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A coupled modeling approach to evaluate nitrogen retention within the Shanmei Reservoir watershed, China

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ABSTRACT

To simulate impacts of nitrogen retention in the reservoir on nitrogen nutrient transported from the upland watershed to the ocean, a coupled watershed-reservoir modeling system, consisting of a watershed distributed model (SWAT) and a two-dimensional water quality model (CE-QUAL-W2), was developed. The coupled modeling system was well calibrated, and simulated values mainly agreed with observed data, demonstrating that the SWAT and CE-QUAL-W2 coupled modeling system can be used to assess hydrodynamic and water quality processes in a complex watershed comprised of an upland watershed and a downstream reservoir. Applying the coupled model, a long time simulation was conducted to analyze the temporal characteristics of nitrogen exported from the watershed and to reveal the effect of nitrogen retention in the reservoir at annual, monthly and daily scales. The results showed that nitrogen export from the watershed is closely associated with precipitation and runoff. The wet season was the critical period of nitrogen loss, whereas the dry season is the critical period for water quality management. The reservoir serves mainly as a nitrogen sink at annual scale due to the effect of nitrogen retention, but within the year, it may act as a sink during the wet season and a source during the dry season, which is significantly influenced by inflow runoff, nitrogen load and reservoir regulation.

1. Introduction

Networks of streams play an important role in delivering excess nitrogen to coastal systems (Tappin, 2002; Shen et al., 2003; Li et al., 2007). On the global scale, the dissolved substances and particulate matter transported by rivers account for 90% of the transported fluxes from land to marginal seas. Social development and human activities, such as fertilizer application and discharge of livestock waste water and domestic sewage, have caused serious non-point pollution at the watershed scale. This has resulted in the deterioration of surface water quality and the eutrophication of rivers, lakes and reservoirs (Guasmi et al., 2010; Abdelkader et al., 2012), greatly increasing the quantity of nutrients transported by rivers from upland watersheds to the ocean (Yan et al., 2010). To fulfill the growing water demands, a large number of water conservation projects have been built to retain river water in dams and significantly changed the hydrological characteristics, physical transformations, nutrient transfers and transport fluxes (Kelly, 2001; Klaver et al., 2007). Nitrogen in reservoirs is primarily removed from water by certain processes that include sediment burial, temporary storage in biomass and denitrification (Saunders and Kalff, 2001; Syvitskl et al., 2005), which may reduce the nitrogen transported downstream and slow the trend of eutrophication in estuary waters (Putz and Benndorf, 1998).

Due to the impact of dams on nitrogen retention within watersheds, the reservoirs serve as an important sink for nitrogen (Nielsen et al., 2001; Koszelnik and Tomaszek, 2002), which has been garnered a great deal of concern. Ounissi and Bouchareb (2013) assessed the nutrient fluxes from dams into Mediterranean coastal waters of three rivers and found that dams can annually trap up to 51–98% of the dissolved inorganic nitrogen (DIN). Hejzlar et al. (2009) compared four European catchments with diverse climate, hydrology, and nutrient loads from diffuse and point sources, and concluded that the retention values varied greatly, with tendencies toward higher retention in catchments

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with lakes compared to primarily or entirely lakeless catchments. After the construction of Three Gorges Dam in China, approximately 2–7% of DIN from the upland watershed was held in the reservoir (Zhang and Zhang, 2003). Harrison et al. (2009) found that, although reservoirs occupy 6% of the global lentic surface water, they retain approximately 33% of the total N removed by lentic systems. However, another study found that reservoirs retained very little nitrogen from watersheds of the Northeastern US (Seitzinger et al., 2002).

When analyzing the changes of nitrogen fluxes and retention, not only should the physical, chemical and biological processes of the reservoir be considered, a quantitative knowledge of nitrogen loss and export at the watershed scale is also needed (Hejzlar et al., 2009). In recent years, a number of field-based modeling studies have investigated the N removal within reservoirs, which is correlated with N loading, water residence time, temperature and mean depth (Dillon and Molot, 1990; Windolf et al., 1996; Saunders and Kalff, 2001; Harrison et al., 2009). However, the empirical formula used in these models do not have the ability to reflect the effects of dynamic changes in hydrological cycle and nutrient losses from the watershed on nutrient retention in the reservoir. Due to their ability to overcome the disadvantages mentioned above, distributed hydrological models, such as SWAT (Neitsch et al., 2005), HSPF (Kourgialas et al., 2010), AnnAGNPS (Binger et al., 2009), IWMM (Lindenschmidt et al., 2007), have been widely applied to simulate non-point-source (NPS) nitrogen pollution. However, such models primarily use steady-state 1-D empirical procedures, such as QUAL2E, and lack the capacity to accurately simulate the hydrodynamics and water quality processes of larger and deeper waterbodies (e.g., lakes, stratified reservoirs, complex flows and stratified estuaries where 2-D or 3-D computations are required) (Xu et al., 2007; Debele et al., 2008). To properly reflect the association among the complex network of watershed-waterbody systems, increasing numbers of researchers have coupled the hydrological models of upland watersheds and downstream waterbodies, such as CE-QUAL-W2 (Cole and Wells, 2008), WASP (Wool et al., 2003), EFDC (Caliskan and Elci, 2009). For example, Xu et al. (2007) coupled six HSPF and two CE-QUAL-W2 models in a complex way to simulate two reservoirs and the associated drainage areas. Debele et al. (2008) developed an intermediate program to extract outputs from SWAT at required subbasins and reach outlets and converts them into acceptable CE-QUAL-W2 inputs to couple these two models. Zhang et al. (2012) presented a Multi-level Watershed-Reservoir Modeling System (MWRMS), integrating SWAT, EFDC and WREM, to simulate the hydrological and biogeochemical processes in a small prairie watershed. These coupling models have reasonably taken into account the impacts of upland watershed ecological changes induced by human activities on the ecological dynamic processes of nutrients in the large downstream waterbodies, yet they have not been applied to the study of nitrogen retention within reservoirs. We attempted to apply the coupled model to investigate nitrogen loss from a watershed and to evaluate the dam effects on the nitrogen retention.

Rapid population growth and socioeconomic and agricultural development in the Shanmei Reservoir watershed in southeast of China have substantially increased pollutant loads delivered to the reservoir. High total nitrogen concentrations have deteriorated the water body and accelerated the eutrophication trend, causing a serious impact on the water quality with regard to irrigation and water supply. Shanmei Reservoir is the only one large sized reservoir in Jinjiang River watershed, with a distance of 58.86 km away from the estuary. The area of Shanmei Reservoir watershed accounts for 20% of whole Jinjiang River watershed, which received a large amount of nutrient loading due to the human activity. Therefore, effects of the reservoir on the nitrogen retention would make a great deal of sense to the N input to the ocean. To investigate the nitrogen retention within Shanmei Reservoir which is influenced by the nitrogen transported from the upland watershed, a coupled watershed-reservoir modeling system consisting of a watershed distributed model (SWAT) and a two-dimensional laterally averaged water quality model (CE-QUAL-W2) was developed. Moreover, the temporal characteristics of nitrogen loss from the upland watershed was analyzed, and how the nitrogen retention in the reservoir differed at various time scales (annual, monthly and daily) was evaluated based on the coupled model.

2. Materials and methods

2.1. Study area

The Shanmei Reservoir, located at the midpoint of the Jinjiang River in southeastern China, is a large integrated reservoir with irrigation, power generation and water supply functions, which supplies drinking water for more than 4 million residents downstream of the reservoir. It has a drainage area of 1023 km^2. The main land uses in the watershed are forest (68%), orchard (12%), arable land including rice and rainfed cropland (11%), and urban (5%), as well as surface water, grassland, and bare land. The watershed is drained by two rivers, the Taoxi and Huyangxi rivers. The Longmentan water is transferred from the Minjiang River. These rivers feed into the Shanmei Reservoir (Fig. 1a). The average annual runoff into the reservoir is 14×10^8 m^3, of which 4.17×10^8 m^3 is from the Longmentan water transfer. The reservoir has a total storage capacity of 6.55×10^8 m^3 and an effective storage of 4.72×10^8 m^3. The Shanmei Reservoir is a deep reservoir with a 50 m maximum depth, and covers the surface area of 26 km^2 with a length of 12 km and a maximum width of 7 km.

2.2. SWAT model

The SWAT (Soil and Water Assessment Tool) model is a dynamic, semi-distributed and physically based model developed by the USDA Agricultural Research Service (ARS) (Arnold and Fohrer, 2005). It has become an effective means of predicting long-term impacts of land management measures on water, sediment, and agricultural nutrient loss in large, complex watersheds and has been widely applied for dealing with quantity and quality issues including NPS pollution (Ullrich and Volk, 2009; Moriasi et al., 2013; Chen et al., 2014). It has also been applied to the Shanmei Reservoir watershed (Liu et al., 2013; Yang et al., 2013).

The spatial data used in SWAT include a Digital Elevation Model (DEM), the land cover and soil maps. The topography was represented by 30 × 30 m elevation raster (Fig. 1b), which was obtained from the International Scientific Data Platform of the Chinese Academy of Sciences (http://datamiffor.csdb.cn/admin/datademMain/jsp). The soil information map (1:500,000) from the Soil Fertilizer Laboratory of Fujian Province was used to identify ten soil types in the watershed (Fig. 1c). The land cover data of 2006 was obtained from an interpretation of the Landsat Thematic Mapper (TM) remote-sensing images, which were classified into eight types including rice, rainfed cropland, forest, orchard, grassland, medium density residential, water body and bare land (Fig. 1d). In addition, the daily precipitation and climate data for 1990–2010 were obtained from 16 precipitation stations and two weather stations. In the study, the Shanmei Reservoir watershed was divided into 38 subbasins and 297 hydrology response units (HRUs), shown in Fig. 1a.