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Hydrology and phosphorus transport simulation in a lowland polder by a coupled modeling system☆

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ABSTRACT

Modeling the rain-runoff processes and phosphorus transport processes in lowland polders is critical in finding reasonable measures to alleviate the eutrophication problem of downstream rivers and lakes. This study develops a lowland Polder Hydrology and Phosphorus modeling System (PHPS) by coupling the WALRUS-paddy model and an improved phosphorus module of a Phosphorus Dynamic model for lowland Polder systems (PDP). It considers some important hydrological characteristics, such as groundwater–unsaturated zone coupling, groundwater–surface water feedback, human-controlled irrigation and discharge, and detailed physical and biochemical cycles of phosphorus in surface water. The application of the model in the Jianwei polder shows that the simulated phosphorus matches well with the measured values. The high precision of this model combined with its low input data requirement and efficient computation make it practical and easy to the water resources management of Chinese polders. Parameter sensitivity analysis demonstrates that K_{uptake}, c_{Q2}, c_{W1}, and c_{Q1} exert a significant effect on the modeled results, whereas $K_{\mathrm{resuspensionMax}}$, K_{settling}, and $K_{\mathrm{mineralization}}$ have little effect on the modeled total phosphorus. Among the three types of uncertainties (i.e., parameter, initial condition, and forcing uncertainties), forcing uncertainty produces the strongest effect on the simulated phosphorus. Based on the analysis result of annual phosphorus balance when considering the high import from irrigation and fertilization, lowland polder is capable of retaining phosphorus and reducing phosphorus export to surrounding aquatic ecosystems because of their special hydrological regulation regime.

1. Introduction

A large number of polders exist in the lowland areas, especially in the river deltas and lakeside zones (Jiang et al., 2007; Kovar et al., 2014; Zhao et al., 2010). Excessive phosphorus load can causes significant eutrophication in many freshwater ecosystems (Liu et al., 2016; Schindler et al., 2008), because phosphorus has been regarded as a dominant limiting nutrient in many aquatic systems and a key control of algal bloom (Abell et al., 2010; Elser et al., 1990). Phosphorus export from these polders has received much attention because such export significantly affects the water quality and aquatic ecosystem of downstream rivers and lakes. Given the increasingly intensified agricultural activities, polders are often thought to be long-term phosphorus sources. Nevertheless, this viewpoint would be objectionable when the large input of phosphorus from precipitation and extraterritorial irrigation are considered. For example, irrigation practices can contribute an amount of phosphorus from extraterritorial eutrophied rivers to polder ecosystem. Therefore, understanding the nutrient cycle of the polders and estimating the nutrient exchange between polders and their surrounding water bodies is beneficial for us to identify nonpoint pollution sources and to find reasonable measures for mitigating the eutrophication of lakes and rivers.

Many types of hydrological models have been developed and applied in simulating the rainfall-runoff processes and phosphorus cycles at catchment scale, e.g., SWAT (Abbaspour et al., 2015; Arnold et al., 1998; Bannwarth et al., 2014), HSPF (Donigan et al., 1984; Uygun and Albek, 2015), GR4J (Perrin et al., 2003), and MIKE-SHE (Christiaens and Feyen, 2002; Ma et al., 2016; Refsgaard et al., 1995). Nevertheless, these existing models were primarily developed based on the sloping catchment and are not appropriate for lowland polders with specific natural features (shallow groundwater, capillary rise, groundwater–surface water

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interactions) and human-induced processes (artificial irrigation and pumping discharge). To meet the demand for modeling rainfall-runoff processes in lowland catchments, Brauer et al. (2014a) proposed the Wageningen Lowland Runoff Simulator (WALRUS) to represent some important processes in lowland zones, such as groundwater–surface water feedback, saturated and unsaturated zone coupling, and wetness-dependent flow routes. This model was significantly improved by Yan et al. (2016a) for use in multi-land-use polders with paddy fields and pumping stations and this improved version is called the WALRUS-paddy model. These improvements include the processes of adopting different methods for runoff generation in different land uses, adding an irrigation and drainage scheme for paddy rice fields, and introducing a new stage-discharge relation function for culvert and pumping discharge, and facilitate the application of the model to East Asian polders, such as Chinese, Korean, Japanese polders. This model has been tested and proven to be capable of providing accurate estimates of catchment discharges in two Chinese lowland polders (i.e., Jianwei polder and Jiangxiang polder) (Yan et al., 2016a, 2016b). Moreover, a phosphorus balance model of the Phosphorus Dynamic model for lowland Polder systems (PDP) was proposed by Huang et al. (2016) to better account for the phosphorus transport in surface runoff within the lowland polder, however, it doesn't consider the related processes in groundwater flow.

To better describe the phosphorus cycle, this study included some functions that represent the groundwater transport of phosphorus in the phosphorus balance module of PDP. This modified module was then coupled to the WALRUS-paddy model to produce a new tool called the lowland Polder Hydrology and Phosphorus modeling System (PHPS). The performance of the PHPS and its sensitivity and uncertainty analyses were evaluated using the hydro-meteorological data from the Jianwei polder in east China. Based on the modeled results and phosphorus balance, the role of polder ecosystems in the nutrient transport of the entire floodplain catchment was investigated.

2. Development of lowland Polder Hydrology and Phosphorus modeling System (PHPS)

2.1. Overview of the WALRUS-paddy model

The WALRUS-paddy model is a lumped and conceptual rainfall-runoff model, which is an improved version of the WALRUS model and is based on water balance. It comprises four modules: dryland, paddy field, surface water, and residential area water balance modules. The dryland and paddy field modules both include two reservoirs, namely, a quickflow reservoir and a soil reservoir (coupled vadose–groundwater reservoir). A key state variable called storage deficit of vadose zone (d_V) determines both the evapotranspiration reduction (β) and wetness index (W) which divides the precipitation into a part that percolate to the soil matrix (P_V) and another part that flows into the surface water by quick flow routes(P_Q). Groundwater drainage or infiltration of surface water (f_{GS}) is computed based on the differences in the water level between the surface water (h_S) and the groundwater (d_G). All water that does not pass through the soil matrix flows towards the surface water via a quickflow route (f_{QS}), which stands for overland flow, local ponding, and macropore flow. Additionally, the paddy field has an irrigation and drainage scheme with three critical water depths for optimal rice growth to represent complicated water management operations.

For the impervious residential areas, a runoff coefficient is chosen as the method for estimating the drainage of residential areas. For the surface water, the water inflow components include precipitation (P_s), the drainage of paddy field, dryland, and residential area. Evapotranspiration (ET_S) and catchment discharge (Q) are the water outflow components. Catchment discharge (Q) consists of culvert and pumping discharge, which is computed by the relation between the surface water level (h_S) and three threshold water levels (i.e., threshold water levels to start culvert drainage $hS_{\mathrm{culvert}}^{\mathrm{start}}$, to start pump drainage $hS_{\mathrm{pump}}^{\mathrm{start}}$, and to stop pump drainage $hS_{\mathrm{pump}}^{\mathrm{stop}}$). More details and explanation about the model structure can be obtained from Yan et al. (2016a) and Brauer et al. (2014a).

2.2. Improved phosphorus balance module of PDP

The phosphorus module of PDP is a mass–conserving model presented by Huang et al. (2016). It explicitly represents the phosphorus transportation from each type of land use to surface water, as well as the physical and biological processes of phosphorus in surface water. However, this module does not consider the related processes in groundwater flow, which are important components of the phosphorus cycle. Therefore, some functions that are related to phosphorus in groundwater flow are incorporated into the module in this study.

In the revised module, surface water receives phosphorus from the drainage of each land use type and precipitation, whereas exports phosphorus through catchment discharge. Here, phosphorus is separated into two components: particulate and dissolved phosphorus. As a result, the changes in the concentrations of particulate and dissolved phosphorus in surface water ($\mathrm{d}PP_S$ and $\mathrm{d}DP_S$) are computed as follows:

$$\frac{dPP_S}{dt} = \frac{P_S \cdot PP_{\mathrm{Pr}} + f_{QS1} \cdot PP_{QS1} + f_{GS1} \cdot PP_{GS1} + f_{QS2} \cdot PP_{QS2} + f_{GS2} \cdot PP_{GS2} + f_{rS} \cdot PP_{rS}}{h_S \cdot a_S + Q} + cPP_S \tag{1}$$

$$\frac{\mathrm{d}DP_{\mathrm{S}}}{\mathrm{d}t} = \frac{P_{\mathrm{S}} \cdot DP_{\mathrm{Pr}} + f_{\mathrm{QS1}} \cdot DP_{\mathrm{QS1}} + f_{\mathrm{GS1}} \cdot DP_{\mathrm{GS1}} + f_{\mathrm{QS2}} \cdot DP_{\mathrm{QS2}} + f_{\mathrm{GS2}} \cdot DP_{\mathrm{GS2}} + f_{\mathrm{rS}} \cdot DP_{\mathrm{rS}}}{h_{\mathrm{S}} \cdot a_{\mathrm{S}} + Q} + cDP_{\mathrm{S}} \tag{2}$$

where PP_{pr} and $\mathrm{DP}_{\mathrm{Pr}}$ denote the particulate and dissolved phosphorus concentrations of the precipitation (mg/L), respectively. PP_{QS1} and DP_{QS1} are the particulate and dissolved phosphorus concentrations of quickflow from paddy fields (mg/L), respectively, and PP_{GS1} and DP_{GS1} denote the particulate and dissolved phosphorus concentrations of groundwater drainage from paddy fields (mg/L), respectively. $PP_{\mathrm{QS2}}$and DP_{QS2} represent the particulate and dissolved phosphorus concentrations of quickflow from dryland