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Paddy Field Water Movement Through Soil Profiles Under Different Water Management Practices: A HYDRUS 1D Model Study

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ABSTRACT

Physical measurement of hydrological processes through soil profile is very complicated and time-consuming. Complex and coupled physical processes like water movement with soil matric potential in puddled paddy field can be simulated using physical process-based model HYDRUS 1D. The model simulation was setup for the multilayered (different soil materials at 0-15 and 15-30 cm depth) paddy fields having continuous flooded irrigation (CFI) practice and water saving Alternate Wetting and Drying (AWD) practice. Measured soil physical properties of three Bangladesh Rice Research Institute (BRRI) regional station farms (Kushtia, Sirajganj, and Rangpur) were used as model input, initial and boundary conditions configuration. The model was calibrated and validated using the water data of a dry season field experiment in Kushtia. The calibrated (RMSE of 0.54 cm, d of 0.94, NSE of 0.89) water level data validated successfully with observed water level data of AWD practiced paddy field (d of 0.95, NSE of 0.92). Soil water content reached the threshold/critical level in AWD practice (-101 cm of water soil matric potential at 15 cm soil depth) earlier in light textured soil (loam or sandy loam) compared to heavy textured soil (clay). The physical properties of the layered soils (i.e., soil particle size distribution and soil water release curve, SWRC) did not affect much on water movement in CFI practice, but it had substantial impact on field water movement under AWD practice. The change in soil water storage followed the general trend for respective soil water holding and releasing capacity, clay soil was heavier and released water slowly than that of loam or sandy loam soils. The positive water flux above 15 cm of soil profile mainly drove the water flow due to evapotranspiration and soil water and pressure distribution along the soil profile while the negative fluxes below 15 cm of soil depth due to infiltration or percolation contributed as a secondary force. A basic understanding of HYDRUS simulated results would lead to realize the total physio-hydrological environment in the paddy field.

Key words: HYDRUS 1D, AWD, continuous flooded irrigation, soil physical properties, paddy field

INTRODUCTION

Rice is the largest water consuming stakeholder in irrigated agriculture although water for rice cultivation is going to be scared soon. Water is turning to a costly input for rice production due to increasing demand of other users like industry and urbanization (Bouman and Tuong, 2001; Loeve *et al.*, 2007). In Asia, where rice dominates 40-46 percentage of crop net irrigated area (Li and Barker, 2004; Bouman *et al.*, 2007a), water saving practices are popularizing in recent times as available water resource is reaching its limit in this region. The water saving irrigation technologies for rice cultivation, includes alternate wetting and drying (AWD) practice, saturated soil culture, direct seeding rice, aerobic rice, are now being widely adopted in rice growing areas. Continuous ponding condition in paddy fields leads to huge water misuse during Boro season in the irrigation projects as well in farmer's management (Sattar *et al.*, 2009). Compared to continuous flooding irrigation practice, farmers do not need to irrigate the paddy field frequently in AWD practice. When soil water depletes below a critical or threshold level, farmers need to irrigate the field. Many researchers have reported that AWD practice

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saves irrigation water over the continuously flooded irrigation practice, and it does not have any impact on rice yield (Bouman *et al.*, 2007a; Cabangon *et al.*, 2004; Zhang *et al.*, 2009; Kukal *et al.*, 2005; Mishra *et al.*, 1990; Liu *et al.*, 2005; Sharma *et al.*, 2002; Singh *et al.*, 2002; Tabbal *et al.*, 2002). The AWD fields had the same yield as continuous flooding and beneficially saved 16-24% in water costs and 20-25% production costs, and thus water productivity is always higher for AWD practice over conventional irrigation practice (Roy and Sattar, 2009).

Water flow through the cultivated paddy field is the result of highly complex and coupled hydrological and physical processes. The processes are often very complicated and ambiguous. The understanding, explaining, and evaluating those complicated processes with respect to field observation is really time consuming and sometimes very costly. Considering the adverse situations for practical field measurement, using computer models to interpret the soil processes are becoming very common. Water movement through the multilayer soil profile has been investigated by using conceptual models both in continuous flooded paddy field and AWD practiced paddy field (Bouman *et al.*, 2007b; Inthavong *et al.*, 2011; Khepar *et al.*, 2000, Luo *et al.*, 2009; ten Berge *et al.*, 1995; Chen and Liu, 2002; Chen *et al.*, 2002; Garg *et al.*, 2009; Janssen and Lennartz, 2009). HYDRUS is a physical process model that deals with soil water and solute movement processes both horizontally and vertically using numerical simulations. HYDRUS 1D and HYDRUS (2D/3D) have been used by many investigators around the world to simulate water movement in agricultural fields under different irrigation scheme for different crops including transplanted rice (Ramos *et al.*, 2012; Phogat *et al.*, 2010; Sutanto *et al.*, 2012). HYDRUS model (Šimůnek *et al.*, 2008, 2012) is a very effective and useful model option for heat and water flow simulation. HYDRUS models can predict and simulate different hydrological processes like rainfall, snowfall, evaporation, transpiration, infiltration, root zone water accumulation, soil water holding capacity, capillary movement of water in the soil, drainage, irrigation, groundwater movement and storage and all directional movement of flow within any homogeneous or layered soil profile (Šimůnek *et al.*, 1998, 2012; Šimůnek and Bradford 2008; van Genuchten *et al.,* 1980).

In recent past, some studies for puddled paddy fields water flow indicated that Richard equation could be capable of solving field-scale water flow variation (Wopereis *et al.*, 1992, 1994; Tuong *et al.*, 1994; Liu *et al.*, 2001; Chen and Liu, 2002; Chen *et al.*, 2002; Tournebize *et al.*, 2006). HYDRUS model (Šimůnek *et al.,* 1998) uses Richard equation to solve numerical simulations in combination with van Genuchten model (1991). The convenience of the model is that it can simulate the processes for water movement from measured soil physical and hydraulic properties, which can be achieved from field or laboratory tests, in addition to the appropriate boundary and initial conditions (Warrick, 2003). In this study, we set our objective to simulate and explain irrigation water movement in multi-layered paddy field soil profile at different locations of Bangladesh both in continuously flooded irrigation (CFI) practice and AWD practice based on the measured soil physical properties and field observed experimental data.

METHODOLOGY

The HYDRUS 1D model simulations were setup for Kushtia (23°54´51˝ N, 89°05´56˝ E), Sirajganj (24°24´9.9˝ N, 89°38´43.44˝ E) and Rangpur (25°41´42˝ N, 89°16´03˝ E) region. The model was run for two water management practices: (a) Continuously flooded irrigation (CFI) and (b) Alternate wetting and drying (AWD). The depth of the soil profile for the simulation was taken 30 cm considering the root zone of the rice plant. In each location, measured soil physical properties information of soil samples from two soil depths (0-15 cm and 15-30 cm) were taken as input to simulate water movement along the paddy field soil profile. The soil samples were collected from three research farms of BRRI regional station Kushtia, Sirajganj and Rangpur, respectively. The soil physical properties were measured for each location by collecting soil samples from soil profile (up to 30 cm) of different spots at 0-15 cm, and 15-30 cm depths using standard protocols (Dane and Topp, 2002). Two different soil samples were collected from each depth: one core sample for bulk density determination and soil textural analysis; another for soil water retention curve construction by pressure plate apparatus. Soil samples for bulk density measurement were collected with a core sampler. Each core was made of stainless-steel having 5 cm height and 5 cm diameter. Bulk density of soil samples was determined after oven drying the core soil samples at 105°C for 72 hours (Black and Hartge, 1986). The soil textural analysis of the collected samples was conducted by hydrometric method (Bouyoucos, 1951). The soil samples were soaked overnight in a mixture of 100 ml Calgon solution (5% NaOH Meta Phosphate solution) and 100 ml distilled water. Then sand, silt and clay percentages were calculated from hydrometer measurements. USDA soil texture triangle was used to identify the soil textural class of respective soil sample (USDA 1975). Table 1 presents the textural class and particle distribution of all soil materials used for simulation.

The soil water retention curve (SWRC) was determined for each soil layer in 0.05 bar, 0.1 bar, 0.33 bar, 1 bar, 3 bar, 5 bar and 15 bar by using pressure plate apparatus (Soil Moisture Equipment Corp., USA). Field capacity (1/3 bar or 0.33 bar) and wilting point (15 bar) are the upper and lower limits of available moisture. Later, the soil pressure units were converted from kPa to cm of water (1 kPa = 10.1972 cm of water) for convenient modeling. The soil samples were saturated in water for 24 hours before placing on the apparatus. The individual wet weight of soil samples was measured after extracting the soil moisture with different bars. After completing all moisture extraction in different bars, the soil samples were oven dried at 105°C for 72 hours (Dane and Hopmans, 2002, Roy *et al.*, 2018). Figure 1 shows the SWRC of each soil layer in each location. All other soil hydraulic parameters were predicted using van Genuchten-Mualem soil hydraulic property model (van Genuchten, 1980). Input values in HYDRUS model of soil hydraulic properties (saturated water content, residual water content, hydraulic conductivity etc.) for all soils were considered for simulation (Table 2).

Table 1. Soil texture and bulk density of different soils used for model simulation.

Location	Soil layer (cm)	Sand (%)	Silt (%)	Clay (%)	Textural class	Bulk density (gm/cm^3)
Kushtia	0-15	22	16	62	Clay	1.45
	15-30	21	19	60	Clay	1.48
Sirajganj	0-15	32	48	20	Loam	1.13
	15-30	36	44	20	Loam	1.49
Rangpur	0-15	46	40	14	Loam	1.22
	15-30	58	30	12	Sandy loam	1.14

During the model simulation, atmospheric boundary condition with surface runoff was selected as upper boundary condition and free drainage was selected as lower boundary condition. Moisture content at field capacity of each soil layer was setup as initial conditions for simulation. Observation node was setup at 15 cm depth in the soil profile. Figure 2 presents the initial condition setting before running the HYDRUS 1D model. The time duration was considered 15 days for each simulation with respect to the water level data obtained from an experiment conducted in dry season of 2019-2020 in BRRI Kushtia regional station farm (BRRI, 2019). The variety was BRRI dhan58, growth duration was 150 days and 40 days of seedlings were transplanted in this experiment. The actual field duration, considered for modeling purpose, was 21 DAT (Day after transplanting) to 35 DAT.

Table 2. Hydraulic properties of soils from different locations used in HYDRUS 1D model.

Location	Soil layer	Residual water content, θr cm³/cm³	Saturated water content, θs cm³/cm³	Alpha, α 1/cm	n	Saturated hydraulic conductivity, K cm/hr
Kushtia	0-15 cm	0.10	0.46	0.02	1.23	0.42
	15-30 cm	0.10	0.46	0.02	1.24	0.40
Sirajganj	0-15 cm	0.07	0.47	0.01	1.63	2.37
	15-30 cm	0.06	0.38	0.01	1.52	0.39
Rangpur	0-15 cm	0.05	0.43	0.01	1.55	1.94
	15-30 cm	0.05	0.46	0.02	1.46	4.45

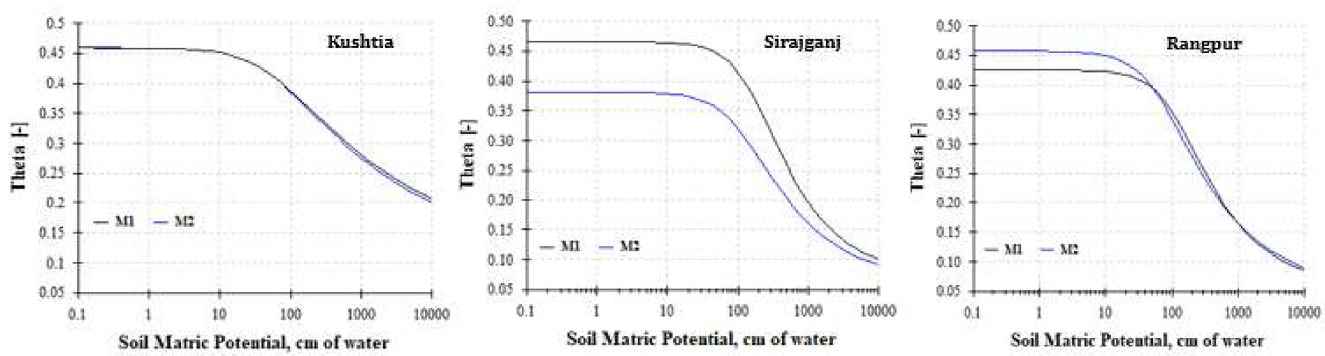


Fig. 1. Soil water retention curves (SWRC) of Kushtia, Sirajganj and Rangpur soils. The y axis is volumetric water content (Theta) in cm³/cm³. M1 and M2 are the soil materials of 0-15 cm depth and 15-30 cm depth, respectively at each location.

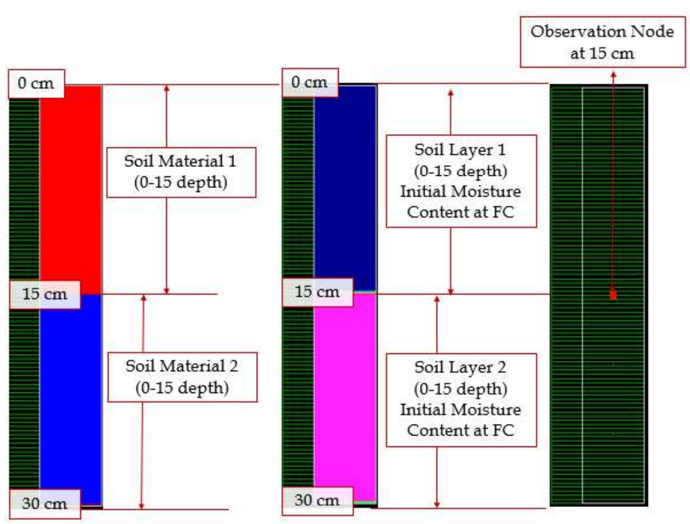


Fig. 2. Initial conditions setup along the multi-layered soil profile in HYDRUS 1D model.

In this study, the model was calibrated and validated with respect to actual field observed water level data of the experiment (BRRI, 2020). The simulated water level calculated from soil matric potential data of CFI practice and corresponding observed water level data were used for model calibration. Model validation was done in AWD practice using calibrated data of CFI practice. The observed evapotranspiration (ET) data and actual irrigation application amount in both CFI and AWD practice were applied in model simulation (Table 3). An amount of 6 cm irrigation was given in three times at Day 1, Day 7, and Day 13 in CFI practice. In AWD practice, only one irrigation (6 cm) was supplied at Day 1.

Table 3. Date wise irrigation amount and Evapotranspiration (ET) during the simulation period.

Day	Irrigation in CFI, cm	Irrigation in AWD, cm	Evapotranspiration, ET cm
1	6	6	0.2
2	0	0	0.1
3	0	0	0.2
4	0	0	0.1
5	0	0	0.2
6	0	0	0.2
7	6	0	0.2
8	0	0	0.3
9	0	0	0.1
10	0	0	0.4
11	0	0	0.1
12	0	0	0.1
13	6	0	0.2
14	0	0	0.5
15	0	0	0.1

The model performance was evaluated by (i) the root mean square error (RMSE), (ii) index of agreement (d) (Willmott, 1982), and (iii) Nash-Sutcliffe modeling efficiency (NSE) (Nash and Sutcliffe, 1970).

$$(i)\ RMSE = \sqrt{\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{N}} \tag{1}$$

where, O_i is the measured value and Pi is the predicted value.

$$(ii) d = 1 - \frac{\sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \tag{2}$$

where, $\bar{O}$ is the measured mean and $\bar{P}$ is the predicted mean.

$$(iii) NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - O)^2} \tag{3}$$

where, O is the observed average.

The simulation outputs from the model for Kushtia, Sirajganj and Rangpur regions were analyzed comprehensively and discussed based on water content distribution along the soil profile, soil matric potential distribution along the soil profile, soil water flux variation along the soil profile, and soil moisture storage along the soil profile during the simulation period in days for both CFI and AWD practice.

RESLUTS AND DISCUSSION

During the model calibration, water level data were calibrated with simulated soil matric potential for CFI practiced paddy field of Kushtia. Figure 3a presents the simulated volumetric water content variation with the duration of the simulation period. The simulation started from the initial soil water content at field capacity (0.35 cm^3/cm^3). After the irrigation application of 6 cm at Day 1, Day 7, and Day 13, soil water content hiked to saturated water content and then gradually decreased. Figure 3b is shows the corresponding soil matric potential variation with time in the CFI field of Kushtia. Soil matric potential reduces with increased soil water content and vise-versa (Hillel, 1998). The simulated results showed the same trend here. The observed water level of the experiment (BRRI, 2020) calibrated along with the soil matric potential variation. The simulated water level data after calibrating showed a satisfactory agreement (d = 0.94) with the observed field water level data. The model performed a very well prediction (NSE = 0.89) with a RMSE of 0.54 cm (Fig. 4a). The model was then conducted for AWD practiced paddy field for validation purpose. For the validation (Fig. 4b), simulated water level data of AWD practiced paddy field matched with field observed water level data reasonably (d = 0.95, NSE = 0.91).

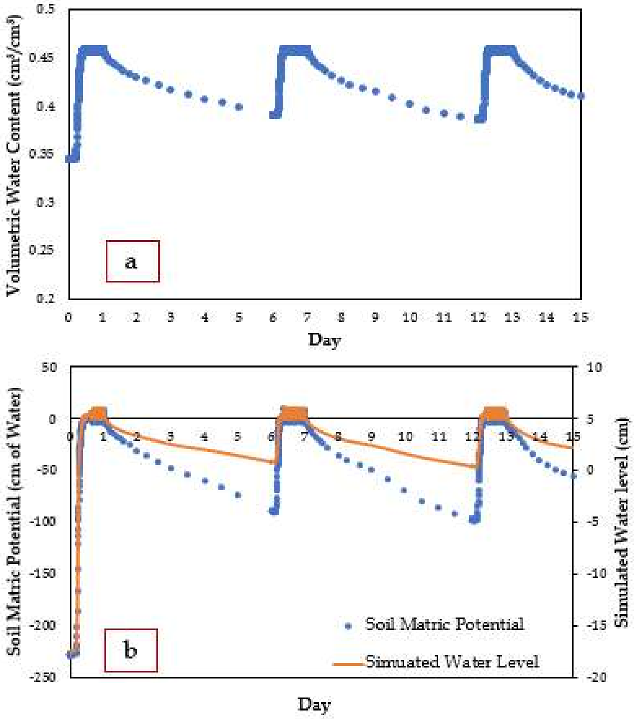


Fig. 3. Continuous flooded irrigation in paddy field of Kushtia (a) variation of simulated soil water content with time; (b) variation of simulated soil matric potential with time and calibrated water level with soil matric potential variation.

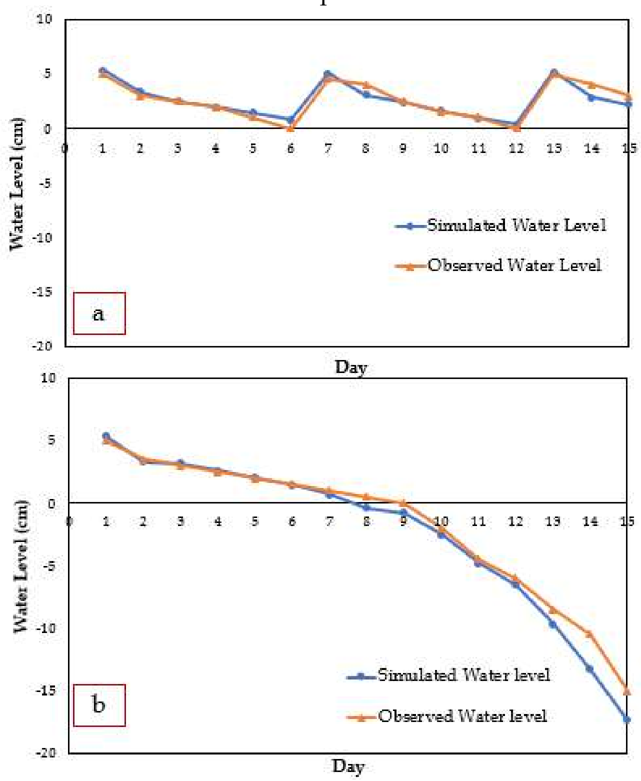


Fig. 4. (a) Simulated (after calibration) and observed water level in CFI field of Kushtia; (b) simulated water level validation with the observed water level in AWD field of Kushtia.

Figure 5 describes the soil water content variation along the soil profile during the simulation period. In all the simulations, the initial soil water content was at field capacity of the respective soil material. It was assumed according to field condition that after the initial crop settling (20 DAT), the fields of both water management reached at field capacity uniformly, which is denoted as T0 in the Fig. 5a-5f. Under AWD practice, paddy field soil water environment moves between being saturated to being saturated and unsaturated alternatively. So, the difference was huge between the water movement through the soil profile of continuously flooded field and AWD practiced field. Various studies reported different threshold levels for AWD practice. The level could be varied from the soil matric potential at 10 cm depth of soil of -20 kPa to -30 kPa for average root zone soil matric potential (Tuong *et al.*, 2005; Kukal *et al.*, 2005; Luo *et al.*, 2009). The threshold level differs because those critical values were derived based on different soil physical properties of a specific field experiment. To make the simulation precise, we followed -101 cm of water (-10 kPa) soil matric potential at 15 cm depth of soil profile (Tuong, 2008) as the threshold level when soil water content reached at field capacity. The simulation profiles clearly showed that the soil moisture never went to field capacity, or even closer to it in CFI practice. In AWD practice, it was obvious that soil moisture content reached field capacity before the next irrigation applied. However, the time for reaching field capacity differed among the soil texture. In clay soil of Kushtia (Fig. 5b), the 15-day soil water contents along the soil profile (T5) reached depth and exactly crossed the field capacity line at 15 cm depth. So, the total irrigation interval was 15 day with a safe yield. On the contrary, in the loam soils of Sirajganj and Rangpur (Fig. 5d and Fig. 5f), the 12-day soil water content line (T4) crossed the field capacity at 15 cm depth. It indicates that, for

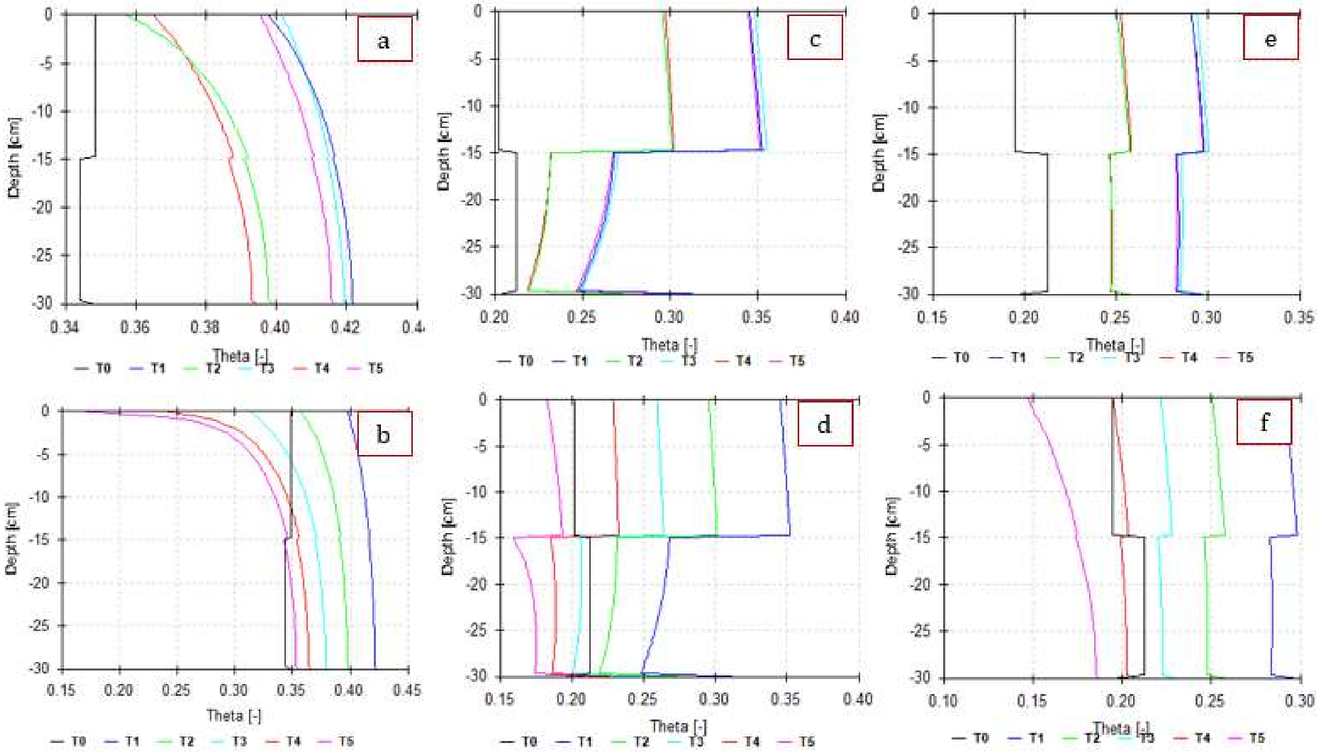


Fig. 5. Simulated soil water content variation along the soil profile for (a) CFI at Kushtia, (b) AWD at Kushtia, (c) CFI at Sirajganj, (d) AWD at Sirajganj, (e) CFI at Rangpur, and (f) AWD at Rangpur. The soil water content status presented at simulation starting (T0), at 3 days (T1), at 6 days (T2), at 9 days (T3), at 12 days (T4) and, at 15 days (T5).

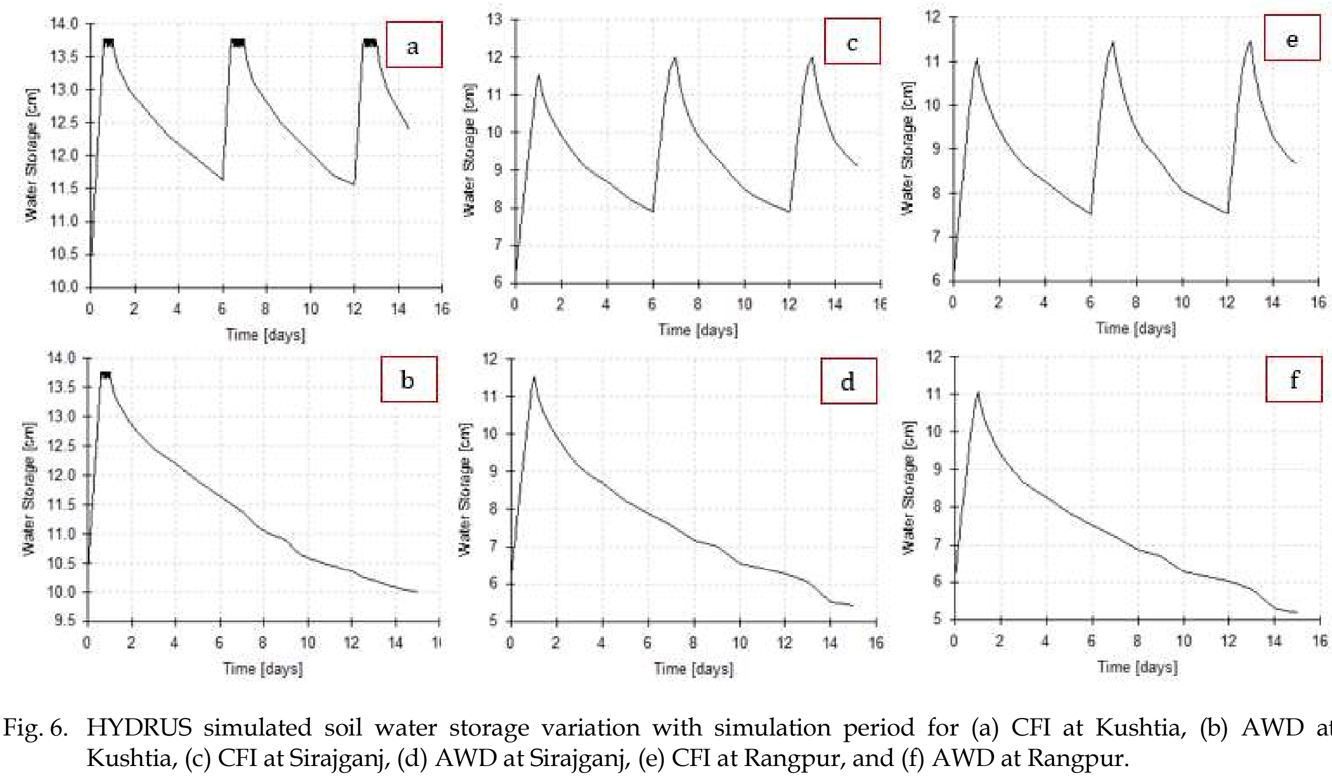
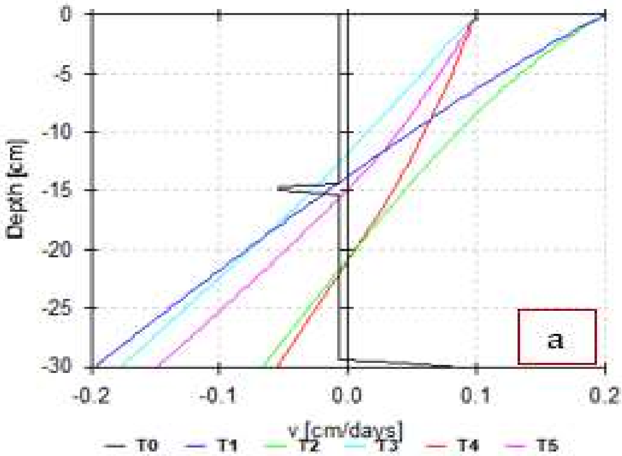


Fig. 6. HYDRUS simulated soil water storage variation with simulation period for (a) CFI at Kushtia, (b) AWD at Kushtia, (c) CFI at Sirajganj, (d) AWD at Sirajganj, (e) CFI at Rangpur, and (f) AWD at Rangpur.

loam soil or light-textured soil, 15 days irrigation interval would be a bit risky in terms of safe AWD practice. Thus, it would be better to apply irrigation before 12 days after the previous irrigation event. The soil water content distribution along the soil profile of Sirajganj (Fig. 5c and 5d) is remarkably different than other soil profiles. The SWRCs of the layered soils in Sirajganj, taken for simulation, were very much different (Fig. 1). Though both soil materials are similar in terms of soil textural analysis (Table 1), their bulk density values were greatly varied. Due to high bulk density at the second soil layer (15-30 cm), the soil water content reduced 0.35 cm^3/cm^3 to 0.25 cm^3/cm^3 (Fig. 5c and 5d) after 3 days (T1). As discussed earlier, soil moisture reached at field capacity at 15 cm depth after 14 days (T4), however, T5 is showing a slight increase in soil water content below 15 cm depth after 15 days. The soil might be tightly packed and was releasing water slowly compared to the first layer (0-15 cm). So, after 15 days, the first layer dried up, but second layer continued to emanate water. In case of Rangpur, the soil profile scenario was completely reversed compared to Sirajganj. In Rangpur, the second layer (15-30 cm) soil profile was sandy loam soil having less bulk density than that of the first layer soil (loam). The volumetric soil water content of the second layer, especially close to saturation, was higher compared to the first layer volumetric water content at near saturation (Fig. 1). Even after 15 days of irrigation in AWD practiced paddy field, the soil water content along the depth gradually varied with increasing trend, and the higher water content indicated better water holding capacity of second layer soil material, i.e., sandy loam soil.

Figure 6 presents the water storage variation, i.e., total water availability with respect to soil profile depth, along with the simulation period. After the irrigation event, soil water storage picked up to saturated level (13.8 cm, equal to saturated water content 0.46 cm^3/cm^3 of clay soil, Table 2) according to Figure 6a and 6b. In CFI paddy field, water storage variation followed the same trend throughout the simulation duration, i.e., the next irrigation was applied when water storage reached around 11.5 cm (0.38 cm^3/cm^3), practically when water was disappeared from soil surface and soil water content was far higher than field capacity even close to saturation (Fig. 5a). On the other hand, water storage fell from saturated condition to field capacity condition (13.8 cm to 10 cm) in AWD practiced paddy field after 15 days. In Sirajganj and Rangpur soils (loam soils), water storage was comparatively lower than the soils of Kushtia (clay soils). As shown in Figure 6c and 6e, soil water storage, after second and third irrigation events, had the added amount compared to water storage after the first irrigation amount. The reason is probably, the water amount received in soil profile after first irrigation was not sufficient to saturate the soil completely as the initial condition was at field capacity (around 0.22 cm^3/cm^3). According to Figure 6d and 6f, it is evident as Figure 5d and 5f shows that light textured soil in Sirajganj and Rangpur region should be irrigated after 10-12 days of an irrigation event in AWD practice.

A comparative understanding of the water flux variation between CFI practice and AWD practice can be obtained from Figure 7. The figure presents the water flux variation along the soil profile after simulation starting (T0), after 3 days (T1), after 6 days (T2), after 9 days (T3), after 12 days (T4) and after total simulation duration or, 15 days (T5) for the Kushtia fields. According to Figure 7a, in CFI practice field, the positive flux above 15 cm of soil and negative flux below 15 cm of soil indicated the same amount of evapotranspiration and infiltration after 3 days of an irrigation event (T1). After 6 days (T2), negative water flux below 15 cm of soil became smaller due to less infiltration; however, positive water flux above 15 cm of soil remained same as evapotranspiration was happening every day. After 9 days, the negative flux below 15 cm of soil again increased, because second irrigation was applied at Day 7,



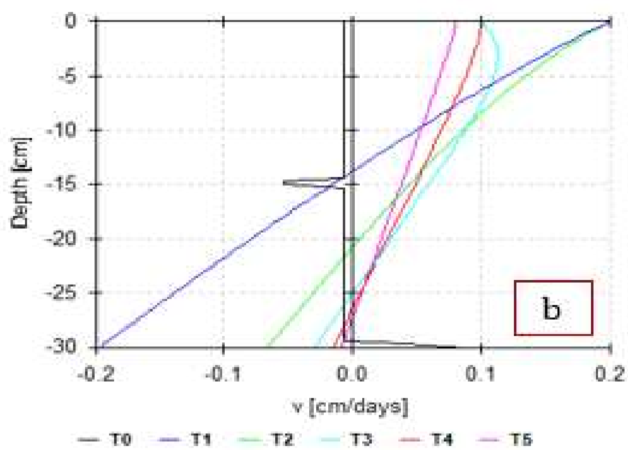


Fig. 7. Variation of water flux along the soil profile for (a) CFI at Kushtia and (b) AWD at Kushtia. The water flux (cm/days) denoted as before simulation (T0), 3 days (T1), 6 days (T2), 9 days (T3), 12 days (T4) and 15 days (T5).

which increased the infiltration through the soil profile. Water flux variation along the soil profile repeated as T4 after 12 days of the simulation period (after 5 days of second irrigation event). It also repeated as T3 after 15 days of the simulation period (after 2 days of third irrigation event). A representing water flux variation scenario after 3, 6, 9, 12 and 15 days, respectively, can be observed in AWD practiced paddy fields. Because the soil profile just received one initial irrigation event throughout the simulation period. After 3 days (T1), both the positive water flux above 15 cm of soil profile as well as negative water flux below 15 cm of soil profile were higher as both evapotranspiration and infiltration happened simultaneously. After six days (T2), negative flux below 15 cm of soil reduced as infiltration reduced, but positive flux above 15 cm of soil remained the same as evapotranspiration continued. Infiltration stopped after almost nine days of only irrigation event (T3), so negative flux below 15 cm of water disappeared. As evapotranspiration was being in progress, positive water flux was observed until the end of the simulation period of 15 days (T4 and T5).

CONCLUSION

The water movement through multilayered soil profile of the paddy field in CFI practice and in AWD practice was simulated using HYDRUS 1D physical process-based model. Measured soil physical and hydraulic properties of three BRRI regional station farms were used as model input and initial conditions. The relevant properties (i.e., soil particle size distribution and SWRC) of layered structure of soil profile governed the water movement through the soil profile. The simulated results indicates that irrigation interval could be shorter in light textured soil compared to the heavy textured soil depending on the water storage and water releasing capacity of the soil. The positive water flux like evapotranspiration primarily controls soil water content and soil matric potential balance and distribution when negative flux acts as a secondary force at deeper soil profile due to infiltration or percolation. This model simulation study would give a basic understanding of the water movement through different soil profile under different water management practices in Bangladesh, which might help to get an insight about the total crop-soil-water based physical and hydrological process environment in paddy field.

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