App. Envi. Res. 44(2) (2022): 68-85

Applied Environmental Research

Journal homepage : http://www.tci-thaijo.org/index.php/aer

Groundwater Quality Assessment Using Groundwater Quality Index and Multivariate Statistical Methods and Human Health Risk Assessment in a Coastal Region of the Vietnamese Mekong Delta

Nguyen Thanh Giao*, Phan Kim Anh, Huynh Thi Hong Nhien

Department of Environmental Management, College of Environment and Natural Resources, Can Tho University, Can Tho 900000, Vietnam

* Corresponding author: ntgiao@ctu.edu.vn

Article History

Submitted: 2 January 2022/ Revision received: 29 April 2022/ Accepted: 1 May 2022/ Published online: 14 June 2022

Abstract

This study aimed to evaluate the suitability of groundwater for drinking purposes and assess the associated human health risks for different age groups in a coastal province of Mekong Delta, Vietnam. Twenty groundwater samples were collected in Soc Trang Province, and various water quality parameters were analyzed. The data were employed to calculate entropy-weighted groundwater quality index (EWQI), principal component analysis (PCA), cluster analysis (CA), and non-carcinogenic and carcinogenic risks for adult and children health. The results revealed that groundwater in some locations, especially in GW19, was polluted by hardness, total dissolved solids, NH_4^+, Cl^-, Fe, total coliform, and *E. coli*. In addition, 5 principal components from the PCA results could explain 84.5% of the total variation of groundwater quality, which also suggested that the potential groundwater pollution sources were geochemical processes, agricultural activities, domestic and industrial wastewater, seawater intrusion, and excessive nitrogen fertilizer application. The CA results showed that monitoring locations can be divided into 4 clusters based on their similarities in groundwater quality, and the most polluted group was found at cluster IV (GW19). The computed EWQI values ranged from 20.05 to 738.52, with approximately 45% of total samples classifying good to excellent water quality. The sampling points with undrinkable quality are mainly located in the northeast and center of the province. The ratio of children and adults under the threat of adverse health effects due to drinking groundwater contained non-carcinogenic substances (NH_4^+, NO_2^-, NO_3^-, Cd, Cu, F^-, Mn, and As) ranged from 5 to 40%, and children had higher risks compared to adults. Additionally, the consumption of As-contaminated groundwater also poses carcinogenic risks for children, female and male adults ranging from 4.80×10^{-6} to 1.33×10^{-4}. The findings of this study can provide helpful information for policymakers in the development of long-term water management strategies to protect community health.

Keywords: Entropy-weighted groundwater quality index; Principal component analysis; Cluster analysis; Health risk assessment; Soc Trang

https://doi.org/10.35762/AER.2022.44.2.6

Introduction

Groundwater is one of the key freshwater sources for domestic uses, agricultural production, and industrial development. Over the past decades, it has been even more important in the coastal areas due to the pollution and saline intrusion of surface water [1–2]. The volume of groundwater exploitation in the Mekong delta was estimated at 350,000 m^3 d^{-1} to provide for water supply plants, industries, and others [3]. In addition to the overexploitation, an increase in population, industrial and agricultural activities compromise groundwater quality. For example, groundwater in a semi-arid area of northwest China was seriously contaminated by nitrite, nitrate, fluoride [4], and nitrate (>50 mg L^{-1}) and chloride (>1000 mg L^{-1}) contamination in groundwater was reported in a coastal region of the Mekong Delta [5]. The groundwater quality in India was also under the threat of deterioration due to the impacts of geogenic and anthropogenic activities [6]. Thus, groundwater quality assessment has become an essential task in the development of management and protection strategies for this precious water resource.

Contaminated groundwater usage in the long term has detrimental impacts on human health. The non-carcinogenic risks for oral and dermal exposure to chloride and nitrate contaminated groundwater in Soc Trang Province were reported for infants (0.01 to 20.0), females (0.01 to 17.7), and males (0.01 to 15.0) [5]. According to Zhang et al. (2020) [4], exposure to groundwater containing non-carcinogenic compounds (nitrate, nitrite, ammonium, manganese, fluoride, and chromium) can pose hazard risks for males (0.0002 to 38.75), females (0.0002 to 49.29), and children (0.0003 to 84.32). If the calculated ratios of non-carcinogenic risk are greater than 1, this risk is unacceptable, and people face the risk of adverse health effects. Due to intensive groundwater exploitation, over 20 million people in the Mekong delta suffer the risk of arsenic contamination [7]. The study of Phan and Nguyen (2018) [8] showed that cancer risks for children and adults owning to the consumption of As-contaminated groundwater in An Giang were ranged from 8.66×10^{-4} to 8.26×10^{-2}. These figures were over the acceptable limit of cancer risk for humans (1×10^{-6}). Therefore, human health risk assessment for abiding groundwater consumption is of paramount importance for public health considerations.

Several methods have been widely applied to evaluate groundwater quality, such as water quality index (WQI), principal component analysis (PCA), and cluster analysis (CA). WQI is an effective tool for assessing water quality with large datasets because it can combine different water parameters into one index. This index has been used to categorize different water quality classes [4, 6, 9]. In the original method, the parameters are normally weighted on the basis of their importance to water quality that is decided based on the experts' practical experience. However, this conventional weighting method can cause uncertainties because their experience is subjective, and some precious information can be lost [4, 9]. Only a small change in the weighting values can significantly affect the final GWQI values and the later water quality assessment. To overcome this limitation, entropy has been introduced and then widely employed to determine the weight of the water quality parameters. It can improve the objectivity of the WQI calculation by eliminating the influence of human preferences on the importance of each parameter [10–11]. Moreover, many previous studies have used PCA to identify the parameters that mainly contributed to the variation of the original dataset without the loss of important information [12–14]. CA is applicable to group the monitoring locations based on the similarities of their water characteristics [12, 16], which in turn helps water management and possibly reduces the number of sampling points. These multivariate statistical methods can greatly provide insights into water quality; however, only a few studies in Vietnam applied these methods to groundwater quality assessment, especially in the coastal region.

This study was conducted in Soc Trang Province, one of the coastal regions of the Mekong Delta, Vietnam. Groundwater has played a critical freshwater resource for over a century because it has high yields, good quality, and low extraction costs [17]. However, there was a decline in groundwater levels (0.01–0.55 m a^{-1}) in all aquifer systems from 1996 to 2017, which means that the ratio of current groundwater abstraction is higher than that of recharge [18]. Additionally, improper well protection, seawater intrusion and human wastes have gradually deteriorated the groundwater quality in this region [17]. Therefore, the main objectives of this study are to (1) appraise the groundwater quality using EWQI, (2) determine the key parameters that influence the variations of groundwater quality, (3) group locations with the same groundwater quality, and (4) assess non-carcinogenic and carcinogenic risks of different groups of people for drinking groundwater.

Materials and methods

1) Study area

Soc Trang, a coastal province, is located in the southeast of the Mekong Delta. It has administrative boundaries adjacent to 4 provinces, including Hau Giang, Tra Vinh, Vinh Long, and Bac Lieu. The terrain is relatively flat, with the shape of a gentle basin, comprising flat land, alternating lowlands and dunes. The altitude is relatively low and divided by the rivers and canals and irrigation canals; thus, it is easy to be infiltrated by seawater. Soc Trang has a tropical monsoon climate, divided into two distinct seasons: the rainy season (from May to October) and the dry season (from November to April next year). The aquifer system includes 7 hydrogeological units: Holocene (qh), Upper Pleistocene (qp_3), Middle-Upper Pleistocene (qp_{23}), Lower Pleistocene (qp_1), Middle Pliocene (n_{22}), Lower Pliocene (n_{21}) and the Upper Miocene (n_{13}). Groundwater is mainly exploited for domestic purposes in the Middle-Upper Pleistocene (qp_{23}), Lower Pleistocene (qp_1) and Upper Miocene (n_{13}) layers, especially the most concentrated in the Middle Pleistocene – above (qp_{23}) [19].

2) Groundwater monitoring locations and chemical analysis

Groundwater samples were collected four times in 2020 from 20 wells served for Soc Trang water supply companies and the national groundwater monitoring system, as presented in Figure 1 and Supplementary material (SM) 1. Twenty chemical and biological parameters including pH, chemical oxygen demand (COD), total dissolved solids (TDS), total hardness, ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), chloride (Cl^-), sulfate (SO_4^{2-}), cadmium (Cd), lead (Pb), copper (Cu), zinc (Zn), phosphate (PO_4^{3-}), total iron (Fe), fluoride (F^-), manganese (Mn), arsenic (As), total coliforms and *E. coli* were analyzed for each groundwater sample. The in-situ pH measurement was implemented, and other parameters were analyzed in the laboratory at the Can Tho City Environmental and Natural Resources Monitoring Center using standard methods [20].

3) Entropy-weighted groundwater quality index (EWQI)

Groundwater parameters including pH, TDS, total hardness, NH_4^+, NO_2^-, NO_3^-, Cl^-, SO_4^{2-}, Cd, Pb, Cu, total coliforms, total Fe, F^-, Mn, As, and *E. coli* were used to calculate EWQI. The equation is presented in Eq. 1 [10–11].

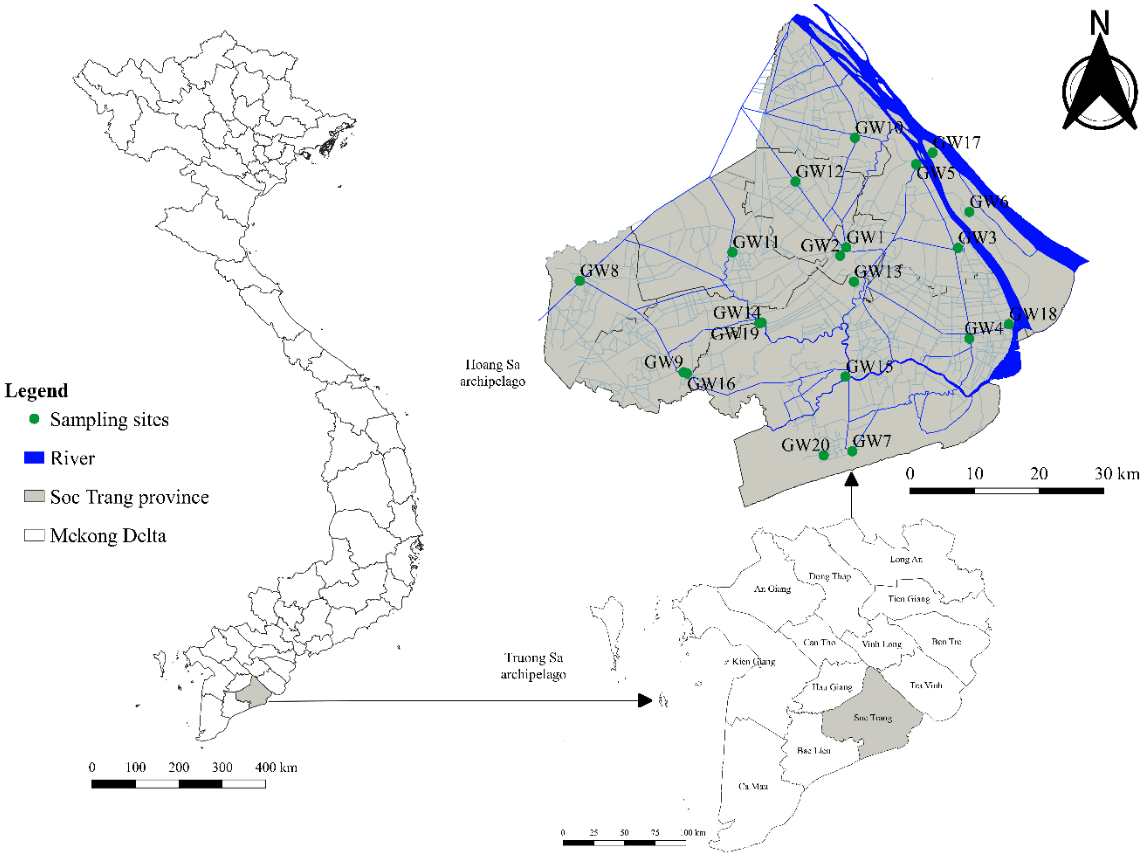

Figure 1 Map of groundwater monitoring locations in Soc Trang Province.

$$\mathrm{EWQI} = \sum_{i=1}^{n} W_j Q_j \qquad \text{(Eq. 1)}$$

where, n: the number of parameters, W_j: entropy weight for the j^th parameter, Q_j: the quality rating of the j^th parameter.

The entropy weight (wj) is calculated based on the following steps:

Step 1: Normalize the initial matrix (X) related to groundwater quality parameters, shown as Eq. 2.

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \qquad \text{(Eq. 2)}$$

where, m (i = 1, 2, …, m) is the total number of groundwater samples, and n (j = 1, 2, …, n) represents the number of groundwater water parameters.

The standardized value (y_{ij}) is calculated using Eq. 3.

$$y_{ij} = \frac{x_{ij} - (x_{ij})_{min}}{(x_{ij})_{max} - (x_{ij})_{min}} \qquad \text{(Eq. 3)}$$

where, x_{ij} represents the j^{th} evaluated groundwater parameter of i^{th} sampling groundwater sites.

After that, the initial matrix (X) is converted to the standard matrix, as presented in Eq. 4.

$$Y = \begin{bmatrix} y_{11} & \cdots & y_{1n} \\ \vdots & \ddots & \vdots \\ y_{m1} & \cdots & y_{mn} \end{bmatrix} \qquad \text{(Eq. 4)}$$

Step 2: The information entropy (e_j) is computed using Eqs. 5 and 6:

$$e_j = -\frac{1}{lnm} \sum_{i=1}^{m} y_j ln y_j \qquad \text{(Eq. 5)}$$

$$y_j = \frac{y_{ij} + 10^{-4}}{\sum_{i=1}^{m}(y_{ij}+10^{-4})} \quad \text{(Eq. 6)}$$

Step 3: Obtain entropy weight (w_{j1}) using Eq. 7.

$$w_j = \frac{1-e_j}{\sum_{j=1}^{n}(1-e_j)} \quad \text{(Eq. 7)}$$

Quality rating (Q_j) is computed using Eq. 8.

$$Q_j = 100 \times \frac{V_o - V_j}{S_n - V_j} \quad \text{(Eq. 8)}$$

where, V_o: the observed value of jth parameter at a certain monitoring site; V_j: the ideal values which are considered "0" for drinking water except pH [6]. In the case of pH, V_j is 7.0 (neutral pH) and S_n is 8.5. Sn values of TDS, total hardness, NH_4^+, NO_2^-, NO_3^-, Cl^-, SO_4^{2-}, Cd, Pb, Cu, total coliforms, total Fe, F^-, Mn, As, and *E. coli* are 1500, 500, 1, 1, 15, 250, 400, 0.005, 0.01, 3, 3, 5, 1, 0.5, 0.05, and 1, respectively [21].

The groundwater quality classification is based on the computed EWQI values, as presented in Table 1. The EWQI spatial distribution was shown in the map by the interpolation with inverse distance weighted method. EWQI values of the predicted sites would reduce from the monitoring locations. ARCGIS version 10.2 software was used to conduct this spatial inter-polation.

Table 1 Groundwater quality classification based on computed EWQI values [6, 20]

EWQI	Classification
0 – 25	Excellent
26 – 50	Good
51 – 75	Poor
76 – 100	Very poor
>100	Unsuitable

4) Human health risk assessment

Human health risk assessment to estimate non-cancer and cancer risks for drinking groundwater was investigated according to the United States Environmental Protection Agency (EPA) standard [22]. The non-carcinogenic risks were estimated for humans consuming groundwater containing NH_4^+, NO_2^-, NO_3^-, Cd, Cu, F^-, Mn, and As. Moreover, As is classified into group A "Human carcinogen" [23]. The non-carcinogenic and carcinogenic risks are calculated as follows:

$$CDI_i = \frac{C \times IR \times EF \times ED}{BW \times AT} \quad \text{(Eq. 9)}$$

where, CDI is the chronic daily intake for jth chemical (mg kg^{-1} d^{-1}); C is average jth chemical concentration consumed over the exposure time (mg L^{-1}); IR is intake rate (L d^{-1}); EF is exposure frequency (days a^{-1}); ED is exposure duration (years); BW is the average body weight over the exposure period (kg); AT is averaging exposure time (days). If a chemical can cause cancer, AT is equal to ED times 365. For the carcinogenic chemical, AT is set at 25,550 days.

For non-carcinogenic chemicals, the hazard quotient (HQ) is calculated as shown in Eq. 10.

$$HQ_i = \frac{CDI_i}{RfD} \quad \text{(Eq. 10)}$$

where, RfD is reference dose (mg kg^{-1} d^{-1}). RfD values for oral exposure were referenced from the risk assessment website of EPA: NH_4^+ (0.97 mg kg^{-1} d^{-1}), NO_2^- (0.1 mg kg^{-1} d^{-1}), NO_3^- (1.6 mg kg^{-1} d^{-1}), Cd (5×10^{-4} mg kg^{-1} d^{-1}), Cu (0.04 mg kg^{-1} d^{-1}), F^- (0.04 mg kg^{-1} d^{-1}), Mn (0.14 mg kg^{-1} d^{-1}), and As (3×10^{-4} mg kg^{-1} d^{-1}) [24].

The total non-cancer risk is determined based on the sum of the hazard quotient of all substances, as in Eq. 11.

$$HQ_{total} = \sum_{j=1}^{8} HQ_i \qquad \text{(Eq. 11)}$$

If $HQ_{total} > 1$, human is facing with risk of adverse health effects. If $HQ \leq 1$, there is no adverse health effect anticipated.

In Mekong Delta, As contamination has long been considered a major groundwater problem, which has potentially caused cancer risks for local people [7]. There was no detection of Cd in most groundwater samples in the study area. Thus, only As is calculated for the cancer risk. In the case of the carcinogenic chemical, cancer risk (CR) is estimated as in Eq. 12.

$$CR = CDI \times SF \qquad \text{(Eq. 12)}$$

where, SF is the slope factor for the carcinogenic contaminant per mg kg^{-1} d^{-1}. The SF of As for oral exposure is 1.5 per mg kg^{-1} d^{-1} [24]. If CR is lower than 1×10^{-6}, the cancer risk is typically defined as acceptable [22]. The key parameters used to calculate human health risk for consuming groundwater are presented in Table 2.

5) Multivariate statistical analyses

The CA and PCA were employed to group the monitoring location with the similar groundwater quality and to identify key parameters resulting in variations in groundwater quality and potential pollution sources [12, 16]. Both CA and PCA analyses were performed using Primer 5.2 software (PRIMER-E Ltd, Plymouth, UK).

Results and discussion

1) Groundwater quality assessment in Soc Trang

The results of chemical and microbial parameters to evaluate groundwater quality in Soc Trang in 2020 are given in Table 3. These parameters were compared to the Vietnamese technical regulation on groundwater quality (QCVN 09-MT:2015/BTNMT) [21] and World Health Organization [25].

Table 2 Parameters for human health risk calculation [4]

	IR (L day^{-1})	EF (days $year^{-1}$)	ED (years)	BW (kg)	AT (days)
Male	1.5	365	30	70	10,950
Female	1.5	365	30	55	10,950
Children	0.7	365	12	15	4,380

Table 3 Analyzed parameters of groundwater quality in Soc Trang

No.	Parameter	Unit	Min	Max	Mean	SD	Acceptable level	
							Vietnam	WHO
1	pH		6.64	7.83	7.18	0.34	5.5 – 8.5	7 – 8
2	TDS	mg L^{-1}	281.3	8,055	1,023.2	1,669.2	1,500	600 – 1,000
3	Total hardness	mg L^{-1}	43.70	2,967.4	363.07	623.97	500	200
4	NH_4^+	mg N L^{-1}	0.244	10.8	2.98	3.12	1	0.2
5	NO_2^-	mg N L^{-1}	0.001	0.008	0.003	0.00	1	-
6	NO_3^-	mg N L^{-1}	0.003	0.109	0.045	0.03	15	50
7	Cl^-	mg L^{-1}	5.55	4,319.3	349.33	940.72	250	250

Table 3 Analyzed parameters of groundwater quality in Soc Trang (*continued*)

No.	Parameter	Unit	Min	Max	Mean	SD	Acceptable level	
							Vietnam	WHO
8	SO_4^{2-}	mg L^{-1}	21.10	408.40	134.13	93.09	400	250
9	PO_4^{3-}	mg L^{-1}	0.10	0.89	0.27	0.19	-	-
10	Total Fe	mg L^{-1}	0.044	19.8	2.17	4.34	5	0.3
11	F^-	mg L^{-1}	0.214	0.9	0.45	0.23	1	1.5
12	Zn	mg L^{-1}	ND	ND	ND	ND	3	3 – 5
13	Mn	mg L^{-1}	0.034	2.03	0.25	0.46	0.5	0.1 – 0.4
14	Cd	µg L^{-1}	ND	0.30	0.025	0.08	5	3
15	Pb	µg L^{-1}	ND	2.50	0.51	0.74	10	10
16	Cu	µg L^{-1}	ND	23.00	9.35	10.70	1,000	2,000
17	As	µg L^{-1}	0.40	7.60	2.02	1.90	50	10
18	COD	µg L^{-1}	0.59	13	1.75	2.71	-	-
19	Total coliform	MPN 100mL^{-1}	ND	88	12.25	23.05	3	ND
20	*E. coli*	MPN 100mL^{-1}	ND	31	4.45	9.10	ND	ND

Remark: ND: not detected (Limits of quantification: Zn (0.03 mg L^{-1}), Mn (0.02 mg L^{-1}), Cd (0.2 µg L^{-1}), Pb (0.5 µg L^{-1}), Cu (3 µg L^{-1}), As (0.4 µg L^{-1}))

pH of groundwater was within the acceptable limits, ranging from 6.64 – 7.83. Groundwater samples with pH > 7 accounted for precisely 70% of total samples; that is, groundwater in this region is slightly alkaline. The cause of this phenomenon is a saltwater intrusion in the coastal regions that increases strong base and weak acid salts in aquifers [26]. In An Giang Province, Vietnam, the average pH values were 6.7 – 7.2 in the dry season and 6.5 – 6.9 in the wet season [9].

TDS concentration was in the range of 281.3 – 8,055 mg L^{-1}, with an average of 1,023.2 ± 1,669.2 mg L^{-1}. Almost all monitoring wells with TDS concentration were within the acceptable limits, except for GW19. TDS contamination can be attributed to domestic and industrial wastewater, agricultural runoff, sewage pipe leakage, and dissolution of mineral-bearing rocks [27]. In Ca Mau Peninsula, TDS concentrations in the Middle-Upper Pleistocene significantly varied from 0.3 – 24.75 g L^{-1} because of high concentration of Cl^-, HCO_3^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, and Na^+ [28]. The collected groundwater sample in GW19 with the highest TDS value (8,055 mg L^{-1}) in this study was also exploited in the Middle-Upper Pleistocene as in the study at Ca Mau Peninsula.

Total hardness ranged between 43.7 and 2,967.4 mg L^{-1}, and only GW19 had the total hardness higher than the acceptable limit of the Vietnamese standard. There were 13 out of 20 monitoring wells with total hardness exceeding the WHO standard. Using groundwater with high total hardness is likely to affect human health, such as heart disease and kidney stones [6]. Dissolved calcium and magnesium salts in groundwater can result from water passing through mineral-bearing rocks and soils and then carrying them into aquifers [6]. In addition, Dao et al. (2016) [28] found that the hardness of groundwater in the Ca Mau Peninsula was attributed to wastewater from domestic and industrial activities.

NH_4^+ concentration in groundwater was in the range of 0.24 to 10.8 mg L^{-1}, and 35% of monitoring locations with NH_4^+ concentration were within the Vietnamese standard (1 mg L^{-1}). Several studies showed that NH_4^+ contaminated groundwater has been observed in some provinces in the Mekong Delta, such as 0.07 – 2.55 mg L^{-1} in An Giang [29] and up to 7 mg L^{-1} in Tra Vinh [30]. There was a seasonal variation of NH_4^+ concentration in An Giang Province, namely from 0.43 – 3.17 mg L^{-1} in the dry season and from 0.23 – 2.83 mg L^{-1} in the wet season [9]. Excessive nitrogen fertilizer application in agricultural practices can be the primary source of ammonium in groundwater. Furthermore, improper wastewater treatment for domestic and livestock activities, septic tank leakage, and aquacultural wastewater also contributed to ammonium contamination [29–30].

Low NO_2^- concentration (<0.01 mg L^{-1}) in groundwater was detected in the study area, which was within the acceptable limit. Only a few NO_2^- present in groundwater is since it is quickly converted to nitrate.

NO_3^- concentration found in the range of 0.003 to 0.109 mg L^{-1} was within the acceptable limits for groundwater. Drinking groundwater containing high NO_3^- concentrations can cause serious health problems, namely, methemoglobinemia, gastric cancer [30], birth malformations, and hypertension [31]. Several previous studies have shown that NO_3^- concentration is relatively varied from 0.24 to 12.16 mg L^{-1} in Ca Mau Peninsula [28], 0.04 – 0.15 mg L^{-1} in Dong Thap [32], and 0.008 – 0.047 mg L^{-1} in Soc Trang [33]. NO_3^- in groundwater can be from both natural and anthropogenic activities such as nitrogen fertilizer overapplication, livestock waste, agricultural runoff, and industrial wastewater [11, 33].

Cl^- concentration of groundwater was considerably varied from 5.55 – 4,319.3 mg L^{-1}, and most monitoring locations had this concentration within the acceptable limits, except for GW2, GW4, GW13 and GW19. Especially, Cl^- concentration of GW19 was over 17 times higher than the standard for groundwater. However, in the study of Nguyen et al. (2021) [33], all groundwater samples in Soc Trang Province from 2016 – 2018 had Cl^- concentration within the acceptable limits, ranging from 115.7 – 171.5 mg L^{-1}. Higher Cl^- contents in groundwater can threaten human health [6, 34]. The primary sources of Cl^- in groundwater can be derived from domestic wastewater, agricultural pesticides, industrial waste, and saltwater intrusion [26, 28]. The study of Le et al. (2021) [18] reported that groundwater levels in the Mekong delta had been decreased from 0.01 – 0.55 m a^{-1}, which can lead to more severe effects of seawater intrusion. Previous studies reported that Cl^- concentration ranged from 0.7 – 14,534.5 mg L^{-1} in Ca Mau Peninsula [28], and 5.55 – 10.86 mg L^{-1} in Dong Thap [32].

SO_4^{2-} concentration in groundwater samples was in the range of 21.1 to 408.4 mg L^{-1}. The highest SO_4^{2-} concentration was detected in GW19 and only this sample exceeded the acceptable limit. According to Dao et al. (2016) [28], 21% of total samples from Soc Trang Province with SO_4^{2-} concentration were greater than the standards because sulfates are formed by the dissolution of gypsum and minerals. However, another study conducted in Soc Trang reported that SO_4^{2-} concentration was within the standards from 53 – 250 mg L^{-1} [26]. High SO_4^{2-} concentration in drinking water is likely to cause diarrhea in humans [35].

Total Fe of groundwater ranged from 0.04 – 19.8 mg L^{-1}, with an average of 2.17 ± 4.34 mg L^{-1}. Only GW2 and GW4 had total Fe concentrations exceeding the Vietnamese standard, by 5.46 and 19.8 mg L^{-1}, respectively. However, the WHO standard for total Fe in groundwater (0.3 mg L^{-1}) was significantly lower than the Vietnamese standard (5 mg L^{-1}), and all groundwater samples with total Fe were higher than the WHO standard. According to Nguyen et al. (2021) [33], total Fe concentration in groundwater in Soc Trang tended to increase over time from 0.81 – 2.19 mg L^{-1} in the period of 2016 – 2018. Fe concentration of groundwater was also detected in An Giang from 0.07 – 2.16 mg L^{-1} [8] and Tra Vinh 1.5 – 10 mg L^{-1} [30]. The primary source of Fe in groundwater is the dissolution of Fe-bearing rocks, and its existence does not cause harmful effects on humans [6].

The average PO_4^{3-} concentration was about 0.27 ± 0.19 mg L^{-1}, with a maximum value of 0.89 mg L^{-1} (GW19) and a minimum value of 0.10 mg L^{-1} (GW20). Agricultural activities are considered a major source of P diffusion in groundwater [36–37]. There are currently no regulations about PO_4^{3-} concentration in groundwater from both Vietnam and WHO. Moreover, it is not regularly monitored neither potable water nor groundwater, because P is not a major threat to human health [38]. According to Griffioen (2006) [39], high PO_4^{3-} concentration in groundwater in the western Netherlands was related to high ammonia, close neutral pH and anoxic condition. It is consistent with the finding in this study; namely, GW19 had the highest PO_4^{3-} concentration (0.89 mg L^{-1}) and NH_4^+ concentration (10.8 mg L^{-1}).

F^- concentration was in the range of 0.21 – 0.90 mg L^{-1}, which was within the acceptable limits for groundwater. In the study of Ram et al. (2021) [6], F^- concentration in groundwater in India ranged from 0.11 – 0.39 mg L^{-1} due to the natural dissolution of F-bearing minerals and rocks.

Concentrations of heavy metals in groundwater were analyzed in this study. There was no detection of Zn in the groundwater, while the concentration of Mn varied from 0.03 – 2.03 mg L^{-1}. GW19 had Mn concentration over 4 times higher than the Vietnamese standard. The concentrations of Cd, Pb and Cu were ranged from below the detection limit to 0.30, 2.50 and 23 μg L^{-1}, respectively, which were within the acceptable limits. Concentration of As was varied from 0.40 – 7.60 μg L^{-1}, which was within allowable limits of both Vietnam and WHO standards. This As concentration is slightly lower than in other regions in Mekong Delta, such as 4.71 – 550.58 μg L^{-1} in An Giang [8] and up to nearly 70 μg L^{-1} in Tra Vinh [30]. Exposure to As in the long term can lead to skin disorders, diabetes, blood pressure and increase the risk of cancers [40]. Heavy metals in groundwater are attributed to both natural and anthropogenic processes. Since the Mekong Delta has young and rich sediments, it made anoxic conditions and then facilitated the release of heavy metals such as As, Mn, and Fe [41–42]. Moreover, improper wastewater treatment plants, wastewater pipe leakage, and other human activities also contributed to heavy metals in groundwater.

An average COD concentration was about 1.75 ± 2.71 mg L^{-1}, with a minimum value of 0.59 mg L^{-1} at GW9 and a maximum of 13 mg L^{-1} at GW13. COD is used to measure the amount of oxygen required for the chemical oxidation of organic matter. It means that all groundwater samples in this study contained organic matter. Nam et al. (2019) [26] explained that the organic contamination of groundwater could be caused by surface water pollution that percolates into the aquifers.

Coliform density ranged from below the detection limit to 88 MPN 100 m L^{-1}, and 55% of total samples with coliform density exceeded the Vietnamese standard (3 MPN 100 m L^{-1}). However, several previous studies in this province reported that coliform density was relatively low and within the standard from 2016 – 2018 [26, 33]. According to the Vietnamese and WHO standards, *E. coli* should not be detected in groundwater; however, groundwater samples with the existence of *E. coli* accounted for 45% of the total. These high *E. coli*-detected locations coincided with high coliform density, including GW3, GW6, GW10, and GW16–20. According to Nguyen et al. (2021) [33], abandoned wells in the province did not improperly seal, which in turn groundwater is contaminated by microorganisms. In addition, septic tank leakage, livestock wastewater, and wild animal fecal matter can also contribute to the microbial contamination of groundwater.

2) Entropy-weighted groundwater quality index (EWQI)

EWQI values and quality classification corresponding with each monitoring location are presented in Table 4. The EWQI results were varied from 20.05 at GW5 to 738.52 at GW19. Only 5% of total groundwater samples are classified as excellent quality for drinking (EWQI <25). The majority of collected groundwater samples are categorized as good water quality (26<EWQI<50), accounting for 40% of the total samples. However, 25% of the samples are unsuitable for drinking purposes (EWQI> 100). The groundwater samples classified as poor and very poor are accounted for 20% and 10%, respectively. Combined with the characteristics of sampling locations (Supplementary Material (SM) 1), groundwater exploited in the Lower Pleistocene and Upper Miocene tends to be better than in the Middle-Upper Pleistocene.

Spatial distribution based on the computed EWQI values at 20 monitoring sites is illustrated in Figure 2. It can be seen that groundwater from the south to the central province tends to be more polluted than its vicinity. The reason is that this area is the center of agricultural production in the province, with various activities such as rice cultivation, aquaculture, and animal husbandry. Groundwater in the east and northeast of the province is more polluted where wells are located near the Hau River, even unsuitable for drinking purposes. Besides the effect of geogenic processes and climate change effects, anthropogenic activities in the inland areas, such as over-application of nitrogen fertilizers, polluted surface water, livestock wastewater, and septic tank leakage, are deemed to have significant impacts on groundwater quality.

3) Principal component analysis (PCA)

As presented in Table 5, the results of PCA method could explain 99.2% of total variations in groundwater quality with 11 PCs. According to Kale et al. (2020) [43], the eigenvalue is the criteria to decide the importance level of each component in the original data set. Since the eigenvalues from PC1 to PC5 were greater than 1, these PCs were further considered to determine potential groundwater pollution sources.

Table 4 EWQI values and quality class for each monitoring location

Sample	EWQI value	Class
GW1	26.74	Good
GW2	43.11	Good
GW3	108.43	Unsuitable for drinking
GW4	84.13	Very poor
GW5	20.05	Excellent
GW6	513.40	Unsuitable for drinking
GW7	51.73	Poor
GW8	47.08	Good
GW9	38.73	Good
GW10	76.58	Very poor
GW11	38.10	Good
GW12	36.85	Good
GW13	28.89	Good
GW14	54.21	Poor
GW15	52.17	Poor
GW16	71.84	Poor
GW17	120.85	Unsuitable for drinking
GW18	33.63	Good
GW19	738.52	Unsuitable for drinking
GW20	136.93	Unsuitable for drinking

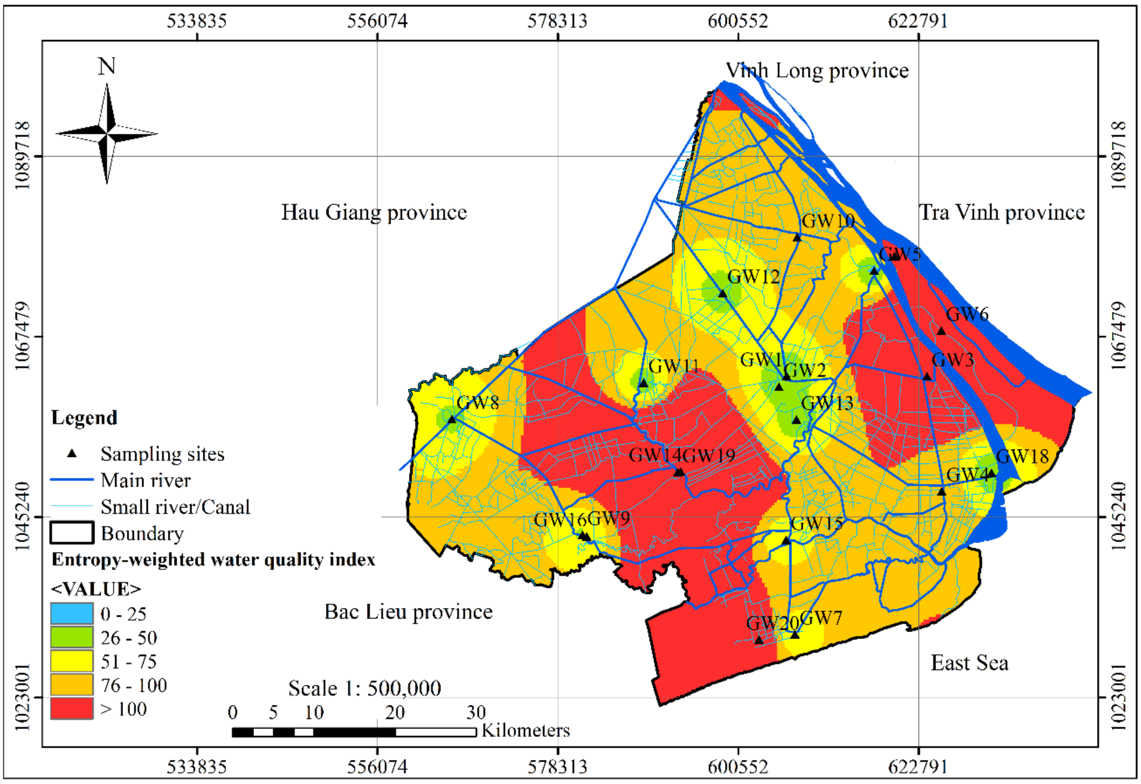

Figure 2 Spatial distribution map of groundwater quality in Soc Trang Province.

Table 5 PCA for groundwater quality data in Soc Trang in 2020

Parameters	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11
pH	0.15	0.39	-0.41	-0.05	-0.04	-0.08	-0.04	0.20	0.29	-0.49	-0.16
COD	-0.34	0.09	0.11	-0.12	-0.02	-0.08	-0.10	0.06	-0.01	-0.12	0.03
TDS	-0.34	0.18	0.05	-0.09	-0.04	-0.10	-0.03	-0.05	-0.05	-0.05	0.03
Hardness	-0.35	0.09	0.09	-0.01	-0.03	-0.05	-0.03	0.02	-0.17	0.12	0.16
NH_4^+	-0.22	0.13	0.07	0.27	-0.37	0.35	-0.17	0.39	0.21	0.40	-0.45
NO_2^-	-0.07	-0.15	0.05	0.52	-0.28	-0.59	0.32	-0.17	-0.04	0.04	-0.12
NO_3^-	-0.21	-0.37	-0.11	-0.04	0.26	0.01	0.15	-0.16	0.73	0.25	0.10
Cl^-	-0.34	0.16	0.07	-0.10	-0.02	-0.11	-0.07	-0.07	-0.08	-0.07	0.00
SO_4^{2-}	-0.24	0.32	-0.11	0.08	-0.22	0.13	0.41	0.14	0.26	-0.11	0.52
Pb	0.02	0.20	0.19	0.35	0.54	-0.28	-0.44	0.32	0.15	0.09	0.22
Cu	-0.07	0.31	0.17	0.06	0.55	0.11	0.61	0.06	-0.14	0.05	-0.37
Total coliform	-0.25	-0.25	-0.34	-0.04	0.20	0.18	0.03	0.05	-0.09	-0.08	-0.20
E. coli	-0.28	-0.20	-0.32	-0.02	0.15	0.15	-0.05	0.08	-0.33	0.09	0.17
PO_4^{3-}	-0.28	0.05	0.18	0.16	0.06	0.15	-0.26	-0.54	0.19	-0.41	-0.28
Fe	-0.01	-0.29	0.37	-0.47	-0.06	-0.25	0.11	0.41	0.17	-0.21	-0.20
F^-	0.01	0.37	-0.33	-0.40	0.00	-0.37	-0.09	-0.26	0.07	0.48	-0.20
Mn	-0.33	0.01	0.17	-0.21	-0.03	-0.17	-0.04	0.09	-0.07	0.01	0.03
As	-0.20	-0.21	-0.44	0.20	0.05	-0.29	-0.04	0.27	-0.08	-0.18	-0.18
Eigenvalues	7.89	2.41	2.05	1.53	1.33	0.87	0.63	0.53	0.32	0.18	0.11
% Variation	43.9	13.4	11.4	8.5	7.4	4.8	3.5	3	1.8	1	0.6
Cum.% Variation	43.9	57.2	68.6	77.1	84.5	89.4	92.9	95.8	97.6	98.6	99.2

Five PCs could explain up to 84.5% of the total variation in groundwater quality in this study area. PC1 accounted for 43.9% of total variation with a weak correlation to COD (-0.34), TDS (-0.34), total hardness (-0.35), and Mn (-0.33). COD and TDS in groundwater were associated with organic pollution, which can be from agricultural runoff, septic tanks, and domestic and industrial wastewater [27]. Moreover, TDS, total hardness and Mn in groundwater also depend on the subsurface structure, which means that minerals and rocks can dissolute and release Ca, Mg, or Mn into the aquifers. PC2 accounted for 13.4 of the total variation, which is characterized with weak correlations to pH (0.39), NO_3^- (-0.37), SO_4^{2-} (0.32), Cu (0.31), and F^- (0.37). The pH fluctuation in groundwater was contributed by agricultural wastewater, detergents, industrial wastewater, and dissolved CO_3^{2-} compounds [44]. SO_4^{2-}, Cu, and F^- in groundwater can result from natural processes and depend on the subsurface structure. Water passes through the minerals, gypsum, and rocks and carries SO_4^{2-}, Cu, and F^- into the aquifers. NO_3^- contamination can be caused by both point sources (e.g., industrial waste, intensive animal husbandry) and non-point sources (e.g., excessive nitrogen application, agricultural runoff) [11, 33]. The relative contribution to the overall variation of PC3, PC4, and PC5 was 11.4%, 8.5%, and 7.4%, respectively. In PC3, there were weak correlations with pH (-0.41), total coliform (-0.34), *E. coli* (-0.32), Fe (0.37), and As (0.44). Total coliform and *E. coli* are considered indicators for groundwater microbial contamination caused by septic tank leakage, livestock wastewater, and wild and cattle fecal matters. PC4 showed a medium correlation with NO_2^- (0.52) and weak correlations with Pb (0.35), Fe (-0.47), and F^- (0.40). PC5 also had medium correlations with Pb (0.54) and Cu (0.55). In addition to the natural release of heavy metals, anthropogenic activities such as industrial wastewater, dumpsites, and metal pipe corrosion, are also responsible for the existence of these metallic compounds in aquifers [14]. Thus, it can be implied that the variation of groundwater quality in Soc Trang in 2020 was very complex and influenced by both natural and artificial sources.

4) Spatial variation of groundwater quality

Using Ward's linkage method, a dendrogram was created based on the groundwater quality of monitoring locations, as illustrated in Figure 3. In the same distance, monitoring wells were divided into 4 clusters.

The groundwater characteristics of clusters are shown in Table 6. The cluster I comprises of 4 monitoring sites (i.e., GW1, GW2, GW12, GW 13) in the Soc Trang City and Chau Thanh District, which are characterized as insignificant pollution. The cluster II is the biggest cluster including 13 monitoring locations (i.e., GW3, GW5, GW7–11, GW14–18, GW20). Groundwater in this cluster was slightly polluted by NH_4^+, total coliforms, and *E. coli*. Similarly, the cluster III, including GW4 and GW6, also polluted by NH_4^+, but the microbial contamination in this cluster was more serious than the clusters I and II. Additionally, the concentration of Fe in this cluster was far higher than other clusters and exceeded the acceptable limits. GW19 is divided into a separate cluster IV since this location was heavily polluted by TDS, total hardness, NH_4^+, Cl^-, SO_4^{2-}, total coliform, *E. coli*, and Mn. This monitoring well is located in My Xuyen District and nearby the Nhu Gia River. Its vicinity was residential areas, seafood processing companies, paddy fields, and other agricultural fields. Therefore, wastes from these human activities and polluted surface water can extremely affect groundwater quality in this area.

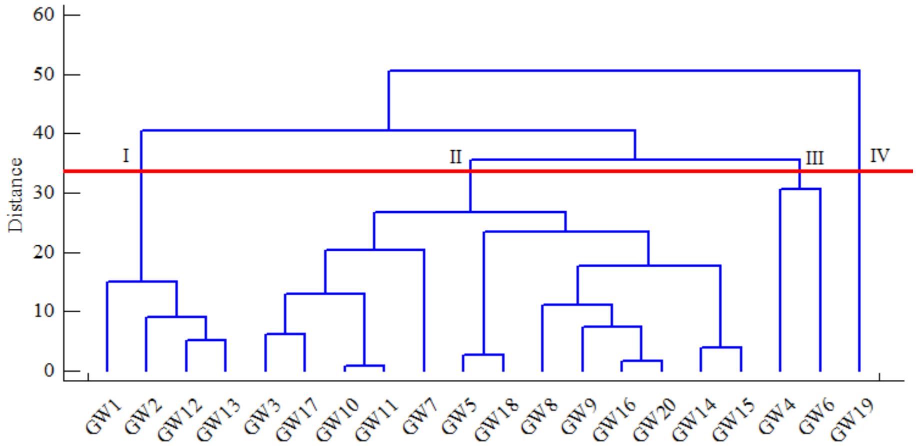

Figure 3 Clustering monitoring locations based on groundwater quality.

Table 6 Mean values of groundwater parameters for each cluster

Parameters	Unit	I	II	III	IV
pH		7.66	7.11	6.87	6.74
COD	mg L^{-1}	0.96	1.05	2.25	13.00
TDS	mg L^{-1}	913.08	582.39	592.55	8055.00
Hardness	mg L^{-1}	67.48	263.41	299.85	2967.40
NH_4^+	mg N L^{-1}	0.36	3.45	1.31	10.80
NO_2^-	mg N L^{-1}	0.002	0.003	0.002	0.004
NO_3^-	mg N L^{-1}	0.02	0.04	0.09	0.09
Cl^-	mg L^{-1}	248.38	100.72	182.18	4319.30
SO_4^{2-}	mg L^{-1}	133.53	126.48	47.95	408.40
PO_4^{3-}	mg L^{-1}	0.15	0.27	0.17	0.89
F^-	mg L^{-1}	0.85	0.34	0.30	0.55
Pb	µg L^{-1}	0.52	0.58	0.00	0.60
Cu	mg L^{-1}	0.01	0.01	0.00	0.02
Total Fe	mg L^{-1}	1.41	1.22	10.16	1.60
Mn	mg L^{-1}	0.09	0.12	0.48	2.03
As	µg L^{-1}	1.58	1.57	4.20	5.30
Total coliform	MPN $100mL^{-1}$	2.00	5.77	48.00	66.00
E. coli	MPN $100mL^{-1}$	0.00	2.23	15.50	29.00

5) Human health risk assessment

The results of non-carcinogenic risks for adults and children due to drinking contaminated groundwater are presented in Table 7. Children are the most susceptible to consuming groundwater containing non-carcinogenic substances (i.e., NH_4^+, NO_2^-, NO_3^-, Cd, Cu, F^-, Mn, and As). Groundwater samples with HQ_{total} of children were larger than 1 accounted for 40%, including GW1, GW2, GW6, GW7, GW12, GW13, GW17, and GW19. This suggests that once children drink groundwater in these locations, they are at risk of adverse health effects. The percentage of groundwater samples with HQ_{total} exceeding 1 for males and females are 5 and 10% of total samples, respectively. Children are more susceptible to contaminated groundwater because their body weights are considerably smaller than adults [4]. Notably, groundwater at GW19 causes an extremely high risk of non-carcinogenic effects on both children and female and male adults.

Table 7 Non-carcinogenic and carcinogenic risks for adults and children drinking groundwater

Samples	HQ_{total}			Cancer risk		
	Male	Female	Children	Male	Female	Children
GW1	0.61	0.77	1.32	1.93E-05	2.45E-05	1.68E-05
GW2	0.59	0.76	1.30	1.65E-05	2.10E-05	1.44E-05
GW3	0.33	0.42	0.72	2.76E-05	3.51E-05	2.40E-05
GW4	0.33	0.42	0.72	1.10E-05	1.40E-05	9.60E-06
GW5	0.32	0.41	0.70	3.17E-05	4.03E-05	2.76E-05
GW6	0.80	1.02	1.74	1.05E-04	1.33E-04	9.12E-05
GW7	0.76	0.97	1.66	7.44E-05	9.47E-05	6.48E-05
GW8	0.32	0.40	0.69	5.51E-06	7.01E-06	4.80E-06
GW9	0.39	0.49	0.84	1.52E-05	1.93E-05	1.32E-05
GW10	0.31	0.39	0.67	2.20E-05	2.81E-05	1.92E-05
GW11	0.31	0.40	0.68	1.79E-05	2.28E-05	1.56E-05
GW12	0.66	0.84	1.44	3.99E-05	5.08E-05	3.48E-05
GW13	0.51	0.65	1.11	1.10E-05	1.40E-05	9.60E-06
GW14	0.36	0.46	0.78	6.89E-06	8.77E-06	6.00E-06
GW15	0.45	0.58	0.99	1.24E-05	1.58E-05	1.08E-05
GW16	0.42	0.53	0.91	1.65E-05	2.10E-05	1.44E-05
GW17	0.60	0.76	1.30	2.34E-05	2.98E-05	2.04E-05
GW18	0.23	0.30	0.51	1.10E-05	1.40E-05	9.60E-06
GW19	1.25	1.59	2.73	7.30E-05	9.29E-05	6.36E-05
GW20	0.34	0.43	0.74	1.65E-05	2.10E-05	1.44E-05

The carcinogenic risk of children drinking As-contaminated groundwater was ranged from 4.80×10^{-6} to 9.12×10^{-5}, which was over the acceptable risk level ($CR<10^{-6}$). The highest carcinogenic risk for children was found at GW6, with a ratio of 9 in 100,000 children under the cancer risk. Both male and female adults had a higher carcinogenic risk than children since they have longer exposure duration to As-contaminated groundwater, with the range of 5.51×10^{-6} to 1.05×10^{-4} for males and 7.01×10^{-6} to 1.33×10^{-4} for females. According to Phan and Nguyen (2018) [8], the cancer risks for children and adults consuming As-contaminated groundwater in An Giang Province were ranged from 8.66×10^{-4} to 8.26×10^{-2}. The study of Buschmann (2008) [42] warned that approximately 2 million people in the Mekong delta floodplains are facing the most serious cancer risk due to drinking As-poisoned groundwater without any treatment. It is notable that although As concentrations in this study area were within the Vietnamese standard, it also causes a great carcinogenic risk for both children and adults.

Based on the results of this study, although groundwater quality is generally classified as good, it is not completely healthy for local people to consume in the long term. Some certain groundwater samples extracted from the Middle-Upper Pleistocene were heavily polluted. In this study, both non-cancer and cancer risks for humans were calculated based on the assumption that groundwater is the main drinking water source. Moreover, this study has not calculated the cancer risks for Cd in groundwater due to the limitations of analysis techniques. To overcome these limitations, potential strategies are suggested to prevent pollution and ensure the safety of this water source for human consumption:

• Wells with signs of serious deterioration such as GW19 need to reduce production capacity or stop working. In the long run, in-situ water treatments should be installed.

• It is necessary to raise local people's awareness about water protection and enlighten them about the potential risks of consuming contaminated groundwater.

• Future studies about water quality and quantity with better analysis techniques should be conducted more to support policymakers in developing sustainable development goals.

• Also, it is important to have extensive research on Vietnamese groundwater exposure data in the study area to have a precise prediction for the human health risks since the current study referenced the Chinese data.

Conclusions

Groundwater quality in Soc Trang, a coastal area in the Vietnamese Mekong Delta, was evaluated using entropy-weighted groundwater index and multivariate statistical methods. In general, the quality of groundwater in the province met the Vietnamese and WHO standards, but there were signs of NH_4^+, Cl^-, Fe, total coliform, and *E. coli* pollution at some monitoring points. The groundwater sample at GW19 was heavily polluted by TDS, total hardness, NH_4^+, Cl^-, SO_4^{2-}, total coliform, total Fe, and *E. coli*. The results of PCA showed that 5PCs could explain 84.5% of the total variation in groundwater quality. The correlation between parameters and PCs has suggested that subsurface structure and anthropogenic activities significantly influenced groundwater quality, such as dissolution of rocks and minerals, agricultural runoff, over-application of nitrogen fertilizer, and industrial wastewater. Based on the similarity of groundwater quality, monitoring location can be divided into 4 clusters, especially cluster IV, including only GW19 where serious microbial and chemical pollution occurred. The computed EWQI values ranged from 20.05 – 738.52, suggesting groundwater quality in this study area fluctuated from excellent to unsuitable for drinking. The majority of samples were classified as good quality, accounting for 40% of total samples. In addition, 40% of total groundwater samples (HQ_{total} >1) can pose the risk of adverse health effects for children consuming groundwater containing non-carcinogenic substances (NH_4^+, NO_2^-, NO_3^-, Cd, Cu, F^-, Mn, and As). The carcinogenic risks of both adults and children for drinking As-contaminated groundwater were ranged from 4.80×10^{-6} to 1.33×10^{-4}, which exceeded the acceptable risk. Therefore, it can be seen that local people are taking high risks of non-carcinogenic and carcinogenic effects since using these groundwater sources. To ensure public health, it is necessary to have water treatments before consumption and regularly monitor to detect groundwater pollution promptly.

Acknowledgments

The Department of Environmental and Natural Resources, Soc Trang Province, is acknowledged for providing useful data. The scientific and personal views presented in this paper do not necessarily reflect the views of the data provider.

References

[1] Wagner, F., Tran, V.B., Renaud, F.G. Groundwater resources in the Mekong Delta: Availability, utilization and risks, in the Mekong Delta System. Springer Environmental Science and Engineering, 2012, 201–220.

[2] Alcérreca-Huerta, J.C, Callejas-Jimenez, M.E., Carrillo, L., Castillo, M.M. Dam implications on salt-water intrusion and land use within a tropical estuarine environment of the Gulf of Mexico. Science

of the Total Environment, 2019, 652, 1102–1112.

[3] Phuc, D.D., General on groundwater resources. Department of water resources management, Water sector review project. Project ADB-TA-4903 VIE, 2008.

[4] Zhang, Q., Xu, P., Qian, H. Groundwater quality assessment using improved water quality index (WQI) and human health risk (HHR) evaluation in a semi-arid region of northwest China. Exposure and Health, 2020, 12, 487–500.

[5] Tran, D.A., Tsujimura, M., Ho, H.L., Dang, D.H., Vo, P.L., Doan, T.H., Nguyen, T.V. Groundwater quality evaluation and health risk assessment in coastal lowland areas of the Mekong Delta, Vietnam. Groundwater for Sustainable Development, 2021, 15, 100679.

[6] Ram, A., Tiwari, S.K., Pandey, H.K., Chaurasia, A.K., Singh, S., Singh, Y.V. Groundwater quality assessment using water quality index (WQI) under GIS framework. Applied Water Science, 2021, 11, 1–20.

[7] Erban, L.E., Gorelick, S.M., Zebker, H.A., Fendorf, S. Release of arsenic to deep groundwater in the Mekong Delta, Vietnam, linked to pumping-induced land subsidence. Proceedings of the National Academy of Sciences, 2013, 110, 13751–13756.

[8] Phan, K.A., Nguyen, T.G. Groundwater quality and human health risk assessment related to groundwater consumption in An Giang Province, Viet Nam. Journal of Vietnamese Environment, 2018, 10, 85–91.

[9] Minh, H.V.T., Avtar, R., Kumar, P., Tran, D.Q., Ty, T.V., Behera, H.C., Kurasaki, M. Groundwater quality assessment using fuzzy-AHP in An Giang Province of Vietnam. Geosciences, 2019, 9, 330.

[10] Li, C., Gao, Z., Chen, H., Wang, J., Liu, J., Li, C., ..., Xu, C. Hydrochemical analysis and quality assessment of groundwater in southeast North China Plain using hydrochemical, entropy-weight water quality index, and GIS techniques. Environmental Earth Sciences, 2021, 80, 1–15.

[11] Wu, J., Zhang, Y., Zhou, H. Groundwater chemistry and groundwater quality index incorporating health risk weighting in Dingbian County, Ordos basin of northwest China. Geochemistry, 2020, 80, 125607.

[12] Nguyen, T.G., Phan, K.A., Huynh, T.H.N. Spatiotemporal analysis of surface water quality in Dong Thap province, Vietnam using water quality index and statistical approaches. Water, 2021, 13, 336.

[13] Abou, Z.B., Hafez, R. Hydrochemical, isotopic and statistical characteristics of groundwater nitrate pollution in Damascus Oasis (Syria). Environmental Earth Sciences, 2015, 74, 2781–2797.

[14] Misi, A., Gumindoga, W., Hoko, Z. An assessment of groundwater potential and vulnerability in the Upper Manyame Sub-Catchment of Zimbabwe. Physics and Chemistry of the Earth, 2018, 105, 72–83.

[15] Jackson, J.E., A user's guide to principal components. John Wiley & Sons, 2005, 587.

[16] Egbueri, J.C. Groundwater quality assessment using pollution index of groundwater (PIG), ecological risk index (ERI) and hierarchical cluster analysis (HCA): a case study. Groundwater for Sustainable Development, 2020, 10, 100292.

[17] An T.D., Tsujimura M., Le P.V., Ha D.T., Van H.N. Isotopic and hydrogeochemical signatures in evaluating groundwater quality in the coastal area of the Mekong Delta, Vietnam. In International Conference on Geo-Spatial Technologies and Earth Resources 2017 Oct 5, 293–314.

[18] Le, D.N., Nguyen, T.V.K., Nguyen, D.V., Tran, A.T., Nguyen, H.T., Heidbüchel, I., Apel, H. Groundwater dynamics in the Vietnamese Mekong Delta: Trends, memory effects, and response times. Journal of Hydrology: Regional Studies, 2021, 33, 100746.

[19] Department of Natural Resources and Environment of Soc Trang Province. Report on the current state of the environment in Soc Trang Province in the period of 2016 –2020. 2021.

[20] Federation Water Environmental, American Public Health Association. Standard methods for the examination of water and wastewater. American Public Health Association (APHA): Washington, 2005.

[21] Ministry of Natural Resources and Environment. National technical regulation on groundwater quality. 2015. [Online] Available from: https://vanbanphapluat.co/qcvn-09-mt-2015-btnmt-chat-luong-nuoc-duoi-dat [Accessed 10 October 2021].

[22] United States Environmental Protection Agency. Risk assessment guidance for superfund. Office of Emergency and Remedial Response, 1989

[23] United States Environmental Protection Agency. Guidelines for carcinogen risk assessment. Federal Register, 1986, 51, 33992–34003.

[24] United States Environmental Protection Agency. IRIS A to Z List of Chemical Assessments. [Online] Available from: https://iris.epa.gov/AtoZ/?list_type=alpha [Accessed 10 October 2021].

[25] World Health Organization, Guidelines for Drinking-Water Quality: Fourth edition incorporating the first addendum. Geneva, 2017.

[26] Nam, N.D.G., Akira, G., Kazutoshi, O., Trung, N.H., Ngan, N.V.C. Assessment of groundwater quality and its suitability for domestic and irrigation use in the coastal zone of the Mekong Delta, Vietnam. Water and Power, 2019, 173–185.

[27] Boyd, C., Claude, E. Water Quality: An introduction. Kluwer academic publishers, USA, 2000, 2061.

[28] Dao, H.H., Nguyen, K.V., Tra, S.T., Bui, V.T. Assessment of groundwater quality of middle-upper Pleistocene aquifer in Ca Mau peninsula. Science and Technology Development Journal, 2016, 19, 35–44.

[29] Nguyen, T.G. Chemical and microbial characteristics of surface and groundwater in the areas burying swine infected with African swine fever in An Giang province, Vietnam. Journal of Energy Technology and Environment, 2021, 3, 1–10.

[30] Be, N.V., Tuyen, T.T. Status of exploitation, management and quality of sand dune groundwater in Tra Vinh Province. Journal of Science Can Tho University, 2007, 95–104.

[31] Majumdar, D., Gupta, N. Nitrate pollution of groundwater and associated human health disorders. Indian journal of environmental health, 2000, 42, 28–39.

[32] Pham, T.H.V.T. Assessment of drilling water quality at Tan Thanh commune, Thanh Binh District, Dong Thap Province. Ho Chi Minh City Open University Journal of Science, 2019, 14, 119–128.

[33] Nguyen, T.G., Le, T.H.T, Lam, N.T.L. Survey on current status of management, exploitation, use and quality of groundwater in Vinh Chau, Soc Trang. Journal of Agriculture and Rural Development, 2021, 11, 162–169.

[34] Pius, A., Jerome, C., Sharma, N. Evaluation of groundwater quality in and around Peenya industrial area of Bangalore, South India using GIS techniques. Environmental monitoring and assessment, 2012, 184, 4067–4077.

[35] United States Environmental Protection Agency. Health effects from exposure to

high levels of sulfate in drinking water study, 1999.

[36] Heathwaite, A.L., Dils, R.M., Liu, S., Carvalho, L., Brazier, R.E., Pope, L., and May, L.A tiered risk-based approach for predicting diffuse and point source phosphorus losses in agricultural areas. Science of the Total Environment, 2005, 344, 225–239.

[37] Withers, P., Haygarth, P. Agriculture, phosphorus and eutrophication: A European perspective. Soil Use and Management, 2007, 23, 1–4.

[38] Meinikmann, K., Hupfer, M., Lewandowski, J. Phosphorus in groundwater discharge–A potential source for lake eutrophication. Journal of Hydrology, 2015, 524, 214–226.

[39] Griffioen, J. Extent of immobilisation of phosphate during aeration of nutrient-rich, anoxic groundwater. Journal of Hydrology, 2006, 320, 359–369.

[40] United States Environmental Protection Agency. Edition of the drinking water standards and health advisories, 2018.

[41] Agusa, T., Kubota, R., Kunito, T., Minh, T.B., Trang, P.T.K., Chamnan, C., Tanabe, S., Arsenic pollution in ground-water of Vietnam and Cambodia: A review. Biomedical research on trace elements, 2007, 18, 35–47.

[42] Buschmann, J., Berg, M., Stengel, C., Winkel, L., Sampson, M.L., Trang, P.T.K., Viet, P.H. Contamination of drinking water resources in the Mekong delta floodplains: Arsenic and other trace metals pose serious health risks to population. Environment International, 2008, 34, 756–764.

[43] Kale, A., Bandela, N., Kulkarni, J., Raut, K. Factor analysis and spatial distribution of water quality parameters of Aurangabad District, India. Groundwater for Sustainable Development, 2020, 10, 100345.

[44] Hoko, Z. An assessment of quality of water from boreholes in Bindura District, Zimbabwe. Physics and Chemistry of the Earth, 2008, 33, 824–828.