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Modelling hydrology and water quality processes in the Pengxi River basin of the Three Gorges Reservoir using the soil and water assessment tool

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ABSTRACT

The Pengxi River is one of the main tributaries on the north shore of the Three Gorges Reservoir (TGR) and currently faces water quality deterioration and algal bloom problems. The Soil and Water Assessment Tool (SWAT) with a TGR specific database was utilized to evaluate the hydrology and water quality processes of the Pengxi River Basin. The flow and its nutrient content were assessed by the model, and the largest pollutant load generation areas of this basin were identified. The Generalized Likelihood Uncertainty Estimation (GLUE) method was used to conduct sensitivity analysis, model calibration and validation. Results of sensitivity analysis showed that CN2 (initial SCS runoff curve number for moisture condition II) was most sensitive for runoff, while RCN (concentration of nitrogen in rainfall) and FILTERW (width of edge of field filter strip) were most sensitive for nitrogen and phosphorus loadings respectively. Determination of the most sensitive parameters on the rate of change of SWAT outputs was identified. The coefficient of determination (R^2) in the validation ranged from 0.66–0.85 for daily stream flow and 0.70–0.86 for nutrient yield. Average annual water yield for the entire basin was found to be 3.93 billion m^3 from 2010 to 2013, while average annual total nitrogen yield was 9406 t, and average annual total phosphorus yield was 984 t. The simulation results indicate that runoff appeared to vary significantly throughout the year and from year to year, and was correlated with precipitation. Higher pollutant load generation areas were mainly concentrated in the central and southern part of the Pengxi River basin. This study is expected to have major implications for identifying non-point source (NPS) and water quality management policies and approaches.

1. Introduction

Being the world's largest hydropower project, the Three Gorges Project contributes significantly to socio-economic aspects in China, for instance, flood control, power generation, navigation and water supply (Zhao et al., 2013; Zhang et al., 2012b). However, increasing amounts of nitrogen (N) and phosphorus (P) from non-point sources (NPS) have become a major determinant of water quality in the Three Gorges Reservoir (TGR), since the reservoir impoundment started in 2003 (Shen et al., 2009, 2013c; Bieger et al., 2014; Zhang et al., 2015). From 2009–2013, abundant nutrients together with favourable hydrological and environmental conditions facilitated outbreaks of algae blooms in more than 20 tributaries of TGR, especially in backwater areas. Pengxi River Basin, one of the most typical TGR tributary basins, has the largest backwater areas in the TGR, in which the occurrence of water bloom has become more frequent in recent years. This water environmental issue is becoming more complex because of the spatial variation of the geology and geomorphology, soil types, vegetation covers, land uses, and dispersed pollutant sources in the Pengxi River basin. Therefore, selecting the Pengxi River basin as our study area is a logical choice and also of great use to the whole TGR study, since the hydrology and water quality processes in this area have rarely been studied.

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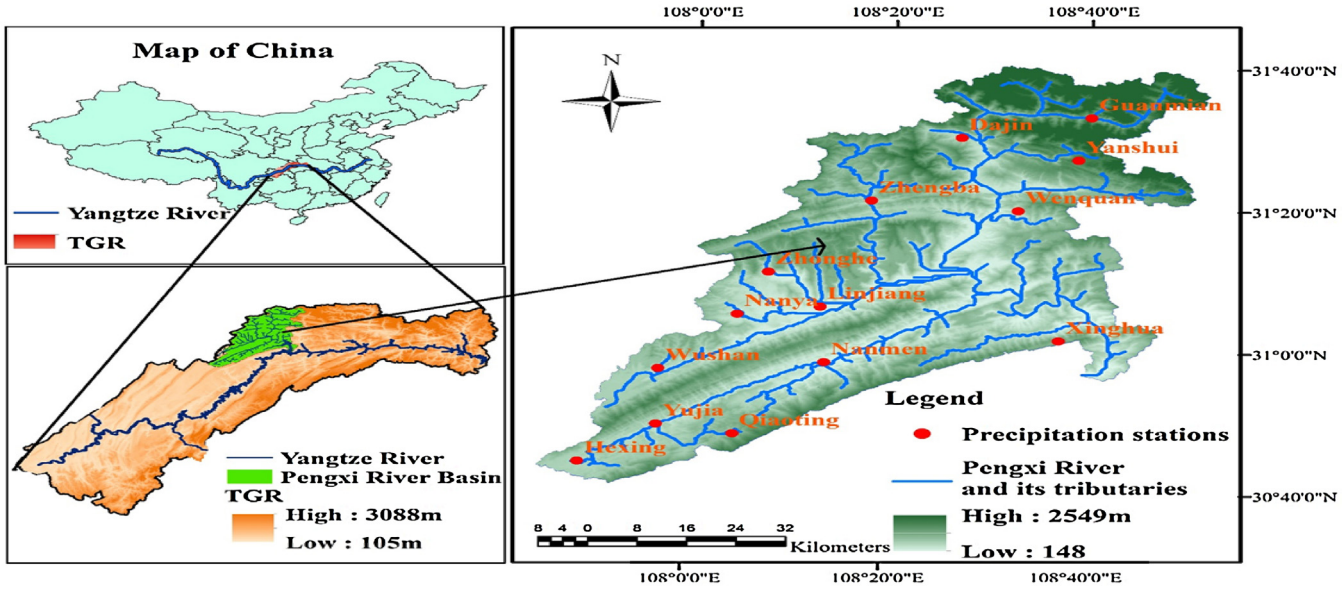

Fig 1. Location of the Pengxi River Basin in the Three Gorges Reservoir (TGR) and its drainage system. The blue line on the map on the right corresponds to the Pengxi River and its tributaries. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

It is widely agreed that study of NPS pollution is difficult and lacks accuracy mainly because of the heterogeneity of hydrological processes affected by climate, topography, soils, and land use patterns (Mishra and Kar, 2011; Randhir and Tsvetkova, 2011; Zhang et al., 2010). Mathematical modelling has been an important approach in the simulation, investigation and estimation of NPS pollution. In the last two decades, NPS pollution has been widely assessed by distributed parameter and physical process-based watershed models at varying scales and locations (Michalak et al., 2013; Johnston and Smakhtin, 2014). The Soil and Water Assessment Tool (SWAT), one of the most widely used hydrological models (Neitsch et al., 2011), which has demonstrated a wide range of applications in modelling varying characteristics of NPS pollution (Dechmi et al., 2012; Abeysingha et al., 2015; Ghoraba, 2015). The SWAT simulation has also performed well for decision-making support on watershed management on daily, monthly and annual bases (Shen et al., 2012b, 2013a; Zhang, 2010).

However, the requirements for large data inputs with increasing watershed size may limit the applicability of existing models in large watersheds (Shen et al., 2014; Zeng et al., 2015). The SWAT model was jointly developed by the Agriculture Research Service of the United States Department of Agriculture (USDA-ARS) and Texas A&M Agrilife Research based on databases specific to American geographical characteristics (Arnold et al., 1998). Considering the physical environmental differences between America and China, and the incompleteness of monitoring networks and shortage of field data in China, the applicability of SWAT may be somewhat limited and may produce errors (Shen et al., 2012a, 2014). Therefore, it is important to build a more localized basic database and develop a reasonable parameterization of specific watersheds in China for improved application of SWAT. Based on the characteristics of the original databases, this study established a local database together with a suitable parameterization to better account for TGR conditions. This research uses the Pengxi River basin of the TGR as a study area using SWAT with a more localized database.

The specific objectives of this study are: (i) to develop a localized database for the TGR and assess the most sensitive parameters on the rate of change of SWAT output for runoff, total nitrogen (TN) and total phosphorus (TP); (ii) to assess the performance of SWAT in simulating streamflow and nutrient transport in the mountainous Pengxi River basin in the TGR, with a suitable localized database; and (iii) to simulate NPS pollution (TN and TP) and assess its spatial variation and temporal characteristics using a validated SWAT model. Through an adequate understanding of hydrological processes and water quality of the Pengxi River Basin, and recognizing the migration and transformation mechanisms of NPS pollutants, our research findings are meaningful for preventing NPS pollution and improving the water quality of the entire TGR.

2. Methodology

2.1. Study area

The Pengxi River (30°50′–31°42′N, 107°56′–108°54′E) is one of the main tributaries on the north shore of the TGR, located in the middle reach of the Yangtze River, and about 250 km upstream from the Three Gorges Dam. The main stream length of the Pengxi River is about 182 km. The Pengxi River Basin comprises a watershed area of about 5,172.5 km^2, with altitude variation from 148 m to 2549 m above mean sea level (Fig. 1). The average annual discharge is about 3.41 billion m^3. The basin has a continental subtropical monsoon climate with average annual precipitation between 1100 mm to 1500 mm, with more than 80% falling between June and October [Fig. 2(a)]. The daily temperature ranges from a maximum of 42 °C to a minimum of −4.5 °C [Fig. 2(b)]. Average relative humidity and wind speed are relatively constant [Fig. 2 (c) and (d)]. The dominant soil types in the basin are purple soil, yellow soil and paddy soil [Fig. 3(b)]. The basin is a mixed land use area, with approximately 30% of the basin area covered by farmland which is expected to affect diffuse nutrient inputs considerably [Fig. 3(c)]. The basin has an average slope of 33%, ranging from 1% to 44% [Fig. 3(d)].

The Pengxi River Basin is strongly influenced by the Three Gorges Project, with the establishment of new district towns and rural resettlements. Land use patterns in the basin have changed dramatically since the 1990s because of the socio-economic development, and also as a result of the construction of the TGR (Zhang et al., 2009). The land cover of Pengxi River basin is typical, where the headwater is maintained in pristine condition and has a low population density, while along the middle and lower reaches, human activities become more intensive. In 2013, the total population of the Pengxi River Basin reached 4.771 million, while the