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Development and application of a nitrogen simulation model in a data scarce catchment in South China

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ABSTRACT

The Xitiaoxi catchment is one of the most important catchments in the Taihu Basin in southeastern China. It contributes a significant amount of surface runoff and nutrient to Taihu Lake. Understanding the nutrient cycling and identification of critical non-point source pollution in this catchment are therefore of primary importance. In this paper, the Xinanjiang-Nitrogen (XAJ-N) model, a conceptual model of nutrient mobilization and transport is developed by integration of the Xinanjiang rainfall–runoff model, the Integrated Nitrogen CAtchment (INCA) model and the Modified Universal Soil Loss Equation (MUSLE). It is implemented with the environmental modelling language PCRaster and estimates the water fluxes and nutrient loadings on a cell-by-cell basis in daily time steps. The model includes the nitrogen cycling processes of mineralization, leaching, fixation, volatilization, nitrification, denitrification and plant uptake. Nitrogen is assumed to be mobilized by surface runoff and groundwater. The model performance was verified by comparing simulated and measured daily discharge and nutrient loadings. The results showed a fairly good relationship between predicted and observed values. Due to the scarce observed data, the simulation results were also validated using an internal mass balance method and values from the literature. It showed that the modelling approach can be used as a tool to estimate the export of nutrient with a daily resolution at a catchment scale.

1. Introduction

With increasing population and rapid economic development, surface water is heavily polluted due to large amount of municipal sewage, industrial wastewater and non-point source pollution in China. Especially in the Taihu Basin, water pollution has become a serious environmental problem in view of the fact that algae bloom occurred much more frequently, extending its coverage and simultaneously persisting throughout the summer in recent years (Qin et al., 2007). Since the point source pollution is easily controlled, the diffuse non-point source pollution has received increased attention in recent decades (Edwards and Withers, 2008). Excessive nutrients from intensive agriculture discharged into aquatic systems contribute main pollutants to surface water in the Taihu Basin, thereby causing serious ecological problems such as eutrophication, algal bloom, oxygen depletion and decrease of biodiversity. It is therefore essential to quantify the nutrient load and identify the critical sources in the catchment.

In order to improve the water quality and to reduce pollutants, a considerable amount of studies have focused on the estimation of non-point source pollution (Ding et al., 2010). The non-point source pollution is strongly linked to hydro-chemical processes, and thus hydrological models are commonly used to estimate the nutrient loadings and to quantify the effects of agricultural activities on water quality and quantity. A variety of models have been developed to simulate hydrological processes, nutrient transport through surface runoff, soil infiltration, and groundwater flow, as well as in-stream nutrient processes at different scales. Examples include ANSWERS (Beasley et al., 1980), SWRRB (Williams et al., 1985), SWAT (Arnold et al., 1998), HSPF (Donigian et al., 1995), AGNPS (Young et al., 1989), INCA (Whitehead et al., 1998a; Wade et al., 2002) and LASCAM (Viney et al., 2000). Some of these models provide long-term, daily simulation of nutrient load in large catchments (Arnold and Fohrer, 2005; Viney et al., 2000), whereas others are event-based (e.g. SPNM, SWRRB, AGNPS, ANSWERS) and are clearly unsuitable for long-term continual predictions. Although the long-term continuous nutrient models are capable of providing accurate results, a large number of parameters cannot be obtained from field measurements and must instead be determined through model calibration. An additional constraint to model development and verification is that water quality and hydro-meteorological

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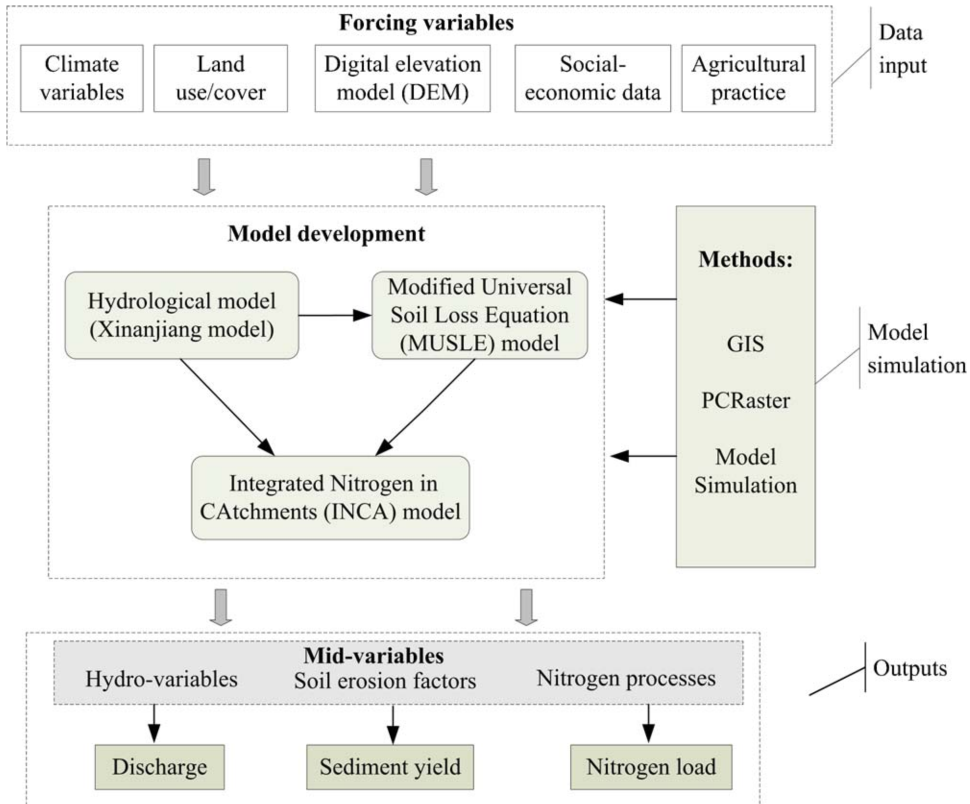

Fig. 1. The framework of the nitrogen simulation in the XAJ-N model.

data are rarely simultaneously collected in a satisfactory resolution. For locations without long-term data collection, estimates based on hindcast model applications might be available (Breuer et al., 2008).

The PCRaster program (http://pcraster.geo.uu.nl) is a dynamic and distributed environmental modelling language (Van Deursen, 1995; Wesseling et al., 1996), which provides a raster GIS modelling environment. Since most of the models mentioned above require extensive input and calibration parameters, dynamic modelling language is a powerful tool for development of environmental models. There have been several models developed for nutrient flux estimation using PCRaster in different temporal and spatial scale. The PolFLow model (De Wit, 2000) calculated average N and P loads for 5-year periods and has been applied to several large catchments (e.g. Rhine, Elbe). The RiNUX model (Loos et al., 2009) was designed to simulate monthly sediment yields and nutrient loads using global datasets. These models obtained satisfying precision but are unsuitable for different spatial-temporal scales.

The study area, Xitiaoxi River catchment, is one of the most important rivers draining into Taihu Lake. The current agricultural practice is a very intensive multi-cropping system with irrigated summer rice–winter wheat (or rapeseed) rotations. The high yields of rice in the catchment are achieved through high nutrient application rates. In recent years, an increasing impact on water quality is attributed to nutrients from intensive agricultural activities transported with surface water to Taihu Lake. A large number of studies investigated the nutrient loading because of the high frequency of algae blooming in Taihu Lake. Lai et al. (2006) and Yu et al. (2007) used the SWAT model to investigate the nutrient transport in the Taihu Basin with long-term annual simulation time steps. These studies provided good insights into the spatial and temporal characteristics of the nutrient cycle in the Taihu Basin. However, the nutrient dynamics in soil and water are still not clear. The nutrient simulation at annual scale cannot represent the seasonal changes. Furthermore, the missing daily or weekly data sets limit the application of models. Therefore, the objectives of this study are: (a) to develop a simple nutrient transport model named Xinanjiang-Nitrogen (XAJ-N) model by integration of hydrology, soil erosion and nitrogen dynamics at the watershed scale and (b) to apply the XAJ-N model for understanding the characteristics of nitrogen cycle in the Xitiaoxi catchment. In the model, the Xinanjiang rainfall–runoff model was applied in PCRaster for hydrological modelling (Zhao et al., 1980; Zhao, 1992). Nutrient dynamics are simulated based on the Integrated Nitrogen CAtchment (INCA) model (Wade et al., 2002), and the particulate nitrogen was predicted by the soil erosion model using the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). Due to limited available data, both the observed data and an internal mass balance method were applied for model validation.

2. Model concepts and methods

2.1. Model overview

The model framework, as shown in Fig. 1, includes all the components with the input data, modelling methods and output variables for the XAJ-N model. The forcing variables mainly consist of climate variables, land use/cover, digital elevation model (DEM), social-economic data and agricultural practice. In general, the XAJ-N model is composed of three different modules for estimating river discharge, sediment yield and nitrogen dynamics. The first module is the water flux model which assesses the amount of runoff from soil zone and groundwater in the catchment based on the Xinanjiang model concept (Zhao et al., 1980; Zhao, 1992) using PCRaster. The second module applies the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) to estimate the sediment yield and particulate nitrogen, and the third module uses the data produced by the hydrological model as input data to simulate nitrogen transport based on the Integrated Nitrogen CAtchment (INCA) model