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Evaluation of soil water percolation under different irrigation practices, antecedent moisture and groundwater depths in paddy fields

Baoli Xu[a], Dongguo Shao[a,*], Xuezhi Tan[a,b], Xia Yang[a], Wenquan Gu[a], Haoxin Li[a]

[a] State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, PR China
[b] Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta, T6G2W2, Canada

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ABSTRACT

Understanding soil water percolation in paddy fields is helpful to optimize irrigation schedule for rice production and improve water use efficiency under various irrigation practices and groundwater depths. Calibrated HYDRUS-1D model was used to simulate soil water movement and water balance in this study. We conducted scenario analyses based on the model to evaluate the combined effects of irrigation amount in an irrigation event (irrigation amount), irrigation duration, antecedent soil moisture, and groundwater depth on deep percolation (DP) in paddy fields. Results showed that during an irrigation event, there would be higher DP in paddy fields with higher antecedent soil moisture (≥ -10 kPa), larger irrigation amount (7 cm) and/or free drainage in the bottom of rice root zones. We also used a classification and regression tree model to analyze the relative contribution of different factors to DP. Results indicated that antecedent soil moisture was the primary factor that contributed 46.3% of DP variation. Groundwater depth contributed 32.5% of DP variation, while irrigation amount (18.7%) and irrigation duration (2.5%) contributed least for DP variation. Furthermore, effects of these factors on DP interacted with each other. In scenario analysis, the contribution of antecedent soil moisture increased from 16.1% to 65.2% as the groundwater depth increased. When irrigation amount rose from 1 cm to 5 cm, the contributions of antecedent soil moisture increased to 77.6% from 57.1%; when irrigation amount was 7 cm, the contributions of antecedent soil moisture decreased to 46.4%. The contribution of irrigation amount rose to 55.7% from 28.4% with the increase of antecedent soil moisture, while the contributions of groundwater depth to DP showed opposite variation to irrigation amount as antecedent soil moisture altered. Based on relative contribution of these factors, optimal combinations of irrigation practices, antecedent soil moisture and groundwater depth were screened out to control DP for promoting rice growth and improving water use efficiency.

1. Introduction

Percolation is a vital component of water balance in hydrologic processes in which water moves downward to groundwater. As a pathway for water losses from the rice root zone, deep percolation (DP) reduces water use efficiency in paddy field and accounts for 50–80% of water input (Belder et al., 2007; Cesari de Maria et al., 2016). Moreover, nitrogen leaching which is a threat to the groundwater environment is closely linked with DP (Refsgaard et al., 1999; Bouman et al., 2007). Therefore, it is necessary to understand how percolation is generated and its influential factors in paddy fields.

Even though lysimeter experiments (e.g., Bethune et al., 2008; Hatiye et al., 2016) could measure the percolation of very small paddy soil profiles, it is difficult to directly measure on-site percolation in paddy fields. Thus, field percolation is often estimated as the residual of field water balance (Wang et al., 2012). However, the estimated percolation resulting from water balance analysis was not always reliable because of uncertainties in measuring other water balance components such as evapotranspiration. Although lysimeter experiments can precisely measure percolation, it is expensive to set up instruments and lysimeter is limited to some standard paddy fields. Thus, lysimeters are rarely used to measure paddy fields percolation. Consequently, a process-based model with numerical solution to water movement has been a widely-

* Corresponding author.
E-mail addresses: blxu@whu.edu.cn (B. Xu), dgshao@whu.edu.cn (D. Shao), xtan1@ualberta.ca (X. Tan), yxelina@163.com (X. Yang), gwquan@163.com (W. Gu), hxliwhu@whu.edu.cn (H. Li).

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used and efficient approach to estimate percolation on field scale, due to its low cost and flexibility. In addition, the percolation in paddy fields under a much wider range of scenarios including those in extreme conditions can be assessed in numerical models with calibrated parameters (Bah et al., 2009; Jyotiprava Dash et al., 2014; Lai et al., 2016).

DP was closely related to water input, and DP represented the largest water losses in rice fields, especially for irrigated fields (Li et al., 2014). Peng et al. (2011) and Tan et al. (2013) found that DP decreased in paddy fields under alternate wetting and drying (AWD) irrigation, because AWD irrigation significantly decreased irrigation frequency and water inputs compared to continuously flooded irrigation. Ochoa et al. (2007) indicated that DP was significantly correlated with amount of irrigation water applied in flooded irrigation. Nevertheless, Janssen and Lennartz (2009) reported that ponded water depth in paddy fields had little influence on percolation rates. Besides, water input (irrigation or rainfall) patterns were highly associated with DP and solute leaching from paddy fields during rice growth season (Wang et al., 2010; Schwen et al., 2012). The duration of each irrigation event eliminated the differences in the vertical component of the wetting front between pulse irrigation and continuous irrigation (Elmaloglou and Diamantopoulos, 2008). However, the combined effects of these factors on DP have not been studied for paddy fields under various irrigation practices and surface storage capacity.

The antecedent soil moisture is a criterion of implementing irrigation in some irrigation methods (Kukal et al., 2005; Tuong et al., 2005; Luo et al., 2009). The relationships between DP and antecedent soil moisture have been explored in some studies. Low antecedent moisture allows the soil to store more water and DP will not occur until soil water content is higher than the field capacity (Hatiye et al., 2016), even though smaller antecedent pressure head of dry land may increase percolation and seepage rates in flooded fields (Chen et al., 2002). Lai et al. (2016) found that the antecedent soil moisture showed more significantly positive correlation with DP than water input and its characteristics. Nevertheless, DP was not sensitive to the antecedent soil moisture in the research of Ochoa et al. (2007) in which flood irrigation was applied. Bethune et al. (2008) found no significant correlation between DP and the antecedent soil moisture before irrigation events in paddy fields under surface irrigation. The discrepancies illustrate the necessity to further clarify the complexity of the relationship between DP and antecedent soil moisture, and the potential processes of soil water movement that affect the relationship between them.

DP also changes along with the groundwater depths (GWD). In lowland paddy fields with a shallow depth, the vertical soil water movement can switch from DP into capillary rise, so the groundwater could contribute to rice-use water (Boling et al., 2007). The capillary rise is weakened with the higher groundwater depth (Luo and Sophocleous, 2010; Hatiye et al., 2016). Studies on the contribution of groundwater depth to DP or capillary rise have been reported. However, the contribution of groundwater depth to the exchange of soil water and groundwater needs to be quantified to our knowledge.

In paddy fields, different combinations of water management methods instead of a single method are usually adopted, but the combined effects of water management measures on DP are not well understood. The interaction of different influential factors on DP in paddy fields should been considered to enhance our understanding of DP process. Besides, the influences of water management measures of irrigation practices on water balance components were rarely studied using HYDRUS-1D. Furthermore, it is essential in establishing an optimal irrigation scheme or controlled irrigation to improve water use efficiency by controlling DP based on scenario analysis. In this study, using a calibrated HYDRUS-1D, factors including irrigation amount in an irrigation event (irrigation amount, IA), irrigation duration (ID), antecedent soil moisture (AM) before an irrigation event, and groundwater depth (GWD) were selected for scenarios analysis of DP in paddy fields. These factors are easy to be controlled in rice production. The objectives of this study are (i) to quantify relative contributions of different factors to DP, (ii) to analyze the interactive impacts of different factors on DP, and (iii) to explore an optimal field water management strategy to control DP.

2. Materials and methods

2.1. Field experiments

The study site (112°10′, 30°49′; elevation of 72 m) is located in Zhanghe Irrigation District (ZID), Jingmen City, China. The study site has a typical subtropical monsoon climate and receives average annual rainfall of 915.0 mm. 56.1% of the yearly rainfall occurs between May and September and rainfall has a high seasonal and annual variability. In ZID, annual 20 cm pan evaporation ranges from 1300 to 1800 mm and annual mean air temperature is 16 °C. The soil is a typical lowland paddy soil. Rice (*Oryza sativa*) is the main crop planted. Irrigation water is supplied by the Zhanghe Reservoir and water saving irrigation is widely adopted in paddy fields for rice planting.

Field experiments were conducted in 2010 and 2011 during the rice growing season by a split-plot design. Details of the experimental layout were described by Tan et al. (2014). The soil profile in paddy fields consisted of three layers, i.e., the cultivated horizon layer (CHL), the plow pan layer (PPL) and the illuvial horizon layer (IHL) (Table 1). Three replicates of 250 cm^3 undisturbed soil cores were sampled in each layer. Bulk density and particle size distribution were determined with stove-drying method and soil particle size and shape measurement system (AZ-S0300), respectively. Soil saturated hydraulic conductivity was measured with constant head method and soil water retention was estimated with simplified evaporation method in Hyprop System, based on which van Genuchten's θ–h relationships were optimized. Soil properties of each soil layer were shown in Table 1. During the rice growing season, alternate wetting and drying (AWD) irrigation was applied and the amount of irrigation volume for each irrigation event was 3 cm. The upper limit of ponded water depth was 10 cm throughout rice growing season. The lower limit of pressure head were 0 cm in turning green period, −50 cm in early tillering period and −150 cm in late tillering period at the depth of 18 cm, and in booting and heading period and milk ripening period the lower limit were −100 cm and −50 cm, respectively, at the depth of 33 cm. Drainage

Table 1
Soil particle classification and hydraulic parameters of soil profile in the study site.

Soil layer (cm)	Sand (%)	Silt (%)	Clay (%)	ρ_b (g cm^{-1})	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	n	K_s (cm d^{-1})
CHL (0–18)	20.2	45.5	34.3	1.33	0.098	0.43	0.021	1.31	7.43(7.89)
PPL(18–33)	16.1	44.7	39.2	1.56	0.069	0.38	0.011	1.23	0.48(0.45)
IHL (33–100)	36.4	37.2	26.4	1.43	0.062	0.41	0.034	1.41	18.2

CHL, cultivated horizon layer; PPL, plow pan layer; IHL, illuvial horizon layer; ρ_b, bulk density; θ_r, residual volumetric water contents; θ_s, saturated volumetric water contents; α and n, fitting parameters of soil water characteristic curve; K_s, saturated hydraulic conductivity and the calibrated values were shown in parentheses.