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The role of groundwater recharge in groundwater exploitation of the Red river delta plain

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Abstract:

The Red river delta plain (RRDP), the second largest delta in Vietnam, is situated in the northern region of the country and spans an area of 21,260 km² and supports a population of over 22.9 million inhabitants. Groundwater extraction primarily occurs from quaternary sedimentary aquifers, with a total discharge of approximately 1.5 million m³/day. However, certain localities, such as Hanoi and Nam Dinh, have exhibited signs of over-exploitation, leading to associated issues such as depletion, land subsidence, saltwater intrusion, and water pollution. Groundwater recharge in the study area primarily originates from various sources including rainfall, irrigation, wastewater, and the river system. The objective of this study is to evaluate the contribution of groundwater recharge to groundwater exploitation reserves within the Red river delta. To achieve this, a three-dimensional (3D) model employing the MODFLOW code was developed and refined through the comparison of modelled and actual groundwater levels within the surveillance network. The refined model's budget analysis indicated that the recharge of quaternary aquifers by means of rainfall, irrigation, and effluent occurs year-round, with the peak recharge happening during the monsoon season (approximately 68% of rainfall) and the nadir during the arid season (approximately 10% of rainfall). Throughout the monsoon period, the river system predominantly replenishes the quaternary aquifers, contributing approximately 9.51-17.36% to the overall water balance of the aquifers. The influx from fractured aquifers at the fringe of the plain to the quaternary aquifers remains consistently minimal year-round.

Keywords: **groundwater modelling, groundwater recharges, quaternary aquifer, Red river delta**.

Classification numbers: **4.2, 5.3**

1. Introduction

Groundwater recharge is the process by which water infiltrates the ground, adding to the groundwater reservoir [1]. There are three main types of groundwater recharge: i) Direct recharge, where excess soil moisture percolates vertically down to the water table. ii) Indirect recharge, occurring through infiltration and percolation via riverbeds or lakes. iii) Localised recharge, happening at concentrated points such as joints, depressions, sinkholes, or rivulets [2, 3]. Groundwater recharge plays a critical role in the water balance of a basin and is key to the sustainable use of water resources. However, measuring groundwater recharge directly is challenging [4]. B.R. Scanlon, et al. (2002) [5] suggested using multiple methods to estimate groundwater recharge and then comparing the results of each. Understanding the contribution of groundwater recharge to the regional groundwater flow system is crucial for management and economic reasons, as indicated by J.G. Arnold, et al. (2000) [6], R. Hirata, et al. (2012) [7], and C.R. Hearne, et al. (2010) [8]. Groundwater recharge typically feeds local flow systems as base flow [9], while some may exit the basin into deeper aquifers, termed groundwater outflow to the regional system.

The Red river delta plain, covering over 21,260 km² and home to 22.9 million people in Vietnam, heavily relies on groundwater resources, with a daily extraction rate exceeding 3 million m³/d. However, signs of over-exploitation, such as depletion, land subsidence, saline water intrusion, and water contamination, have been observed in certain areas like Hanoi and Nam Dinh [10]. While various studies have focused on groundwater recharge in the RRDP, most have concentrated on specific points or local areas, and a comprehensive regional study has yet to be conducted. Earlier research by P.Q. Nhan (2000) [11] used modelling to estimate groundwater recharge, allocating 87% to the rainy season and 56.28% to the dry season. The limitations of data and lack of validation from alternative methods, however, cast uncertainties on these findings. T.L. Tran (2011) [12] applied isotope hydrology to assess groundwater recharge in Dan Phuong, Hanoi, identifying a linkage between the Holocene and Pleistocene aquifers with a 19.4% contribution from leaky sources. The study noted that during the rainy season, the Holocene aquifer was recharged by the river, whereas in the dry season, it discharged into the river. P.Q. Nhan, et al. (2019) [10] used isotope hydrology to assess the interaction between the Red river and groundwater, showing

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that Red River water contributed 50, 52, and 57% to well fields in Ha Dinh, Mai Dich, and Phap Van, respectively. D. Postma, et al. (2017) [13] dated groundwater and determined recharge from the Red river to aquifers using Tritium/Helium dating in the Nam Du area. F. Larsen, et al. (2008) [14] employed isotopes and modelling to assess recharge from the Red river and rainwater to quaternary aquifers in Dan Phuong. V.C. Doan (2015) [15] utilised GIS, MODFLOW, and water table fluctuation methods to evaluate groundwater resources in the RRDP. D.H. Trieu (2022) [16] employed modelling and water table fluctuation methods to categorise Red river boundary conditions and bedrock boundaries in the Southwest of Hanoi, with groundwater recharge and discharge varying from -191 m³/day/km to 227 m³/day/km. Recently, P.Q. Nhan, et al. (2022) [17] utilised GIS and remote sensing to analyse factors and to zone direct groundwater recharge in the RRDP. They quantified the recharge using ^{3}H dating, yet its role in aquifer systems remains unclear. Therefore, this study aims to comprehensively assess the contribution of direct groundwater recharge, stemming from sources such as rainwater, irrigation, and wastewater, to the aquifer system.

2. Study area

2.1. Location and natural conditions

The study area, delineated in Fig. 1, spans an extensive area exceeding 21,260 km² within the bounds of the RRDP. Positioned within a tropical humid monsoon climate, the territory experiences a pronounced dry season from November to April, accounting for 15% of annual precipitation, contrasted by a significant rainy season from May to October, delivering 85% of annual rainfall. The area is characterised by persistently high relative humidity levels, averaging 84.5% annually.

Annual climatic variations across the delta include precipitation ranging from 1,200 to 2,700 mm and evaporation from 828.2 to 1,057.1 mm. Temperature profiles show a marked seasonal variance, peaking at 35 to 39°C, with an annual mean between 23 and 23.5°C. Diurnal temperature fluctuations are substantial, with a range of 8 to 15°C in summer and 4 to 13°C in winter. The RRDP is defined by a complex hydrological network, with the Red river system and the Thai Binh river system as prominent features, where drainage densities vary from 0.4 to 0.7 km/km².

The terrain within the RRDP is varied, encompassing coastal areas below 1 m, terraced riverine zones from 7 to 15 m, hilly regions at 50 to 100 m on the plain, and mountainous regions ascending to 900 m on the western and north-western edges. The landscape is sculpted by fault systems, particularly the Northwest-Southeast, Northeast-Southwest, and sub-meridian faults, which dictate the tectonic activity and subdivide the plain. The eastern and south-eastern coastline stretches approximately 200 km from Quang Ninh to Thanh Hoa, affected by saline intrusion from waves, tides, and river dynamics, influencing the coastal ecosystem, agriculture, and shallow aquifers.

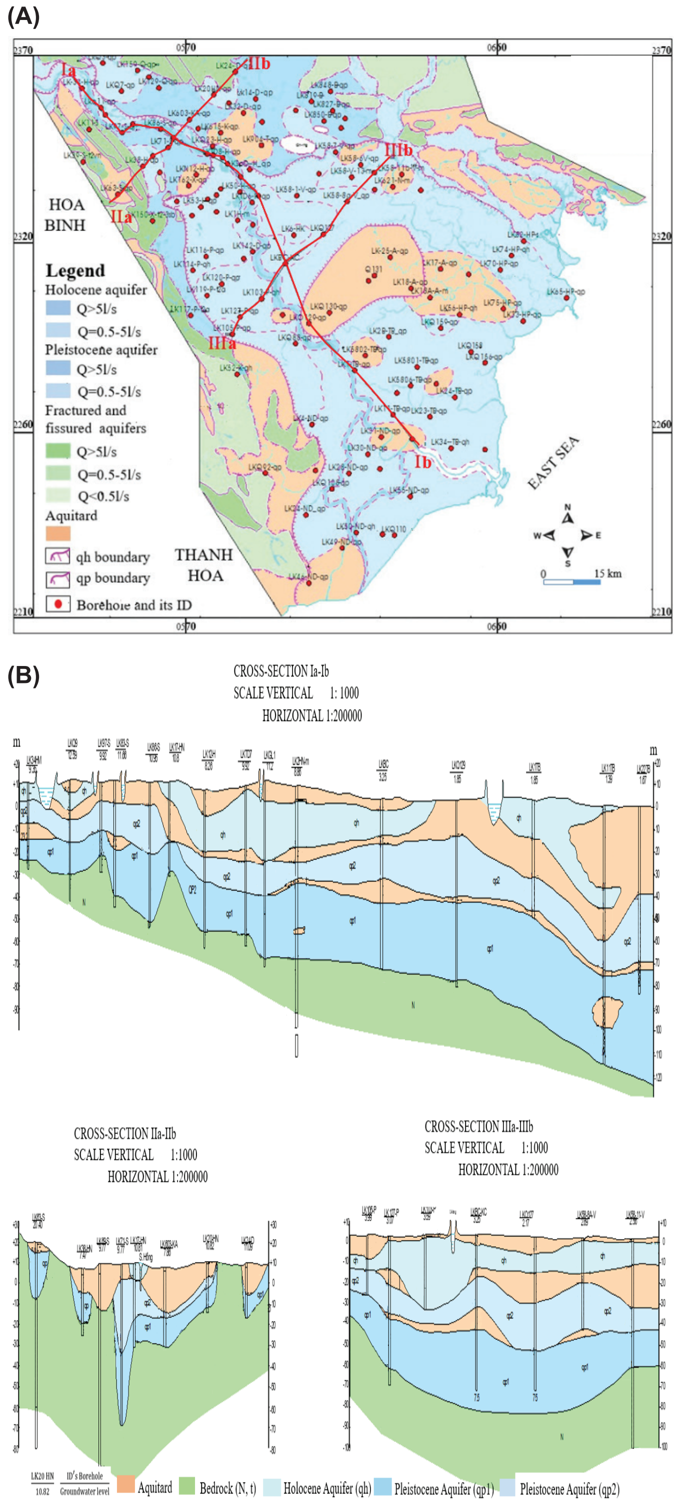


Fig. 1. Hydrogeological map of the Red river delta plain (A) and cross-sections of hydrogeology in the Red river delta plain (B). The fraction $\frac{\mathrm{LK105-P}}{3.99}$ indicates the borehole over the static water level. The numerical values accompanying the borehole diagram denote the depths of the layers, screens, and depth of borehole. The colours and symbols representing the aquifers and aquitards on the map are given in the figure (modified from [18]).

2.2. Hydro-geology settings

The RRDP segment under study lies in the northwest of the Red River sedimentary basin, distinguished by sediment deposits from the Paleogene, Neogene, and Quaternary periods. Flanked by mountain ranges bearing Palaeozoic and Mesozoic strata, the sedimentary deposits of the RRDP have formed across five fining-upward cycles, outlined by T.L. Tran (2011) [12]. These cycles, ranging from the lower to upper Pleistocene and lower to upper Holocene, comprise varied sedimentary makeups from coarse-grained alluvial and fluvial to fine-grained deltaic-lacustrine and swamp deposits. The Pleistocene aquifers, recharged by the adjacent mountains, exhibit an average annual replenishment of 100 to 400 mm [11]. The hydraulic gradients typically span 0.05 to 0.15, and the groundwater flow velocity within Holocene aquifers is several tens of meters annually [12].

3. Materials and methods

3.1. Construction of the groundwater flow model and evaluation of the role of groundwater recharge in groundwater exploitation

The differential equation of motion of groundwater under heterogeneous and anisotropic environment is as follows:

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

where K_{xx}, K_{yy}, and K_{zz} are the aquifer hydraulic conductivities in the *x*, *y,* and *z* directions, respectively; S_s specific storage of the aquifer; *h* hydraulic head in the aquifer; *t* is time; and *W* is the source and/or sink of the aquifers. Equation (1), in conjunction with the specified boundary and initial conditions for the aquifers, constitutes a mathematical model for the flow of groundwater. To address the aforementioned equation, it is imperative to identify the function *h(x, y, z, t)* that complies with Eq. (1) and the prescribed boundary conditions. The temporal evolution of *h* will describe the characteristics of the groundwater flow, enabling the calculation of both the flow rate and the flow direction.

To evaluate the role of direct groundwater recharge to groundwater exploitation within the RRDP, we rely on recent research data as the basic inputs for building a groundwater flow model. These datasets include:

- Updated regional data derived from the hydrogeological map with scale of 1/200,000 (Fig. 1) compiled by V.T. Tam, et al. (2018) [19].

- A comprehensive survey of the current state of groundwater exploitation, conducted in support of the Hong-Thai Binh river basins planning, as presented by the Department of Water Resources Management (2020, 2022) [19, 20].

- Delineation and quantification of direct groundwater recharge across the delta, analysed by P.Q. Nhan, et al. (2022) [17].

- Assessment of groundwater recharge from the bedrock and the hydraulic interaction between the Red river and groundwater in Hanoi and its vicinity, as researched by D.H. Trieu (2022) [16].

- A comprehensive assessment of the impact of urbanisation on groundwater resources in Hanoi, executed with precision by V.T. Tam, et al. (2018) [18].

These datasets serve as the cornerstone for the groundwater flow model within the RRDP.

The groundwater flow model was constructed utilising GMS software by Aquaveo (2018) [21], with calibration performed via data from the national monitoring network and our recent investigations. Post-calibration, the RRDP model's results were analysed using the BUDGET package. These budget assessments and predictive scenarios highlighted the contribution of direct groundwater recharge to groundwater exploitation in the RRDP.

3.2. Input data and conceptual model for the groundwater system

- *Digital Elevation Model (DEM):* This model is created from contour lines and elevation data on a 1:50,000-scale topographic map, covering 47 map sections with 500x500 m dimensions. The process within ArcGIS involves two steps:

1. Generation of a triangular irregular network (TIN) using contour lines, elevation points, and local key elevations. TIN modelling preserves elevation point shapes and sharp peaks.

2. Interpolation of the DEM map from the TIN using the natural neighbour method, ensuring accurate representation by referencing surrounding points and avoiding elevation anomalies.

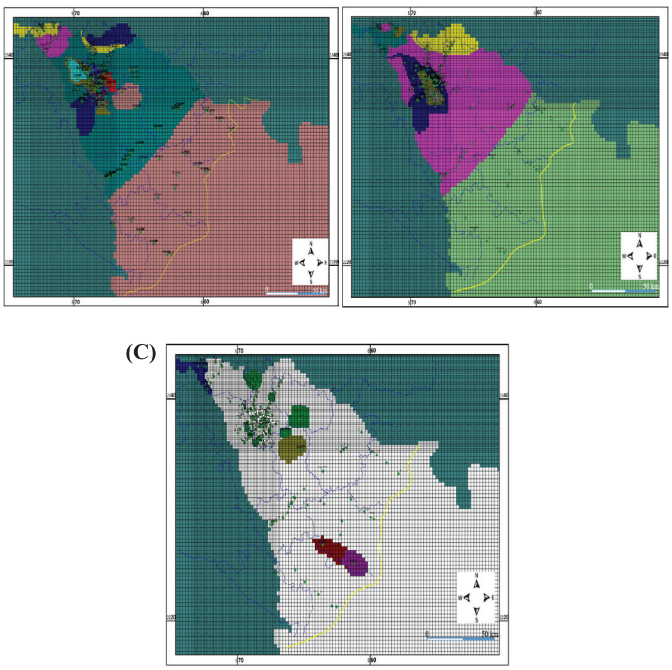
- *Model grid development:* The modelling area, which has been expanded to 14,860 km², intentionally extends beyond the eastern boundary of the Pleistocene aquifer. Investigations have indicated that the Pleistocene aquifer in the eastern sector of the Northern region projects into the sea and is not confined by the current coastline, thus justifying the model's spatial extension. The research area has been methodically divided into a grid format, consisting of 162 rows and 223 columns, each cell measuring 1000x1000 m. Notably, within the Hanoi vicinity, grid resolution has been refined to 500x500 m in response to the dense clustering of extraction wells.

- *Stratigraphic layer classification:* The stratigraphic layout was interpolated from an extensive dataset of 728 well logs, as detailed by P.Q. Nhan, et al. (2022) [17]. This information has been stratified into four key layers for hydrogeological assessment, including the surface aquitard layer (Aquitard 1), the Holocene aquifer (qh), the interjacent Holocene-Pleistocene aquitard (Aquitard 2), and the Pleistocene aquifer (qp).

- *Hydrogeological parameters:* The model incorporates essential hydrogeological parameters hydraulic conductivity (*K*) and storativity (*S*), are integrated into the model in accordance with previously established research findings. These parameters have been rigorously delineated and extensively documented in recent research conducted by P.Q. Nhan, et al. (2022) [17]. For the Holocene aquifer, hydraulic conductivity values range from a minimum of 0.02 m/day to a maximum of 158 m/day, with an average of 26.1 m/day. In the case of the Pleistocene aquifer, these values range from a minimum of 0.5 m/day to a maximum of 184 m/day, with an average of 34.75 m/day (Fig. 2).

(A) (B)

(C)



(D)

	$K_x=K_y=10K_z$		$K_x=K_y=10K_z$		$K_x=K_y=10K_z$		$K_x=K_y=10K_z$
	0.34		27.86		$5x10^{-4}$		$1.68x10^{-4}$
	100.0		13.49		4.0		30.0
	0.02		$363x10^{-4}$		150.0		10^{-4}
	34.76		1.0		40.0		27.40
	$48x10^{-4}$		102.4		60.0		10^{-3}

Fig. 2. Hydrogeological parameters. K_x, K_y, and K_z denote the hydraulic conductivity in the *x*, *y*, and *z* dimensions, respectively, for both the Holocene **(A)** and Pleistocene **(B)** aquifers. Additionally, specific storativity (S_s), specific yield (S_y), effective porosity (Eff Por), and total porosity (Tot Por) are defined for the Pleistocene aquifer **(C)**. Notably, the storativity coefficient for the Holocene aquifer is explicitly set at 0.01. The hydraulic conductivities K_x, K_y and its colour of Holocene and Pleistocene aquifers **(D)**.

- *Groundwater recharge:* The data on groundwater recharge that was integrated into the model stems from the recent research conducted by P.Q. Nhan, et al. (2022) [17] (Fig. 3). This encompasses a comprehensive methodology that utilises remote sensing for interpreting conditions conducive to groundwater recharge, coupled with an overlay analysis conducted via GIS techniques. To refine this approach, it is crucial to accurately determine the relative significance of various contributing factors through the implementation of the analytical hierarchical process (AHP). Additionally, the application of the direct measurement method employing the radioactive isotope ^{3}H has proven to be exceedingly effective for verification purposes.

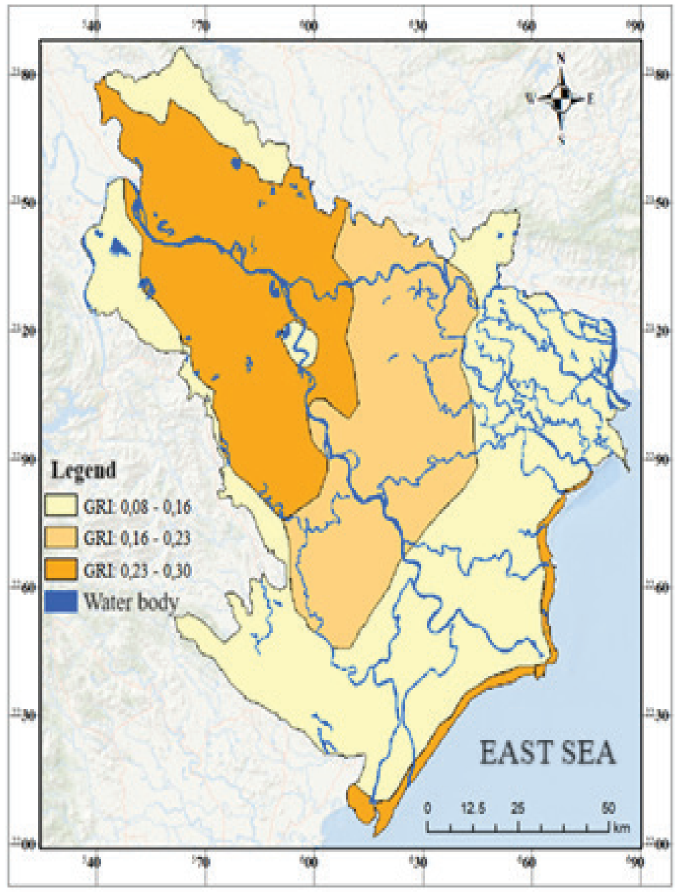


Fig. 3. Zonation of direct groundwater recharge within the Red river delta plain. The map is characterised by the GRI index, delineated into three ranges: 0.08-0.16, 0.16-0.23, and 0.23-0.30. These intervals correspond to direct groundwater recharge rates of 188, 372, and 429 mm/year, respectively [17].

- *Boundary conditions:* The boundary conditions for the model, as delineated in Section 3.1, are based on up-to-date scholarly findings. For the simulation of the Red-Thai Binh river systems, the general head boundary (GHB) method is adopted, utilising river bed conductance figures from P.Q. Nhan (2000) [11] and D.H. Trieu (2022) [16]. The evaporation boundary conditions are defined by averaging meteorological data collected over thirty years. Inputs concerning groundwater recharge from bedrock formations are derived from the findings of D.H. Trieu (2022) [16]. The seaward boundaries follow the hypotheses of V.H. Hoan, et al. (2022) [22], which postulate the extension of freshwater into the ocean as influenced by topographic elevation and geological bed characteristics. This assumption establishes constant head (CH) conditions along the model's boundaries, with head values informed by offshore freshwater equipotential levels (Fig. 4).

(A)

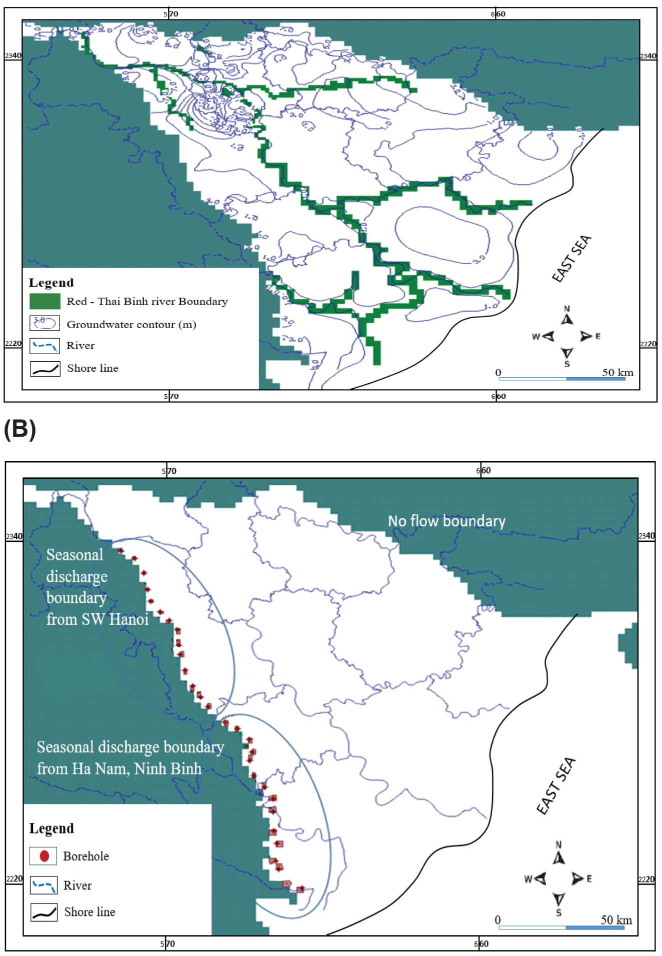


Fig. 4. Boundary conditions of the model. (A) The simulation of the Red - Thai Binh river systems incorporating the general head boundary, with equipotential head denoted by blue lines; **(B)** A no-flow boundary established in the Northeast, while a seasonal discharge boundary (time independent discharge) is implemented southwest of the plain.

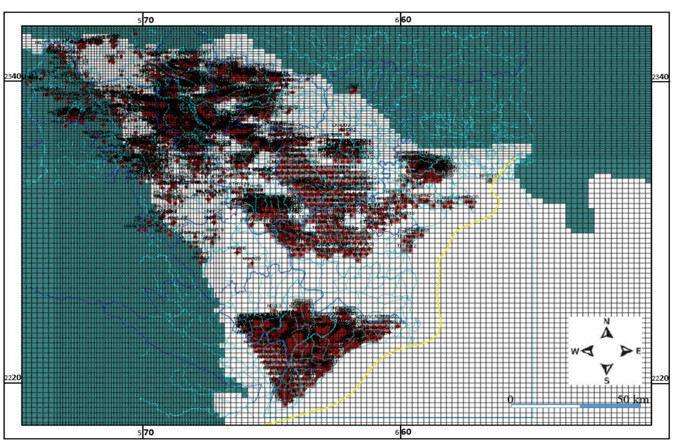


Fig. 5. The spatial arrangement of groundwater extraction sites within the Red river delta plain. The presence of extraction wells are denoted by red dots.

Table 1. Groundwater extraction across the entire Red river delta plain [18, 20].

No.	Province/city	Extraction (m^3/day)		
		Industrial wells	*Domestic wells*	*Total*
1	Hanoi	670931	124180	795111
2	Vinh Phuc	25900	52361	78261
3	Hung Yen	114490	7800	122290
4	Bac Ninh	42000	55118	97118
5	Hai Duong	18200	64259	82459
6	Ha Nam	5508	24492	30000
7	Hai Phong	-	-	34000
8	Thai Binh	9546	39454	49000
9	Nam Dinh	-	-	120000

The current status of groundwater extraction in the RRDP over the period from 2005 to 2018 is illustrated in Fig. 5. The details of the cumulative groundwater extraction throughout the entire RRDP are provided in Table 1.

Thus, the total amount of groundwater exploited throughout the delta is approximately 1,500,000 m^3/day.

4. Results and discussion

4.1. Model calibration

Within the designated study area, a three-dimensional model based on GMS software has been developed and subsequently calibrated against observed groundwater levels within the monitoring network. Calibration, particularly aimed at resolving any model instability, utilised data from both local and national monitoring wells spanning from January 1996 to January 2018. The national monitoring network utilises a borehole system within the aquifers as a benchmark for water level comparison in the model. The calibration data set encompasses 128 observation boreholes, with 88 situated in the Pleistocene aquifer and 40 in the Holocene aquifer. The monitoring data are systematically gathered and maintained within a database by the National Centre for Water Resources Planning and Investigation [23]. A comparative evaluation of water levels over time, recorded at the monitoring boreholes within both the Holocene and Pleistocene (Figs. 6-8) aquifers, is detailed below. This comparison clearly delineates the variations between the observed and modelled groundwater levels.

The comparison between observed and modelled groundwater levels at the monitoring boreholes throughout the RRDP is illustrated in Fig. 9.

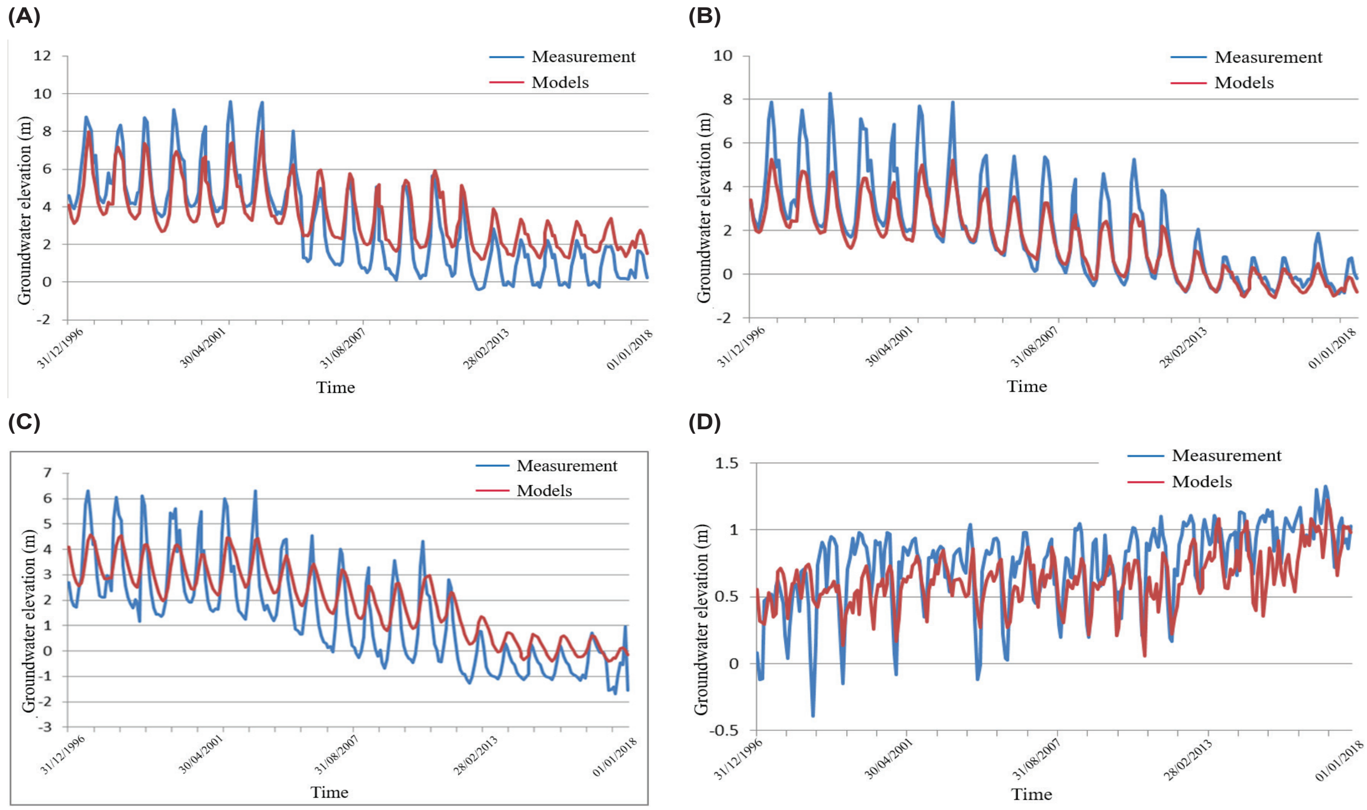


Fig. 6. Discrepancy analysis between modelled and observed groundwater levels at Holocene aquifer monitoring boreholes: (A) Q.33, (B) Q.76, (C) Q.77, and (D) Q.108.

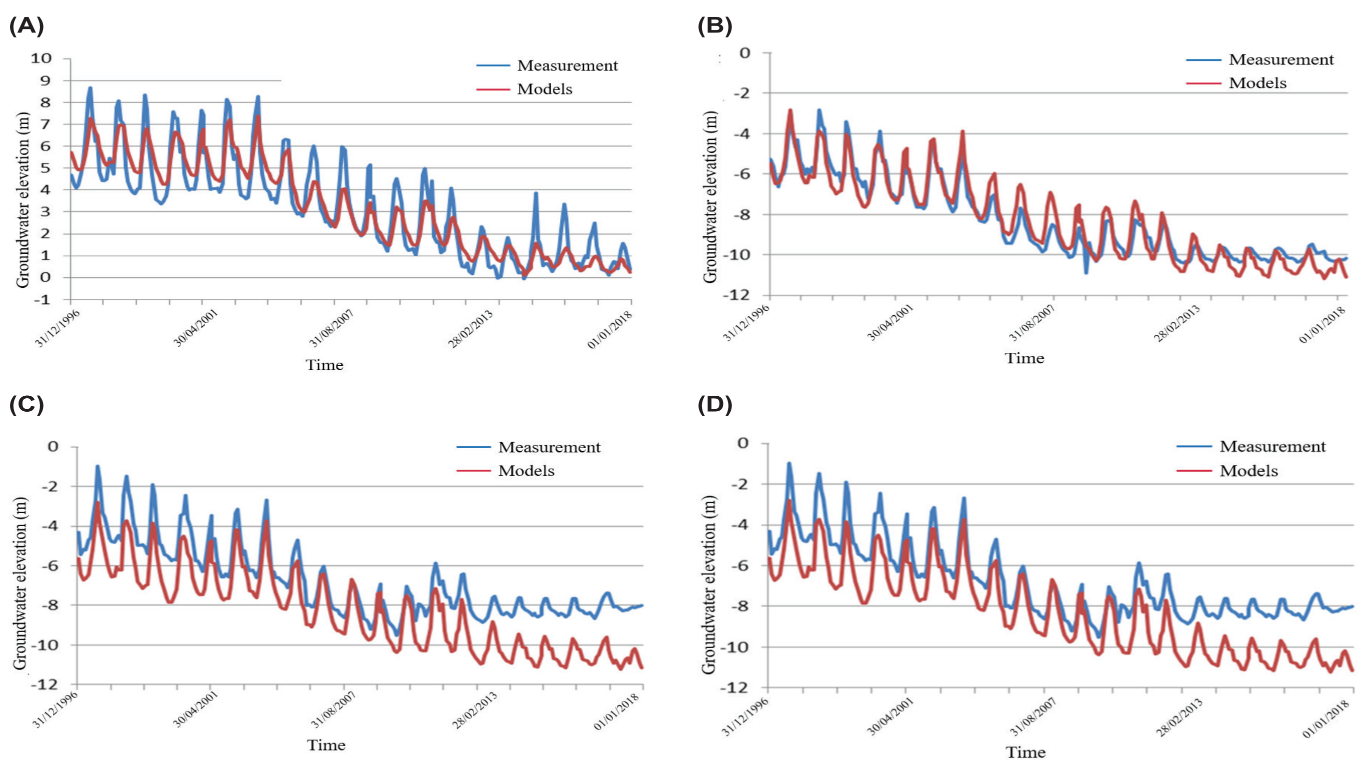


Fig. 7. Discrepancy analysis between modelled and observed groundwater levels at Pleistocene aquifer monitoring boreholes: (A) Q.23, (B) Q.32, (C) Q.35, and (D) Q.77.

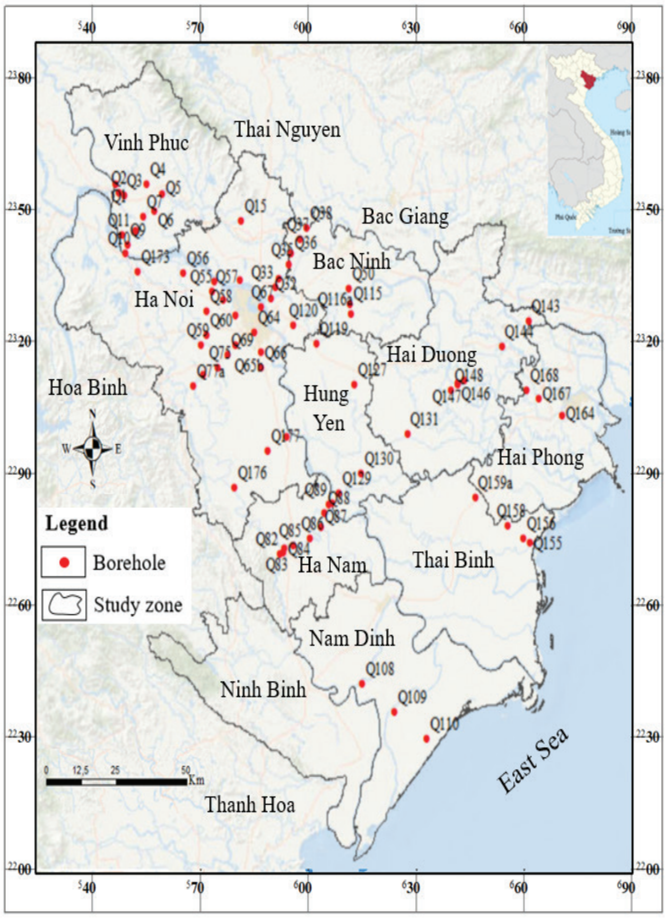


Fig. 8. Location of monitoring boreholes used for comparison of modelled and observed groundwater levels.

The error evaluation for the Holocene aquifer has identified a maximum discrepancy of 1.4 m at monitoring borehole Q.64, and conversely, a negligible error at monitoring borehole Q.85. The mean error across the dataset is calculated to be 0.197 m, with a mean absolute error of 0.861 m, and a normalised root mean square (NRMS) error stands at 5.9%. For the Pleistocene aquifer, error margins at monitoring sites peak at 1.96 m at borehole P.73a, and at borehole Q.164a, the error is again recorded at 0.0 m. The resultant average error is 0.067 m, with a mean absolute error of 0.906 m, and an NRMS error computed to be 2.621%.

The majority of data points are captured within the 95% confidence interval, suggesting a high level of precision. Despite some data points showing significant absolute errors, the relative errors are maintained within acceptable bounds, affirming adherence to prescribed error margins. It is observed that these points are notably situated near to extraction well fields, where modelled data and actual observations often show considerable variances. Thus, the scrutiny of model errors validates that the parameters align with the defined standards of reliability. When contrasted with preceding models for the RRDP [11], the current model exhibits enhanced reliability.

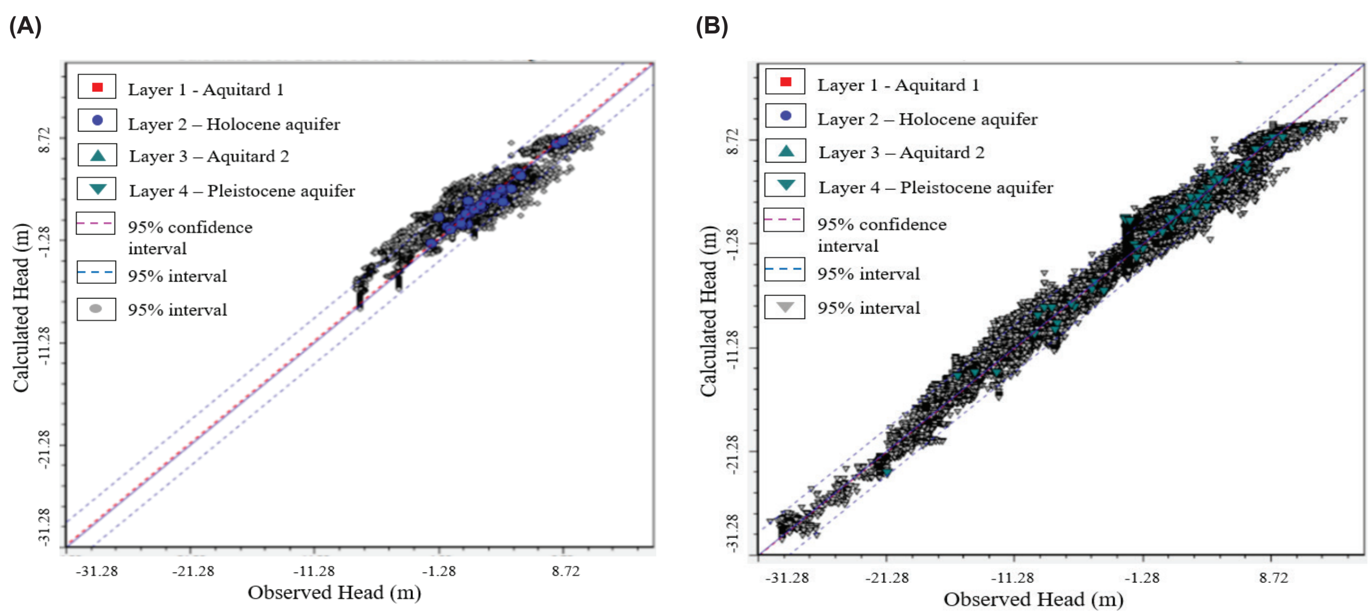


Fig. 9. Comparison of observed and modelled groundwater levels at monitoring boreholes in Holocene aquifer qh (A) and Pleistocene aquifer qp (B) throughout the entire the Red river delta plain. The red dashed line represents the zero-error value, while the green dashed line delineates the 95% confidence interval around its values.

4.2. Evaluating the role of groundwater recharge on groundwater exploitation in the Red river delta plain

Post-calibration, the BUDGET package was utilised to meticulously calculate the water balance for both the Holocene and Pleistocene aquifer systems across the RRDP. Through detailed examination of the water balance components, our objective is to thoroughly evaluate the impact of groundwater recharge on regional groundwater exploitation. The water budget figures, analysed via the ZONE BUDGET, are detailed for the qh and qp aquifer systems for the months of March, June, September, and December (Table 2, Fig. 10). It is important to note that the period from October to March is characterised as the dry season, whilst April to September marks the rainy season.

Table 2. Temporal distribution of water balance components (%) in quaternary aquifers within the Red river delta plain, indicating inflow and outflow with positive and negative signs, respectively.

	Storage	Sea	Exploitation	Direct recharge	Evaporation	River	Leakage	Fractured aquifers in the plain's edge
March	13.94	-2.47	-29.86	39.47	-21.32	-0.48	0.00	0.71
June	-29.32	-1.52	-18.38	67.63	-28.34	9.51	0.00	0.43
September	-53.56	-1.25	-13.91	66.67	-15.63	17.36	0.00	0.32
December	59.74	-1.86	-22.67	9.75	-33.24	-12.25	0.00	0.53

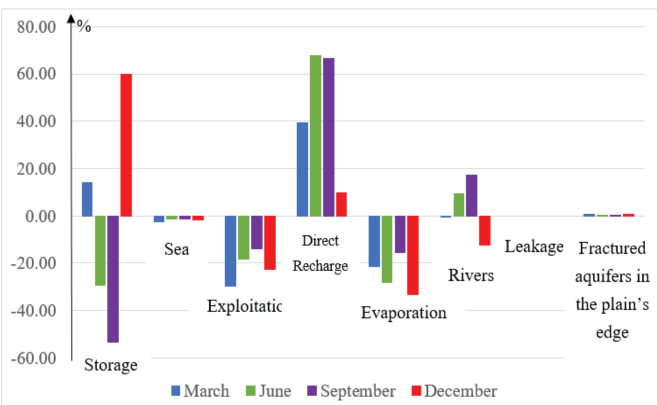


Fig. 10. Temporal representation of water balance components in quaternary aquifers within the Red river delta plain, illustrating inflow and outflow with positive and negative signs.

Figure 10 illustrates the constituents contributing to the groundwater balance within the quaternary aquifer system. Positive values signify inflows contributing to the aquifer system, whereas negative values denote outflows. This analysis specifically addresses the impact of groundwater recharge sources on the quaternary aquifer system within the RRDP. Based on the aforementioned results, several key observations can be stated as follows:

- Throughout the year, the direct groundwater recharge into the quaternary aquifer system shows considerable seasonal variation. The highest recharge rates, constituting 67.63% (equivalent to 5,607,868 m^3/day), occur during the rainy season, which significantly decreases to about 9.75% (equivalent to 664,326 m^3/day) in the dry season. A contrast between direct groundwater recharge and total groundwater extraction within the study area indicates a stark imbalance during the dry season, where extraction exceeds recharge. This imbalance suggests a potential for depletion of groundwater storage, which may lead to a drop in groundwater levels, especially in zones remote from river courses. The presence of depression cones throughout the study area corroborates this situation.

- The combined effects of aquifer system storage changes and ground evaporation persist year-round, collectively accounting for 13.94 to 59.74% of the total, which translates to a volume ranging from 705,693 to 4,085,660 m^3/day.

- Recharge from river systems into the quaternary aquifer is most pronounced during the rainy season, ranging from 9.51 to 17.36% of the total recharge, equating to a volume between 788,378 and 1,928,548 m^3/day.

- Recharge from bedrock boundaries at the delta's margins into the Quaternary aquifer system and the groundwater outflow to the sea from this system are consistent throughout the year, albeit in relatively minor volumes.

5. Conclusions

- Evaluating groundwater recharge sources is imperative for managing sustainable groundwater exploitation effectively. The recent quantitative research on groundwater recharge sources in the RRDP regions provides essential data, enabling precise impact assessment on a delta-wide scale through groundwater modelling.

- The Quaternary aquifer system's recharge in the RRDP primarily comes from direct groundwater recharge, such as precipitation, irrigation return flow, and wastewater. Additionally, water from fractured aquifers at the edge of the plain and river inflow into the aquifers also contribute significantly.

- There is temporal and spatial variability in the groundwater recharge sources for the quaternary sedimentary aquifer system within the RRDP. Direct recharge fluctuates by 4,943,542 m^3/day across March, June, September, and December. Recharge from the fractured aquifers at the plain's edge alters by 35,886 m^3/day, and the variance in river-sourced recharge is about 1,140,169 m^3/day during these periods.

- Groundwater extraction in the RRDP is relatively constant throughout the year [19]. In the dry season (October to March), extraction primarily depends on aquifer storage, direct groundwater recharge, and fractured aquifers at the plain's edge. During the rainy season (April to September), extraction is influenced by direct recharge, followed by river water, with additional contributions from fractured aquifers at the plain's edge.

CRediT author statement

Viet Hung Le: Methodology, Data analysis, Validation, Writing; Quy Nhan Pham, Thi Linh Phung, Van Canh Doan: Methodology, Data analysis, Writing; Quoc Cuong Tran: Methodology, Validation, Reviewing, Editing; Tran Trung Dang: Methodology, Validation.

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COMPETING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

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