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Research and assessment of potential groundwater exploitation reserves in coastal areas of Ninh Thuan province

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ABSTRACT

This paper presents the results and assessment of the groundwater exploitation reserves in coastal areas of Ninh Thuan province. The research was based on determining the exploitation reserves of all grid cells with dimensions 500 m × 500 m distributed in fresh-salted water areas of the Holocene (qh) and Pleistocene (qp) aquifers. Each grid was assigned the corrected hydrogeological parameter values (depth, gravity coefficient, hydraulic conductivity, and drawdown level). The calculation results show that the total amount of potential exploitation reserves in the entire qh and qp aquifers-distributed areas is 561.8×10^6 m^3 per day, whereas in the freshwater area is 345.4×10^6 m^3 per day (61.5%), and the saline water area is 216.4×10^6 m^3 per day (38.5%). These potential exploitation reserves can be used for groundwater exploitation management and planning in Ninh Thuan province.

Keywords: Potential exploitation reserve, Ninh Thuan province, Holocene aquifer (qh), Pleistocene aquifer (qp).

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INTRODUCTION

Ninh Thuan province has been identified as possessing the scarcest water resource among the coastal provinces in the country. The average annual rainfall is low, reaching only 700–800 mm/year, unevenly distributed, and mainly occurs in the rainy season [1–3]. The dry season lasts long, with the majority of the surface water poured into the sea. According to the hydrogeological results report of Ninh Thuan province, the characteristics of the stratum structure and the water-bearing aquifers are easy to receive permeable water from the surface and quicky drain water to sea and river; however, it also witnesses moderate rainwater absorption since thin aquifer can only store little water, or weak permeable topsoil leading to large surface runoff and rapid discharge to the sea because of the sloping terrain [4–7, 8]. Therefore, groundwater (GW) resources in this area are poor, scarce, and have less potential for groundwater exploitation.

The GW potential exploitation reserve of the two aquifers Holocene (qh) and Pleistocene (qp) in Ninh Thuan province has been studied and calculated by many studies [4, 9–11]. Pham Ngoc Minh (2012) [4] determined the GW potential exploitation reserves by the proportion of separate static reserves for each stratum qh and qp with the average value is 330.59 m^3/day/km^2. The result of calculating the GW potential reserves using the numerical modeling method (Modflow model) of Nguyen Minh Khuyen [9] in the Cai river basin in Phan Rang is 134,374 m^3/day. Tong Ngoc Thanh et al., (2015) [11] calculated the GW potential exploiting reserves in freshwater areas of Ninh Thuan province by the method of taking the percentage of intrusion of static reserves, resulting in the average of freshwater and saline water being 468,126 m^3/day and 53,883 m^3/day, respectively. However, the reserve and quality of groundwater in Ninh Thuan province depend on many factors, such as topography, exploitation flow, natural conditions, rainfall infiltration amount, and demand for groundwater exploitation. Therefore, the groundwater potential exploitation reserves change annually. As a result, this paper aims to study and calculate potential groundwater exploitation by the calculation method on grid cells with the latest data sources to date. Identifying distribution conditions and the GW potential exploitation reserves in freshwater areas can be exploited in the coastal area of Ninh Thuan province, thereby making forecasts about changes in reserves and groundwater quality.

HYDROGEOLOGICAL CHARACTERISTICS

Porous aquifer in undivided Quaternary sediments

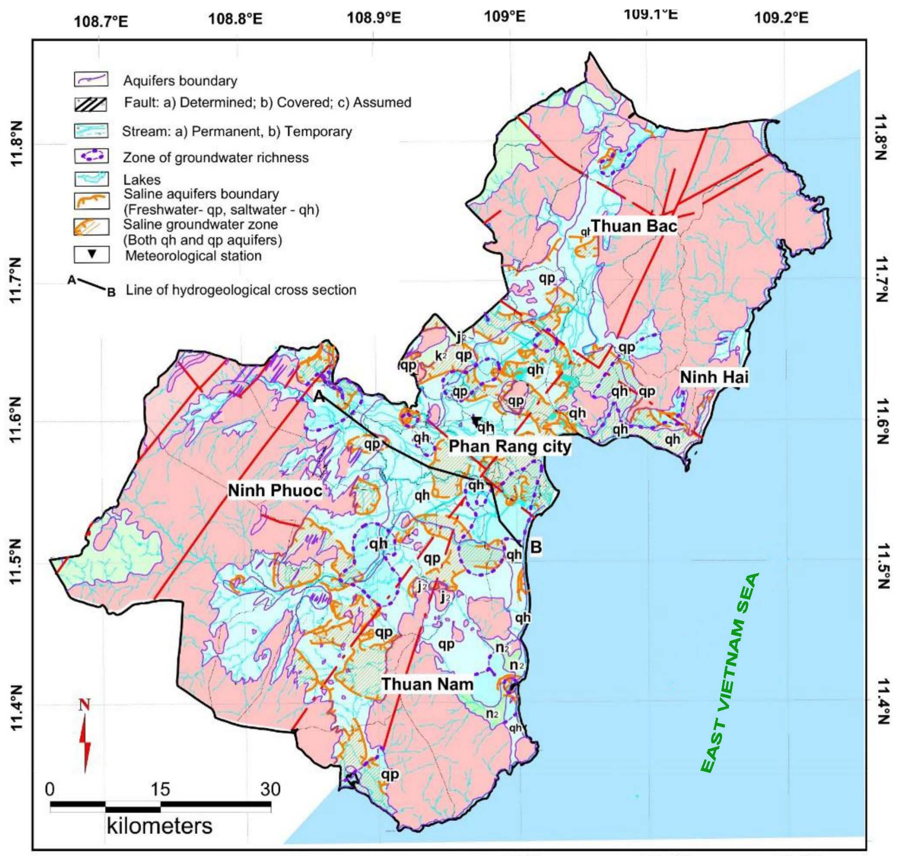
The aquifers are scattered and distributed in many places in the Phan Rang plain: along the Cai river, Phan Rang, and other places; and along the two banks of the Lu river, from Nhi Ha to near Phuoc Dan, from Quan The to Lam Hai. Soil and rock containing water are either pebbles or gravel mixed with clay, sand, or mixed clay, mixed sand. The hydraulic conductivity of mixed clay is from 0.1 m/day to 0.5 m/day; meanwhile, sand and mixed sand are from 5–8 m/day. The thickness of the aquifer is from 5 m to 15 m. The water depth is from 1.5 m to 3.0 m [4, 5].

The amplitude of water level fluctuations over the year is from 5 to 6m, and the flow of water vessels ranges from 0.1 L/s to 0.2 L/s. The source for the aquifer is rainwater and water from aquifers in the original weathered crust. As a result, that creates partial pressure for the Quaternary sedimentary aquifer around Quan The 1 village. Here, the groundwater emerges above the ground forming a swampland [4, 5].

Porous aquifer in Holocene sediment (qh)

The aquifer is distributed mainly in the Phan Rang plain and scattered along small rivers. Soil-containing water is formed from various sources: river-swamp (abQ_2), river-sea-swamp ($ambQ_2$), sea (mQ_2), and sea-wind (mvQ_2). River-swamp sediments are distributed mainly in the center of the plain, along National

Highway 1 from Ninh Hai to Phan Rang and Highway 27 from Phuoc Son to the estuary of Cai river, Phan Rang. Soil containing water is sand-mixed with grit, gravel, clay, and mixed clay. The hydraulic conductivity of sand mixed gravel is 1–3 m/day. The thickness of the aquifer is 0.5–3 m (Figs. 1, 2). The flow of water is 0.05–0.11 L/s [4, 5].



LEGEND A

Aquifer	Age	Symbol	Thickness (m)	Lithology	Water potential	
					Poor	Medium
Porous aquifer	Undivided Quaternary aquifer	q	2–8	Clay, sands macadam, pebbles		
	Holocene	qh	1–16	Silt and sand mixed with grits, macadam and pebble		
	Pleistocence	qp	2–35	Sands and gravels mixed with silt and clay		
Fractured aquifer	Lower Pliocene	n_2	6–31	Gritstone, quartz sandstone		
	Lower Cretaceous	k_2	500–1,350	Dacite, ryodacite, felsite andesitodacite and tuff		
	Middle Jurassic	j_2	600–1,280	Fractured shale		
Impermeadble formation			200–500	Granite biotite-hornblende, granite biotite-muscovite, granite porphyr, granite aplite, granite alaskite, granosyenite, granosyenite porphyr, granodiorite biotite, monmodiorite		

Figure 1. Hydrogeological map of study area in Ninh Thuan province

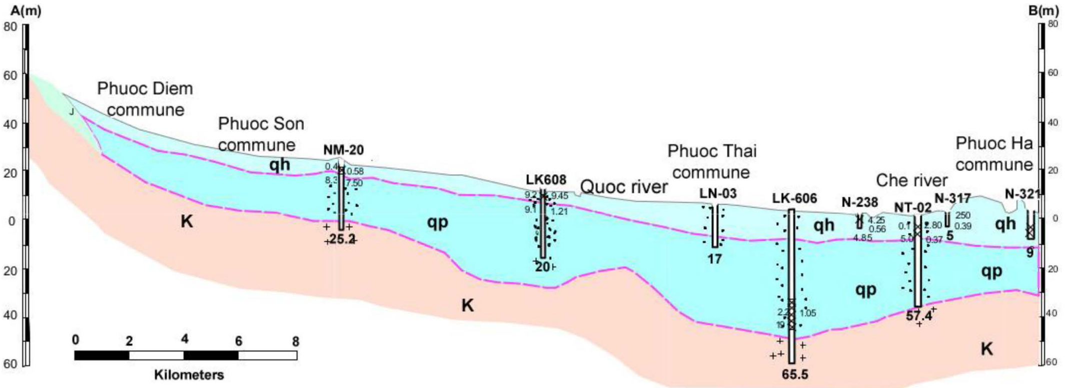


Figure 2. Hydrogeological section along line AB

River-sea-swamp sediments are distributed around Phuoc Dan, along the Cai river in small patches. Soil containing water is sand with grit, gravel, sand, and mixed clay. In some areas, where the composition is mainly sand and mixed gravel, the hydraulic conductivity reaches 10–25 m/day; if it is either mixed sand or mixed clay, the hydraulic conductivity is 0.4–5 m/day. The thickness of the aquifer is 3 m to 20 m. The depth of stagnant water is from 0.5 m to 1.5 m. The amplitude of water level fluctuation during the year is 0.5 m. Marine sediments are distributed on sea shelves 1–2 m high, or 4–5 m in some places, in Van Hai, Dong Hai, North Nhon Hai, and along the coastal area from Cai river's estuary to the North of Vung Tron. Rock and soil containing water are sand-containing corals, shells, and mussels. The thickness of the aquifer is 5–25 m. The hydraulic conductivity is 10 m/day. The wind-sea sediments are distributed in the south of Phan Rang, along the coast from the estuary of the Cai river, Phan Rang, to Mui Dinh. The composition of soil rock containing water is small-grained sand with a thickness of 4–6 m, sometimes up to 10–15 m. The water depth is 1–3 m. The flow of the visible water stream is 0.1–0.5 L/s. The borehole flow rate is 0.1–1.01 L/s. Hydraulic conductivity is 1–5 m/day [4, 5].

Porous aquifers in Pleistocene sediment (qp)

Aquifers are widely distributed in the Phan Rang Plain; however, most are covered by Holocene sediments. They are only exposed on the ground in the Northern, Western, and Southern fringes of the Ninh Hai plain and plateau. Different sources form soil containing water: river sediment, sea, sea-wind, and river-sea. Rocky soil containing water is mainly pebbles, gravel, and sand mixed with clay and corals. The thickness of the aquifer is 5–30 m. The water depth is from 1–3 m (Figs. 1, 2). The flow rate of standard boreholes is from 1–5 L/s. The hydraulic conductivity is from 0.1–10 m/day. The amplitude of water level fluctuation is usually 1–3 m. Although the Pleistocene sediments have many different origins, the petrographic composition is relatively identical. They can be grouped into one aquifer, making it the most significant unit in the Phan Rang delta. The main supply sources are rainwater, water from the Cai river, Phan Rang, Lu river, and Nhat Canal. Rainwater and river water is permeated through the visible area on the ground to form freshwater areas [4, 5].

METHOD

Potential GW exploitation reserves include Dynamic and Static reserves. Potential GW extraction reserves were determined according to the following formula [12–14].

Formula to calculate potential exploitation reserves and exploitation flow on grid cells

Potential exploitation reserves (Q_{KT}) = Dynamic reserves (Q_{TN}) + Static reserves (V_{TN}) [15].

$$Q_{KT} = Q_{TN} + V_{TN}; \quad V_{TN} = \frac{\alpha\ V_{\text{aquifer}}}{t_{KT}}; \quad Q_{TN} = \mu \frac{\Delta H + \Delta Z}{365} f \tag{1}$$

in which: V_{aquifer}- volume of water storage; α- coefficient of encroachment on natural static reserves; t_{KT}- time of exploitation (usually fixed at 27 years = 10,000 days); μ- gravity release coefficient; H- amplitude of water level fluctuation; Z- the value of drawdown water level; f- area of aquifers.

One of the methods to determine groundwater exploitation reserves is to observe the exploitation flow of all grid cells with defined measuring values based on various factors such as the homogeneity of soil and rock-containing water, population density, the position of future water supply, and needs. The formula of M. Masket - Ph. M. Botrever (Drobnokhod et al., 1982) [14] aims to determine the approximate exploitation flow from each grid cell as follows:

$$\text{For confined aquifer } Q = \frac{\left[s_{CP} + \left(Q_{TN} + Q_{LC} \right) \dfrac{t_{KT}}{\pi R_{DD}^2 \mu *} \right] \pi R_{DD}^2}{\dfrac{t_{KT}}{\mu *} + \dfrac{R_{DD}^2}{2Km} \ln \dfrac{R_{\mathrm{DD}}}{r_{GL}}} \tag{2}$$

$$\text{For unconfined aquifer } Q = \frac{\left[s_{CP} \left(1 - \dfrac{s_{CP}}{2H} \right) + \left(Q_{TN} + Q_{LC} \right) \dfrac{t_{KT}}{\pi R_{DD}^2 \mu} \right] \pi R_{DD}^2}{\dfrac{t_{KT}}{\mu} + \dfrac{R_{DD}^2}{2KH} \ln \dfrac{R_{DD}}{r_{GL}}} \tag{3}$$

in which: S_{CP}- the appropriate value of drawdown water level; μ*- elastic water released coefficient; μ- gravity water released coefficient; t_{KT}- time of exploitation; K- hydraulic conductivity; m- thickness of the confined aquifer; H- thickness of the unconfined aquifer; Q_{TN}- dynamic natural reserves; Q_{LC}- absorbed water reserve (from ponds, lakes, rivers, and streams); R_{DD}- radius of large wells (R_{DD} = 0.565Δx); Δx- length of one grid's side; r_{GL}- radius of large wells (with the number of exploitation boreholes about 2–3 and equally distributed, the radius of large wells is approximately 10 m).

Model construction for calculating the potential exploitation reserves

Diagram the region of model construction and divide grid cells to calculate the potential groundwater reserves

The research modeling area is determined according to the hydrogeological and topographical characteristics of Ninh Thuan province, the study area containing impermeable rock and groundwater (q, qh, and qp) (Fig. 3).

The study area in the Ninh Thuan Delta is divided into grid cells measuring values as 500 m × 500 m. The grid cells are mainly 500 m × 500 m squares, in which those adjacent to the study area are quadrangular or triangular. The total number of grid cells is 2,565 (2,907 in total) (Fig. 4a). Each grid cell is identified with an ordinal number and parameters to calculate potential exploitation reserves (layer thickness, gravity release coefficient, water conductivity coefficient).

The study area is identified with saline-fresh groundwater [16], determining grid cells to calculate potential exploitation reserves in fresh or saline areas. The fresh groundwater area comprises 1,577 grid cells, whereas the saline groundwater contains 988 grid cells (Fig. 4b).

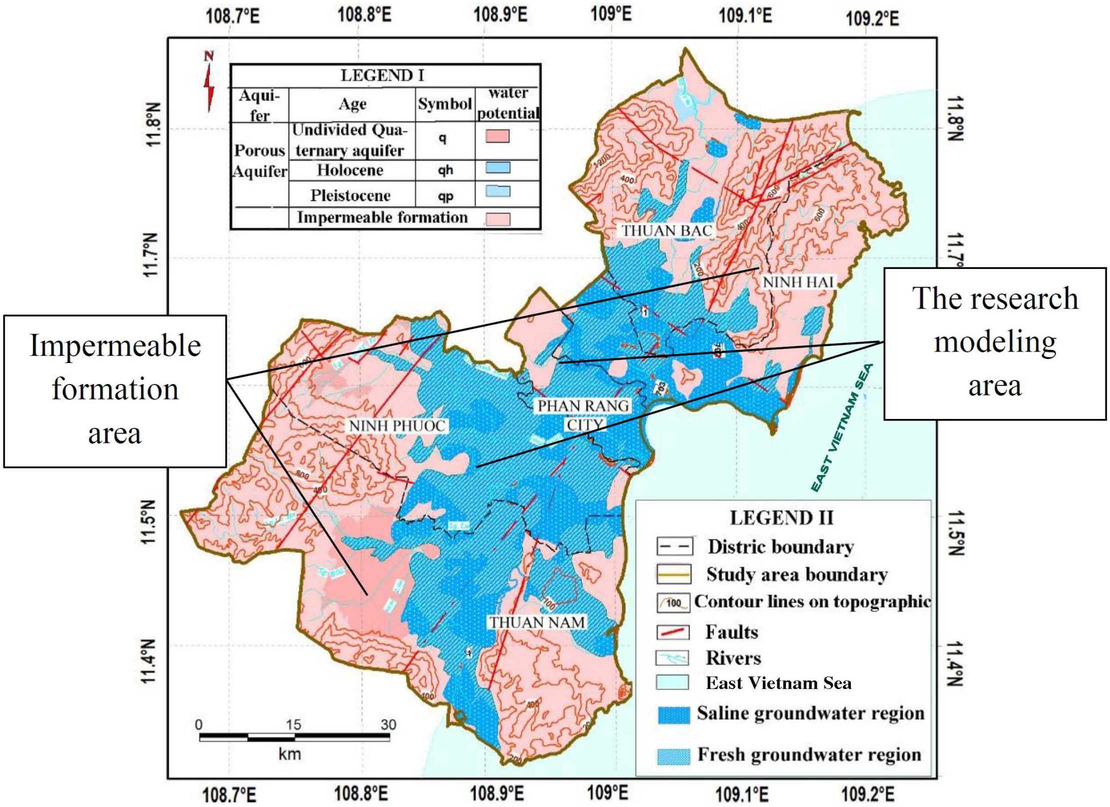


Figure 3. The research modeling area

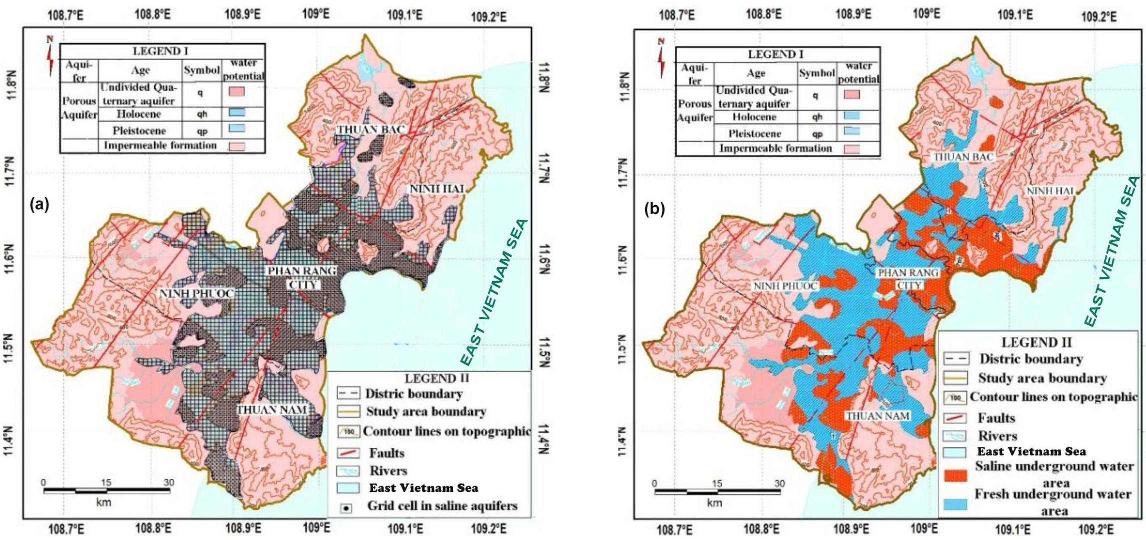


Figure 4. Grid cells (a) and fresh-salt water distribution (b)

Hydrogeological parameters

The thickness of qh and qp aquifers: Interpolation according to geological Kriging method using ArcGIS software. The thickness of the qh aquifer at the boreholes varies from 0.15 m to 14.54 m; meanwhile, the qp aquifer at the boreholes ranges from 0 m to 42.9 m

[4, 5]. On the cross-sections, the most significant thickness of both aquifers is found in the northeast (Thuan Nam district) and tends to be thinner to the South and Southeast of the Thuan Bac district (Figure 5).

The hydraulic conductivity K: Regionalize the hydraulic conductivity of soil-rock layers according to the model layers, which are interpolated based on the boreholes data of the two aquifers (Figure 6) [4, 5].

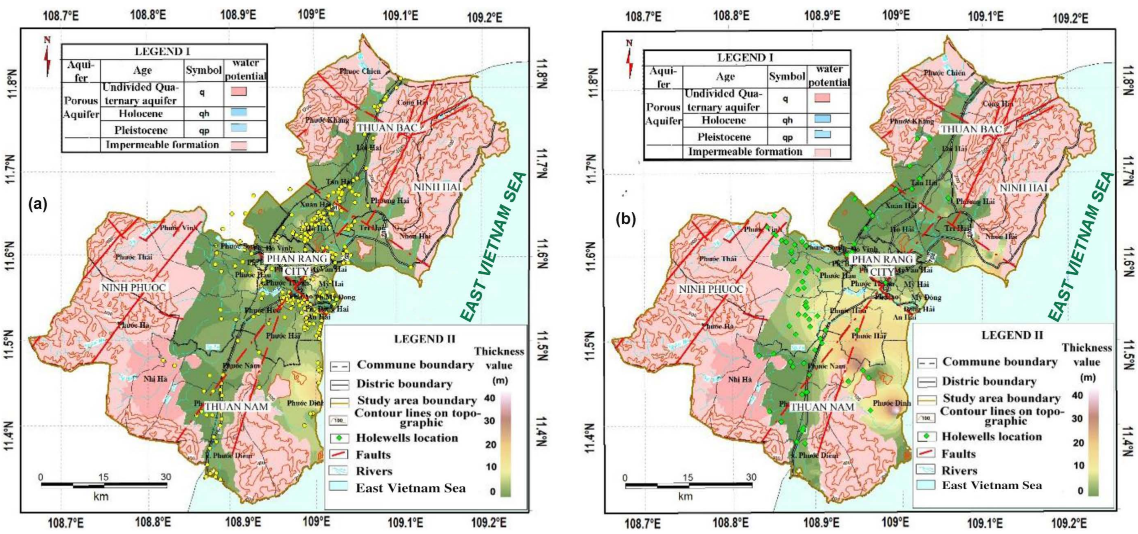
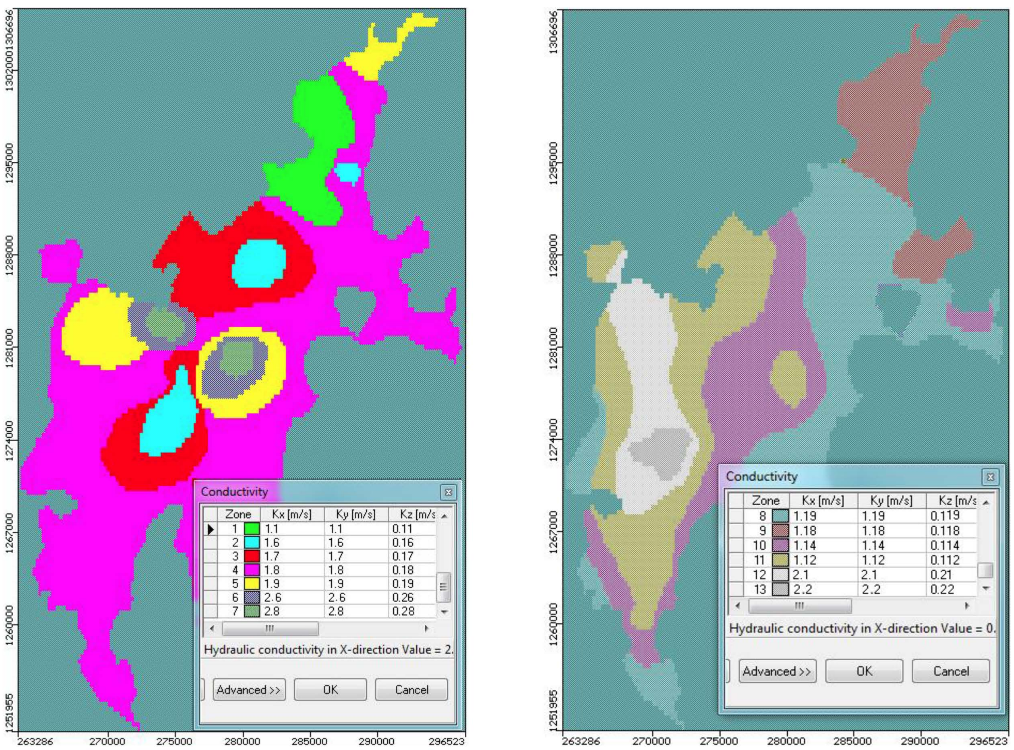


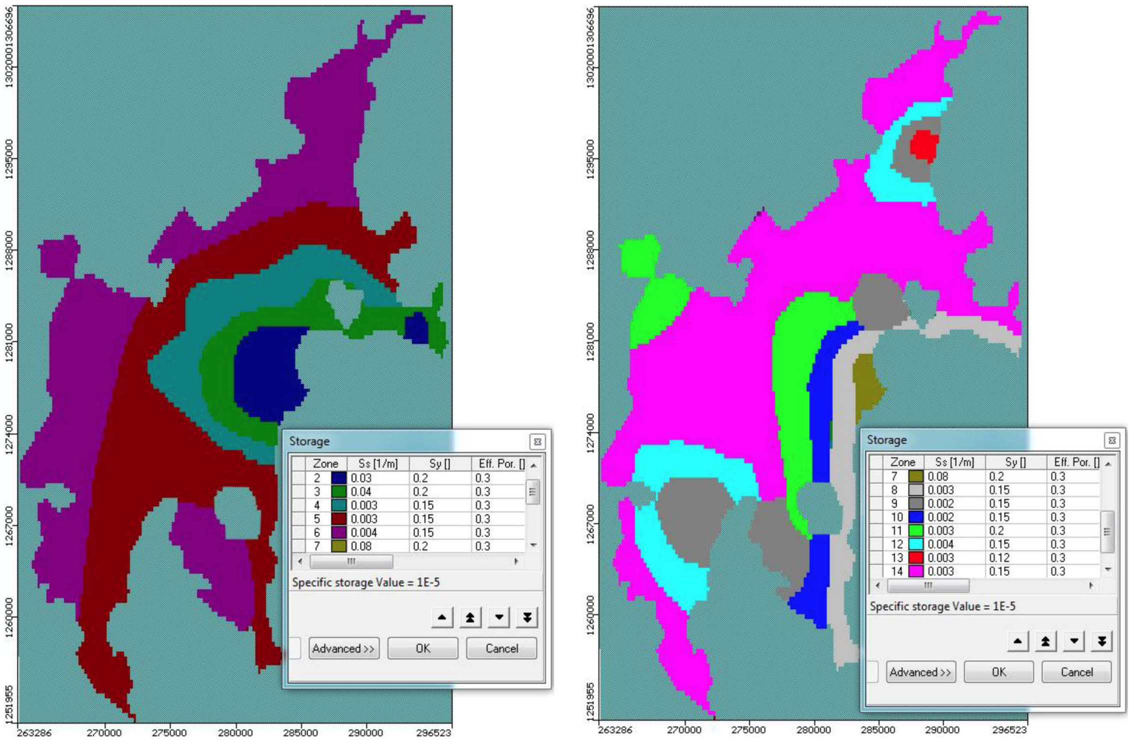
Figure 5. The map of the Holocene (a) and Pleistocene (b) aquifer's thickness



(a) (b)

Figure 6. The hydraulic conductivity of the qh (a) and qp (b) aquifers

The Specific storage: Is determined through the theoretical formula: Distribution of the water-released coefficient of soil-rock layers according to model layers, which are interpolated based on boreholes data of the two aquifers (Figure 7).



(a) (b)

Figure 7. The Specific storage of the qh (a) and qp (b) aquifers

Rainfall supplied to strata: Is simulated, and its average is calculated through the total rainfall, according to the properties of the soil and the amount of permeable rainfall supplied to groundwater from May to May 12, which is 0.380 m, accounts for 44.9% of the precipitation depth [1–5, 17]. A total volume of 289–10^6 m^3 of rainwater can infiltrate the Quaternary sediments aquifer as over 760 km^2 in the coastal plain of Ninh Thuan province. Thus, the recharge rate for the qh and qp aquifers is proportional to the precipitation amount.

The amount of appropriate water drawdown level scp: Is equal to half of the aquifer thickness [18].

The radius of the large well (R_{gl}): Is equal to 10 m for grid cells with an area of 250,000 m^2 and equal to 5 m for grid cells with an area of less than 250,000 m^2.

Operation and correction of the hydrogeological parameters

The model was operated to determine the boundary conditions of the model domain, such as the appropriate boundary conditions with defined inflow or water levels. The type of aquifer was also determined: Independent or permeable through the layer's top and bottom.

The model implementation in 30-time steps was compared with the water drawdown level diagram by the Division for Water Resources Planning and Investigation, 2012 [4]. The results show that the boundary condition with the determined water drawdown level suits the model. After consideration, the input data set calculates the underground water reserves.

Table 1. Table of hydraulic conductivity, Specific storage after adjustment

Aquifer	Zone	K_x (m/day)	K_y (m/day)	K_z (m/day)	μ*(1/m)	μ
Holocene aquifer's	1	2.1	2.1	0.21	0.03	0.14
	2	1.6	1.6	0.16	0.04	0.14
	3	1.7	1.7	0.17	0.003	0.14
	4	1.8	1.8	0.18	0.003	0.14
	5	1.9	1.9	0.19	0.004	0.14
	6	2	2	0.2	0.03	0.14
	7	2.2	2.2	0.22		
Pleistocene aquifer's	1	1.16	1.16	0.16	0.003	0.11
	2	1.18	1.18	0.18	0.002	0.11
	3	1.14	1.14	0.14	0.003	0.11
	4	1.12	1.12	0.12	0.004	0.11
	5	1.1	1.1	0.11	0.003	0.11
	6	1	1	0.1	0.003	0.11

RESULTS AND DISCUSSION

The natural static and dynamic reserves of qh and qp aquifers

The natural static groundwater reserves of the aquifers

The entire distribution area: The total distribution area of aquifers is 570.1 km^2. The total volume of the aquifer is determined as 4,588.5 × 10^6 m. The water release coefficient of the qh aquifer is 0.14, and the qp aquifer is 0.11. The average gravity release coefficient of aquifer qh and qp is 0.125 [4, 5]. Thus, the total static reserve is calculated as 573.6 × 10^6 m^3. Figure 8 shows a static groundwater reserve in the entire distribution are.

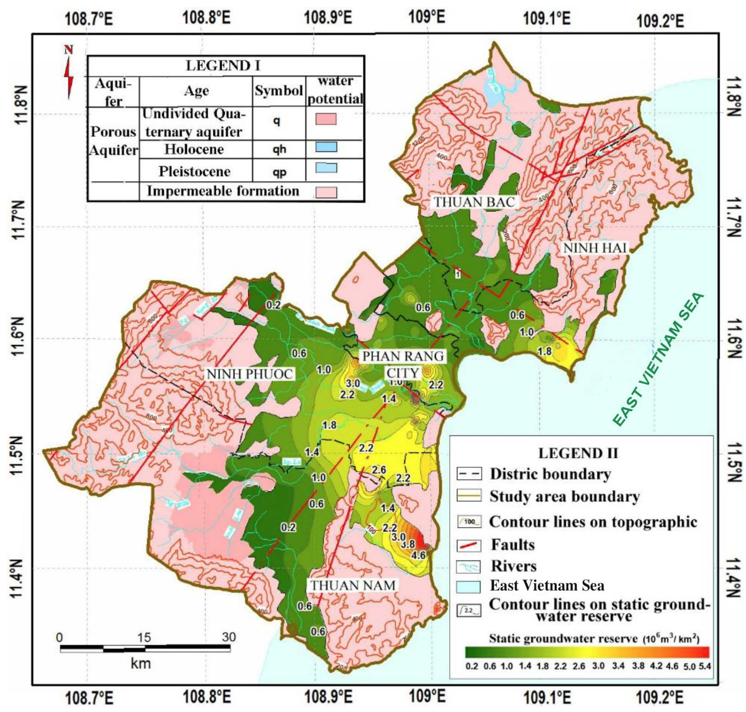


Figure 8. Static groundwater reserve in the entire distribution area

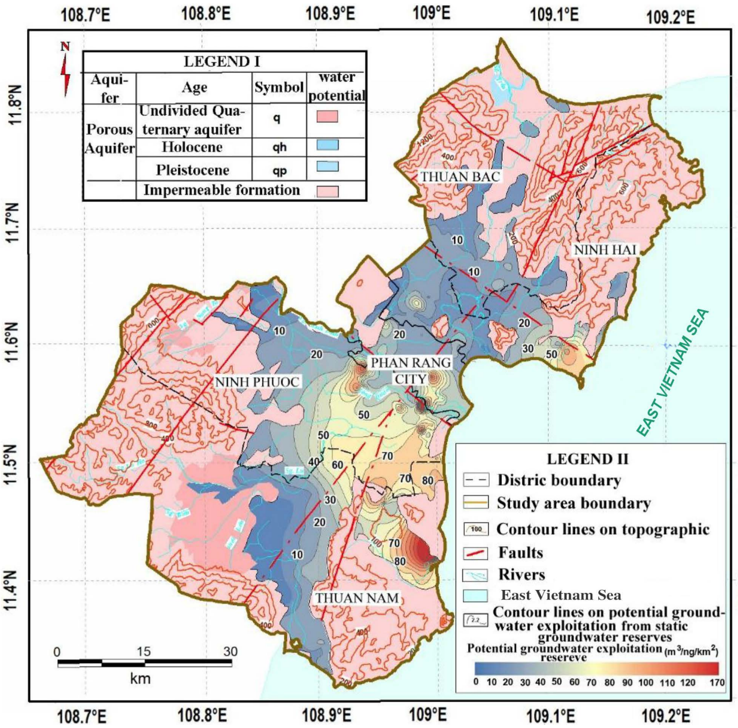


Figure 9. Potential groundwater exploitation from static groundwater reserves in the entire distribution area

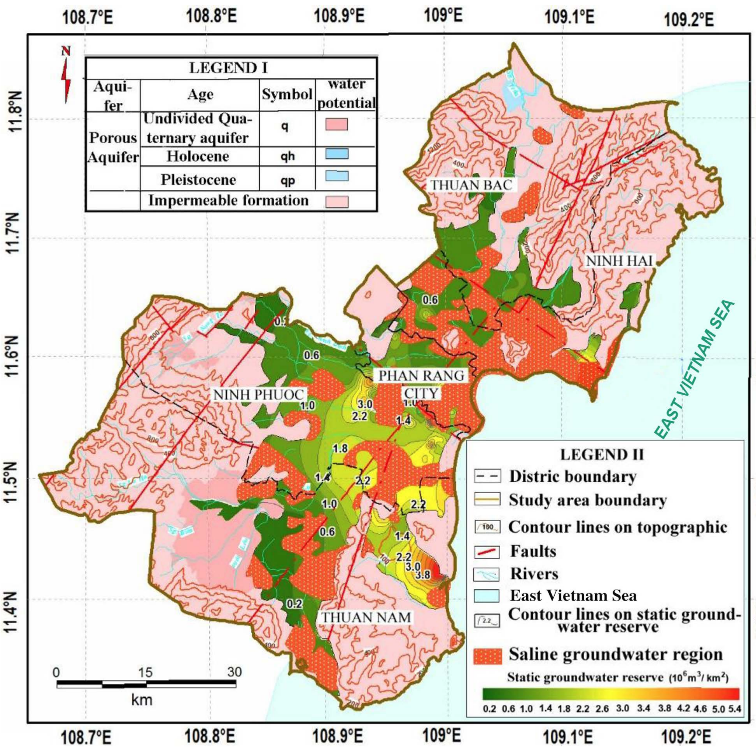


Figure 10. Static groundwater reserve in the distribution of freshwater

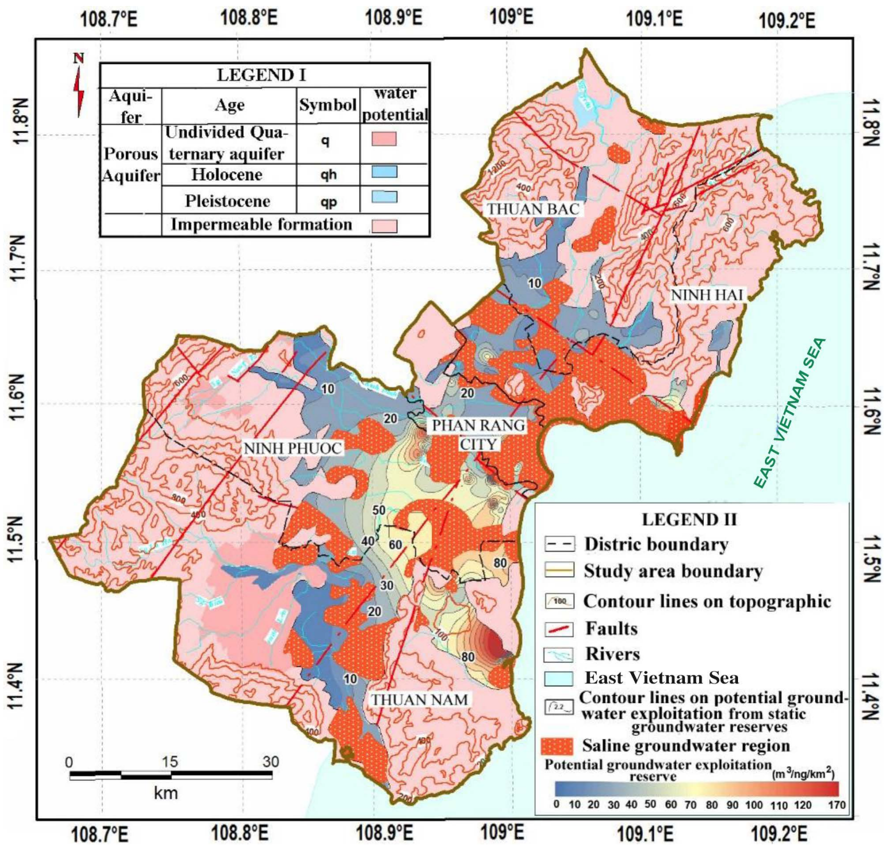


Figure 11. Potential groundwater exploitation from static groundwater reserve in the distribution of freshwater

Exploitation reserves are calculated as 30% of total static reserves, resulting in 172.1 × 10^6 m^3 for 10,000 days corresponding to a flow rate of 17,207 m^3/day, equivalent to 30.2 m^3/day/km^2 (Figure 9).

Distribution of freshwater: The distribution of freshwater aquifer is 349.8 km^2 (61.4% of the total area). The volume of the aquifer, according to the distribution of freshwater area, is determined as 2,922 × 10^6 m^3 (63.7% of the total volume). The water release coefficient of the qh aquifer is 0.14, and the qp aquifer is 0.11. The average gravity release coefficient of the aquifer qh and qp is 0.125. Thus, the static reserve on the freshwater distribution area is calculated as 365.2 × 10^6 m^3 (Fig. 10). Exploitation reserves are calculated as 30% of total static reserves, resulting in 109.6 × 10^6 m^3 for 10,000 days corresponding to a flow rate of 10,957 m^3/day, equivalent to 31.3 m^3/day/km^2 (Fig. 11).

The dynamic groundwater reserves of the aquifers

Dynamic reserves might include many components, such as the amount of water flow through the aquifer's cross-section, permeability from the upper and lower layers, and the flow from the outer boundary to the strata. Dynamic reserves are determined by infiltration from the upper layer through the lower layer of rainwater from May–November from 2014 to 2018.

Natural dynamic reserve: The average natural dynamic reserve is calculated as 0.594 × 10^6 m^3/day, equivalent to 1,041 m^3/day/km^2 from the average value infiltrating the aquifer from rainwater of 0.38 m/year. Effectual natural dynamic reserve: The average adequate supply from rainwater accounts for 13.5% of the total rainfall (as the total annual rainfall is 0.853 m), which is equivalent to a total natural dynamic reserve of 65.65 × 10^6 m^3 per year in the entire area, in which the average is 179.9 × 10^3 m^3/day, which is equivalent to 315.5 m^3/day/km^2.

Table 2. Total rainwater infiltration from May–December 2014–2018

Year	Rainfall depth (m)	Infiltration	K = 0,013 m/day	K = 0,058 m/day	K = 0,102 m/day	K = 0,146 m/day	K = 0,200 m/day
2014	0.503	R* (m)	0.193	0.292	0.304	0.272	0.204
		P** (%)	38.3	58.0	60.5	54.0	40.6
2015	0.805	R (m)	0.228	0.356	0.381	0.324	0.238
		P (%)	28.3	44.2	47.3	40.3	29.6
2016	1.285	R (m)	0.380	0.641	0.673	0.583	0.409
		P (%)	29.5	49.9	52.4	45.3	31.8
2017	0.847	R (m)	0.303	0.482	0.511	0.439	0.316
		P (%)	35.7	56.9	60.2	51.8	37.3
2018	0.827	R (m)	0.287	0.437	0.458	0.408	0.308
		P (%)	34.8	52.8	55.4	49.4	37.3
Average	0.853	R (m)	0.280	0.440	0.470	0.410	0.300
		P (%)	33.3	52.4	55.2	48.2	35.3
		R (m)	0.380				
		P (%)	44.9				

Potential exploitation reserves of qh and qp aquifers

The coastal area of Ninh Thuan province is divided into grid cells with an area of 500 m^2 (500 m × 500 m). The hydrogeological parameters, the appropriate drawdown water level, and the proportion of rainfall infiltration equivalent to the amount of water supplied based on the results of the predicting model of aquifer qh and qp on all 2,565 grid cells are determined. The appropriate drawdown water level is equal to half of the aquifer thickness. The porous Holocene aquifer (qh) water release coefficient is 0.14, and the porous Pleistocene aquifer (qp) is 0.11. The average gravity water release coefficient of the aquifer qh and qp is 0.125.

The qh and qp aquifers are identified as unconfined aquifers; thus, the exploitation reserve is calculated based on formula (3) of M. Masket - Ph. M. Botrever (Drobnokhod et al., 1982) [14]. Calculation results show that the total potential reserves of the qh and qp aquifers corresponding to the appropriate water level depth equal 1/2 their thickness, which is 561.8 × 10^6 m^3/day, the average is 219,02 m^3/day/km^2 (Fig. 12). Besides, the potential exploitation reserves of the qh and qp aquifers on the freshwater distribution are 345.4 × 10^6 m^3/day (Figure 13).

The results of calculating the study area's average groundwater potential exploitation reserve are 219.02 m^3/day/km^2. Thus, the average groundwater potential exploitation reserve is lower than the result, according to author Pham Ngoc Minh (2012) is 330.59 m^3/day/km^2. However, the calculation method of Pham Ngoc Minh (2012) only calculates the percentage of intrusion of separate static reserves for each aquifer qh and qp, while this paper calculates according to hydraulic aquifers is only qp aquifer (if there is no qh layer above) and for both qh and qp aquifers (if qh aquifer covers the qp aquifer) and the appropriate water level depth equal 1/2 their thickness. In summary, the results evaluated the potential for forecasting groundwater resources for the whole region and the freshwater area, providing data for research and development as well as potential exploitation of groundwater in the study area, especially the work of developing water resources, limiting salinity, and improving saline groundwater.

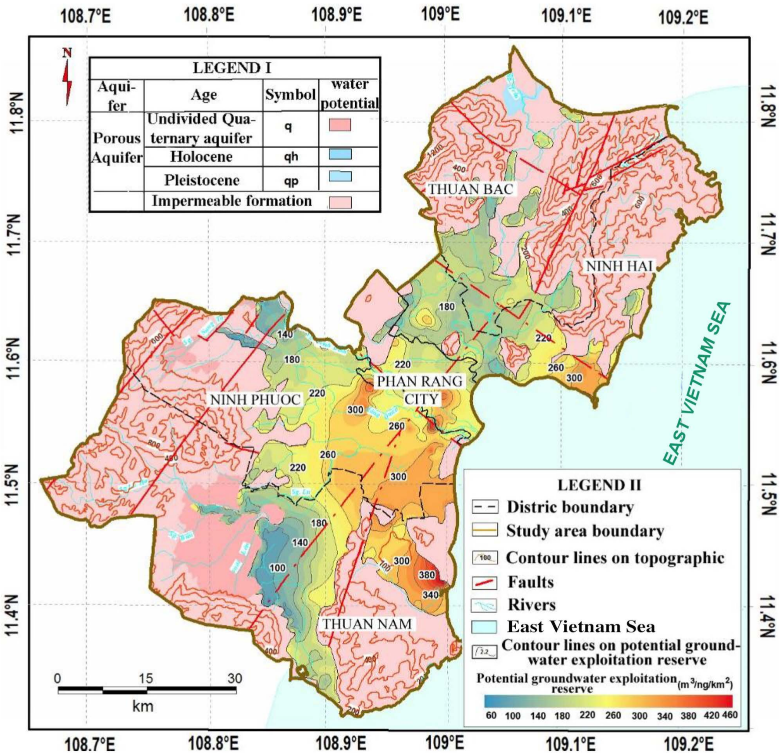


Figure 12. Potential groundwater exploitation in the entire distribution area

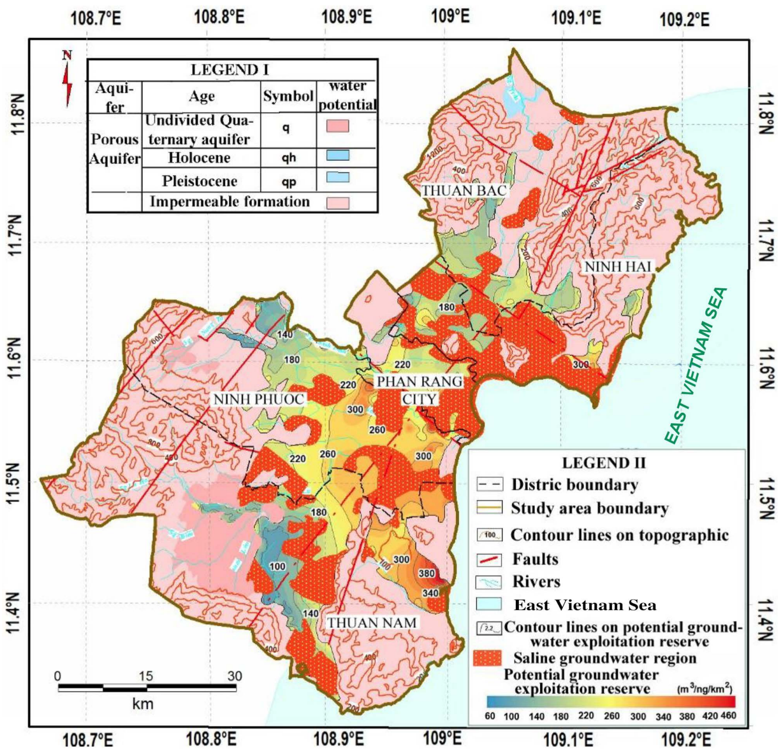


Figure 13. Potential groundwater exploitation in the distribution of freshwater

CONCLUSION

The coastal area of Ninh Thuan province has two exploited aquifers contributing to the betterment of people's lives, the qh and qp aquifers. The article has organized 2,565 grid cells with dimensions of 500 m × 500 m to calculate the potentially exploitable reserves of the primary aquifer in the study area, which are qh and qp aquifers distributed over the freshwater area.

Static reserves in the entire distribution and freshwater areas are 573.6×10^6 m^3 and 365.2×10^6 m^3, respectively. The exploitable reserve accounts for 30% of the total static reserve in 10,000 days, corresponding to the flow rate of 17,207 m^3/day and 10,957 m^3/day.

The dynamic GW reserve, including natural dynamic and effective natural dynamic reserves supplied by rainfall and evaporation, is calculated based on the amount of water infiltration from rainwater to aquifers with the value of 1,041 m^3/day/km^2 and 315.5 m^3/day/km^2, respectively.

Total potential exploitable reserves of qh and qp aquifers according to grid cells determined over the entire area and freshwater distribution areas are $561.8 \times 10^6 m^3$/day and 345.4×10^6 m^3/day, respectively.

The potential exploitation of groundwater reserves can be applied to manage and plan for effective groundwater exploitation in Ninh Thuan province.

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