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Identifying non-point source priority management areas in watersheds with multiple functional zones

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ABSTRACT

The concept of water functional zones promotes the comprehensive supervision and scientific oversight of non-point source (NPS) pollution at the watershed scale. Therefore, understanding the spatial distributions and temporal trends in watershed priority management areas (PMAs) is important in the study and efficient management of NPS pollution. However, no comprehensive studies of PMAs have been conducted to protect water quality effectively in watersheds with multiple water functional zones. In this study, a new framework is presented that quantifies the perturbations of multiple spatial assessment units to the quality of nearby water bodies in various water functional zones. This innovative approach, which combines the Soil and Water Assessment Tool (SWAT) and statistical analysis, was applied to characterize multiple-level PMAs with a case study of the Daning River watershed in China. Based on the results, the advantage of this new framework is better suited to downstream areas, particularly in dry periods and severely polluted watersheds. This paper reinforces the view that the concept of zoning should be taken seriously in the framework of PMAs targeting. From the aspect of watershed management, these new PMAs can offer an optimal strategy for locating comprehensive and cost-effective management practices at the watershed scale, particularly in large watersheds or long river systems.

1. Introduction

Stable river ecosystems play an important role in sustainable development by providing various functions, such as supplying drinking water and irrigation water and creating habitats for fish farming; thus, these ecosystems contribute to social development (Karr and Scholosser, 1978). Typically, the assignment of particular water bodies to specific uses, known as water functional zones, is considered to be a useful option for mitigating watershed conflicts. The concept of water functional zones promotes comprehensive supervision and effective and scientific oversight of river pollution at the watershed scale (Chang, 2008; Huang et al., 2010). In such a

Abbreviations: NPS, non-point source; PS, point source; PMAs, priority management areas; SWAT, soil water assessment tool; AGNPS, agricultural non-point source model; HSPF, Hydrological Simulation Program-Fortran; DEM, digital elevation model; HRUs, hydrologic response units; MAU, multiple assessment unit; SCA, Sub-outlet Concentration Approach; SLAA, Sub-watershed Load per Area Approach; TP, total phosphorus.

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system, the primary concern of watershed management is to distinguish multiple water functional zones within a watershed and to make clear distinctions among control strategies based upon their required water quality standards for the common good (Su et al., 2011; Yang et al., 2012a). Indeed, there are numerous existing watershed management approaches integrating the concept of water functional zones (Sabatini et al., 2007; Cheruvelil et al., 2008).

A typical water functional zone is defined as a series of water bodies with similar water quality standards based on their natural regional properties and societal demands (Su et al., 2011; Yang et al., 2012b). Evaluating the assimilative capacity of water bodies and limiting the total amount of pollution discharge based on zoning can scientifically support the exploitation, utilization, protection and management of water resources and can help realize the sustainable utilization of water resources. In general, water body impairments are commonly caused by both point source (PS) pollution and non-point source (NPS) pollution (Wu and Zheng, 2013). Recently, PS pollution has been significantly reduced through the implementation of systematic laws, standards and comparatively high-quality engineering measures. Therefore, efforts have largely shifted to NPS pollution, and these efforts typically include determining priority management areas (PMAs) or critical source areas (CSAs) for an impaired water body (Trevisan et al., 2010). As a result of the non-point, distributed and mixed nature of NPS pollution (Buchanan et al., 2013; Chen et al., 2014a,b), PMAs are defined as relatively small yet sensitive portions of watersheds where a large amount of NPS pollutants are produced. Therefore, characterizing the spatial distribution of PMAs within watersheds with multiple functional zones would improve our understanding of water quality impairment and would help researchers establish priorities for watershed management.

Model analyses are useful for identifying the spatial distribution of PMAs according to their common features. In recent years, physical-mechanism-based and distributed models, such as the Agricultural Non-point Source Pollution Model (AGNPS), the Soil and Water Assessment Tool (SWAT) and the Hydrological Simulation Program-Fortran (HSPF), have been successfully used to identify PMAs (White et al., 2009; Zhang et al., 2014). In these studies (Panagopoulos et al., 2011; Alam and Dutta, 2012; Giri et al., 2012), the criteria for targeting PMAs can be categorized by land use and by the quality of nearby water bodies. In the land use category, PMAs are defined as sensitive areas where the pollutant discharge exceeds the local tolerance. This concept may have limited utility for watersheds with water functional zoning because environmental threats cannot be recognized without considering the effects of pollutants on water bodies. In the water quality category, PMAs are defined as upstream areas of particular river sections in which the water quality violates the associated standard. Under this definition, the focus has generally been placed on key tributaries, specific drinking watershed inlets or other key physical boundaries (Lee et al., 2012). However, the existing methods give little consideration of upstream inputs, even though they may also contribute to changes in the downstream water quality (Wei et al., 2013). In fact, except for the headwaters, the pollutant flux at a particular location within a river network depends not only on the local pollutant inputs but also on the complex physical, chemical and biological processes within the entire upstream river network (Munafo et al., 2005; Chen et al., 2014a, 2014b). Overall, traditional frameworks are generally based on uniform water quality standards for an entire watershed (Flipo et al., 2007; Yang et al., 2012a, 2012b). Thus, it is not always practical to use these traditional approaches because a host of factors have imposed changes on multiple functional zones, especially for the distributed nature of NPS pollution under varying hydrological and environmental circumstances. Despite the common use of water zoning schemes worldwide, no comprehensive studies have been conducted within the framework of water functional zones. This incomplete framework should be further reinforced by incorporating the reality of multiple functional zones into PMAs targeting for more effective NPS management strategies.

Therefore, the main objectives of this work are to 1) establish a new PMAs framework for multiple functional zones, 2) classify multiple levels of PMAs within a watershed and 3) explore the impact of seasonal hydrological conditions on the spatial distribution of watershed PMAs. These objectives have been achieved using a combination of watershed modeling and statistical techniques in the Daning River watershed, which is located in the Three Gorges Reservoir Region, China. Detailed information regarding the framework is presented below.

2. Materials and methods

2.1. *The description of the new MAU-PMAs framework*

The proposed PMAs framework, shown in Fig. 1, integrates the concept of water functional zones by quantifying the pollution emissions from multiple assessment units (MAUs) and their effects on the quality of the nearby water body. Specifically, watershed modeling is used to determine the temporal and spatial variability of NPS pollution at the watershed scale. Next, pollutant fluxes from each assessment unit are analyzed by excluding the impact of upstream inputs. Finally, multiple levels of PMAs are established to satisfy water quality standards for corresponding water functional zones.

Step 1. Delineation of the river network and assessment units

In this step, the river network is extracted from a constructed digital elevation map (DEM) using the hydrology module of ArcGIS (Shen et al., 2013c). Then, the watershed is described as a system of sub-watersheds and reaches (Liu and Weller, 2008; Miller et al., 2013). An assessment unit, such as a typical sub-watershed, is defined by the variations in the hillslope and valley morphology, whereas the stream reaches are outlined by the landscape, cross section, channel relief and surrounding terrain. Commonly, the climate, landscape, land use, soil type and human activities affect the spatial variation of NPS pollution. With the development of detailed spatial GIS data and physically based models, a watershed can be divided into many smaller spatial units based on the spatial input data to determine the spatial heterogeneity of the NPS pollution, which therefore facilitates a more detailed description of