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Modeling of nutrient export and effects of management practices in a cold-climate prairie watershed: Assiniboine River watershed, Canada

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ABSTRACT

Non-point source pollution due to agricultural activities is an important problem that has been threatening water resources in Canadian prairie watersheds. The development of strategies to prevent nutrient loss depends on the quantification of nutrient mobilization and transport across a watershed. Integrated eco-hydrological models can play an important role in this regard. However, current model applicability to cold-climate Canadian prairie watersheds is limited due to the complex dynamics of nutrient export under the existence of numerous landscape depressions and freeze-thaw cycles. The aim of this study was to evaluate an eco-hydrological model for nutrient export prediction and assess the impacts of management practices for a cold-climate prairie watershed. To achieve the objectives, a new version of the SWAT model called SWAT-PDLD, which combines SWAT and a Probability Distributed Landscape Depressions (PDLD) model, along with a seasonally varying soil erodibility factor, was applied to a Canadian prairie watershed (the Assiniboine River watershed, Saskatchewan, Canada). The PDLD module is used to simulate the effect of the numerous landscape depressions that exist in these watersheds on streamflow, whereas a seasonally varying soil erodibility factor is used to take into account seasonal variation of sediment and nutrient generation due to the cold climate conditions. Model calibration and uncertainty analysis were performed using the Sequential Uncertainty FItting (SUFI-2). The study shows that the SWAT-PDLD model with seasonally varying soil erodibility simulates the daily nutrient export in a cold prairie watershed satisfactorily as confirmed by both graphical plots and statistical measures. A sensitivity analysis of sub-watershed discretization revealed that the streamflow is relatively insensitive to sub-watershed discretization but it did affect sediment and nutrient export. Importantly, the model shows that both filter strips and cover crops decreased sediment, phosphorous, and nitrogen export, while conservation tillage increased phosphorous export in the study watershed.

1. Introduction

Environmental problems due to increased non-point source pollution such as nutrient loadings are a problem of global importance (Chambers et al., 2001; Newham et al., 2004; De and Bezuglov, 2006; Santhi et al., 2006). Canadian prairie watersheds are not exceptions, if not worse, as agriculture is a dominant economic force (Crumpton and Goldsborough, 1998; Assiniboine Watershed Stewardship Association, 2000; Huel et al., 2000; Statistics Canada, 2011). According to Statistics Canada (2011), the amount of fertilized agricultural land in the Canadian prairies increased by nearly 400% between 1971 and 2006, whereas total agricultural land increased by only 5% during the same period. The major shift in the amount of fertilized land occurred between 1976 and 1981 (Statistics Canada, 2010). With this increase in agricultural activity, excess inputs of nutrients into waterbodies have been observed on the Canadian prairies. For instance, Bourne et al. (2002) indicated that increases in nitrogen and phosphorous loads, 13% and 10% respectively, have occurred in Lake Winnipeg during the period between 1973 and 1999.

Nutrients are essential elements required for plant growth, however, excessive inputs of nutrients into an aquatic ecosystem can lead to significant negative impacts on water quality. Eutrophication is among the many environmental problems caused by excessive nutrient enrichment as evidenced by frequent fish kills in Canadian prairie lakes such as The Lake of the Prairies and Lake Winnipeg (Hall and Leavitt, 1999; Chambers et al., 2001; Jones and Armstrong, 2001; Saskatchewan Watershed Authority, 2005; Lake Winnipeg Stewardship Board, 2006; Salvano et al., 2009). In fact, eutrophication frequency and severity are showing

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increasing trends in Canadian prairie watersheds (Hall and Leavitt 1999; Chambers et al., 2001; Dube et al., 2011). Furthermore, increased agricultural activities proposed by the Saskatchewan Ministry of Agriculture (Saskatchewan Ministry of Agriculture, 2013) and expected future climate change (Shrestha et al., 2012) have the potential to further worsen water quality degradation in the region.

In order to guide the development of an appropriate remediation strategy, information about how nutrient export processes are occurring across a watershed is required (Panagopoulos et al., 2012). Simulation models can play an important role in quantifying nutrient loss and export processes (e.g., Zhang and Jørgensen, 2005; Elshorbagy and Ormsbee, 2006; Barlund et al., 2007; Dong et al., 2014). A wide range of nutrient loss and export models have been developed and applied to different watersheds (Merritt et al., 2003; Borah and Bera, 2003; Booty and Benoy, 2009). Each model was initially developed for a specific region and goal, and differed from other models in complexity, data requirements, and spatial and temporal resolution (Merritt et al., 2003). However, modeling nutrient export from Canadian prairie watersheds remains difficult. Much of the difficulty of this problem is because the landscape is dominated by numerous landscape depressions (potholes) that vary in storage capacity and have a dynamic connectivity (Shaw et al., 2011; Shook et al., 2013). Also as a result, there are numerous non-contributing areas to streamflow in the region (Godwin and Martin, 1975; Shaw et al., 2011; Shook et al., 2013). The dynamic connectivity between landscape depressions leads to dynamic non-contributing areas, which invalidates most conventional models that assume a fixed contributing area (Shook et al., 2013).

In considering a single depression, the major components of the water budget include precipitation on the water surface, surface runoff from uplands, evapotranspiration, surface outflow (overflow) when a depression is filled beyond capacity, and seepage (Woo and Rowsell, 1993; Winter and Woo, 1990; Hayashi et al., 1998; Fang and Pomeroy, 2008). The most significant input to the prairie landscape depression water budget is upland snowmelt, which is vital for the existence of wetlands because of reduced surface runoff due to high evapotranspiration rates and low soil moisture over the summer (Hayashi et al., 1998; Labaugh et al., 1998; Fang and Pomeroy, 2008). The other inputs include precipitation directly on the depression and surface runoff during intense rainfall events (Hayashi et al., 1998; Labaugh et al., 1998; Fang and Pomeroy, 2008). Evapotranspiration within the wetland and shallow lateral flow at the periphery of the wetland, which is affected by the transpiration of nearby plants, are the main pathways for water leaving the depressions (Woo and Rowsell, 1993; van der Kamp and Hayashi, 2009). However, the influence of deep groundwater exchange on the water budget of the depressions is limited due to the low hydraulic conductivity of the deeper underlying tills (van der Kamp and Hayashi, 2009).

In considering the nutrient budget, for a prairie watershed with depressions nutrients are mobilized from open fields. Some portion of these nutrients directly reaches the watershed outlet. However, in a prairie watershed much are trapped, transformed, and stored in the depressions (Neely and Baker, 1989; Johnston, 1991; van der Valk and Jolly, 1992; Crumpton and Goldsborough, 1998; Murkin, 1998). Nutrients in the depression water can be exchanged to the atmosphere (nitrogen only), sediment-interstitial water, and living and dead biomass through biogeochemical processes (Crumpton and Goldsborough, 1998; Brunet, 2011). Several past studies demonstrated that depressions in the prairie region are nutrient sinks (Neely and Baker, 1989; Crumpton et al., 1993; Moraghan, 1993; Reddy et al., 1999; Birgand et al., 2007).

The other challenge in modeling a Canadian prairie watershed is that it exhibits a cold-climate hydrology (Pomeroy et al., 2007). The hydrological processes in the region are highly influenced by snow accumulation and melt, runoff over frozen ground, infiltration into frozen or partially frozen soil, and freeze-thaw processes. The majority of the runoff occurs over a few weeks in the spring when the melt rate of the snowpack exceeds the reduced infiltration rate to frozen soils (Granger et al., 1984; Gray and Landine, 1988). The mobilization and transport of pollutants, such as sediment and nutrients, are also influenced by the cold-climate conditions (Deelstra et al., 2009; Han et al., 2010). Several studies show that pollutant mobilization and export are higher during the snowmelt period (e.g., McConkey et al., 1997). This is mainly because of increased soil erodibility during freeze-thaw cycles (Wall et al., 1988), increased surface runoff enhanced by reduced infiltration in frozen or partially-frozen soils (Gray et al., 2001), and the longer duration of the snowmelt-runoff period as compared to individual rainfall-runoff events (Tiessen et al., 2010).

With respect to modeling of Canadian prairie watersheds, there is much research on how to handle the thousands of landscape depressions that may exist within a watershed (Abedini, 1998; Su et al., 2000; Pomeroy et al., 2007; Fang and Pomeroy, 2008; Wen et al., 2011; Shrestha et al., 2012; Mekonnen et al., 2015; Mekonnen et al., 2016a,b). An approach that uses a probability distribution to model dynamic storage on the landscape is increasing in use for large-area watersheds (e.g., Abedini, 1998; Mekonnen et al., 2016a). The Soil and Water Assessment Tool (SWAT) was recently modified to consider landscape depression storage heterogeneity using this probability distribution approach (with the algorithm called "Probability Distributed Landscape Depressions" (PDLD)) (Mekonnen et al., 2016a). The upgraded SWAT model, called SWAT-PDLD, calculates runoff from landscape depressions based on the available storage capacity of a depression and considers storage capacity variations across the watershed. SWAT-PDLD was tested in simulating the daily streamflow for two Canadian prairie watersheds (the Assiniboine and Moose Jaw River watersheds Saskatchewan, Canada) and showed improved performance over the lumped synthetic storage approach used in the existing version of SWAT (Mekonnen et al., 2016a). Additionally, the SWAT-PDLD was modified to include seasonally varying soil erodibility parameters, which showed good performance in simulating sediment export in the same watersheds (Mekonnen et al., 2016b). The goal of the latter study was to better replicate variations in soil erodibility between frozen, thawing, and unfrozen soils as observed by McConkey et al. (1997).

The objectives of this study are the following: (1) to evaluate the applicability of the SWAT-PDLD model with seasonally varying soil erodibility for nutrient export simulation in a Canadian prairie watershed (the Assiniboine River watershed, Saskatchewan, Canada); and (2) to assess the potential impacts of several agricultural management practices on nutrient export in this watershed using SWAT-PDLD. In order to achieve the objectives, the SWAT-PDLD model was applied in simulating nutrient export in the Assiniboine watershed. Model calibration and uncertainty analyses of SWAT-PDLD were done using a Sequential Uncertainty FItting algorithm (SUFI-2) (Abbaspour et al., 2004). Model performance was evaluated using both multiple statistical criterions and graphical plots. In addition, a sensitivity analysis was performed to evaluate the influences of sub-watershed discretization level. Finally, the impacts of three different management practices on phosphorous and nitrogen export for the study watershed are assessed.

The management practices evaluated were filter strips, also known as vegetative filter or buffer strips, a change in tillage practice to conservation tillage, and planting red clover as a cover crop. Filter strips, which are used to filter sediment, nutrients, and chemicals, are vegetated areas that are situated beside surface water bodies (Waidler et al., 2009). Conservation tillage includes practices from minimum tillage, which involves only one tillage pass in