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Simulating the impact of watershed management for surface water quality protection: A case study on reducing inorganic nitrogen load at a watershed scale

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ABSTRACT

The management and control of non-point source pollutants (NPSPs) has been an increasing concern throughout the world. Controlling NPSP is critical to achieve the goals for improving surface water quality. This study used the Soil and Water Assessment Tool (SWAT) model to compare the effects of different kinds of watershed management measures on the transport of sediments and nutrients (ammonium nitrogen and nitrate nitrogen) in one of the main tributaries of the Xiangjiang River, the Zhengshui River. Our results confirmed that agricultural areas were the dominant sources of nutrients and sediment in the watershed and that a filter strip can significantly mitigate surface water pollution by intercepting and absorbing nutrients. We hypothesized five management plans to improve water quality for achieving the standard set by the National Twelfth Five-Year Plan (NTFYP). These plans were assessed according to their effects, economic cost efficiency and social impacts. The results showed that all five plans can successfully meet the goal of the NTFYP to reduce pollutant loads at the outlet of the watershed by more than 10%; and the results showed that plan that focused on critical source areas (CSAs) did not show its superiority as previous studies had theoretically suggested when the economic and social impacts were considered. Meanwhile, plans which considered economic factors and cost effectiveness would be more feasible and suitable as their cost efficiency were 10% and 30% higher than that of CSA plans for NO_3^- and NH_4^+, respectively, and their social impacts were much lower than other plans. Moreover, regression analysis further revealed the main characteristics of subbasin controlling the treatments efficiency of the inorganic nitrogen. Our study highlights the significance of combining theory with actual practice and would facilitate the selection and implement of more effective and reasonable measures to improve water quality.

1. Introduction

Nitrogen pollution (e.g., ammonium and nitrate) is a major problem in surface water of intensive urban and agricultural systems throughout the world (Volk et al., 2009; Zhang et al., 2010a,b; Ouyang et al., 2010). This is especially true in China due to rapid urbanization at an average level of 1.2% per year and intensified crop yield in limited crop lands to support the dense population (Huang et al., 2009; Zhang et al., 2010a,b; Guo et al., 2010; Zhao et al., 2008; Simelton, 2011). To mitigate surface water deterioration, governments began to make policies to promote the management of surface water quality, such as the European Union (EU) Water Framework Directive (WFD) (Hering et al., 2010). The Chinese government has also recognized the situation and has promulgated a series of decrees to mitigate and control the pollution of surface water. Among these, the National Twelfth Five-Year Plan (2011–2015, hereafter called NTFYP) has targeted a reduction in ammonium (NH_4^+) and oxynitride (mainly the nitrate nitrogen (NO_3^-)) loads of 10% by the year 2015 as the principal objective for surface water.

The sources of nitrogen pollution can be divided into point source pollution (PSP) and non-point source pollution (NPSP). PSP, which mostly comes from urban and industrial sources, is easier to control by increasing the construction of wastewater treatment plants as PSP generally come from sewage draining exit and its source is fixed. In contrast, NPSP is difficult to measure and control as it comes from many diffuse sources and is characterized by random and intermittent occurrence (Shen et al., 2012;

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Zhang et al., 2010a,b). During the last several decades, water quality has not improved significantly despite considerable efforts. This lack of improvement has been ascribed by many researchers to the contribution of NPSP, especially from agricultural activities (Oeurng et al., 2011; Prasuhn and Sieber, 2005; Leu et al., 2004). Additionally, nutrients from agricultural activities have generally been regarded as one of the dominant ways to accelerate the eutrophication of surface water (Wang et al., 2006). The large amount of nutrients and sediment loss from land surface to water bodies can cause problems such as toxic algal blooms, oxygen deficiency and may further make the water unsuitable for usage of daily life and the industrial and agricultural production (Carpenter et al., 1998). Thus, the need to reduce the nitrogen load from agricultural areas has been well recognized as the primary goal for improving surface water quality. Further, Carpenter et al. (1998) had pointed out that to manage agricultural NPSP, managing the landuse types, identifying the pollution source, controlling the input of nutrients (mainly by fertilizer application), and intercepting the transportation of NPSP were mainly ways to mitigate the deterioration of surface water. Additionally, the ideas have been generalized as best management practices (BMPs), which include reducing the agricultural area, reducing chemical fertiliser application, and building a filter strip along the river bank (Volk et al., 2009; Sahu and Gu, 2009; Parajuli et al., 2008), and have been widely used to eliminate or mitigate NPSP loads during the past decades. For example, Zhang et al. (2011) presented the study in Beijing and pointed out that restoring forest on unutilized land and slope arable land could be an effective method for reduction of NPSP. Through evaluating the pollution loss in different tillage systems, Munodawafa (2007) had advocated the improved agricultural activities instead of conventional tillage to reduce the soil erosion and nutrients loss. Comprehensive management strategies, such as the progressive management plans that contained various kinds of methods, have also been proposed to achieve the water quality improvement required by European Water Framework Directive (WFD) (Volk et al., 2009).

Among the BMPs, the construction of a filter strip was more popular because of its fewer impacts on landscapes of watershed and easier to implement. The filter strip is a kind of permanent vegetation zone, and its role of reducing NPSP has been extensively proven (Volk et al., 2009; Parajuli et al., 2008; Inamdar et al., 2001). For instance, Lee et al. (2010) reported an approximately 5% reduction in the total nutrient load after building a 20-m-wide filter strip along the river channel in the Gyeongancheon watershed of South Korea. This research also noted that a filter strip with a width of 5–10 m has the highest efficiency. In the Walnut Creek watershed of America, a simulation showed that a large-scale filter strip that transformed 50% of the subbasin area would reduce 94% of the NO_3^- load in surface runoff (Sahu and Gu, 2009). Additionally, this method seems more applicable and suitable in China because it has not reduced either agricultural land area or fertiliser application which would inevitably decrease total grain production and consequently cause a severe food security problem in China.

Before making and implementing measures for pollution control, it is necessary to target specific areas for management. Generally, it is accepted that pollution control in the targeted subbasin would be much more effective and cheaper than the first-come, first-served approaches (Veith et al., 2001). Recently, critical source areas (CSAs) were used to identify the main sources of the pollutants. Furthermore, CSAs targeted for managing and controlling pollutants have been widely regarded as an effective tool to improve water quality (White et al., 2009; Strauss et al., 2007; Gburek et al., 2002). However, economic cost and social impacts, which were very important factors (Anbumozhi et al., 2005), have rarely been taken into account when the feasibility of the method was evaluated. For the former, it included the costs for constructing the related facilities and their maintenance cost. While social impact mainly concerned on people's willingness for applying BMPs because such behaviours might occupy the agricultural land or residential land and consequently impact local agricultural production and daily life of river residents. The Soil and Water Assessment Tool (SWAT), which was developed by the United States Department of Agriculture (USDA), was used in this study to assess the pollution control measures. The SWAT model is a physical-based model that incorporates land-cover, topography, soil characteristics, climate conditions, and land use management. SWAT model is suitable for linking landscape factors to stream flows (Tian et al., 2012) and to simulate the surface runoff and flow in river channel. Meanwhile, this model is widely used to simulate NPSP transportation and the effects of management practices and has been proved effective in many watersheds (Lee et al., 2010; Shang et al., 2012; Pisinaras et al., 2010; Lam et al., 2010). Additionally, simulations on the level of hydrologic response units (HRUs) divided the watershed into units according to the characteristics of land use types and soil types, which allowed researchers to identify the source, find out the impact factors and analyze the production mechanism of NPSP pollution. The SWAT model is suitable for this study, as the simulation of flow and nutrient transportation are needed to identify the critical pollution areas, and the function of simulating management practices is also necessary to identify the areas that should be managed preferentially.

The Zhengshui Watershed was selected for this study as a representative research region characterized by intensive agricultural land use. This watershed is one of the main tributaries of the Xiangjiang River. According to the China Water Quality Yearbook (2005–2009), the Xiangjiang River is one of the most polluted tributaries of the Yangtze River due to high amounts of nitrogen input from intensive agricultural activities (Zhang et al., 2010a,b). The main objectives of this study were to simulate variations of inorganic nutrient pollution in the lower catchments of the Yangtze River and to determine which pollution controlling measure is more suitable to reduce inorganic nutrient pollution and to achieve our goal for clean surface water.

2. Materials and methods

2.1. Study watershed description

The Zhengshui Watershed is located in the downstream portion of the Yangtze River and has a catchment area of 3470 km^2. The watershed belongs to the continental subtropical monsoon climate and has an average annual precipitation and temperature of 1350 mm and 17.2–19.4 °C, respectively. The elevation of the watershed ranges from 40 m to 1112 m. Six land use types (Fig. 1) have been identified in this watershed, and the dominant land use types are agricultural and forest, which comprise 42% and 54% of the total watershed, respectively (Table 1).

2.2. The SWAT model

In this study, the SWAT model was used to investigate the stream flow, sediments, and nitrogen pollution in the watershed. In this model, a 90-m digital elevation grid, land use (Table 1) map and soil map from 2000 were used to delineate subbasins and HRUs. Climate data, which included a daily series of meteorological data, precipitation, temperature, solar radiation, wind speed and relative humidity during the simulation period, were collected to structure the environmental characteristics. Additionally, agricultural activities, such as the fertiliser and livestock manure applications and cropping patterns in the watershed were assembled from the