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Detection of sensitive soil properties related to non-point phosphorus pollution by integrated models of SEDD and PLOAD

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ABSTRACT

Effectively identifying soil properties in relation to non-point source (NPS) phosphorus pollution is important for NPS pollution management. Previous studies have focused on particulate P loads in relation to agricultural non-point source pollution. In areas undergoing rapid urbanization, dissolved P loads may be important with respect to conditions of surface infiltration and rainfall runoff. The present study developed an integrated model for the analysis of both dissolved P and particulate P loads, applied to the Meiliang Bay watershed, Taihu Lake, China. The results showed that NPS P loads up to 15 kg/km^2 were present, with particulate P loads up to 13 kg/km^2. The highest loads were concentrated in the south-eastern region of the watershed. Although particle P was the main contributor to NPS P loads state, the contribution of dissolved P was significant, especially in sub-basins with significant amount of artificial land cover. The integration of dissolved P and particulate P loads provided more accurate evaluation of NPS P pollution. NPS P loads were found to correspond to specific soil properties. Soil organic matter and total nitrogen were shown to influence dissolved P loads, while total phosphorus and soil particle composition proportion were more closely related to particulate P loads.

1. Introduction

Phosphorus (P) is an essential element for crop growth and a primary nutrient of inland lakes (Norton et al., 2012). Excessive discharge of P can significantly affect water quality (Smith et al., 2001; Delpla et al., 2011). In recent decades, the non-point source (NPS) P loading has become a priority for water pollution management in many catchments (Evanylo et al., 2008; Yang, 2009a,b), in relation to lake eutrophication. In order to control water eutrophication, reducing P discharge is considered an effective solution (Castoldi et al., 2009). Therefore, understanding NPS P pollution loads and control factors are important for the protection of the watershed environment.

Identifying spatial P pollution loads is an important aspect of managing catchment related eutrophication. A large number of NPS models have been developed (Table 1). In general, these can be divided into two categories: empirical models (SWAT, ANSWERS, and AGNPS, etc.) and the physically based models (RUSLE, SEDD, and PLOAD, etc.) (Laurent and Ruelland, 2011; Beasley et al., 1980; Wang et al., 2012; Shen et al., 2011; Gburek and Sharpley, 1998). The physically based models have shown accurate estimation of pollutants in small spatial scale, but are limited due to complexity and excessive reliance on detailed field observations. These make these models less unsuitable for large spatial scales (McDowell et al., 2002; Bechmann et al., 2009). Empirical models are widely used in watershed monitoring with various advantages such as condensed structures, accessible parameters and simple and efficient operation (He et al., 2011, 2012).

The NPS P loads are categorized as: particulate loads under agriculture non-point source pollution (ANPS) condition and the dissolved loads under impervious surface runoff, in which the soil P is lost from the particulate state (sediment adsorption state). Many studies determine particulate P loads by classical empirical models, in particular the Universal Soil Loss Equation (RUSLE), which has been widely applied to evaluate soil erosion modulus by integrating several factors including climate, land use, soil, topography, vegetation and enrichment ratio of sediment pollutants

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Table 1
Commonly used NPS models.

Models	Type	Output information	Required parameters
SWAT	Physically based	The pollutants (total nitrogen and total phosphorus) delivery process, including three modules such as runoff, soil erosion and river delivery.	Rainfall, runoff, evaporation, channel attenuation, silt and sediment deposit, cultivation measures, land use, soil texture, soil composition, soil organic matter, soil total nitrogen, soil total phosphorus, etc.
AGNPS	Physically based	Nutrient material circulation driven by agriculture non-point source pollution, the output information was grid and pixel based.	Rainfall, runoff, soil infiltration rate, sediment deposit, land use, fertilizer consumption, total phosphorus and total nitrogen contents in fertilizers and pesticides, soil moisture, etc.
RUSLE	Classical empirical	The soil loss amounts	Land use, soil type, rainfall, slope, vegetation status
SEDD	Classical empirical	The amounts of nutrients loss in particulate state	Soil loss amounts, sediment delivery ratio, nutrients concentration status in sediment
PLOAD	Classical empirical	The loss amounts of nutrients in runoff	Rainfall, land use, pollutants concentration in runoff

(Terranova et al., 2009; Ouyang et al., 2010). Based on the fundamental form of RUSLE, the sediment delivery distributed (SEDD) model has been recently improved by researchers (Fu et al., 2006; Jain and Kothyari, 2000). One of the improvements is to take sediment delivery factor into account, and thereby the loss of soil sediment absorbed nutrients can be quantitatively and more precisely monitored (Yang et al., 2012). More importantly, under rapid urbanization in eastern China in recent decades, the increased impermeable land surfaces in these areas impact overall surface infiltration and rainfall runoff, and cause soil nutrients to be lost in the dissolved state (Ouyang et al., 2012). Therefore, dissolved P loss has gained more attention in large scale NPS research (Wang et al., 2014). The PLOAD model is a generic GIS-based NPS screening model proposed by USEPA (2003) and has been widely used in simulation of runoff coefficients under storm conditions, suggesting that the PLOAD could be an ideal choice for dissolved P loss assessment of dissolved pollutant concentrations (Lee et al., 2008; Kemanian et al., 2011). Above all, as dissolved P (Dis-P) and particulate P loads (Par-P) constitute the entire NPS P loads (Tot-P), an effective model should integrate them for the accurate assessment of NPS P loads, especially in urban-rural mixed regions (Cui et al., 2003). In this context the SEDD and PLOAD approaches represent an ideal choice.

Based on the assessment and monitoring results of NPS P loads, studies have demonstrated that NPS P pollution load is influenced by rainfall, topography, land use, soil properties, hydrologic process and human activities (Strauss et al., 2007; Razafindrabe et al., 2010; Petrosell et al., 2014; Wu et al., 2012). Soil erodibility factor (K) has been used to represent the impact of land use and rainfall features on soil characteristics, and also demonstrate the critical influence on NPS P loads status directly (Recanatesi et al., 2013). The erodibility factor can be calculated by identifying soil organic matter content and soil mechanical composition. Therefore, the soil properties including soil organic matter (SOM), soil acidity, soil nutrients and soil particle composition influence NPS P loads, and more information on the relationship between NPS P and critical soil properties is needed.

With the rapid urbanization and significant land use change, the watershed of Meiliang Bay has experienced the most severe eutrophication. This watershed is a typical urban–rural mixed area in Yangtze River Delta and Taihu basin and suffers from severe NPS pollution (Duan et al., 2015). The objectives of the present study are: (i) assess the watershed P loss status based on the model that considers both dissolved P and particulate P loads together; (ii) analyze relationships of Dis-P and Par-P to the total P loads (Tot-P) and the underlying soil properties. The results from this study provide fundamental information for managing NPS in mixed use watersheds.

2. Materials and methods

2.1. Study site

The watershed region of Meiliang Bay is located in the eastern coast of China and south of the Yangtze River Delta, the area is 486.2 km^2. This region is located in a peri-urban area between Wuxi and Changzhou cities, which have undergone massive economic development and changing agricultural land use. The study area has undergone rapid urbanization in the last 30 years, and a large number of arable lands and forestlands were replaced by artificial land cover (Li et al., 2007). Nowadays, more than 30% of the area is impervious surface and 55% is arable land. The average annual precipitation at the study area is 1035 mm, and the main rainfall season is from May to October. The annual mean runoff depth is 688 mm and the annual average temperature is 15.6 °C. The main soil type in this area is bleached paddy soil, which covers more than 85% of the study site. Soil organic matter (SOM), total P (TP), total nitrogen (TN) content is 1.97 g kg^{-1}, 0.07 g kg^{-1} and 0.12 g kg^{-1} respectively. Sand proportion accounts for 13.14% and pH is 5.97 (Gong et al., 2003). Moreover, the sub-watershed has a dense river network, consisting of three trunk streams with their tributaries such as Wujin Port, Yangxi and Liangxi Rivers, which flow into Meiliang Bay of the Taihu Lake. Eighteen sub-basins were generated by ArcGIS based on three inflow rivers (Fig. 1).

2.2. Quantitative evaluation of NPS P loads

2.2.1. Adsorbed NPS P loads component

The SEDD model was used to assess the NPS particulate P loads, which was followed with the basic Revised Universal Soil Loss Equation (RUSLE), attached sediment factor and sediment delivery ratio into the model formulation (Cui et al., 2003; Yang et al., 2012). The model was calculated in ArcGIS using 30 m × 30 m spatial grids

$$Par\ (P) = A_i \times P_{sed} \times SDR_i \quad (1)$$

where $Par(P)$ is the particulate P load per unit area (kg km^{-2} year^{-1}); P_{sed} expresses the sediment total P concentration status (g kg^{-1}); SDR_i is the sediment delivery ratio (%) for each grid, which is calculated based on the following model:

$$SDR_i = \exp(-\beta t_i) \quad (2)$$

where t_i is the travel time (h) from the grid i to the nearest river channel along the flow path and β is a coefficient lumping together the effects of roughness and runoff along the flow path (Ferro, 1997). The sensitivity of SDR to β is watershed-specific, and the value of 0.304 was used because this value produces smallest mean relative square error between modeled and measured sediment yield (Guo et al., 2004; Strauss et al., 2007; Zhou and Wu, 2008). Travel time was calculated (Eq. (3)) (Jain and Kothyari, 2000), using