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An approach for assessing impact of land use and biophysical conditions across landscape on recharge rate and nitrogen loading of groundwater

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ABSTRACT

Assessing the impact of agricultural practices on groundwater quality is a must for environment management, however, such assessment is difficult because of dynamics of land use in interaction with topographic and climatic conditions. In this study, a multiple regression approach for assessing land use impact on groundwater quality and quantity was developed by using the ANCOVA test to select regression model variables from key input variables to a widely used and well-calibrated SWAT (Soil and Water Assessment Tool) model system. This approach can upscale model prediction for a small watershed with the calibrated SWAT model to a large watershed, generating spatial and temporal estimations of groundwater recharge and nitrate loading for the large watershed. It can also be used to evaluate the impacts of land use, soil types and climatic factors on water quality and quantity. Precipitation, air temperature, evapotranspiration, land use and soil types are determined as the most important factors for estimating monthly groundwater recharge rates and nitrate loading with the developed approach. Among various agricultural crops examined, potato is determined as the critical crop to have the highest impact on groundwater nitrate loading. The predictions of the groundwater monthly recharge multiple regression models developed in this study show good agreement with the SWAT model prediction ($R^2 > 0.77$). The monthly nitrate loading models perform a little bit poorly but still show reasonable agreement with the SWAT model with R^2 values > 0.60. Furthermore, the developed approach can be easily plugged into large-scale groundwater simulation models (e.g., MODFLOW) to address spatial variability of landscape characteristics in terms of non-point source pollution.

1. Introduction

Groundwater recharge is defined as "the entry into the saturated zone of water made available at the water-table surface, together with the associated flow away from the water-table within the saturated zone" (Freeze and Cherry, 1979). Groundwater recharge is an important hydrological process for both groundwater and surface water systems (Lerner et al., 1990) because of its relation to the movement of chemicals (e.g., nitrate). Therefore, quantifying recharge rates accurately, in particular their spatial distributions, is imperative for proper management and protection of groundwater resources, and critical for hydrologists, land managers, and policy makers for several decades (Giri et al., 2005).

Estimating the spatial pattern of groundwater recharge rate is normally difficult, because groundwater recharge rate is not only dependent on the climatic conditions (e.g., precipitation and evapotranspiration), but is also impacted by land use, soil characteristics, and topographic and geological conditions (Chen and Lee, 2003; Lee et al., 2007; Troch et al., 2009) and their interactions at

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temporal and spatial scales (Jyrkama and Sykes, 2007). Currently, groundwater recharge rates are estimated with the following four approaches: (1) unsaturated-zone drainage, (2) water balance, (3) water-table fluctuations in wells, and (4) baseflow separation (Risser et al., 2005). However, these methods can only generate an average recharge rate for entire watersheds or capture zones of wells, lacking the capability to generate spatially distinguished estimates for different parts of a watershed. A better estimation of groundwater recharge rate must account for the spatial and temporal variations in it (Jyrkama and Sykes, 2007), because a single value estimate of recharge rate for an entire watershed is over simplistic, lacking resolution and confidence, in particular, for studying non-point source pollution and designing pollution abatement measures for agricultural operations (Dripps et al., 2006). It would also be beneficial to develop a method to estimate recharge rate with less data demanding than complex model systems (e.g., SWAT) and to provide estimation over extended spatial scales with an incorporation of various more dynamic impacting factors (e.g., climate condition, land use change).

In an agriculture-dominated watershed, the nutrient nitrate (N) lost from fields can often be transported to surface and groundwater systems, causing non-point source pollution, and degrading water quality. The contaminated water may cause health problems when consumed by people, being a cause of methemoglobinemia (Jabro et al., 2006). High nitrate concentrations (i.e., above 10 mg N L^{-1}) in surface and groundwater have been frequently reported around the world (Neill, 1989; Rao, 2006; Rivett et al., 2008). In New Brunswick, Canada, there were similar reports of nitrate content exceeding 10 mg N L^{-1} in water samples collected from domestic wells and stream water in the northwest of the province, particularly near potato fields (Chow et al., 2011). Other studies carried out in other provinces of Canada indicated that fertilizer and manure applications are contributing nitrates to the watershed at a rate exceeding environmental health limits on agricultural land although no lethal cases have been reported (Geng et al., 1996; Jiang and Somers, 2009; Yang et al., 2009).

Accurately quantifying nitrate leaching into groundwater from different fields is generally difficult (Jiang and Somers, 2009) due to spatial and temporal variations in nitrate leaching with crops, tillage, soil, and topography in the recharge zones of these groundwater systems. With insufficient quantitative analysis, it is impossible to quantify the effect of nitrate contaminant on groundwater and to provide valuable insight to land managers and policy makers for the identification of environment-friendly agricultural operations. With modern technology in geo-referencing, it has become feasible to adopt field/subfield-based agricultural operations to minimize the impacts of agriculture on water quality (Cambouris et al., 2006). Therefore, estimating groundwater recharge and nitrate loading into groundwater under different land use at the large watershed scale is necessary, but has been proven to be very difficult or unrealistic through field work alone due to the spatial heterogeneity in surface and unknown geological conditions under the land surface (Troch et al., 2009).

Computer-based hydrological models can be useful tools for estimating recharge rate and nutrient loading of surface and groundwater at various scales (Lerner et al., 1990). A properly validated model can provide a fast and cost effective way to estimate impacts of various agricultural practices on hydrological components and water quality indicators. Model prediction could assist policy makers in making informed decisions. For example, the Soil Water Assessment Tool (SWAT) has been widely used in agricultural applications around the world.

SWAT is considered the primary semi-distributed, process-based hydrologic model for evaluating impacts of land management practices on water, sediment and agricultural chemical yield in large complex watersheds with varying soils, land use and management conditions over long periods of time under different climatic and topographic conditions (Arnold et al., 1994; Neitsch et al., 2005; Yang et al., 2009). Theoretically, SWAT is able to estimate spatial recharge rate and nitrate leaching to deep soil layers and can be used for analyzing the impact of land use on recharge rate and nitrate loading into groundwater systems (Neitsch et al., 2005). However, the SWAT model can only be used for watersheds where it has been calibrated. In addition, model calibration and validation are usually constrained by data availability and ease of use. When up-scaling a calibrated model prediction of groundwater recharge rate and nitrate loading for a small watershed to a large watershed, it is usually the land use that determines the quality of a particular model prediction. Therefore, a model calibrated for a specific watershed at a specific time cannot be directly transferred to other regions with different land uses, biophysical conditions, or at a different time (Calder, 1992). However, given the fact that the groundwater recharge and nitrate loading can be calculated for each hydrological response unit (HRU) within the SWAT model, its prediction of groundwater recharge rate and nitrate loading after a valid calibration can be summarized according to key variables (e.g., land use), then fit to simple empirical models. The fitted models would allow extrapolation of SWAT model results to areas where calibration data are unavailable.

The objective of this study is to explore a novel method for up-scaling SWAT model predictions from a small watershed to a large watershed level through the following steps: (1) calibrating the SWAT model for estimating monthly groundwater recharge rate and nitrate loading; (2) examining the impact of land use when interacting with soil, topography and climatic conditions on groundwater recharge rate and nitrate loading; and (3) developing empirical models that can be used to estimate spatially explicit groundwater recharge and nitrate loading under different land use, topographic, soil, and climate conditions.

2. Materials and methods

2.1. Research site

The Black Brook Watershed (BBW) (47°5′N–47°9′N, 67°44′W–67°48′W) is located in northwestern New Brunswick, Canada, and it has a history of intensive agricultural land use. It has been the subject of long term research examining the impacts of various agricultural activities on water quality for decades (Chow et al., 2011). The area of the watershed is 14.5 km^2, with 65% covered by agricultural land, 21% by forests, and 14% by residential areas and wetlands (Fig. 1 and Table 1). Elevation in the watershed ranges from 180 to 260 m above mean sea level. The climate of the region is moderately cool with approximately 120 frost-free days annually (Yang et al., 2009). The annual mean temperature is 3.2 °C. Annual average precipitation is about 1100 mm (Xing et al., 2009). Snow-melting leads to major surface runoff and groundwater recharge events, with the highest stream discharge typically estimated between March and May (Chow et al., 2011; Li et al., 2014; Zhang et al., 2013). The annual evapotranspiration is estimated to be about 400 mm, using SWAT model calibrated in this study. Soil survey at the scale of 1:10,000 identified six mineral soils including: Grand Falls, Holmesville, Interval, Muniac, Siegas and Undine and one organic soil: St. Quentin (Fig. 2 and Table 2; Mellerowicz et al., 1993). Slopes vary from 1–6% in the upper basin to 4–9% in the central area, and in the lower portion of the watershed, slopes are more strongly rolling at 5–16% (Valentin, 2002). The primary hydrogeological unit in the BBW is overlain by a relatively thin layer of glacial drift with a highly fractured, limestone bedrock aquifer (Kierstead, 1993). Average groundwater depth from 2008 to 2009 is about 10 m with