Ecological Modelling 268 (2013) 123–133

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Identifying critical source areas of nonpoint source pollution with SWAT and GWLF

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ARTICLE INFO

Article history:
Received 15 June 2013
Received in revised form 13 August 2013
Accepted 14 August 2013
Available online 14 September 2013

Keywords:
SWAT
GWLF
Critical source area
Water quality modelling
Nonpoint source pollution

ABSTRACT

Identification of critical source areas (CSAs) (areas contributing most of the pollutants in a watershed) is important for cost-effective implementation of best management practices. Identification of such areas is often done through watershed modeling. Various watershed models are available for this purpose, however it is not clear if the choice (and complexity) of a model would lead to differences in locations of CSAs. The objective of this study was to use two models of different complexity for identifying CSAs. The relatively complex Soil and Water Assessment Tool (SWAT) and the simpler Generalized Watershed Loading Function (GWLF) were used to identify CSAs of sediment and nutrients in the Saugahatchee Creek watershed in east central Alabama. Models were calibrated and validated for streamflow, sediment, total nitrogen (TN) and total phosphorus (TP) at a monthly time scale. While both models performed well for streamflow, SWAT performed slightly better than GWLF for sediment, TN and TP. Sub-watersheds dominated by urban land use were among those producing the highest amount of sediment, TN and TP loads, and thus identified as CSAs. Sub-watersheds with some amount of agricultural crops were also identified as CSAs of TP and TN. A few hay/pasture dominated sub-watersheds were identified as CSAs of TN. The identified land use source areas were also supported by field collected water quality data. A combined index was used to identify the sub-watersheds (CSAs) that need to be targeted for overall reduction of sediment, TN and TP. While many CSAs identified by SWAT and GWLF were the same, some CSAs were different. Therefore, this study concludes that model choice will affect the location of some CSAs.

1. Introduction

Approximately 67% of lakes, reservoirs and ponds, and 53% of rivers and streams in the U.S. are classified as impaired, needing immediate attention (USEPA, 2013). Impairment of water bodies due to elevated levels of nutrients and sediments originating from upland areas (i.e. watersheds) is a serious problem around the world. High level of nutrients can cause problems such as toxic algal blooms, oxygen deficiency, fish kills, and loss of biodiversity. These problems can also make the water unsuitable for drinking, industrial, agricultural and recreational use (Carpenter et al., 1998).

Watershed management offers a strong basis for developing and implementing effective management strategies (such as riparian zones, vegetation strips, retention ponds, etc.) to protect water resources (USEPA, 2003). Past efforts in reducing pollutant loads from watersheds have mainly focused on point sources and have failed to adequately address the impact of nonpoint sources. If nonpoint sources of pollutants are not addressed, water bodies can continue to be impaired (USEPA, 2003). However, nonpoint sources of nutrients and sediments are difficult to identify and control because they originate from spatially and temporally varying areas (Carpenter et al., 1998).

The level of sediment and nutrient contribution from different parts of a watershed can vary substantially. Some typically small and well defined areas contribute much of the sediment, P, and N into the watershed outflow (Walter et al., 2000; Pionke et al., 2000) and over relatively short periods (Dillon and Molot, 1997; Heathwaite et al., 2005). But in many situations source areas are not well defined but diffused. Certain areas with a particular type of soil, land use/cover and slope are more vulnerable than the others in terms of nutrient and sediment loss. These areas are known as critical source areas (CSAs). It is extremely important to identify these sources of pollutants for cost-effective management practices.

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http://dx.doi.org/10.1016/j.ecolmodel.2013.08.007

Identifying nutrient and sediment loss prone areas in a watershed and concentrating management efforts in those areas have been recommended in numerous studies (e.g., Nonpoint Source Task Force, 1984; Tim et al., 1992; Zhou and Goa, 2008). Such areas can be identified through sub-watershed level water monitoring, simulation modeling, or both (Sharpley et al., 2002). Direct water monitoring and field studies are usually costly and labor intensive, and require a number of years of monitoring to sufficiently account for climatic fluctuations. The use of watershed models, such as Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) and Generalized Watershed Loading Function (GWLF) (Evans et al., 2002), can avoid most limitations associated with field studies and can help in identifying and prioritizing sub-watersheds for cost-effective implementation of management practices (Tripathi et al., 2005; Ouyang et al., 2008; Georgas et al., 2009).

GWLF has widely been used for estimating streamflow, nitrogen (N) and phosphorus (P) loadings (Swaney et al., 1996; Lee et al., 2000), hydrochemistry (Schneiderman et al., 2002) and also for assessing changes in streamflow (Chang, 2003; Wu et al., 2007) and water quality (Tu, 2009) under different land use scenarios. GWLF has also been used for identification of CSAs at sub-watershed level (Markel et al., 2006; Georgas et al., 2009). Similarly, SWAT has been used around the world for predicting streamflow, and sediment and nutrient loads from watersheds (Spruill et al., 2000; Kirsh et al., 2002; Veith et al., 2005; Srivastava et al., 2006; Jha et al., 2007; Niraula et al., 2012a,b). SWAT has also been used in several studies for identification and prioritization of CSAs of sediments and nutrients (Tripathi et al., 2005; Ouyang et al., 2008; White et al., 2009; Ghebremichael et al., 2009; Panagopoulos et al., 2011; Shang et al., 2012; Niraula et al., 2012a).

Wanger et al. (2007) studied the impact of alternative water quality models, by comparing GWLF and SWAT, on pollutant loading for Total Maximum Daily Loadings (TMDL) development. The use of alternative water quality models resulted in differences in required sediment reduction. The SWAT model load estimates were consistently larger than loads from GWLF. However, it is not clear if the use of different models would lead to different CSAs that are significant enough for practical implementation of Best Management Practices (BMPs). In a related study, Niraula et al. (2012b) found that calibration of the SWAT model had very little effect on locations of nutrients and sediment CSAs. Therefore, the objective of this study was to assess the effect of model choice on CSA locations. Two models of different complexity, SWAT and GWLF, were used for this purpose. Both models were utilized to identify sediment and nutrients CSAs in the Saugahatchee Creek watershed in east central Alabama.

2. Methodology

2.1. Study area

The 570 km^2 Saugahatchee Creek watershed (Fig. 1), selected for this study, is a sub-watershed of the Lower Tallapoosa sub-basin in east central Alabama. The watershed, as determined using National Land Cover Data (NLCD, 2001), was comprised of 67.8% forest, 10.0% grassland, 11.7% agricultural land (hay/pasture and row crops) and 8.4% urban area (Fig. 1). Although most of the watershed lies in the Piedmont physiographic province, a small portion lies in the Coastal Plains. The Piedmont covers a transitional area between the mostly mountainous Appalachians in the northeast and the relatively flat Coastal Plains in the southeast Alabama. While the soils in the Piedmont are dominated by loam and sandy loam, soils in remaining coastal plains are sandy loam based on the STATSGO soil database. Elevation in the watershed varies from 103 to 255 m. The study area is characterized by hot summers and mild winters with average temperatures of 26 °C and 7 °C, respectively. The long term annual average rainfall in the watershed is 1336 mm. Alabama Department of Environmental Management (ADEM) has identified two segments within the Saugahatchee Creek watershed as being impaired for nutrients and organic enrichment/dissolved oxygen (ADEM, 2008). The nutrient of concern in both of the tributaries is phosphorus. ADEM also recommended development of TMDLs for addressing water quality problems in this watershed.

2.2. Watershed models

2.2.1. Soil and Water Assessment Tool (SWAT)

The SWAT is a semi-distributed model that was primarily developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large complex watersheds over long periods of time (Neitsch et al., 2005). The model inputs consist of topography, soil properties, land use/cover type, weather/climate data, and land management practices. The watershed is sub-divided into sub-watersheds and each sub-watershed is further divided into hydrological response units (HRU) based on topography, land use, and soil (Neitsch et al., 2005).

Surface runoff in each HRU was estimated using a modification of the Soil Conservation Service Curve Number (SCS-CN) method (USDA, 1972). In the curve number method, daily precipitation is partitioned between surface runoff and initial and continued abstractions as a function of antecedent soil moisture condition. The total sub-watershed discharge computed by SWAT includes runoff from its HRUs and subsurface flow including lateral flow and return flow. Flow in SWAT is routed through channels using either Muskingum routing method or variable storage coefficient method (Neitsch et al., 2005). The latter was used in this study. Erosion and sediment yield from each HRU are estimated based on the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). Sediment is routed through channels using a modification of Bagnold's sediment transport equation (Bagnold, 1977). This equation estimates sediment transport capacity as a function of flow velocity. The model either deposits or erodes sediment, depending on the sediment load entering the channel and the capacity of the flow.

SWAT models nitrogen and phosphorus cycles through five different pools of nitrogen (two inorganic forms: NH_4^+ and NO_3^-; three organic forms: fresh, stable and active) and six different pools of phosphorus (three inorganic forms: solution, active and stable; three organic forms: fresh, stable and active) in soil (Neitsch et al., 2005). Mineralization, decomposition, and immobilization are important processes in both N and P cycles. Organic N and P transport with sediment is estimated using a loading function developed by McElroy et al. (1976) and later modified by Williams and Hann (1978). Daily organic N and P runoff losses are calculated by loading functions based on the concentrations of these elements in the top soil layer, the sediment yield, and an enrichment ratio. Nitrate concentration in mobile water is calculated and multiplied with mobile water volume to estimate total nitrate lost from the soil layer. Mobile water is the sum of runoff, lateral flow and percolation. The soluble P removed in runoff is estimated using the P concentration in the top soil layer, runoff volume and a P soil partitioning coefficient. Further details can be found in Neitsch et al. (2005).

2.2.2. Generalized Watershed Loading Function (GWLF)

The GWLF model is a combined distributed/lumped parameter, continuous watershed model (Evans et al., 2002), which has the ability to simulate runoff, sediment, and nutrient (N and P) loads from various source areas, each of which is considered uniform with respect to soil and cover. GWLF uses land use, soil, and daily weather data for calculation of water balance. For estimation of sediment and nutrient loads, monthly calculations are made based