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Research article

Comparative assessment of groundwater recharge estimation using physical-based models and empirical methods in Upper Greater Mae Klong Irrigation Project, Thailand

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Abstract

Importance of the work: Physical-based groundwater recharge modelling can help in studying the impacts of climate change on groundwater resources.

Objectives: To conduct a comparative assessment for large-scale groundwater recharge estimation in the Upper Greater Mae Klong Irrigation Project.

Materials & Methods: Two physical-based models *(*WetSpass and SWAP*)* were used to estimate groundwater recharge and the outcomes were compared with the results from empirical and water balance-based methods. Groundwater recharge modelling was investigated based on model type, data requirements, model complexity, model adaptability and model performance.

Results: The average annual recharges estimated using the WetSpass and SWAP models were 183.59 mm/yr and 133.63 mm/yr, respectively, or 20.19% and 13.98% of the average annual rainfall, respectively. The WetSpass model provided more robust and consistent recharge estimates than the SWAP model, based on yearly and seasonal recharges. In addition, the WetSpass model estimated the groundwater recharge rates in similar ranges to the recharges estimated using the empirical methods and the water balance-based approach with coefficient of determination values in the range 0.60–0.64. The SWAP model produced inconsistent values of groundwater recharge for some specific periods due to the non-uniformity of the rainfall data used.

Main finding: The distribution of simulated recharges based on the WetSpass model could be spatially displayed on a geographic information system-based platform to deliver fundamental input data for the groundwater system that could assist decision makers in the sustainable management of groundwater resources from both short-term and long-term perspectives.

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Introduction

Groundwater recharge is the fundamental element of the hydrological processes of the subsurface water system replenishing some water into the aquifer system. Measuring rates of groundwater recharges in the field has become a tough task because it occurs beneath the ground surface. Furthermore, the recharge rates from field measurement have large uncertainties and errors due to the unprecedented climatic conditions and surrounding environment. However, the estimation of groundwater recharge is necessarily important for an evaluation of groundwater potential and the risk of groundwater depletion. It has been emphasized that estimation of the natural groundwater recharge is a pre-requisite in the assessment of groundwater systems for sustainable groundwater resources management (Huang and Pang, 2013; Rwanga, 2013). In more recent years, considerable attention has been devoted to groundwater recharge studies globally to investigate the groundwater dynamics and potential impact of climate change on the groundwater depletion (Srisuk and Nettasana, 2017; Hughes et al., 2021; Jannis et al., 2021). Comprehensive studies on the local-scale and broad-scale assessments of groundwater recharge have been intensively carried out in the arid and semiarid regions of China, particularly on the North China Plain where groundwater supply has been extensively utilized. It was found that the diffuse recharge in the shallow, unconfined aquifer varied sparsely with local precipitation on the North China Plain; in addition, the higher recharges were significantly affected by intensive irrigation (Huang and Pang, 2013). A simple soil-water balance model was used to quantify the areal groundwater recharge from the irrigated croplands to unconfined alluvial aquifers underlying Luancheng county in the western part of the North China Plain (Kendy et al., 2004). A one-dimensional unsaturated flow model (Hydrus–1D) was used to obtain better estimates of groundwater recharge and to investigate the effects of irrigation and water table depth on groundwater recharge on the Hebei Plain (Lu et al., 2011). The unknown term of groundwater recharge was also explored in the Mekong River Basin using a regional regression model to map groundwater recharge for agricultural utilization (Lacombe et al., 2017). In Thailand, groundwater recharge varies greatly with seasonal rainfall and specific land use types. For example, the assessment of groundwater potential in the Thachin and Mae Klong River Basins was studied in 2008; the recharge rates were estimated and classified according to the specific crops and land use types in the area (Department of Groundwater Resources, 2008). In addition, the potential sites of groundwater recharge in arid and semiarid regions in Asia have been assessed in numerous studies by applying geospatial and multi-criteria decision analysis technologies (Kadam et al., 2020; Kaewdum and Chotpantarat, 2021; Xu et al., 2021). The potential of utilizing groundwater resources in transboundary aquifers has received much attention for the sustainable development of groundwater systems (Liu et al., 2020; United Nations Educational Scientific and Cultural Organization, 2006).

Nowadays, several techniques are used to estimate the quantity of groundwater recharge, based upon different types of data and models, such as water table fluctuation, the water balance-based approach in the unsaturated soil zone, Darcy's law, empirical methods, groundwater flow models and tracer techniques (Hiwot, 2008; Healy, 2010; Saghravani et al., 2013). Selecting the proper techniques for groundwater recharge estimation is accordingly subject to available data, local geographical and topographical conditions, the spatial and temporal scales required and the reliability of results (Islam et al., 2016). Physical-based groundwater recharge models have been widely used as they can estimate both the spatial and temporal distributions of groundwater recharge based on the specific physical parameters in the specific area. In addition, the precision of model estimation is strongly associated with the successful performance of the calibration and validation procedures of the groundwater recharge model selected. Therefore, estimates of groundwater recharge must be validated and compared among the techniques used for groundwater recharge estimation.

In Thailand, surface water is the major sources of water for agricultural and non-agricultural purposes, with contributions coming from 22 river basins through river networks, dam and reservoir systems and canal irrigation systems *(*Reference*)*. Groundwater has been considered as a supplementary source when the quantity of surface water is critically limited. However, groundwater still plays a major role in some specific areas where surface water sources have been over-abundantly used or are difficult to access due to unsuitable topography limiting inland waterways into upland areas. Groundwater sources have been utilized for agricultural and industrial purposes in some specific areas in northern, northeastern and western Thailand. By aiming to supply water sufficiently for the various sectors under the framework of basin management, the concept of conjunctive use and coordinating the uses of surface water and groundwater has been promoted in the long-term national water strategy-water action plans of Thailand since 2004 (Water Resources Association, 2004). In addition, extensive research has been undertaken into this area to boost the efficient and sustainable present and future uses of groundwater.

The purpose of the current study was to conduct a comparative assessment of the groundwater recharge estimation in the

Upper Greater Mae Klong Irrigation Project (UGMKIP), in western Thailand using the physical-based models. The rates of groundwater recharge obtained from the physical-based model were investigated and compared with those rates obtained from empirical methods and a water balance-based approach in the unsaturated soil zone. There has been a rapid increase in the development of physical-based groundwater recharge models over the past few decades. Principally, physical-based groundwater recharge models have been implemented under a water balance approach based on parameters of water quantities that can be physically measured (Rwanga, 2013). The WetSpass and SWAP models are renowned physical-based models for groundwater recharge estimation and were selected to describe the water processes for estimating groundwater recharge potential. The use of empirical formulae is an easy means to quickly estimate groundwater recharge, especially for decision making processes in water resources management (Adeleke, 2015). Consequently, several empirical formulae were also used in the current study to derive the rates of groundwater recharge as a function of rainfall data. The robust groundwater recharge rates would be expected to be beneficial key information for the sustainable development of groundwater resources in this region.

The temporal and spatial variations of groundwater recharge and the response of groundwater systems are predominantly influenced by the climate pattern, local topography, water table depth, aquifer characteristics and implementation of irrigation practice (Alley, 2009).However, the evaluation of recharge rates in the current study was based on the assumption that groundwater recharge could be explained using two physical-based models estimated under the same hydrogeological circumstances without considering seepage from current irrigation practice, available soil water storage and recharge from boundaries and rivers. The recharge rate was defined as the land recharge which explains the widespread movement of water from the ground surface to the water table as a result of the climate pattern over the given area and penetrating to the unsaturated soil zone.

Materials and Methods

Study area and current use of groundwater

The Upper Greater Mae Klong Irrigation Project, located in western Thailand, was selected as the study area. It occupies three irrigated Operation and Maintenance Projects: 1) Phanom Thuan (PNT); 2) Song Phi Nong (SPN); and 3) Bang Len (BL), covering an area of approximately 1,758 km^2 in the Mae Klong and Tha Chin River Basins (Fig. 1A). Most of the study area is upland area with the highest surface elevation of +400 m above mean sea level and gradually flattening in the east to nearly the mean sea level. The main agricultural crops are rice and field crops which constitute of 35.89% and 30.03% of the entire area, respectively, with the remaining 34.03% being vegetables and water bodies, as illustrated in Fig. 1B. The distribution of land use is related to specific soil types. Paddy field and field crop areas lie are clay, loam and sandy loam soils, as shown in Fig. 1C. The layered structure of the aquifer system in this region can be distinguished into one unconfined aquifer and eight confined aquifers with thickness ranges of 20–90 m. Bangkok Clay makes up the topsoil layer, based on soft marine clay deposits. Beneath the Bangkok Clay layer are unconsolidated and semi–consolidated sediments intervened by the aquitard. Only a small amount of flow can pass through the aquitard that is adjacent to the aquifer layers. Each aquifer contains large volumes of soil voids for groundwater storage. This aquifer system is replenished naturally by rainfall and surface water from surface water bodies.

According to the limit of surface water supplied under gravity through the water conveyance structures, groundwater has been mostly used in the upland areas as an additional water source for agriculture and livestock, domestic water consumption, industrial and commercial businesses, and other miscellaneous services in the Greater Mae Klong Irrigation Project (GMKIP) (Teartisup and Kerbsueb, 2013). Surveying and monitoring groundwater source in this region is the responsibility of the Department of Groundwater Resources (DGR). There are 10 observation wells registered under the DGR in three provinces (Nakhon Pathom, Suphanburi, Kanchanaburi). These have been installed to different depths of the soil types in the range from –1 m to –204 m, as shown in Fig. 2A. The groundwater is extracted by pumping from private and government wells, as shown in Fig. 2B. More than 500 pumping wells were installed during 2000–2016 in the UGMKIP, having an average discharge rate of 215 m^3/d and 78.20 m^3/d for daily pumping for 16 hr and 24 hr, respectively, for the government and private wells, respectively. The total amount of groundwater abstraction in the UGMKIP is currently 42.16 Mm^3/yr or 12.31% of the total amount of groundwater used in the GMKIP. Most of the private wells installed in this region draw water from shallow aquifers for agricultural use by farmers. Although the proportion of groundwater use is not so much nowadays, the groundwater needs has been expected to increase predominantly according to the recent establishment of the economic development plan under the East-Water Economic Corridor Program to increase border trade between Thailand and Myanmar as well as under the Mainland Southeast Asian Neighbors project in the near future (Chirathivat and Cheewatrakoolpong, 2015).

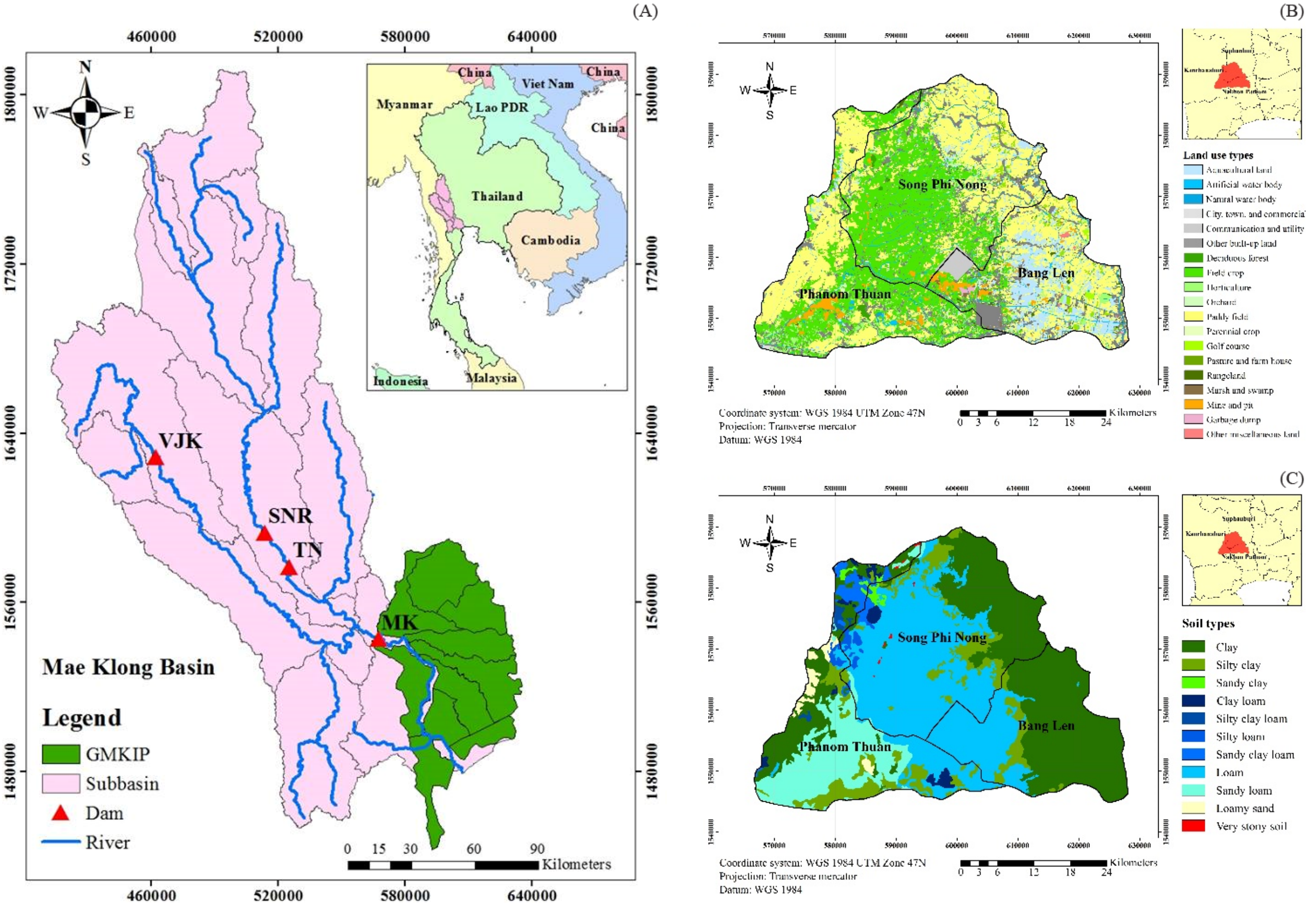

Fig. 1 Location of Mae Klong River Basin, land use type and soil type in the Phanom Thuan-Song Phi Nong-Bang Len Operation and Maintenance Projects: (A) location of Mae Klong River Basin; (B) land use types; (C) soil types

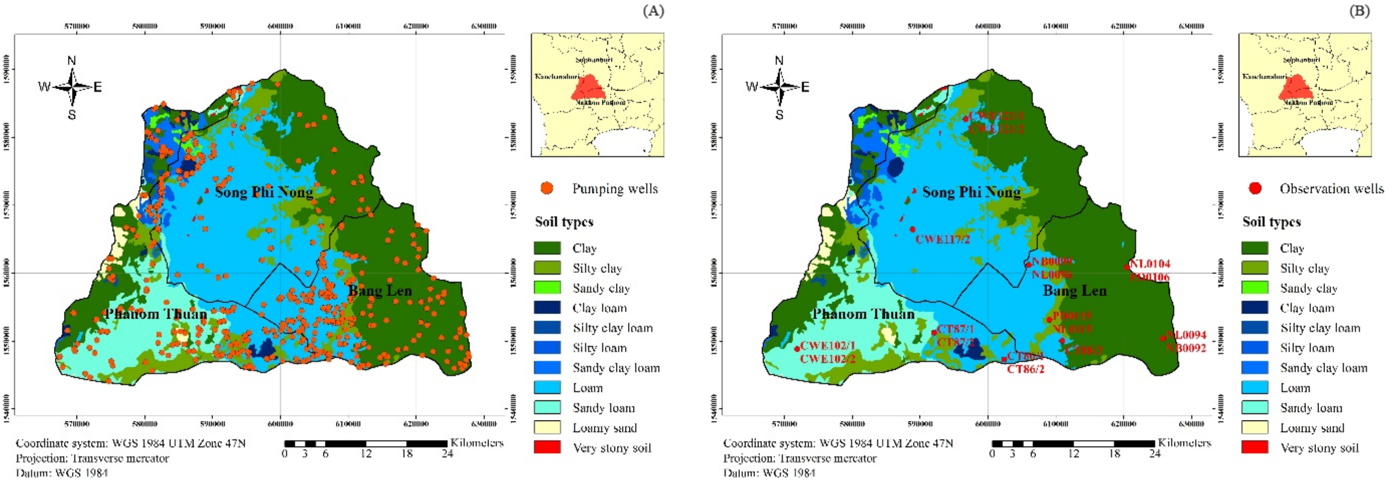

Fig. 2 Distribution of pumping wells and observation wells installed in different soil types

Selected groundwater recharge models

The potential groundwater recharge rates during 2000–2017 in the UGMKIP were estimated using two physical-based models: 1) the water and energy transfer between soil, plants and atmosphere under quasi steady state (WetSpass) model; and 2) the Soil Water Atmosphere Plant (SWAP) model that are discussed in more detail below. WetSpass is a spatially distributed water balance model for estimating long-term average rates of groundwater recharge. The spatial variation of groundwater recharge rates generated using WetSpass can be visually presented over the entire area. SWAP is a conventional one-dimension, semi-distributed numerical model; therefore, rates of groundwater recharge estimated using SWAP can be presented for the particular area of interest. The predicted results of groundwater recharge based on these two models were obtained and displayed in different formats. The input structures for these two models required pre-processing as an initial step to ensure that the inputs could be adequately represented under the same circumstances.

WetSpass model

WetSpass is a one-dimension, steady-state spatial distribution water balance model (Batelaan and De Smedt, 2007; Woldeamlak et al., 2007; Molla et al., 2019). The principle of WetSpass model combines the water balance approach with a geographic information system (GIS) to determine the spatial distribution of potential groundwater recharge. The potential groundwater recharge in each raster cell of the boundary is calculated using the water balance equation. However, the water balance equation used in WetSpass is designed for vegetated areas, as expressed in Equation 1 (Batelaan and De Smedt, 2007; Rwanga, 2013):

$$P = I + Sv + Tv + Rv \tag{1}$$

where P is the average seasonal precipitation, I is the interception fraction by vegetation type, S_v is the surface runoff, T_v is the actual transpiration and R_v is the groundwater recharge, with all parameters measured in liters per time interval.

Groundwater recharge is the residual term in the water balance equation which can be calculated in each raster cell of the boundary using Equation 1. The total water balance of one raster cell can be calculated using the specific equation for each water balance component divided into vegetated, bare soil, open water and impervious parts of the raster cell, as expressed in Equations 2–4, respectively (Batelaan and De Smedt, 2007):

$$ET_{raster} = avET_v + asE_s + aoE_o + aiE_i \tag{2}$$

$$S_{raster} = avS_v + asS_s + aoS_o + aiS_i \tag{3}$$

$$R_{raster} = avR_v + asR_s + aoR_o + aiR_i \tag{4}$$

where ET_{raster} is the total evapotranspiration in a raster cell, S_{raster} is the surface runoff in a raster cell, R_{raster} is the groundwater recharge in a raster cell and the subscripts $_{av}$, $_{as}$, $_{ao}$ and $_{ai}$ represent the vegetated, bare soil, open water and impervious area fractions of a raster cell, respectively, with all parameters measured in liters per time interval.

SWAP model

The SWAP model is a one-dimension, semi-distributed numerical model developed for soil water flow, soil heat flow and solute transport simulations under unsaturated or saturated soil conditions in the zone of aeration with plant-soil interactions. The SWAP model is designed for the simulation of flow and transport processes for growing seasons and long-term periods at field scales. It also can be applied for water and salinity management, irrigation scheduling, transient drainage processes, plant growth affected by water and salinity, pesticide leaching to ground water and surface water, regional drainage from topsoils toward different surface water systems, optimization of surface water management and the effects of soil heterogeneity (Kroes et al., 2017). The SWAP model is numerically solved using Richard's equation (Hiwot, 2008), a nonlinear partial differential equation representing vertical movement of water in unsaturated soil based upon water balance equation, as expressed in Equation 5 (Lin, 2012):

$$\mathrm{R}^2 = \frac{\left[\sum_{i=1}^{N}(m_i - \bar{m}_i)(\tilde{m}_i - \hat{m}_i)\right]^2}{\sum_{i=1}^{N}(m_i - \bar{m}_i)^2 \sum_{i=1}^{N}(\tilde{m}_i - \hat{m}_i)^2} \tag{5}$$

where, $C(\theta)$ is the differential water capacity ($\partial\theta/\partial h$ θ is the volumetric water content (measured in cubic meters per cubic meter) h is the soil water pressure head (in millimeters), $K(\theta)$ is the hydraulic conductivity (millimeters per day), H is the hydraulic head (in millimeters) *and* $U(z, t)$ is a sink term representing water which is lost at a depth z and time t due to transpiration.

Data collection

The data used for groundwater recharge modelling can be categorized into several groups: topographical, meteorological, land use, soil and groundwater. The required data were collected from the various data sources and prepared in a format suitable to import into the WetSpass and SWAP models.

These two models are substantially different in both algorithm and model type but apply the same concept of water balance. Descriptions of the input data for the WetSpass and SWAP models are listed in Table 1.

Groundwater recharge estimation using WetSpass and SWAP models

Estimating groundwater recharge in the UGMKIP was undertaken based on the WetSpass and SWAP models, using the definition of groundwater recharge as the amount of infiltrated water passing through the unsaturated zone (including the root zone and the intermediate vadose zone) to saturated zone (Bear and Cheng, 2008). In fact, there is no factor influencing the behavior of infiltrated water in the intermediate vadose zone. Therefore, the infiltrated water passing downward through the plant root zone can be regarded as groundwater recharge (Todd, 1980), as can be seen in Fig. 3A. However, the factor of surface irrigation supplied to crops in the field was not taken into account for the formulation of groundwater recharge model in the current study and only the physical-based hydrologic parameters were considered to quantify the natural recharge.

The groundwater recharge using WetSpass was simulated over the entire area of the UGMKIP, corresponding to the assigned grid size identified in the model settings. Three simulation points representing the distributions and relations of land uses and soil types in the vegetated areas of UGMKIP, were selected for the SWAP model to estimate the potential groundwater recharge in the vertical direction. To make the results comparable, the area-weighted average method was then used to transform the spatial values of recharge rates from WetSpass into representative recharge rates at the corresponding simulated points from the SWAP model. The representation of groundwater recharge modelling in the study area by WetSpass and SWAP and the input data are presented in simplified form in Figs. 3B and 3C, respectively.

Comparison of potential groundwater recharge

The groundwater recharge simulations based on the WetSpass and SWAP models were conducted during 2000–2017 in the UGMKIP. To ensure the reliability of the modelling results, the groundwater recharge rates were compared with those achieved based on the empirical formulae and water balance-based approach. These have been sparsely used as conventional methods for groundwater recharge estimation. Estimating the recharge rates of groundwater using the water balance-based approach can be implemented corresponding to the basic components of the water cycle. The computation of groundwater recharge can be accomplished using Equation 6 (Batelaan and De Smedt, 2007):

$$R = P - I - S - EI \tag{6}$$

where R is the annual groundwater recharge, P is the average annual rainfall, I is the annual interception (estimated using the rainfall interception coefficient), S is the annual surface runoff (estimated using the runoff coefficient) and ET is the annual evapotranspiration, with all parameters measured in liters per time interval.

Table 1 Input data for WetSpass and SWAP models

Data type	Input data	Unit	WetSpass	SWAP
Topographical data	Digital elevation model (DEM)	m	✓	-
	Slope	°	✓	-
Meteorological data	Rainfall	mm	✓	✓
	Average temperature	°C	✓	✓
	Maximum and minimum temperature	°C	-	✓
	Potential evapotranspiration	mm	✓	✓
	Wind speed	m/s	✓	✓
	Vapor pressure	kPa	-	✓
	Solar radiation	kJ/m^2	-	✓
	Rainfall duration	-	-	✓
Land use data	Land use type	-	✓	-
	Land use parameters	-	✓	-
Soil data	Soil type	-	✓	✓
	Soil parameters	-	✓	✓
Groundwater data	Groundwater level	m (measured from ground surface)		-
Plant data	Crop parameters	-	-	✓

WetSpass = water and energy transfer between soil, plants and atmosphere under quasi steady state; SWAP = annual soil water atmosphere plant

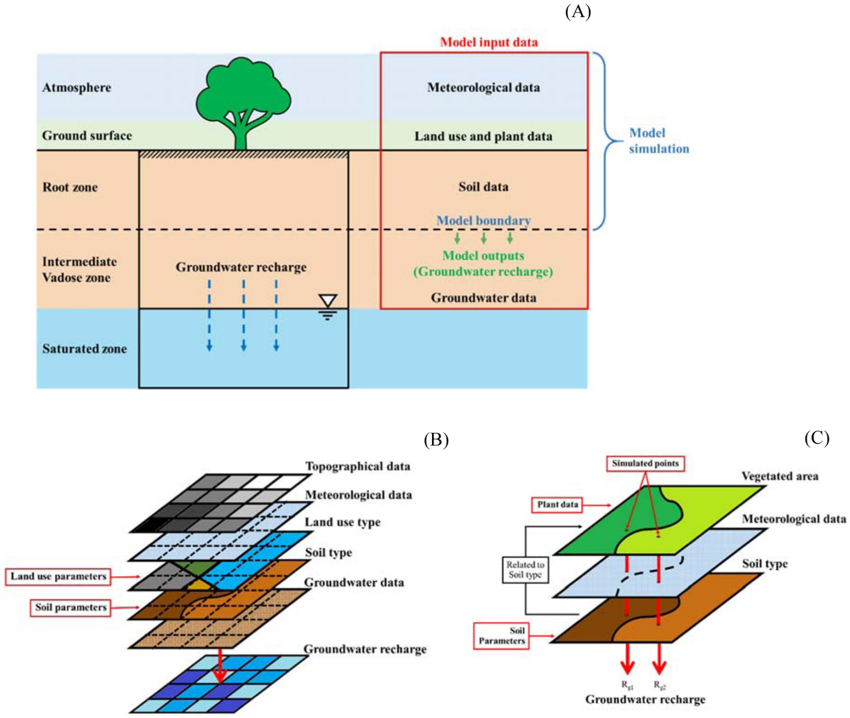

Fig. 3 Simplified representation of groundwater recharge modelling in this study: (A) occurrence of groundwater recharge and model simulation; (B) water and energy transfer between soil, plants and atmosphere under quasi steady state (WetSpass) model; (C) annual soil water atmosphere plant (SWAP) model

Other studies have reported that empirical equations have been broadly applied for the estimation of groundwater recharge worldwide (Ali et al., 2017). Khalil et al. (2018) studied the relationships between annual groundwater recharges using the WEAP model and empirical equations in the Mae Klong River Basin, Thailand. Their results showed that the ranges of correlation were relatively high, varying from 0.781 to 0.815. Therefore, four empirical equations were selected: 1) Chaturvedi formula (CF); (2) Sehgal formula (SF); 3) Krishna Rao formula (KRF); and 4) Bhattacharya formula (BF), according to Bhattacharya et al. (1954), Chaturvedi (1973), Krishna (1970) and Sehgal (1973), respectively, in which groundwater recharge is determined as a function of rainfall data. The following equations express the empirical relation between groundwater recharges and rainfall data:

Chaturvedi formula (CF)

$$R = 2.0(P-15)^{0.4} \quad (7)$$

where R is the groundwater recharge (measured in inches per year) and P is the annual rainfall (in inches).

Sehgal formula (SF)

$$R = 12.6(P-406.4)^{0.5} \quad (8)$$

where R is the groundwater recharge (measured in millimeters per year) and P is the annual rainfall (in millimeters).

Krishna Rao formula (KRF)

$$R = K(P-X) \quad (9)$$

where R is the groundwater recharge (measured in millimeters per year) and P is the annual rainfall (in millimeters) and the values of K and X depend on the values of P as follows:

If P is in the range 400–600 mm, then $R = 0.20(P-400)$ (10)
If P is in the range 600–1,000 mm, then $R = 0.25(P-400)$ (11)
If P is the range 1,000–2,000 mm, then $R = 0.30(P-500)$ (12)
If P is more than 2,000 mm, then $R = 0.35(P-600)$ (13)

Bhattacharya formula (BF)

$$R = 3.47(P-38)^{0.4} \quad (14)$$

where, R is the groundwater recharge (measured in centimeters per year) and P is the annual rainfall (in centimeters).

The statistical relationships between the results based on the WetSpass and SWAP models and the empirical formula were investigated using the coefficient of determination (R^2), which is widely used as statistical parameter for the evaluation of model performance to explain the dispersion between observed and simulated values. The values of R^2 are in the range of 0–1, where a zero value describes no relationship between the observed and simulated values and value approaching 1 reflects a strong correlation between the observed and simulated values (Krause et al., 2005).

Results and Discussion

Comparative assessment of annual recharges obtained using physical-based models and empirical methods

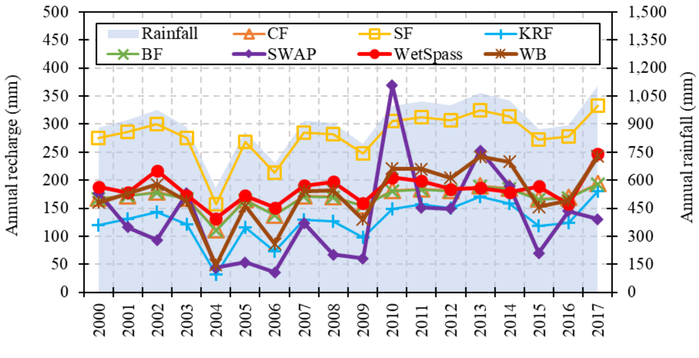

Fig. 4 Annual groundwater recharge during 2000–2017

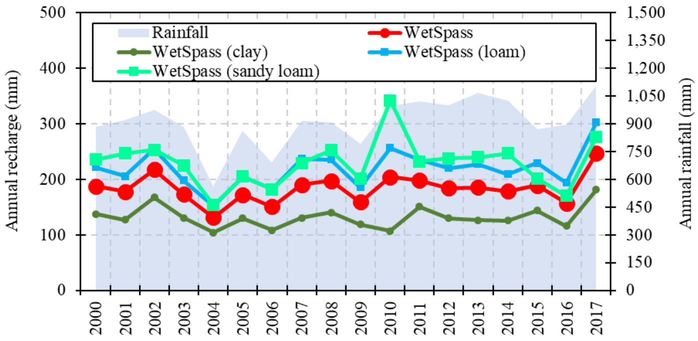

Fig. 5 Annual water and energy transfer between soil, plants and atmosphere under quasi steady state (WetSpass*)* recharges classified by soil type

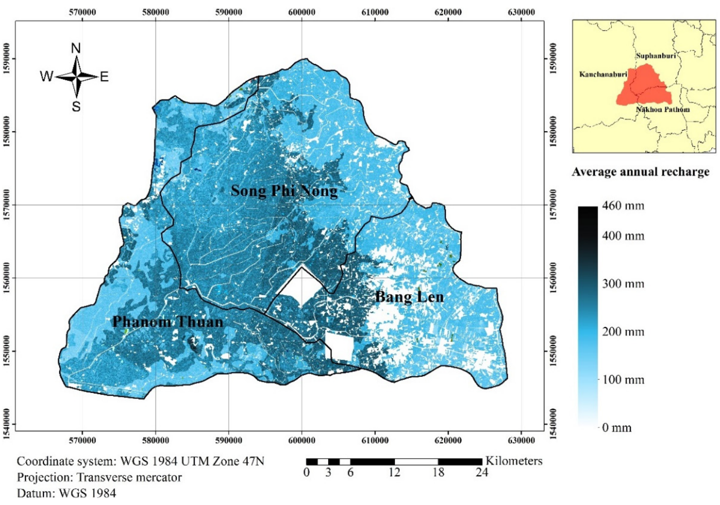

Fig. 6 Spatial distribution of average annual water and energy transfer between soil, plants and atmosphere under quasi steady state (WetSpass) recharges during 2000–2017

The values of annual groundwater recharge obtained using the WetSpass and SWAP models during 2000–2017 in the study area are presented in Fig. 4. The average annual rates groundwater recharge predicted using the WetSpass and SWAP models in the UGMKIP were 183.59 mm/yr and 133.63 mm/yr, respectively, or 20.17% and 14.68%, respectively, of the average annual rainfall (910.16 mm). The average annual WetSpass recharges of clay, loam and sandy loam soils during 2000–2017 were 132.21 mm, 219.67 mm and 229.65 mm, respectively, or 14.44%, 24.00% and 25.09%, respectively, of the average annual rainfall (910.16 mm), as shown in Fig. 5. The clay soil produced the lowest extent of groundwater recharge compared to the loam and sandy loam soils. The average annual WetSpass recharge rates of the loam and sandy loam soils were in a similar range during 2000–2017, except during 2010 when the recharge rate in the sandy loam soil clearly increased, probably due to the heavy rainfall in the area with the sandy loam soil during the wet season in 2010, particularly at the 130022 station in Tha Muang district. The WetSpass outputs were provided in spatial format and are visualized in Fig. 6. The spatial distribution range for the average annual groundwater recharges was 0–460 mm and was related to the distribution of soil type. The groundwater recharges in the loam and sandy loam area in the Phanom Thuan and Song Phi Nong Operation and Maintenance Projects were very similar due to their similarities in the distribution of land use and soil properties. The rate of groundwater recharge in clay soil, especially in the Bang Len Operation and Maintenance Projects was the lowest. However, the no recharge area did not correspond to the distribution of land use types because: 1) the land cover was classified as impervious, including city, town, commercial, community and utility, and other built-up land; and 2) the amount of evapotranspiration was much higher than the inflow from rainfall. This is generally the case for open water bodies such as aquacultural land, artificial water bodies and natural water bodies. As these areas are not covered by plants, the value of actual evapotranspiration is substantially increased by the effects of wind speed and soil evaporation. The average annual SWAP recharges of clay, loam and sandy loam soils during 2000–2017 were 27.23 mm, 206.71 mm and 233.89 mm or 2.97%, 22.58% and 25.55%, respectively, of the average annual rainfall (910.16 mm). The average annual soil recharge from the SWAP model is expressed in Fig. 7. Similar to the WetSpass recharge prediction, the lowest extent of SWAP recharge was in clay soil (nearly zero since 2005). The average annual SWAP recharge predictions of the loam and sandy loam soils had similar fluctuation patterns during 2000–2017. However, the recharge rate in the sandy loam soil in 2010 presented the highest peak due to an extreme rainfall event occurring in the sandy loam area.

Comparing these results with other studies, the annual recharge predictions based on the WetSpass model in the UGMKIP was closer to those from the WEAP model for which the average annual recharge for the entire area of the Mae Klong Basin accounted for 23.89% of the average annual rainfall (Khalil et al., 2018). The amount of groundwater recharge based on the four empirical equations (CF, SF, KRF and BF) in the UGMKIP equated to 18.69%, 30.68%, 13.79% and 18.55%, respectively, of the average annual rainfall (910.16 mm), which were in a similar range to that evaluated using the WEAP model in the Mae Klong Basin (Khalil et al., 2018). In addition, the water balance (WB)-based approach in the unsaturated soil zone predicted an annual recharge rate in the UGMKIP of 174.99 mm/yr. In other words, 18.75% of average annual rainfall (910.16 mm) was predicted as potential groundwater recharge based on the water balance estimation, as shown in Fig. 8.

The empirical recharge rates based on the CF, SF, KRF and BF equations were compared with those obtained using the WetSpass and SWAP models as well as the WB approach, as shown in Fig. 8. The ranges for the average annual WetSpass, CF, BF and WB recharges were similar, being in the range 18.55–20.17% of the annual rainfall. The average annual SWAP recharge was relatively similar to the KRF recharges except for the notable value in 2010 for the SWAP model. The groundwater recharge percentages based on the SWAP model and the KRF equation were 14.68% and 13.78%, respectively, of the annual rainfall, which were slightly lower than the values from the WetSpass model, the CF and BF equations and the WB approach. SF recharge (30.68% of annual rainfall) was definitely higher than those obtained from the other methods. Since the groundwater recharge based on the by empirical equations is subject to the rainfall data, the pattern of annual empirical recharge received during 2000–2017 definitely conformed to the annual rainfall patterns. Furthermore, the pattern of annual WetSpass recharge during 2000–2017 was similar to the empirical recharge patterns; however, it had less variability than the annual empirical recharge. Estimating the groundwater recharge based on the WetSpass model applied the simplified water balance equation in each simulation time step. In contrast, the groundwater recharge based on the SWAP model used the Richard's equation in which the recharge rates were accumulated continuously in each time step of the simulation period. Therefore, the variability in the SWAP recharge estimate tended to be higher than for the WetSpass recharge. The WB recharge was estimated on an annual basis using elements of the observed hydrological data in the study area, such as rainfall, interception, surface runoff and evapotranspiration. Interception and surface runoff were calculated using rainfall interception and runoff coefficients that are strongly correlated with the rainfall data. Evapotranspiration was estimated based on the Thornthwaite method which is significantly associated with temperature data (Chen et al., 2005). The monthly temperature variability in the study area was definitely low, which explained the lower variability in evapotranspiration estimated during 2000–2017 using the Thornthwaite method, which also had a pattern of WB recharge that was relatively similar to the empirical recharges.

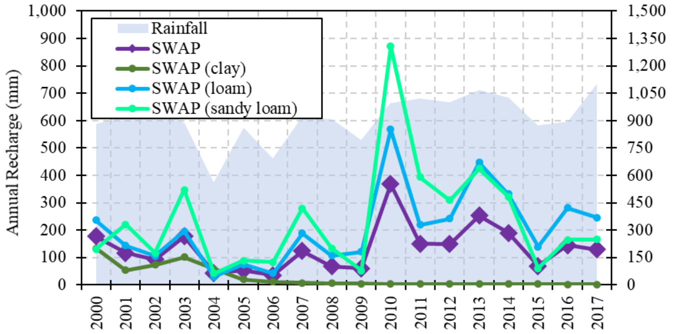

Fig. 7 Annual soil water atmosphere plant (SWAP) model recharges classified by soil type

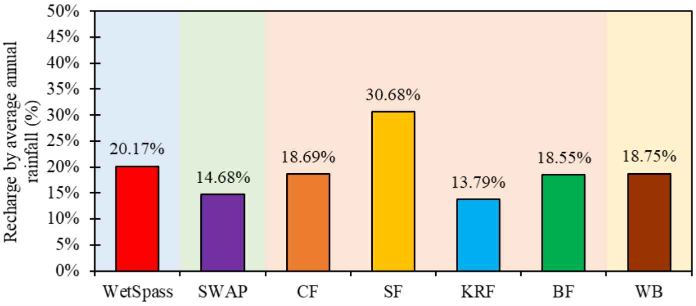

Fig. 8 Average annual recharge expressed as a percentage of average annual rainfall, where WetSpass = water and energy transfer between soil, plants and atmosphere under quasi steady state; SWAP = annual soil water atmosphere plant; CF = Chaturvedi formula; SF = Sehgal formula; KRF = Krishna Rao formula; BF = Bhattacharya formula; WB = water balance-based approach

Nevertheless, the annual recharge amounts obtained from these two physical-based models were still higher than those recharge rates used for the assessment of the safe aquifer yield based on the mathematical model in the Tha Chin and Mae Klong Basins. As mentioned previously, the groundwater recharge analysis undertaken by the DGR was estimated and classified according to the specific crops and land use types in the area. The recharge rates in paddy fields, sugarcane fields, forest and other areas in the Thachin and Mae Klong River Basins amounted to 29.00 mm/yr, 103.90 mm/yr, 83.20 mm/yr and 62.50 mm/yr, respectively (DGR, 2008).

Annual recharge relationships between physical-based models and empirical methods

The R^2 value was used to evaluate the relationships based on the annual recharge estimates from the physical-based models and empirical methods and also the WB-based approach, as shown in Table 2. The R^2 values for the the WetSpass recharge and the empirical and water balance recharges were in the range 0.60–0.64, suggesting a relatively good correlation. However, the R^2 values (0.33–0.42) indicated a poorer correlation between the SWAP recharge and the empirical and WB recharges. There were strong correlations between the empirical recharges and the WB recharge ($R^2 = 0.95$–1.00).

The values of statistical parameters significantly explicit the model variability between the simulated recharge and the empirical recharge. The relationship between annual rainfall and groundwater recharge based on the different techniques is shown in Fig. 9. An increase in annual rainfall had an inverse relationship with the simulated recharge predicted by the WetSpass and SWAP models and the empirical recharges. Model calibration and validation of these two physical-based models were conducted during 2000–2010 and 2011–2017, respectively, by benchmarking with the recharge rates calculated using the WB-based approach. Notably, the annual rainfall for the calibration period was mostly lower than 1,000 mm, whereas it was slightly more than 1,000 mm for the validation period. The high variability in annual rainfall was reflected in the statistical efficiency of model calibration and validation in a negative manner for both the root mean square error and R^2. In other words, when rainfall variability was low, there was a strong correlation between the simulated and empirical recharges.

To enable a meaningful comparison between the two models, the spatial values of groundwater recharge from the WetSpass model were classed and arranged corresponding to specific soil types (clay, loam and sandy loam) and then the weighted arithmetic mean method was used to estimate the average values of annual recharges. The simulation from the SWAP model was conducted by separating into three simulation points representing clay, loam and sandy loam soils. The groundwater recharges classified by the different soil types are summarized in Table 3 and also expressed as a percentage of average annual rainfall in Fig. 10.

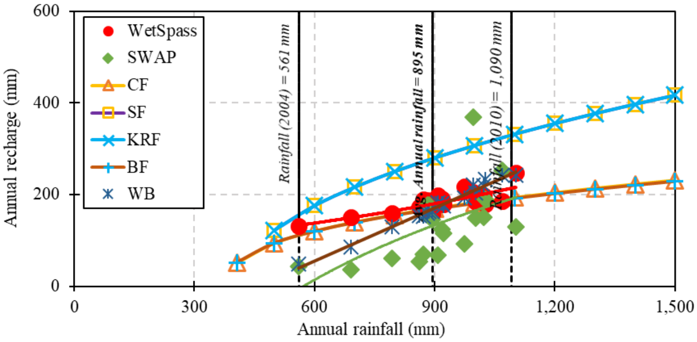

Fig. 9 Relationship of annual groundwater recharges and annual rainfall, where WetSpass = water and energy transfer between soil, plants and atmosphere under quasi steady state; SWAP = annual soil water atmosphere plant; CF = Chaturvedi formula; SF = Sehgal formula; KRF = Krishna Rao formula; BF = Bhattacharya formula; WB = water balance-based approach

Table 2 Coefficient of determination (R^2) of simulated annual recharge compared to empirical and water balance-based approach

	WetSpass	SWAP	CF	SF	KRF	BF	WB
WetSpass	1.00	0.11	0.62	0.62	0.64	0.62	0.60
SWAP	0.11	1.00	0.33	0.33	0.34	0.33	0.42
CF	0.62	0.33	1.00	1.00	0.98	1.00	0.95
SF	0.62	0.33	1.00	1.00	0.99	1.00	0.96
KRF	0.64	0.34	0.98	0.99	1.00	0.99	0.98
BF	0.62	0.33	1.00	1.00	0.99	1.00	0.95
WB	0.60	0.42	0.95	0.96	0.98	0.95	1.00

WetSpass = water and energy transfer between soil, plants and atmosphere under quasi steady state; SWAP = annual soil water atmosphere plant; CF = Chaturvedi formula; SF = Sehgal formula; KRF = Krishna Rao formula; BF = Bhattacharya formula; WB = water balance-based approach

Table 3 Average annual recharge distribution during 2000–2017

Model	Average annual recharge classified by soil type (mm)			Average annual recharge (mm)
	Clay	Loam	Sandy loam	
WetSpass	132.21	219.67	229.65	183.59
SWAP	27.23	206.71	233.89	133.63
WB	79.63	235.09	281.09	174.99

WetSpass = water and energy transfer between soil, plants and atmosphere under quasi steady state; SWAP = annual soil water atmosphere plant; WB = water balance-based approach

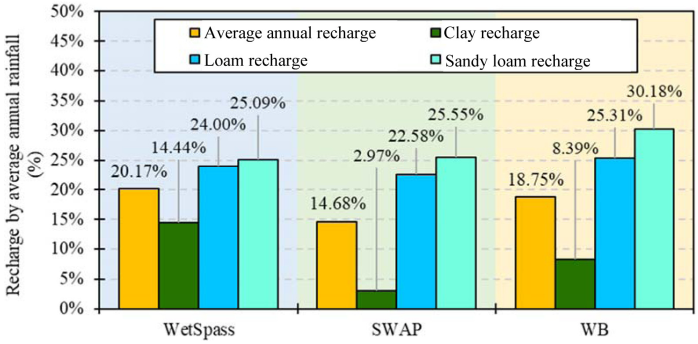

Fig. 10 Groundwater recharge in the different soil types expressed as a percentage of average annual rainfall, where WetSpass = water and energy transfer between soil, plants and atmosphere under quasi steady state; SWAP = annual soil water atmosphere plant; WB = water balance-based approach

These results indicated that for the WetSpass, SWAP models and the WB equation, soil types and their properties had a major impact on the groundwater recharge, as can be seen in Fig. 10. The ranges in values of the WetSpass and SWAP recharges in the loam and sandy loam soils were similar, but not for the recharge in the clay soil, which was much lower in the SWAP model than that obtained using the WetSpass model because the bottom boundary conditions of the SWAP model specified free outflow. In addition, the fine textual structure of clay soil played an important role in preventing any transmission flow into the deeper soil layers. Thus, the groundwater recharges in clay soil had the lowest values. However, the WetSpass recharges, expressed as the percentage of average annual rainfall, were closer to the recharges obtained from the WB equation.

Comparative assessment of seasonal recharges obtained from physical-based models

The effects of season on groundwater recharges were considered and compared in this study. The seasons in western Thailand are commonly divided into dry and wet, with the dry season usually from December to April and the wet season begins in May and usually ends in November. The analysis indicated that 90% of the average annual rainfall (894.48 mm/yr) occurred in the wet season, with only 10% in the dry season. As can be seen in Fig. 11, groundwater recharges in the dry season based on the WetSpass model were much lower than in the wet season. The average groundwater recharge in the dry season was 22.07 mm or 12.03% of the average annual recharge. However, the high variability in the inter-seasonal recharge in the dry season was due to the non-uniformity of the rainfall data used. Furthermore, the distribution of average monthly rainfall in the dry season was mostly at the end of that season in April when summer storms usually occur. On the other hand, the average groundwater recharge in the wet season was 161.52 mm or 87.97% of the average annual recharge. The higher portion of WetSpass recharge was generally found in the wet season due to the high inflow from rainfall. However, the average seasonal recharges based on the WetSpass model were 23.20% and 19.79% of the average seasonal rainfall in the dry and wet seasons, respectively, indicating that a higher percentage of groundwater recharge with respect to rainfall data occurred in the dry season. This reflected that the environmental conditions and hydrogeologic properties in the dry season are well suited promoting groundwater recharge into the soil layers. In addition, the extent of groundwater recharges in the wet season was much higher than in the

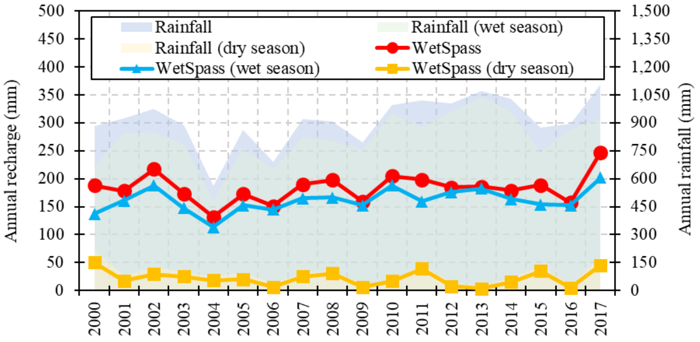

Fig. 11 Seasonal recharges based on water and energy transfer between soil, plants and atmosphere under quasi steady state (WetSpass) model

dry season based on the SWAP model, as shown in Fig. 12. However, based on the long-term simulation using the SWAP model at three simulated points, there was a distinct peak in the groundwater recharge in the wet season in 2010 in Phanom Thuan, Song Phi Nong, when the amount of annual rainfall on the sandy loam and loam soils was definitely high and deviated substantially from the normal value. Although the seasonal recharge obtained using the WB-based approach was not very evident, the effect of seasonality in the groundwater recharge was definitely substantial in this region based on detailed investigation of the WetSpass and SWAP recharges.

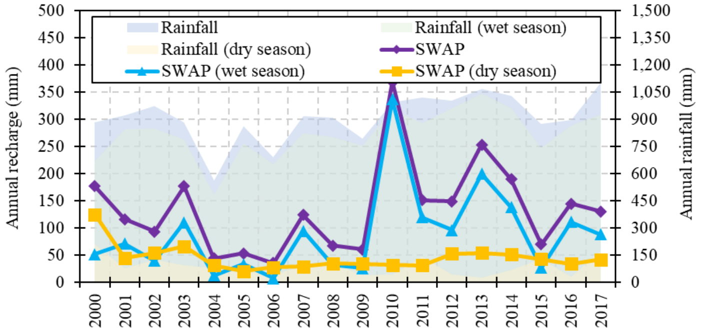

Fig. 12 Seasonal recharges based on soil water atmosphere plant (SWAP) model

Comparison of groundwater recharge modelling

The suitability of the groundwater recharge models for use in the study area was based on five key factors: model type, data requirements, model complexity, model adaptability and model performance. WetSpass is a one-dimension, steady-state spatial distribution model based on the simplified water balance principle, while SWAP is a one-dimension, semi-distributed numerical model solved using the Richard's equation in the vertical direction. These two models attempt to derive the true recharge in the vadose soil zone using highly accurate weather, vegetation and soil data (Panigrahi and Goyal, 2016). The SWAP model required less input data than the WetSpass model. However, the WetSpass model provided a simple structure for data entry. Regarding model adaptability, the groundwater recharge simulation in the WetSpass model was principally based on spatial analysis, which can handle well the physical changes in a large specified region, where the effects of land use and land cover changes are necessarily important to the environment. In contrast, the simulation using the SWAP model was based on a numerical formula in which the static values of key parameters are specified as representative of the study area. Based on the efficiency of the model results obtained in this study, the WetSpass model provided more robust and reliable results than the SWAP model when the yearly and seasonal recharges were diagnosed. The WetSpass model also provided results of simulated annual recharges that were closer to those predicted using empirical methods and WB-based approaches with R^2 values in the range 0.60–0.64, with those predicted using the WEAP model also similar (Khalil et al., 2018).

Climate variability influences dynamic changes in the hydrogeological characteristics of a groundwater system, specifically altering the spatial and temporal manners of groundwater recharge. Consequently, the physical-based modelling considering site-specific physical properties has become more useful for groundwater recharge estimation particularly, at the meso-scale to large-scale. It can also help to reduce the limitations involved in conducting field measurement which produces a high degree of uncertainty of the measured recharge as well as being time- and cost-consuming. Therefore, the two physical-based models (WetSpass and SWAP) were selected to conduct the comparative assessment of groundwater recharge estimation with empirical methods and the water balance-based approach in the UGMKIP, Thailand. The modelling processes of WetSpass and SWAP were implemented using the same input dataset and boundary conditions. The results based on the WetSpass model consisted of robust values of spatial and temporal recharges. However, there were inconsistent values of groundwater recharge based on the output using the SWAP model, predominantly in some specific periods due to the non-uniformity of the rainfall data. As the precision of model estimation is strongly correlated with the successful application of calibration and validation procedures for the physical-based models and as the groundwater recharge certainly varied with local rainfall, it was essential to calibrate and validate the model parameters in accordance with the characteristics of rainfall events and changes in the climatic pattern in the region. This verified that the model results were more reliable and could be utilized for both short-term and long-term recharge prediction. In summary, the physical-based models could predict groundwater recharge values in a similar range to that of other techniques, such as empirical equations, the water balance approach and the WEAP model. An important advantage of applying physical-based models is that the simulated recharges can be visualized on both spatial and temporal distribution platforms at local and regional scales. This leads to a better understanding of the fundamental inputs to the groundwater system for assessing groundwater vulnerability to the surrounding environment and evaluating groundwater potential for sustainable groundwater resources management.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Acknowledgements

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References

Adeleke, O.O., Makinde, V., Eruola, A.O., Dada, O.F., Ojo, A.O., Aluko, T.J. 2015. Estimation of groundwater recharges using empirical formulae in Odeda local government area, Ogun State, Nigeria. Challenges 6: 271–281. doi.org/10.3390/challe6020271

Chirathivat, S., Cheewatrakoolpong, K. 2015. Thailand's economic integration with neighboring countries and possible connectivity with south Asia. ADBI Working Paper Series No. 520. Asian Development Bank Institute. Tokyo, Japan.

Ali, M.H., Mubarak, S., Islam, A., Biswas, P. 2017. Comparative evaluation of various empirical methods for estimating groundwater recharge. ACRI. 11: 1–10. doi: 10.9734/ACRI/2017/37432

Alley, W.M. 2009. Groundwater. Encyclopedia of Inland Waters. Academic Press. New York, NY, USA.

Bear, J., Cheng, A.H.-D. 2008. Modeling Groundwater Flow and Contaminant Transport. Series: Theory and Applications of Transport in Porous Media, Vol. 23. Springer. New York, NY, USA.

Batelaan, O., De Smedt, F. 2007. GIS–based recharge estimation using coupling surface–subsurface water balances. J. Hydrol. 337: 337–355. doi.org/10.1016/j.jhydrol.2007.02.001

Bhattacharya, A.P., Jindal, S.R., Srivastava, B.P. 1954. Penetration of Rainwater to Groundwater Table in Western U.P., India. Memo No. 25. U.P.I.R.I Tech. Uttar Pradesh, India.

Chaturvedi, R.S. 1973. A Note on the Investigation of Ground Water Resources in Western Districts of Uttar Pradesh. Annual Report. U.P. Irrigation Research Institute. Uttar Pradesh, India.

Chen, D., Gao, G., Xu, C.Y., Guo, J., Ren, G. 2005. Comparison of the Thornthwaite and pan data with the standard Penman-Monteith estimates of reference evapotranspiration in China. Clim. Res. 28: 123–132.

Department of Groundwater Resources. 2008. Assessment of Safe Yields of the Unconsolidated Aquifers Using Mathematical Model in the Tha Chin and Mae Klong Basin Areas (Full report). Department of Groundwater Resources. Bangkok, Thailand.

Healy, R.W. 2010. Estimating Groundwater Recharge. Cambridge University Press. Cambridge, UK.

Hiwot, G.G. 2008. Groundwater recharge modelling; A case study in central Veluwe, the Netherlands. M.Sc. thesis, Geo–Information Science and Earth Observation, International Institute for Geo–information Science and Earth Observation, Enschede, the Netherlands.

Huang, T., Pang, Z. 2013. Groundwater recharge and dynamics in northern China: Implications for sustainable utilization of groundwater. Procedia Earth Plan. Sci. 7: 369–372. doi.org/10.1016/j.proeps.2013.03.182

Hughes, A., Mansour, M., Ward, R., Kieboom, N., Allen, S., Seccombe, D., Charlton, M., Prudhomme, C. 2021. The impact of climate change on groundwater recharge: National–scale assessment for the British mainland. J. Hydrol. 598: 126336. doi.org/10.1016/j.jhydrol.2021.126336

Jannis, E., Adrien, M., Annette, A., Peter, H. 2021. Climate change effects on groundwater recharge and temperatures in Swiss alluvial aquifers. J. Hydrol. 11: 100071. doi.org/10.1016/j.hydroa.2020.100071

Islam, S., Singh, R.K., Khan, R.A. 2016. Methods of estimating groundwater recharge. Int. J. Eng. Assoc. 5: 2320–0804.

Kadam, A.K., Umrikar, B.N., Sankhua, R.N. 2020. Assessment of recharge potential zones for groundwater development and management using geospatial and MCDA technologies in semiarid region of Western India. SN Appl. Sci. 2: 312. doi.org/10.1007/s42452-020-2079-7

Kaewdum, N., Chotpantarat, S. 2021. Mapping potential zones for groundwater recharge using GIS technique in the Lower Khwae Hanuman Sub–basin Area, Prachin Buri Province, Thailand. Front. Earth Sci. 9: 717313. doi: 10.3389/feart.2021.717313

Kendy, E., Zhang, Y., Liu, C., Wang, J., Steenhuis, T.S. 2004. Groundwater recharge from irrigated cropland in the North China Plain: Case study of Luancheng County, Hebei Province, 1949–2000. Hydrol. Process. 18: 2289–2302. doi.org/10.1002/hyp.5529

Khalil, A., Rittima, A., Phankamolsil, Y., Talaluxmana, Y. 2018. Groundwater recharge estimation using WEAP model and empirical relations in the Mae Klong Basin, Thailand. In: Proceedings of 7th International Conference on Environmental Engineering, Science and Management. Udon Thani, Thailand, pp. 1–9.

Krause, P., Boyle, D.P., Base, E. 2005. Comparison of different efficiency criteria for hydrological model assessment. Adv. Geosci. 5: 89–97. doi.org/10.5194/adgeo-5-89-2005

Krishna, R. 1970. Hydrometeorological aspects of estimating groundwater potential, Seminar Volum. Groundwater Potential of Hard Rock Areas of India. Bangalore, India, pp. 1.

Kroes, J.G., van Dam, J.C., Bartholomeus, R.P., et al. 2017. SWAP Version 4, Theory Description and User Manual. Wageningen, the Netherlands.

Lacombe, G., Douangsavanh, S., Vongphachanh, S., Pavelic, P. 2017. Regional assessment of groundwater recharge in the Lower Mekong Basin. Hydrology 4: 60. doi.org/10.3390/hydrology4040060

Lin, H. 2012. Hydropedology: Synergistic Integration of Soil Science and Hydrology. Academic Press. Cambridge, MA, USA.

Liu, Y., Wang, P., Ruan, H., Wang, T., Yu, J., Cheng, Y., Kulmatov, R. 2020. Sustainable use of groundwater resources in the transboundary aquifers of the five central Asian countries: Challenges and perspectives. Water 12: 2101. doi.org/10.3390/w12082101

Lu, X., Jin, M., van Genuchten, M.T., Wang, B. 2011. Groundwater recharge at five representative sites in the Hebei Plain, China. Ground Water 49: 286–294. doi.org/10.1111/j.1745-6584.2009.00667.x

Molla, D.D., Tegaye, T.A., Fletcher, C.G. 2019. Simulated surface and shallow groundwater resources in the Abaya-Chamo lake basin, Ethiopia using a spatially-distributed water balance model. J. Hydrol. Reg. Stud. 24: 100615. doi.org/10.1016/j.ejrh.2019.100615

Panigrahi, B., Goyal, M.R. 2016. Modeling Methods and Practices in Soil and Water Engineering. Apple Academic Press. Boca Raton, FL, USA.

Rwanga, S.S. 2013. A review on groundwater recharge estimation. In: Proceedings of International Conferences on Civil and Environmental Engineering. Johannesburg, South Africa, pp. 156–160.

Saghravani, S.R., Yusoff, I., Mustapha, S., Saghravani, S.F. 2013. Estimating groundwater recharge using empirical method: A case study in the tropical zone. Sains Malaysiana 42: 553–560.

Sehgal, S.R. 1973. Ground Water Resources of Punjab State. 3rd Annual Research Session, Central Board of Irrigation and Power. New Delhi, India.

Srisuk, K., Nettasana, T. 2017. Climate change and groundwater resources in Thailand. J. Groundw. Sci. Eng. 5: 67–75.

Teartisup, P., Kerbsueb, P. 2013. Land subsidence prediction in central plain of Thailand. Int. J. Environ. Sci. Dev. 4: 59–61. doi: 10.7763/IJESD.2013.V4.304

Todd, D.K. 1980. Groundwater Hydrology. University of California. Berkeley, CA, USA.

Water Resources Association. 2004. Water Resources Management Strategies and Action Plans of Thailand. Bangkok, Thailand.

Woldeamlak, S.T., Batelaan, O., De Smedt, F. 2007. Effects of climate change on the groundwater system in the Grote–Nete catchment, Belgium. Hydrogeol. J. 15: 891–901. doi.org/10.1007/s10040-006-0145-x

United Nations Educational Scientific and Cultural Organization. 2006. Transboundary Aquifers in Asia with Special Emphasis to China. UNESCO Office. Beijing, China.

Xu, G., Su, X., Zhang, Y., You, B. 2021. Identifying potential sites for artificial recharge in the plain area of the Daqing river catchment using GIS–based multi–criteria analysis. Sustainability 13: 3978. doi.org/10.3390/su13073978