



Hydrological modeling of the pipestone creek watershed using the Soil Water Assessment Tool (SWAT): Assessing impacts of wetland drainage on hydrology



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ABSTRACT

Study region: Prairie Pothole Region of North America.

Study focus: The Prairie Pothole Region of North America has experienced extensive wetland drainage, potentially impacting peak flows and annual flow volumes. Some of this drainage has occurred in closed basins, possibly impacting lake water levels of these systems. In this study we investigated the potential impact of wetland drainage on peak flows and annual volumes in a 2242 km² watershed located in southeastern Saskatchewan (Canada) using the Soil Water Assessment Tool (SWAT) model.

New hydrological insights: The SWAT model, which had been calibrated and validated at daily and monthly time steps for the 1997–2009 period, was used to assess the impact of wetland drainage using three hypothetical scenarios that drained 15, 30, and 50% of the non-contributing drainage area. Results of these simulations suggested that drainage increased spring peak flows by about 50, 79 and 113%, respectively while annual flow volumes increased by about 43, 68, and 98% in each scenario. Years that were wetter than normal presented increased peak flows and annual flow volumes below the average of the simulated period. Alternatively, summer peak flows presented smaller increases in terms of percentages during the simulated period.

1. Introduction

There are numerous applications of the Soil Water Assessment Tool (SWAT) model around the world. However, implementations of SWAT in the cold regions of North America, where snow processes have an important role in the overall annual hydrological cycle, are limited. Wang and Melesse (2005) evaluated the SWAT model's snowmelt hydrology in a 4340 km² watershed located in northwestern Minnesota simulating daily, monthly, and seasonal streamflows. The model performed well in simulating monthly, seasonal, and annual mean flows. The performance of the model simulation for daily flows was not as good but still had a satisfactory performance. Another study by Ahl et al. (2008) calibrated and validated the SWAT model at daily and monthly time steps for a 22.5 km² watershed in central Montana. Results of this simulation suggested that the SWAT model performed acceptably for spring and early summer snowmelt but performed poorly for late summer and winter base flow. The model performed better at monthly than daily time steps, and snowmelt parameters such as snowmelt temperature and snowpack temperature factor were the most sensitive parameters. Zhang et al. (2008) used the SWAT model to simulate runoff from an ungauged 114,345 km² mountain river basin using three different snowmelt algorithms, based on a temperature index, a temperature index plus elevation band, and on an

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energy budget. Of these three algorithms, the one based on the temperature index plus elevation had a performance comparable to the simulation carried out with SWAT using the energy budget model. Simulation with the temperature algorithm had the worst performance due to its simplicity. The runoff simulation using the temperature index plus elevation algorithm was almost as good as using the energy balance algorithms.

In Canada, the SWAT model and its snow module were also applied to a northern watershed in Quebec (Troin and Caya, 2014). The model was calibrated adjusting 17 parameters for a period of five years and validated for another two periods of 17 and 15 years, and showed a satisfactory performance. The model simulated the timing and the magnitude of the spring runoff well and the results were comparable to other models such as the Streamflow Synthesis and Reservoir Regulation (U.S. Army Corps of Engineers, 1991) that had been implemented in that watershed. Also in Canada, Rahbeh et al. (2011) applied the SWAT model to a small watershed ($\sim 34 \text{ km}^2$) in the Canadian Prairies. This watershed was characterized by extensive irrigation, an upstream inlet, low runoff and only three years of records. Their approach was to calibrate the model using the more traditional one-way calibration method, in which the record was split into two and was used to calibrate and validate the model, and the less common two-way calibration method. This consists of splitting the recorded time series into two periods, A and B; the model is then calibrated and validated using periods A and B but is also calibrated and validated using the opposite period, B and A respectively. The SWAT model was successfully calibrated for the different scenarios used but could not be validated for any of the scenarios.

The Canadian Prairies form part of the Pothole Region of North America (PRNA) and its geography is characterized by thousands of shallow wetlands. These wetlands have been drained since the first Europeans started to cultivate in the PRNA, to maximize the land and have an easier access to it (Johnson et al., 2008), resulting in considerable wetland loss. In the USA, wetland loss has been severe; it was estimated that by 1991 the number of wetlands had been reduced by between 50 and 70% (Dahl and Johnson, 1991). In the Canadian Prairies the wetland loss is also significant and it is estimated that around 70% of wetlands have been lost (Dahl and Johnson, 1991).

Wetland drainage affects some hydrological processes such as storage, evaporation, and infiltration, as well as the timing in which the drainage area initially contributing to the wetlands contributes flow to the main channel. The watersheds within the PRNA are dominated by the principle of fill and spill, and water levels in the wetlands fluctuate mostly because of the runoff. The vertical flux of ground water in or out of wetlands is considered insignificant in the overall balance (van der Kamp and Hayashi, 2009). In these areas, wetlands might or might not contribute to runoff during a determined event, depending on the magnitude of the event, the water level prior to the runoff event, and the antecedent soil moisture conditions. This makes the contributing drainage area to runoff variable from year to year, season to season, and even from event to event. This behavior was initially observed during the 1950s (Stichling and Blackwell, 1957), and was refined in the mid-1970s when the concepts of Effective Drainage Area (EDA) and Gross Drainage Area (GDA) were introduced in the Canadian Prairies (Godwin and Martin, 1975). The EDA is the area that is expected to contribute to runoff during a normal year, which has a return period of 2 years. The GDA is the topographic limit of the watershed, which in practical terms is expected to contribute to runoff only during an extreme low-frequency event (e.g. a 1:1000 years event; SaskWater, 1993). The area that is found outside of the EDA but within the GDA is defined as the non-contributing drainage area (NCDA) and is usually characterized by a large number of wetlands with no or low connectivity; these are not expected to contribute runoff to the main channel by filling and spilling during a normal runoff year. Therefore, the simulation of the hydrological processes of watersheds with variable contributing drainage areas is not trivial.

The variable contributing drainage area issue was addressed by Wang et al. (2008), who introduced the concept of the hydrologic equivalent wetland (HEW) to simulate daily and monthly flows in a 4506 km^2 watershed in northwestern Minnesota. One of the objectives of that study was to incorporate the thousands of wetlands in the region into SWAT. The HEW concept is based on the maximum volume that a wetland can store, its surface area and the fraction of the sub-basin area that drains into the wetland. The HEW model was evaluated for a period of seven years (1969–1975) at daily, monthly, and seasonal time steps, and the performance of the model varied through the different time steps. However, when comparing this approach to other methodologies used to model wetland-dominated watersheds, such as the synthetic wetland approach, the HEW was found to be a superior method for incorporating wetlands into the SWAT model.

The relevance of wetlands for biodiversity and hydrology in terms of water quantity and quality has been widely studied for decades (e.g., Duffy, 1998; Landers and Knuth, 1991). In the PRNA, Vining (2002) simulated streamflow and wetland storage for the period 1981–1998 in the Starkweather Coulee watershed located in North Dakota. This study used a Digital Elevation Model (DEM) to estimate the spill elevation of wetlands previously identified by the National Wetlands Inventory and Geographic Information Systems to determine surface areas and depths. That watershed had a GDA of 803 km^2 , from which 544 km^2 were reported to contribute to runoff regularly (EDA). The drainage area was divided into 50 hydrological response units (HRU) for which the water balance was calculated. In order to account for and simplify the number of wetlands in each HRU, one equivalent wetland that was the sum of all the wetlands in the HRU, was included in the model. Wetlands in this watershed presented an average depth of 0.67 m and volume was estimated as function of the surface area. A modified version of the U.S. Geological Survey's Precipitation Runoff Modeling System was used to simulated daily flows and wetlands levels. The results of this study suggest that the model underestimated peak flows during spring runoff for all years but one; the poor performance capturing peak flows was attributed to the lack of a subroutine in the model for frozen soils.

Bullock and Acreman (2003) reviewed the literature on the role of wetlands in the hydrological cycle, and found more than 150 studies, including several that addressed the impact of wetlands on flows downstream. They concluded that the long-standing beliefs that wetlands always reduce floods, contribute to groundwater recharge, and regulate river flows were not always true. A large number of floodplain wetlands reduce or delay floods but not all of them. Fewer than half of the studies reviewed by Bullock and Acreman (2003) that addressed wetlands in the headwaters noted reduced or delayed flooding. However, wetlands in the headwaters

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