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Evaluating the risk of phosphorus loss with a distributed watershed model featuring zero-order mobilization and first-order delivery☆,☆☆,★

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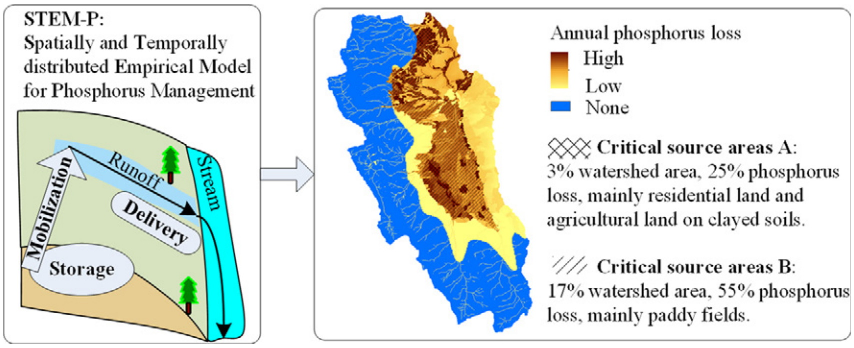
HIGHLIGHTS

- Simulate phosphorus loss processes across landscape as storage-mobilization-delivery
- Grid-based travel time along flow paths considered in phosphorus delivery process
- Spatially distributed results for identifying sub-field critical source areas
- Model results facilitate the selection, design and placement of management practices.

GRAPHICAL ABSTRACT



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ABSTRACT

Many semi-distributed models that simulate pollutants' losses from watersheds do not handle well detailed spatially distributed and temporal data with which to identify accurate and cost-effective strategies for controlling pollutants issuing from non-point sources. Such models commonly overlook the flow pathways of pollutants across the landscape. This work aims at closing such knowledge gap by developing a Spatially and Temporally Distributed Empirical model for Phosphorus Management (STEM-P) that simulates the daily phosphorus loss from source areas to receiving waters on a spatially-distributed grid-cell basis. STEM-P bypasses the use of complex mechanistic algorithms by representing the phosphorus mobilization and delivery processes with zero-order mobilization and first-order delivery, respectively. STEM-P was applied to a 217 km^2 watershed with mixed forest and agricultural land uses situated in southwestern China. The STEM-P simulation of phosphorus concentration at the watershed outlet approximated the observed data closely: the percent bias (P_{bias}) was −7.1%, with a Nash-Sutcliffe coefficient (E_{NS}) of 0.80 on a monthly scale for the calibration period. The P_{bias} was 18.1%, with a monthly E_{NS} equal to 0.72 for validation. The simulation results showed that 76% of the phosphorus load was transported with surface runoff, 25.2% of which came from 3.4% of the watershed area (classified

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as standard A critical source areas), and 55.3% of which originated from 17.1% of the watershed area (classified as standard B critical source areas). The standard A critical source areas were composed of 51% residences, 27% orchards, 18% dry fields, and 4% paddy fields. The standard B critical source areas were mainly paddy fields (81%). The calculated spatial and temporal patterns of phosphorus loss and recorded flow pathways identified with the STEM-P simulations revealed the field-scale critical source areas and guides the design and placement of effective practices for non-point source pollution control and water quality conservation.

1. Introduction

Water-quality deterioration caused by excessive nutrient discharge has been widely documented (Davis and Koop, 2006; Ma et al., 2011; Novotny, 1999; Smith, 2003). Non-point source (NPS) pollution is identified as a leading environmental threat. The control of water pollution by non-point sources of nutrients remains a challenge for scientists and managers since the processes of pollution storage, mobilization, and delivery are complex. Accurate and cost-effective pollution control and sustainable watershed management require detailed information on (1) reliable estimation of pollution load, (2) reliable identification of critical source areas (CSAs) (Chen et al., 2013; Shen et al., 2011), and (3) tracking pollutant pathways and flow paths of polluted runoff. Accurate estimation of pollution load is imperative to assess the gap between target water quality standard and the field concentrations of pollutants. The reliable identification of CSAs facilitates effective watershed management by implementing proper practices in the most critical areas. The flow paths and travel time of polluted runoff impact the sediment and nutrient loads that reach receiving water bodies given that forests, grasslands, and wetlands retain pollutants by sedimentation, adsorption, and biotransformation (Chescheir et al., 1991; Uusi-Kamppa et al., 2000). The effective placement and design of pollutant control facilities such as buffer strips and artificial wetlands relies on detailed information about the pathways of pollutants from their points of origin to the discharge areas (Loáiciga et al., 2015; Sadeghi et al., 2017). However, the available tools including NPS pollution indices and models present significant challenges to provide all the three types of information cited above, especially the flow pathways and their impact on pollutant transfer.

NPS pollution indices, such as the Phosphorus Index (PI), are widely used to identify CSAs. Originally, the PI (Lemunyon and Gilbert, 1993) was designed for field-scale pollution risk ranking based on both "source" and "transport" characteristics. Subsequently, the PI was modified for watershed-scale assessment by improving the weighting method of hydrologic connectivity to a stream network (Gburek et al., 2000). More recently, a phosphorus index based on runoff travel time was developed to further improve the PI's capability to represent the effect of a drainage network on phosphorus loss potential (Buchanan et al., 2013). Improved PI methods combine empirical observations about source characteristics and knowledge about transport potential and are used for watershed-scale identification of phosphorus CSAs. The PI, however, is limited in its ability to simulate phosphorous dynamics given that it is primarily a tool for relative pollution risk assessment rather than for the quantitative estimation of pollution export.

Another approach to NPS pollution management is through the use of models. Empirical or "black-box" models, such as the Export Coefficient Model (ECM), have been successfully applied to the estimation of pollution loads from the small watershed scale to the regional and national scales (Johnes, 1996; Malve et al., 2012; Winter and Duthie, 2000). The classical ECM is a lumped model and only the spatial variation of land covers is accounted, which is not detailed enough for CSAs identification. By contrast, physically-based process models, such as Soil and Water Assessment Tool, or SWAT (Arnold et al., 1998), Hydrological Predictions for the Environment or HYPE (Lindström et al., 2010), and Annualized Agricultural Non-Point Source Pollution Model or AnnAGNPS (Bingner and Theurer, 2001), account for the spatial variations of soils, land use, topography and management practices. They simulate pollutant loads after calibration and can identify CSAs. However, these models are seldom used in practice by conservation specialists for delineating CSAs and for implementing measures to control pollutants emanating from non-point sources. The relatively infrequent application of the latter models might be explained by their generation of simulation results that are meaningful for naturally occurring hydrologic catchments within the landscape (usually sub-watershed), while management of non-point pollutants in rural settings is meaningful at the farm-scale (Ghebremichael et al., 2013), which represents a human-induced partition of the landscape. Also, the farm-scale flow paths and travel times of runoff are not delineated by these models, and their impact on nutrient dynamics during transport is not accounted for. Another reason for the limited applications for the cited physically-based process models may be found in their complexity, which means that the data requirements, parameterization, and calibration make their application computationally and logistically burdensome, especially in large watersheds of regional scales (Alexander et al., 2002; Heathwaite, 2003).

This paper develops a Spatially and Temporally distributed Empirical Model for Phosphorus management (STEM-P) to address the limitations of the available tools in supporting accurate and cost-effective management. The STEM-P model satisfies three objectives: (1) reasonably accurate estimation of phosphorus export, (2) field or sub-field identification of CSAs, and (3) delineates the flow paths and considers travel time of phosphorus runoff. The STEM-P considers the impacts of flow pathways on phosphorus dynamics during transport. In addition, it is a process-based empirical model, that is, it relies on simple empirical equations and limited parameters to represent the most critical landscape processes (mobilization and delivery) that impact phosphorus loss for practical applications of pollutant control measures.

2. Method

2.1. Model development

Operational models for non-point source phosphorus management, such as Phosphorus Indicators Tools (Heathwaite et al., 2003) divide the processes by which phosphorus moves from the landscape to water bodies into three categories: storage, mobilization, and delivery. Storage is the balanced process of background phosphorus content that results from phosphorus input and output (e.g. harvest) in the landscape when precipitation does not occur. Mobilization is the process by which phosphorus moves from the landscape to the water pathways in soluble and particulate forms. The delivery process consists of the changes of phosphorous quantity and forms in surface runoff as it moves downstream overland or through the drainage network. It includes sedimentation, adsorption, plant uptake, microbial transformation, and other processes, resulting in the reduction of phosphorus content in pollutant runoff. STEM-P focuses on (i) the mobilization process by which phosphorus is released from a landscape to surface runoff, and on (ii) the delivery process of phosphorus as it moves with surface runoff. The mobilization process of phosphorous from non-point sources is assumed to be a zero-order mobilization mechanism. Its delivery is represented as first-order retention. The proposed STEM-P