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Assessing the spatial and temporal variations of water quality in lowland areas, Northern Germany

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SUMMARY

The pollution of rivers and streams with agro-chemical contaminants has become one of the most crucial environmental problems in the world. The assessment of spatial and temporal variations of water quality influenced by point and diffuse source pollution is necessary to manage the environment sustainably in various watershed scales. The overall objectives of this study were to assess the transferability of parameter sets between lowland catchments on different scales using the ecohydrological model SWAT (Soil and Water Assessment Tool) and to evaluate the temporal and spatial patterns of water quality in the whole catchments before and after implementation of best management practices (BMPs).

The study area Kielstau catchment is located in Northern Germany as typical example of lowland – flood plain landscape. Sandy, loamy and peat soils are characteristic for this area. Land use is dominated by arable land and pasture. In this study we examined two catchment areas including Kielstau catchment 50 km^2 and its subcatchment, namely Moorau, with the area of 7.6 km^2. The water quality of these catchments is not only influenced by diffuse sources from agricultural areas but also by point sources from municipal wastewater treatment plants (WWTPs). Diffuse sources as well as punctual entries from the WWTPs are considered in the model set-up. For this study, the calibration and validation of the model were carried out in a daily time step for flow and nutrients. The results indicate that the parameter sets could be transferred in lowland catchments with similar environmental conditions. Shallow groundwater is the major contributor to total nitrate load in the stream accounting for about 93% of the total nitrate load, while only about 7% originates in surface runoff and lateral flow. The study also indicates that applying a spatially distributed modeling approach was an appropriate method to generate source maps showing the spatial distribution of TN load from hydrologic response units (HRUs) as well as from subbasins and to identify the crucial pollution areas within a watershed whose management practices can be improved to control more effectively nitrogen loading to water bodies.

1. Introduction

In recent years, many efforts have been made worldwide to mitigate the impairment of point and diffuse source pollution of the aquatic environment. The cause of water quality deterioration is mostly associated with diffuse source pollution due to the intensification of agricultural activities and the development of large urban areas, in which agriculture has been identified as the major contributor of diffuse source pollution of water resources (Duda, 1993; Lam et al., 2010). The European Water Framework Directive (EC, 2000) is a current legislation that demands the good status of surface waters and groundwater to be maintained until 2015. This predetermined status mentions both the qualitative and quantitative characteristic of the river, streams, and other water bodies. However, the ecology and hydrology of a lowland river reflect not only the conditions and processes within the river itself but also impacts of the floodplain corresponding with the river (Lasserre et al., 1999).

Lowland catchments are ecosystems with low flow velocity, a high groundwater table, and flat topography (Schmalz et al., 2009; Krause et al., 2007). Hydrological conditions and nutrient dynamics of lowland river systems and the adjacent floodplains are strongly controlled by the interactions between surface water and shallow groundwater (Sophocleous, 2002; Winter, 1999). In the past centuries different melioration measures such as river regulation, installation of drainage, and pumping stations have been implemented in order to enlarge areas as well as render better cultivation conditions for agriculture. These have led to a change in the water balance, nutrient dynamics, and subsequently floodplain ecology (Bullock and Acreman, 2003; Schmalz et al., 2009). Thereby, the quality of surface water and groundwater of those lowland areas is also affected significantly due to the changes of transformation and transport of nutrient and pollutants (Devito and Dillon, 1993; Andersen, 2004).

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Lowland areas are an important link between agricultural high lands and downstream water bodies, as they can be effective in retaining sediment and particulate P (Turner et al., 2006), thereby decreasing the downstream load and influencing water quality in downstream aquatic systems (Johnston, 1991). During storage in the lowland, P transformations may either increase or decrease the bioavailability of sediment P, a role of lowlands often overlooked or underestimated (Reddy et al., 1999). Streams are often thought to be long-term sediment sinks (Reddy et al., 1999; Kadlec, 2005). Therefore, the stream flow transformation processes alter not only sediment transport, but also the chemical form or bioavailability of the P in the river systems.

For the lowlands of Northern Germany, the increase in intensive agriculture and ecological policies within the last years have substantially influenced the natural water and nutrient balance, so the management of water quality in these lowland areas has become more important. The evaluation of new regulations and degradation of water bodies caused by point and diffuse source pollution requires modeling studies in order to assess the impact of those new policies as well as water pollution on the surrounding environment. Model scenarios can be helpful in finding reasonable measures for assessing environmental ecological status while taking into account relevant factors such as climate, land, and water use (Krysanova et al., 2005). In this study, the SWAT model has been chosen to predict flow and nutrient load from watersheds. Many studies have used SWAT to evaluate the impact of BMPs on hydrologic processes and water quality at different watershed scales (Tripathi et al., 2005; Arabi et al., 2007; Lam et al., 2011). Gassman et al. (2007) have indicated that a key strength of SWAT is a flexible framework allowing the simulation of a wide variety of structural and nonstructural BMPs such as conservation tillage, cover crops, nutrient management, buffer strips, flood prevention structures, grass water way, and parallel terraces. Although management scenarios of watershed are routinely simulated with SWAT, variations in spatial patterns of implementation are less frequently done, especially for lowland areas where the transport of pollutants and nutrients is strongly influenced by features such as flat topography, and shallow groundwater. Spatially distributed modeling is needed to evaluate the crucial areas within the watershed whose management practices can be improved aiming at controlling better nutrient load to water bodies (Haverkamp et al., 2005).

The objectives of this study were to: (1) evaluate the performance capabilities of the SWAT to simulate flow and nutrient load in complex mesoscale lowland catchments and assess the transferability of parameter sets between lowland catchments of different scale; (2) evaluate the transportation of nutrient in different pathways from the fields to the streams of lowland catchments; and (3) assess the temporal and spatial variations of nutrient loads in the whole catchment before and after implementation of BMPs and to identify crucial subbasins which provide significant nitrogen loads compared to other subbasins within the watershed. Then, appropriate BMPs are further proposed to improve water quality in those crucial subbasins as well as the whole catchment.

2. Materials and methods

2.1. Study area

The study area Kielstau catchment is located in Northern Germany as part of a lowland area in Schleswig-Holstein. The highest and lowest elevation of the Kielstau topography is 79.9 and 27.3 m, respectively (Fig. 1). The area of the Kielstau catchment is about 50 km^2. The river Kielstau has a total length of 17 km and flows through Lake Winderatt towards the gauge Soltfeld, located at the outlet of Kielstau watershed. The six wastewater treatment plants (WWTPs) built within the Kielstau watershed are Husby, Hürup Nord, Hürup Weseby, Hürup Süd, Ausacker, and Freienwill (Fig. 1). Hürup Nord, Hürup Weseby, and Hürup Süd are located along the longitudinal Hennebach tributary (461, 447, and 240 population equivalents). Ausacker and Freienwill are located on the river Kielstau (1880 and 350 population equivalents). In addition, various small tributaries and water from drainage pipes and ditches flow into the river Kielstau. The drainage fraction of agricultural area in the Kielstau catchment is estimated at 38% (Fohrer et al., 2007).

Moorau catchment is a subcatchment within the Kielstau catchment (Fig. 1). The total drainage area of the Moorau catchment is about 7.6 km^2. The distance between the Kielstau outlet and the Moorau outlet is about 12 km. Moorau is one of the two important tributaries of the river Kielstau from the north. There is a WWTP, namely Husby, situated at the beginning of the Moorau tributary with 3000 population equivalents. All the water including chemicals from WWTP discharges into the stream Moorau then flows to the river Kielstau.

Land use is dominated by arable land and pasture in both the Kielstau and the Moorau catchment. The dominant soils of the Kielstau catchment are Stagnic Luvisols and Haplic Luvisols, while Stagnic Luvisols and Gleyic Antrosols are dominant soils of the Moorau catchment. Land use and soil maps used in this study can be seen in Fig. 1. The mean annual temperature is 8.2 °C (station Flensburg, 1961–1990, DWD, 2009a). The mean annual precipitation is about 841 mm/a (station Satrup, 1961–1990, DWD, 2009b).

In the Kielstau catchment, diffuse source pollution of nutrients results mainly from various farms, which apply fertilizers or animal husbandry in the vicinity of the river as well as from urban areas. The combinations of these diffuse sources and point sources influences instream water quality considerably (Schmalz et al., 2007).

2.2. Monitoring of the watershed

The Soltfeld gauging measurement station has been installed at the outlet of the Kielstau catchment (Fig. 1). The hourly discharge data used for this study (1993–2008) were measured from this station by Staatliches Umweltamt Schleswig (2009). At the Moorau station, the water level data (October 2007–June 2009) were measured by the Department of Hydrology and Water Resources Management – Institute for the Conservation of Natural Resources at Kiel University (CAU Kiel). Calculation of the Moorau discharge at the Moorau station was based on the rating curve between water level and discharge which was obtained by the relation between stream velocity and area cross section at the Moorau outlet (Tavares, 2006). The average daily discharge is given in Table 1.

The collection and analysis of daily water samples took place during the period from May 2006 to December 2008 for the Kielstau catchment and from November 2007 to March 2009 for the Moorau catchment by the Department of Hydrology and Water Resources Management – Institute for the Conservation of Natural Resources at Kiel University (CAU Kiel, 2009). At the Soltfeld gauging and Moorau station, water samples were collected, filtered, and frozen for further laboratory analysis. Nutrient concentrations in the water samples were quantified by photometry and ion chromatography in the laboratory. The average concentrations of nutrient for both the Kielstau and Moorau catchment are shown in Table 1.

In general, the measured average concentration values of all parameters exceed the allowable limit of class II of the LAWA standard (LAWA, 1998) whose quality class II (moderately polluted) represents the target value for water quality until the year 2015 according to the European Water Framework Directive (EC,