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Using GMS modeling method: calculation of potential exploitation of groundwater in Bac Lieu Province, Vietnam

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ABSTRACT

The paper presents the results of research on assessing and determining the potential groundwater exploitation reserves in Bac Lieu Province, the middle-upper Pleistocene aquifer (qp_{2-3}) and the lower Pleistocene aquifer (qp_1) using a numerical model. The authors used GMS (Groundwater Modeling System) software to model aquifers, assign calibrated hydrogeological parameter values, input water level and exploitation data up to 2030, and determine groundwater reserves, sources of groundwater reserves, and water level reductions. Model results show that the water level of the qp_{2-3} aquifer in 2030 at the monitoring borehole Q597030 is -14.5 m, lower than in 2011, 2015, and 2023 by 7.98, 6.07, and 0.502, respectively. Similarly, for the qp_1 aquifer, the water level at monitoring borehole Q597040 is -15.994 m, lower than 2011, 2015, and 2023 by 6.93, 5.885, and 1.994, respectively. The potentially exploitable reserves of fresh and saline groundwater of the qp_{2-3} aquifer in 2023 and 2030 will decrease by 3,120.6 and 527.35 m³/day, respectively. The total potential exploitable reserves of the qp_{2-3} aquifer in 2023 and 2030 will be 409,937.37 and 406,279.35 m³/day, respectively. The potential exploitable reserves of the qp_1 aquifer in the freshwater area in 2023 and 2030 will decrease by 6,077.08 m³/day. The potentially exploitable reserves of the qp_1 aquifer in 2023 and 2030 will be 74,603.69 and 68,526.61 m³/day, respectively. Based on the results of the study on potential exploitable groundwater reserves in the study area, this approach is applied to effectively manage and plan groundwater exploitation in Bac Lieu province.

Keywords: Potentially exploitable reserves, groundwater, middle-upper Pleistocene aquifer (qp_{2-3}), lower Pleistocene (qp_1), GMS model, Bac Lieu Province.

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Introduction

Bac Lieu province has surface water sources affected by tidal regimes, which are often saline and polluted [1–3]. The trend of saline intrusion into coastal aquifers is becoming more serious due to the lack of surface water and increasing demand (especially for agriculture). The trend of saline intrusion into coastal aquifers is becoming more serious due to the lack of surface water and increasing demand, especially for agriculture [4]. In addition, shallow aquifers are mostly brackish or saline, which is not suitable for drinking or daily life. Therefore, groundwater in deep layers (qp_{2-3} , qp_1 ,...) is a safe choice and has become the main source of water supply for activities in Bac Lieu province [5]. Due to socio-economic development, population growth, and urbanization, water resources are under great pressure from exploitation and use; the annual exploitation flow exceeds recharge in most underground aquifers, leading to a gradual decrease in groundwater levels each year [2, 5].

The formation of groundwater reserves is determined by assessing potential exploitation reserves in the area. Potential development reserves can be determined using methods such as balance analysis and mathematical modeling. Some groundwater modeling programs were developed based on various methods. The most famous models (GUIs) include the Visual Modular Three-Dimensional Finite-Difference Flow Model (Visual MODFLOW) [6], the Finite Element Subsurface Flow System (FEFLOW) [7], and the Groundwater Modeling System (GMS) [8], among others. FEFLOW, which uses the finite element method for modeling, and GMS and Visual MODFLOW are the most popular software packages applied in groundwater studies [9–24].

The GMS software is a graphical user interface for many groundwater models, such as FEMWATER, SEEP2D, SEAM3D, MT3DMS, MODFLOW (with many packages), RT3D, MODPATH, MODAEM, and SEAWAT. In this study, the MODFLOW model was chosen for its high efficiency and extensive use in groundwater studies. This model simulates the flow in three dimensions using the finite difference method for both steady-state and transient conditions.

Therefore, the application of modeling methods (using GMS software) and analytical methods to study the formation of groundwater reserves, calculate potential reserves, and assess water-level reduction in the period from the previous research (2023) to the current research (2023) and to 2030 has practical scientific significance. GMS software has many superior features, so this study chose GMS 7.1 to model the groundwater system in the study area and determine the sources of groundwater reserves and water-level fluctuations over time.

Hydrogeological characteristics

Hydrogeology of the study area with a system of 7 porous aquifers in sediments: Holocene (qh) and upper Pleistocene (qp_3), middle-upper Pleistocene (qp_{2-3}) and lower Pleistocene (qp_1), middle Pliocene (n_2^2) and lower Pliocene (n_2^1), upper Miocene (n_1^3) and middle-upper Miocene (n_1^{2-3}) [27]. Shallow aquifers (qh and qp_3 aquifers) are mostly brackish/salty and cannot be exploited. Deep aquifers have a wide distribution area, a thick, weakly permeable layer, and a high water storage capacity. Most of the freshwater distribution area includes qp_{2-3} , qp_1 , n_2^2 , n_2^1 , n_1^3 , and n_1^{2-3} aquifers [27]. According to the report on the current status of water exploitation and use [28], over 95% of the total number of small-scale exploitation wells are concentrated in the qp_{2-3} aquifer, and the remaining 5% have a flow rate > 200 m³/day in the qp_1 and n_2^2 aquifers. Therefore, the qp_{2-3} and qp_1 aquifers have been and are under pressure from groundwater exploitation. Therefore, this paper focuses on studying the current water level and salinity in these two aquifers.

Pore aquifers in the upper-middle Pleistocene (qp_{2-3}) sediment

The upper-middle Pleistocene aquifer is widely distributed across the entire study area, but is unexposed at the surface, yet forms the poor Long Toan formation (Q12–3lt) directly above. The depth of reaching the formation roof ranges from 47.7 m to 117.5 m, with an

average of 75.7 m. The depth of the bottom formation ranges from 77.0 m to 172.0 m, with an average of 125.0 m. Formation thickness varies from 5.00 m to 100.3 m, averaging 46.2 m [25].

The petrographic composition of the aquifer includes fine-grained sand to medium-

gravel sand with grey ashes, blue-grey, and yellow-grey colors; and powder sand, powder, and powder clay with brown, blue-grey, yellow-grey, and white-grey colors, with clear rhythm and stratification. The actual thickness of rocks containing water ranges from 14.00 m to 76.30 m, averaging 43.97 m [25].

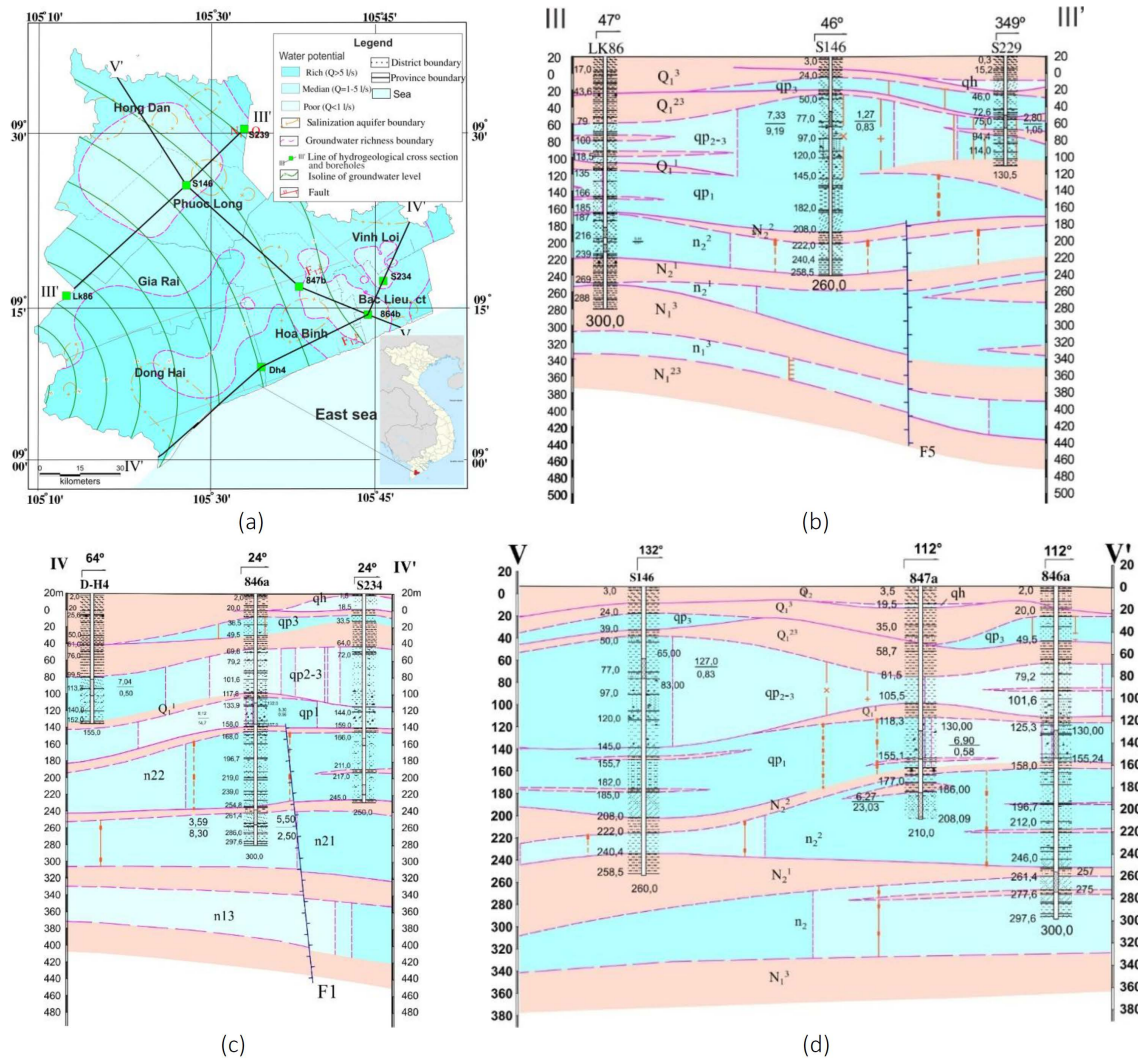


Figure 1. Hydrogeological and cross-section. (a) Hydrogeological map; (b) Hydrogeological cross-section III-III'; (c) Hydrogeological cross-section IV-IV'; (d) Hydrogeological cross-section V-V' in the study area [26]

The ranges from 6.07 L/s to 41.67 L/s, with an average of 21.57 L/s. The drawdown of groundwater level ranges from 4.0 m to 28.0 m; flow rates range from 0.257 L/sm to 6.250 L/sm, and the water level varies from 1.61 m to 6.71 m. The coefficient of water conductivity is

695.69 m²/day. The permeability coefficient is 15.84 m/day, the coefficient of water gravity discharge is 0.174, and the coefficient of water elastic discharge is 0.0000984 [25].

The chemical composition of the aquifer changes. Based on the total mineralization

value, the confined aquifer area is divided into two zones: the freshwater and saltwater zones. The freshwater region ($M < 1$ g/L) is widely distributed in the study area, including Bac Lieu City and the entire northern areas (Long Thanh, Tan Thanh, Chau Hung communes - Vinh Loi district; Hiep Thanh, Vinh Trach - Bac Lieu City). The saltwater area ($M \geq 1$ g/L) is located in a few small spots in the eastern and southern parts of Bac Lieu Province [26, 27].

In general, it has abundant water storage capacity and mostly contains freshwater. Groundwater in this region has been a potential resource for people to exploit.

Pore aquifers in the lower Pleistocene (qp_1) sediment

The lower Pleistocene aquifer is widely distributed across the entire study area, at the surface, yet creates at the surface, yielding poor Ca Mau formation (Q_1^{1cm}) and is located above the very poor Nam Can formation (N_2^{2nc}).

The depth of reaching the formation roof ranges from 82.5 m to 212.0 m, with an average of 138.3 m. The depth of the bottom formation ranges from 153.6 m to 2,160 m, with an average of 179.6 m. Formation thickness varies from 4.00 m to 128.5 m, averaging 41.3 m. The petrographic composition of the aquifer includes fine-grained sand to medium-gravel sand, fine-powder sand, gray-brown, and gray ashes, interspersed with layers of sand powder, brown, and gray powder [27].

The water storage capacity of the aquifer: the water level varies from 5.30–6.90 m; the drawdown of the groundwater level ranges from 5.66–14.70 m; the flow rate is 8.12–9.90 L/S; and the flow rate ranges from 0.552–1.610 L/sm. Hydrogeological parameters: The coefficient of water conductivity is 635.32 m^2/day , the hydraulic conductivity is 17.25 m/d, the specific yield is 0.716, and the specific storage is 0.0000825.

The freshwater region ($M < 1$ g/L) is mainly distributed in the study area, covering about 2,560 km^2 (accounting for 99.03% of the total area). Good quality can be used for living. The saltwater area ($M \geq 1$ g/L) is located in the

eastern part of Phuoc Long district, covering 25 km^2 and accounting for 0.07% of the floor distribution area.

In general, because the qp_1 aquifer is widely distributed, has abundant water storage capacity, and mostly contains freshwater, groundwater in this region has been a potential resource for people to exploit.

Materials and methods

Data sources

This study has inherited documents on geology, hydrogeology, topography, geomorphology, and hydrometeorology from previous studies in the research area, with the purpose of providing a basis for field surveys and model data.

The authors surveyed the current status of groundwater exploitation and use in the locality and compiled statistics on exploitation data.

From the field trip, 53 VES stations measured from Mar. 2024 are used to determine the geoelectrical structure of the aquifers. Apart from VES data, 300 pore water samples at the pumping wells were collected in March 2023 for measuring electrical conductivity and analyzing chemistry (Fig. 1).

The VES data are interpreted using inversion methods that are constrained by available well data. The bulk resistivity and layer thickness at each VES station are obtained from this interpretation process. The structure of the geoelectrical cross-section in the study area is determined. It consists of five layers in the Quaternary sediment, corresponding to three aquifers and two unconfined layers.

Formula to calculate potential exploitation reserves

Potential exploitation reserves (Q_{kTTN}) = Dynamic reserves (Q_d) + Static reserves (Q_{tdh}) (1) [28].

Evaluating dynamic reserves (also known as recoverable reserves) of research using modeling methods using GMS software.

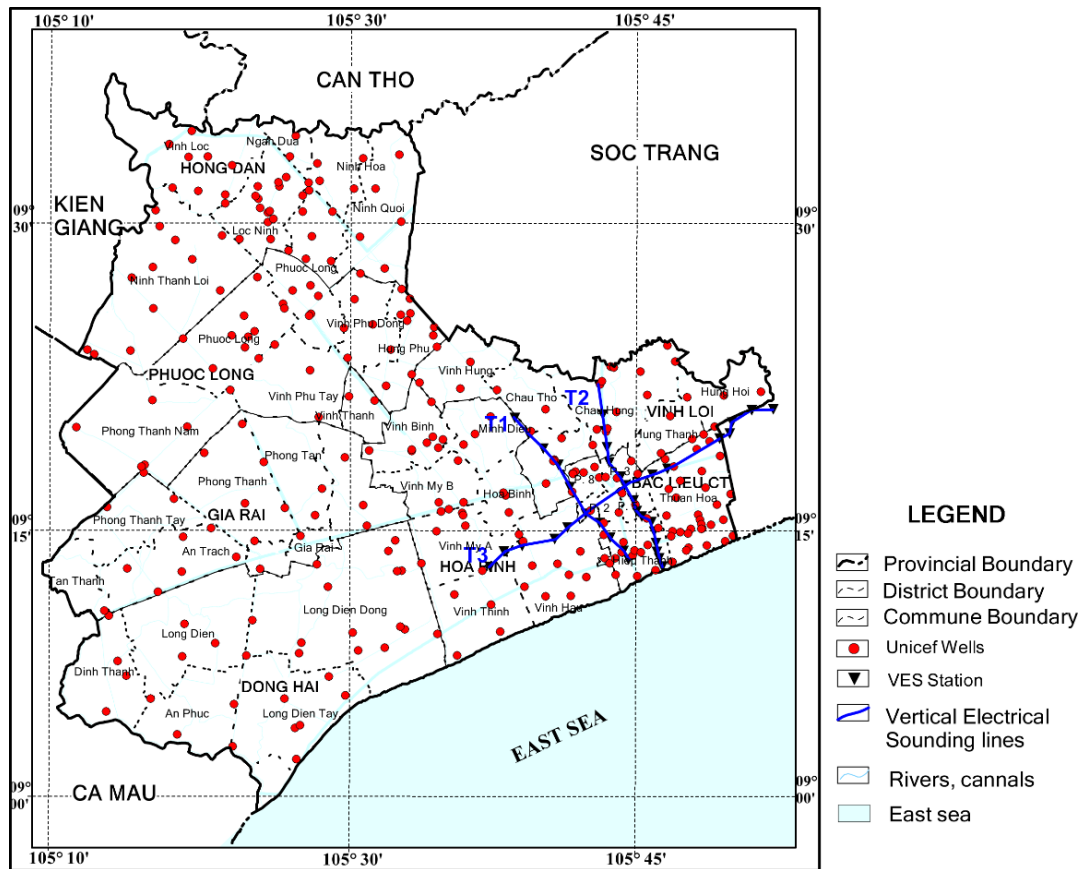


Figure 1a. Water sample and VES data from the field trip in the study area

The MODFLOW numerical model is constructed from two basic equations—the Darcy equation and the principle of conservation of mass (mass balance). Governing Equations.

The three-dimensional groundwater flow with constant density through a heterogeneous and anisotropic porous medium can be described by the equation:

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h}{\partial z} \right) \pm W = Ss \frac{\partial h}{\partial t} \quad (2)$$

where: K_{xx} , K_{yy} , and K_{zz} are hydraulic conductivity coefficients (L/T) in x, y, and z directions, respectively; h is the pressure head (L); Ss is specific storage (1/L); and W is recharge/discharge rate per unit volume (1/T). The environment is unconfined, isotropic, and heterogeneous ($K_{xx} = K_{yy} = K_{zz} = K$), and hence, the governing equation based on Dupuit assumptions [29] in two-dimensional form can be written as:

$$\frac{\partial}{\partial x} \left(K_h \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_h \frac{\partial h}{\partial y} \right) \pm W = Sy \frac{\partial h}{\partial t} \quad (3)$$

where: Sy is the specific yield (dimensionless). The static storage of groundwater in aquifers is studied using the elastic static storage formula, which is as follows:

$$Q_{tdh} = \alpha \frac{\mu^* \cdot F_2 \cdot h_a}{t_{kt}} \quad (4)$$

where: α : intrusion coefficient, μ^* : elastic water release coefficient; F_2 : pressure distribution area of the aquifer (m^2); h_a : pressure column height on the roof of the pressure aquifer (m); t_{kt} : exploitation time (taken as 10,000 days).

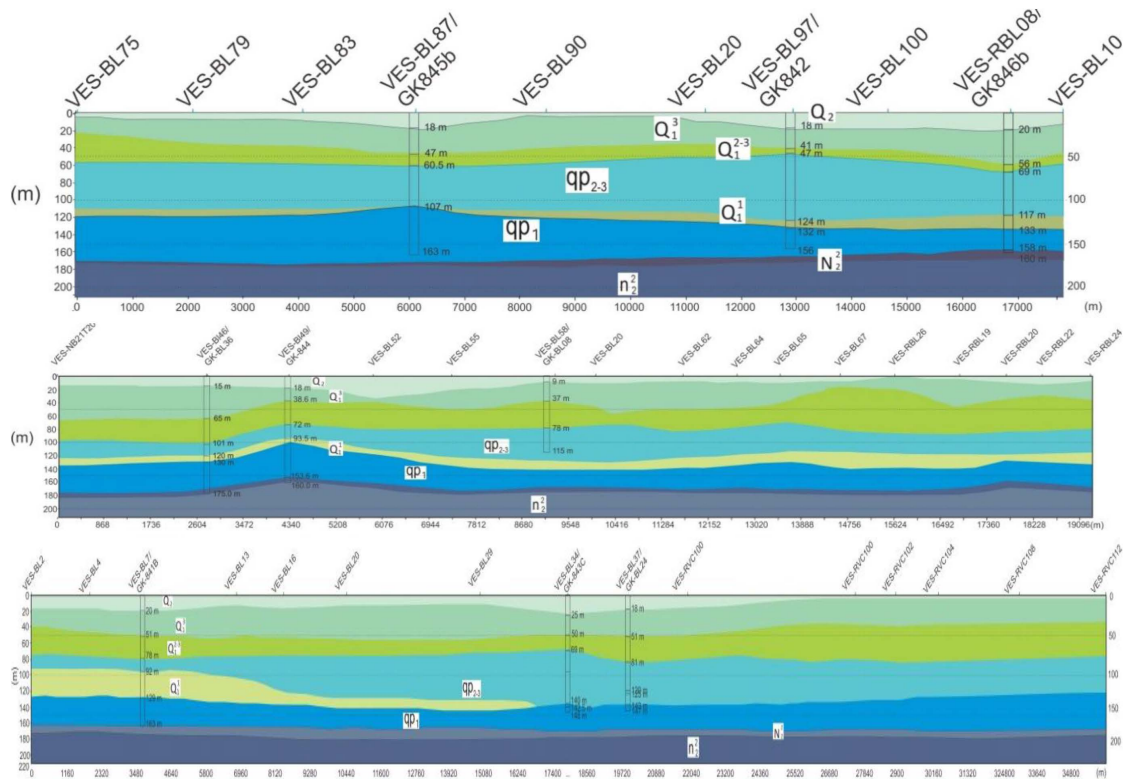


Figure 1b. The structure of the geo-electrical cross section (T1, T2, T3) from the VES and wells data

The modeling method

Groundwater conceptual model

The first and most important step in groundwater modeling is constructing the conceptual model of the groundwater system, which represents a simplified version of the actual aquifer system.

- Model Computational Grid: The results of the groundwater model depend on the size of the computational grids. In this study, the modeling grid consists of 150 rows and 150 columns with a total of 205,209 nodes, a total of 180,000 cells (of which the total number of active cells is 104,600 and the total number of inactive cells is 75,400), and the size of each cell is approximately 475 m × 475 m. Each grid cell is identified by a serial number and has parameter values used to calculate potential exploitable reserves (roof depth, bottom depth; gravity water release coefficient, water conductivity coefficient, initial water level, boundary conditions, exploitation conditions,...) (Fig. 2a).

- Model classification: The simulation model has 8 layers, including 4 weakly permeable/water-proof layers and 4 porous water-containing layers (Fig. 2b). The model layers are interpolated from hydrogeological data and hydrogeological boreholes studied previously, and the results of the analysis of the electric depth measurement value of the authors. Below are the roof depth and bottom depth of the qp_{2-3} and qp_1 aquifers (Fig. 3).

- Constant head: This type of boundary simulates the East Sea, distributed in the Southeast of the area. Here, the water level at the boundary is set to $H = 0$ m.

- River boundary: The river boundary is simulated for the river system. In the study area, there is a dense river and canal system. Therefore, in the model, the author simulates the main large rivers and canals (Fig. 4): Ca Mau-Bac Lieu River, Ngan Dua River, Quan Lo-Phung Hiep Canal, Canh Den Canal, Cong Hoa Canal, and Dong Hai Canal.

- Hydraulic conductivity, the specific: Hydraulic conductivity, the specific of porous

and weakly permeable aquifers are simulated according to zones, and the data are referenced from hydrogeological reports, and hydrogeological boreholes [25]. The results of

solving the stable and unstable inverse problems have determined the permeability coefficient and water release coefficient of the aquifers (Fig. 5).

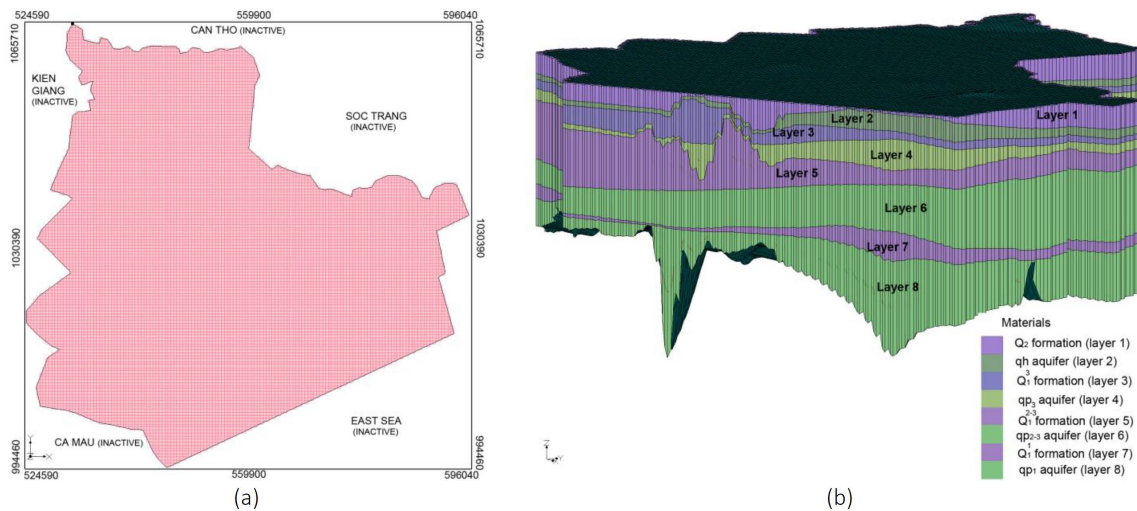


Figure 2. (a) Model grid and (b) 3D image simulating model layers of the study area in the model

- Recharge value: The amount of rainfall that provides infiltration to groundwater is calculated based on the average rainfall of Bac Lieu province (from 1995 to 2023) combined with the permeability coefficient of the sediment layers on the surface, to adjust the rainfall supplied to groundwater. The results indicated that the infiltration value accounts for 1.31% of the rainfall.

- Evaporation value (ET): The evaporation value boundary is assigned the largest evaporation modulus value for the cells where evaporation occurs. Similarly, the evaporation from the groundwater surface is estimated based on the potential evaporation measured at the hydrological station (about 5–10% of the potential evaporation). The average annual evaporation in Bac Lieu province over many years is 755.9 mm/year. Evaporation data from the groundwater surface is also calibrated by solving the inverse problem to correct the model.

- Initial water level conditions: Initial data on water level elevation values provide input to the model, the topic uses 2011 water level data for the qh, qp₃, qp₂₋₃, and qp₁ aquifers. Below is an image showing the extracted model 2

water-level elevation values for the qp₂₋₃ and qp₁ aquifers (Fig. 6).

- Exploitation data: According to the data collected from the investigation results on the current exploitation status in 2011, the stratigraphy and exploitation depth of the current exploitation clusters are concentrated in the qp₂₋₃ and qp₁ aquifers. The main types of exploitation works are centralized water supply works exploited in the qp₂₋₃ and qp₁ aquifers, drilled wells, and dug wells, mainly exploited in the qp₂₋₃ aquifer (Table 1). Due to the large number of exploitations, the study calculated the large wells based on the center of each commune. The total exploitation volume of the entire aquifer was divided equally among the exploitation wells of each layer, then adjusted at each time step during the model calibration process (Fig. 7).

The data on the salinity boundary of the qp₂₋₃ aquifer are the result of the investigation and analysis of groundwater samples, which are then interpolated into the numerical model. For the qp₁ aquifer, water quality is good, and most water samples are freshwater (TDS < 1,000 mg/L). Therefore, in this paper, the authors divide the salinity zone of the qp₂₋₃ aquifer for calculation (Fig. 8).

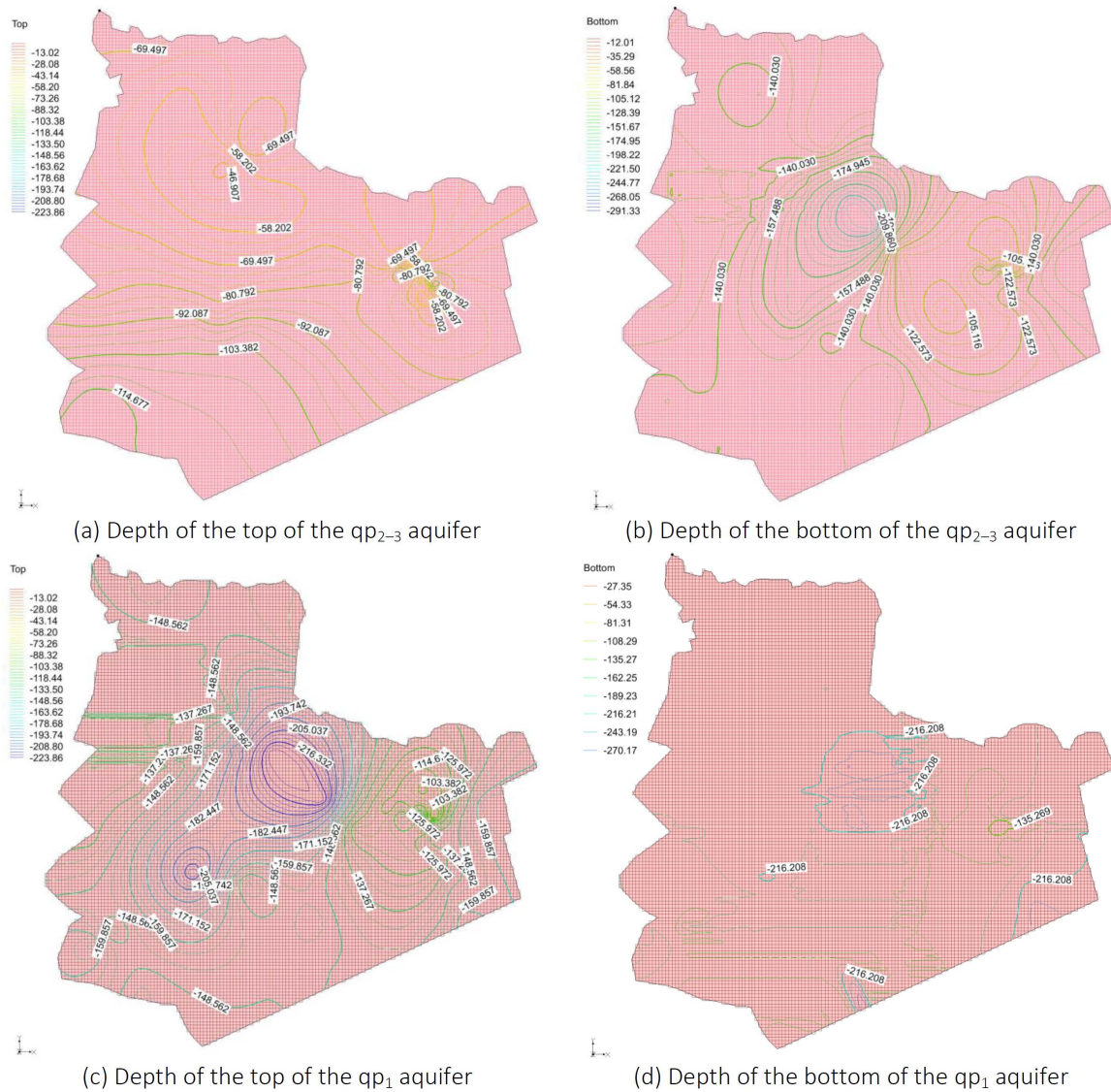


Figure 3. Depth of the top and bottom of the qp₂₋₃ and qp₁ aquifers

Table 1. Total groundwater exploitation flow

Aquifer	Total groundwater exploitation flow $\geq 200 \text{ m}^3/\text{d}$			Total groundwater exploitation flow $< 200 \text{ m}^3/\text{d}$			Total		
	2011	2015	2023	2011	2015	2023	2011	2015	2023
qh	0	0	0	0	0	0	0	0	0
qp ₃	0	0	0	106	0	0	106	0	0
qp ₂₋₃	23.540	85.000	97.081	150.779	200.581	260.100	174.319	285.581	357.181
qp ₁	43.543	45.811	53.566	18.295	23.011	26.210	61.838	68.822	79.776

- Monitoring data: Water level monitoring data (static and dynamic water levels) at two concentrated exploitation wells of Bac Lieu

Water Supply Joint Stock Company. Due to limited monitoring borehole data, the study uses two monitoring boreholes for the two

main research aquifers: qp₂₋₃ (Monitoring project number Q597030 - period 2011–2023) and qp1 (Monitoring project number Q597040 - period 2020–2023) (Fig. 9).

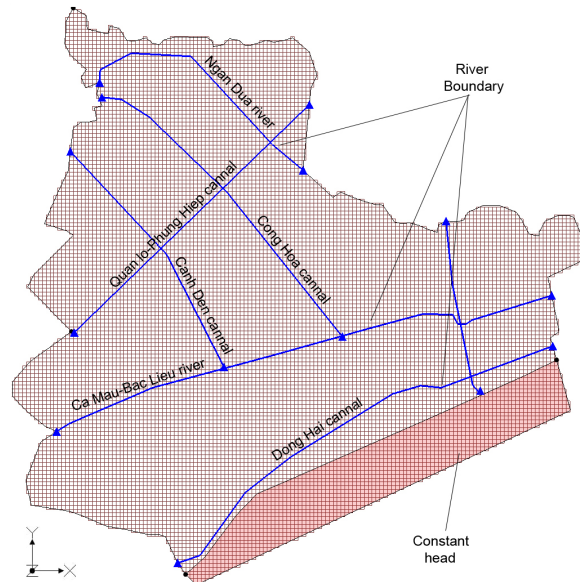


Figure 4. Boundary condition simulation on the river head model

Properties

Feature type: Polygons Show: All BC type: ANY/NONE

Show point coordinates

ID	Color	Auto assign layer	From layer	To layer	Horizontal K (m/d)	Vertical K (m/d)	Spec. storage (1/m)	Spec. yield	Porosity
All									
2		L	2	2	20.0	2.0	2.0e-006	0.03	0.03
3		L	2	2	15.0	1.5	0.0005	0.163	0.163
4		L	2	2	20.0	2.0	2.0e-006	0.03	0.03

Help... Add Point Delete Point OK Cancel

(a) The qh aquifer

Properties

Feature type: Polygons Show: All BC type: ANY/NONE

Show point coordinates

ID	Color	Auto assign layer	From layer	To layer	Horizontal K (m/d)	Vertical K (m/d)	Spec. storage (1/m)	Spec. yield	Porosity
All									
2		Us...	4	4	15.0	1.5	0.00034	0.179	0.179
3		Us...	4	4	5.0	0.5	2.0e-006	0.02	0.02
4		Us...	4	4	5.0	0.5	2.0e-006	0.02	0.02

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(b) The qp₃ aquifer

Properties

Feature type: Polygons Show: All BC type: ANY/NONE

Show point coordinates

ID	Color	Auto assign layer	From layer	To layer	Horizontal K (m/d)	Vertical K (m/d)	Spec. storage (1/m)	Spec. yield	Porosity
All									
2		U...	6	6	20.0	2.0	0.00054	0.06	0.06
3		U...	6	6	15.0	1.5	0.00075	0.06	0.06
4		U...	6	6	15.0	1.5	0.00075	0.06	0.06
5		U...	6	6	22.0	2.2	0.00045	0.05	0.05
6		U...	6	6	22.0	2.2	0.00045	0.05	0.05
7		U...	6	6	24.0	2.4	0.0003	0.045	0.045

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(c) The qp₂₋₃ aquifer

Properties

Feature type: Polygons Show: All BC type: ANY/NONE

Show point coordinates

ID	Color	Auto assign layer	From layer	To layer	Horizontal K (m/d)	Vertical K (m/d)	Spec. storage (1/m)	Spec. yield	Porosity
All									
1		L	8	8	20.0	2.0	0.00054	0.06	0.06
3		L	8	8	15.0	1.5	0.00075	0.06	0.06
4		L	8	8	22.0	2.2	0.00038	0.09	0.09
5		L	8	8	22.0	2.2	0.00038	0.09	0.09
6		L	8	8	24.0	2.4	0.0003	0.045	0.045

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(d) The qp₁ aquifer

Figure 5. Hydraulic conductivity is specific to the four water-bearing layers in the model

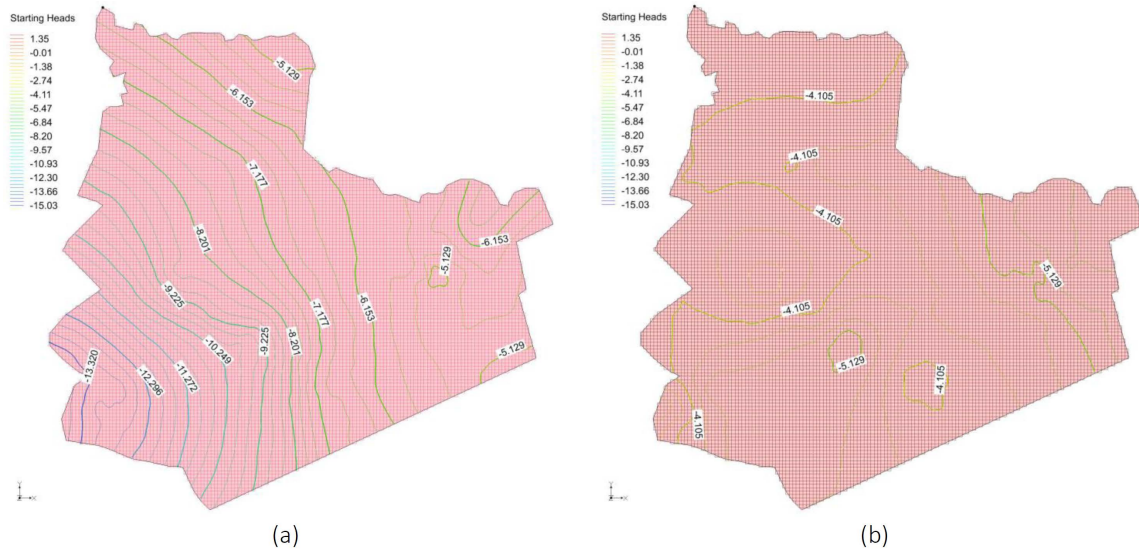


Figure 6. (a) Water level elevation of the qp_{2-3} aquifer and (b) water level elevation The qp_1 aquifer was simulated in the model in 2011

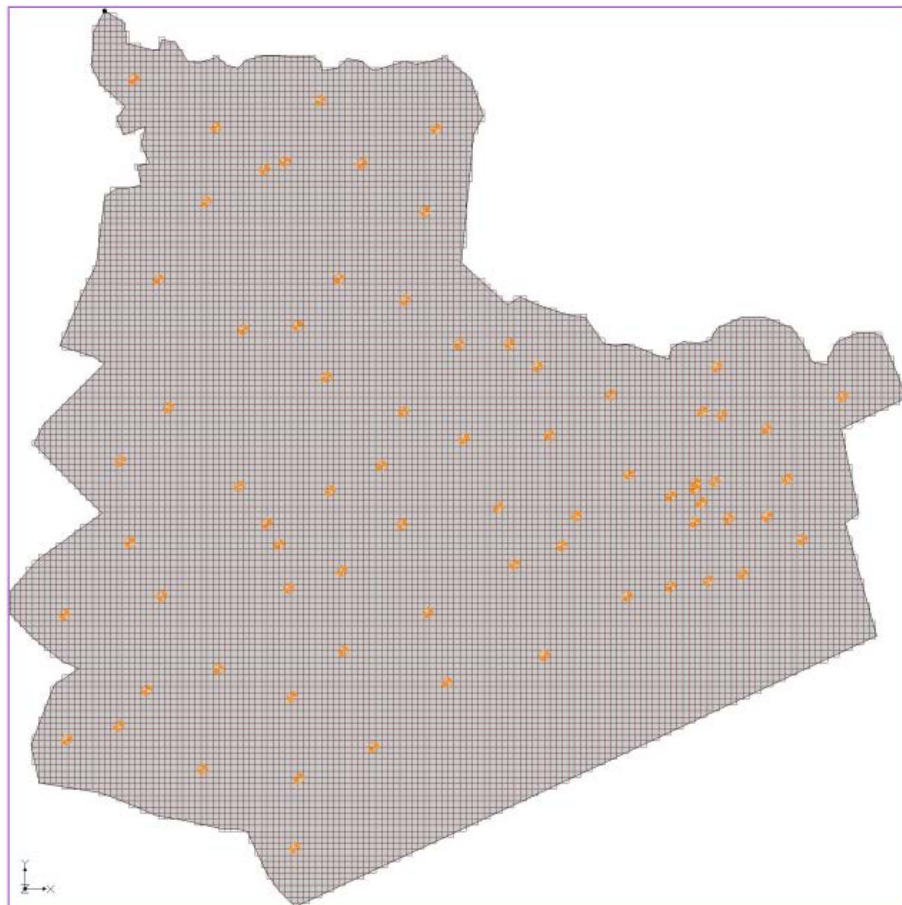


Figure 7. Simulation diagram of water exploitation wells at qp_{2-3} and qp_1 aquifers

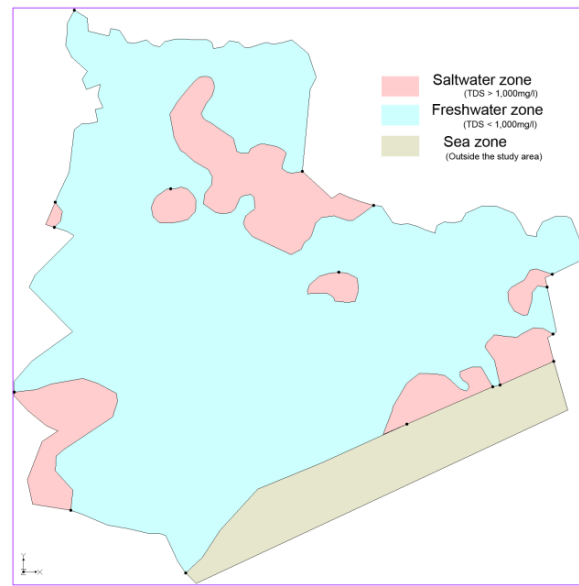


Figure 8. Distribution map of fresh and saltwater areas in the qp_{2-3} aquifer

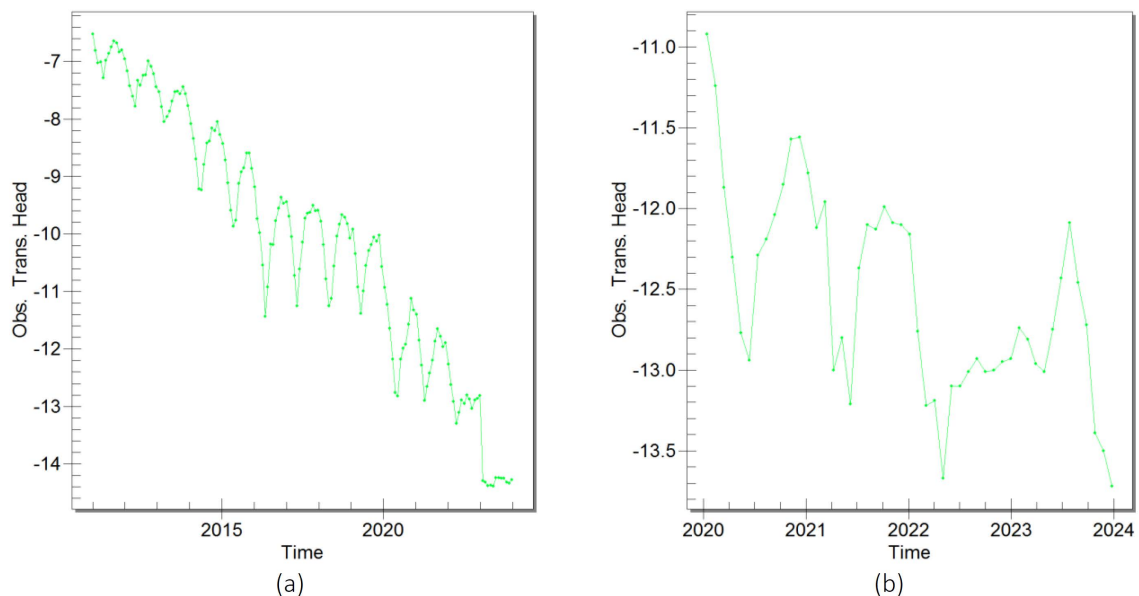


Figure 9. Chart of static water level changes at (a) qp_{2-3} and (b) qp_1 aquifers

Revising model

* Steady-state model:

The stability problem was calibrated many times, with the solution from each time used as the initial water level condition for the next time. The implementation of this iteration problem ended when the model's initial water level was established. The calibration result of

the stability problem in January 2011 established the current water level with the types of errors recorded at the monitoring locations (Fig. 10). The calibration process showed that the boundary conditions at the model boundaries almost did not affect the solution of the problem, showing that the diagramming and establishment of boundary conditions were quite suitable for reality.

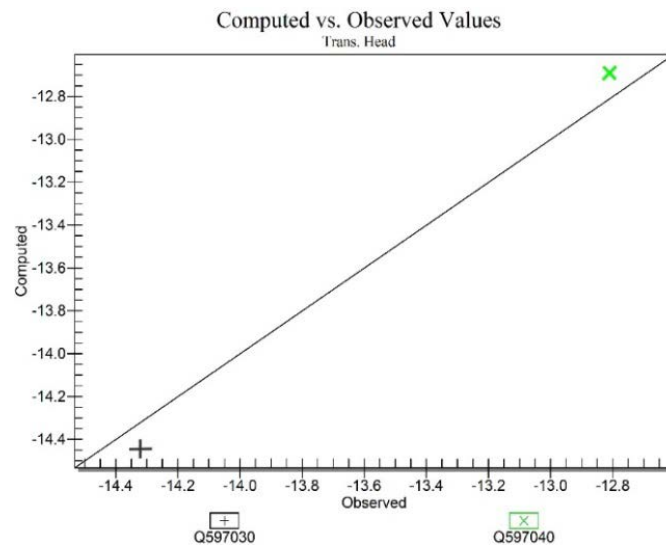


Figure 10. Error graph between the observed water level and the calculation based on the stable inverse problem model at the monitoring borehole

** Transient model:*

The groundwater movement model in the study divided the calibration process into 243 time steps (cycles), each lasting 30 days. The author conducted the calibration in stages, with the last step of each stage being the first step of the next. The starting time was from January 2011 to December 2030 (Fig. 11) (for the monitoring borehole Q597030 in the qp_{2-3} aquifer). The average step-by-step calibration errors < 0.5 m.

The calibration of the instability problem was performed in 49 calculation steps from January 2020 to the end of December 2023 (Fig. 12) (for the monitoring borehole Q597040 in the qp_1 aquifer). The average step-by-step calibration errors < 0.5 m.

The errors when adjusting the model using the stable and unstable inverse problem are within the allowable error limits. After adjustment, the input data set is used to calculate the groundwater reserves and lower the allowable water level in the study area (Table 2).

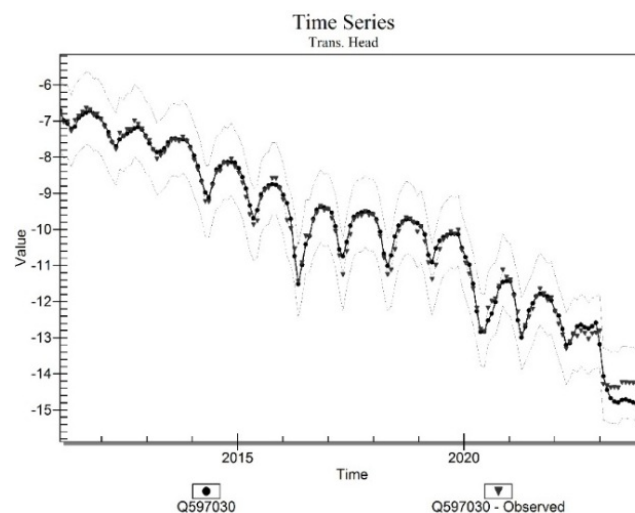


Figure 11. Error graph of the unstable inverse problem model correction at borehole Q597030

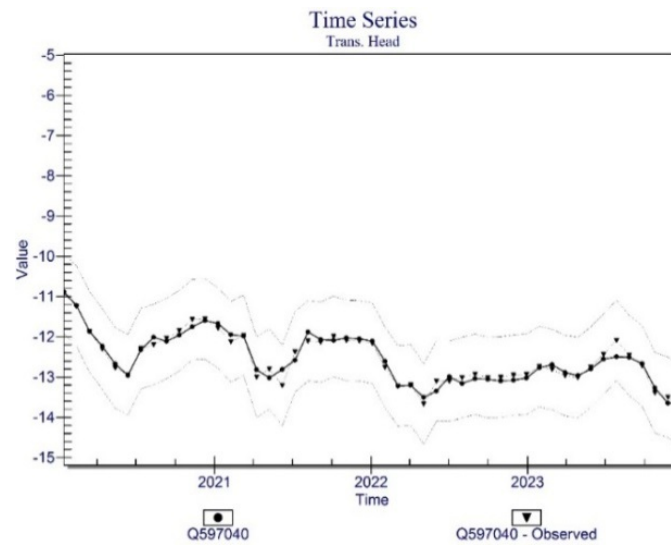


Figure 12. Error graph of the unstable inverse problem model correction at borehole Q597040

Table 2. Summary table of parameter results after adjustment

Layers	Zone	K_x (m/ng)	K_y (m/ng)	K_z (m/ng)	μ^* (1/m)	μ	n_0
Layer 1	1	20	20	2	2.0×10^{-6}	0.03	0.03
Layer 2 (qh aquifer)	1	20	20	2	2.0×10^{-6}	0.03	0.03
	2	15	15	1.5	0.0005	0.163	0.163
	3	18	18	1.8	2.0×10^{-6}	0.025	0.025
Layer 3	1	5	5	0.5	2.0×10^{-6}	0.02	0.02
Layer 4 (qp ₃ aquifer)	1	15	15	1.5	0.00034	0.179	0.179
	2	5	5	0.5	2.0×10^{-6}	0.02	0.02
	3	5	5	0.5	2.0×10^{-6}	0.02	0.02
Layer 5	1	0.001	0.001	0.0001	0.00054	0.1	0.1
Layer 6 (qp ₂₋₃ aquifer)	1	20	20	2.0	0.00054	0.06	0.06
	2	15	15	1.5	0.00075	0.06	0.06
	3	22	22	2.2	0.00045	0.05	0.05
	4	24	24	2.4	0.0003	0.045	0.045
Layer 7	1	0.001	0.001	0.0001	0.00038	0.183	0.183
Layer 8 (qp ₁ aquifer)	1	20.0	20.0	2.0	0.00054	0.06	0.06
	2	15.0	15.0	1.5	0.00075	0.06	0.06
	3	22.0	22.0	2.2	0.00038	0.09	0.09
	4	24.0	24.0	2.4	0.0003	0.045	0.045

Results and discussion

Lower water level and calculating dynamic reserves

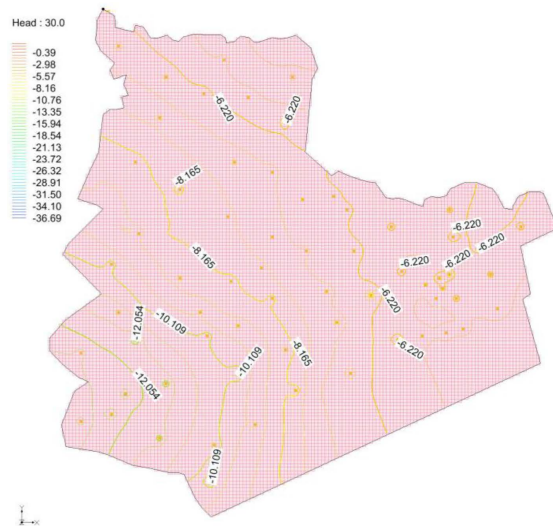
Water level change over time

For the qp₂₋₃ aquifer, the water level has dropped the most over the years of study (from

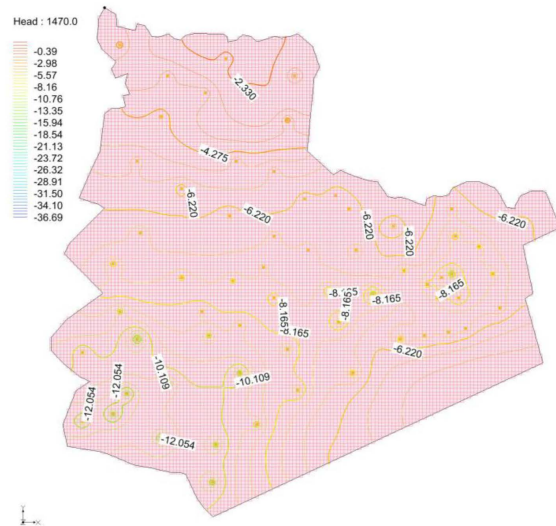
2011 to 2030) in the Southwest region (in the territory of Dong Hai and Gia Rai districts). The water level at the current status of 2030 is -17.9 m (Fig. 13d). Based on the simulated model water level over time at the observation borehole Q597030, the water level in 2015 (-8.43 m) (Fig. 13b) is 1.91 m lower than the water level in 2011 (Fig. 13a); similarly, the water level in 2023 (-13.998 m) (Fig. 13c) is 5.568 m lower than the

water level in 2015. However, the water level in 2030 at the monitoring borehole location

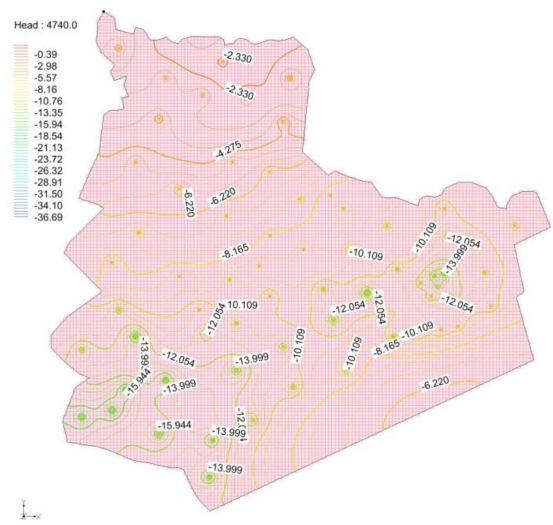
changed little, but decreased sharply in the southwest area of Dong Hai district.



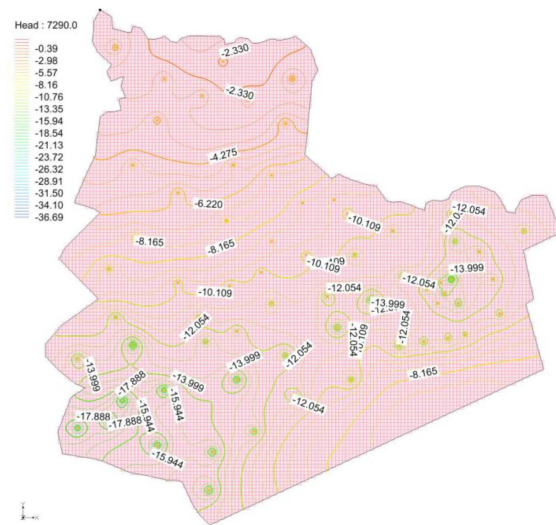
(a) Water level elevation of qp₂₋₃ aquifer on 31/1/2011 in the model



(b) Water level elevation of qp₂₋₃ aquifer at 10/1/2015 in the model



(c) Water level elevation of qp₂₋₃ aquifer on 24/12/2023 in the model



(d) Water level elevation of qp₂₋₃ aquifer on 17/12/2030 in the model

Figure 13. Water level elevation of the qp₂₋₃ aquifer at different times in the model

Table 3. The water level changes over time (2011–2030)

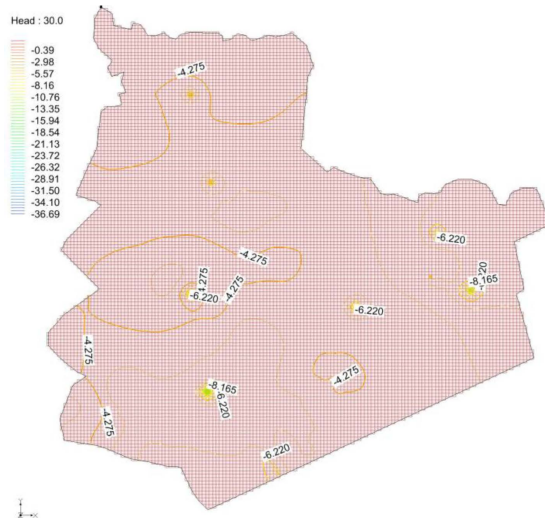
Aquifer/Year	2011	2015	2023	2030	Average (19 years)
qp ₂₋₃	-6.52 m	-8.43 m	-13.998 m	-14.5 m	0.42 m
qp ₁	-9.064 m	-10.109 m	-14.0 m	-15.994 m	0.37 m

For the qp₁ aquifer, the water level has dropped the most over the years (2011–2030)

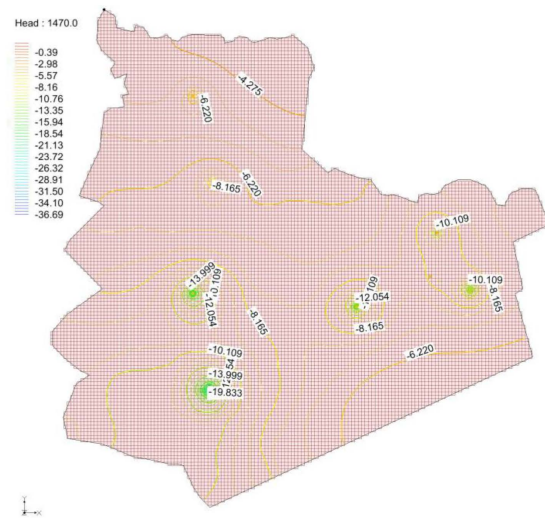
in the Southwest region (in the territory of Dong Hai and Gia Rai districts). The water level

in 2030 is -23.78 m (Fig. 14d). Based on the simulated water level at the observation borehole Q597040, the water level in 2015 (-10.109 m) (Fig. 14c) is 1.045 m lower than the water level in 2011 (Fig. 14a); similarly,

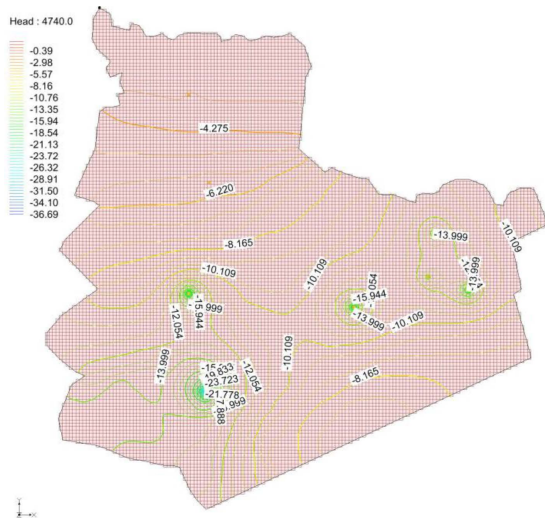
the water level in January 2023 (-14.0 m) (Fig. 14c) is 3.89 m lower than the water level in 2015; The water level in 2030 (-15.994 m) (Fig. 14d) was 1.99 m lower than the water level in 2023.



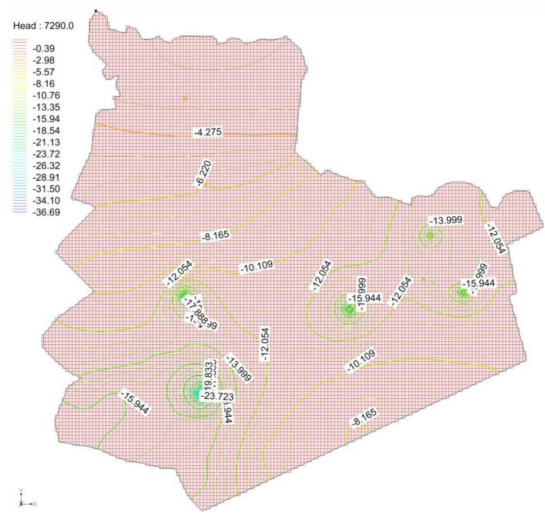
(a) Water level elevation of qp_1 aquifer on 31/1/2011 in the model



(b) Water level elevation of qp_1 aquifer on 10/1/2015 in the model



(c) Water level elevation of qp_1 aquifer on 24/12/2023 in the model



(d) Water level elevation of qp_1 aquifer on 17/12/2030 in the model

Figure 14. Water level elevation of the qp_1 aquifer at different times in the model

Dynamic reserve calculation

* Dynamic reserves calculated of the qp_{2-3} aquifer:

The model, after adjusting the input parameters and boundary conditions by solving

the stable and unstable inverse problem, shows that the model is relatively suitable for actual conditions, so the model will be used as a basis for solving the unstable forward problem to determine the dynamic reserves and sources of dynamic reserves for the study area.

To evaluate the water balance, the authors run the Zone Budget software package, which calculates the water balance from GMS simulation results, thereby determining the components flowing to and from the equilibrium area. To determine the source of reserve formation, the author gets the ID for the model layers. The model run results for determining the natural dynamic reserves in the freshwater/saltwater zones (10/2023 and 10/2030) of the qp_{2-3} and qp_1 aquifers.

The amount of water formed in the qp_{2-3} aquifer within the freshwater area at the current status in 2023 is 330,036.23 m³/day, and in the future in 2030 is 326,905.56 m³/day, a decrease of 3,130.67 m³/day. The decrease in dynamic reserves at different times is due to the reserve-formation components; details are presented in Tables 4 and 5. The groundwater balance of the qp_{2-3} aquifer at both times depends on storage components, replenishment from the upper and lower layers, the border areas, and saltwater inflow. Because the dynamic reserves calculated

under the scenario of keeping the wells' exploitation flow equal to the current exploitation flow are not much different at the two times, the reserves at the two times are not much different.

The amount of groundwater formed by the qp_{2-3} aquifer in the saline water area at the current time in 2023 and 2030 is 77,041.84 m³/day and 76,514.49 m³/day, respectively, a difference of 527.23 m³/day. The decrease in dynamic reserves at different times is due to the reserve-formation components; details are presented in Tables 4 and 5. The groundwater balance of the qp_{2-3} aquifer at both times depends on storage components, replenishment from the upper and lower layers, the border areas, and saline water inflow. Because the dynamic reserves calculated under the scenario of keeping the wells' exploitation flow equal to the current exploitation flow are not much different at the two times, the reserves at the two times are not much different.

Table 4. The total water volume of the qp_{2-3} aquifer in the year 2023

Year	2023				Total	
	Freshwater		Saltwater			
	Flow in	Flow out	Flow in	Flow out	Flow in	Flow out
Storage	29,812.01	5,670.8	5,227.1	1,328.4	35,039.11	6,999.2
Well	0	294,297.2	0	71,328.1	0	365,625.3
Freshwater/Saltwater		328.5	328.5		328.5	328.5
upper layer	274,379.5	0	55,248.94	0	329,628.44	0
lower layer	14,095.7	29,730.2	3,484.4	4,385.3	17,580.1	34,115.5
East flowing	11,749.02	9.58	12,752.9	0	24,501.92	9.58
TOTAL IN	330,036.23	330,036.28	77,041.84	77,041.8	407,078.07	407,078.08

Table 5. The total water volume of the qp_{2-3} aquifer in the year 2030

Year	2030				Total	
	Freshwater		Saltwater			
	Flow in	Flow out	Flow in	Flow out	Flow in	Flow out
Storage	16,972.7	2,473.7	2,860.04	391.68	19,832.74	2,865.38
Well	0	290,072.2	0	71,328.1	0	361,400.3
Freshwater/Saltwater	0	85.59	85.59	0	85.59	85.59
upper layer	287,702.7	0	57,994.1	0	345,696.8	0
lower layer	10,072.96	34,268.4	2,783.1	4794.7	12,856.06	39,063.1
East flowing	12,157.2	5.56	12,791.66	0	24,948.86	5.56
Total	326,905.56	326,905.45	76,514.49	76,514.48	403,420.05	403,419.93

The total water volume of the qp_{2-3} aquifer in 2023 is 407,078.07 m³/day. Of which, the change in the static reserve inflow of the qp_{2-3} aquifer is 35,039.11 m³/day. The amount of seepage replenished from the upper layer is 329,628.44 m³/day, and that from the bottom up is 17,580.1 m³/day. The amount of seepage from the southeast (sea) flowing in is 24,501.92 m³/day. To balance the groundwater in the aquifer, the amount of water flowing in is approximately equal to the amount flowing out. Thus, in addition to the exploited water volume of -365,625.3 m³/day, the remaining surplus is the drainage from the peripheral area. -7,008.78 m³/day, which flows into the saltwater area -328.5 m³/day, and seepage and drainage to the lower and upper aquifers are -34,115.5 m³/day (Table 4). Thus, the dynamic reserve in the saltwater area of the qp_{2-3} aquifer is 407,078.08 m³/day.

The total water volume of the qp_{2-3} aquifer in the year 2030 is 403,420.05 m³/day. Of which, the change in the static reserve inflow of the

qp_{2-3} aquifer is 19,832.74 m³/day. The amount of seepage replenished from the upper layer is 345,696.8 m³/day, and that from the bottom up is 12,856.06 m³/day. The amount of seepage from the Southeast (sea) flowing in is 24,948.86 m³/day, and the amount of flow from the freshwater area is 85.59 m³/day. To balance the groundwater in the aquifer, the amount of water flowing in is approximately equal to the amount flowing out. Thus, in addition to the exploited water volume of -361,400.3 m³/day, the remaining surplus is the drainage from the peripheral area -2,870.94 m³/day, which flows into the saltwater area -85.59 m³/day, and seepage and drainage to the lower and upper aquifers are -39,063.1 m³/day (Table 5). Thus, the dynamic reserve in the saltwater area of the qp_{2-3} aquifer is 403,419.93 m³/day.

* *Dynamic reserves calculated of the qp_1 aquifer:*

The model results determine the dynamic reserves at the year 2023 and 2030 of the qp_1 aquifer as follows in Table 6:

Table 6. The dynamic reserves for the saline water area

Year	Freshwater			
	2023		2030	
	Flow in	Flow out	Flow in	Flow out
Storage	20,439.59	1,926.54	11,158.9	10.14
Well	0.0	54,508.0	0.0	53,208.0
Freshwater/Saltwater	0.0	0.0	0.0	0.0
upper layer	39,351.99	14,472.31	42,741.9	11,607.5
lower layer	0.0	0.0	0.0	0.0
East flowing	11,115.4	0.0	10,929.0	4.15
Total	70,906.91	70,906.86	64,829.83	64,829.8

The total water volume of the qp_1 aquifer in the year 2023 is 70,906.9 m³/day. Of which, the change in the static reserve flowing into the qp_1 aquifer is 20,439.6 m³/day. The amount of seepage added from the upper layer is 39,351.93 m³/day. The inflow from the Southeast (sea) is 11,115.4 m³/day. To balance the groundwater in the aquifer, the amount of water flowing in equals approximately the amount flowing out. The amount of water exploited is -54,508 m³/day; the remaining amount is drained from the outer zone at -1,926.54 m³/day, and the seepage draining to

the lower and upper aquifers is -14,472.31 m³/day (Table 6).

The total water volume of the qp_1 aquifer in the year 2030 is 64,829.83 m³/day. Of which, the change in the static reserve flowing into the qp_1 aquifer is 11,158.9 m³/day. The amount of seepage added from the upper layer is 42,741.9 m³/day. The inflow from the Southeast (sea) is 10,929.0 m³/day. To balance the groundwater in the aquifer, the amount of water flowing in equals approximately the amount flowing out. The amount of water exploited is -53,208.0 m³/day; the remaining

amount is drained from the outer zone at $-14.29 \text{ m}^3/\text{day}$, and the seepage draining to the lower and upper aquifers is $-11,607.5 \text{ m}^3/\text{day}$ (Table 6).

Static reserve (Q_{tth})

The static storage reserves of the aquifers qp_{2-3} and qp_1 in the saltwater and freshwater areas are calculated according to formula (4). The elastic release coefficient has been corrected. The results of the static storage reserves calculation are presented in Table 7.

Table 7. Static storage reserves of the qp_{2-3} layer and the qp_1 layer in saltwater and freshwater areas

The aquifer	Area (km^2)	The Specific storage	Coefficient of encroachment on natural static reserves α	Amplitude of water level fluctuation (m)	The static storage reserves (m^3/d)
Freshwater zone					
qp_{2-3}	2,065.81	0.00054	0.3	71.58 m	2,395.5
qp_1	2,465.81	0.00038	0.3	131.51 m	3,696.78
Saltwater zone					
qp_{2-3}	400	0.00054	0.3	71.58 m	463.8

Note: Mining time is taken as 10,000 days.

Potential exploitation reserves

The potentially exploitable reserves of the qp_{2-3} and qp_1 aquifers in the saltwater and freshwater areas are determined according to formula (1). Based on the static reserves and

dynamic reserves of the freshwater and saltwater areas calculated in 4.1 and 4.2. The results of calculating the potentially exploitable reserves for the saltwater and freshwater areas of the two qp_{2-3} and qp_1 aquifers are presented in Table 8 as follows:

Table 8. Potentially exploitable reserves of qp_{2-3} and qp_1 aquifers in saltwater and freshwater areas

Year	The aquifer	Area (km^2)	Dynamic reserves (m^3/d)	Static reserve (m^3/d)	The potentially exploitable reserves (m^3/d)
2023	Freshwater zone				
	qp_{2-3}	2,065.81	330,036.23	2,395.5	332,431.73
	qp_1	2,465.81	70,906.91	3,696.78	74,603.69
	Saltwater zone				
	qp_{2-3}	400	77,041.84	463.8	77,505.64
2030	Freshwater zone				
	qp_{2-3}	2,065.81	326,905.56	2,395.5	329,301.06
	qp_1	2,465.81	64,829.83	3,696.78	68,526.61
	Saltwater zone				
	qp_{2-3}	400	76,514.49	463.8	76,978.29

Conclusion

Using the modeling method combined with the analytical method to calculate the lowering of water levels and potential groundwater reserves based on the use of input data and boundary conditions calibrated by the GMS model. Model results show that the water level of layer qp_{2-3} in 2030 at the monitoring borehole Q597030 is -14.5 m ,

lower than in 2011, 2015, and 2023 by 7.98, 6.07, and 0.502, respectively. Similarly, for the qp_1 aquifer, the water level at monitoring borehole Q597040 is -15.994 m , lower than in 2011, 2015, and 2023 by 6.93, 5.885, and 1.994, respectively.

- The potentially exploitable reserves of fresh and saline groundwater of the qp_{2-3} aquifer in 2023 and 2030 will decrease by 3,120.6 and $527.35 \text{ m}^3/\text{day}$, respectively. The

total potential exploitable reserves of the qp_{2-3} aquifer in 2023 and 2030 will be 409,937.37 and 406,279.35 m^3/day , respectively.

- The potentially exploitable reserves of the qp_1 aquifer in the freshwater area in 2023 and 2030 will decrease by 6,077.08 m^3/day . The potentially exploitable reserves of the qp_1 aquifer in 2023 and 2030 will be 74,603.69 and 68,526.61 m^3/day , respectively.

- The source of dynamic reserves of aquifers is determined to be the infiltration of rainwater, recharge from rivers, recharge from the slopes, and recharge from the east of the East Sea. Here, recharge from rainwater infiltration and rivers and canals is the main source, so to ensure environmental stability and sustainability, it is necessary to comply with regulations to protect the groundwater environment from contamination.

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