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WALRUS-paddy model for simulating the hydrological processes of lowland polders with paddy fields and pumping stations

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ABSTRACT

Simulating the rain-runoff process in lowland polder will lead to improvements to hydrological modeling of entire floodplain catchments. The lumped Wageningen Lowland Runoff Simulator (WALRUS) provides an efficient and reliable model for simulating the hydrological processes in lowland catchment with shallow groundwater. However, this model needs to be improved before being applied to Chinese polders, which have multiple land use types and pumping stations. This study proposes an improved version called WALRUS-paddy that accounts for the discharge from multi-sources, including drylands, paddy fields, residential areas, and water areas. A water management scheme is incorporated to control the irrigation and drainage operation in paddy rice fields and the groundwater flow between the paddy field and the adjacent dryland is considered. In addition, a new stage-discharge relation function is introduced to represent the discharge process of the polder with pumping stations and culverts. Then, the model is validated in the Jianwei polder of east China. The modeled results agree well with the observed discharge and show that the improved model can provide good estimates of the discharge in this polder district. Thus, the improved model is feasible and helpful for water resources management of Chinese polders.

1. Introduction

Lowland polders are widely distributed throughout the floodplains, especially in river deltas and lakeside zones (Jiang et al., 2007; Zhao et al., 2010; Koch et al., 2013). For instance, approximately 30% of Taihu Basin, East China is occupied by polders (Yan et al., 2015a). Although polders can prevent lowland areas from natural disasters to some extent by constructed embankments, flooding and climate change may still cause extensive damage to the local community in these districts as a result of dense population, advanced economy and low elevation (Wandee, 2005; Koch et al., 2013). To alleviate the effects of these natural disasters, exploring and simulating the specific hydrological processes of highly controlled polders have special significance for regional risk assessment and water resources engineering design. Furthermore, the hydrological modeling of the entire floodplain of a catchment will be improved by a more thorough the hydrological study of the polder.

Various types of hydrological models have been proposed and used for simulating hydrological processes such as SWAT (Arnold et al., 1998; Abbaspour et al., 2015), HSPF (Donigan et al., 1984; Uygun and Albek, 2015), SSFR (Minnich, 1986; Niedda et al., 2014), GR4J (Perrin et al., 2003), Xin'anjiang (Zhao, 1992; Yan et al., 2015b) and MIKE-SHE (Christiaens and Feyen, 2002). However, most of these models are suitable for freely draining areas with sloping surfaces, and are not designed for flat lowland polders with shallow groundwater, where polder-specific hydrological characteristics are not explicitly described (e.g., capillary rise, groundwater–surface water interactions). Cases of the resulting problems are seen by Koch et al. (2013) and Luo et al. (2013), who used SWAT in northeastern Germany and in eastern China's polders, respectively. In addition, the polders are human-nature hydrological entities where the hydrological processes are affected not only by the natural factors (e.g., precipitation and evapotranspiration), but also by the intensified human activities (e.g., human-induced drainage and irrigation) (Buysse et al., 2015), which bring a great challenge for hydrological simulation. These problems have caught the attention of hydrologists (Engkagul, 1993; Hesterbery et al., 2006; Bormann and Elfert, 2010; Koch

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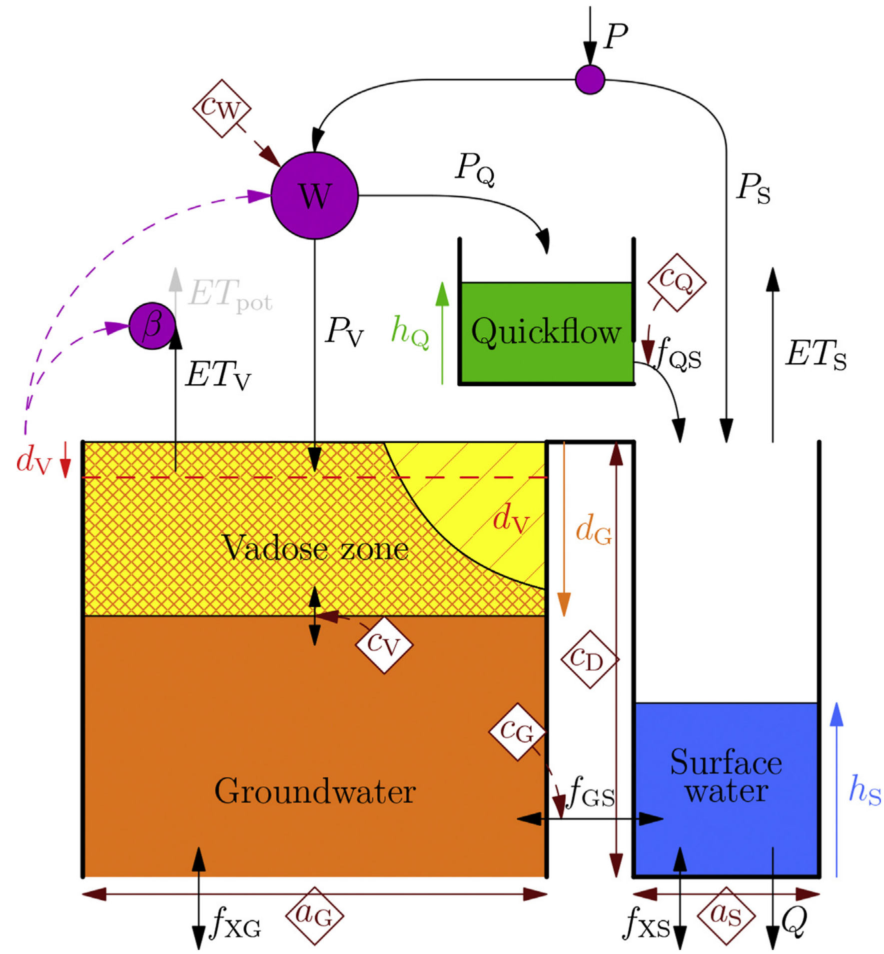

Fig. 1. Overview of the original WALRUS model (Brauer et al., 2014a). Black arrows are water fluxes, brown diamonds the model parameters, and arrows in the colour of the reservoir they belong to the reservoir state. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al., 2013), who have increasingly recognized that a model is required to better represent the dynamic groundwater level and to reflect the manual operation. To deal with the problems described above, Brauer et al. (2014a) recently developed a lumped parametric rainfall–runoff model—the Wageningen Lowland Runoff Simulator (WALRUS), of which the model structure is evidently distinct from previous rainfall–runoff models. WALRUS better considers the main specific processes of the lowland catchments in the following four perspectives: first, it closely integrates the groundwater zone with the vadose zone to capture the interactive process wherein the groundwater table responds to change in the unsaturated zone and vice versa. Second, it efficiently determines the varying division between fast and slow flow routes by a changeable wetness index. Third, a surface water reservoir is introduced to describe the groundwater–surface water feedback, which considers the groundwater drainage and infiltration of surface water. Finally, surface water supply/extraction and groundwater seepage are considered in the model, which can influence the entire system. This model has been used and tested for the two Dutch lowland catchments (Cabauw polder and Hupsel Brook catchment) and proven to generate accurate and reliable estimates of the catchment discharge (Brauer et al., 2014b). However, this model as a lumped type mainly focuses on the lowland areas predominated by dry land such as grasslands, and only considers the average situation of the catchment. When the current WALRUS model is applied to the Asian subtropical monsoon zone, especially eastern China's polders, it may fail to completely consider the characteristics of the field and reflect the complicated water management operation, because multiple land use types generally exist within the polder including residential areas, paddy field, dryland, and water areas (Yang and Zhu, 2013) and each type has different pattern of runoff production. Specially, the water transport of a paddy field where rice is planted is more complicated (Chen et al., 2014; Sakaguchi et al., 2014; Arnáez et al., 2015; Boulange et al., 2014) because of the increased water consumption in the paddy rice growth period.

The objectives of this study were to (1) give a description of the modified version of WALRUS model, here called WALRUS-paddy, for simulating the catchment discharge of lowland polders with multi-type land use, especially including paddy rice fields and pumping stations, (2) test the model with the observed hydro-climatic data from a polder called Jianwei in east China, and (3) investigate the capability of the model to analyze the effect of water management.

2. Model description

The original WALRUS contains three reservoirs as seen in Fig. 1, including a soil reservoir (coupled vadose-groundwater reservoir), a quickflow reservoir and a surface water reservoir. Precipitation (P) enters the three different reservoirs, of which a constant fraction (a_S) falls on the surface water reservoir (P_S). The soil wetness index (W) dynamically divides the remaining precipitation into a portion that slowly percolates to the soil matrix (P_V) and another portion that is routed to the surface water through a quick flow path (P_Q). Water is depleted by evapotranspiration from the surface water (ET_S) and vadose zone (ET_V). A state variable of storage