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Development and application of watershed-scale indicator to quantify non-point source P losses in semi-humid and semi-arid watershed, China

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ABSTRACT

Quantifying non-point source (NPS) phosphorus (P) pollution loads is essential for watershed nutrients management. This study intended to develop a NPS P indicator which (1) was suitable in semi-humid and semi-arid watersheds of Northern China; (2) integrated the key NPS P loss factors and constructed them in a simple and physically understandable way and (3) kept P loss forms distinctively separate. An inverse distance-based delivery ratio was proposed to count for the P delivery efficiency from source to watercourses. We applied this P indicator in Luan River Watershed (LRW) of northern China under typical hydrological years and seasons. Results demonstrated that this NPS P indicator predicted reasonable NPS TP loads using simple methods and readily obtainable inputs. The sub-watersheds located in the south of LRW were recognized as the high risk areas of NPS P loss to Panjiakou reservoir. The upland and paddy fields near the river channels were particularly posing high risk and thus should be treated with prioritized management practices such as soil conservation and recommended fertilization. Rainfall-runoff related variables rather than P source variables explained more of the spatial variation in NPS P load and percentages. Using this tool could give policy makers insight into the component and location of NPS P pollution that needs to be the focus of policy at watershed scales before sophisticated studies were conducted in smaller scales.

1. Introduction

Phosphorus (P) is widely regarded as a limiting nutrient for primary production in aquatic systems, and in excess it may impair water quality by accelerating the production of algae and aquatic plants (Correll, 1998). Reducing nutrient inputs into water bodies is considered as the most effective strategy for controlling water pollution and sustaining high ecological status (Conley et al., 2009). Owing to the effective control of point sources in the past decades, non-point sources (NPS) particularly agricultural activities have become the leading contributor to water quality degradation worldwide. In 2010, a national pollution census first indicated that in China the agriculture's contribution to total P loads in receiving waters was up to 67.4% (Zhang, 2010a), which has raised extensive interests on NPS pollution from both government and scientists.

Quantifying loads of NPS pollution and its components is essential for watershed or regional nutrient management planning. Approaches including export coefficient models (ECM) (Ding et al., 2010; Johnes, 1996) and mechanistic models (e.g., SWAT, HSPF) (Mishra et al., 2007; Shen et al., 2014) have been applied world widely in NPS pollutant load estimation. The ECM has the advantage of requiring less data and has fewer parameters, but doesn't consider the influence of spatial heterogeneity of rainfall and underlying surfaces (Ding et al., 2010). The mechanistic models can provide accurate results, but often encounter difficulties in application because of their complicated structures and strict requirements for the input data (Zhang, 2010b). This phenomenon was particularly prominent in countries without long term and spatially dense monitoring data and basic or empirical field studies, such as China (Ongley et al., 2010; Shen et al., 2012).

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The Chinese researchers have developed several local NPS P quantification methodologies (Chen et al., 2008, 2010; Han et al., 2011; Yang et al., 2012). Chen et al. (2008, 2010) proposed a model framework to analyze the biogeochemical P flows in agro-ecosystem on the basis of emission inventory and full P balance calculation. The P inputs included P brought by mineral fertilizer, livestock manure, other organic fertilizers, precipitation, seeding and irrigation, and the outputs included plant uptake, runoff and leaching. Han et al. (2011) introduced a concept of net anthropogenic phosphorus accumulation and calculated it in Beijing by deriving data from fertilizer use, human food and animal feed, non-food P and riverine P. Yang et al. (2012) estimated the potential P loads from cropping, animal production and rural living in a typical county of Northern China Plain. These methodologies were mostly established on a P-balance basis and the outputs were generally indicative of the potential losable P in source. Whereas the NPS P loss potential was not determined by source potential alone, but also by transport potential (Gburek et al., 2000). Few of these studies took consideration of the role of P transport factors (e.g., runoff, field to stream distances) in determining P delivery routes and efficiency, except for Yang et al. (2012) who used scenarios of delivery coefficients to count the likely P delivery ratios from source areas to watercourses. In addition, the terrain P enters watercourses as dissolved P (DP) carried by surface and subsurface runoff and particulate P (PP) associated with eroded soils (Sharpley et al., 2003). They vary greatly in their relevance to aquatic eutrophication because DP is readily bio-available and PP potentially bio-available (Boström et al., 1988). Separating TP loads into these forms and pathways would allow a detailed examination of the P load composition and of the factors influencing both the relative and absolute magnitude of these P components.

The main objective of this work was to develop an indicator to quantify the NPS P losses by integrating a range of contributory factors determining NPS P loss from terrain to water within a single calculation system. Our target is an estimator which follows the principle that the coincidence of high source potential and high transport potential determined the actual high NPS pollution risk; keeps P transport forms (e.g., DP and PP) and processes (e.g., surface runoff, subsurface runoff and soil erosion) distinctly separate; and is structured in a way that the individual parameters of calculation have physical meaning. A second objective of this study was to apply NPS P indicator in a semi-humid and semi-arid watershed of China and characterize the variations in NPS P predictions in response to hydrological condition changes in order to obtain important insights into P management in watershed scale.

2. Methods and methodology

2.1. Site description

Luan River watershed (LRW) is a sub-basin of Hai River Basin (HRB) in Northern China. The Luan River originates near the border between Hebei Province and Inner Mongolia, flowing through plateau, mountain and plain from west to east. This study mainly investigated the mountainous part of LRW located at the upstream of an important Panjiakou Reservoir (Fig. 1).

Due to the data availability, nine sub-watersheds with hydrometric stations installed in the outlets were applied with LRW NPS P indicator (LRW-PI). These sub-watersheds were drained by Budeng river, Yixun river and Yimatu river in the north, by Wulie river, Laoniu river and Xingzhou river in the middle and by Pu river, Liu river and Sa river in the south (Fig. 1). Sub-watershed boundaries were delineated by ArcSWAT tool in ArcGIS 9.3 software (ESRI, Inc., Redlands, CA) based on a digital elevation model (DEM) expressed as a 90 m raster and the geographic coordinates of hydrometric stations.

The LRW is characterized by a semi-humid and semi-arid monsoon climate and an annual average rainfall of 520 mm. Influenced by the topography, rainfall decreases from the south to the north. More than half of the annual rainfall occurred between June and September. Percentages of different soil types or land uses in each

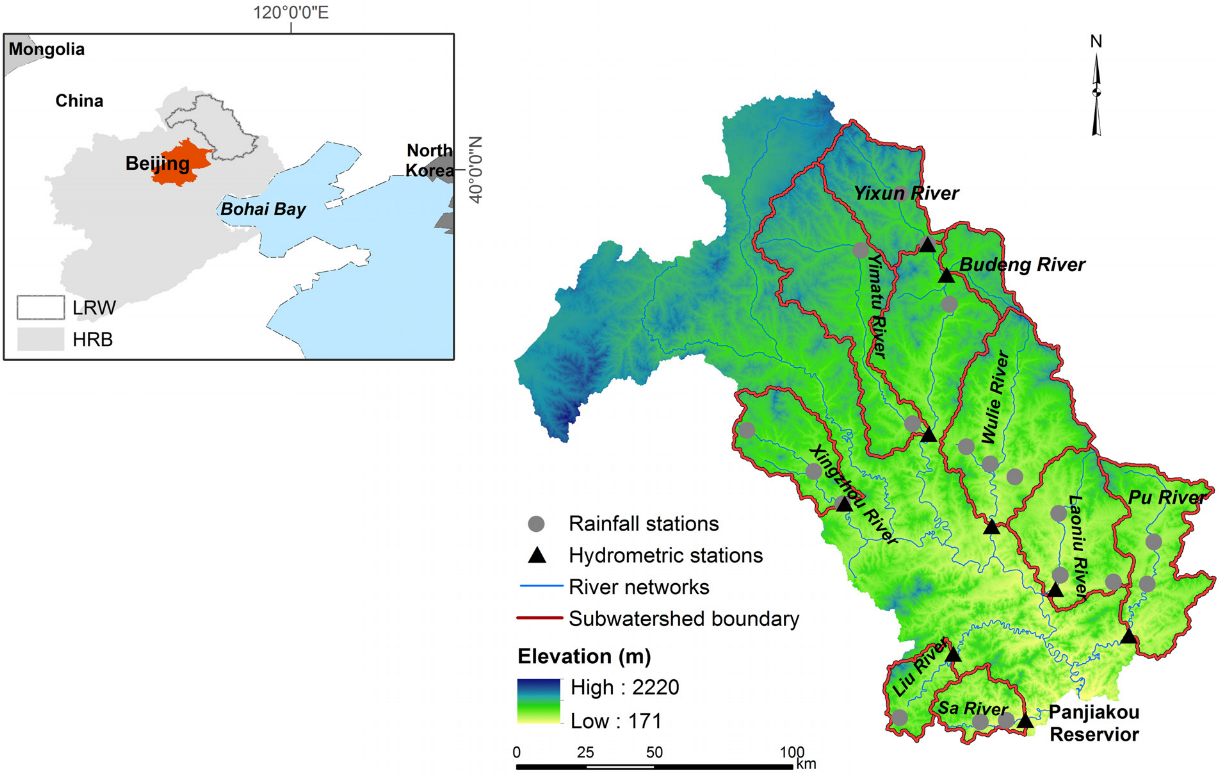

Fig. 1. Locations of Luan River Watershed and the studied sub-watersheds.