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Original Article

Segment-based assessment of riparian buffers on stream water quality improvement by applying an integrated model

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A B S T R A C T

As Best Management Practices, Riparian buffers are crucial to reduce pollutant loadings from upland area to streams. While fixed-width riparian buffer zones are relatively simple to be designed and implemented, variable-width buffer zones have the benefit to protect biogeochemical and ecological functions of riparian zones. With the variation of width, vegetation type, and topography, the filtering function of the riparian buffers could be varied from segment to segment along a stream. The developed REMM-SWAT interface could be used to assess riparian buffer zones at a segment level. This interface could obtain characteristics of each buffer segment and generate upland water and pollutants input, simulated with SWAT model, for each segment. From the modelling, the contribution of each segment in reducing sediment, nitrogen, and phosphorus varied drastically from one to another. The maximum reduction of runoff, sediment, nitrogen, and phosphorus for unit riparian buffer length was 3.83 mm m-1 yr-1, 202.4 kg m-1 yr-1, 1.01 kg m-1 yr-1, and 132.49 g m-1 yr-1, respectively. The minimum reduction of these pollutants was zero as there was no buffer drainage area for some buffer segments. As riparian buffers have numerous functions, the design of the buffers should comprehensively consider each of its function. This developed software could be applied as an assistant tool with other riparian buffer tools for varied-species and –width riparian buffer zones design.

1. Introduction

Riparian buffers are permanent vegetation strips along water, which i) protect the bank of rivers, ii) provide habitat for terrestrial and aquatic organisms, iii) directly or indirectly affect many important structural and functional processes in stream ecosystems, and iv) reduce sediment and nutrient loading from upland area to water bodies (USEPA, 1995; Aguiar Jr. et al., 2015; Johnson and Almlöf, 2016). Riparian buffer zones have been widely accepted as a Best Management Practice (BMP; Jobin et al., 2004).

Most of the existing buffer zones are generally established by leaving the too wet or too steep area adjacent to streams as they are not convenient for agricultural purposes (Osmond et al., 2002). As a result, the width and vegetation species of riparian buffers vary from different reaches of the same stream and even from segments to segments (the riparian buffers, which are separated into independent buffer area at each side of the streams). With the variation of site conditions, such as slope, soil, vegetation, and amount of upland sediment and nutrient input, the ability of riparian buffers to attenuate water pollutant varies from segments to segments of the riparian buffers within a watershed (Lowrance et al., 2000; Tiwari et al., 2016). Segment is the basic study and management unit of riparian buffers (Schoonove et al., 2006; Tiwari et al., 2016).

As an important component, understanding the effectiveness of riparian buffers is beneficial to watershed planning and management. Field experiments and model simulations provide two methodologies to assess riparian buffers in field situations. Comparing with field experiments, model-based assessments cost less and results can be evaluated within a short period when sufficient data is available for model simulation.

Several hydrological models have been widely applied to evaluate the impacts of agricultural management practices on environmental pollution, such as the Soil and Water Assessment Tool (SWAT), the Annualized Agricultural Nonpoint Source Pollution (AnnAGNPS) model and the Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) model (Yuan et al.,

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2001; Arnold and Fohrer, 2005). With their specific modelling purposes, these models could not be used to simulate the effectiveness of riparian buffers (Bosch et al., 2004). For example, SWAT was developed with the assumption that Hydrologic Response Unit (HRU) is the basic component of watersheds and there are no interactions among the HRUs. With this assumption, the modelling processes is simplified, but the model cannot simulate the functions of riparian buffers as it cannot capture water flux from upland to riparian buffers (Liu et al., 2007). To overcome the drawbacks, SWAT extended its function by simulating the riparian-buffer reduction of upland-coming pollutants with empirical equations based on HRU-averaged riparian buffer species and width (Neitsch et al., 2005). The riparian-buffer module of SWAT could not simulate varied nutrient conversion and pollutant reduction within riparian buffers (Cho et al., 2010).

The riparian buffer models, such as the Vegetative Filter Strip Model or VFS (Munoz-Carpena et al., 1999), the Riparian Ecosystem Management Model or REMM (Lowrance et al., 2000, 2001), and the Riparian Soil Model or RSM (Brovelli et al., 2012) have been specifically designed to simulate processes of riparian systems. Both of the models could not be run independently and requires upland input generated by other models. With the apparent gap between the two types of models, they could not be used to evaluate the pollutant reduction by riparian buffers (Liu et al., 2007).

The REMM and GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) models were integrated to simulate the effectiveness of riparian buffers at a field scale, where GLEAMS model were used to generate upland inputs to REMM (Gerwig et al., 2001; Tucker et al., 2001).

The integration of SWAT and REMM has been achieved to simulate the function of riparian buffers in reducing upland pollutants to streams, in which SWAT output is served as input of REMM by mimicking riparian buffers receiving runoff and associated pollutants from their corresponding contribution upland areas (Cerucci and Conrad, 2003; Liu et al., 2007).

Cerucci and Conrad (2003) created a GIS interface integrating SWAT and REMM to simulate pollutant abatement by each riparian segment. In the interface, each watershed was divided into independent small sub-watersheds, each corresponding to one riparian buffer segment, either at the left or right side of rivers. Runoff, sediment, and nutrients output from each small sub-watershed was simulated by SWAT and treated directly as input of REMM. The GIS interface automatically manipulated the REMM input files generated from SWAT output and the site characteristics, such as the slope and length of the buffer, the slope of the upland drainage.

Liu et al. (2007) developed a GIS interface to couple SWAT and REMM at a sub-watershed level. The interface treated right and left segments into one entity. In each sub-watershed, the entire riparian buffer is treated as the three species and same width. This interface isolated upland into impoundment, buffer drainage (contributing flow and pollutants in sheet flow form into riparian buffers) and concentrated drainage areas (contributing channel flow before it reaching to riparian buffers). The model assumed that the riparian buffer only filters water flowing out from upland sheet flow drainage area. Similar to work of Cerucci and Conrad (2003), this interface calculates the attributes of riparian buffers and connected output of SWAT and input of REMM automatically.

Ryu et al. (2011) enhanced the SWAT-REMM integration of Liu et al. (2007) by; (1) designating riparian buffers at specific reaches in the watersheds, (2) Extracting local soil properties for REMM from soil database, and (3) applying weather data from multiple stations in a large-scale watershed.

As the riparian buffers, such as width, vegetation species and upland contributing buffer drainage area corresponding to each buffer segment, vary from place to place along streams, the effectiveness of pollutant reduction could be varied from segment to segment. With the current developed SWAT-REMM models, the efficiency of this type of riparian buffers could not be assessed properly. For planning and management purposes to the riparian buffers with varied width and vegetation species and upland parameters, a new SWAT and REMM integrated model is needed.

The objective of this study is to develop a GIS interface to assess the effectiveness of species and width-varied buffers in reducing sediment and nutrients (nitrogen and phosphorus) from land to streams at a riparian segment level. The methodology developed in this study made the maximum use of the aforementioned two modelling methodologies.

2. Model development

2.1. Computer software used

The Riparian Ecosystem Management Model (REMM) was developed for evaluating the effectiveness of riparian buffers in reducing the nonpoint source pollutants (NPSP) from upland area to down streams. This process-based model simulates the interactions of hydrology, soil erosion, nutrients, and vegetation dynamics at a field scale and a daily time step (Lowrance et al., 2000; Altier et al., 2002). REMM has been validated and evaluated extensively using field data (Bosch et al., 1998; Williams et al., 1998; Tilak et al., 2014). The input variables of REMM, such as water fluxes, sediment and nutrients need to be either measured by field experiments or simulated by other dynamic models.

The Soil and Water Assessment Tool (SWAT) is a distributed process model to simulate the impact of pollutant loads from point and nonpoint sources on stream water quality (Neitsch et al., 2005). SWAT simulates energy, water, carbon, nutrients, and pollutant dynamic processes in land and water bodies in one watershed. The model requires the atmospheric weather driving forces and site information of soil properties, topography, vegetation, and land management practices in the subbasins (Arnold and Fohrer, 2005). SWAT can be applied from large- to small-scale watersheds (Cerucci and Pacenka, 2003).

As more and more simulation work is based on ArcSWAT, ArcObject and C# are used as the platform for the development of this GIS interface. Besides ArcObject, Microsoft COM objects of Excel and Access are also referred for transferring data from ArcSWAT to REMM and organizing the input exported from SWAT and model parameter files for REMM. The developed interface is run on ArcGIS 9.3.

2.2. The conceptual model

The width and species composition and density in riparian buffers determine the effectiveness of each buffer segment. Each buffer segment has its own corresponding buffer drainage, concentrated drainage, and impoundment areas. Runoff and pollutants only that go through the riparian buffers are effectively filtered by riparian buffers (Dosskey et al., 2002; Verstraeten et al., 2006; Liu et al., 2007). Runoff, sediment, and nutrients flow out from buffer drainage area are simulated with ArcSWAT. The processes of runoff, sediment, and nutrients in each buffer segment are simulated with REMM. The ArcGIS interface developed in this study automatically divided the riparian buffer zones into separated segments, extracted the attributes of each segment, and organized the output of SWAT into the input file format of REMM. Fig. 1 shows the conceptual model to integrate ArcSWAT and REMM (modified from Liu et al., 2007).