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Modelling the regulation effects of lowland polder with pumping station on hydrological processes and phosphorus loads

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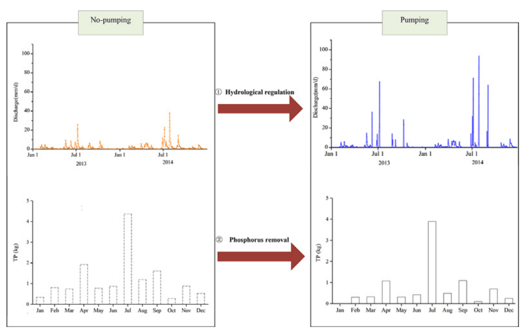
HIGHLIGHTS

- PHPS was used to evaluate the hydrological effect of polder.
- Polder with pumping station significantly affected the discharge processes.
- Polder with pumping station reduced phosphorus export.

GRAPHICAL ABSTRACT



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ABSTRACT

Exploring the hydrological regulation of a lowland polder is essential for increasing knowledge regarding the role of polders associated with pumping stations in lowlands. In this study, the Lowland Polder Hydrology and Phosphorus modelling System (PHPS) was applied to the Jianwei polder as a case study for quantifying the regulation effects of a lowland polder with pumping on discharge and phosphorus loads. The results indicate that the polder significantly affected the temporal distribution and annual amount of catchment discharge. Compared with a no-pumping scenario, an agricultural polder with pumping stations generated a sharper discharge hydrograph with higher peak-values and lower minimum-values, as well as an 8.6% reduction in average annual discharge. It also decreased the phosphorus export to downstream water bodies by 5.33 kg/hm^2/yr because of widespread ditches and ponds, a lower hydraulic gradient, and increased retention times of surface water in ponds.

1. Introduction

Low elevations, flat terrains, and intensified human activities have made lowland catchments more vulnerable to the effects of flooding and droughts that are caused by climate change and water pollution. In past decades, there has been a significant trend of increasing the numbers and area of polders in lowlands (especially in deltas and lake-side zones) to prevent flooding throughout the world (Abdullah-Al-Mamun et al., 2017; Alam et al., 2017; Budiyono et al., 2017; Gao et al., 2017; Hesse et al., 2008). As an example, Chinese polders constitute a total area of more than 400,000 km^2 (Zhan, 2005), and feature low elevations, dense drainage networks, and fertile agricultural fields.

Phosphorus is the key factor that controls freshwater eutrophication in most Chinese lowland catchments, and it has been investigated extensively in various catchments (Dai et al., 2017; Liu et al., 2012; Liu et al., 2016). Some studies have hypothesized that the phosphorus

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export from polders increases the risk of eutrophication problems in downstream water bodies and threatens their ecological and socio-economic functions (Kennish, 2017; Rozemeijer et al., 2014; Van Puijenbroek et al., 2004). In contrast, other studies considering the high phosphorus import from fertilization and irrigation have argued that a polder can act as a sink and reduce the phosphorus export (Huang et al., 2016; van der Grift, 2017; Vermaat and Hellmann, 2010). Thus, clarifying the roles of polders is becoming increasingly important for water management. Nevertheless, very few studies have quantified the regulation effects of polders on hydrological processes (e.g., flood hydrographs, water flow, carbon and nutrient exchange between polders and their surrounding rivers) compared to a free-flowing lowland. It has been preliminarily recognized that levees and pumping stations interfere with the hydrological connections between lowlands and large river channels (Hesse et al., 2008).

A large number of catchment models, e.g., SWAT (Abbaspour et al., 2015; Arnold et al., 1998; Bannwarth et al., 2014), HSPF (Donigan et al., 1984; Uygun and Albek, 2015), and GR4J (Perrin et al., 2003) have been used as effective tools for simulating water flow and nutrient cycling, as well as for examining the effects of water management practices on the eco-hydrological processes of a sloping catchment (Her et al., 2017; Kundu et al., 2017; Metcalfe et al., 2017; Talib and Randhir, 2017; Xie and Cui, 2011; Yan et al., 2016c; Zimmermann et al., 2017). However, most of these existing models are unsuitable for highly regulated lowland polders with shallow groundwater tables and water levels that are controlled by weirs and pumping stations. Some processes that are important in polders must be considered in hydrology modelling, including groundwater-unsaturated zone coupling, surface water-groundwater interaction, artificial irrigation, culvert and pumping discharge, and complicated nutrient cycles in surface water. Recently, a Wageningen Lowland Runoff Simulator (WALRUS) was originally proposed by Brauer et al. (2014a) and then significantly improved by Yan et al. (2016a) (renamed WALRUS-paddy) to simulate lowland polder rainfall-runoff processes. More recently, the WALRUS-paddy model was coupled with an improved phosphorus module of a Phosphorus Dynamic model for lowland Polder systems (PDP) (Huang et al., 2016) to form a lowland Polder Hydrology and Phosphorus modelling System (PHPS) (Yan et al., 2016b), which better described the hydrology and phosphorus processes of lowland polders. The PHPS has been tested by Yan et al. (2016b) and Yan et al. (2016a) using two-year discharges (2013–2014) and one-year (2014) phosphorus data from the Jianwei polder. They have proven to be satisfactory for simulating hydrological and phosphorus processes associated with the Jianwei polder, respectively.

The main objective of this study is to analyse the regulation effects of a polder with pumping through comparison with an assumed "no-pumping" scenario. We applied calibrated PHPS to the Jianwei polder to explore the effects of a polder with a heavily managed water system on discharge and phosphorus processes. The Jianwei polder is herein chosen because it has a multi-element dataset (including water quantity and phosphorus data) and has been used as an experimental field for previous development of the PHPS (Yan et al., 2016b). These aims will be achieved by comparing the simulated hydrological variables under a pumping scenario to those under a no-pumping scenario. Shedding light on these problems will provide some insights into polder hydrology and provide a scientific basis for sustainable water resource management in lowland areas.

2. Study area and data resource

The Jianwei polder (1.06×10^5 m^2) is a typical Chinese agriculture polder that lies in the northwestern part of the Taihu Basin (Fig. 1). The catchment is surrounded by the river, which flows eastward into Lake Taihu, and it is mainly rural, with paddy fields covering 50.1% and drylands covering 21.7% of the area. The remaining land consists of residential areas (19.2%) and surface water areas (9%), which includes ditches and ponds. In contrast with a freely draining catchment, the surface water level is controlled by three pumping stations and a culvert through irrigation and drainage, which regulate the water and nutrient exchanges between the polder and surrounding rivers. The soil is mainly a silt loam. No industrial pollution sources and sewage treatment works exist within the catchment.

The Jianwei polder belongs to a subtropical monsoon climate zone, which has a long-term average annual precipitation of 1082 mm and average annual pan evaporation of 849 mm. The majority of the precipitation falls between March and September and is closely related to semitropical monsoonal activity. During high-intensity rainfall events, runoff is delivered by ditches to and temporarily stored in the ponds, after which water is exported by the culvert or pumping station to the surrounding river if the surface water level exceeds the threshold levels.

A dataset of land use, soil texture, discharge at the outlet, meteorological, vegetation coverage, and water quality data was collected from this polder to drive the PHPS modelling system. Land use data was derived from remote sensing imagery. Soil samples from arable land were collected to obtain soil texture data. Daily discharge at the outlet provided pumping and culvert discharges. Daily meteorological data was measured using a Hobo rain gauge within the catchment and was provided by the nearest national weather station. Monthly vegetation coverage was monitored from five sites in the surface water (ditches and ponds) (V1–5) as model input variable *VI*(vegetation coverage index of aquatic plant). Phosphorus concentration data were obtained from water and sediment sampling at twelve sites (W1–10, S1–3) over different time intervals. Samples W4–W10 were collected from drainage water from drylands, paddy fields, residential areas, and precipitation, which are the model input variables. The samples were analysed for total phosphorus (*TP*) and dissolved phosphorus (*DP*) using the ammonium molybdate spectrophotometric method (GB 11893-89, GB: China National Standard). Particulate phosphorus (*PP*) was calculated as the difference between *TP* and *DP*. Most data spanned from January 2013 to December 2014, except for one-year of phosphorus data from 2014. Further details about the dataset are available from Yan et al. (2016a) and Yan et al. (2016b).

3. Methodology

3.1. Lowland polder hydrology and phosphorus modelling System (PHPS)

The PHPS is a new coupling of the WALRUS-paddy rainfall-runoff model with a revised phosphorus module of PDP (Fig. S1). It explicitly considers some important features in Chinese polders, including (1) groundwater—surface water feedback, (2) saturated and unsaturated zone coupling, (3) runoff generation of multi-landuse, (4) frequent irrigation and drainage for paddy rice growth, (5) human-induced culvert and pumping discharges, and (6) complicated physical and biological processes of phosphorus in surface water. This model was developed based on the conservation of matter, and it has six modules including the dryland, paddy field, surface water, and residential area water balance modules, as well as a phosphorus balance module. This coupled model has a simpler structure, fewer input data requirements, and fewer calibrated parameters (nine water quantity parameters and five water quality parameters), compared to other models such as MIKE SHE, SWAT, and AGNPS. These advantages facilitate the model's application to flood prevention and engineering design. An overview of the model structure is provided in the supplementary material. A full description of the model and its parameters are given in Yan et al. (2016b).

3.2. Model calibration and validation

The PHPS models have been calibrated and validated in the Jianwei (Yan et al., 2016a; Yan et al., 2016b). They reported good agreement