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Mathematical model for interactions and transport of phosphorus and sediment in the Three Gorges Reservoir

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ABSTRACT

Phosphorus fate and transport in natural waters plays a crucial role in the ecology of rivers and reservoirs. In this paper, a coupled model of hydrodynamics, sediment transport, and phosphorus transport is established, in which the effects of sediment on phosphorus transport are considered in detail. Phosphorus adsorption is estimated using a mechanistic surface complexation model which is capable of simulating the adsorption characteristics under various aquatic chemistry conditions. The sediment dynamics are analyzed to evaluate the deposition and release of phosphorus at the bed surface. In addition, the aerobic layer and anaerobic layer of the sediments are distinguished to study the distribution of phosphorus between dissolved and particulate phases in the active sediment layer. The proposed model is applied to evaluate the effects of various operating rules on sediment and phosphorus retention in the Three Gorges Reservoir (TGR). Results show that the proposed model can reasonably reflect the phosphorus transport with sediment, and management scenarios that influence sediment retention will also influence the phosphorus balance in the TGR. However, modest operational changes which have only minor effects on sediment retention also have limited influence on the phosphorous balance.

1. Introduction

Phosphorus, one of the key nutrients affecting water quality, is the major limiting factor for eutrophication (Schindler, 2006; Elser et al., 2007). Thus the phosphorus transport process plays a crucial role in the aquatic ecological environment. In recent decades, human activities have greatly changed the inherent characteristics of many inland waters (Zhang et al., 1999; Syvitski et al., 2005; Dai et al., 2008) resulting in substantial effects on nutrients, including phosphorous. Impoundment of rivers for reservoirs can result in a significant increase in sediment and phosphorus retention, posing serious environmental concerns (Camargo et al., 2005; Yao et al., 2009). Operational controls on the reservoir can be used to minimize the retention of phosphorous. This has encouraged the development of models of phosphorous transport to evaluate different operating scenarios and develop optimal control approaches. To maximize their utility, these models should accurately describe key phosphorous transport processes, particularly phosphorous–sediment interactions.

Sediment particles have a strong affinity to phosphorus due to the high specific surface areas and surface active sites (Davis and Kent, 1990; Wang et al., 2009; Fang et al., 2013). Most phosphorus in waters are adsorbed by sediment particles and transported in the particulate phase (Withers and Jarvie, 2008). The adsorbed phosphorus may accumulate at the bed surface due to sediment deposition and can later be released by resuspension. Phosphorus partitioning from the solids to the interstitial waters also exchanges with the overlying water (House and Denison, 2002; Wang et al., 2003) as a result of hyporheic exchange and other processes. Understanding phosphorus–sediment interactions is critical to understanding phosphorous transport in the system.

Mathematical modeling is an effective tool for predicting the phosphorus transport, and a great number of water quality models have been developed over recent decades (Wool et al., 2001; Park et al., 2008). Early models often ignored sediment dynamics, which does not allow evaluation of the effect of sediment management operations on phosphorus transport (Broshears et al., 2001). Subsequently, a great number of models that incorporate sediment dynamics were proposed (Larsen et al., 1979; Wool et al.,

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2001; Chu and Rediske, 2011). Most of these models consider largely empirical relationships, such as a linear distribution coefficient K_d or first order adsorption (rate constant k_1) and desorption (rate constant k_2) to represent the adsorption of phosphorus by sediment (Wool et al., 2001). Other simplifications included a sedimentation coefficient K_s and an erosion coefficient K_u to characterize the deposition and resuspension of phosphorus at the bed surface (Chu and Rediske, 2011), or a constant phosphorus release rate at the sediment–water interface (Larsen et al., 1979). It is difficult to choose reasonable values for these parameters due to the lack of a fundamental mechanistic basis, and these parameters are site-specific and not easily extended. In addition, most of these models do not represent a comprehensive evaluation of the effects of sediment on phosphorus transport but are instead focused on specific processes.

This paper aims to develop a model of the coupled hydrodynamics, sediment and phosphorus transport, in which the effects of sediment on phosphorus transport are comprehensively considered. A mechanistic surface complexation model, which can better describe surface adsorption phenomena by treating surface adsorption reactions as complexation reactions, is applied to analyze the adsorption of phosphorus on sediment particles. Then the riverbed deformation is included to characterize the deposition and resuspension of phosphorus at the bed surface. In addition, the aerobic and anaerobic layers are distinguished to study the distribution of phosphorus in the active sediment layer, which accounts for the exchange of phosphorus between the bottom sediment and the overlying water. The proposed model is applied to predicting phosphorus transport in the Three Gorges Reservoir (TGR) in central China and evaluating the effectiveness of various operating rules on sediment and phosphorus retention in the reservoir.

2. Materials and methods

2.1. Description of study area

The Three Gorges Project (TGP), the largest hydraulic project in the world, is located in the Yangtze River as shown in Fig. 1. The TGP is made up of the concrete gravity dam, reservoir, and power station and navigation structures. The Three Gorges Dam (TGD) has a crest elevation of 185 m with the normal pool level (NPL) of 175 m relative to the Chinese water datum. The return periods of the design flood and the maximum flood for the dam are 1000 year and 10000 year +10%, respectively. The total capacity of the Three Gorges Reservoir (TGR) formed by the TGP is 393 × 10^8 m^3, with a flood control capacity of 221.5 × 10^8 m^3. The surface area is 1084 km^2 under the NPL of 175 m, with the watershed area of over 1.0 × 10^6 km^2. The flow velocity of the main channel decreased to 0.13–0.24 m/s after impoundment (Wu et al., 2012). It is estimated that the monthly retention time of the TGR ranges from 5 to 77 d with the mean value of 27 d (Xu et al., 2011), indicating that the main stem is vertically well-mixed and remains unstratified for the majority of the year. The total installed hydroelectric capacity is 22500 MW. The impoundment of the TGR started on June 1st, 2003, and subsequently the first generating unit was put into operation. On October 26th, 2010, the water level at the dam first reached the NPL of 175 m.

The TGP is operated to support a variety of objectives including flood control, hydropower generation, navigation, and water storage. There are also many complex problems associated with reservoir operation including sedimentation and ecological impacts. Table 1 shows the variations of annual runoff and sediment discharge before and after the impoundment of the TGR (CWRC, 2000–2010). Cuntan station is located in the tail of the TGR and can be regarded as the upstream control section. Yichang station is 38 km downstream from the TGD and can be regarded as the downstream control section. Then the sediment delivery ratio (SDR) is estimated to be 27.6% (=0.54/1.96) in the post-TGP period (2003–2010), which is much smaller than that of the pre-TGP period (1950–2002). Simultaneously, the upstream nutrients are also intercepted by the TGR due to the strong affinity of phosphorus to sediment particles. An accurate simulation of the sediment and phosphorus transport and its response to operating conditions is necessary for the optimal operation of the TGR.

2.2. Hydrodynamic-sediment-phosphorus transport model

2.2.1. Hydrodynamic module

The hydrodynamic module consists of continuity equation and momentum equation, assuming vertically and laterally uniform

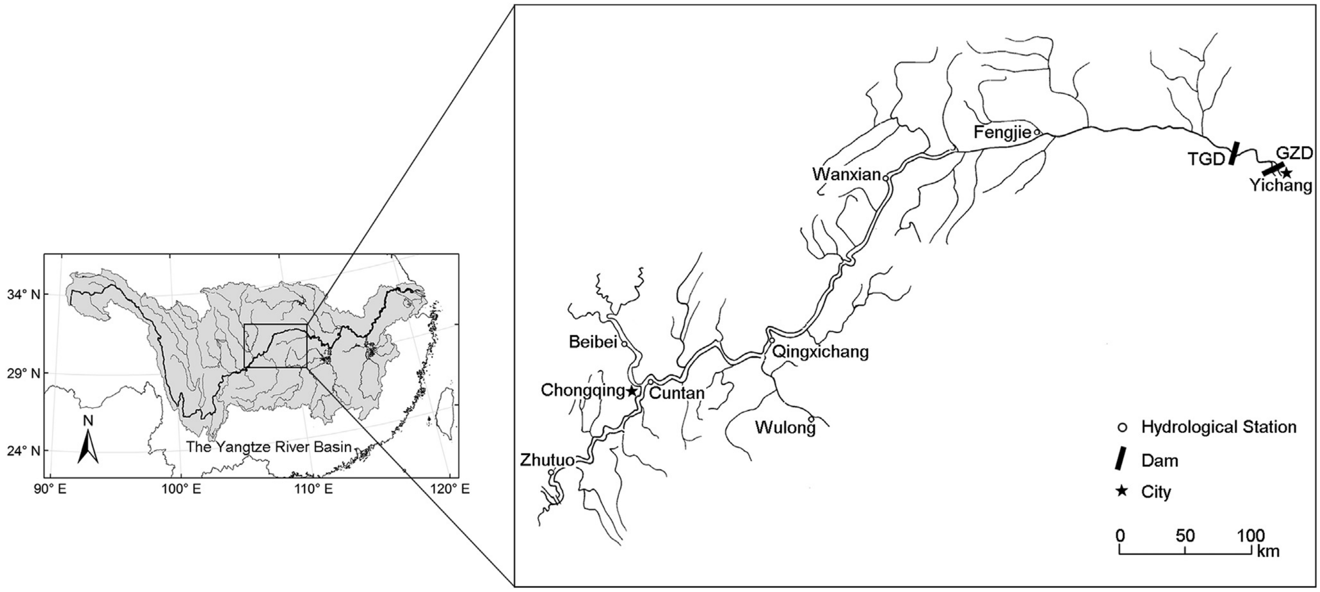

Fig. 1. Sketch map of the Three Gorges Reservoir.