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Groundwater and surface water interaction in Hau River, Mekong Delta: A preliminary investigation

NGUYEN Ngoc Tuong Tri[1,3], DANG Van Tuc[2,3], HA Quang Khai[2,3*], VO Dan Thanh[2,3], NGUYEN Thuy Dung[1,3], VO Le Phu[2,3]

[1] Faculty of Geology, University of Science (HCMUS), Ho Chi Minh City, Vietnam
[2] 2Faculty of Environment and Natural Resources, Ho Chi Minh City University of Technology (HCMUT), Ho Chi Minh City, Vietnam
[3] Vietnam National University Ho Chi Minh City, Ho Chi Minh City, Vietnam
[*] *Corresponding email: quangkhai02@hcmut.edu.vn*

Abstract: *This study investigates the interaction between groundwater and surface water in An Phu, An Giang province, an arsenic hotspot in the Mekong Delta. Eight boreholes were installed in the shallow aquifer for hydrogeological investigation and groundwater level monitoring. To quantify the recharge rate, additional data—such as Hau (Bassac) River water levels, rainfall, evaporation, temperature, and groundwater abstraction rates—were collected to generate a high-resolution 3D groundwater flow model. The model was then calibrated using the PEST tool under both steady-state and transient conditions. The results show that the shallow aquifer is semi-confined, allowing surface water to infiltrate directly into the aquifer system. Recharge flux varies by location and time, ranging from 0 to 14.1% of rainfall. As a result, the average groundwater recharge rate is 3,200 m³/day, with values ranging from 0 to 72,000 m³/day. Recharge primarily occurs during the rainy season. Groundwater also contributes to the Hau River, with a mean flow of 1,300 m³/day during the dry season. Meanwhile, the Hau River contributes approximately 2,240 m³/day to the aquifer system during the rainy season. This study provides a method for quantifying groundwater-surface water interactions on a local scale, which can be valuable for groundwater management in the area.*

Keywords: *Groundwater; surface water; Mekong Delta; groundwater flow modelling; PEST tool.*

1. Introduction

Groundwater is a crucial resource for drinking, irrigation, industrial use, and environmental sustainability (Griebler and Avramov, 2015). Groundwater plays a vital role in maintaining river flows (Sophocleous, 2002), supporting ecosystems (Griebler and Avramov, 2015), and buffering against droughts. Additionally, groundwater's natural filtration process provides water quality benefits, which can help mitigate the impacts of climate change (Bachand et al., 2014). However, over-extraction of groundwater can lead to severe consequences, including aquifer depletion, water quality degradation (Burri et al., 2019), and land subsidence highlighting the need for responsible management to ensure its long-term sustainability (Khorrami and Malekmohammadi, 2021; Kondolf et al., 2022; Bagheri-Gavkosh et al., 2021).

In Vietnam, over 55 million people rely on groundwater for their daily needs (Carrard et al., 2019), making the understanding of groundwater dynamics and managing this resource in a sustainable manner are the top priorities. The Mekong Delta (MD) region, the world's third-largest delta, covers approximately 40,000 km² and is the most productive agricultural region in Vietnam (Cao et al., 2022). Groundwater is crucial to the region's sustainable development, providing about 2 million m³/day of freshwater for a wide range of uses (Ha et al., 2024). However, over-extraction of groundwater in the Mekong Delta has led to challenges such as acidification, salinization, and land subsidence (Ha et al., 2019; Minderhoud et al., 2017).

The aquifers in the Mekong Delta are also a significant source of arsenic (As) contamination, particularly in shallow aquifers (<100 m depth) due to geological conditions like rich organic matter and a reducing environment (Erban et al., 2014; Asta et al., 2019). As a result, millions of people in the region are exposed to potentially toxic levels of arsenic in groundwater (Berg et al., 2007; Merola et al., 2015).

Despite the importance of groundwater in the Mekong Delta, the understanding of its aquifer systems remains unclear. For example, many previous studies assumed that the aquifer system is confined, suggesting that the recharge rate is low (Erban et al., 2014; Minderhoud et al., 2017; Pham et al., 2019; Ha et al., 2024). Other studies found little evidence for the significant role of rainfall and river water in groundwater recharge (Tweed et al., 2020). However, recent research suggests that groundwater recharge from rainfall and river water may play a more significant role, influencing the groundwater's geochemical characteristics (Duy et al., 2021; Tu et al., 2022). The hydrogeological conditions in the MD are highly complex and recharge condition may vary depending on location.

A poor understanding of the aquifer system at a local scale can result in inaccurate interpretations of hydrogeochemical processes, leading to poor groundwater management decisions. To address this knowledge gap, our study focused on the Khanh An commune, An Phu district, An Giang province, MD. Eight monitoring wells are installed to assess the geological strata and monitor groundwater levels. Additionally, groundwater flow model with the PEST tool is applied to quantify groundwater recharge, discharge, and storage in the study area. The findings of this study are crucial for informing water management strategies in the region.

2. Study area

The study area covers an area of about 11.5 km^2, including Khanh An commune, Long Binh town and a part of Khanh Binh commune, An Phu district, Mekong Delta (Fig. 1). This area is located in the Vietnam – Cambodia border which is the first place of Hau River (one of the two main branches of the Mekong Delta; also called as Bassac River) enters the Vietnamese Mekong Delta region. The main river systems in the area includes Binh Di River and Hau River. Topography is relatively flat terrain, with elevations ranging from 0.5 to 3.0 m and gradually decreasing from the riverside to the inland.

The temperature in the study area exhibits seasonal variations, with the dry season generally seeing a rise in temperature, though the temperature differences between months are not extreme. The average annual temperature is around 27.6°C, with a modest variation of approximately 5.1°C between the highest and lowest temperature months. The highest temperatures, reaching around 30°C, occur during April and May, while the coldest months span from December to February, with temperatures ranging from 24.6°C to 27.7°C. Rainfall in the area follows a distinct seasonal pattern, with the rainy season occurring from May to November and the dry season from December to April. The average annual rainfall ranges between 1,000 and 1,300 mm, with the majority of rainfall (83-89%) occurring during the rainy season. The average annual air humidity is about 72%, with seasonal fluctuations. During the dry season, humidity averages 80%, reaching a low of 72%, while the rainy season sees humidity levels rise to around 85%.

Hydrological conditions in the area are influenced by the semi-diurnal tidal regime of the East Sea and the flow dynamics of the Mekong River, particularly the Tien and Hau Rivers (Bassac River). These factors play a significant role in the formation of the "flood season," which typically occurs from August to December. This seasonal flooding is a result of both the seasonal rains and the tidal influences from the sea. However, the construction of a closed dike system for agricultural purposes restricts flooding to areas outside the dike system.

Groundwater in this region is known for having high concentrations of arsenic (As), which is attributed to the reductive dissolution of iron (Phan et al., 2019; Wang et al., 2018; Asta et al., 2019). In the past, groundwater was exploited for drinking and irrigation. However, according to our initial surveys during 2023-2024, drinking water is supplied by water supply plants using surface water. While, groundwater is mainly used for irrigation in recent years due to the awareness of high As concentrations. The groundwater is mainly extracted from 18 to 30 m below land surface, in Holocene aquifer.

3. Methodology

This study applies groundwater flow modelling to simulation of 3D flow conditions in the shallow aquifer systems (Fig. 2). At the beginning data collection is conducted to create input file for groundwater model development. Groundwater model is then developed, calibrated, and validated with observation data before using for groundwater flow assessment.

3.1. Data collection

Daily rainfall and hourly water level data of Hau (Bassac) River during March 2023 to March 2024 are collected from An Giang Provincial Hydrometeorological Station for this study. The rainfall and river water level station are located about 2 km from KA-W5 (Fig. 1). Groundwater extraction data is also collected from An Phu District Department of Natural Resources and Environment.

3.2. Hydrogeological investigation

In the area, no hydrogeological investigation has been conducted so far, the groundwater levels data is also not available in the study area. Thus, five wells are installed with depth of 20 to 22 m (from land surface) in the Holocene aquifer during March, 2023. During well installation, sediment cores are collected for understanding lithological characteristics, well casing and screen using PVC material are installed for monitoring groundwater levels. The wells are drilled by using the rotary drilling technique with bentonite as the drilling fluid. The length of well screens varies from 6 to 12 m and located in sandy layers. The wells development is conducted after well installation for removing all particle inside of the well. Monitoring wells is also checked and pumped every month for groundwater quality sampling and checking groundwater levels. A sensor is installed in the well for monitoring groundwater levels every 15 minutes. The wells name MW1, MW2, MW3 are additionally installed for monitoring groundwater level in the area for enhancing groundwater levels data (Fig. 1). Groundwater level in the wells is measured manually every day at 7 am in the morning.

3.3. Groundwater modelling

Groundwater flow model is simulated for the shallow aquifer (up to 30 m) and uses two river (Binh Di and Hau) reaches as the model boundary (Fig. 1). The model is conducted using the MODFLOW 2005 code of USGS (Harbaugh, 2005). The governing partial - differential equation for the three-dimensional flow of groundwater of constant density through porous earth material of the code is described in eq.1 below:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \qquad (1)$$

Where K_{xx}, K_{yy}, and K_{zz} are values of hydraulic conductivity in x, y, and z dimensions, respectively (m/day); h is groundwater level in the aquifer (m); W is a volumetric flux per unit volume and represent sinks or sources (1/day), and t is time (day).

The input parameters for the groundwater flow model include aquifers strata and characteristics, boundary conditions, recharge flux, river water level, and conductance coefficients, etc. Thus, the collected data and hydrogeological investigation information are used to build a 3D groundwater flow model for the area (Fig. 2). The 3D grid cells cover an area of about 11.5 km² (Fig. 1c). The total number of grid cells is 74,256, with cell sizes of 40 m (x) x 40 m (y) x 5 m (z). According to geological condition of the area (detail description in section 4.1), the vertical grids are simply divided into a total of 6 layers, the first layer represent for silty to fine sand on the shallowest part. The sandy layer is about 25 m thick and dived into 5 sub-layers for detail simulation of water flow. The recharge areas are divided into six zones (R1–R6), each with a different recharge flux, based on the morphological conditions in the area (Fig. 3).

The groundwater model is calibrated under steady-state conditions to identify unknown parameters such as the groundwater recharge rate and river conductance, with the support of parameter estimation tools (PEST) (Fig. 2). The steady-state model is initially run for the dry season with no groundwater recharge to estimate river conductance coefficient, and then the model is run for the rainy season to estimate the initial recharge rate. The recharge rate and river conductance coefficient values are used as input parameters for the transient models. During calibration, the recharge rate is adjusted to achieve the best fit between the calculations and the daily observed groundwater levels from May 2023 to May 2024.

4. Results

4.1. Geological condition

Based on core samples from five monitoring wells (KA-W1 to KA-W5), drilling records from MW1 to MW3, and interviews with local farmers regarding private well construction, the stratigraphy down to 30 meters depth can be broadly divided into three zones (Fig. 4). The uppermost unit generally comprises silty to fine sand, while the underlying layer consists of fine to coarse sand. Notably, silty sediments are present from the surface down to approximately –6 m elevation in KA-W3. In contrast, KA-W1 shows a silty sand layer above –1 m elevation. For KA-W4, KA-W2, and KA-W5, the top layer is dominated by fine sand, observed above –4 m, –2 m, and –1 m elevation, respectively. The deeper fine to coarse sand unit lies beneath these elevations. Drilling of MW1–MW3 was terminated at 30 meters depth due to the encounter of hard red Pleistocene clay. Collectively, these observations suggest that the shallow Holocene aquifer is semi-confined, allowing partial infiltration of surface water. This contrasts with previous interpretations that described the Holocene aquifer as fully confined (Erban et al., 2014; Minderhoud et al., 2017; Ha et al., 2019), and thus provides new insight into the local hydrogeological setting.

4.2. Model calibration

a) Steady state conditions

Calibration is conducted in steady state condition for dry and rainy seasons. In the dry season model, the recharge from precipitation is assumed to be negligible (recharge = 0 m/d) due to negligible of rainfall and high evaporation; the groundwater extraction rate is assigned with an average exploitation flow of 10 m^3/day/well, as provided by the Department of Natural Resources and Environment (DONRE) of An Giang province. Unknown parameters such as hydraulic conductivities, conductance coefficient is estimated by using PEST tool of model. The obtained hydraulic conductivities and conductance coefficients from dry season model is then used for the groundwater model in the rainy season for calculation of recharge rate in the study area.

In the rainy season model, according to the field survey, groundwater is mostly extracted for irrigation, and groundwater pumping is negligible in the rainy season due to heavy rain. Thus, the groundwater extraction rate is set to 0 m^3/day per well. The unknown parameter, recharge, is also estimated using the PEST tool.

The PEST calibration results demonstrate a good fit (RMSE = 0.1 m) between observed and modeled groundwater levels during both the dry and rainy seasons (Fig. 5a, b). During the dry season, the model shows that groundwater levels in inland areas can drop to more than -3 meters, falling below the river water level. This suggests that groundwater extraction is causing a decline in groundwater levels, which may, in turn, induce river water to flow into the aquifer system. In contrast, during the rainy season, the groundwater level nearly reaches the land surface. The model also indicates that the conductance coefficients are approximately 4.51 (m^2/d)/m for the Hau River and 0.81 (m^2/d)/m for the Binh Di River. The estimated recharge flux during the rainy season ranges from 7.2×10^{-9} to 2.2×10^{-5} m/day, which represents approximately 0.0001% to 0.19% of the total rainfall, with an average of 0.11% of the total daily rainfall.

b) Sensitivity analysis

Sensitivity analysis is conducted for parameters such as conductance, flow rate, hydraulic conductivities, and recharge flux to understand the important factor that has more influence on groundwater flow model results. The conductance, flow rate, permeability and recharge flux are assigned to increase to 10%, 20% and 50%, respectively. The results reveal that groundwater extraction rate is the most sensitive parameter following hydraulic conductivity and recharge rates (Fig. 6). The river with conductance is being the least sensitive parameters.

4.2. Transient calibration

The hydrogeological parameters of calibrated models are used as input conditions to transient model. However, the initial transient model shows poor agreement between calculated groundwater level and observation data (Fig. 7), then the groundwater recharge flux is adjusted for finding the agreement between observation and simulation groundwater levels. As a result, the final calibration step showed the lowest different values (< 0.6 m) between observation data and calculation data (Fig. 7). The result suggests that recharge rate may vary according to local condition. Particularly, in zone 1, 2, 3, 4, 5, and 6 the recharge fluxes vary from 0 to 0.012, 0 to 0.014, 0 to 0.017, 0 to 0.017, 0 to 0.012 and 0 to 0.0012 m/day, respectively (Fig. 8). The recharge fluxes are about 0 to 9.8%, 0 to 11.8%, 0 to 14.1%, 0 to 14.1%, 0 to 9.8%, and 0 to 1% of daily rainfall. The result also recommends that even the PEST tools is widely applied with steady state model calibration (Doherty and Hunt, 2010; McLane, 2024), however, it may underestimate groundwater recharge. Moreover, the recharge rate may not be in linear relationship with rainfall, and recharge rate is much dependent on rainfall intensity, locations.

4.3. Groundwater flow budget

The temporal variation of simulated groundwater flow components from March 2023 to March 2024 reveals pronounced seasonal dynamics in the Hậu River region (Fig. 9). The model estimated an average groundwater recharge rate of approximately 3,200 m^3/day, with values ranging from 0 to 72,000 m^3/day, primarily occurring during the rainy season (May–October). This period coincided with peaks in recharge flux (green line). In contrast, during the dry season (November–March), recharge declined to near-zero, while storage inflow (brown line) increased progressively, suggesting aquifer replenishment driven by lateral inflows and reduced extraction.

Groundwater–surface water interactions also exhibited seasonality. During the dry season, the aquifer contributed an average of 1,300 m^3/day to the Hau River. Conversely, during the rainy season, the Hau River supplied approximately 2,240 m^3/day to the aquifer system. Among all water balance components, regional groundwater inflow from model boundaries accounted for the largest contribution, with an average of 9,200 m^3/day, providing sustained support to aquifer levels across seasons. Groundwater abstraction from wells contribute to storage decline during the dry season.

6. Conclusion

This study investigates the interaction between groundwater and surface water in An Phu, An Giang, Mekong Delta. Eight monitoring wells were installed to assess groundwater levels and hydrogeological conditions. The study found that the shallow aquifer system in the area is semiconfined, allowing surface water to easily infiltrate into the aquifer. Groundwater flow modeling, along with the PEST tool, indicates that groundwater in the area is influenced by groundwater extraction for irrigation, rainwater, and the river water system. The conductance coefficients are approximately 4.51 (m²/d)/m for the Hau River and 0.81 (m²/d)/m for the Binh Di River. The recharge rate is up to 14.1% of rainfall, varying according to time, rainfall amount, and location. Generally, recharge mainly occurs during the rainy season, and the mean groundwater recharge rate is about 3,200 m³/day, varying from 0 to 72,000 m³/day. Groundwater also contributes to the Hau River with a mean flow of 1,300 m³/day during the rainy season. The Hau River also contributes about 2,240 m³/day to the aquifer system during the dry season. Our findings highlight the importance of local conditions that can influence the recharge rate. The results are crucial for groundwater management in the area.

Tables and figures (with descriptions)

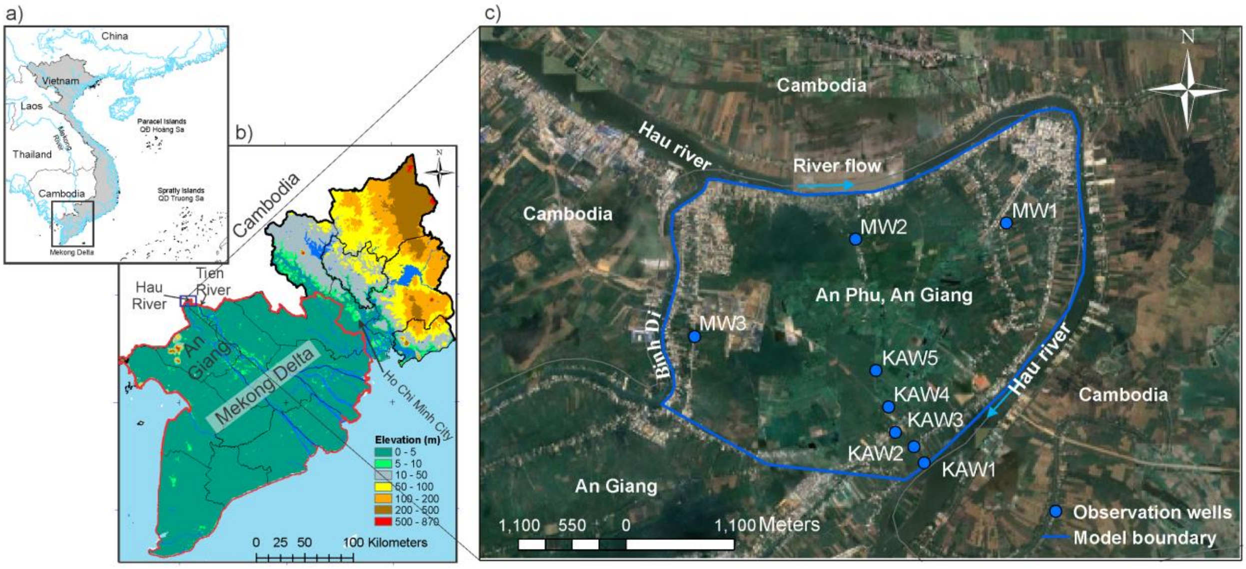

Fig. 1. Location of Mekong Delta, Vietnam (a); topography map of Mekong Delta, Vietnam (b); location of study area and 08 installed observation wells in An Phu, An Giang (c)

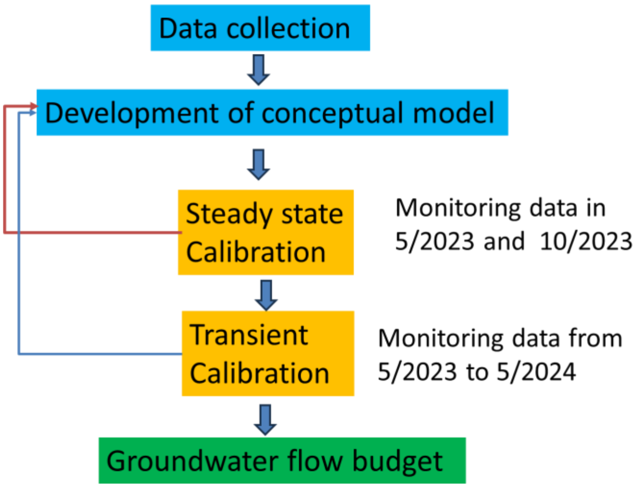

Fig. 2. Flow chart of groundwater modelling application

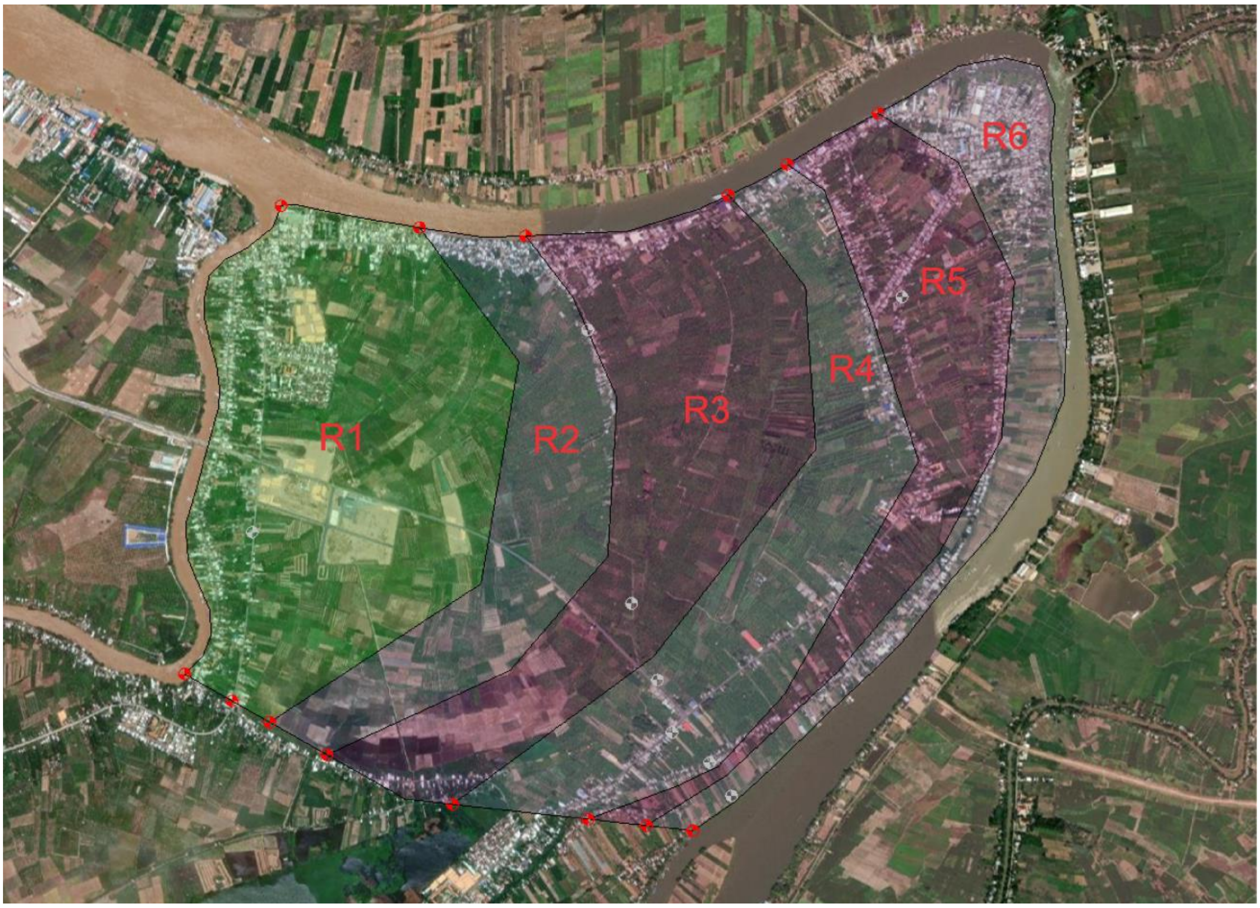

Fig. 3. Groundwater recharge zones (R1-6 stand for recharge zone ID)

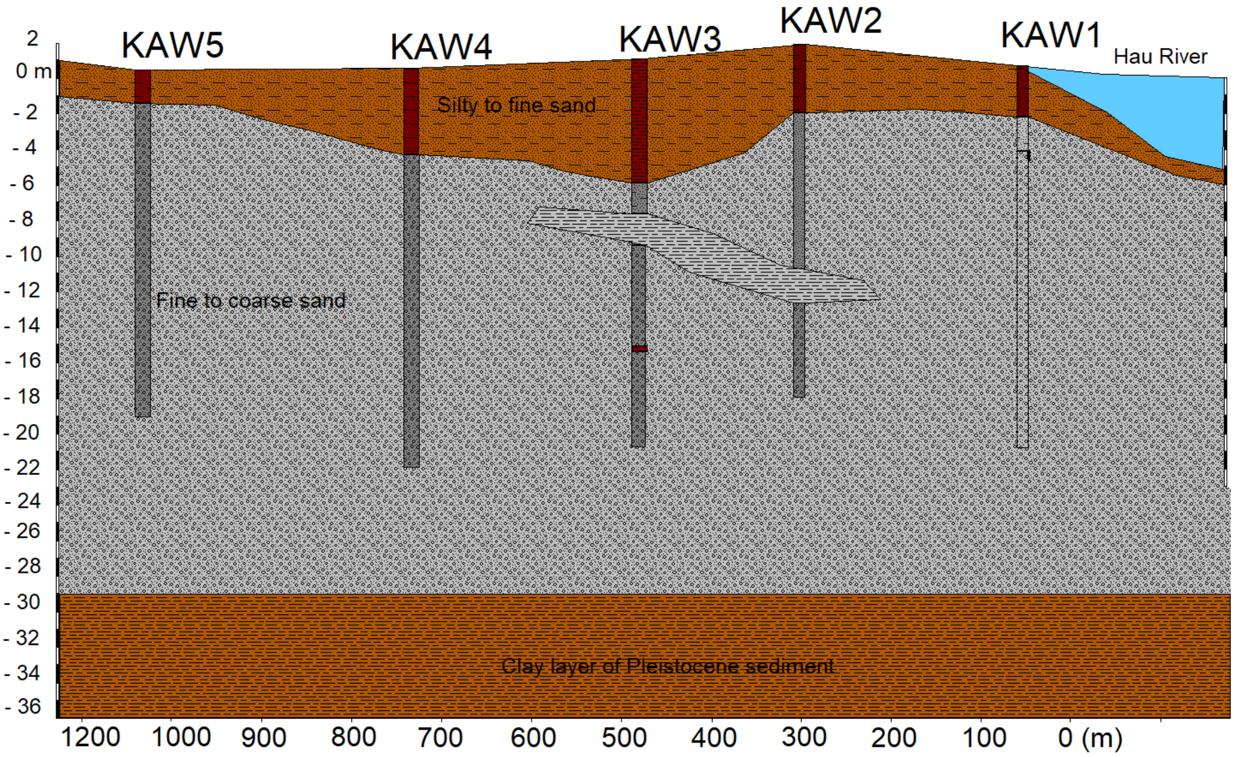

Fig. 4. Geological cross-section from KAW1 to KAW5

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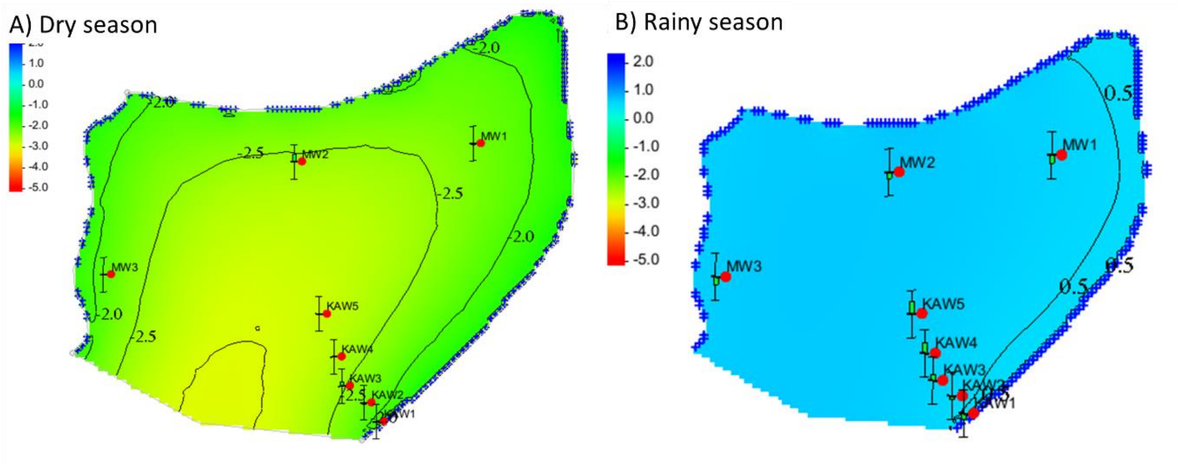

Fig. 5. Calibrated groundwater levels in the dry season (a) and rainy season (b). The color scale and contour lines indicate the simulated groundwater levels, and the box plot with green color indicates good agreement between observed and simulated groundwater levels at observation wells.

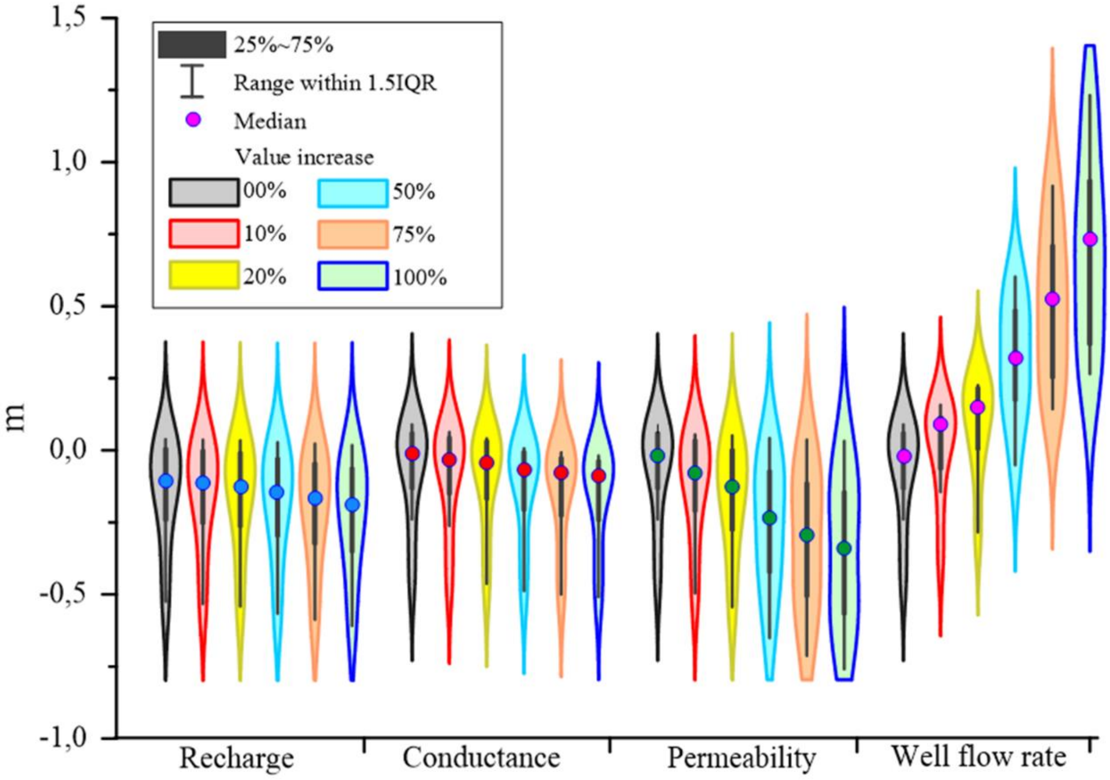

Fig. 6. Sensitivity analysis results

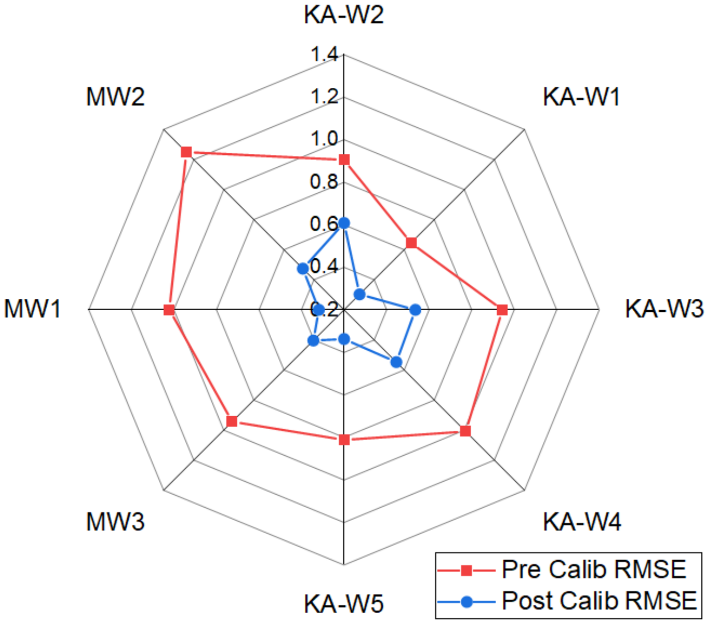

Fig. 7. Calibration results of transient models

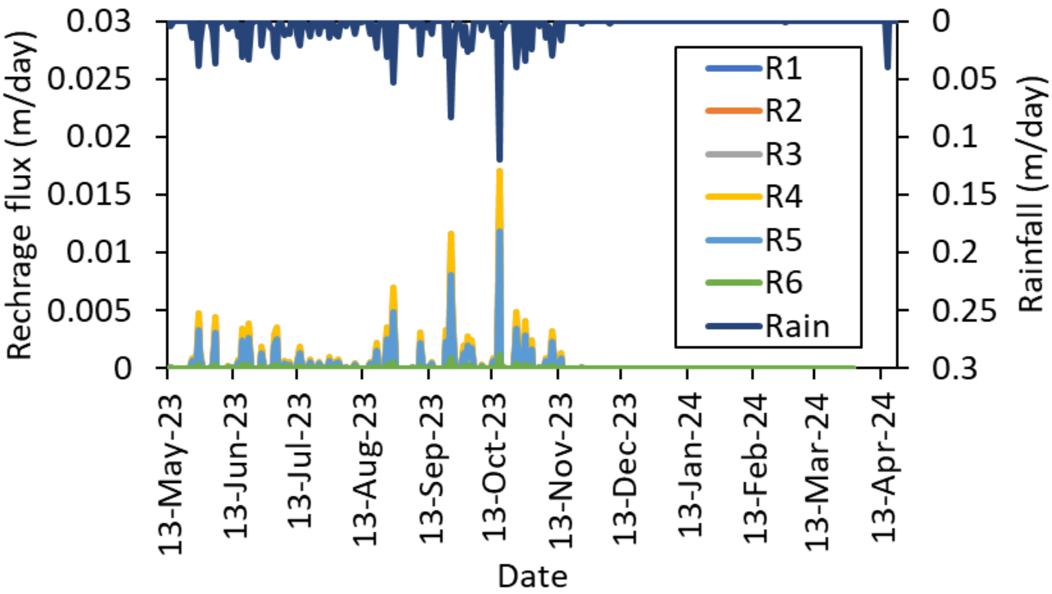

Fig. 8. Daily recharge flux and rainfall in the study area

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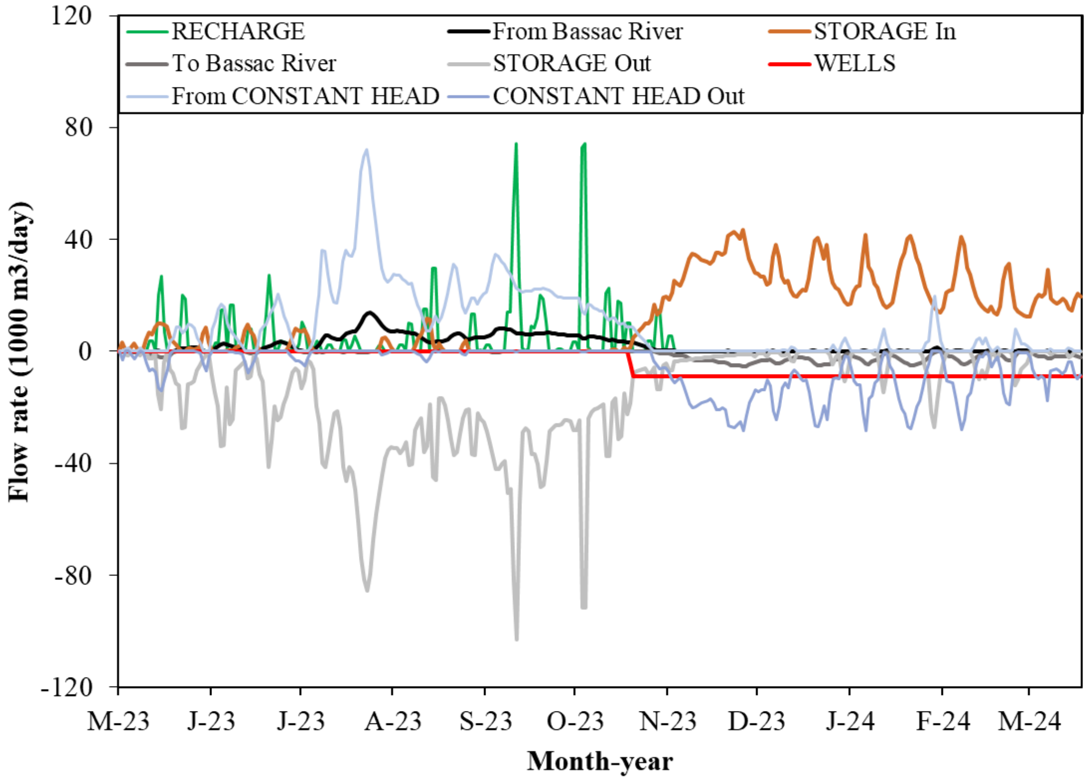

Fig. 9. Groundwater flow budget in the Khanh An, An Phu, An Giang province

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