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Enhancing the SWAT model for simulating denitrification in riparian zones at the river basin scale

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ABSTRACT

Riparian zones have significant impact on nitrate removal despite their small areas. Most research on riparian zones have been implemented at small scales. Direct measurement at large scale is infeasible, thus using models is a good alternative. This study introduces a modified SWAT model, referred as SWAT_LS. Two modifications were implemented: (i) adding hydrological routing from upland areas to riparian zones; and (ii) adding a module to simulate denitrification in riparian zones based on the Riparian Nitrogen Model. SWAT_LS was applied to the Odense river basin in Denmark, a densely tile-drained agricultural river basin. Compared to SWAT, SWAT_LS provides an equally good performance for streamflow, and a significant improvement in nitrate predictions. SWAT_LS predicts that current riparian zones remove only 4–17% of nitrate loads because 70% of the riparian areas are bypassed due to subsurface drainage implementation. This ability would dramatically increase to 25–85% if riparian zones are entirely undrained.

1. Introduction

At the interface between terrestrial and aquatic ecosystems, riparian zones play an important role in nitrogen removal, despite the small proportion of land area that they cover (Imhol et al., 1996; Roth et al., 1996). One of the main interests related to riparian zones is their effects on nutrient contributions, particularly nitrate, to freshwater systems. Low concentrations of nitrate have been reported in riparian-zone groundwater, not only in undisturbed headwater watersheds (Campbell et al., 2000; McDowell et al., 1992; Sueker et al., 2001), but also in agricultural watersheds (Hill, 1996; Jordan et al., 1993). The possible mechanisms explaining the attenuation of nitrate loads in riparian zones are: plant uptake, microbial immobilisation, and denitrification. While microbial immobilisation and uptake by vegetation likely play supporting roles in the fate and transport of nitrate, denitrification is the main mechanism for groundwater nitrate attenuation (Cey et al., 1999; Rivett et al., 2008).

Denitrification is highly variable in time and space due to the variability of its controlling factors such as level of saturation of the soil column, dissolved organic carbon in the soil, vegetation and temperature. Therefore, it is particularly difficult to quantify where, when and how much denitrification occurs (Groffman et al., 2006; Seitzinger et al., 2006). Direct measurements of denitrification at river basin or large regional scales are not feasible. Terrestrial and aquatic models are able to integrate the current understanding of the denitrification process with large-scale measurements to quantify nitrogen losses. Boyer et al. (2006) reviewed a variety of terrestrial landscape models that are able to quantify sources of nitrogen and estimate nitrogen losses. These models range from simple mass balance models (Howarth et al., 1996; van Breemen et al., 2002) to field-scale models (DAYCENT (Parton et al., 1996), the denitrification-decomposition (DNDC) model (Li et al., 1992), the EPIC model (Sharpley and Williams, 1990; Williams et al., 1984), GLEAMS (Leonard et al., 1987), and DRAINMOD-N II (Youssef et al., 2005)), and to catchment-scale models (The Integrated Nitrogen in Catchments (INCA) model (Whitehead et al., 1998) and the Regional Hydrological Ecosystem Simulation System (RHESSys) (Band et al., 1991, 2001)).

Additionally, there are some small-scale models that are specifically designed to simulate nutrient processes in riparian zones, which include the Wetlands Water Quality Model (WWQM) (Chavan and Dennett, 2008), the Wetland Solute Transport Dynamics (WETSAND) (Kazezyılmaz-Alhan et al., 2007), and the Riparian Nitrogen Model (RNM) (Rassam et al., 2008). The latest one is a conceptual model that estimates the removal of nitrate as a

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result of denitrification occurring when groundwater and surface waters interact with riparian buffers. In the RNM, it is assumed that the denitrification rate declines with depth which is supported by Hill (1996) and Pinay et al. (1993) who found that denitrification occurs in the surface sediments and decreases sharply with depth.

There are river-basin-scale models that deal with predictions of pollutant loading from diffuse sources and wetland/riparian models for simulating hydrological and chemical processes including denitrification in wetlands/riparian zones. However, there are limited studies on integrating wetland/riparian zone models in river basin modelling to evaluate the effects of wetlands/riparian zones at river basin scales. Few efforts have been done to extend the capacity of catchment models to simulate riparian zones/wetlands (Hattermann et al., 2006) or integrate wetland models in catchment models (Arheimer and Wittgren, 2002; Rassam et al., 2008). However, none of these studies couple riparian zones with hillslope processes in river basins.

The Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998) is a semi-distributed model that can simulate the impact of land management activities on water quantity and quality, sediment transport, pesticides and nutrient leaching in large complex river basins. Hydrological and water quality processes in the landscape are computed at the level of Hydrological Response Unit (HRU) which represents a unique combination of soil, land use and slope types. Because HRUs are not necessarily contiguous and have no interaction with each other, the ability of SWAT to simulate transport processes across landscape units is limited. This was identified as an important shortcoming of the model (Arnold et al., 2010; Bosch et al., 2010; Gassman et al., 2007). To simulate the effect of riparian zones, SWAT predicts the flow retention and nutrient removal in riparian zones based on the areal percentage using empirical equations derived from the Vegetative Filter Strip Model (VFSMOD) (Muñoz-Carpena et al., 1999) and observations (White and Arnold, 2009). Although this module is able to approximately evaluate the importance of riparian zones for the whole basin using empirical equations, there is no specific process simulated in the buffer zones. Hence, VFSMOD does not account for the contribution of nutrient loads from upland HRUs to riparian zones.

Recent attempts to incorporate landscape routing into SWAT may help to better represent transport processes in a river basin. Arnold et al. (2010) introduced a hillslope approach for SWAT that allows flow routing between three landscape units, i.e., divide, hillslope, and valley bottom. This landscape model, in a test by Bosch et al. (2010) on a low-gradient coastal plain basin, gave a satisfactory prediction of annual streamflow, but a poor estimate of monthly flow and an overestimation of groundwater flow, which led to a conclusion that additional details may be required to properly simulate hydrological interactions. Rathjens et al. (2015) developed a fully distributed grid-based SWAT model, incorporating the hillslope approach by Arnold et al. (2010) in simulating landscape flow routing between grids. The grid-based SWAT model showed good predictions in both daily and monthly time steps in the Little River basin near Tifton, Georgia, USA. However, the complexity of the grid-based SWAT model limits its application beyond small-scale river basins. SWAT-LUD (Sun et al., 2016) is a new module developed to simulate the surface water – groundwater exchange in the river/groundwater interface. In a case study located in a meander of the alluvial plain of the Garonne River in France, the module could predict groundwater levels very well and reflect actual water exchange between the river and the aquifer. Although SWAT-LUD was not able to provide spatial distribution of hydraulic heads like physically-based models such as MODFLOW, it provided a good estimation of surface water-groundwater interactions using a simple model.

The objective of this paper is to introduce a modified version of SWAT, called SWAT_LS to improve the representation of transport processes from upland areas to riparian zones, evaluate the importance of riparian zones in nitrogen removal across the river basin, and compare the functioning of drained riparian zones versus naturally functioning riparian zones. Two main modifications to the SWAT model were made: (i) modifying the related hydrological SWAT code to be able to represent landscape routing across the upland area and riparian zone, following the approach of Arnold et al. (2010), and (ii) adding the Riparian Nitrogen Model (RNM) into SWAT to simulate denitrification process in riparian zones. The modifications of SWAT_LS were based on the SWAT2005 version. The SWAT_LS model was then applied in the Odense River basin in Denmark, a densely tile-drained agricultural river basin. Drainage of wetlands and field drainage have considerably reduced the natural capacity to remove pollutant loads of the Odense Fjord and river basin. In recent years, wetlands have been reconstructed and the watercourse has been restored gradually with an expectation to improve nutrient retention and removal in the future. Therefore, the effect of riparian zones on nutrient retention and removal is of interest.

2. Methodology

2.1. The modified SWAT model (SWAT_LS) to simulate the impact of riparian buffers on nitrate removal by denitrification

SWAT divides a river basin into multiple subbasins, each of which is then split into multiple Hydrological Response Units (HRUs) (Neitsch et al., 2011). HRU is a unique combination of soil, land use and slope types. All hydrological and water quality processes in the landscape are computed at HRU level. Subbasin outputs are simply the aggregation of estimations from HRUs in the corresponding subbasin. Interaction between HRUs are not taken into account in the SWAT model.

Inspired by the hillslope approach of Arnold et al. (2010), the SWAT code version 2005 was adapted to include a simplification of two landscape units: *upland* and *riparian*. Two main modifications were made to SWAT_LS:

(i) Adding landscape routing from the upland area to the riparian zone
(ii) Adding a module to the SWAT model to simulate denitrification in riparian zones based on the Riparian Nitrogen Model (RNM)

2.1.1. Landscape routing from the upland area to the riparian zone

In order to perform landscape routing from the upland area to the riparian zone, the river basin is divided into two landscape units: *upland* and *riparian*. The landscape division is implemented in the HRU definition of the SWAT_LS model setup, which is described in detail in section 2.2.2 (*Creating landscape map to define HRUs*). Each HRU is then given an identification to reflect which landscape unit it belongs to, by assigning a position reference to each HRU in the river basin.

Fig. 1 describes the differences in hydrological routing between HRUs and streams in SWAT_LS compared with SWAT2005. Two hydrological routing approaches are described in a subbasin in which we assumed that there are two HRUs. In SWAT2005, HRU A and HRU B are individually routed directly to the river and the discharge to the river is the aggregation of flow generated from two HRUs. In SWAT_LS, we used the simplest example in which both