

Examination of land recharges using soil moisture approach: Case study in Thailand

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Abstract: Knowing recharge rate is important for determining sustainable yields a groundwater system especially in the dry year. Traditionally, due to the difficulty of measurement, groundwater recharge can be estimated based on lysimeter, unsaturated zone water balance, Darcy flux, water table fluctuation, tracer, and parameter optimization from groundwater modeling. Therefore, land recharge rate sometimes cannot be evaluated and lead incorrectly equated with the sustainable yield of an aquifer.

This paper examined the land recharge estimation using soil moisture approach to be applied to develop groundwater modeling. First, the daily land recharge is simulated using Hydrologic Evaluation of Landfill Performance (HELP) model with field experimental data in the study area of Phitsanulok, Thailand. Second, the proportion between rainfall and percolation in upper aquifer is applied to detect the land recharges in Saigon River basin, South East of Vietnam. Finally, the groundwater balance was assessed by employing new land recharge estimation into groundwater modeling during 1995-2015. The performance of land recharge estimation using soil moisture approach is evaluated due to statistic parameters and the regression of peizometric head and found that the soil moisture approach gave better estimate land recharge than the previous trial-error method's.

This examination provided a procedure to estimate better land recharge from rainfall using soil moisture approach for developing groundwater modeling so that the groundwater yields can be more accurate in the water resources and disaster management as in the consecutive drought years.

Keywords: soil moisture approach, field measurement, land recharges, groundwater modeling

1. Introduction

Under the pressure of social economic growth in the Southeast Asia countries, the water resources is

facing a critical shortage during current drought years, thus, groundwater becomes an essential resource to meet increasing water demand. However, the

excessive extraction of groundwater causes dramatically damage to groundwater such as pollution, land subsidence, salt intrusion, and deeper drawdown. Hence, in order to develop social sustainability, groundwater resources need to be assessed and planned to meet increasing abstraction. There are three main factors impact to groundwater system: land recharge from rainfall, leakage from river, groundwater pumping (Koontanakulvong and Siriputtichaikul 2003). Although, land recharge is one of important factor, investigation of land recharge estimate still remains a challenging task.

Water pass through soil perform under infiltration and percolation. Infiltration usually refers to water movement from the surface into the subsurface. The infiltration rate can be measured from field tests such as: single ring, double rings, the well permeameter (Wu and Zhang 1994, Sangbun, Sangchan and Mekpruksawong 2014). Percolation rate, which 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. So, the percolation used to estimate indirectly from lysimeter, unsaturated zone water balance, Darcy flux, and water table fluctuation, tracer. (Scanlon, Healy and Cook 2002, King 2015). Besides, the percolation rate in general is much lower than the initial surface infiltration rate. Thus, land recharge can be estimated via “trial- error method” with infiltration rate as initial value from soil type or climate conditions (Koontanakulvong and Siripubttichaikul 2002, Koontanakulvong and Suthidhummajit 2015). Hence, land recharge rate sometimes cannot be evaluated and lead incorrectly equated with the sustainable yield of an aquifer

The paper examined the land recharge from rainfall using soil moisture approach for developing groundwater modeling. First, the daily percolation is simulated using Hydrologic Evaluation of Landfill

Performance (HELP) model in Phitsanulok, Thailand. The results are verified with observed soil moisture measurement in the field with instruments developed in this study. Second, the proportion between rainfall and percolation in upper aquifer is applied to detect the land recharges in Saigon River basin, South East of Vietnam. Finally, the groundwater balance is assessed by employing new land recharge estimation into groundwater modeling during 1995-2015. The performance of land recharge estimation using soil moisture approach is evaluated due to statistic parameters and the regression of peizometric head.

This examination provides a procedure to estimate better land recharges from rainfall for developing groundwater modeling so that the groundwater yields are more accurate in the water resources and disaster management like in the consecutive drought years.

2. Methodology

In this study, the percolation is estimated using soil moisture approach. This simulation is verified by observed soil moisture in the field. During this part, the percolation is analyzed to find the ratio between land recharge and effective rainfall. Then, the results are applied in Saigon river basin model to examine the feasibility of ratio with similar soil type assumption. The performance of land recharge from new ratio is justified due to statistic parameters and the regression of peizometric head. The approach of this study is summarized as Figure 1.

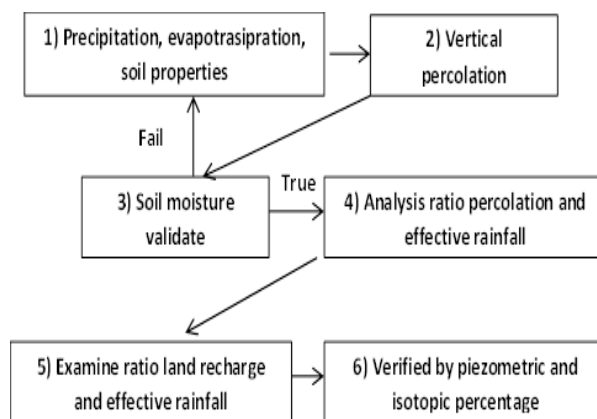


Figure 1: Approach of study

2.1 Field measurement

The soil moisture is converted from electrical resistance which was measured by modifying soil moisture sensor. The circuit includes Arduino board, soil moisture module, and soil moisture sensor (copper plate). The circuit of resistance of soil moisture sensor is shown in Figure 2.

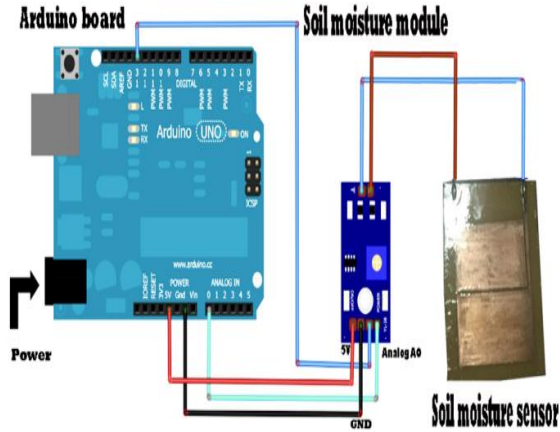


Figure 2: The schematics of digital measurement soil moisture

The motivation of soil moisture sensor in this paper is adapted from low-cost soil moisture profile probe (Kojima et al. 2016). The soil moisture sensor includes 2 parts: sensing parts and reading board. First, the copper sensing part consisted of two wide bars, with a width and length of 25 and 55 mm, respectively (Figure 3). There was a 1 mm gap between the two bars. These two bars work as a resistor. The wiring part extended to the end of the copper plate and was connected to a soil moisture module. Then, the soil moisture sensing parts and wiring are attached to the aluminum bar (Figure 4). The circuit includes five soil moisture sensing parts to measure the electrical resistance of soil at 1m, 2m, 3m, 4m, and 5m. Second, to measure the soil moisture, Arduino board, which is an open-source electronics platform, is used during field measurement. The reader board consists of soil moisture module (Figure 5) and Lambda board (Figure 6). The soil moisture module measures the soil resistance, while the Lambda board records the data hourly. The power is supplied from USB 5v 1A

of power bank. The data are recorded on SD card and downloaded weekly.

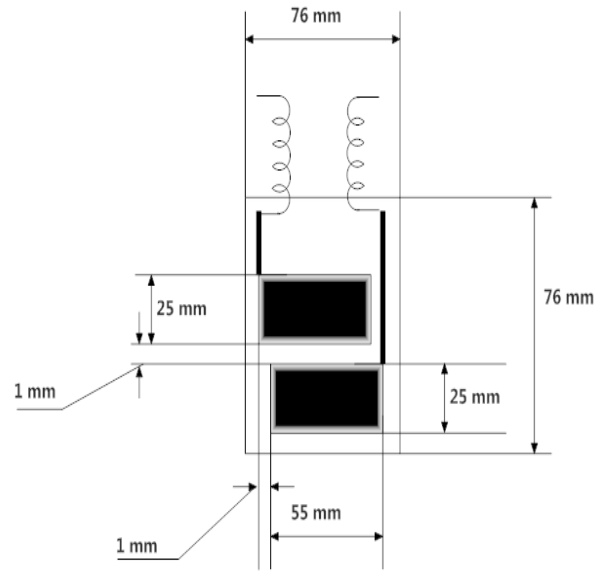


Figure 3: Schematic of copper circuit sensing part



Figure 4: Modified soil moisture sensors.

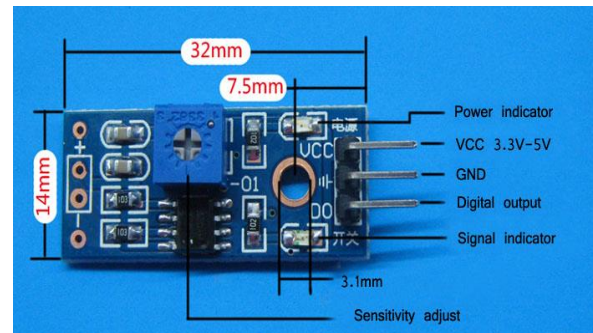


Figure 5: Soil moisture module

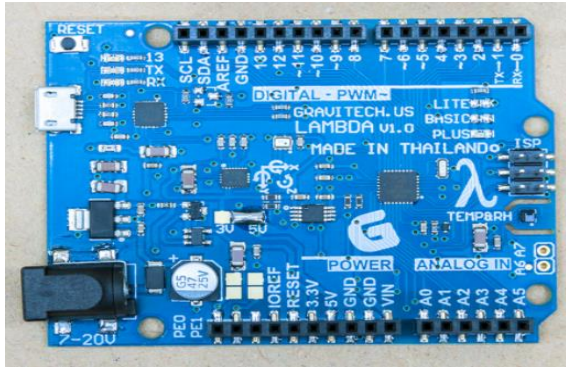


Figure 6: Lambda board

To set up the soil moisture sensor in the field, there required 2 boreholes. One bore hole is to monitor the groundwater level of shallow aquifer. Another borehole, drilled 5 m depth with 4 inches diameter is to put the sensor equipment. PVC pipe, which opened screen at sensing sensor depth (Figure 7), is inserted into the second borehole. Then, the soil moisture bar is injected into the borehole. Finally, fill up the borehole by soil at respective depth (Figure 8).



Figure 7: PVC pipe projected borehole



Figure 8: Fill up soil in to borehole

2.2 Sensor Calibration

The measured electrical resistance of the soil at each depth needs to be converted to volumetric water content (VWC). In this study, there is an assumption that the rainfall and soil type are homogeneous. Hence, the percolation is only accounted by vertical flow during the experiment. Then, calibration curve was done via the gravimetric method. Based on Figure 9, we concluded that a linear function $y = -0.0644x + 65.518$, where y : volumetric water content (VWC) m^3/m^3 ; x : electrical resistance of soil (Ω).

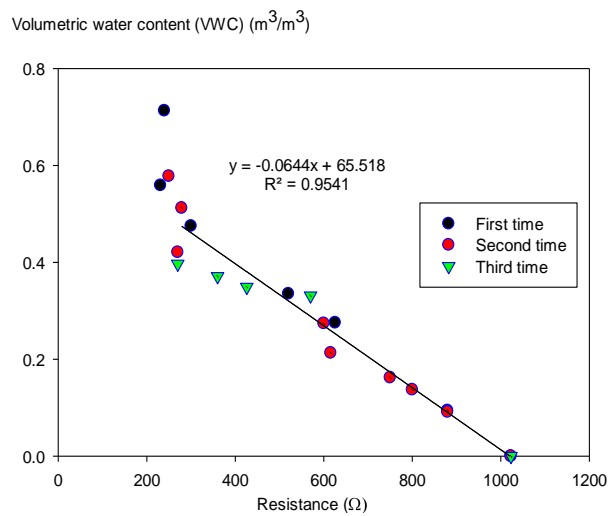


Figure 9: Relationship between volumetric water content (VWC) and electrical resistance obtained from the calibration experiments.

2.3 Percolation simulation theory

The percolation is simulated by Hydrologic Evaluation Of Landfill Performance (HELP). The percolation rate at which water moves through a porous medium as a saturated flow governed by gravity forces is given by Darcy's law (Manual of HELP):

$$q = K * i = K \frac{dh}{dt} \quad (1)$$

where

q = rate of flow (discharge per unit time per unit area normal to the direction of flow), meters/day

K = hydraulic conductivity, meters/day

i = hydraulic head gradient, dimensionless

h = piezometric head (elevation plus pressure head), meters

l = length in the direction of flow, meters

This equation is also applicable to unsaturated conditions provided that the hydraulic conductivity is considered a function of soil moisture and that the piezometric head includes suction head.

For vertical percolation layers with constant pressure, the piezometric head gradient in the direction of flow is unity, and the rate of flow equals the hydraulic conductivity:

$$i = \frac{dh}{dl} = 1 \quad (2)$$

$$q=K \quad (3)$$

For low permeability vertical percolation layers and soil liners, the hydraulic head gradient is

$$i = \frac{dh}{dl} = \frac{h_w+1}{l} \quad (4)$$

where

h_w = pressure head on top of layer, meters

The unsaturated hydraulic conductivity is estimated by Campbell's equation. Multiplying the water content terms (θ , θ_r and ϕ) in Equation below by the segment thickness yields an equivalent equation with the water content terms expressed in terms of length:

$$K = K_s \left(\frac{SM-RS}{UL-RS} \right)^{3+\frac{2}{\lambda}} \quad (5)$$

Here, SM, RS, and UL represent the soil water content (θ), residual soil water content (θ_r), and saturated soil water content (ϕ) of the segment, each expressed as a depth of water in meters. The HELP program uses Equation 5 to compute unsaturated hydraulic conductivity

Based on Equations (3) and (5), the drainage from segment j during the time step i , $DR_{i(j)}$, is as follows:

$$DR_i(j+1) = K_s(j) * i * DT \left[\frac{SM_i(j)-RS(j)}{UL(j)-RS(j)} \right]^{3+\frac{2}{\lambda}} \quad (6)$$

$K_{S(j)}$ = saturated hydraulic conductivity of segment

j , meters/day

DT = the time step size, days

$$= 1 / N$$

Mid-point routing is based on the following equation of continuity for a segment:

Δ Storage = Drainage in - Drainage out - Evaporation + leachate Recirculation + Subsurface flow

$$\Delta SM_i(j) = 0.5\{[DR_i(j)+DR_{i-1}(j)] - [DR_i(j+1)+DR_{i-1}(j+1)] - [ET_i(j) + ET_{i-1}(j)] + [RC_i(j) - RC_{i-1}(j)] + [SI_i(j) + SI_{i-1}(j)]\} \quad (7)$$

$$\Delta SM_i(j) = SM_i(j) - SM_{i-1}(j) \quad (8)$$

where

$\Delta SM_{(j)}$ = change in storage in segment j , meters

$DR_{i(j)}$ = drainage into segment j from above during time step i , meters

$SM_i(j)$ = soil water storage of segment j at the mid-point of time step i , meters

$ET_i(j)$ = evapotranspiration from segment j during time step i , meters

$RC_i(j)$ = lateral drainage recirculated into segment j during time step i , meters

$SI_i(j)$ = subsurface inflow into segment j during time step i , meters

Hence, the $DR_i(j+1)$ can be solve as equation below

$$DR_i(j+1) = -2[UL(j) - RS(j) \left[\frac{DR_i(j+1)}{K_s(j) i DT} \right]^{\frac{\lambda_j}{3\lambda_j+2}} + 2[SM_{i-1}(j) - RS(j)] + DR_{i-1}(j) + DR_i(j) - DR_{i-1}(j+1) - ET_{i-1}(j) - ET_i(j) + RC_{i-1}(j) + RC_i(j) + SI_i(j) + SI_{i-1}(j)] \quad (9)$$

The HELP program solves this equation for $DR_{i(j+1)}$ iteratively using $DR_{i-I(j+1)}$ as its initial guess in the right hand side of Equation (9). If the computed value of $DR_{i(j+1)}$ is within 0.3 percent of the guess or 0.1 percent of the storage capacity of segment j , the computed value is accepted; else, a new guess is made and the process is repeated until

the convergence criteria are satisfied. After $DR_{i(j+1)}$ is

computed, the program computes $SM_{i(j)}$ using Equation 8. Constraints are placed on the solution of $DR_{i(j+1)}$ and $SM_{i(j)}$ so as to maintain these parameters within their physical ranges; 0 to $K_s DT$ for $DR_{i(j+1)}$, and $WP_{(j)}$ to $UL_{(j)}$ for $SM_{i(j)}$. The $SM_{i(j)}$ will be validated with monitor soil moisture in field.

2.4 Groundwater modeling

Groundwater-flow models are used to simulate aquifer response, in terms of head (ground water level) and fluxes into and out of an aquifer, to natural and human-induced stresses; the governing equation represents in three dimensional movement of ground water is (User guide of GMS)

$$\frac{\delta}{\delta x} \left[K_{xx} \frac{\delta h}{\delta x} \right] + \frac{\delta}{\delta y} \left[K_{yy} \frac{\delta h}{\delta y} \right] + \frac{\delta}{\delta z} \left[K_{zz} \frac{\delta h}{\delta z} \right] + W = S_s \frac{\delta h}{\delta t} \quad (10)$$

Where

K_{xx} , K_{yy} and K_{zz} are the values of hydraulic conductivity along the x, y, and z coordinate axes and h is the potentiometric head (hydraulic head)

W is a volumetric flux per unit volume representing sources and/or sinks of water, where negative values are water extractions, and positive values are injections/recharge. It is a function of space and time (i.e. $W = W(x, y, z, t)$).

S_s is the specific storage of the porous material and may be function of space.

t is time.

3. Study area

3.1 Field measurement in Thailand

The field examination area is Amphoe Phrom Phiram, Phitsanulok Province, Upper Central Plain Thailand (Figure 10). The average elevation is approximately 40-60 meters above mean sea level. The upper aquifer in this area is defined as a semi unconfined layer with 40m thickness. The deposit of aquitard is brown sand 10%, and black clay 90%. Due to the soil profiles, the aquifer profile consists of

poorly graded sand, fine to medium sand 96% and 4% clay. The soil type in this is soil type T1 ($K < 0.125$ cm/hr) (Koontanakulvong and Suthidhummajit 2015). The field porosity, capacity of the soil and the wilting point are 0.48 vol/vol, 0.3 vol/vol and 0.175 vol/vol, respectively. (Kantasinee Chaengpui et al. 2015)

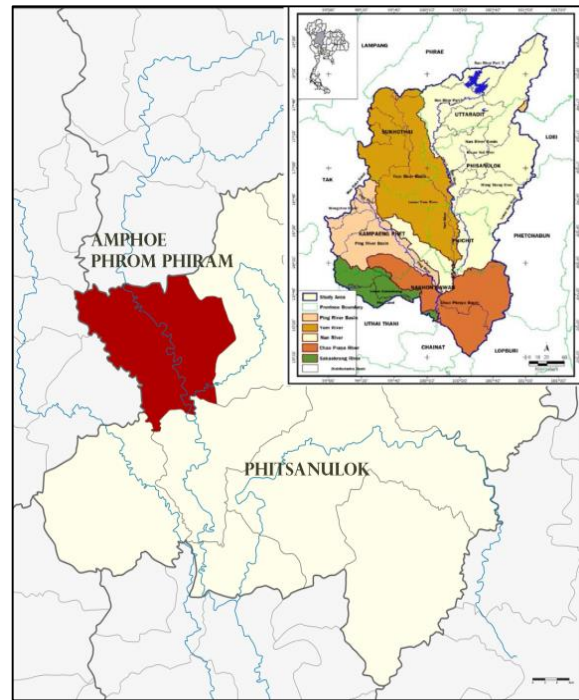


Figure 10: Amphoe Phrom Phiram, Phitsanulok province, Upper Central Plain Thailand.

3.2 GW model application in Vietnam

Study area stretches from latitude 10.320 E to 11.201 E and from longitude 106.215 N to 107.024 N with an area of 6,640 km² (Figure 10). It covers all area of Ho Chi Minh City and some districts of Dong Nai, Binh Phuoc, Binh Duong, Long An and Tay Ninh Province. The area presents feature tropical climate. Mean annual rainfall is at 1,612 mm and mean annual temperature is at 27°C. Terraced plain mainly characterize the topography of the area with elevation vary from 0 MSL to 70 MSL. In the area, there are 3 major river as Sai Gon River, Vam Co Dong River, and Dong Nai River. Regarding Hydrogeology, there are three aquifers interacted with river system, and distributing from top to bottom respectively as follows: upper-Pleistocene (qp_3), Upper Middle

Pleistocene (qp₂₋₃), Lower Pleistocene (qp₁), and one aquifers disconnect with river system: Holocene (qh). Piezometer head of upper-Pleistocene (qp₃), Upper Middle Pleistocene (qp₂₋₃), Lower Pleistocene (qp₁) are oscillated follow the fluctuation of rainfall and river stage. Under increasing abstraction rapidly, groundwater levels in all of aquifers are declining with annual rate 0.04m in upper Pleistocene aquifer and 0.9m in lower Pleistocene aquifer. In 2012, the abstraction is estimated at 600,000 m³/day and occupies 34% of water supply. The estimated land recharge account 7% - 18% water storage in this area (Khai and Koontanakulvong (2015), Long and Koontanakulvong (2017)).

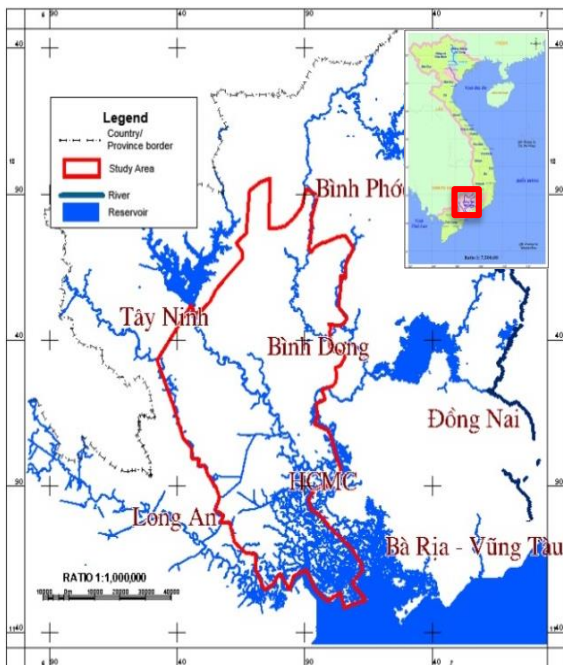


Figure 11: Saigon River Basin

4. Results and discussion

4.1 Ratio of percolation and effective rainfall

Figure 12 shows simulated soil moisture and observed soil moisture. Although there are some obvious differences between the simulated and the observed results, the figure shows that the model gives satisfactory results. The mean error, RMSE, and R² are -3.08, 6.18, and 0.586, respectively. Moreover, the soil moisture was generally similar with rainfall

patterns. Hence, the simulated percolation from HELP could apply to analyse the land recharge in this case study.

Figure 13 shows the simulated percolation and effective rainfall. The percolation is in the range 0 - 0.035 mm/day, with the mean 0.0126 mm/day. Although, the lag time between effective rainfall and percolation is 2 days, the pattern of percolation is similar to effective rainfall. Besides, the recharge function cannot perform clearly due to the limited data at this stage. In this study, the ratio between percolation and effective rainfall was attempt to identified 0.0019. The mean percolation and ratio between percolation and effective rainfall are similar with coefficient of recharge which was estimated by trial - error method (Koontanakulvong and Suthidhummajit 2015). Therefore, the ratio between percolation and effective rainfall have possibility to apply for very low permeability soil type ($k < 0.125$ cm/hr). The ratio applied for zone with very low permeability soil type in Sai Gon River Basin to examine the feasibility of this ratio.

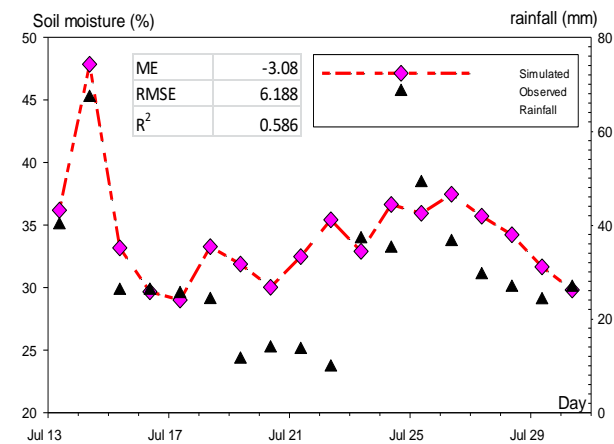


Figure 12: Soil moisture simulated vs observed

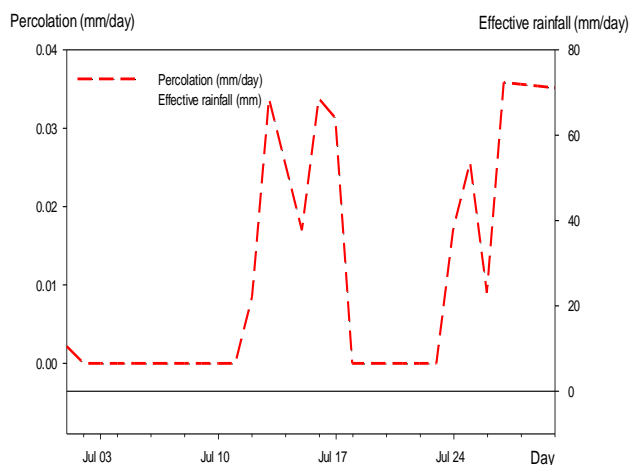


Figure 13: Simulated percolation and effective rainfall

4.2 Examine ratio of percolation and effective rainfall

In order to examine the ratio of percolation and effective rainfall, the ratio was applied to estimate land recharge for groundwater modeling in Saigon River Basin. Then, this recharge compares with recharge rate estimate via “trial – error” from (Long and Koontanakulvong (2017)) (Figure 14). Figure 11 indicated that the new ratio gave recharge more than the recharge estimated from trial and error method.

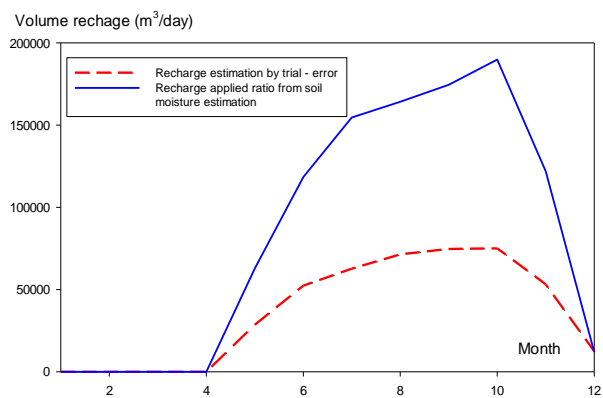


Figure 14: Average monthly recharge from 1995-2015

Figure 15 showed the regression of computing piezometric and observation in 2 cases: land recharge estimated from soil moisture approach and land recharge estimated from the trial – error method. The

result of land recharge estimated from soil moisture approach with $R^2 = 0.56$ are better than the one using land recharge from trial- error method with $R^2=0.25$.

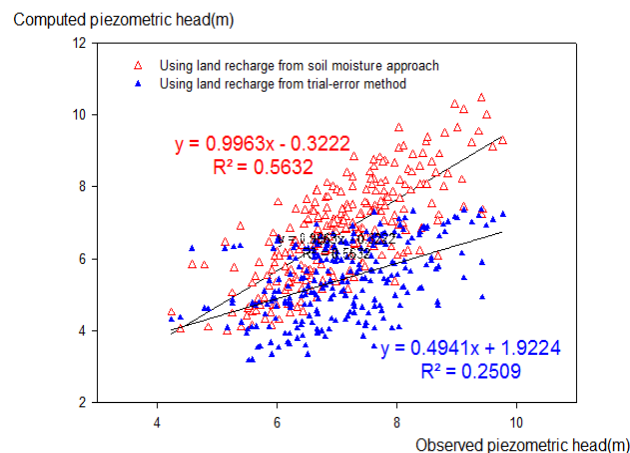


Figure 15: The regression of computing piezometric head and observation in 2 cases: land recharge estimated from soil moisture approach and land recharge estimated from the trial – error method.

Moreover, the results of two models show that the model used recharge estimated from ratio between percolation and effective rainfall was better with all indicators such as average residual error (ME) and mean absolute error (MAE) as well as RMSE were smaller than the model used recharge estimate from trial - error (Table 1). Therefore, the ratio between percolation and effective rainfall is applicable and produced better land recharge estimate in this study.

Table 1: Comparison error of two estimated land recharge

	Estimated land recharge from the trial – error method.			Estimated land recharge estimated from soil moisture		
	ME	MAE	RMSE	ME	MAE	RMSE
Aquifer 1	0.77	0.85	0.91	0.51	0.81	1.2
Aquifer 2	0.31	1.43	1.61	-0.232	0.8	1.2
Aquifer 3	-0.31	0.89	1.36	0.41	0.64	1.17
Aquifer 4	0.09	2.83	4.1	0.34	0.74	1.01

5. Conclusions

In this study, the better performance of piezometric heads using the ratio between percolation

and effective rainfall estimated from soil moisture from the field measurement, proved to be feasible in practical application.

Based on the results from the field experiments, the modified sensor could capture the dynamic change in soil moisture at 5m depth. Therefore, this sensor is feasible to develop better land recharges estimation.

The soil moisture monitoring procedure can be applied to others soil type to estimate the land recharge from rainfall.

Though the relationship between land recharge and effective rainfall has not revealed thoroughly due to limited field data. Further studies should be conducted to have more and longer data series to understand better recharge process and to develop better recharge function via soil moisture approach.

This examination provided a procedure to estimate better land recharge from rainfall using soil moisture approach for developing groundwater modeling so that the groundwater yields can be more accurate in the water resources and disaster management like in the consecutive drought years.

Acknowledgement

This paper could not be accomplished without the support of Ph.D sandwich program scholarship from AUN – Seednet and the Water Resources Department, Faculty of Engineering, Chulalongkorn University. The authors also thank to the staff at Division for Water Resources Planning and Investigation for the South of Vietnam, Southern Regional Hydrometeorology Center Department of Resources and Environmental, Center for Nuclear Techniques in Ho Chi Minh City, Water Supply Experiment Station 2 and RID field officers for data collection and field experiment.

References

- 1) Hill, M. C., E. R. Banta, A. W. Harbaugh & E. R. Anderman. 2000. MODFLOW-2000, the US Geological Survey modular ground-water model; user guide to the observation, sensitivity, and parameter-estimation processes and three post-processing programs. US Geological Survey; Branch of Information Services.
- 2) Kantasinee Chaengpui, Weera Srisa-ad, Sujin Charoonsak & S. P. P. Srima. 2015. Study on Consumptive Use of Dragon Fruit (2nd year). In Irrigated Agriculture Newsletter, 8. Royal Irrigation Department.
- 3) Khai, H. Q. & S. Koontanakulvong. 2015. Impact of Climate Change on groundwater recharge in Ho Chi Minh City Area, Vietnam. In Int. Conf. on Climate Change and Water & Environment Management in Monsoon Asia, Bangkok, Thailand.
- 4) King, J. 2015. Comparison of alternative estimators of deep percolation in full and deficit irrigation. Colorado State University.
- 5) Kojima, Y., R. Shigeta, N. Miyamoto, Y. Shirahama, K. Nishioka, M. Mizoguchi & Y. Kawahara (2016) Low-Cost Soil Moisture Profile Probe Using Thin-Film Capacitors and a Capacitive Touch Sensor. Sensors, 16, 1292.
- 6) Koontanakulvong, S. & P. Siriputtichaikul. 2002. Determination of recharge rate from soil classification map in GW modelling. In 17. World congress of soil science, Bangkok (Thailand), 14-21 Aug 2002.
- 7) Koontanakulvong, S. & P. Siriputtichaikul. 2003. Groundwater Modeling In the North Part of the Lower Central Plain, Thailand. In International Conference On Water and Environment, Bhopal,

India, Vol. Ground Water Pollution, 180-187.

- 8) Koontanakulvong, S. & C. Suthidhummajit (2015) The role of groundwater to mitigate the drought and as an adaptation to climate change in the Phitsanulok irrigation project, in the Nan basin, Thailand.
- 9) Long, T. T. & S. Koontanakulvong. 2017. Groundwater balance and river interaction analysis in Pleistocene aquifer of the Saigon River basin, South of Vietnam by stable isotope analysis and groundwater modeling. In THA 2017 International Conference. Bangkok: THA 2017
- 10) Sangbun, W., S. Sangchan & P. Mekpruksawong (2014) Groundwater Recharge in the Irrigated Upstream Area of the Regulating Gate in the Lower Nam Kam River, Thailand. The 9th International Symposium on Social Management Systems SSMS2013, 2-4 December 2013, Sydney, Australia, Vol.1.
- 11) Scanlon, B. R., R. W. Healy & P. G. Cook (2002) Choosing appropriate techniques for quantifying groundwater recharge. *Hydrogeology journal*, 10, 18-39.
- 12) Schroeder, P. R., T. S. Dozier, P. A. Zappi, B. M. McEnroe, J. W. Sjostrom & R. L. Peyton. 1994. Manual of the hydrologic evaluation of landfill performance (HELP) model: engineering documentation for version 3. In Environmental Protection Agency, United States.
- 13) Wu, J. & R. Zhang. 1994. Analysis of rainfall infiltration recharge to groundwater. In Proceedings of Fourteenth Annual American Geophysical Union: Hydrology Days.