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Evaluating the impacts of soil data on hydrological and nonpoint source pollution prediction

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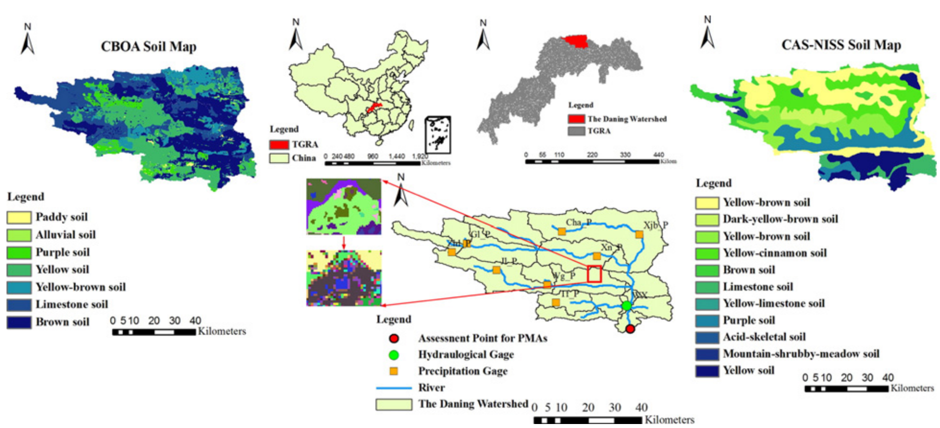
HIGHLIGHTS

- The impacts of available soil data on NPS modeling are quantified.
- This paper provides information for the appropriateness of each soil database.
- Error from soil data to watershed management strategy was assessed.
- The choice of soil data shows great impacts on watershed models.
- This paper also indicates that NPS-TP outputs are more sensitive to soil data.

GRAPHICAL ABSTRACT



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ABSTRACT

Soil data are one key input for most hydrological and nonpoint source (H/NPS) models, and quantifying the error transmission from soil data to H/NPS predictions is of great importance. In this study, two typical soil datasets were compared using the Soil and Water Assessment Tool (SWAT) in a typical mountainous watershed, the Three Gorges Reservoir Region, China. Besides, the effects of soil data resolution were evaluated, and the error transmission from soil data to watershed management strategy was assessed. The results indicate that model outputs are not sensitive to changes of soil data resolution but the choice of soil data greatly impacts the application of watershed models, in terms of the goodness-of-fit indicator, predicted data and related uncertainty. This soil data-induced error would be inevitably magnified from the flow simulation to the NPS prediction stage. This study could indicate that the choice of soil data will lead to significant differences in management schemes for specific pollution periods. These results provide information on the impacts of soil data on the functionality of watershed models and valuable information for the appropriateness of each soil database.

1. Introduction

Soil, which represents the historical processes of the Earth's surface, plays a key role in determining the allocation of water between rainfall, evaporation, infiltration and direct runoff (Essaid et al., 2015). Its

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physical, chemical and biological properties influence the fate of pollutants within watersheds, especially from nonpoint sources (NPSs) (Shen et al., 2013a; Singer and Warkentin, 1996). Thus, soil data which is expressed as attribute layers in a GIS format has become an important input for most hydrological and NPSs (H/NPSs) predictions (Geza et al., 2009; Ramos and Martinez-Casasnovas, 2015). However, due to the application of various sampling/mapping methods, soil data-induced prediction error or uncertainty remains a key challenge for the usage of watershed models (Geza and McCray, 2008).

Typically, there exist various soil datasets that are developed by different agents; therefore, one question that raises is how different mapping approaches affect model outputs (Liu and Gupta, 2007). In the United States, the discrepancies between two commonly used soil data sources, the Soil Survey Geographic database (SSURGO) and the State Soil Geographic database (STATSGO), have been researched widely. The impacts of mapping approach have been demonstrated in simulating total flow (Kumar and Merwade, 2009), peak flow (Wang and Melesse, 2006), and nutrients (Geza and McCray, 2008). These studies have demonstrated that the impacts depend on weather conditions, features of study watersheds, and soil type distributions. For example, Geza and McCray (2008) noted that a SSURGO-based model would produce larger simulated flow, sediment and attached nutrient in most cases. However, Kumar and Merwade (2009) showed that a STATSGO-based simulated flow is relatively higher compared with that using the SSURGO data. Moreover, Wang and Melesse (2006) indicated that although a SSURGO-based model results in better performance for predicting total flow, the two soil datasets have comparable impacts on the peak flow simulation. In this sense, additional studies are needed for different conditions to evaluate the relative appropriateness of each soil database.

Another question is regarding the appropriate resolution/scale of soil maps for describing H/NPS processes at the watershed scale. This issue has been raised because high-resolution maps are often costly, time-consuming, and hard to obtain (Peschel et al., 2006; Schwen et al., 2014). The preparation of high-resolution soil data is especially difficult due to the numerous samplings and laboratory analyses required (Kumar and Merwade, 2009; Moriasi and Starks, 2010). Due to the increased availability of high-resolution data, more studies have focused on quantifying the impacts related to the resolution of digital elevation models (DEMs) and land use maps (Lin et al., 2010; Zhang et al., 2014). Few studies have reported the impacts of soil data resolution, focusing on the transmissions of errors into simulated evapotranspiration and soil water storage analyses (Muttiah and Wurbs, 2002). Even fewer researches have noted the impacts on sediment and nutrient exports (Chaplot, 2005). These studies have demonstrated that soil data resolution determines the basic units for describing various soil properties, e.g., the percentages of sand, silt, and clay, hydraulic conductivity, and bulk density, thus data resolution does impact hydrological prediction (Gatzke et al., 2011). For a specific catchment, a larger percentage of clay soils results in more direct runoff, whereas the presence of more sand or silt loam soils decreases runoff amount (Muttiah and Wurbs, 2002). Moreover, the spatially described soil chemical characteristics would have impacts on the fate of pollutants. For example, the initial accumulation of nutrients within soil layers determines the NPS-nutrient loadings from catchment to streams (Lin et al., 2015). To the best of our knowledge, few studies have investigated the impacts of soil data resolution in defining those hydrological process, as well as functions connected with NPSs.

The objective of this study was to undertake a systematic analysis into the impacts of soil data on H/NPS predictions at the watershed scale. In China, the most commonly available soil dataset for watershed models is the state soil geographic map, which is developed by the Nanjing Institute of Soil Science, Chinese Academy of Sciences (CAS-NISS) (Ye et al., 2011). Chinese agricultural agents have also compiled digital soil maps through generalized detailed surveys at the county level, which can serve as local sources of soil properties. To date, few studies have been conducted to quantify the error-transmission from these two types of Chinese soil maps to H/NPS predictions. Thus, the following tasks were performed: 1) these two commonly used Chinese soil maps were compared and their impacts on the H/NPS predictions were quantified; 2) high-resolution soil data were reassembled into coarser ones, and their impacts were evaluated; and 3) error transmission from soil data to the identification of priority management areas (PMAs) was assessed. The case study was performed using the Soil and Water Assessment Tool (SWAT) in the Upper Daning River (UDR) watershed in China.

2. Materials and methods

2.1. Watershed description

This study was conducted in the UDR watershed, which is located in Wuxi County (affiliated to the municipality of Chongqing), in the Three Gorges Reservoir Region (Fig. 1). The UDR watershed, with a mean annual temperature of 18.4 °C, is characterized by a typical continental monsoon climate in the northern subtropical temperate zone. The annual precipitation ranges within 1030 mm–1950 mm with a mean value of 1182 mm, though 78% of the rainfall occurs in summer due to the influences of the monsoon. As a typical mountainous area, this watershed covers a drainage area of 2421 km^2, while the altitude ranges within 200 m–2605 m with an average value of 1294 m. As noted in our previous study (Chen et al., 2014a,b), the mountainous areas are mainly distributed in the northern and western areas of this region, whereas the central and southern parts are dominated by low-altitude arable land and pasture. Within the UDR watershed, the slope ranges from 0° to 67°, and the average slope is approximately 24°. The pasture represents 12.5%, the arable land occupies 25.3%, and the forest takes up 61.8% of the watershed. The major crops are corn, potato, wheat, rice, cotton, konjak and vegetables. Due to the local historical tendency, the application rates of urea and compound fertilizer are high in this region (with an annual average of 450 kg/ha and 300 kg/ha, respectively). Most fertilizers are applied onto field grounds without much pretreatment, resulting in an elevated level of agricultural NPS pollution. In this study, total phosphorus (TP) has been identified as the limiting factor of eutrophication at most tributaries of the Three Gorges Reservoir Region (Lu et al., 2011; Ma et al., 2011).

2.2. Description of the SWAT model

The SWAT, developed by the United States Department of Agriculture's Research Service (Arnold et al., 1998), was selected for the H/NPS-TP prediction analysis. The SWAT is physically-based and has been developed to predict flow, sediment and pollutants in large complex watersheds with varying soil types, land uses and elevations (Douglas-Mankin et al., 2010). The model is also continuous and runs at daily intervals, wherein the final conditions of the previous day determine the initial setup for the next day (Ahmadi et al., 2013). Moreover, the SWAT is a semi-distributed model, which divides the study watershed into various sub-watersheds connected by the river network. Each sub-watershed would be further delineated into smaller hydrologic response units (HRUs), which represent lumped spatial areas that are comprised of unique soil types, land use and slope degrees (Santhi et al., 2006).

The hydrological component of this model is based on the water balance law, and several processes, including rainfall, interception, evapotranspiration, infiltration, direct runoff, lateral flow and groundwater, have been incorporated (Arnold et al., 1999). The SWAT incorporates a sub-model Soil Conservation Service (SCS) method to simulate surface runoff, and a modified rational method to quantify peak runoff rates (Natural Resources Conservation Service, 1972). The available evapotranspiration approaches are the Penman-Monteith, Hargreaves and Priestley-Taylor equations. The Muskingum and variable storage