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Estimating the optimal width of buffer strip for nonpoint source pollution control in the Three Gorges Reservoir Area, China

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ABSTRACT

Following the implementation of the Three Gorges Dam Project, nonpoint source (NPS) pollution has become a serious problem in the Three Gorges Reservoir (TGR). An urgent need exists to build an ecological shelter buffer (ESB) along the TGR to improve water quality. However, to determine the optimal buffer width of the ESB for NPS pollution control is challenging because of spatial variations in topography, hydrology, slope and drainage patterns in the Three Gorges Reservoir Area (TGRA). In this study, a methodology was established for modelling the ESB using geographic information systems (GIS) technology and was applied to a small-scale ungauged watershed (Panlong basin), a typical watershed along the TGR. A grid terrain analysis, an NPS pollution model, the Soil and Water Assessment Tool (SWAT) and a riparian simulation model, Riparian Ecosystem Management Model (REMM), were combined to estimate the transport of NPS pollutants and pollutant abatement through ESB at the watershed scale. Suitable widths of the ESB were estimated for different objectives of water quality protection to reflect regional variations in physical conditions. The results demonstrated that the ESB width depends strongly on the topographic features, soils types, hydrological conditions and conservation objectives of the TGRA. The estimated ESB with 58 m in the averaged width can achieve the current requirement of water quality of TGRA. Most of the areas with higher values of NPS pollutant concentrations are located in the buffer drainage areas. Accordingly, an ESB, rather than other streams, most likely offers the greatest potential to improve water quality along the reservoir, and it is necessary to install ESBs along the tributary streams for NPS pollution control and water quality protection from a watershed perspective. The resulting map of ESB can indicate specific locations best suited for ESB at watershed scales, and can be applied to field-scale planning. The methodology described in this study demonstrates its capability as a decision support tool to guide ESB building, support land-use decision making and facilitate environmental policy formulation and evaluation throughout the TGRA.

1. Introduction

Nonpoint source (NPS) pollution from agricultural areas is a major challenge in maintaining water quality and is closely associated with human activities (Basnyat et al., 1999; Sliva and Williams, 2001). Dams and their construction profoundly affect river flow patterns and alter disturbance and stress regimes for local plants (Jansson et al., 2000; Shafroth et al., 2002). The Three Gorges Dam (TGD) is situated in the middle reaches of the Yangtze River in south-central China. After the TGD began operation, the environment and ecosystems along the Yangtze's middle reaches experienced fundamental changes (Shen and Xie, 2004; Wu et al., 2004; Stone, 2008; Fu et al., 2010), resulting in the following ecological and environmental problems: (1) reduced water flow from the reservoir has resulted in contaminants accumulating in the reservoir and deteriorating water quality. (2) A total land area of 632 km^2 is submerged whenever the reservoir impoundment reaches the high water level of 175 m, and a large area of original riparian habitat along the shoreline of the reservoir has been destroyed. (3) The transfer of agricultural activities to higher elevations due to the submergence of 238 km^2 of former farmland has resulted in excessive, inappropriate and illegal exploitation of slope lands. In certain cases, forest lands have been cleared for fruits, vegetables and other crops. The water quality of the Three Gorges Reservoir Area (TGRA), including the entire inundated area and 19 administrative units (counties and cities), is increasingly vulnerable to the impacts of NPS pollution. The Chinese government recently addressed critical problems associated with the dam project, emphasising the pollution of the reservoir.

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A significant amount of research has been undertaken to identify management options for minimising NPS pollution from agricultural areas (Barling and Moore, 1994; Mander et al., 1997; Srivastava et al., 2002; Ripa et al., 2006). Vegetated buffers between agricultural fields and rivers are widely used in ecological restoration to reduce agricultural NPS pollution and enhance water quality (Lowrance et al., 1984; Dillaha et al., 1989; Osborne and Kovacic, 1993). Numerous studies have revealed that vegetated buffers can reduce the load of sediment, nutrients and other pollutants in overland runoff from fields to waterways (Magette et al., 1989; Daniels and Gilliam, 1996; Schmitt et al., 1999; Yuan et al., 2009; Dosskey et al., 2010). The State Council of China and several national environmental organisations have attempted various approaches to improve the TGRA water quality. The planned ecological shelter buffer (ESB) is a major undertaking to enhance the ecological infrastructure by constructing vegetated buffer strips along the shorelines of the Yangtze River in the TGRA. The Chinese government hopes the ESB will restore riparian vegetation, decrease the levels of agricultural NPS pollution from adjacent uplands and improve the water quality of the reservoir. However, the width of the ESB has become the main issue facing ecological barrier construction.

A great deal of research has explored the relationship between the width of vegetated buffer strips and the control of NPS pollution loads (Mayer et al., 2005; Zhang et al., 2010). However, most studies have attempted to model and quantify the water quality benefits at field or plot scales (Jordan et al., 1993; Borin et al., 2005). Thus, the specificity of local site and experimental conditions and the relationships between pollutant removal efficacy and associated factors are inconsistent. External factors such as slope, upland contributing areas, vegetation species and soil texture influence the pollutant removal efficacy of vegetated buffers (Bren, 1998; Wenger, 1999). These factors often vary spatially, especially on a watershed scale. To more effectively quantify pollutant capture by buffers and target buffers across entire watersheds, we must simulate NPS pollutant production, transport and reduction at different scales. Many studies have been undertaken to evaluate the optimal width and placement of buffer strips (Dosskey, 2002; Tomer et al., 2003; Correll, 2005; Lin et al., 2008), and a number of models and methods have been developed for this purpose (Lowrance et al., 2001; Lin et al., 2004; Baker et al., 2006; Liu et al., 2007; Tomer et al., 2009; Dosskey et al., 2011). However, the current methods and available models often require detailed measurements of hydrology and pollutants and most of them has been focused on the transverse dimension (perpendicular to the protected area), while the aspects of longitudinal dimension (along the protected area) received less attention. There is still a lack of understanding of buffer effectiveness at the watershed scale.

In TGRA, the reservoir covers more than 1000 km^2 and stretches some 663 km; there are more than 400 tributaries of different sizes in total, and most gauge stations located on its main tributaries. The runoffs and pollutants from the tributaries can be measured and controlled, while the pollutants from the lateral inflow region are difficult to estimate (Liu et al., 2003; Xu et al., 2008). It is necessary to focus on conservation buffers for NPS pollution control in this region for a couple of reasons. First, land use is mainly dependent on elevation and topography in TGRA where land resources are very limited; most towns and agricultural land are concentrated along the TGR due to the relatively flat terrain and small slope. Second, all of these agricultural lands are likely to cause NPS pollution. During rainfall events, NPS pollution from the lateral inflow region transported to the TGR directly. Third, it is unrealistic to build the ESB to cover the entire TGRA because of limited land availability. If it is too wide, it will take up a great deal of developmental and agricultural land. In contrast, if is too narrow, it will not be able to effectively reduce NPS pollution. Therefore, a design method is needed for sizing buffer strips to maximise the conservation potential of limited land in adjacent uplands and protect the environment of the TGRA. The goals of the present study were to (1) develop a computational framework to simulate the optimal width for building the ESB along the TGR in a study watershed; (2) prioritise locations and identify the optimal width for the ESB to achieve specific water conservation goals of the TGRA; (3) assess the performance of the ESB for NPS pollution control in different drainage areas; and (4) provide advice on establishing the ESB for the TGRA.

2. Materials and methods

2.1. Site description

The study area is the 94.26 km^2 area of Panlong Town located in the middle of the TGRA in Chongqing Province, China (Fig. 1a). As the first pilot area chosen by the Three Gorges Project Construction Committee State Council, People's Republic of China, for establishing ESB in 2008 (Fig. 2) and with little urban area and much agricultural land, Panlong's NPS pollution is heavy. Panlong is representative of the TGRA because of its land use patterns, soil type and topographical features. This region has a subtropical humid climate with an annual mean temperature of 17.4 °C and annual precipitation of 1134 mm. The elevation ranges from 175 m at the submerged line of the reservoir to 1809 m at the top of the uplands, and the topography descends markedly from south to north. Land use within Panlong Town is predominantly row crop production. The main agricultural crops are rice, corn and wheat. Chemical fertilisers of N and P are applied at highly variable rates in the different farmlands. Agriculture has been an important source of water pollution. In the last ten years, Panlong Town has lost 30% of its riparian habitat to reservoir impoundment and land reclamation for agricultural and resettlements purposes (SFIPI, 2008). To quantitatively model the hydrological processes and simulate NPS pollution loads, the Panlong basin was delineated according to the administrative boundary of Panlong Town (Fig. 1b).

2.2. Computational framework and data collection

A computational framework was developed to simulate the optimal width for building the ESB, which is schematically shown in Fig. 3. This framework is divided into five parts: Part A, "parameter transfer"; Part B, "source simulation"; Part C, "transport simulation"; Part D, "removal simulation"; and Part E, "width simulation". In Part A, the Soil and Water Assessment Tool (SWAT) model was applied to the Modaoxi basin. After calibrating and validating the model on the basis of observed hydrological and water quality data, the regionalised and calibrated parameter sets for runoff and pollutants were transferred to the ungauged target, Panlong basin, to simulate its upland runoff and NPS load. In Part B, the SWAT model was rebuilt in Panlong basin on the basis of calibrated parameters. An NPS pollution load calculated in areas with different land uses, soils and slopes can be used to locate the NPS pollution source in hydrologic response units (HRUs). In Part C, a "flow accumulation" algorithm was used to determine the amount of runoff and pollutants from the source area flowing through every cell of the digital elevation model (DEM). In Part D, a riparian zone model (REMM) was used to simulate NPS removal efficiency under different ESB scenarios in the entire study area. In Part E, the optimal width of the ESB was delineated and generated in each grid based on the ArcGIS platform.

The models required topological, land cover, meteorological, soil physical and chemical properties, hydrological and water quality data. Topographic maps (1:25,000) and GIS data of the river network, administrative boundaries and land use coverage with