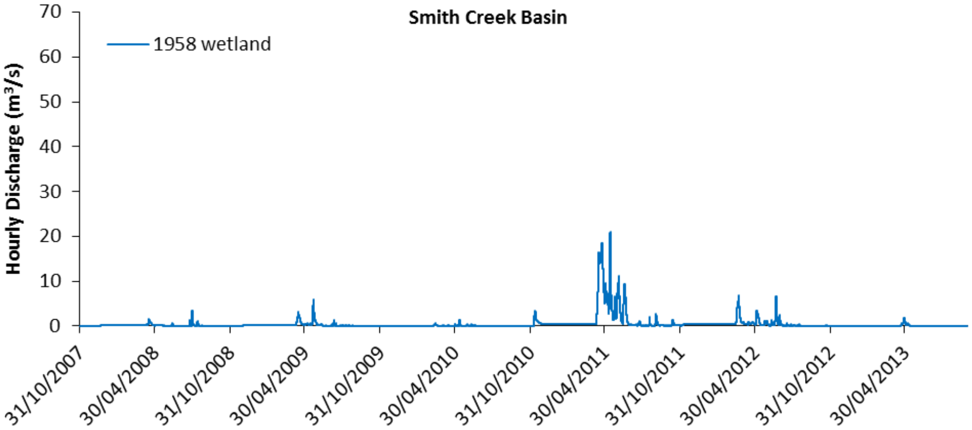

Figure A41. Simulated hydrograph for the 1958 wetland scenario for the whole Smith Creek basin.

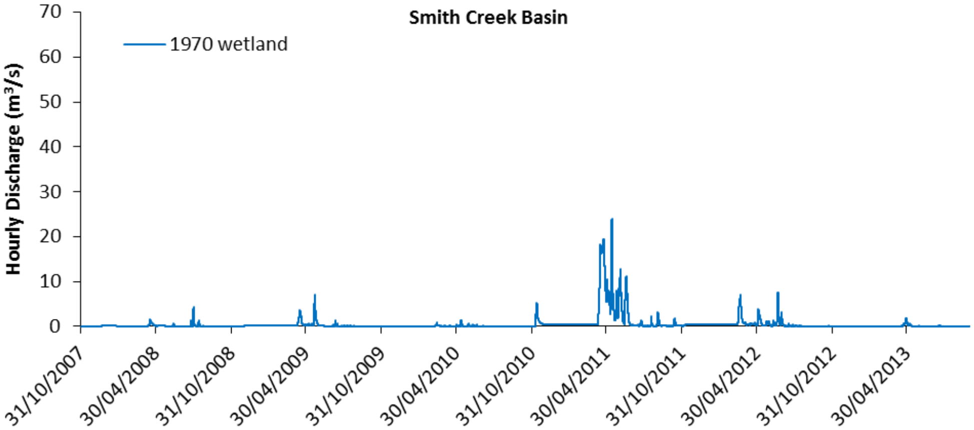

Figure A42. Simulated hydrograph for the 1970 wetland scenario for the whole Smith Creek basin.

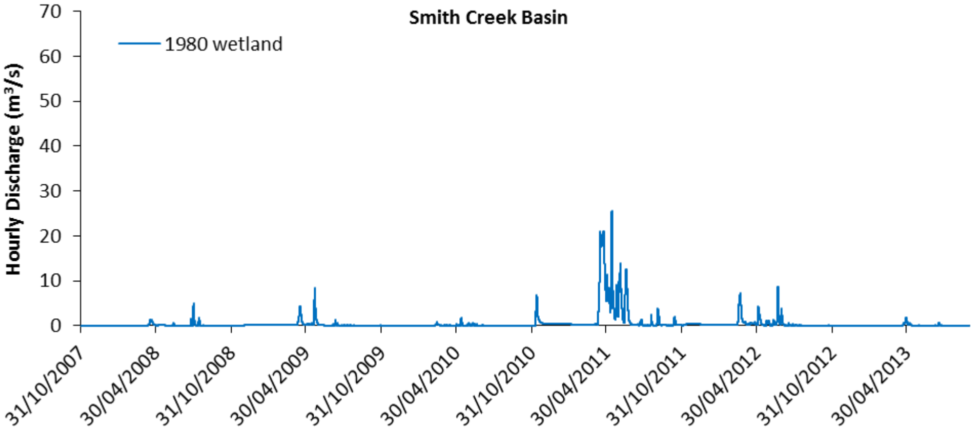

Figure A43. Simulated hydrograph for the 1980 wetland scenario for the whole Smith Creek basin.

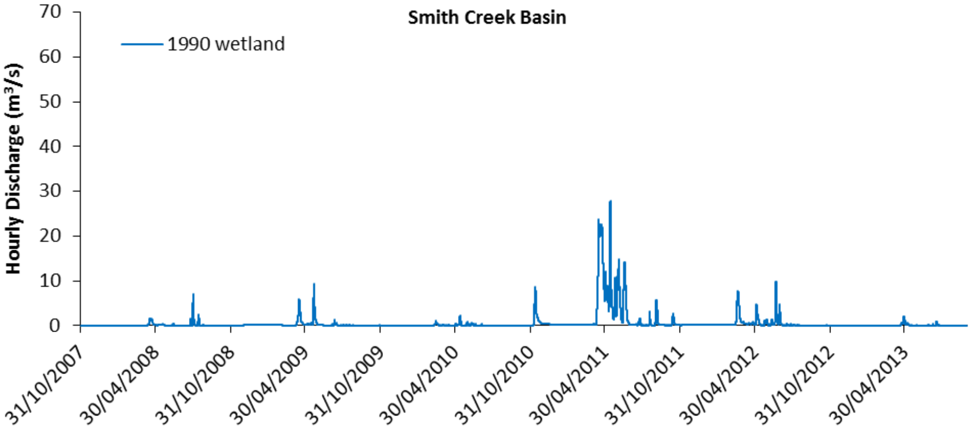

Figure A44. Simulated hydrograph for the 1990 wetland scenario for the whole Smith Creek basin.

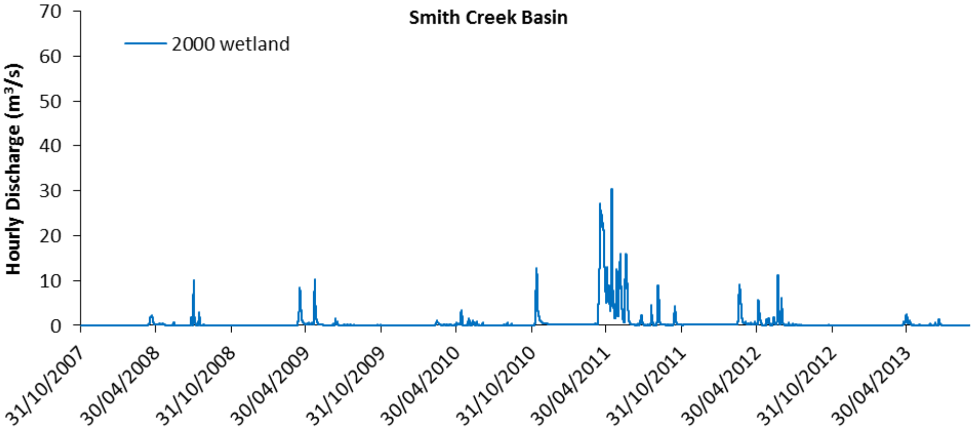

Figure A45. Simulated hydrograph for the 2000 wetland scenario for the whole Smith Creek basin.

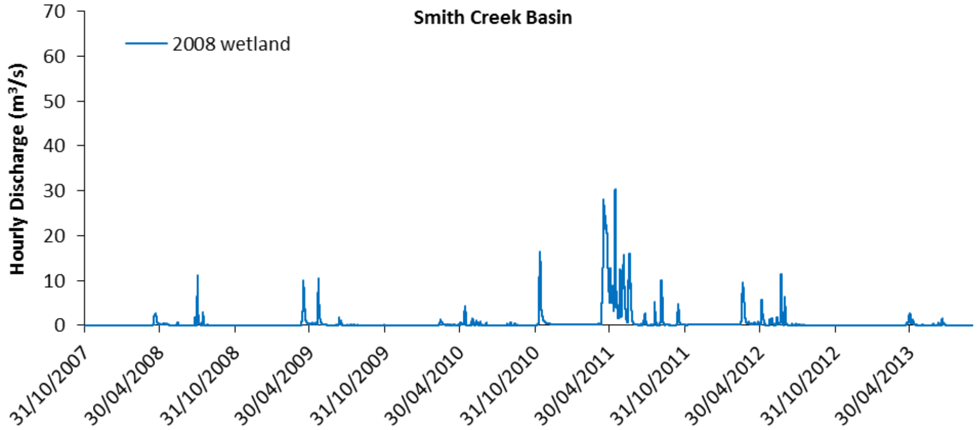

Figure A46. Simulated hydrograph for the 2008 wetland scenario for the whole Smith Creek basin.

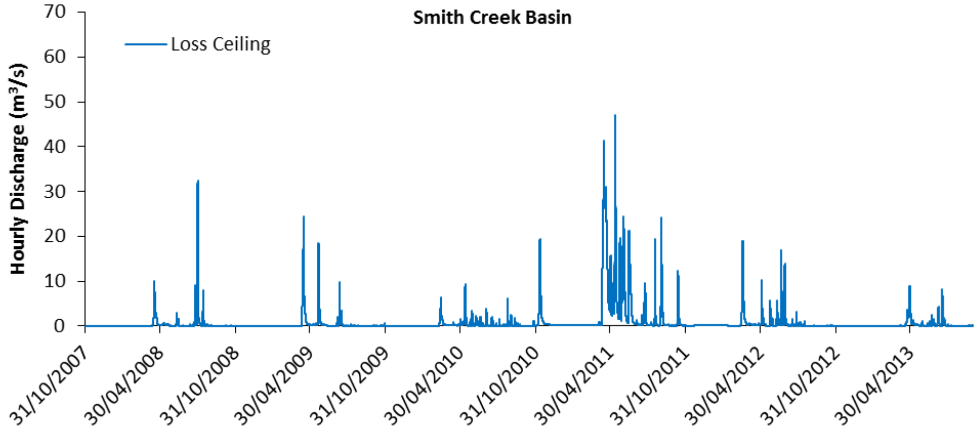

Figure A47. Simulated hydrograph for the “Loss Ceiling” wetland scenario for the whole Smith Creek basin.

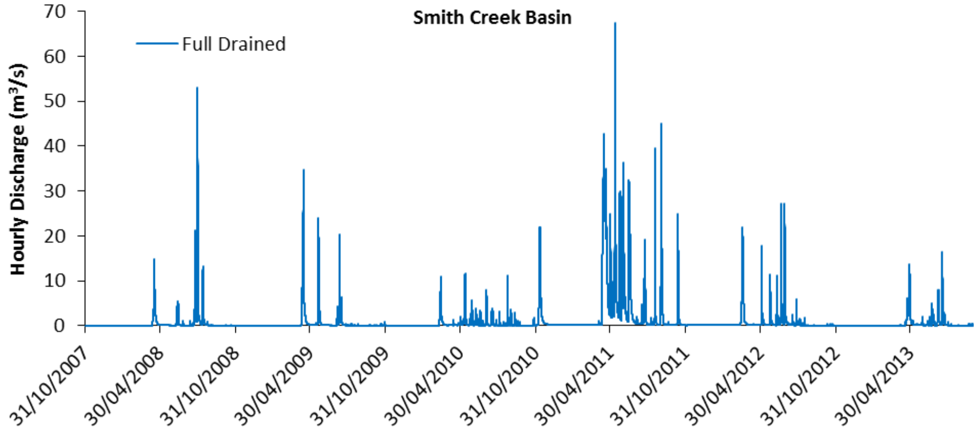

Figure A48. Simulated hydrograph for the “Full Drained” wetland scenario for the whole Smith Creek basin.