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A physically based hydrological model for paddy agriculture dominated hilly watersheds in tropical region

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Summary The hydrological response of tropical or sub tropical hilly agricultural watersheds is controlled by many critical factors such as topography, soil, vegetation, climate, rainfall characteristics, and local land use practices. The effect of these factors is highly interdependent and nonlinear in nature. In most of the hilly watersheds in south-east Asia rainfed paddy agriculture is the most dominating land use pattern. Therefore, both hillslopes and typical hydrological regimes of paddy fields significantly influence the hydrological behavior of these watersheds. However, non-availability of detailed hydro-meteorological data for these watersheds often limits the use of distributed hydrological models. The present study aims at developing a distributed hydrological model at watershed scale with limited hydro-meteorological data. The model describes the physical equations of vegetated hillslopes and paddy fields with other critical hydrological processes of the watershed. The model has been used successfully to simulate the hydrological behavior in two tropical paddy agriculture dominated watersheds (PADW) of the region. The model predicted the peak flow and seasonal runoff coefficients for both the watersheds using daily rainfall data from limited number of raingauge stations. A model sensitivity analysis has shown that average retention depth and degree of soil impermeability in paddy fields are the most influencing parameters.

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Introduction

Paddy agriculture dominates the land use pattern of many watersheds in south-east Asia, where the crop is extensively cultivated under both rainfed and irrigated farming systems (Dutta et al., 2004). India has the largest area in the world under paddy agriculture with the majority of its cultivation being under rainfed farming (Dutta, 2006). In order to efficiently harvest the rainwater, general practice of paddy agriculture in this region is a ''flood-check-basin'' system, where the field is bounded by low-height earth embankments for trapping the rainwater. Due to trapping of overland flow or surface runoff in the plots, the peak of the outflow hydrograph at the basin outlet tends to reduce, whereas, the ponded water in the paddy field percolates downward to saturate the subsoil and recharge the groundwater aquifer.

The adoption of such a unique water harvesting structure results in such typical hydrological regimes in the paddy agriculture dominated watersheds (PADW) (Paulo et al., 1995; Kar and Das, 2000). Chang et al. (2001) studied the benefits of increased water application to paddy fields in Taiwan and developed a conceptual model to represent the hydrological system of paddy fields. The model simulation results showed that the downward percolation increases when the irrigation water increases. However, the percolation reaches a capacity rate no matter how large the amount of water applied. They reported that this phenomenon results from the existence of a hard layer below the paddy field. The effects of raising the height of levees around paddy fields were also studied. Chen and Liu (2002) studied the hydraulic characteristics of water infiltration in a flooded paddy field. They suggested that the least permeable layer, having an average thickness of about 7.5 cm, occurred at the interface of the puddled topsoil and non-puddled subsoil. Chen et al. (2002) developed a three-dimensional finite element model (FEMWATER) to numerically simulate density dependent flow and transport processes in paddy fields of Taiwan. The controlling factors for the processes like vertical percolation and lateral seepage were evaluated. They concluded that a flooded rice paddy performs a significant function in ground water conservation. Experimental and simulation results elucidated water movement mechanisms in rice paddies and clarified the vertical and horizontal flow processes within an unsaturated region. Huang et al. (2003) investigated percolation and seepage through the bunds of flat and terraced paddy fields in Taiwan using the FEMWATER model. They concluded that infiltration in the central area of a terraced paddy field is mainly vertically downward, whereas, flow near the bund is predominantly lateral. However, the lateral seepage flux does not fully saturate the surface of the hillside soil. The simulation clearly showed that the seepage upstream of the paddy field did not move water downstream and was reused as subsurface return flow. Liu et al. (2004) simulated water movement in the paddy fields subjected to various crack conditions using the FEMWATER model. The model simulation results clearly showed that if the cracks develop extensively and penetrate the ploughed soil, the infiltration rate may increase significantly. Yangwen et al. (2005) developed the water and energy transfer process (WEP) model, which was successfully applied to urbanized watersheds, was improved for hydrologic modeling in an agricultural watershed by developing a paddy model. The model was simulated for the Yata watershed (Japan) which had a well established subsurface as well as a surface drainage system in paddy fields. Their results indicated that paddy fields play an important role in reducing flood peaks and conserving low river flow in the watershed. Keeping these hydrological conditions in view, rainfall—runoff modeling of PADW without any artificial drainage system, needs to be addressed accordingly.

The hydrological response of a watershed can be modeled based on the variable source contributing area concepts (Cappus, 1960; Hewlett, 1961; Dunne and Black, 1970). Engmann and Kellerhals (1974) suggested the concept of partial area hydrology where watershed areas are separated into hydrologically active and passive sub-areas. TOPMODEL is one of the first distributed hydrological model attempted based on the variable contributing area concepts (Beven and Kirkby, 1979; Beven and Wood, 1983; Beven et al., 1995; Beven, 2001a). The model makes use of a topographic index of hydrological similarity based on an analysis of the topographic data. Dutta (2002) proposed the concept of distributed hydrologic modeling for major hydrological and hydraulic processes of PADW and proposed the techniques to implicitly introduce agricultural practices into modeling. The hydrologic modeling concept can be attempted at three different scales: field scale, regional scale, and watershed scale. Gupta et al. (2002) and Dutta and Zade (2003) used a fully distributed hydrological model at watershed scale describing unique hydrological regimes in PADW by remotely sensed parameters (*viz*. crop area, crop planting period, crop duration) in order to determine hydrological response of watersheds under different storm events. Zade et al. (2005) analyzed dominant runoff processes in major river basins of India. Their study revealed that major portion of the basins remained saturated throughout the year and this saturated area played a significant role in determining runoff behavior of the basin. Kim et al. (2005) investigated the hydrologic impacts of land use changes on streamflow for an urbanizing watershed with paddy fields. They adopted a gridbased daily hydrologic model which was calibrated with two years (2000—2001) of observed streamflow data and validated using 5 months (2001) of measured soil moisture data and 1 year (2002) of observed streamflow data. The results indicated that paddy fields play an important role in runoff regulation, and the evaluation method can assist regional policy makers in developing land management strategies that minimize hydrologic impacts on streamflow. Chattopadhyay and Dutta (2006) used the temporal and multi-spectral signature of the soil wetness regions formed by monsoon storms in Indian river catchments and analyzed time-series vegetation images to map the wetness regions and their spatial distributions. Rajyalakshmi and Dutta (2006) proposed regionalization of rainfall—runoff processes in some of the catchments of Mahanadi river basin of India considering an instantaneous unit hydrograph approach. The effect of rice agriculture on the watershed rainfall—runoff response was considered as partial sink areas for runoff generation. These partial sink areas were quantified as a sink factor based on