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## Research of fresh/salt water in Upper-middle Pleistocene (qp<sub>2-3</sub>) in Bac Lieu Province

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### ABSTRACT

This study identified the relationship between Total Dissolved Solids (TDS) and Electrical Conductivity (EC) with the  $TDS = 0.6628 * EC = 0.1706$  correlation, in which the correlation coefficient is  $r = 0.984$  and the Standard Error ( $\pm\%$ ) is 2.78%. The TDS content is determined by small relative error and a high correlation coefficient of the conductivity, which applies to calculate the TDS content of other groundwater samples in Bac Lieu Province. Also, the temperature difference in the electrical conductivity measurement affects the TDS content; thus, the study has determined that the temperature compensated constant between the electrical conductivity on the field and those at 25°C is 0.002953. According to the data and the analysis of the TDS content, the fresh-salt water distribution map of the qp<sub>2-3</sub> aquifers has been established, and its boundary has been more detailed and standardized than in the previous study. In particular, TDS values range from 0.437 g/L to 2.0 g/L. The areas that contain brackish and salt water are distributed discontinuously, forming the saline zones in Loc Ninh, Phuoc Long communes in Hong Dan district; Phuoc Long, Hung Phu communes in Phuoc Long district; Vinh Hau, Vinh Binh communes in Hoa Binh district, and Thuan Hoa commune in Bac Lieu city. The saltwater area of the qp<sub>2-3</sub> aquifers is about 398 km<sup>2</sup>, accounting for 16% of the study's total area. The results fresh-salt water distributed mapping provide the environmental management institution with a comprehensive view of the distribution of fresh-salt water to propose effective groundwater exploitation policies.

**Keywords:** Total dissolved solids (TDS), Electrical conductivity (EC), GIS, Upper-middle Pleistocene aquifer (qp<sub>2-3</sub>), Bac Lieu Province.

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## INTRODUCTION

Bac Lieu Province has surface water sources affected by tidal regimes, so the area is frequently salinized and polluted [1–3]. The soil salinity tendency in coastal aquifers becomes more severe due to the lack of surface water and increased groundwater demand (especially for agriculture). In addition, the shallow aquifers are mostly brackish/salt water that is unsuitable for eating or living purposes. Thus, deep groundwater is more reliable and becomes the main water supply for activities in the Bac Lieu Province [4]. However, the document and data for the quality and quantity of deep aquifers: Upper-middle Pleistocene aquifer ( $qp_{2-3}$ ), lower Pleistocene ( $qp_1$ ), Neogene ( $n_2^2$  and  $n_2^1$ ), Miocene ( $n_1^3$  and  $n_1^{2-3}$ ) in the study area are still limited. Under the pressure of socio-economic development, population growth, and urbanization, water resources suffer from heavy exploitation as the annual extraction flows are more significant than the recharge in most aquifers, resulting in groundwater levels falling year by year [2, 4].

In recent years, the shift in groundwater usage from floating rice to shrimp cultivation in low-lying land has been a critical driver of groundwater exploitation in the studied coastal areas. These changes have led to the distribution of salt, which is significantly impacting coastal ecosystems and societies [5]. The deep-water aquifers, the main targets for exploitation, are now facing the pressure they have been subjected to. The continuous decrease in water levels has had a detrimental influence on groundwater aquifers' absorption and storage, degrading surface and lowering water levels [6, 7].

The TDS content is considered an indicator of water salinity in laboratory determination [8]. When salts are dissolved in water, their ions separate and increase the soluble solids and electrical conductivity from the solution [9]. The electrical conductivity of water is related to the ionization concentration of dissolved solids in water. For example, ions from soluble solids in water can generate electrical conductance of water, which can be

measured by a conductivity meter [10]. When correlated with laboratory TDS measurements, estimated conductivity for TDS concentrations' approximate value is usually accurate up to 10% [9, 11, 12]. Although the electrical conductivity (EC) of groundwater depends and is proportional increase to the water temperature [13], the most accurate temperature to measure the electrical conductivity is close to 25°C [14], and the unit used for the EC measurement is mS/cm [15]. The equation could estimate the solid relationship between TDS and EC:

$$TDS = ke \times EC \quad (1)$$

In which the coefficient  $ke$  is between 0.5 and 0.8.

However, when salt concentration reaches a certain level, the electrical conductivity is no longer directly related to the salt concentration. That is because when ion pairs are formed, they reduce each other's electrical charge; thus, if salt concentration is above this level, the TDS content and the electrical conductivity are disproportionate [16].

The area also decides the correlation between TDS and EC, water sampling conditions, the concentration of ions, and the water impurities. Therefore, different coefficients depend on distinct study areas [14].

## HYDROGEOLOGICAL CHARACTERISTICS

Hydrogeological strata in the study area can be classified into 8 pore aquifers in the sediment including Holocene (qh), upper Pleistocene ( $qp_3$ ), upper-middle Pleistocene ( $qp_{2-3}$ ), lower Pleistocene ( $qp_1$ ), middle Pliocene ( $n_2^2$ ), lower Pliocene ( $n_2^1$ ), upper Miocene ( $n_1^3$ ) and upper-middle Miocene ( $n_1^{2-3}$ ). Besides, the hydrogeological strata in the study area can be divided into 2 main parts. The upper part consists of alluvial sediments, clay, and clay soil with a poor coefficient of permeability; the lower part includes fine-grained and coarse sand, pebble gravel, and pebble with a better coefficient of permeability (Figure 1).

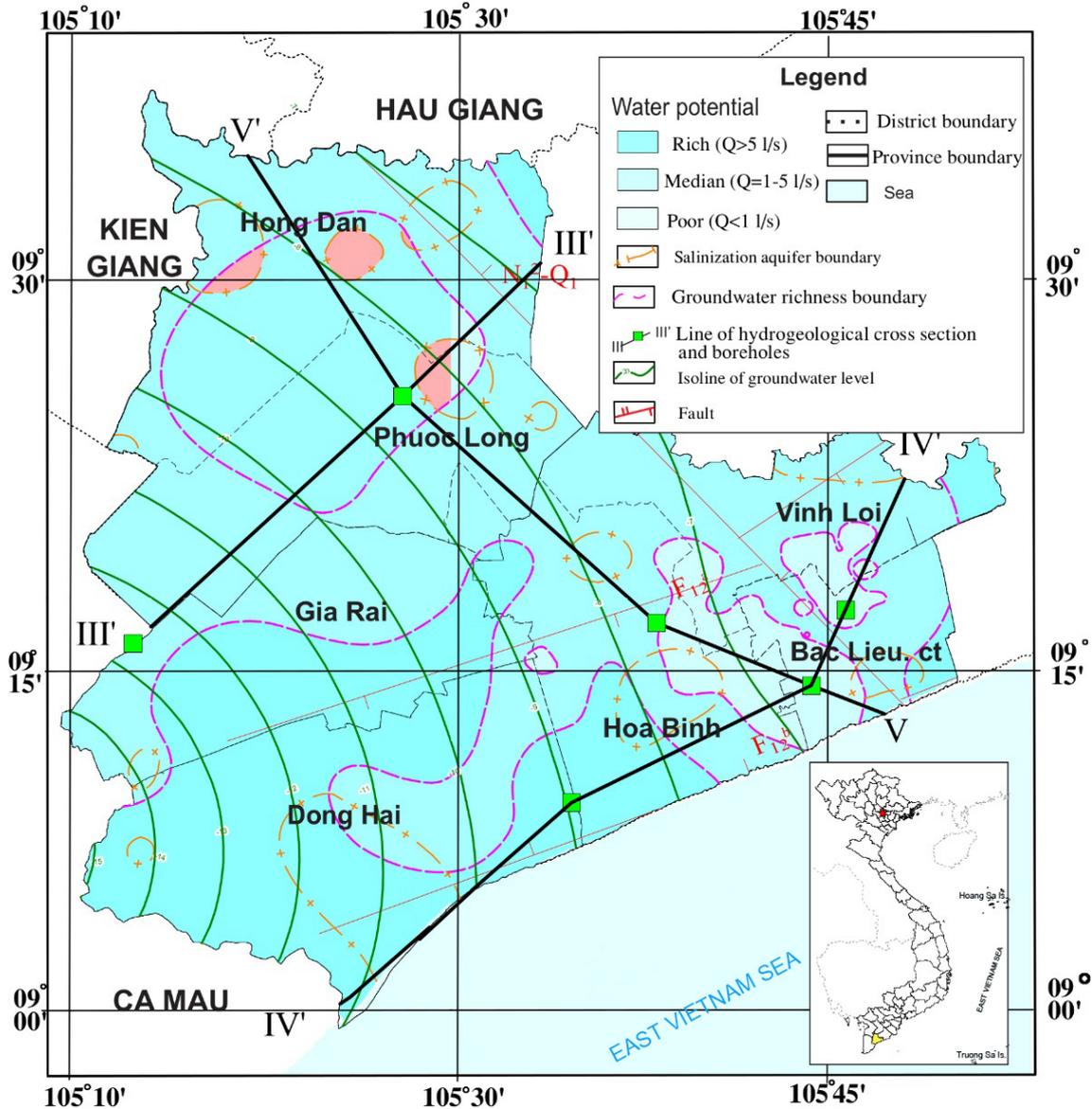


Figure 1. Groundwater resources map of  $qp_{2-3}$  in the study area

Shallow aquifers ( $q_h$  and  $qp_3$ ) are contaminated mainly with brackish/salted groundwater and cannot be used. Deeper aquifers have wide distribution, thick and weak water permeability (Figure 2), and abundant water storage, and most of them include  $qp_{2-3}$ ,  $qp_1$ ,  $n_2^2$ ,  $n_2^1$ ,  $n_1^3$ , and  $n_1^{2-3}$ . According to the Division for Water Resources Planning and Investigation for the South of Vietnam, over 95% of the total small exploitation wells are gathered in the  $qp_{2-3}$  aquifers, while the

remaining 5% of wells, which has flow rate higher than  $200 \text{ m}^3/\text{day}$ , are in the  $qp_1$  and  $n_2^2$  aquifers. Therefore, the  $qp_{2-3}$  aquifers have been under pressure from exploiting groundwater. Since the documents and research data on the  $qp_{2-3}$  water aquifers are restricted, this paper focuses on the actual reflection of the salinity of the upper-middle Pleistocene ( $qp_{2-3}$ ) and the salinity boundary displacement due to the water exploitation impact.

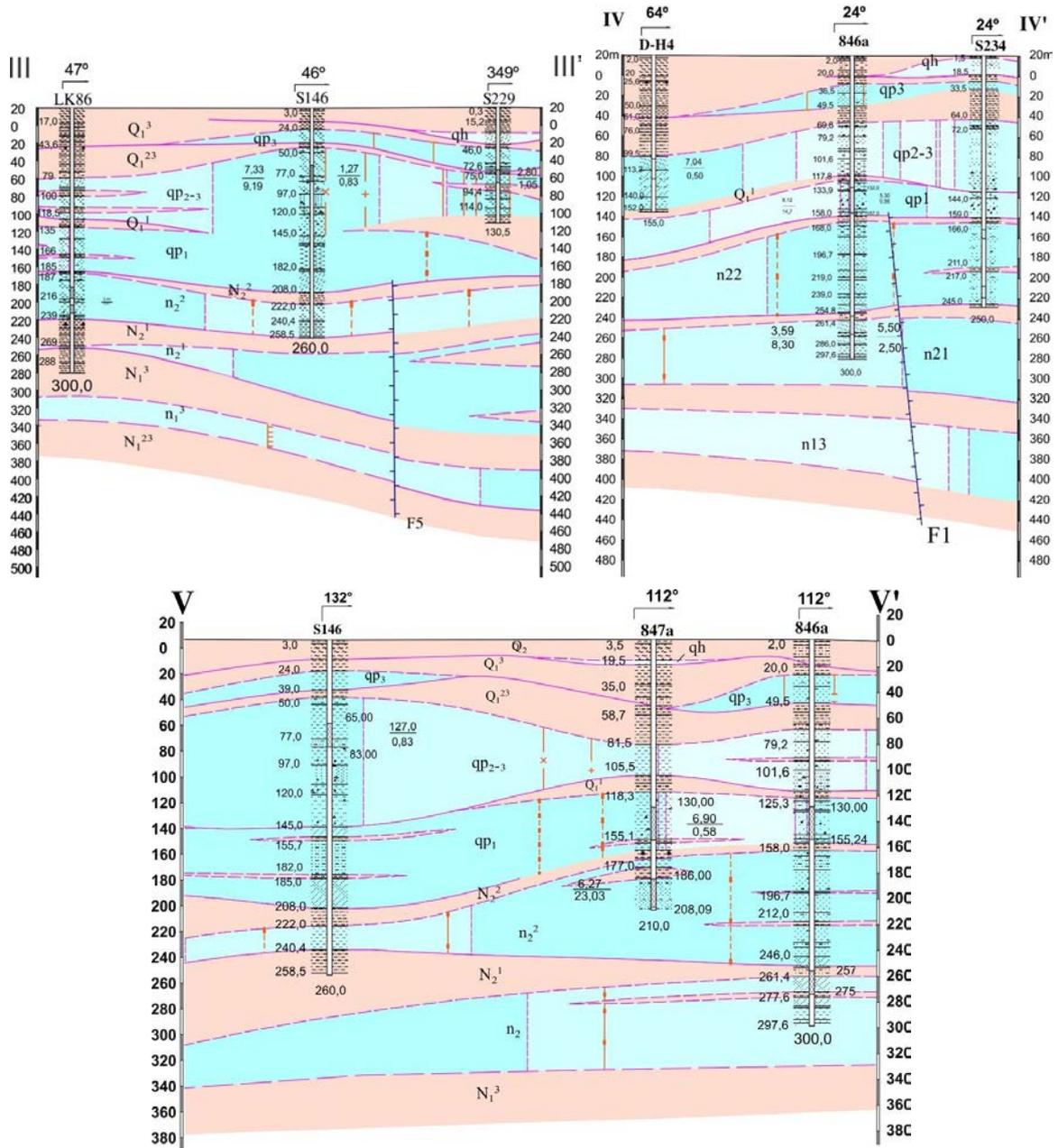


Figure 2. Hydrogeological sections in the study area

**Pore aquifers in upper-middle Pleistocene (qp<sub>2-3</sub>) sediment**

The upper-middle Pleistocene aquifer is widely distributed across the entire study area, unexposed to the surface yet creating a poor Long Toan formation (Q<sub>1</sub><sup>2-3</sup>) covered directly above. The depth to reach the formation roof

ranges from 47.7 m to 117.5 m, averaging 75.7 m. The depth of the bottom formation ranges from 77 m to 172 m, with an average of 125 m. Formation thickness varies from 5 m to 100.3 m with an average of 46.2 m.

The petrographic composition of 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 have clear rhythm and stratification. The actual thickness of rocks containing water ranges from 14 m to 76.3 m, with an average of 43.97 m.

The aquifer's water storage capacity ranges from 6,07 L/s to 41,67 L/s, averaging 21.57 L/s. The groundwater drawdown ranges from 4 m to 28 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 m<sup>2</sup>/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.

The chemical composition of the aquifer has quite complex changes. Based on the value of total mineralization, the confined aquifer area is divided into two zones: fresh water and salted water. Freshwater region ( $M < 1$  g/L) is majorly 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.

In general, since the qp<sub>2-3</sub> aquifer is widely distributed with abundant water storage capacity and mainly contain freshwater, the groundwater in this region has been a potential resource for people to exploit.

## MATERIAL AND METHODS

### Research materials

The paper used 270 water samples from wells, where depths reached the qp<sub>2-3</sub> aquifer in the dry season in Bac Lieu Province in 2023 (Figure 3). A total of 270 water samples were described on-site for characteristics such as temperature, pH, color, smell, sample depth, and electrical conductivity, measured by the calibrated WTW 3430 handheld electrical conductivity meter (Figure 4). The authors selected 93 representative samples from communes perpendicular to the previous

saltwater boundaries. These water samples were preserved and returned to the laboratory to analyze the TDS content and measure electrical conductivity at 25°C.

### Analysis of the total dissolved solids (TDS)

To determine the TDS content, researchers used the dry distillation method. The general principle of this method is to filter the water samples through a standard unit and then dry the water evaporation to a constant weight at  $180 \pm 2^\circ\text{C}$ . The increased weight in the glass cup is the total dissolved solids (TDS).

In addition, it is possible to directly measure the electrical conductivity of groundwater of the confined aquifers at the drilling well based on the correlation between EC and TDS content. However, temperature differences in the two environments during the electrical conductivity measurement process will slightly affect TDS content. Therefore, it is compulsory to standardize temperature before analyzing correlation to advocate the most accurate results.

### Temperature standardization

Approximated TDS values based on linear correlation with EC at laboratory temperature (25°C) bring high efficiency and save the shipping and chemical analysis costs. Field water samples have distinct ion concentrations and temperatures. The temperature difference between the two environments in the EC measurement process will slightly affect the TDS content [17, 18]. Therefore, the paper calculates the temperature compensation constant for water samples in the temperature field versus laboratory is 25°C. The temperature compensation constant will be calculated according to the formula [17]:

$$\partial = \frac{(EC_T - EC_{25}) \times 100}{EC_{25} \times (T - 25)} \quad (2)$$

where:  $T$  is the temperature field to measure electrical conductivity  $EC_T$ ; 25 is the temperature to measure electrical conductivity at 25°C;  $\partial$  is the temperature compensation constant.

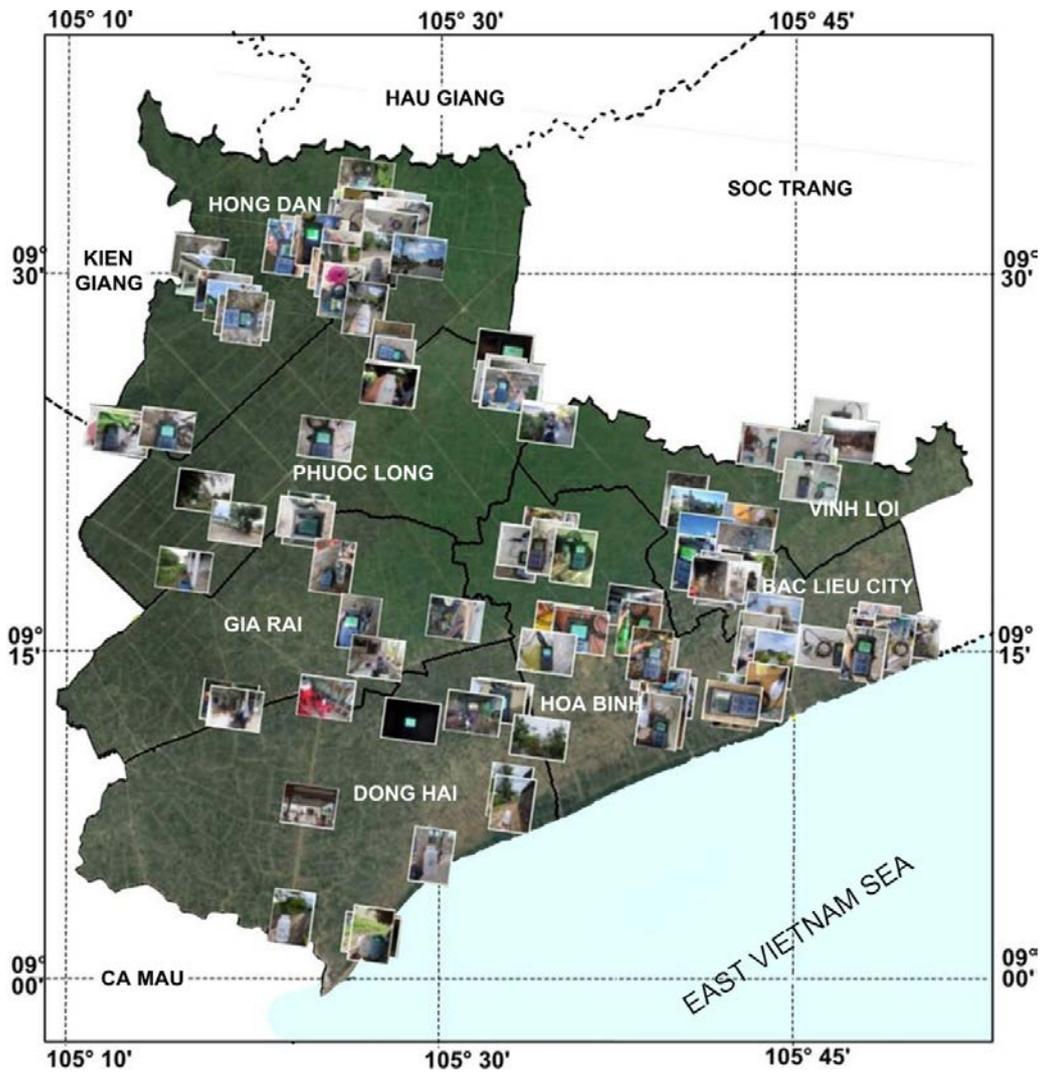


Figure 3. The locations of collecting groundwater samples in the field



Figure 4. Investigate, examine, measure electrical conductivity, and collect samples in the field

**Spatial interpolation Ordinary kriging (OK)**

The determination of the TDS content distribution of the qp<sub>2-3</sub> aquifers is implemented by using the Kriging interpolation technique from the sampling and analysis data. Kriging is a geostatistical method to interpolate values at random and unknown points based on the identified values of nearby points across the spatial field. It is necessary to calculate the parameters of the Variogram structural function to use this method [19]. Accordingly, the Variogram structural function is defined as half of the variance of the increment:

$$\gamma(h) = E[Z(x) - Z(x+h)]^2 \quad (3)$$

where:  $Z(x)$ ,  $Z(x+h)$  are two quantities  $x$  and  $(x+h)$  at a distance  $h$  in the same direction. The structural function is defined as:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x) - Z(x+h)]^2 \quad (4)$$

$N(h)$  is numbers of calculated pairs of points.

A structural function is a tool for quantifying the object’s stability, continuity, or spatial correlation by calculating the mean square value of the difference between two points at a distance of  $h$  and a defined direction.

**RESULT AND DISCUSSION**

The correlation between total dissolved solids (TDS) and electrical conductivity (EC<sub>25</sub>)

*Total dissolved solids (TDS) analysis results*

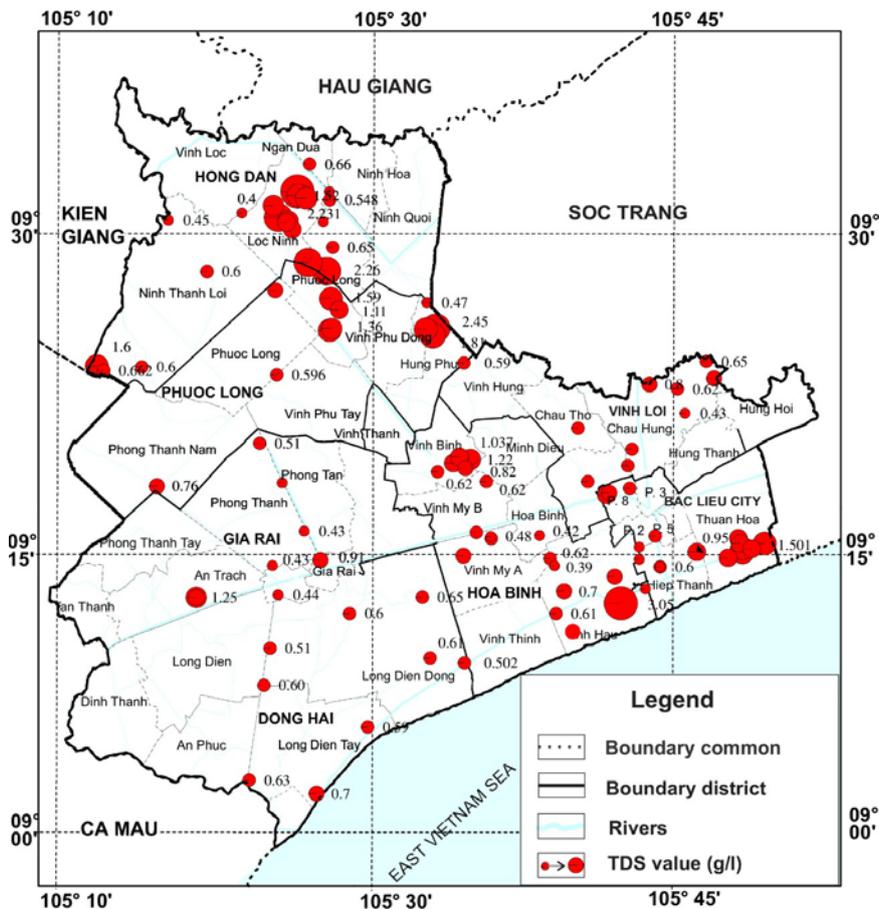


Figure 5. TDS content analysis result of 93 water samples in qp<sub>2-3</sub> aquifer

TDS analysis results of 93 groundwater samples using dry distillation methods are presented in diagrams and graphs in Figure 5. TDS content in water samples ranges from 0.39 g/L to 3.055 g/L. Total groundwater samples with TDS values greater than 1 mg/L were 28, accounting for 30.1% of the total water samples analyzed. The samples with high levels of TDS were concentrated in communes in Hong Dan District (Loc Ninh Commune and Ngan Dua Town), communes of Phuoc Long District (Phuoc Long, Vinh Phu Dong, and Hung Phu Commune), the coastal communes in Hoa Binh district and Bac Lieu City (Vinh Binh, Vinh Hau, Hiep Thanh, and Thuan Hoa Commune).

**Identified the correlation between TDS and EC**

This paper used statistical methods to identify the regressive correlation between TDS content and EC conductivity at 25°C of 93 groundwater samples. The results show that the two parameters are closely correlated, with the coefficient  $r = 0.984$  and the Standard Error error (%) = 2.78%, as increasing conductivity also means increased TDS and vice versa. The regressive equation between TDS and  $EC_{25}$  is shown in Figure 6:

$$Y = 0.6628X - 0.1706 \quad (5)$$

in which: the X axis represents TDS and the Y represents conductivity at 25°C ( $EC_{25}$ ).

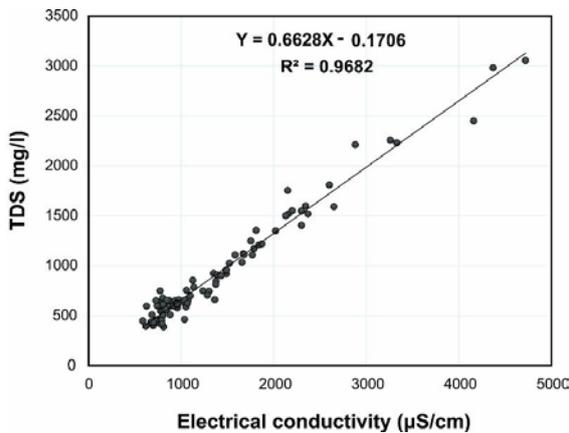


Figure 6. Linear correlation equation between EC and TDS (mg/L)

**Determine the temperature compensation constant between  $EC_7$  and  $EC_{25}$  and calculate the TDS value**

Based on the correlation between TDS and  $EC_{25}$  and the linear correlations equation (2), the TDS value is calculated through the on-site electrical conductivity measurement. However, the on-site EC values measured have differences because their temperature is distinct from the laboratory (25°C), which slightly influences the correlation results of TDS content. Thus, the paper calculates the temperature compensation constant for the water samples of confined aquifers in the study area. The temperature compensation constant will be calculated according to the formula (1) from  $EC_{25}$  and on-site EC electrical conductivity of 93 groundwater samples brought to the laboratory. The calculated temperature compensation constant is  $\partial = 0.002953$ . The results of the TDS content through field electrical conductivity of 207 water samples are presented in Figure 7, shown under a red circle with an increased size corresponding to the TDS contents.

**Evaluating the fresh/saltwater in the upper-middle Pleistocene aquifer**

This section presents the distribution of fresh/salt water with a defined limit as TDS = 1.0 g/L according to WHO drinking water quality standards from samples taken from wells with depths at the  $qp_{2-3}$  aquifers in the study area.

From the analysis and calculation of TDS content, the value varies from 0.37 g/L to 3.055 g/L, and the water quality varies from fresh to salt. However, the characteristics of water samples differ with space and time and change in many different geographical directions. Thus, this study uses geostatistical methods to consider the spatial structure, changes in TDS values, and calculations of TDS at nearby locations. The characteristic parameters of the geostatistical method of 270 water samples, such as mean values, standard deviation, maximum, minimum, variation coefficient,

deviation, and sharpness, are presented in Table 1. The histogram of initial TDS values shows that the water sample data has an abnormal distribution with a peak deviation to the left, a skewness deviation of 2.0447 (greater than 0.75, poor standard distribution data) [19] (Figure 8a), deviations from the standard line of 45 degrees as in Figure 8b. Therefore, the TDS data of the water samples does not have a standard distribution.

The original data needs to be converted to a different format to obtain a small error data interpolation result, which is the logarithm conversion of the TDS values. The LogTDS histogram chart (Figure 8c) shows the distribution close to the standard with symmetrical curves and points near the standard line, as in Figure 8d. SD values 0.4122 and skewness 0.71 are 0.25–0.75 [19] (average standard distribution data).

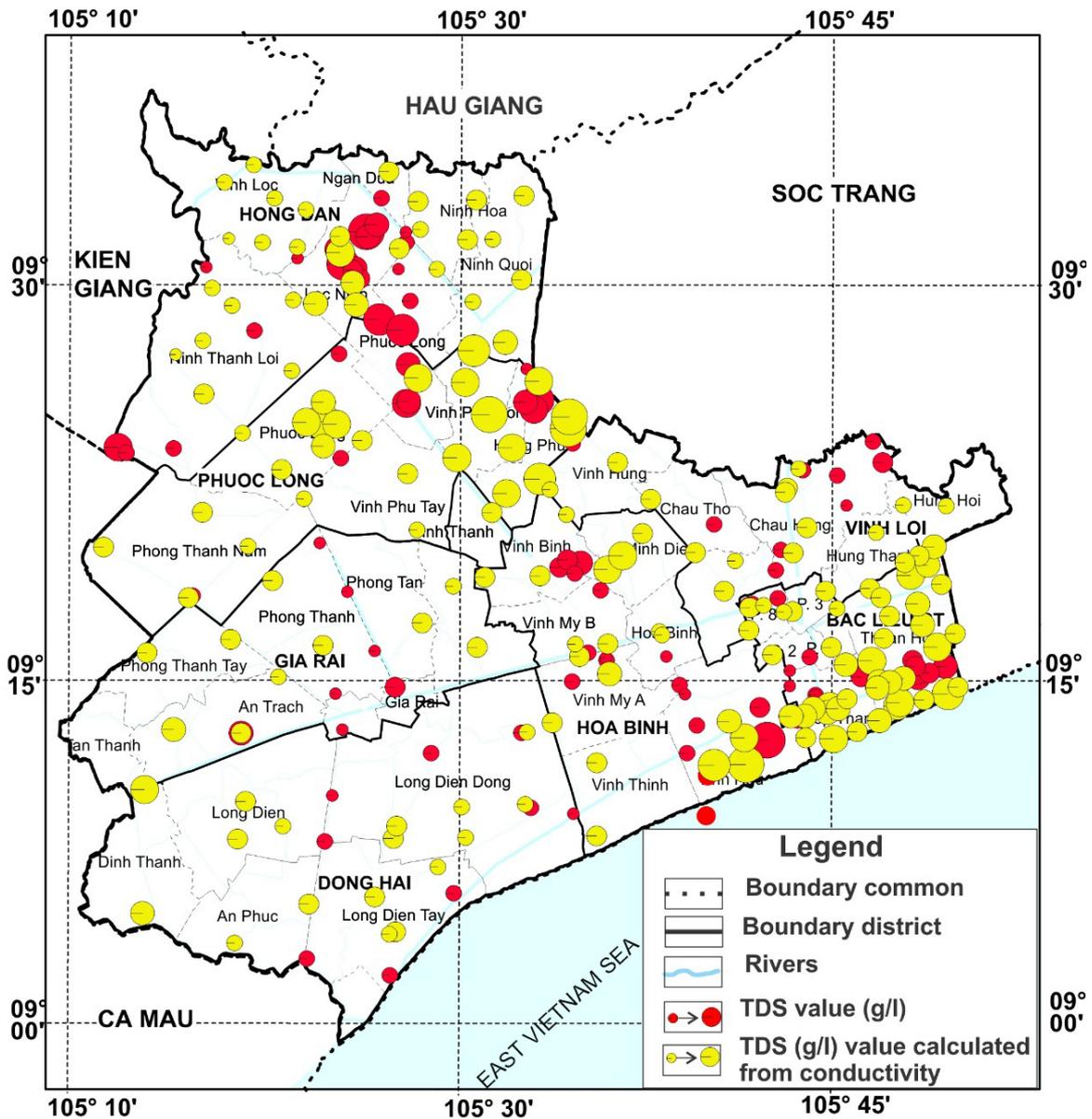


Figure 7. The TDS content results calculated through electrical conductivity

Table 1. The parameters of samples according to the geostatistical method

Variable	Minimum	Maximum	Mean	SD	CV (%)	Skewness	Kurtosis
TDS	372.32	3055	889.94	444.95	19.8	1.943	7.7243
LogTDS	-0.429	0.485	-0.092	0.4122	3.3	0.71	3.1491

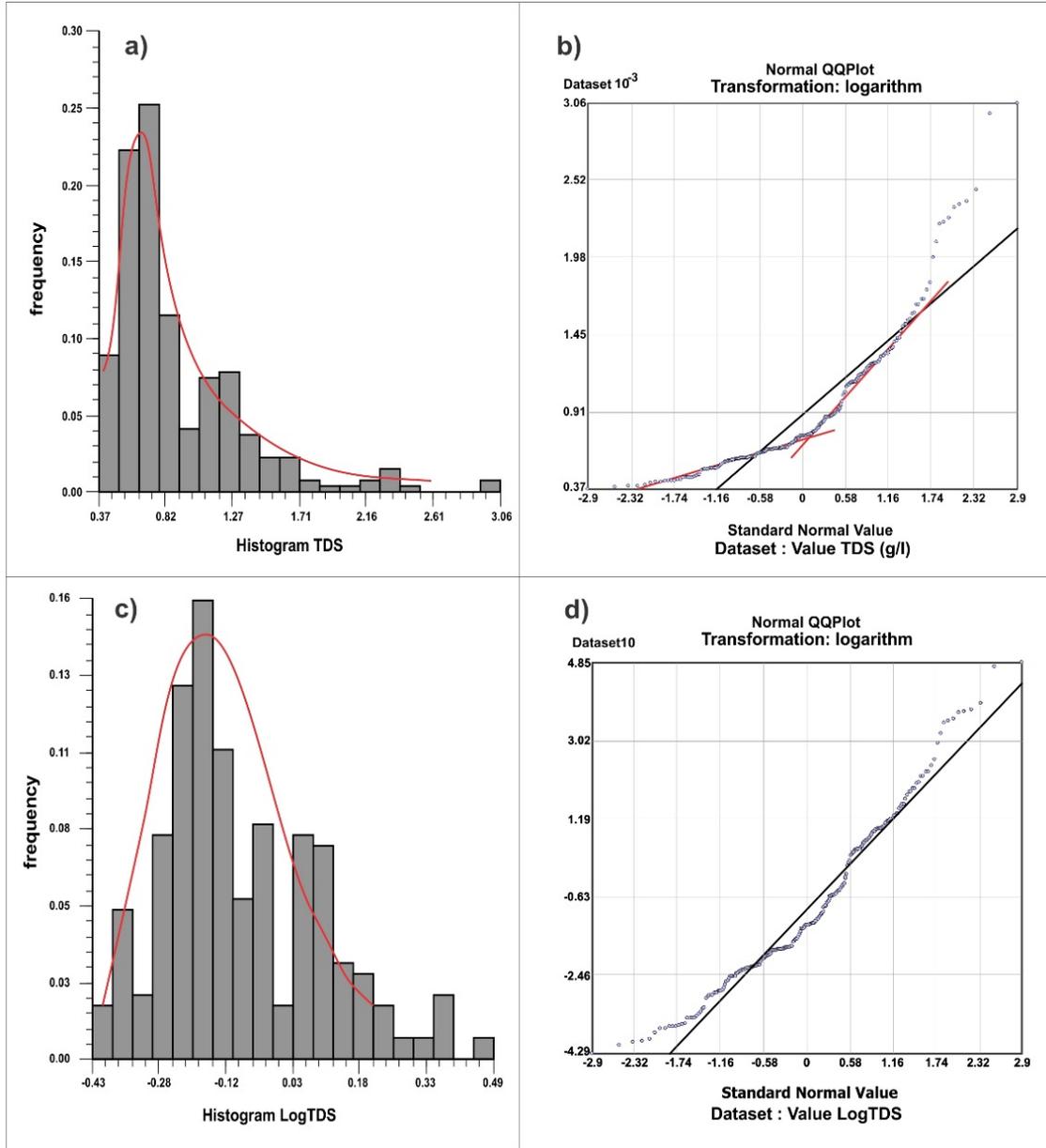


Figure 8. Histogram of TDS values (a), graph QQ Plot of TDS value (b), histogram of logTDS (c), graph QQ plot of logTDS value (d)

The spherical model is applied in the Ordinary Kriging method to interpolate the TDS value. In the trials of the positional angle

directions, the azimuth angle = 67.5 degrees brings the most suitable results as in Figure 9. The parameters of the variogram model are

presented in Table 2, which displays the conditions for implementing LogTDS spatial interpolation values.

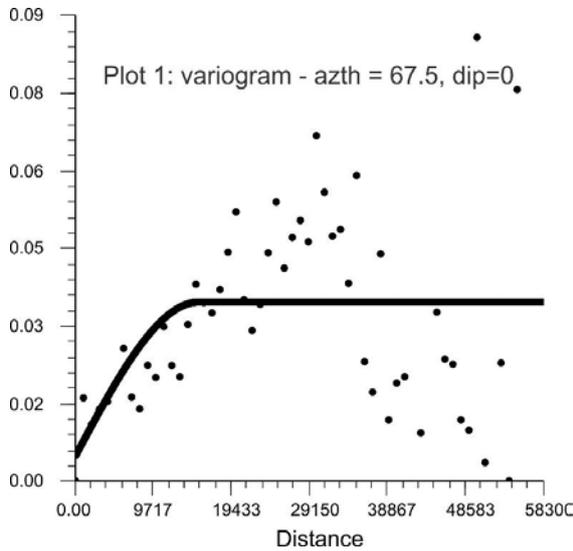


Figure 9. Variogram model of LogTDS value

The result of the logTDS distribution is determined by Ordinary Kring’s interpolation method, expressed as cell values (raster). Next, the authors need to calculate the conversion of the LogTDS value to the TDS value using the Math tool for each cell.

Figure 10 shows the distribution of TDS content and the saltwater boundary on the map. TDS values are divided into two levels: light blue represents freshwater areas with a TDS value less than 1 g/L, and yellow-orange to red range represents saltwater areas with a TDS value larger than 1 g/L. According to WHO water quality standards, the fresh/salt groundwater boundary is determined at TDS = 1 g/L.

According to the interpolation results, TDS values range from 0.438 g/L to 2 g/L. Most of

the groundwater in the qp<sub>2-3</sub> aquifer meets the standard of eating and drinking quality. The areas with brackish/salted water are distributed sparingly, forming the saline zones in Hong Dan District, Phuoc Long District, Hoa Binh, Bac Lieu City, partial Gia Rai District, and Dong Hai District. The saltwater area of the qp<sub>2-3</sub> aquifer covers approximately 398 km<sup>2</sup>, accounting for 16% of the total area in the study area.

Compared to the previous one, the saltwater boundary is different and shifted. In this study, the authors re-standardized the fresh/salt water boundary. They regionalized the contaminated areas in detail thanks to the calculation and analysis results of the field sample. As a result, we visualize a fresh/salt water map of confined aquifers and alert some areas with the risk of salinization. The former saltwater boundaries in the northwestern area of the Hong Dan District (Vinh Loc, Ninh Thanh Loi, and Ninh Hoa communes) have been removed. The salinity boundaries of Loc Ninh - Hong Dan, Vinh Phu Dong, and Hung Phu, Ninh Hoa, Phuoc Long have been more widespread than the old saline area of 84.9km<sup>2</sup> (about 67.58%); thus, the authors recreate a new saline boundary (Zone 1 - Figure 11).

Similarly, the saltwater boundaries of Dong Hai district, Vinh My A - Hoa Binh, and Chau Hung - Vinh Loi have been removed. Instead, to the west of Gia Rai district and Dong Hai, the saltwater has spread an additional area of 65 km<sup>2</sup> (increasing about 89% from the old saline area). It is reconstructed by new saltwater boundaries (Zone 3 - Figure 11). The coastal communes of Vinh Hau - Hoa Binh, Hiep Thanh commune, and Thuan Hoai - Bac Lieu City have identified the new saline boundary (Zone 2 - Figure 11) with an area of 99.31 km<sup>2</sup>, which has spread over the former by 85.94 km<sup>2</sup>.

Table 2. Variogram parameters

Variable	Method	Model	Nugget	Sill	Range	Rate X (*)
LogTDS	Kring	Spherical	0.005	0.031	19,250	0.86

Note: \*: RateX =  $\frac{\text{Sill}}{(\text{nugget} + \text{sill})}$ .

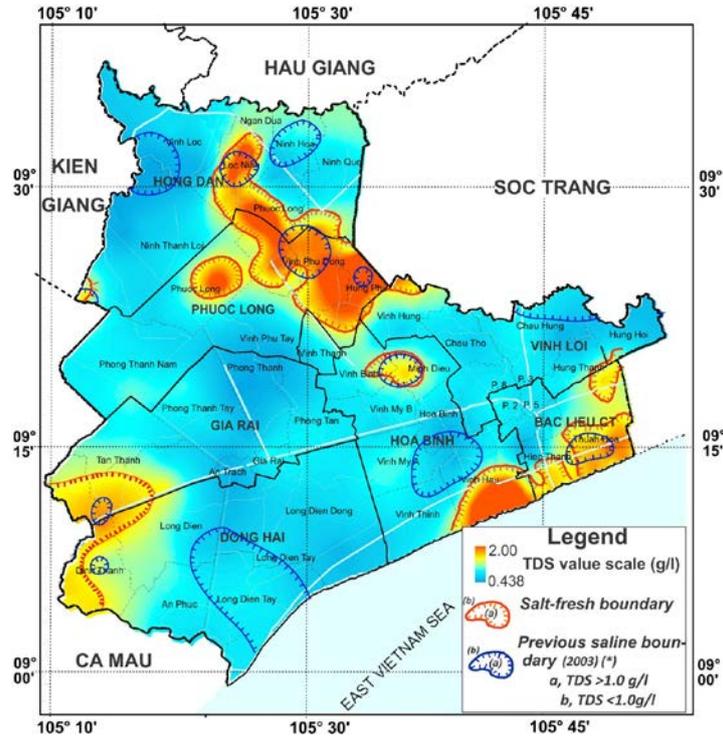


Figure 10. Distribution map of fresh/salt groundwater in qp<sub>2-3</sub> aquifer.  
 Note: (\*) Saltwater boundaries referred to the study by Tran Van Khoang (2003) [21]

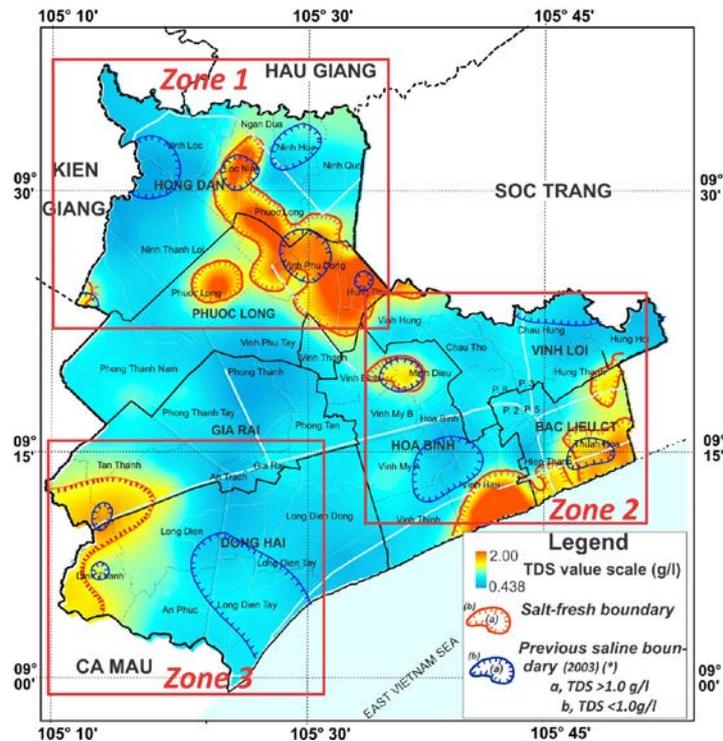


Figure 11. Standardization of TDS distribution and the fresh/salt water boundary in the study area

## CONCLUSION

The article identified the correlation of TDS content and the EC as  $TDS = 0.6628 \cdot EC - 0.1706$ , in which the correlation coefficient  $r = 0.984$  and the Standard Error error (%) = 2.78%. The TDS content is determined by small error electrical conductivity and a high correlation coefficient, and the TDS calculation is applied to other groundwater samples in Bac Lieu Province. The temperature difference in the electrical conductivity measurement also affects the TDS content since the study has determined that the temperature compensation constant between on-site  $EC_T$  and  $EC_{25}$  is 0.002953.

From the data, survey, and analysis of TDS content, a distribution map of the TDS content with the saltwater boundary of the  $qp_{2-3}$  aquifer has been established. The TDS values range from 0.437 g/L to 2.0 g/L. The areas with brackish/salt water are distributed discontinuously, forming the saline zones in Hong Dan, Phuoc Long, Hoa Binh, Bac Lieu City, and partly Gia Rai and Dong Hai. The saltwater area of the  $qp_{2-3}$  aquifer covers approximately 398 km<sup>2</sup>, accounting for 16% of the total study area. The accuracy of the map depends on the distribution of the samples, the quality of sample analysis, and the interpolation method. In this study, the data converted TDS values into logarithms to minimize errors due to the irregular distribution of samples. The fresh-saltwater map results provide environmental organizations with a comprehensive perspective of fresh/saltwater distribution to have an effective groundwater exploitation policy.

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