Application of hydrogeological modelling methods in forecasting seawater intrusion of Pleistocene aquifer in Thai Binh area

Trinh Hoai Thu[1], Nguyen Nhu Trung[2], Le Hong Minh[3], Vu Van Manh[4]

Abstract

This paper presents the application of hydrogeological modelling methods in forecasting seawater intrusion in Thai Binh area. Exploitation by UNICEF well systems have increased both inflow and outflow rate in Pleistocene aquifer by 2.4 times. Model is revised by solving steady state and transient models, all input coefficients have been identified (with Kx = 17.3, Ky =17.3, Kz =1.73, specific storage μ*= 0.0036, specific yield μ= 0.16 and effective porosity n0 = 0.16). By modelling two scenarios, we can show that Thai Binh province can keep on exploiting with the current rate Q = 31500 m3/day, the seawater intrusion in the Pleistocene aquifer is still developing but very slow (remain 99% current freshwater area in 2050). However, Thai Binh groundwater reserves cannot meet 50% of water needs in 2050 (if the exploitation rate is increased to 68000m3/day, only 95% current freshwater area remains in 2050).

Keywords: hydrogeological modelling, Thai Binh, Visual MODFLOW, Pleistocene aquifer.

1. Introduction

1.1. Case study

Thai Binh, a coastal plain province, where is an agriculture and industry center in the Red River delta. With the complicated hydrogeology conditions, although having abundant reserves of groundwater, but almost aquifers are confronted with seawater intrusion. Although there is not any large-scale groundwater exploited station, but thousands of UNICEF wells had been drilled uncontrollably to meet the freshwater demand having reduced the water table. It may be the main reason of seawater intrusion. We use hydrogeological modelling methods to identify effect of UNICEF wells to inflow and outflow rates of Pleistocene aquifer and use the revised input coefficients to forecast seawater intrusion in 2050. Actual state, rate, forecasting and protection of seawater intrusion should be considered to exploit the groundwater resources sustainably.

1.2. Geological setting

The study area is located in the longitude $106^0$06'33''E to $106^0$37'35''E and the latitude $20^0$05'15''N to $20^0$43'57''N. It is about 1542 km^2 and consists of eight districts and one city. The topography of the study area is quite flat. The average elevation is 1-2.5 meter above the sea level. The Quaternary alluvium sediment, including the mud clay, stiff clay, silty-clay, silt-loam, sand, and gravel, covers it completely. The Quaternary sediment may be divided into 5 units: Le Chi unit ($Q_I$lc), Ha Noi unit (Q_{III}-$_{II}$hn), Vinh Phuc unit (Q_{III}^2vp1), Hai Hung unit (Q_{IV}^{1-2}hh1), and Thai Binh unit (Q_{IV}^3tb). There is unconformity separating the Quaternary sediment and the older sandstone,

[1] Vietnam Academy of Science and Technology, 18 Hoang Quoc Viet Str, Hanoi, Vietnam, Ththu@imgg.vast.vn, Institute of Marine Geology and Geophysics

[2] Vietnam Academy of Science and Technology, 18 Hoang Quoc Viet Str, Hanoi, Vietnam, nntrung@imgg.vast.vn, Institute of Marine Geology and Geophysics

[3] VNU University of Science, 334 Nguyen Trai Str, Thanh Xuan Dist, Hanoi, Vietnam, lehongminh.k55@hus.edu.vn

[4] VNU University of Science, 334 Nguyen Trai Str, Thanh Xuan Dist, Hanoi, Vietnam, fesvvm@yahoo.com

siltstone and limestone aged Paleozoic – Neocene. There are three aquifers in Quaternary sediment being the Upper Holocene aquifer (Qh2), the lower Holocene aquifer (Qh1) and the Pleistocene (Qp) and unconfined layer, Hai Hung sub-formation (Q_{IV}^{1-2}hh2) and upper Vinh Phuc sub-formation (Q_{III}^{2}vp2) in Quaternary sediment. According to the hydrogeology data, the main aquifer in Quaternary sediment is Pleistocene. It is considered to be at depth of 26-143 meter and its average thickness is about 29-127 meter. The water qualifies of Pleistocene aquifer can be divided clearly into 2 parts: the seawater (TDS >1000mg/l) is in the southern part and the fresh water (TDS <1000mg/l) is in the northern part of the province.

2. Materials and methods

This study based on hydrogeological modelling methods [8] and calculated by Visual Modflow software.

2.1. Hydro-geological modelling method

Groundwater flow equation: The movement of groundwater is simulated by linear parabolic partial differential equation. It is derived from the mass balance equations of the water volume distribution in aquifers and Darcy's law.

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

Where: K_{xx}, K_{yy}, K_{zz} is the aquifer permeability by the x, y and z directions ($K_{xx} = K_{xx}(x, y, z)$, $K_{yy} = K_{yy}(x, y, z)$, $K_z z = K_{zz}(x, y, z)$). z is the vertical direction.

h: is the water level at the position (x, y, z) at time t.

W: is a real recharge (plus sign) or discharge (minus sign).

S_s: is specific storage ($S_s = S_s (x,y,z)$).

Equation (1) describes water level in conditions of inhomogeneous and anisotropic environment. This equation with the boundary conditions and original condition of the aquifers form mathematical model of groundwater flow.

Solute transport equation: the differential equation simulates solute transport in groundwater in case of ignoring the declining of solute concentration due to chemical reactions or radioactive decay:

$$\frac{\partial}{\partial x}\left(D_{xy}\frac{\partial C}{\partial y}\right)-\frac{\partial}{\partial x}\left(v_x C\right)+q_s\frac{C_s}{\theta}=R\frac{\partial C}{\partial t} \qquad (2)$$

Where:

D_{xy}: Hydrodynamic dispersion coefficient

v_x: the real velocity of ground water

C: Concentration of transport solutes

$q_s\frac{C_s}{\theta}$: Additional source of solutes

R: Retard factor, which indicates the influence degree of the solutes transport by absorbing or releasing.

So far, equations (1) and (3) were solved quite completely by the finite difference and finite element methods. Many hydrogeological laboratories in the world have built modeling programs to calculate groundwater flow model and forecast material transport to apply in hydrogeological studies and pollution forecast.

2.2. Visual MODFLOW

Visual MODFLOW software package includes three main software and many support modules. MODFLOW software is used to calculate the volume, quality and distribution of groundwater flows. Function of ModPath software is calculating the direction and speed of flow when it moves through aquifer system. MT3D software is used to calculate diffusion and transportation processes with chemical reaction of solutes in groundwater flow system [9].

The original version is made by Nilson Guiguer, Thomas Franz, Partrick Delaney and Serguei Shmakov. The commercial version is provided by Waterloo Hydrogeologic Company.

2.3. Input coefficient definition

Grids: The grid system which simulate environment of modelling area, is the finite difference grid. The cells outside the edge is assigned inactive and will not participate in calculation. The finite difference grid is established to calculate in model consists of 130 rows and 111 columns, to be distributed equally with the distance $\Delta x = \Delta y$ = 420m, total number of grid cells is 11430.

Layers: the *"Final report of drawing Thai Binh hydrogeology map, scale 1:50.000"* [4] and *"Final report of finding groundwater in Thai Binh province"* [1] show that cross section of study area consist of 5 layers. Because the 1st, 2nd and 3rd layers are totally seawater, so in this study we only focus in the 4th and 5th layers:

- The 4th layer: is the low permeable layer in Pleistocene sedimentary formations in Vinh Phuc Formation. The average thickness is 12.8m, variation 3-30m. Hydraulic conductivity K = 0.0015m/day; specific storage μ^* = 0.0032; effective porosity n_0 = 0.01; total porosity n = 0.25.

- The 5th layer: is the Qp aquifer in Pleistocene sedimentary formations in Ha Noi Formation. The average thickness is 62.25m with variation 29-68.5m. Permeable layer with high water storage. Average hydraulic conductivity K = 12.43, varies 5 – 18 m/day. Specific storage μ^* = 0.003616, specific yield μ = 0.1677; effective porosity n_0 = 0.18, total porosity n = 0.3. This layer is confined aquifer. Most of this aquifer is seawater, the north of study area is freshwater with TDS < 1000 mg/l. Static water level varies 0.523 – 2.277 m from the ground.

Border and boundary conditions: Thai Binh province is bounded to the West, South West and South by the Red River, the East and the North Sea by Luoc River. Also, in the center of the study area, Tra Ly River crosses from west to east and enters the sea at Tra Ly estuary.

Results of previous geological and hydrological studies of Red River Delta region have confirmed a hydraulic relationship between Red River and the groundwater aquifers [2][4]. However, depending on the region, depending on the distribution of the aquifers and the level of the river cut into the aquifer, the river is high or low affected with aquifers. Red river affects directly to Qh2 aquifer and slightly to Qh1 aquifer. Red river doesn't affect to Qp aquifer. The analytical results show that the particle composition of river bottom sediments generally have small permeability coefficient about (1 - 2.5) x10^{-3} m/s.

The inner boundary conditions in model is the hydraulic relationship between Qp aquifer and Qh1 aquifer by infiltration (the 3rd and 5th layers). According to previous study documents and the National observation construction data. Between Holocene aquifer and Pleistocene aquifer is the Vinh Phuc low permeable layer [7]. In addition, data of observation constructions (Q.156, Q.158 and Q.159) have shown that: water level in Pleistocene aquifer decreases due to exploitation while in Holocene aquifer, water level is almost unchanged. Therefore, boundary conditions type I, H=const, is above Pleistocene aquifer.

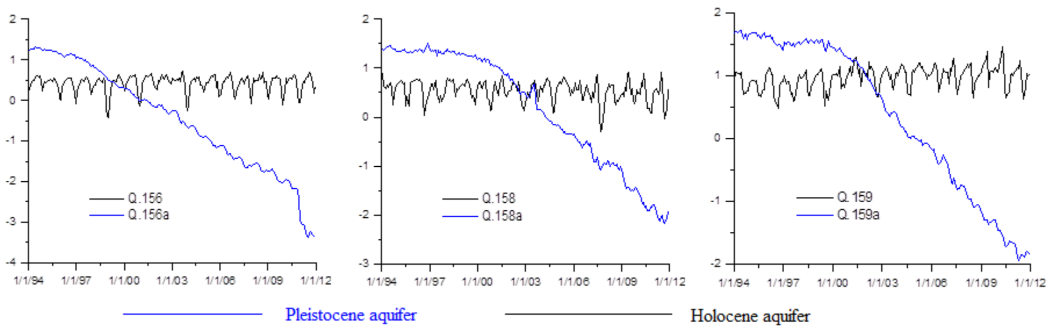

Figure 1: Water level graphs of Pleistocene and Holocene aquifers

The outer boundary conditions: the Pleistocene aquifer has not hydraulic relationship with rivers. According to “Partition Map of groundwater movement Red River Delta region”, [7], the inflow is from northwest direction and flow out to Tokin Gulf (figure 4). To simulate the inflow from northwest direction, model use the boundary condition type II, Q = const, the flow rate is determined by the stability problem in natural conditions.

Tokin Gulf is the eastern boundary of the study area. The sea is the junction of the aquifers. The Pleistocene aquifer is not connected directly with the sea (Tokin Gulf). Go far to the coast, sediment become smoother and finally block water completely. Therefore, the boundary condition used here is type I, H= f(t).

Recharge from precipitation and evaporation: because in this study, the Pleistocene aquifer is the deepest layer, so cannot be affected by precipitation and evaporation.

The original conditions: with the groundwater flow equation is static water level map of Pleistocen aquifer in 1996 [4] and water level isodepth map of Pleistocene aquifer in 2012 (Trinh Hoai Thu, 2012). With the solute transport equation is TDS map of all aquifer in Thai Binh province, 1996 [4] and TDS map in Pleistocene aquifer in Red Delta regions, 2012. The boundary between fresh water area and seawater area is boundary of TDS 1000mg/l, which is identified from the previous study (Trinh Hoai Thu, 2012).

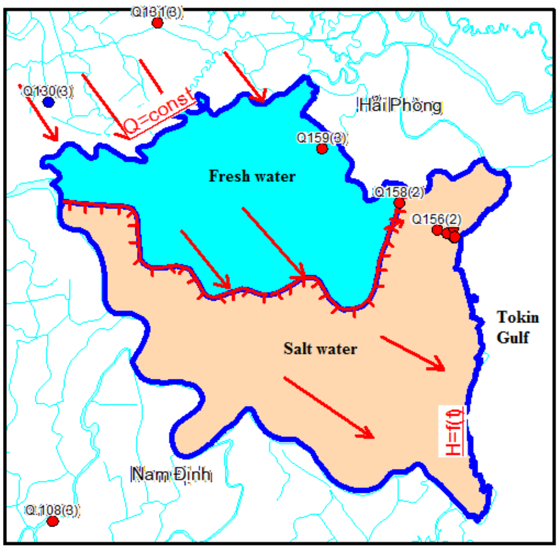

Figure 2: Boundary conditions of Pleistocene aquifer

2.4. Revising model

Model is revised by resolving two models:

Steady-state model: is solved to revise hydraulic conductivity K and revise boundary conditions preliminarily. The target is recovering the static water level in Pleistocene in 1996s (still not be exploited).

Transient model: purpose of resolving unsteady-state model is revising Specific yield and specific storage, keep on revising hydraulic conductivity. In addition, unsteady-state model has mission to revise and correct solute movement. Therefore, this problem has to solve both Groundwater flow and Solute transport equation.

The original condition of unsteady-state model is Water level map of Pleistocene aquifer in 2012 (the results of Steady-state inverse problem). With Solute transport problem is Distribution of TDS in Pleistocene aquifer, 2012 [5]

3. Results and Discussion

3.1. Results of steady-state and transient models

Steady-state model: the results are showed in the below table:

	Q_{in} (m^3/day)	[%]	Q_{out} (m^3/day)	[%]
Northwest boundary	10000	73.36	0.00	0.00
Holocene aquifer	9.68	0.07	25.57	0.18
Exploited wells	0.00	0.00	0.00	0.00
Seawater area	3578.6	26.25	13620	98.08
Total	13632	100.0	13886	100.0

Table 1: Water balance of Pleistocene aquifer in original condition

Results of water balance in the original conditions show that the Q_{in} of the Northwest boundary accounts 73.6% the total inflow rate (Q_{in}). Infiltration from Holocene is only 9.68m^3/day (accounts 0.07% total inflow rate) while the inverse infiltration from Pleistocene is 25.57m^3/day (accounts 0.18% total outflow rate), because in original condition water level in Pleistocene is higher in Holocene. Water flow mainly from fresh water area to seawater area (account 98.08% total outflow rate) – “push seawater to the sea”.

Transient model: Similar to Steady-state, this problem is solved by iterative methods.

Unfortunately, in the Thai Binh area, there is not many observation constructions, especially in centre. In the national observation system, there are only 3 observation bores, 2 bores in Thai Thuy district are Q156 (Thuy Lien commune) and Q158 (Thuy Viet commune); 1 bores in Quynh Phu district is Q159 (An Viet commune). Observation data of bores Q156, Q158 and Q159 are used to revise transient model in exploited condition. The reliability of the model can be assessed through the mean square error.

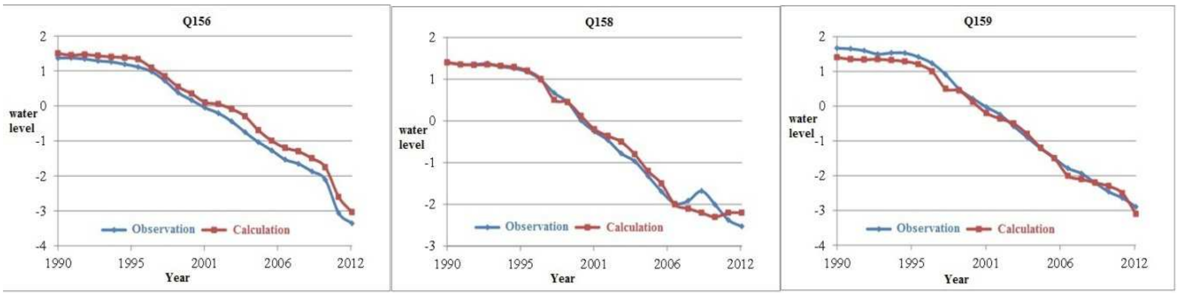

Figure 3: Observation water level and calculated water level at Q156, Q158 and Q159

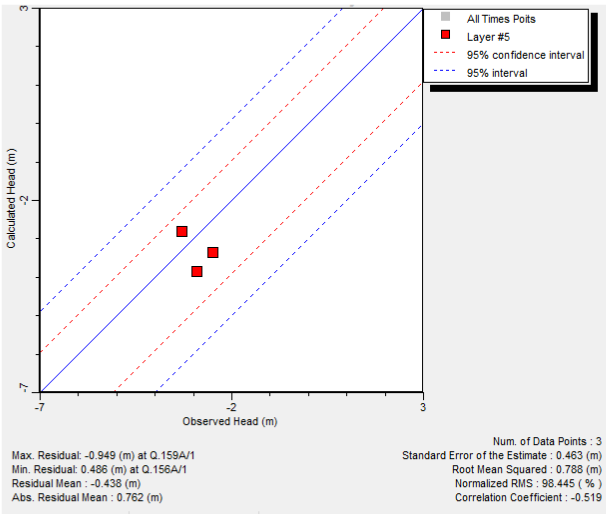

Figure 4: Correlation between calculated water level and observed water level

Error when revise model with transient model, were within permitted limits, average square error reach 0.788m (figure 7).

	Q_{in} (m^3/day)	[%]	Q_{out} (m^3/day)	[%]
Water in Pleistocene aquifer	6.5	0.02	267	0.81
Northwest boundary	10000	31.09	0.00	0.00
Holocene aquifer	188.03	0.58	0.00	0.00
Exploited wells	0.00	0.00	31500	96.12
Seawater area	21974	68.31	1005.6	3.07
Total	32162	100.0	33634	100.0

Table 2: Water balance of Pleistocene aquifer in exploited condition

Water balance calculation results show that by the impact of exploitation, water inflow and out flow rates are changed significantly. The both inflow and outflow rates increase by 2.4 times.

Layer	K_x (m/ng)	K_y (m/ng)	K_z (m/ng)	μ*	μ	n_0
Qh_1	1.10	1.10	0.11	0.0028	0.14	0.14
Low permeable layer	0.001	0.001	0.0001	0.0013	0.02	0.02
Qp	17.33	17.33	1.73	0.0036	0.16	0.16

Table 3: Summary table of input coefficients after revising

We can show that the revised input coefficients is suitable with previous studies [1].

3.2. Seawater intrusion forecasting

Based on real situation of exploitation and water needs in the future, we propose two exploited scenarios to calculate developments of seawater intrusion in 2030, 2050.

Scenario 1: Keep exploitation rate of groundwater in Pleistocene aquifer equal to present Q = 31500 m^3/day.

Scenario 2: Increase exploitation rate to Q = 68000 m^3/day, account to 50% of water needs in 2050 (according to population growth rate of Thai Binh province (Statistics Yearbook, 2010)).

Results:

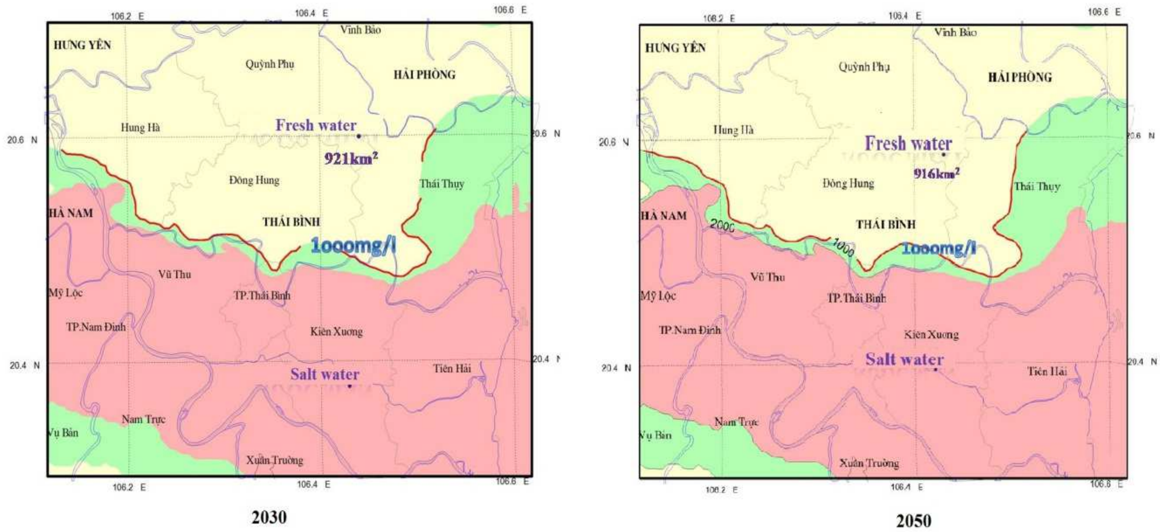

Figure 5. The boundary line 1000mg/l scenario 1

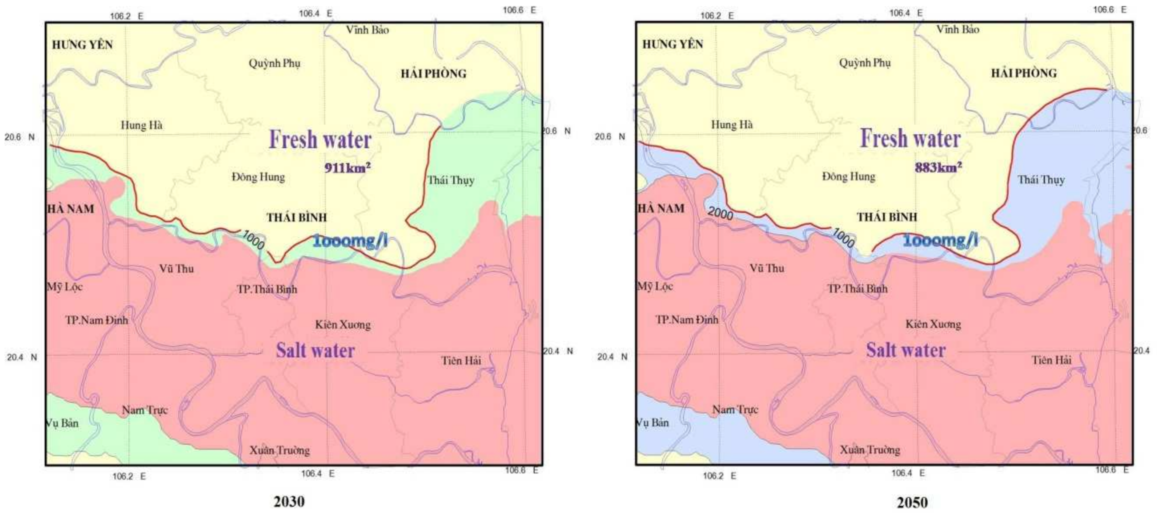

Figure 6. The boundary line 1000mg/l scenario 2

Scenario 1: With Q = 31500 m^3/ day boundary of TDS is 1000mg/l, the total area of fresh water in study area is 925 km^2 in 2012; 2030 decrease to 921 km^2 (99.56%), in 2050, decrease to 916 km^2 (99%). The seawater intrusion is developing but the rate is very slow.

Scenario 2: With exploitation rate 68000 m^3/day and boundaries of TDS is 1000 mg/l, the total area of fresh water in the study area is 911km^2 in 2030 (account 98.4%), 2050 decreased to 883km^2 (account 95.4%). Therefore, compare with scenario 1, we can see that by the exploitation process increases the salinization process in more depth.

4. Conclusion

By solving Steady-state and Transient models, all input coefficient have been identified with K_x = 17.3, K_y =17.3, K_z =1.73, specific storage μ^* = 0.0036, specific yield μ = 0.16 and effective porosity n_0 = 0.16.

Groundwater exploitation from UNICEF well system has increased both inflow and outflow rate in Pleistocene aquifer by 2.4 times.

Forecasting model of seawater intrusion of Pleistocene aquifer in Thai Binh area have showed the changes of TDS level in study area and forecast to 2050. The total area of fresh water in study area is 925 km^2 in 2012 (boundary of TDS is 1000mg/l); With exploitation rate Q = 31500 m^3/ day in 2030 total area of fresh water decrease to 921 km^2 (99.56%) and in 2050, decrease to 916 km^2 (99%); With exploited rate 68000m^3/day , the total area of fresh water in the study area is 911km^2 in 2030 (98.4%) and in 2050 decreases to 883km^2 (95.4%).

With current exploited rate, the seawater intrusion keep developing but the rate is very slow. Thai Binh area can still exploit groundwater with the rate Q = 31500 m^3/day. This is a useful information for further studies and sustainable exploitation for study area.

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