REVIEW ARTICLE

A brief review on SWAT applications in the Great Lakes Watersheds

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Abstract Soil and Water Assessment Tool (SWAT) is an efficient model to simulate hydrology and water quality in large watersheds. During the past decades, SWAT has been used as a decision support tool to evaluate environmental effects of land usage change, BMPs, and hydraulic structures in Great Lakes watersheds. In addition, it has been increasingly used to predict water resources under different climate change scenarios. This paper briefly reviewed SWAT applications in various watersheds draining into the Great Lakes and intended to provide readers with insights regarding water quality issues in the Great Lakes concerned by researchers and capability of SWAT in dealing with those problems. Future development of SWAT with respect to dealing with cold region climate and vegetation conditions was also discussed.

Keywords Water quality · Soluble active phosphorus · Nitrate · Suspended sediment · Climate change

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Water quality issue in the Great Lakes and SWAT model

The Great Lakes basin covers an area of 764 568 km^2 and includes both USA and Canada. The USA portion of the area includes all or part of eight states and the Canadian portion includes part of the Province of Ontario. The basin is one of the most industrialized regions in the world. The municipal, industrial, and commercial use of water resources during urbanization processes in the last century has led to a concomitant deterioration of Great Lakes water quality. Extensive agricultural activities of the surrounding land have complicated this issue. This is particularly the case in the lower Great Lakes basins. Nutrient export to the Great Lakes through stream loading has been identified as a major contributor to water quality problems (Bosch et al, 2011). In the 1970s, Great Lakes experienced eutrophication problems associated with nutrient enrichment. Scientists realized the most effective means of controlling eutrophication is to reduce phosphorus (P) levels (Boyce et al, 1987). During that time, the reduction of loadings from nonpoint sources has received less attention than point source controls as a method of controlling eutrophication. The 1972 Great Lakes Water Quality Agreement brought about attempting to reduce point source loadings of P. Since then annual P loads from tributaries have dramatically decreased and many of the effects of eutrophication in the lakes were reversed (De Pinto et al, 1986). However, Since the mid-1990s Great Lakes (especially Lake Erie) appears to be returning to a more eutrophic state (Force, 2010; Michalak et al, 2013; Murphy et al, 2003), as indicated by increases in cyanobacteria (Bridgeman et al, 2012), the resurgence of extensive benthic algae growth (Depew et al, 2011), and the return of extensive CB hypoxia (Burns et al, 2005). In recent years, the extent of hypoxia and harmful algal blooms (Michalak et al, 2013) has drawn attention to the potential importance of land-derived nutrients in a resurgence of eutrophication symptoms in Lake Erie (Scavia et al, 2014). The problem also extends to other major bays, such as Green Bay in Lake Michigan, Saginaw Bay in Lake Huron, and the Bay of Quinte in Lake Ontario.

Many studies have found that point-source control projects alone were not adequate to reduce nutrient loading (De Pinto et al, 1986; Dolan and McGunagle, 2005). On the other hand, nonpoint sources often account for more than 70% of total stream loadings in Lake Erie (Dolan and McGunagle, 2005), and fertilizer application is the largest input of nitrogen (N) and P in agricultural watersheds (Han and Allan, 2008). As a result, attention has gradually shifted to nonpoint sources to confront water quality problems in the Great Lakes. Watershed characteristics and nutrient inputs determine nutrient loadings to the Great Lakes. Studies demonstrated the relationship between stream nutrient exports and characteristics of watersheds, including land use and nutrients inputs (Baker and Richards, 2002; Han et al, 2011). For example, cropland has larger N and P losses per unit area than pasture or forest (Cooke and Prepas, 1998). Crop land use is associated with P fertilization and increased soil erosion caused by tillage practices (Sharpley, 1999). Clearly, it is important to incorporate point and nonpoint sources of N and P into models as well as other watershed characteristics such as soil, landscape, and management practices to accurately predict nutrient loadings to the Great Lakes. Export of nutrients from agricultural watersheds in the Great Lakes is a major driver in the re-eutrophication of Lake Erie and major embayment, e.g, Saginaw Bay and Green Bay. For this reason, many efforts have been devoted to understanding the relationship between agricultural land use and management practices and water quality using distributed hydrological models in the Great Lakes states (or provinces in Canada). Soil and water assessment tool (SWAT) is one of the most frequently used watershed simulation model. Since the first SWAT application in this area, ongoing studies have promoted understanding of point and nonpoint pollution sources and control in the Great Lakes area.

As a process-based semi-distributed watershed model, SWAT is designed to simulate hydrological processes and predict water quantity and quality as affected by land use, land management practices, and climate change (Arnold et al, 1998; Gassman et al, 2007). It provides a flexible framework that allows for the simulation of the effects of a broad range of BMPs (Fig. 1), such as those associated with the application of fertilizer and manure, cover crops, filter strips, conservation tillage, irrigation, and flood-prevention structures (Bracmort et al, 2006; Gassman et al, 2005; Ullrich and Volk, 2009). It is currently one of the most widely used hydrological models for water resource assessment and watershed management (Gassman et al, 2007; Santhi et al, 2006; Yang et al, 2009a; Yang et al, 2009b). Many studies have used SWAT as a decision-support tool to evaluate the impact of land usage change and BMPs on water resources in large ungauged watersheds (Neitsch et al, 2011). The model analyzes small or large watersheds by discretizing them into subbasins which are then further subdivided into hydrological response units (HRUs) with homogeneous land use and soil properties and slope (Yan et al, 2013; Yang et al, 2009a). The model calculates the water balance (i.e, surface, and subsurface runoff, percolation and base flow, and evapotranspiration and transmission losses), crop growth, nutrient cycling, and pesticide movement at the HRU scale. Water flow, sediment, and nutrient loadings from each HRU in a subbasin are summed and the resulting loadings are then routed through channels, ponds, and reservoirs to the watershed outlet. Model outputs include HRU, subbasin, and watershed values for surface flow, lateral flow, base flow, and sediment and nutrient loadings (Fig.1). In addition, SWAT is a well-documented open-

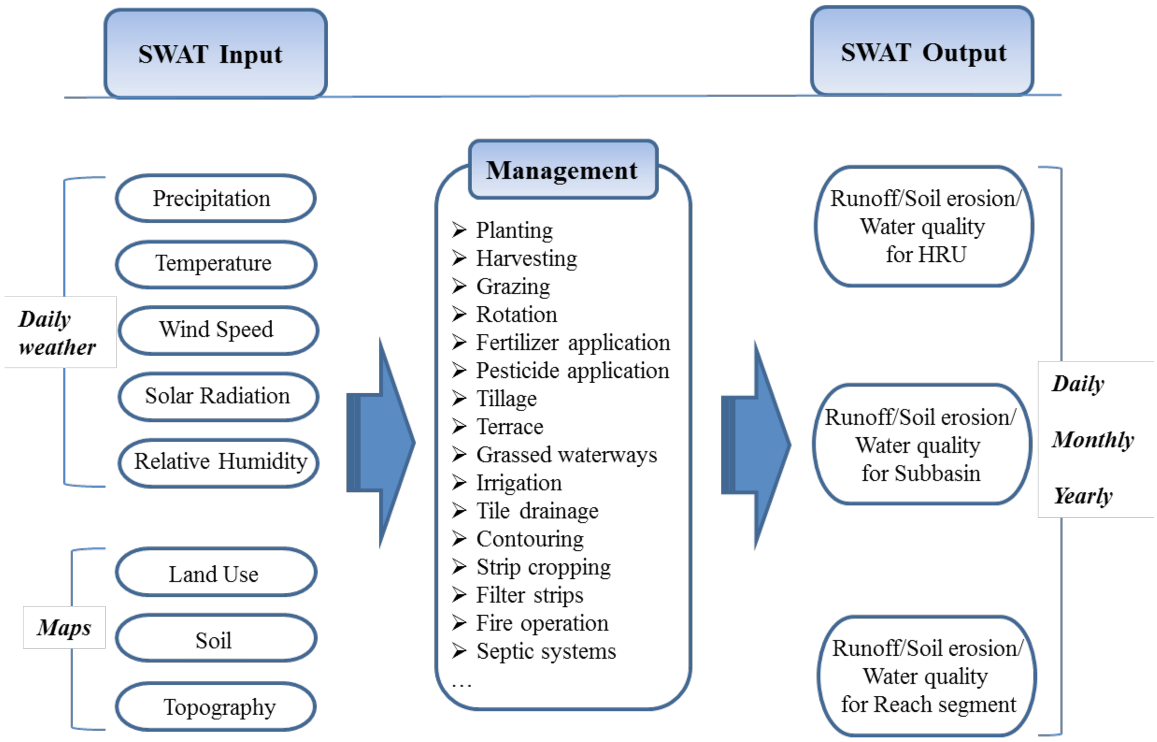

Figure 1. Inputs, outputs, and management options for SWAT

source model with many modifications that have been made to the original source code for different research purposes (Cools et al, 2011; Green and Van Griensven, 2008; Holvoet et al, 2008; Wu et al, 2013; Wu and Liu, 2012).

SWAT application to the Great Lakes Watersheds

SWAT has been applied to the Great Lakes watersheds for different purposes. Several studies have tested SWAT performance in simulating stream flow, sediment and nutrient loadings from watersheds and evaluated the suitability of SWAT for specific watershed conditions. Many studies applied calibrated SWAT in assessment of reduction effects of BMPs on nutrients such as soluble reactive phosphorus. Recently, attention has been turned to couple SWAT with climate change scenarios with the purpose to project future hydrological and biochemical processes and their effects on water quality and quantity in the Great Lakes. Furthermore, several studies were focusing on improving structures and functions in SWAT to adapt cold conditions. For example, Liu et al. (2016) adapted SWAT to Canadian conditions and applied to the Grand River watershed in Southern Ontario to simulate hydrologic processes and to evaluate the potential effects of BMPs including nutrient management, buffer strip, cover crop, and wetland restoration on water quantity and water quality in the watershed.

Model evaluation

Goel et al. (2004) evaluated SWAT for Canagagigue Creek watershed (143 km^2), a tributary of Grand River (draining into Lake Erie) in Ontario, Canada. The results showed that SWAT could be used for simulation of stream flows and sediment loading in the watershed. They also pointed out that winter freezing and spring thawing had great impact on various hydrological processes in the watershed and similar regions of Canada. In addition, Gebremeskel et al. (2005) confirmed the performance of SWAT to simulate stream flow and sediment yield in Grand River basin (7 000 km^2) by comparing with performances of other watershed models. Qi and Grunwald (2005) conducted a spatially distributed calibration and validation of water flow using SWAT in the Sandusky watershed (3 240 km^2) in Ohio, located in the Lake Erie watershed. Their findings showed that simulations of stream flow in the watershed and its subbasins were satisfying except for winter rainfall-runoff events. Furthermore, Grunwald and Qi (2006) assessed the capabilities of SWAT to simulate suspended sediment, phosphorus, and nitrogen loadings in the Sandusky Watershed and two subbasins. With variable simulation success, they concluded that SWAT performed poorly during winter rainfall-runoff events and careful calibration and validation were required to use SWAT. Wu et al. (2006) examined SWAT applicability in a Northern Michigan watershed, a 3,460 km^2 drainage basin to Lake Superior. Results indicated that SWAT was capable of simulating snow-melting dominated watershed. Furthermore, Wu and A Johnston (2008) determined the applicability of SWAT for modeling streamflow in two watersheds of the Ontonagon River basin (3 360 km^2; draining into the Lake Superior) of northern Michigan, which differ in proportion of wetland and lake area. They found model calibration and validation was satisfactory for both watersheds and the snow melting parameters were critical for SWAT application in this area. Bosch et al. (2011) tested SWAT model performance across six watersheds draining into Lake Erie to determine the applicability of SWAT to watersheds of differing characteristics. They suggested that SWAT accurately predicted average stream discharge, sediment, and nutrient loadings for Raisin (2 784 km^2), Maumee (17 030 km^2), Sandusky (3 455 km^2), and Grand (1 896 km^2) watersheds. As a result, SWAT could be used for various scenario testing for those watersheds. Asadzadeh et al. (2015) used SWAT to build watershed models that incorporate detailed information about representative land operation activities in Rouge River (331 km^2) and Duffins Creek (283 km^2) watersheds (draining into Lake Ontario), Southern Ontario, Canada. The models performed satisfactorily in both watersheds and were readily for decision making with respect to future landuse and BMPs. Keitzer et al. (2016) simulated sediment and nutrient processes and stream hydrology using the SWAT for western Lake Erie basin watershed.

Model application

After testing SWAT applicability in the Canagagigue Creek watershed, Goel et al. (2004) continued to evaluate various scenarios of management practices in the watershed for the selection of BMPs. Baumgart (2005) applied SWAT to the Lower Fox River Watershed (draining into Green Bay; 1 650 km^2) in Wisconsin to simulate daily stream flow, and suspended sediment and total phosphorus loadings from both urban and rural non-point sources. Inamdar and Naumov (2006) applied SWAT to determine annual sediment yields and critical source areas of erosion for the Buffalo River Watershed (draining into Lake Erie; 1 098 km^2) in western New York. The authors pointed out that snow parametrization was very important for successful simulation and the original snow hydrology component needs to be upgraded to account spatial variability in watersheds. They also suggested that ice scour may produce substantial amounts of sediment which SWAT could not characterize. Bosch (2008) applied SWAT to the Huron and Raisin watersheds in southeastern Michigan to better understand the effect of impoundments on riverine nitrogen and phosphorus exports. They found that modeled total P and total N loadings increased dramatically when zero impoundment was implemented in the watersheds. Also, impoundments placed close to river mouths or in N and P source areas were most effective at reducing nutrient loadings. Bosch et al. (2011) continued to use tested SWAT to model various sediment and nutrient load reduction strategies, including BMP implementation and source reduction in various combinations for six watersheds draining into Lake Erie (Bosch et al, 2013). Daloglu et al. (2012) used SWAT to model dissolved reactive phosphorus in the agriculture-dominated Sandusky watershed (draining into Lake Erie; 3 926 km^2), located in northwest Ohio, to explore potential reasons for the recent increased P loadings. They pointed out that incorporation of fertilizer especially under no-till practices was highly encouraged to reduce P accumulation in the soil surface layer. Michalak et al. (2013) used SWAT to test the impact of precipitation intensity and agricultural nutrient management practices on expected nutrient loading, to determine whether these factors are likely to be responsible for the loading observed in a record-setting algal bloom event for Lake Erie in 2011. Shao et al. (2013) integrated remote sensing-derived products and SWAT within a GIS modeling environment to assess the impacts of cropland change on sediment yield within four selected watersheds, i.e, St. Joseph River (12 132 km^2), St. Mary River (2 109 km^2), Peshtigo River (3 031 km^2), and Cattaraugus Creek (1 430 km^2) watersheds in the Great Lakes Basin. In the study, sediment yields were predicted to increase for possible future cropland change scenarios including converting other agricultural crop types to corn fields. Makarewicz et al. (2015a) employed SWAT to test the effectiveness of BMPs on land usage and to determine the minimum potential phosphorus concentration expected in the subbasins of Genesee River Watershed. Makarewicz et al. (2015b) continued to apply SWAT to determine the nutrient and sediment contributions of subbasins of Genesee River watershed under the current human-impacted conditions and contrasted against natural conditions. Gildow et al. (2016) used SWAT to evaluate the effectiveness of three practices in Maumee River watershed to reduce soluble reactive phosphorus and total phosphorus load to the Lake Erie. They found that fertilizer placement within the soil had the greatest potential to influence soluble reactive phosphorus loadings.

Climate change scenarios

Wu and Johnston (2007) compared the effects of different climatic conditions on parameter response and sensitivity of SWAT using datasets representing drought versus average conditions in the South Branch Ontonagon River (901 km^2) watershed of northern Michigan. Bosch et al. (2014) simulated various climate scenarios with a range of BMPs to assess possible changes in water, sediment, and nutrient loadings from four agricultural Lake Erie watersheds. They indicated that BMPs become more necessary but less effective under future climates; however, higher BMPs implementation rates still could offset anticipated increases in sediment and nutrient loadings. Cousino et al. (2015) inputted data from CMIP5 models into a calibrated SWAT model of the Maumee River watershed to determine the effects of climate change on watershed yields. Tillage practices were also altered within the model to test the effectiveness of conservation practices under climate change scenarios. They found that No-till practices had a negligible effect on flow but produced 16% lower average sediment loadings than scenarios using current watershed conditions. Verma et al. (2015) studied the impacts of projected climate change on hydrology and water quality within the Maumee River watershed lying in the Lake Erie Basin using SWAT. Compared to the baseline, the model projected a 2.9°C rise in the annual average temperature along with a 3.2% fall in the annual precipitation in the mid-century time-period and annual flow volumes, and suspended solids, total P, nitrate loadings were projected to reduce by 8.5%, 10.4%, 8.5% and 9.9%, respectively.

Conclusion

SWAT is an efficient tool to simulate hydrology and water quality in large watersheds which drain into the Great Lakes. During the past decades, SWAT has been used as a decision support tool to evaluate environmental and economic effects of land use change, BMPs, and hydraulic structures in Great Lakes watersheds. In addition, it has been increasingly used to predict water resources under different climate change scenarios. All those applications are based on the implication that SWAT could provide reliable information on hydrological and biochemical processes from soils, land use units, and subbasins to streams and lakes. However, SWAT is not perfect and it is still under ongoing development by many researchers around the world. The application of SWAT to the Great Lakes area require special considerations subject to cold region climate and vegetation conditions. However, the current released versions of SWAT are incapable of simulating several key processes in winter. For example, SWAT employs an empirical soil temperature module to predict soil temperature in winter (Qi et al, 2016a; Qi et al, 2016b). This module is not sensitive to snow cover evolution in cold regions and tended to underestimate soil temperature in winter.

In addition, the simple temperature index snow module currently equipped with SWAT is insufficient with respect to complex snow evolution processes in cold regions (Qi et al, 2017a). The interactions between snow and soil temperature in cold regions have great impacts on physical, biological, and chemical processes in watersheds. To correctly simulate water quantity and quality in cold regions, modeling of soil moisture distribution, soil temperature, and snow melt need to be improved to accurately simulate freezing and thawing processes (Qi et al, 2017b). We could expect that an enhanced version of SWAT can not only improve hydrology and water quality simulations but also further benefit climate change studies in the Great Lakes.

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