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Hydrologic modeling and evaluation of Best Management Practice scenarios for the Grand River watershed in Southern Ontario

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ABSTRACT

The Grand River is the largest river in Southern Ontario feeding Lake Erie with water, sediment, and nutrients. Understanding the watershed hydrological processes is crucial to support decision making on reducing non-point source pollution from the watershed into Lake Erie. In this study, the Soil and Water Assessment Tool (SWAT) was adapted to Canadian conditions and applied to the Grand River watershed in Southern Ontario to simulate hydrologic processes based on available geospatial, climate, management, flow, and water quality data. The SWAT was calibrated based on flow, sediment, and nutrient concentrations at eight flow gauging stations and seven water quality stations. The calibrated model was then applied to evaluate the potential effects of Best Management Practices (BMPs) including nutrient management, buffer strip, cover crop, and wetland restoration on water quantity and water quality in the watershed. The evaluated results showed that the BMPs of nutrient management and wetland restoration have more significant impacts on nutrient reduction at the watershed outlet to Lake Erie based on the BMP implementation and extent that were applied in this study. The SWAT modeling, findings, challenges, and recommendations for future research in the Grand River watershed are also discussed in this paper.

Introduction

Environment Canada's Great Lakes Nutrients Initiative (GLNI) aims to address the complex problems of recurrent toxic and nuisance algae, nearshore water quality and ecosystem health in the Great Lakes. The main priority tasks are: (1) to establish current nutrient loadings from selected Canadian tributaries, (2) to enhance knowledge of the factors that impact tributary and nearshore water quality, ecosystem health, and algae growth; (3) to establish binational lake ecosystem objectives, phosphorous objectives, and phosphorous load reduction targets; (4) to develop policy options and strategies to meet phosphorous reduction targets; and (5) to develop a binational nearshore assessment and management framework (http://ec.gc.ca/grandslacs-greatlakes/). GLNI promotes a cumulative effects management approach to effectively plan for and manage the complex impacts of man-made developments in the contributing watersheds of the Great Lakes. The application of state of the art watershed and water quality models, to evaluate the achievement of environmental outcomes under various management options, has been identified as a key component in providing decision support for implementing the proposed water quality management framework under the Canada–United States Great Lakes Water Quality Agreement (GLWQA). Therefore, an integrated watershed modeling of the contributing watersheds and assessment of various conservation management practices are crucial in supporting decision making on water management as well as maintaining a healthy water environment of the Great Lakes.

Green cover, crop management, and other conservation programs established under the environmental component of the Canadian Agricultural Policy Framework (APF), have been implemented progressively on the agricultural landscapes of Canada. These programs have been introduced to mitigate the adverse environmental effects of agricultural production and to improve water quality in streams and water bodies. In the Lake Erie Ecosystem Priority (LEEP) report (International Joint Commission, 2014), the implementation of Best Management Practices (BMPs) is promoted in the contributing watersheds to reduce phosphorous and other contaminant loads to Lake Erie. In the Canada-Ontario Farm Stewardship Program (COFSP), a BMP is defined as an agricultural management practice which ensures the long-term health and sustainability of land-related resources used for agricultural production; positively impacts the long-term economic and environmental viability of the agricultural industry; and minimizes negative impacts and risk to the environment. Accordingly, quantifying the effectiveness of these BMPs in reducing non-point source (NPS) pollution and in improving stream water quality has become a priority for an integrated watershed

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management and land use plan. Examples are the US Conservation Effects Assessment Project (CEAP) (Tomer and Locke, 2011) and the Canadian Watershed Evaluation of BMPs (WEBs) Program (Yang et al., 2007) which used a combined monitoring and modeling approach to evaluate the BMP performances across the country at both watershed and field scales.

The Soil and Water Assessment Tool (SWAT), developed by Agricultural Research Service (ARS) of the United States Department of Agriculture (USDA), has been applied extensively across the world to simulate hydrologic processes and examine the impacts of land use and land management changes in agricultural watersheds (Arnold et al., 2012). Example applications of SWAT for simulating the hydrologic processes which encompassed different continents and landscapes include Meaurio et al. (2015), Kushwaha and Jain (2013), and Liu et al. (2008). Example applications of SWAT for estimating water quality behavior and BMP performance in a watershed include Baker and Miller (2013), Dechmi and Skhiri (2013), and Liu et al. (2015). A more detailed documentation of SWAT applications is provided in Gassman et al. (2014). In the Great Lakes region, example applications of SWAT for simulating watershed hydrology and climate change studies include Inamdar and Naumov (2006), Wu and Johnston (2007), Wiley et al. (2010), Bosch et al. (2011), and Daloglu et al. (2012). More recently, SWAT has been used to assess the impact of various land management scenarios on stream flow and water quality in the Great Lakes region, for example, the studies in Bosch et al. (2013), Shao et al. (2013), and Nejadhashemi et al. (2012). However, application of SWAT to Canadian cold weather conditions faces significant challenges, such as simulating snowmelt and runoff processes (Troin and Caya, 2014). As a result of uncertainties from input data, model parameters, and particularly process representations in the model, the timing and magnitude of simulated flood events might not agree with observed data and the statistical performance of SWAT daily simulations might be less satisfactory, causing uncertainties in the BMP scenario assessment.

In this study, we adapted and applied SWAT to characterize hydrologic processes in the Grand River watershed as well as to simulate flow, sediment, and nutrients at the watershed outlet and interior stations. In particular, land management practices including crop management, fertilizer management, tillage management, reservoirs, irrigation, tile drains, water uses, point sources, and wetlands were incorporated into the model to more properly reflect the actual watershed conditions. Based on available data and the watershed planning (GRCA, 2008), various BMP scenarios including nutrient management, buffer strip, cover crop, and wetland restoration were developed, and their impacts on flow and water quality were evaluated using the calibrated and validated SWAT model for the Grand River watershed. This is the first SWAT application for BMP evaluation in the Grand River Basin. An algorithm of rain-on-snow was developed in the model to simulate more properly the snowmelt runoff under local condition. The approach of multi-site and multi-objective calibration was conducted in the calibration and validation processes. Discussions on SWAT performance, modeling results, challenges, and recommendations for future research in the Grand River watershed were also provided in this paper.

Material and methods

The Grand River watershed

The Grand River flows 300 km through southwestern Ontario into Lake Erie and has a drainage area of approximately 6800 km^2, which comprises about 10% of the lake's total Canada/U.S. drainage area (Fig. 1). The watershed hosts approximately 1 million residents, mostly in the central region in cities that include Kitchener, Waterloo, Guelph, Cambridge and Brantford. In addition to nonpoint source pollution from agricultural activities, the Grand River also receives wastewater from about 30 communities of varying sizes. The flow in the Grand River is regulated by four major multi-purpose reservoirs: Luther, Belwood, Conestogo, and Guelph (Fig. 1). The Grand River Conservation Authority (GRCA) operates these reservoirs as a system to control floods and to maintain the river capacity for water supply and wastewater assimilation (Krause et al., 2001). Due to intensification of agriculture and growth of urban centers, the Grand River watershed has been facing significant challenges in managing its water quantity, quality, and ecosystem health (GRCA, 2008; Loomer and Cooke, 2011).

Surface elevation in the Grand River watershed ranges from 173 m above sea level at the mouth to 535 m in the northern headwaters. The slope pattern has a minimum of 0% and a maximum of 37.9%, with an average of 1.55% obtained from the 10-m resolution provincial Digital Elevation Maps (DEM). Major soil types in the watershed are Perth, Huron, Guelph, Burford, and Brantford covering areas of 632, 526, 399, 277, and 276 km^2, and are 9.4%, 7.8%, 5.9%, 4.1%, and 4.1%, respectively, of the watershed. Based on the GRCA land use and landcover data, the watershed has cropland 47.8%, forest 16.5%, pasture 8.3%, grassland 20.8%, urban 4.4%, transportation 0.5%, and open water 1.7% estimated from the GRCA land use map.

The Grand River watershed has a moderate to cool temperate climate. Weather patterns in the watershed consist of four seasons including winter, in which the majority of the precipitation is in the form of snow, and summer, which is hot and humid. A warm winter with little snow accumulation will lead to moderate spring flows, whereas a cold winter with heavy snow can lead to heavy spring runoff and floods (GRCA, 2008). July is the hottest month and January is the coldest month. Precipitation is fairly uniform throughout the year with characteristics of short intense rainfalls and thunderstorms in spring and summer, to steady gentle rainfalls in the autumn, and to heavy snowfalls in winter. Snowfall generally begins in the month of November and ends around April, while August has the highest average precipitation.

Because of varying geology, different hydrologic conditions exist in the watershed. The northern portion of the watershed is largely comprised of till plain characterized by high surface runoff and little ground infiltration. The central portion contains the majority of the watershed's moraines and sand/gravel deposits left by glaciation, resulting in high infiltration and relatively low surface runoff. The southern portion of the watershed is dominated by the Haldimand Clay Plain, which produces extremely high surface runoff with little infiltration (GRCA, 2008). Fig. 2 shows the average monthly flow variation calculated based on the 1990–2013 flow data observed at the York station (Fig. 1). The distribution shows a strong runoff component in winter and spring caused by snowmelt and rain storms.

Data preparation

Three types of input data including geospatial, climate, and land management are required for SWAT setup, while the monitoring data of flow and water quality are required for model calibration and validation. The 10-m DEM for the Grand River watershed was obtained from Land Information Ontario (LIO). The soil data were obtained from Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA), while calculations were conducted to estimate soil attribute values for missing parameters in the user soil table including available water capacity, rock fragment content, moist soil albedo, and Universal Soil Loss Equation (USLE) erodibility factor using equations documented in the SWAT user manual (Neitsch et al., 2010). Other geospatial data including land use, wetland inventory, stream network, and watershed boundary were obtained from GRCA.

The locations of environmental monitoring stations are shown in Fig 1. The watershed has precipitation and temperature data at 12 stations, wind speed and relative humidity data at four stations, and solar radiation at one station obtained from Environment Canada (EC). The missing data for precipitation, temperature, wind speed, and relative humidity were filled using data at nearby stations for the period 1989–2013. For instance, precipitation and temperature data at Mount Forest station, located at the northwest part of the watershed, was