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Watershed derived nutrients for Lake Ontario inflows: Model calibration considering typical land operations in Southern Ontario

Masoud Asadzadeh [a,b], Luis Leon [a,*], Craig McCrimmon [a], Wanhong Yang [c], Yongbo Liu [c], Isaac Wong [a], Phil Fong [a], Gary Bowen [d]

[a] Environment Canada, National Water Research Institute, Burlington, ON, Canada
[b] Civil Engineering Department, University of Manitoba, Winnipeg, MB, Canada
[c] Department of Geography, University of Guelph, Guelph, ON, Canada
[d] Toronto and Region Conservation Authority, Toronto, ON, Canada

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ABSTRACT

Continuous daily simulation of watershed-derived nutrient and sediment loads is required to estimate nearshore water quality in Lake Ontario and the impact of watershed beneficial management practices on lake water quality. In this study, the Soil and Water Assessment Tool (SWAT) is used to build watershed models that incorporate detailed information about representative land operation activities applicable to agricultural watersheds in Southern Ontario. SWAT is calibrated in a multi-objective simulation–optimization framework for the Rouge River watershed with a relatively high spatial resolution monitoring network. These parameters were directly applied to the model for an adjacent watershed, Duffins Creek. The model performed satisfactorily in both watersheds in terms of water balance and temporal, vertical, and spatial redistribution of water. Assessment of the model performance metrics shows a good agreement in the frequency distribution of measured and simulated water quality constituents. Both watersheds are experiencing rapid urbanization, so decision makers in the region may find the developed model useful to analyze the impact of future landuse and operation changes on watershed-derived sediment and nutrients to be delivered into Lake Ontario.

Introduction

Lake Ontario is more than a water resource for over six million residents of the Province of Ontario in Canada. Besides being the main source of drinking and industrial water intake, it also supports recreational activities in its nearshore area. Recently, Lake Ontario nearshore areas have suffered from impairments, such as excessive algae, that can alter their use and negatively impact the development of the region (Makarewicz and Howell, 2007). Invasive mussels in the lake are partly responsible for the resurgence of *Cladophora* by transforming scarce phosphorus into more bioavailable forms of phosphorus (Hecky et al., 2004; Malkin et al., 2008, 2010). Watershed-derived nutrients also play an important role in the resurgence of the nuisance algae, indicating that anthropogenic activities in watersheds that discharge into the lake could certainly impact nearshore water quality (Higgins et al., 2012; Howell et al., 2012). Depew et al. (2011) showed that nearly 95% of the total variation in *Cladophora* could be explained by the joint contribution of watershed-derived nutrients and suspended matter and mussel abundance in the lake.

This study is a step forward in the development of an integrated watershed-lake scale water quality analysis in Southern Ontario by using hydrologic and water quality models, built for the Rouge River and Duffins Creek, which link land use activities to the watershed-derived nutrient response. Both models, for the Rouge River and Duffins Creek watersheds, were constructed using the Soil and Water Assessment Tool (SWAT). Within these watersheds, the Toronto and Region Conservation Authority (TRCA) has been investing in the acquisition of public lands with low intensity agricultural activities to implement beneficial management practices (BMPs) geared towards watershed conservation (TRCA, 2003). Also, both the Rouge River and Duffins Creek watersheds are experiencing some of the most rapid urbanization in the Greater Toronto Area, and it is expected that stakeholders and conservation decision-makers in the region may benefit from the results of this study in designing their plans towards environmental sustainability, both for the watersheds and Lake Ontario. Our study, like others (e.g., Bracmort et al., 2006; Arabi et al., 2007; Baker and Miller, 2013; Bosch et al., 2013), provides a management decision tool that can analyze BMPs and estimate nutrient loadings to be used in the analysis of the water quality and ecology of Lake Ontario. SWAT can integrate a wide range of information about land use activities into the estimation of watershed hydrology and water quality (Eckhardt and Arnold, 2001; Abbaspour et al., 2007; Bekele and Nicklow, 2007; Wu and

* Corresponding author.
E-mail address: luis.leon@ec.gc.ca (L. Leon).

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Johnston, 2007; Easton et al., 2008; Li et al., 2010; Strauch et al., 2012). As the product of more than thirty years of research in the United States Department of Agriculture—Agricultural Research Service, a detailed chronology of SWAT developments are documented in Neitsch et al. (2011). Land modification activities that can be modeled in SWAT include, but are not limited to, the beginning and the ending of the growing season, timing and type of tillage operations, and timing and rate of fertilizer applications. Being able to model these activities, such as the type of tillage which impacts the infiltration rate by leaving different amount of crop residue on the land (Rawls and Richardson, 1983; Hansen et al., 2000; Alvarez and Steinbach, 2009), is needed for baseline modeling and for the analysis of BMPs involving such activities. Finally, one of the main challenges in studying non-point source pollution from watersheds is the low frequency of measured water quality data. The availability of resources for water quality monitoring programs in Southern Ontario, as well as in most jurisdictions around the Great Lakes, is increasingly constrained by costs. The SWAT models developed in this study could potentially be applied to similar watersheds around Lake Ontario that lack adequate monitoring.

Methods and materials

Study area

Our study area includes the Rouge River and Duffins Creek watersheds that cover parts of the cities of Pickering, Toronto, the towns of Ajax, Whitchurch-Stouffville, Markham, and Richmond Hill, as well as the Regional Municipality of Durham. The Rouge River and Duffins Creek drain respectively an area of 331 km^2 and 283 km^2 of land in the South-Central part of the Greater Toronto Area, within a humid continental climate region with warm summers and mild winters moderated by the Great Lakes. Both rivers flow from the Northern Oak Ridges Moraine (elevations as high as 370 m above the sea level) towards Lake Ontario in the south (elevations as low as 64 m above sea level) with a 4.4% average slope. The majority of the population in this region receives drinking water from treatment plants that take the water from Lake Ontario and most of the wastewater is discharged back into the lake after treatment (TRCA, 2012). Therefore, it is assumed that the main source of input water to these watersheds is precipitation and that there is no significant waste treatment point source of nutrients.

Soil and Water Assessment Tool

The Soil and Water Assessment Tool (SWAT version 2009—revision 528) was employed in this study to build the computer model for the Rouge River and Duffins Creek watersheds. SWAT estimates runoff, sediment yield and nutrient loads at the sub-basin level as a continuous watershed scale simulation model that operates on a daily time-step. SWAT divides a watershed into multiple sub-basins that contain smaller homogeneous sectors of soil and landuse characteristics that are called hydrologic response units (HRU). The model generates flow, sediment yield and nutrient loads across all HRUs and then aggregates the constituents for each sub-basin. SWAT routes the resulting flow and loads of sediments and nutrients through the drainage network downstream towards the watershed outlet (Arnold et al., 1998; Di Luzio et al., 2001). The Soil Conservation Service (SCS) method (USDA Soil Conservation Service, 1972) was selected to calculate daily surface runoff because the key parameter (Curve number or CN) is a function of landuse, soil type, soil permeability, antecedent soil water condition, and land slope. The SCS method enables SWAT users to analyze the impact of future landuse scenarios on the hydrology and water quality behavior of the model. The SWAT user manual (Neitsch et al., 2011) provides recommended CN values for different landuse and soil types based on their hydrologic soil group. Erosion, sediment yields, and total suspended solids (TSS) are calculated in SWAT based on the modified Universal Soil Loss Equation (MUSLE). Daily nutrient loads, including total Nitrogen (TN) and total Phosphorus (TP), are estimated by SWAT based on the initial concentration in the top soil, the sediment yield and enrichment ratios, as defined in the nutrient cycles for N and P in the model. For further details about SWAT and all of the main components see Neitsch et al. (2011).

Input data sources

Landuse

Landuse classes in the Rouge River and Duffins Creek watersheds are based on the land cover maps and data prepared by the Toronto and Region Conservation Authority (TRCA). As shown in Table 1 and Fig. 1a, our study area had contrasting landscapes that include agricultural lands and public green spaces co-existing with municipal and/or private sector infrastructure (i.e., sewage treatment plant, potable water intake, power generation station). Statistics from the agricultural census, reported by the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA, http://www.omafra.gov.on.ca/english/stats/crops/index.html) for the period of 2005 to 2011 were reviewed to identify the portion of agricultural lands that produced the major crops in our area of interest. The Durham Regional Municipality includes the Duffins Creek watershed and a portion of the Rouge River watershed. The four major crops planted in the agricultural lands in Southern Ontario were hay, corn, soybean, and winter wheat. Table 2 shows that on average 38% of agricultural lands in the Durham region produced hay, 30% produced corn, 22% produced soybean, and 10% produced winter wheat. According to habitat management in TRCA (B. Clay, pers. comm.) most farmers follow two crop rotation schedules in this area: a) four-year rotation to produce corn, corn, soybean, and winter wheat, or b) two-year rotation to produce corn and soybean. Often, hay is not rotated with any other crops over six to seven years. The generic agricultural class in SWAT was divided into seven sub-classes (Table 3) to emulate these crop rotations and agricultural census statistics. The areal portion of agricultural landuse in each sub-basin was specified for each of the seven landuse sub-classes such that 40% of agricultural land in each watershed produced hay, 30% corn, 20% soybean and 10% winter wheat in each year. The difference between the first six sub-classes in Table 3 comes from the difference in their land operations.

Land operations

A wide range of information about land operations in each HRU was incorporated in the model, including: cultivation, planting, tillage and fertilizer applications, and harvesting. Following Neitsch et al. (2011), all operations were scheduled by their application date. The main source of P and N in our study area came from the fertilizers applied to lawns, gardens and agricultural lands (TRCA, 2002, 2007b). According to Leon et al. (2004), fertilizer application rates in Reesor Creek Survey (1998) were reasonable for watershed modeling purposes in our study area. Table 4 shows that N and P fertilizer application rates utilized in Leon et al. (2004) are consistent with values reported in OMAFRA (2002) for soybean and corn but not for winter wheat and hay. In this study, the N and P fertilizer rates for corn and soybean and the P rate for hay were obtained from Leon et al. (2004) and the other rates were obtained from OMAFRA (2002). According to TRCA (B. Clay, pers. comm.) most farmers in the region apply plow and disc at least in the spring to prepare a seed bed and incorporate the crop residue. Based on OMAFRA (2002), a spring field cultivator or tandem

Table 1
Percent of Rouge River and Duffins Creek watersheds devoted to each major landuse class.

Watershed	Landuse			
	Agricultural	Natural	Urban	Watercourse
Rouge River	40	24	35	1
Duffins Creek	55	35	8	2