Agricultural Water Management 131 (2014) 1–16

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

A modeling approach to evaluating the impacts of policy-induced land management practices on non-point source pollution: A case study of the Liuxi River watershed, China

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ARTICLE INFO

Article history:
Received 3 April 2013
Accepted 10 September 2013
Available online 4 October 2013

Keywords:
Watershed modeling
SWAT
Agricultural policy
Conservation tillage
Optimal fertilization
Non-point source pollution

ABSTRACT

Conservation tillage and fertilization based on soil test have been promoted by the Chinese government in recent years. Their impacts on non-point source pollution were simulated using the Soil and Water Assessment Tool (SWAT) for the Liuxi River watershed, the only one local drinking-water-supply river basin of Guangzhou. The model was calibrated through comparing model outputs with observations to ensure reliable hydrologic, crop yield, and water quality simulations. The model results indicated that, 5% of total nitrogen (TN) load and 12% of total phosphorus (TP) load could be reduced at the watershed outlet by implementing the conservation tillage system of "rice parachute transplanting with no-tillage and straw mulching" for paddy rice fields which account for 9% of the watershed area. It is valuable to develop conservation tillage systems suitable for other types of agricultural land in southern China. When modeling the impacts of various fertilization levels derived from recommended fertilizer doses for medium fertility soil of the Pearl River Delta region where the watershed is located, the total crop yield was estimated to decrease by only 2% for up to 24% and 28% reduction in TN and TP loads at the watershed scale, respectively. The crop yields versus nutrient losses relationship simulated by SWAT indicated that great effects in TN and TP loads reduction could be achieved at the expense of minimal impacts on crop yield through optimal fertilization. The modeling approach presented in this study can be a useful tool for estimating the effects of policy instruments and pollution control measures.

1. Introduction

China has undergone rapid development since the implementation of "economic reform and open-door" policy in 1978. However, the concurrent increase in pollutant discharge has caused an overall deterioration of water quality. As point source pollution has gradually been brought under control in recent years, non-point source (NPS) pollution, especially agricultural NPS, has become a major contributing factor to water pollution in China (Ongley et al., 2010; Wang, 2006; Wang et al., 2004). Therefore, the mitigation of NPS pollution is of great importance for the restoration of water quality.

Best management practices (BMPs) have been widely used as NPS pollution abatement methods through source reduction or transport interruption. BMPs can be classified as managerial BMPs, such as conservation tillage and nutrient management which can be implemented with little or no additional cost, or structural BMPs like grass waterways and detention ponds that require high investment (Donigian and Love, 2002; Ritter and Shirmohammadi, 2000). The basic paradigm of the BMP approach is the implementation of an economically feasible practice or combination of practices for a specific water quality problem (Ritter and Shirmohammadi, 2000). In China, the most common form of water pollution is excess levels of nitrogen and/or phosphorous, which is mainly caused by agricultural NPS pollution (Zhang et al., 2004). The excessive nutrient losses from agricultural areas are largely because of the activities of many small farmers during agricultural production (ADB, 2011). Since land management practices taken by farmers can affect runoff generation, soil erosion, and the amounts of nutrients available for transport, it is possible to achieve effective control of nutrient losses through the change of land management practices by a large number of farmers in response to financial constraints, subsidy or political issues (Burt, 2001; Chaplot et al., 2004).

China has a long history of agricultural production, and traditional land management practices include frequent and deep tillage, crop residue removal and burning, as well as utilization of organic manure to maintain soil fertility. To achieve high crop yield under the pressure of food supply due to the huge population and limited farmland area per capita, the chemical fertilizer

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http://dx.doi.org/10.1016/j.agwat.2013.09.005

application rate has increased dramatically since the 1980s when the use of organic manure has declined rapidly due to the high costs of labor and transport (Gao et al., 2006; Guo et al., 2010). Also, multiple cropping has long been characteristic of Chinese agriculture and its application has been expanded in recent decades (Smit and Cai, 1996). The rapidly increasing consumption of fertilizers, coupled with intensive soil disturbance, has resulted in serious nutrient pollution and land degradation. These problems have led the Chinese government to emphasize the need for implementing practices that can mitigate negative environmental impacts (He et al., 2010). In 2002, the Ministry of Agriculture (MOA) initiated the project of "Demonstration Application of Conservation Tillage" for the dryland farming areas of northern China. With respect to the problem of excessive and unbalanced fertilization, MOA launched the project of "Soil Testing and Fertilizer Recommendation" in 2005 to determine optimal fertilizer application rates which not only match the need of plant growth but also minimize fertilizer-related pollution. Between 2005 and 2010, conservation tillage and fertilization based on soil test were advocated consecutively in the No. 1 document issued by the Chinese central government.

Government promotion has triggered a spreading implementation of conservation tillage practices and fertilizer application based on soil test across the country, and some studies have investigated their impacts on soil properties, crop yields, and nutrient losses based on field experiments (Barton et al., 2004; Cui et al., 2008; Su et al., 2007; Wang et al., 2010). However, there is no adequate information available to show the effectiveness of these practices in NPS pollution abatement at the watershed scale. It is not feasible to evaluate the watershed-scale impacts through field experiments or long-term monitoring. On one hand, the direct up-scaling of field results can be misleading due to the complexity of soil–water–plant interactions (Bärlund et al., 2007). On the other hand, it is difficult to relate water quality improvements with specific practices using monitoring data for a watershed with mixed soil types and land uses, unless extensive sampling points are available both before and after the implementation of BMPs (Santhi et al., 2006). In this context, watershed modeling provides a cost-effective and reliable approach. Moreover, models are capable of answering the "if–then" questions that are valuable for the design of management alternatives and policy instruments. A number of watershed-scale NPS pollution models with various capabilities and degrees of complexity have been developed in the past few decades, including simple export coefficient models like PLOAD (Edwards and Miller, 2001), regression models like SPARROW (Schwarz et al., 2006), and physically-based models such as AnnAGNPS (Bingner et al., 2005), HSPF (Donigian et al., 1984), and SWAT (Neitsch et al., 2011). The simple models are sometime incapable of giving desirable results, while the data and computation requirements for the detailed models are usually enormous which may hinder their applications to large watersheds (Borah and Bera, 2003). Thus, the selection of model should be based on the study purpose and data accessibility.

The Soil and Water Assessment Tool (SWAT) is a physically-based, semi-distributed, and continuous-time model that was developed in the early 1990s to assist water resource managers in assessing the impacts of management and climate on water supplies and NPS pollution in catchments and large river basins (Arnold and Fohrer, 2005). As one of the most widely used watershed-scale hydrologic and NPS pollution models, SWAT has been successfully applied worldwide for water quantity and quality issues such as pollution load estimation (Kirsch et al., 2002; Omani et al., 2012), BMP effects evaluation (Liu et al., 2013; Santhi et al., 2006), land use/climate change impacts assessment (Wilson and Weng, 2011; Zhang et al., 2013), and water resource estimation (Faramarzi et al., 2009; Schuol et al., 2008). Among the various watershed models, SWAT offers the greatest number of agricultural BMP alternatives (Kalin and Hantush, 2003) and provides a feasible framework for the simulation of various management practices (Gassman et al., 2007). Many commonly used practices can be simulated in SWAT with straightforward parameter adjustment, such as changes in fertilizer and pesticide application, tillage operation, crop rotation, and wetlands. Arabi et al. (2007) proposed standardized approaches for simulating specific conservation practices in SWAT, including contour farming, strip cropping, parallel terraces, cover crops, residue management, field borders, filter strips, grassed waterways, lined waterways, and grade stabilization structures. Many previous studies have demonstrated the ability of SWAT in evaluating the impacts of various management practices on NPS pollution. Santhi et al. (2006) predicted the long-term impacts of BMPs (nutrient/forage harvest/residue/brush management, range seeding, grass covering for critically eroding area, grade stabilization structure, and contour farming) in reducing NPS pollution due to the implementation of water quality management plans in a watershed of Texas. Jha et al. (2007) simulated the response of nitrate loadings and corn yield to fertilizer application rates in a watershed located in west-central Iowa. Cibin et al. (2012) used SWAT to quantify the long-term watershed scale impacts of corn stover removal on hydrology and water quality in an agricultural watershed in the Midwest US. A comprehensive review of SWAT applications, including BMP impacts on pollutant losses, can be found in Gassman et al. (2007).

In this study, SWAT was applied to predict the long-term impacts on nutrient losses by implementing conservation tillage and optimal fertilization for the Liuxi River watershed of Guangzhou, China. Guangzhou is one of the most developed cities in China. However, the majority of its local water resources are not suitable for drinking due to pollution, and citizens' drinking water mainly depends on rivers outside the city. Under such circumstance, pollution prevention and control for the Liuxi River watershed is quite important as it is the only one drinking-water-supply river basin located inside the administrative area of Guangzhou. According to monitoring data, the downstream part of the Liuxi River has suffered from serious pollution, especially by nitrogen and phosphorus (GZEMC, 2012). Since previous researches mainly focus on water use planning and point source pollution control, predicting the effects of implementing conservation tillage and optimal fertilization in response to national policy will provide valuable information to decision makers for the design of NPS pollution control strategy.

2. Materials and methods

2.1. Study area

The Liuxi River is regarded as the mother river of Guangzhou, the capital city of Guangdong Province in southern China (Fig. 1a and b). The Liuxi River watershed with an area of 2300 km^2 is situated in the northeast corner of the Pearl River Delta (PRD) region, which is one of the fastest growing regions in China. The watershed spans across three county-level districts (Huadu, Luogang, and Baiyun) and a county-level city named Conghua which occupies about 70% of the watershed area (Fig. 1c). The water of Liuxi River is used for a wide range of sectors, such as drinking water supply, agriculture and industry water use, and recreation. However, the source-water intake near the river outlet was abandoned in 2010 due to pollution, and only intakes located at the middle-stream of river were still in use (Fig. 2).

The study area has a typical subtropical monsoon climate. The mean annual precipitation of the watershed is 1800 mm, mostly occurring in April–September. Forest is the dominant land use type