Deep Percolation Characteristics via Field Moisture Sensor Measurements in Rice Experimental Field, Phitsanulok, Thailand

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Abstract**—**Groundwater recharge is an alternative use for the area where lack of surface water or increasing use of groundwater. In the past studies, there were experiments recharging the water into underground by adding water through the pond or well, making weir under sand dune to help decreasing groundwater in canals or cheeks and studying infiltration rate through the soil surface depending on characteristic of soil. However, basic knowledge on deep percolation characteristics depending on soil type and rainfall pattern is still inadequate.

The objective of research is study deep percolation characteristics and relationship with rainfall and soil type that water percolates into 1-4 meters of soil depth (above shallow zone of groundwater level). The study area is in the Rice Experimental Field of Royal Irrigation Department, Phitsanulok, Thailand. This study designed sensor system and installed soil moisture sensor to measure soil moisture daily in the field. The period of soil moisture measurement is from 13 July 2017 till 30 October 2018 (two wet and two dry periods). The soil samples were collected at each depth from field for test and to determine the relative parameters of Richard's Equation included hydrological data and hydrogeological data for simulating deep percolation by HYDRUS-1D.

The percolation flux of sandy loam from top to bottom is 8.93 to 5.31mm/day in wet period. The average percolation rate of sandy clay at depth 5 meter is 3.33 mm/day in the first year lower to 3.25 mm/day in the second year and the percolation ratio in wet period is higher in dry period both years and the annual average of percolation to effective rainfall is 0.42-0.46. The percolation rate is also affected from rainfall pattern and intensity, i.e., more intensified rainfall, more water content and more percolation

The results from the model help to understand the deep percolation characteristics, the relationship of deep percolation rate with soil moisture content, effects of rainfall pattern and rainfall intensity. It also helped to estimate groundwater recharge and groundwater potentials in areas where the groundwater is used to mitigate the drought.

Keywords:* *deep percolation, infiltration, field moisture sensor measurements, HYDRUS-1D

I. INTRODUCTION

In recent several years, surface water trends to be deficit in some areas. The insufficient surface water resources lead to increase groundwater abstraction especially in dry season. In this last ten years, the tendency of groundwater level declined in the Lower Yom and Nan River due to groundwater use mainly for irrigation use. Groundwater recharge mechanism knowledge is essential to understand groundwater movement especially in the area where groundwater use is excessive.

Deep percolation from irrigation water plays a key role in irrigation demand and groundwater supply by replenishing shallow aquifers at the local and regional scales. Percolation is accounted by vertical flow during the experiment. This phenomenon has also been widely observed and documented by many others [1]. A simple approach for determining deep percolation below the root zone is the use of the water balance method [2]. There are three main factors impacted to groundwater system in Phitsanulok Province: land recharge from precipitation, leakage from river, and groundwater pumping [3], i.e., water passed through soil performs under infiltration and percolation. These two related but different processes describing the movement of moisture through soil. Percolation rate is often equated to recharge in groundwater modeling describe water movement below the root zone. However, percolation measurement is sometime difficult and expensive in the field test. Thus, percolation used is to estimate indirectly from unsaturated zone water balance, Darcy flux, and water table fluctuation [4]. Deep percolation must be monitored below the root zone where it would be constant [5]. In the study, the soil moisture sensor module is used to detect the moisture of the soil or judge if there is water around the sensor. If more water is presented in the soil, the sensor would output resistance of soil which could covert to soil moisture. The motivation of soil moisture sensor is adapted from low-cost soil moisture profile probe [6]. Percolation identified water content in the soil flows below root zone efficiently [7]. The advantage of percolation is to induce recharge to groundwater and dilute chemicals in the soil. Hillel [8] concluded that percolation rate relied on both soil property and water content. Soil properties, affected to percolation, are porosity, void distribution, and void shape while flow properties, affected to percolation, are density and viscosity. The objectives of the study are to develop field sensor system to monitor soil moisture under irrigation field and to understand deep percolation process in the unsaturated zone for developing groundwater modeling.

These investigations aim to understand deep percolation flow from rainfall utilizing soil moisture approach for developing groundwater modeling. Henceforth, the deeper percolation procedure and results will be useful for further determining groundwater yields and groundwater recharge in the consecutive drought years.

II. STUDY AREA

The experimental field site was located in the Rice Water Use Experimental Station 2 of Royal Irrigation Department at Amphoe Phrom Phiram (17º2′0″N, 100˚12′7″E) in the north-western part of Phitsanulok Province, Upper Central Plain, Thailand (see Fig. 1). Due to previous study [9, 10] ,the aquifer profile consists of poorly graded sand and fine to medium sand is 85% , silt is 10% and clay is 5%. It is noted that from the past study, the saturation of water content, field capacity of the soil type and the wilting point of the sandy loam is same soil type soil type in the study area 0.420 %, 0.255 % and 0.175 % [11]

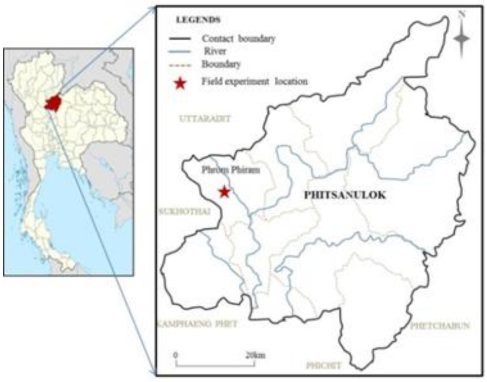

Fig. 1. Experimental site location

III. PROCEDURES AND THEORIES USED

The procedures of study was conducted in steps as follows, First, the field measurement system was designed and installed in Rice Experimental Field, Phitsanulok, Thailand. Daily data of soil moisture and related hydrological data were collected. Second, the daily deep percolation was simulated using the Hydrus 1D model. The water retention parameters were calibrated and verified by field experimental data from 13 July 2017 to October 30, 2018 in the study area. Thirdly, relationship of effective rainfall, soil moisture are analyzed to detect the deep percolation characteristics from the simulated results. Finally, the assessment water balance provides a better understanding of the deep percolation flow of two rainy and two dry periods.

A. Field measurements

At field sites, the Arduino sensors were installed at every meter in 5 meters depth as shown in Fig 2. The soil moisture sensor monitored every 1-meter depth daily. The soil moisture of each soil type at each depth (shown in Table II) was calibrated with moisture measurement in the lab. Then, the measurements in the field site are converted to soil moisture. The circuit includes Arduino board, soil moisture module, and soil moisture sensor (copper plate), automatic data transmit as shown in Fig. 3.

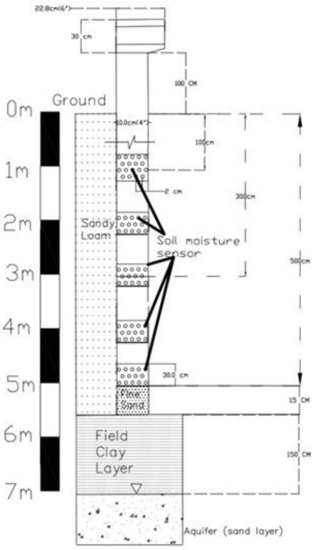

Fig. 2. Field sensor installation

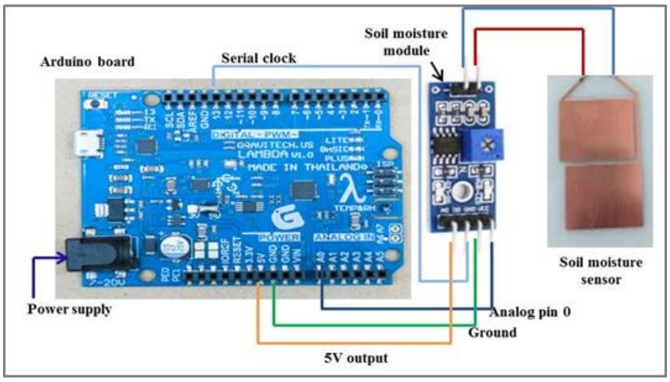

Fig. 3. The schematics of digital measurement of soil moisture by developed sensor

B. Percolation simulation theory

The governing flow equation for the uniform Darcy flow of water in a porous medium is adopted by the following modified form of the Richards' equation: [12]

$$\frac{\delta\theta}{\delta t} = \frac{\delta}{\delta x_i}\left[K\left(K_{ij}^{A}\frac{\delta h}{\delta x_j} + K_{iz}^{A}\right)\right] - S \qquad (1)$$

θ is the volumetric water content, (L^3L^{-3})

K is the hydraulic conductivity (LT^{-1}),

h is the pressures head (L)

S is a sink term [T^{-1}]

x_i (i-1,2) are the spatial coordinates [L],

t is the time (T) and

z is the vertical ordinate (L)

K^A_{ij} are components of a dimensionless anisotropy tensor K^A

K is the unsaturated hydraulic conductivity function $[LT^{-1}]$ given by

$$K(h) = K_s S_e^{1/2}\left[1-\left(1-S_e^{1/m}\right)^m\right]^2 \qquad (2)$$

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{[1-|\alpha h|^n]^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \qquad (3)$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad (4)$$

$$m = 1 - 1/n,\ n > 1 \qquad (5)$$

S_e is the effective water content

θ_r denote the residual water content

θ_s denote the saturated water content

K_s is the saturated hydraulic conductivity

α is the inverse of the air-entry value

n is a pore-size distribution index

The percolation simulation applied rainfall and evaporation of study area from 13 July 2017- 30 October 2018. The upper boundary condition set as atmosphere condition. The bottom boundary condition set as free drain condition. The initial retention parameters (θ_r, θ_s, α , n, K_s) are referred from Rosetta program [13]. The calibrated retention parameters were validated by sensor record data.

IV. RESULTS AND DISCUSSIONS

A. *Field measurement*

In this experiment, the percolation rates at each depth were compared with effective rainfall. The effective rainfall defines as rainfall minus evaporation. Fig. 4 shows sample of field observed water content and accumulated effective rainfall (rainfall-evaporation) during July 13, 2017 - October 30, 2018 at each depth with soils of sandy loam and sandy clay. The observed water content corresponded with effective rainfall. The soil moistures at 1 meter depth are sensitive with rainfall and evaporation events. The lower soil depth has less sensitive with rainfall events. The field monitor period can be split into wet1, dry 1, wet 2 and dry 2 due to the change of rainfall and water content pattern.

Fig. 5 demonstrates relationship of flux in field test and water contents in each depth level during wetting and drying periods in 2017-18. The flux and soil moisture show closed relationship, especially in each periods. The fluxes in wetting period are higher than in drying period. The percolation flux of soil moisture in sandy loam is higher (at the depth of 1 to 4 meter). Sandy clay shows the lowest difference in soil moisture (at 5 meters depth). The soil moisture fluctuates more in the first meter depth due to rainfall input and evaporation output.

The measurement data show that developed soil moisture sensors give reliable values under natural condition. Then, the percolation and water balance analyses can apply the field soil moisture data monitored by installed sensors.

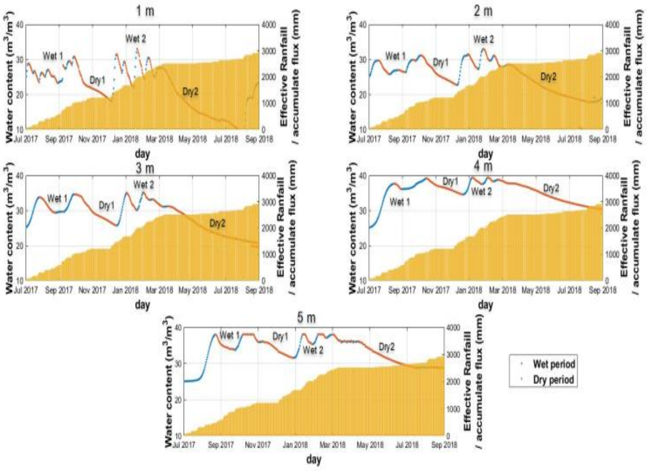

Fig. 4. Observed water content and effective rainfall during July 2017-October 2018

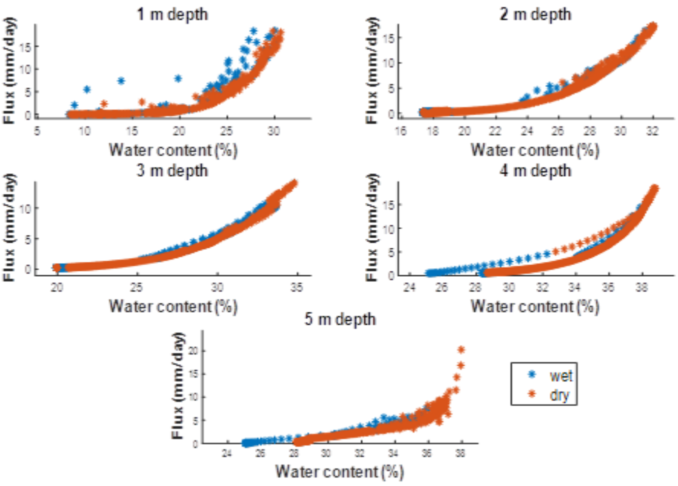

Fig. 5. Relationship of fluxs and water contents in the field test

B. *Calibration and verification of percolation simulation*

The Hydrus 1D model was applied to simulate water content in the soil and calibrated/verified with field water content as shown in Fig. 6. Retention parameter calibrations relied on performance statistics of observed soil moisture. In calibration step, the calculated soil moistures of three soil type match well with observed data. The maximum error (%) is 4.23 to 2.86. The minimum error (%) is 0. The mean error (%) is 0.30 to 1.09. The RMSE is 0.56 to 1.39. The Nash coefficient is 0.62 to 0.97. In verification step, the calculated soil moistures of two soil type are similar with observed data. The maximum error (%) is 5.72 to 2.00. The minimum error (%) is 0. The mean error (%) is 0.3 to 1.57. The RMSE is 0.84 to 1.57. The Nash coefficient is 0.62 to 0.85 (as shown in Table I).

TABLE II shows the soil retention parameter values after calibration. The soil retention parameters are related with soil type. The α, n, K_s parameters decrease in deeper depths. The sandy loam has highest hydraulic conductivity. The lowest hydraulic conductivity is sandy clay.

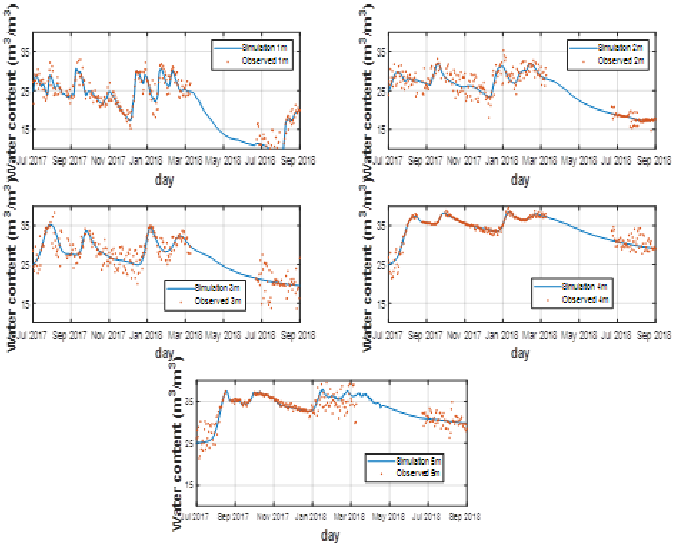

Fig. 6. Calibration and Verification results

TABLE I. ERRORS FROM CALIBRATION AND VERIFICATION

Statistical errors	Calibration					Verification				
	Soil depth					Soil depth				
	1 m	2 m	3 m	4 m	5 m	1m	2 m	3 m	4 m	5 m
Max	4.23	3.51	3.99	2.86	3.83	5.72	2.00	5.05	2.50	3.54
Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00
Mean	1.06	1.06	1.09	0.30	0.77	1.01	0.30	1.57	0.56	0.73
RMSE	1.38	1.30	1.39	0.56	1.17	1.57	0.54	2.12	0.84	1.02
NASH	0.83	0.72	0.80	0.97	0.90	0.83	0.77	0.79	0.85	0.62

TABLE II. SOIL RETENTION PARAMETERS AFTER CALIBRATION

Depth (m)	Soil type	θ_r	θ_s	α	η	K_s
1	Sandy Loam	0.065	0.41	0.0075	1.89	170
2	Sandy Loam	0.065	0.41	0.0065	1.75	150
3	Sandy Loam	0.065	0.41	0.0045	1.65	90
4	Sandy Loam	0.065	0.41	0.0027	1.47	30
5	Sandy Clay	0.100	0.38	0.0021	1.35	25

C. Water balance analysis

TABLE III shows total fluxes at four periods from July 13, 2017- July 1, 2018. The fluxes in deeper depth are lower than in top soil. The fluxes in lower depth also give a lag time compared with flux in upper depth (Fig. 7 as a sample). The percolation of sandy loam is the highest. The sandy clay in bottom has the lowest amount percolation. The gap between fluxes of two soil depth can be explained by the fluctuation water content in its depth.

The percolation fluxes were compared with effective rainfall to find the percolation rate ratio in the study area. The percolation rate ratios decrease from top to bottom depth. The highest ratio is sandy loam. The mean percolation flux of sandy loam from top to bottom is 8.93 to 5.31 mm/day in wet period.

TABLE III. PERCOLATION RATES AT EACH SOIL LEVEL AND PERIOD

Soil depth	Average percolation flux rate (mm /day)					
	Wet 1	Dry 1	Wet 2	Dry 2	Mean	
	July 13 – Oct 31, 2017 (111days)	Nov 1- Dec 16, 2017 (45 days)	Dec 17, 2017 – Mar 31, 2018 (104 days)	1 April – 1 July 2018 (91 days)	Wet	Dry
1m	8.31	1.49	9.59	0.08	8.93	0.55
2 m	6.33	2.68	9.6	0.71	7.91	1.36
3m	6.14	1.72	6.15	0.83	6.14	1.12
4m	5.4	1.67	5.21	0.95	5.31	1.19
5m	4.07	1.37	4.67	1.02	4.36	1.14

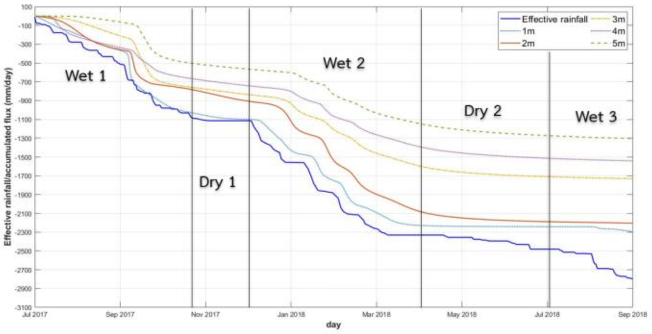

Fig. 7. Simulated accumulated flux at field site of sandy loam and sandy clay

From Table IV, the rainfall in the first period is 1072 mm period in 111 days while the rainfall in the third period is 1086 mm in 104 days. The rainfall intensity in the third period is more than in the first period. This induced more percolation rate in the third period.The average annual percolation of sandy clay at depth 5 meter is 3.33 mm/day in the first year and becomes lower to 3.25 mm/day in the second year.The percolation ratio in wet period is lowwer in dry period both years and the annual average of percolation ration (percolation to effective rainfall) is 0.41-0.43 which is closed to the results in Russia, Colorado State-USA, Vietnam [14-16]. It is noted that the percolation rate in the first year is less than the rate in the second year in annual average of percolation due to different intensity of rainfall in the two years. The comparison between infiltration rate and deep percolation rate in same soil type shows that the infiltration rate is 48 mm/day [17] where the deep percolation is 8.93 mm/day at depth 1 meter during wet period which is 5 times higher than of the deep percolation.

Fig. 8 shows annual water balance and water content change at each soil depth from the simulations in the year 2017-2018. It is noticed that rainfall pattern affected the percolation rate, i.e., more intensified rainfall, more water content in each soil layer and more percolation.

TABLE IV. AVERAGE PERCOLATION RATE AND PERCOLATION RATIO

Percolation data	2017 (156 days)		2018 (195 days)	
	Wet 1	**Dry 1**	**Wet 2**	**Dry 2**
Average percolation rate (at depth 5 m) (mm/day)	3.33		3.25	
Total effective rainfall (mm)	1072	139	1086	186
Total deep percolation flux (mm)	452	68	601	93
Percolation ratio (period)	0.42	0.44	0.45	0.5
Percolation ratio (annual)	0.42		0.46	

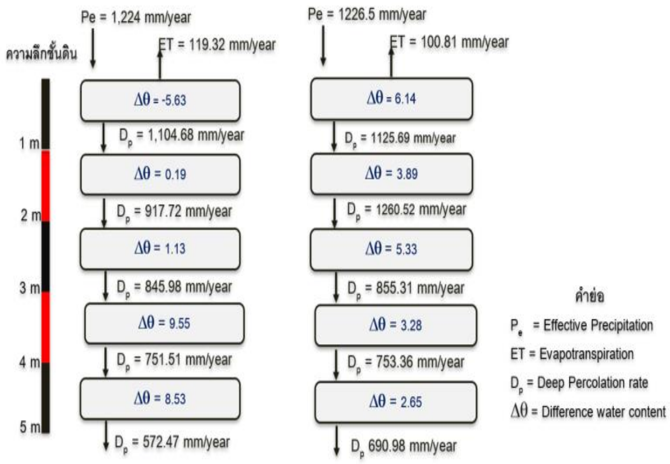

Fig. 8. Water balance and water content change in 2017-2018

V. CONCLUSIONS

The developed soil moisture sensor system gave reliable values of soil moisture under natural condition. The field monitored data with the application of HYDRUS 1-d model can estimate percolation rate and analyze water balance in each soil depth in more details.

The percolation fluxes were compared with effective rainfall to find the percolation rate ratio in study area. The percolation rate ratios decrease from top to bottom depth. The highest ratio is sandy loam. The second ratio is sandy clay. The percolation flux of sandy loam from top to bottom is 8.93 to 5.31mm/day in wet period. The average percolation rate of sandy clay at depth 5 meter is 3.33 mm/day in the first year lower to 3.25 mm/day in the second year and the percolation ratio in wet period is higher in dry period both years and the annual average of percolation to effective rainfall is 0.42-0.46. The percolation rate is also affected from rainfall pattern and intensity, i.e., more intensified rainfall, more water content and more percolation.

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