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Groundwater Quality Assessment in the Middle-Upper Pleistocene Aquifer

Le Diem Kieu [1], Pham Quoc Nguyen [1*]

[1] *Faculty of Agriculture, Natural resources and Environment, Dong Thap University, Dong Thap, 81000, Vietnam.*

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Abstract

The study was conducted to assess groundwater quality and identify the main pollution sources of groundwater in Hau Giang province, Vietnam. Groundwater samples were collected at five locations (GW1-GW5) at qp_{2-3} aquifer in May and October 2022. Principal component analysis (PCA), cluster analysis (CA), water pollution index (WPI), and groundwater quality index (GWQI) were applied in the study. The results revealed that the groundwater quality was influenced by TDS, NH_4^+-N, permanganate index, and Fe. On the basis of WPI, GW2 and GW3 had the lowest water quality, exceeding a value of 1. The results of GWQI showed that groundwater quality was divided into three categories (excellent, poor, and unsuitable for drinking) in May and four categories (good, poor, very poor, and unsuitable for drinking) in October. The study also revealed seasonal variations in groundwater quality, particularly in GW5 (Vi Thuy district, Hau Giang, Vietnam). The CA results formed four water quality groups in both periods based on the similarity of groundwater parameters. PCA results presented that the three PCs explained 79.55% of the variation in groundwater quality. Three potential sources of pollution are derived from the discharge of wastewater (domestic, industrial, and agricultural), landfilling, and seawater intrusion.

Keywords: Cluster Analysis; Groundwater Quality Index; Principal Component Analysis; Water Pollution Index.

1. Introduction

Groundwater plays a crucial role in drinking water supply, agricultural irrigation, and economic development worldwide [1, 2]. It is particularly crucial for arid and semi-arid regions due to rare rainfall and insufficient or polluted surface water [3]. However, rapid urbanization and population growth have significantly affected groundwater quality. The discharge of industrial wastewater and domestic wastewater, the use of fertilizers and pesticides in agriculture for a long time, and the process of burying waste have led to serious groundwater pollution, typically organic pollution, nitrogen, and heavy metals, and subsequently human health problems [4–7]. In addition, coastal areas and those affected by seawater intrusion face high chloride content in groundwater, leading to salinization in aquifers, which seriously affects water quality and the community's ability to meet water demand [8]. The significance of groundwater to human health and its vulnerability to pollution problems has led to numerous studies to assess groundwater quality [9]. Various multivariate statistical analyses have been successfully applied in many previous studies, such as assessing groundwater quality by principal component analysis (PCA) and cluster analysis (CA) [10–12].

Furthermore, in the past few years, various pollution indices such as water quality index (WQI) [13-16], heavy metal assessment index (HEI) [17], water pollution index (WPI) [18, 19], and ecological risk index (ERI) are both commonly

* Corresponding author: pqnguyen@dthu.edu.vn

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used in the field of water environmental assessment. In which the water quality index (WQI) is widely used in water quality monitoring programs to assess the overall quality of water used for drinking purposes, providing reliable information to local communities and authorities [5, 14, 20-22]. The WQI index is used as a tool to aggregate water quality parameters and is expressed as a single value [20]. Depending on the range of WQI values, the monitored water source has different water quality, meeting different water use needs. Therefore, the variety of indices and assessment methods could provide more apparent and accurate information about water quality in a specific/similar area.

Hau Giang is a province in the Mekong Delta that has had remarkable socio-economic development in recent years. In 2022, the growth rate of gross product (GRDP) in Hau Giang province is estimated at 113.94%, ranking first in the Mekong Delta and fourth in the country [23]. Facing the speed of economic development and urbanization, the demand for water in domestic and production activities of the province has increased. Hau Giang province is a locality with an interlaced river system, with a total length of about 2,300 km [24]. The province's water surface area is estimated at 11,500 ha, and the average amount of surface water exploited to serve industrial and service production activities is about 200,000 m^3/day. However, surface water in Hau Giang province has been seriously polluted, typically organic, coliform, and TSS pollution [25, 26]. The main reason is due to the production activities of enterprises, companies, daily activities, and trade services in the area. Since then, groundwater has become an important water source in the area. In the province, there are a total of 40,614 wells that are used for exploiting and using groundwater for various purposes (e.g., food, daily life, and production), with a total volume of 58,186 m^3/day [27].

Consequently, ensuring the quality of groundwater is essential for public health safety. The study aims to determine groundwater quality in the study area by various indices and the main sources of pollution affecting water quality caused by some pollutants in the groundwater.

2. Material and Methods

2.1. Site Description

Hau Giang is a province of the Mekong Delta (Vietnam), with a total area of 1,622.23 km^2 and a population of 729,900 people [28]. The province is located at the coordinates from 9º30'35" to 10º19'17" North latitude and from 105º14'03" to 106º17'57" East longitude. Hau Giang province has a system of interlaced rivers and canals with a total length of about 2,300 km [24] and a relatively large density of 1.5 km/km^2, of which the Hau riverside area of Chau Thanh district has a density of up to 2 km/km^2. In addition to abundant surface water resources, the province also has quite rich groundwater resources with a total potential exploitation reserve of about 2.8 million m^3/day, including seven main aquifers: Holocene (qh), Upper Pleistocene (qp_3), Middle-Upper Pleistocene (qp_{2-3}), Lower Pleistocene (qp_1), Middle Pliocene (n_2^2), Lower Pliocene (n_2^1), and Miocene (n_1^3) [29]. Among them, the Middle-Upper Pleistocene aquifer (qp_{2-3}) has the most abundant groundwater reserve, estimated at 451,321 m^3/day [29], serving as the primary source of water supply for the region's daily activities.

2.2. Description of Groundwater Sampling and Analysis

The study monitored five wells throughout the province to assess groundwater quality in the middle-upper Pleistocene aquifer (qp2-3). The five groundwater monitoring locations are signed from GW1 to GW5 (Figure 1), namely Hoa Tien Water Supply Station (GW1, with the depth of about 110 m) and Water Supply and Sewerage Joint Stock Company-Urban Works Hau Giang (GW2, with the depth of about 117.5 m) in Vi Thanh City, Campus of Military Command of Hoa An Commune (GW3, with the depth of about 120 m) in Phung Hiep District, Campus of Management Board of Industrial Parks of Hau Giang Province in Chau Thanh District (GW4, with a depth of about 180 m), and People's Committee of Vi Thang Commune in Vi Thuy District (GW5). Groundwater samples were collected twice in 2022 (i.e., May and October). Groundwater samples were collected according to national standards in Vietnam regarding guidance on groundwater sampling (TCVN 6663-11:2011) [30].

After collection, samples were stored in the dark and refrigerated at 4°C during transportation to the laboratory. The samples were analyzed within 24 hours. Nine parameters, including pH, total dissolved solids (TDS), total hardness (TH), permanganate index (PI), ammonium (NH_4^+-N), nitrite (NO_2^--N), sulfate (SO_4^{2-}), chloride (Cl^-), and iron (Fe), were analyzed according to standard methods [31]. The pH and TDS criteria were measured directly in the field, and the permanganate index was analyzed in the laboratory of the Center for Environmental Technology in Ho Chi Minh City of the Institute of Environmental Technology. Other parameters were analyzed in the laboratory of the Center for Natural Resources and Environment Monitoring of Hau Giang province. Methods for analyzing groundwater parameters and their limit values [32] are presented in Table 1.

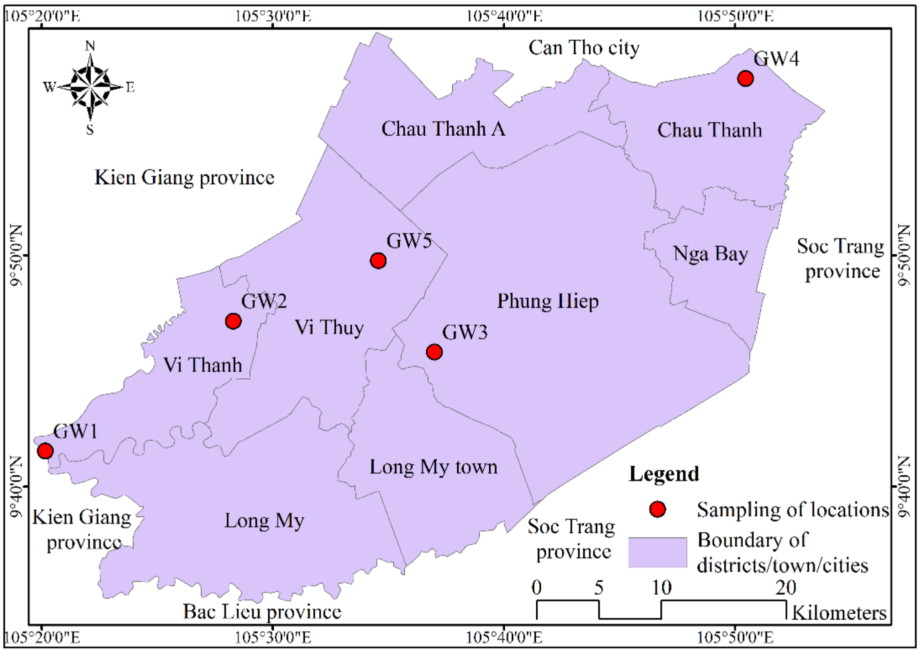

Figure 1. Map of the groundwater sampling locations in Hau Giang province

Table 1. Groundwater quality parameters and limit values

No.	Parameter	Name/number of the method	Limit values	
			QCVN 09-MT:2015/BTNMT	WHO
1	pH	TCVN 6492:2011	5.5 - 8.5	7 - 8
2	TDS	HD. DHTN.04-TDS	1500	600 - 1,000
3	Total hardness	TCVN 6224:1996	500	200
4	Permanganate index	TCVN 6186:1996	4	-
5	NH_4^+-N	TCVN 6179-1:1996	1	0.2
6	NO_2^--N	TCVN 6178:1996	1	-
7	SO_4^{2-}	SMEWW 4500-SO_4^{2-}.E:2012	400	250
8	Cl^-	TCVN 6194:1996	250	250
9	Fe	TCVN 6177:1996	5	0.3

2.3. Data Analysis

2.3.1. Groundwater Quality Index

Groundwater Quality Index (GWQI) is used in the study to reflect the groundwater quality status at each specific well, showing the variation of water quality over space and time of observation. Groundwater parameters (i.e., pH, TDS, TH, PI, NH_4^+-N, NO_2^--N, SO_4^{2-}, Cl^-, and Fe) were used to calculate the GWQI according to Equation 1 [20, 21, 33]:

$$\mathrm{GWQI} = \sum_{i=1}^{n} \mathrm{SI_i} = \sum_{i=1}^{n} \mathrm{W_i} \times \mathrm{q_i} \tag{1}$$

where n is the number of groundwater quality variables, W_i is the relative weight of each parameter, q_i is the quality rating scale and SI_i is the sub-index of each parameter.

The relative weight (W_i) represents the role of the parameter in the whole set of monitoring data and it can be calculated according to Equation 2 [34]:

$$\mathrm{W_i} = \frac{\sum_{i=1}^{n} \frac{1}{Si}}{Si} \tag{2}$$

where S_i is the limit value of each parameter specified in QCVN 09-MT:2015/BTNMT. Specifically, the limit values used in the equation were 8.5 of pH, 1500 for TDS, 500 for TH, 4 for PI, 1 for NH_4^+-N, 1 for NO_2^--N, 400 for SO_4^{2-}, 250 for Cl^- and 5 for Fe.

The quality rating scale (q_i) is determined by the quotient between the concentration of each environmental parameter (C_i) and the corresponding standard limit according to QCVN 09-MT:2015/BTNMT (S_i) and the result is multiplied by 100. The formula for calculating q_i is as Equation 3 [21].

$$q_i = \frac{C_i}{S_i} \times 100 \quad (3)$$

The scale of assessing groundwater quality through the GWQI index is divided into five levels: (1) "excellent" when GWQI is less than 25, (2) "good" when GWQI ranges from 26 - 50, (3) "poor" when the GWQI ranges from 51 - 75, (4) "very poor" when the GWQI ranges from 76 - 100, and (5) "not suitable for drinking water" when the GWQI is greater than 100 [13]. The study used QGIS software (version 3.28) to build a GWQI map based on two observations (May and October 2022). The RGB color palette is used to represent the status of groundwater quality in the study area.

2.3.2. Water Pollution Index (WPI)

The water pollution index was applied to assess the level of groundwater contamination [18]. This index was calculated based on nine water quality parameters (i.e., pH, TDS, TH, PI, NH_4^+-N, NO_2^--N, SO_4^{2-}, Cl^- and Fe). In the first step, the pollutant load (PLi) of parameters (except for pH) is calculated using Equation 4. For the calculation of PLpH, if the value of pH is less than 7, the PLpH is determined by Equation 5. In contrast, if pH is greater than 7, Equation 6 was used:

$$PL_i = 1 + \left(\frac{C_i - S_i}{S_i}\right) \quad (4)$$

$$PL_{pH} = 1 + \left(\frac{C_i - 7}{S_{i1} - 7}\right) \quad (5)$$

$$PL_{pH} = 1 + \left(\frac{C_i - 7}{S_{i2} - 7}\right) \quad (6)$$

in which C_i is the parameter's monitoring concentration and S_i is the maximum or standard limit value in Vietnamese. S_{i1} and S_{i2} are the minimum and maximum limit values of pH. After calculating the pollutant loads, the WPI is calculated as the average of the pollution load values of the parameters using Equation 7.

$$WPI = \frac{1}{n}\sum_{i=1}^{n} PL_i \quad (7)$$

Based on the classification, the WPI values are classified the groundwater quality four levels, including excellent quality (WPI<0.5), good quality (0.5≤WPI<0.75), moderate pollution (0.75≤WPI<1) and high pollution and not suitable for human consumption (WPI ≥1) [35].

2.3.3. Multivariate Analysis

In this study, multivariate statistical methods, including principal component analysis (PCA) and cluster analysis (CA), were applied to determine the main indicators affecting groundwater quality and pollution sources and groups of monitoring stations with similar groundwater quality [6, 11, 36]. Input data of PCA is the value of nine groundwater quality parameters at five monitoring stations at two monitoring times in May and October in Hau Giang province. PCA transforms the original variables of the groundwater dataset into uncorrelated new variables or axes called principal components (PCs). In which, the PC with the highest Eigenvalues sets the most critical variations in the groundwater quality data set. For CA, input data includes the value of nine groundwater variables and the GWQI index value at each monitoring station according to the monitoring time. Ward's method and Euclidean distance are used in CA analysis to classify groundwater quality. CA results are presented as dendrograms, providing a visual summary of the cluster analysis. This study performed PCA and CA using SPSS (version 20.0) and Statgraphics (version XVI), respectively. Besides, the statistically significant difference in groundwater characteristics between the two monitoring periods was tested by Independent-Samples T-test (p<0.05), performed using SPSS 20.0 software. Figure 2 briefly illustrates the methodology used in this study.

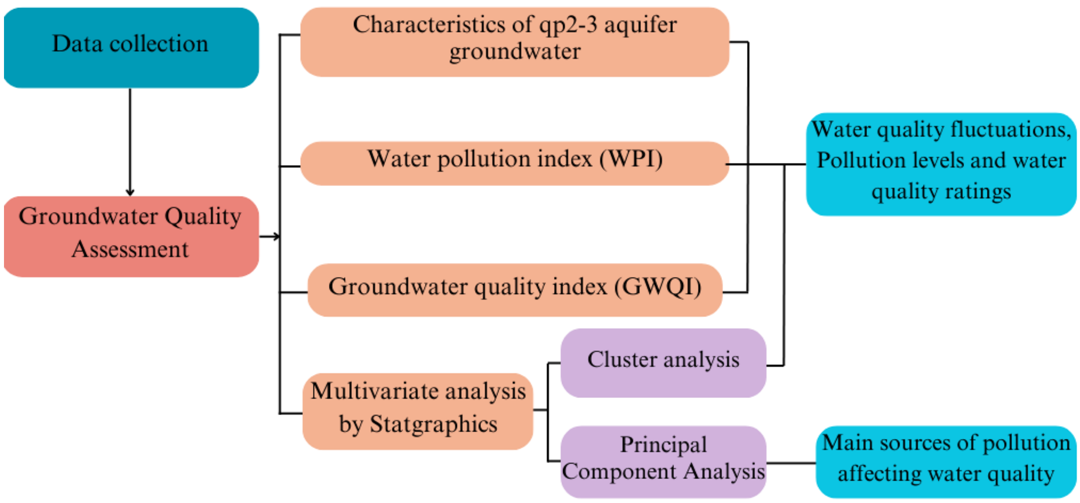

Figure 2. Flowchart of research method

3. Results and Discussion

3.1. Characteristics of qp_{2-3} Aquifer Groundwater in Hau Giang Province

Table 2 summarized the groundwater characteristics of the Middle-Upper Pleistocene aquifer (qp_{2-3}) in Hau Giang province in May and October 2022. The pH of groundwater remained similar over two sampling times with no statistical difference (p>0.05). In May, pH fluctuated in the range of 6.75-7.58, with an average of 7.05±0.33, while the pH in October was in the range of 6.72-7.24, with an average level of 6.87±0.22. The average pH values from both periods were within the Vietnamese limit (QCVN 09-MT:2015/BTNMT) and the WHO standard. The pH value in the qp_{2-3} aquifer groundwater in this study area was relatively higher than that of Ba Ria - Vung Tau province (pH 6.0-7.3) [37] but lower than that in Can Tho City (pH 6.69-8.22) [38] and Ca Mau Peninsula (pH 6.75-9.18) [39]. The pH of groundwater in Hau Giang did not fluctuate much over time when compared with the quality in the period of 2017-2019 [40] and not over the range of 6.5-8.5 to be toxic to humans [41]. From that, it was found that the groundwater in the study area has a suitable pH for drinking purposes.

Table 2. Seasonal variations of groundwater quality in the Middle-Upper Pleistocene (qp_{2-3})

No.	Parameter	Unit	May			October			Limit values	
			Mean ± SD	Min	Max	Mean ± SD	Min	Max	Vietnam*	WHO
1	pH	-	7.05±0.33[a]	6.75	7.58	6.87±0.22[a]	6.72	7.24	5.5-8.5	7-8
2	TDS	mg/L	185.01±402.50[b]	0.66	905	1236±889.43[a]	370	2600	1500	600-1,000
3	TH	mg/L	460±386.63[a]	192	1120	971.20±744.79[a]	254	1870	500	200
4	PI	mg/L	3.10±1.93[a]	0.77	5.28	7.02±6.65[a]	0	16.08	4	-
5	NH_4^+-N	mg/L	1.22±1.22[a]	0.04	2.54	1.09±0.85[a]	0.25	2.04	1	0.2
6	NO_2^--N	mg/L	0.01±0.01[a]	0	0.02	0.01±0.03[a]	0	0.06	1	0.9
7	SO_4^{2-}	mg/L	81.60±37.61[a]	42	125	149.24±156.87[a]	13.4	326.14	400	250
8	Cl^-	mg/L	731.40±806.74[a]	18	1823	1212.34±1333.27[a]	12.76	3155	250	250
9	Fe	mg/L	1.74±0.69[a]	0.86	2.65	1.91±2.14[a]	0	5.21	5	0.3

*National technical regulation on groundwater quality (QCVN 09-MT:2015/BTNMT); If a and b are in the same row, there is a statistically significant difference (p<0.05) and vice versa.

Total dissolved solids (TDS) in the groundwater of the qp_{2-3} aquifer fluctuated largely between the two monitoring periods. In May, the TDS concentration ranged from 0.66 mg/L to 905 mg/L, averaging 105.01±402.50 mg/L. In October, the average TDS value increased 12 times (p<0.05) to 1,236±889.43 mg/L with a fluctuated range of 370–2,600 mg/L, in which three and one groundwater samples exceeded the QCVN 09-MT:2015/BTNMT standard and WHO standard, respectively. High TDS content can be influenced by industrial and domestic wastewater [33, 38]. Consuming groundwater with high TDS content can cause cardiovascular and kidney diseases [42]; thus, the groundwater in this area might only be suitable for agricultural irrigation purposes, especially in the areas where TDS content ranges from 1,000-3,000 mg/L [33]. In nearby study areas, the TDS levels in groundwater were also high and tended to exceed the Vietnamese allowable limit, including Ca Mau Peninsula (TDS 8,089 mg/L) [39], Ba Ria-Vung Tau (TDS 10,220 mg/L) [37], and Soc Trang province (TDS 8,055 mg/L) [43]. The high TDS can be attributed to the presence of high concentrations of HCO_3^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, and Cl^- ions in groundwater [33, 42].

Total hardness (TH) is mainly from Ca^{2+}, Mg^{2+}, carbonates, sulfates, and chlorides of calcium and magnesium salts [4]. According to the monitoring period, the TH concentration in the groundwater of aquifer qp_{2-3} in Hau Giang province had a dramatic fluctuation, ranging from 192-1,120 mg/L, reaching an average of 460±386.63 mg/L in May to 254-1,870 mg/L with an average of 971.20±744.79 mg/L in October. However, this fluctuation was not statistically significant between the two monitoring periods (p>0.05). In May, there was one groundwater sample (20%) and four groundwater samples (80%), with TH higher than the Vietnam threshold and WHO standard, respectively. In October, the number of groundwater samples increased to three (60%) and five (100%), with TH content exceeding Vietnamese and WHO's allowable limits, respectively. Compared with other areas in the Mekong Delta in recent years, the groundwater qp_{2-3} aquifer in Hau Giang province has a higher TH content than that in Ca Mau Peninsula (TH 10-1,164.8 mg/L) [39] and Can Tho City (35.50±14.77-150.19±58.69 mg/L) [38]. The classification of groundwater based on TH shows that the qp_{2-3} aquifer in Hau Giang province belongs to hard to very hard water [9]. Apart from domestic and industrial wastewater sources, high TH in groundwater could also result from rock layers [22, 42]. Therefore, direct use of qp_{2-3} aquifer in the study area may negatively affect human health since TH levels greater than 300 mg/L adversely affect human health, such as kidney problems and kidney stone formation [33].

Permanganate index (PI) is one of the main physicochemical parameters for assessing groundwater pollution from dissolved organic impurities [44, 45]. PI values from the qp_{2-3} groundwater monitoring stations ranged from 0.77–5.28 mg/L (an average of 3.10±1.93 mg/L) and 0-16.08 mg/L (an average of 7.02±6.65 mg/L) at the monitoring times of May and October, respectively. Despite the statistical analysis showing no significant change in the permanganate index over time (p>0.05). It was found that 40% of groundwater samples (2 wells) exceeded the Vietnamese allowable limit at both times of the year, with higher PI contamination in October up to four times of the standard. These findings, consistent with the TDS values, indicate a high level of organic pollution in October. Moreover, the contribution of unsanitary solid waste management to organic groundwater pollution [45, 46] is a serious concern.

Nitrogen compounds are one of the most prominent pollutants in groundwater, which are partly from soil organic nitrogen but mainly originated from human activities such as fertilizer use in agriculture [1, 9, 47]. According to the analysis results, the qp_{2-3} aquifer groundwater in the study area tended to be contaminated with NH_4^+-N in both periods of 2022, exceeding the recommended limits of Vietnam and WHO (Table 2). Nevertheless, the concentration of NH_4^+-N in the qp_{2-3} aquifer in 2022 tended to decrease compared to the period 2017-2019 [40]. In May, NH_4^+-N concentrations fluctuated in the range of 0.04-2.54 mg/L, reaching an average of 1.22±1.22 mg/L and in October, the NH_4^+-N concentrations fluctuation of 0.25-2.04 mg/L was observed with an average of 1.09±0.85 mg/L. The concentration of NH_4^+-N in the qp_{2-3} aquifer in this study was lower than those from previous studies in similar areas: Ba Ria-Vung Tau (5.18±14.98-5.4±12.81 mg/L) [37], Ca Mau Peninsula (up to 3.68 mg/L) [39] and Soc Trang province (up to 10.8 mg/L) [43]. NH_4^+-N does not directly affect human health, but it will have negative effects on humans when ammonium is converted into nitrite and nitrate. For NO_2^--N, the concentration in the aquifer qp_{2-3} of the study area was very low, within the allowable limit of QCVN 09-MT:2015/BTNMT and WHO standard, ranging from 0-0.06 mg/L. There was no statistically significant between the two monitoring periods (p>0.05). Low NO_2^--N concentrations in groundwater were also observed in some other study areas, such as Tongchuan in China [9] and Soc Trang province in Vietnam [43].

The concentration of SO_4^{2-} in groundwater qp_{2-3} aquifer in Hau Giang province fluctuated over time, the difference. In May, the range of SO_4^{2-} concentration was 42-125 mg/L with an average of 81.60±37.61 mg/L, whereas the wider range of 13.4-326.14 mg/L with a higher average of 149.24±156.87 mg/L was observed in October. However, the difference between the two sampling periods is insignificant ($p>0.05$), and the values were still within the allowable limits. According to Ramesh & Thirumangai (2014) [4], SO_4^{2-} concentration greater than 150 mg/L can cause irritation to the human gastrointestinal tract. Thus, using groundwater at GW4 (SO_4^{2-} 326.14 mg/L) and GW5 (SO_4^{2-} 314.26 mg/L) may negatively affect human health. Compared with previous data in the same area, SO_4^{2-} concentrations in qp_{2-3} aquifer observed in this study are higher than the observation in 2017-2019 [40]. In addition, SO_4^{2-} concentration in groundwater in the study area tended to be higher than the coastal areas of Bengkalis city (25-62 mg/L), Chota Nagpur plateau (14-97 mg/L) and Koyra (2.24-85.16 mg/L) [11, 12, 41]. SO_4^{2-} can be naturally present in groundwater from the weathering of sulfate minerals and gypsum-containing sedimentary rocks [12] or it can come from the use of fertilizers, domestic wastewater consisting of chemicals such as cleaning agents [4, 48, 49]. It should be noted that the rainy season in Vietnam also plays a role in higher SO_4^{2-} concentrations in groundwater [38].

The fluctuation range of Cl^- in the qp_{2-3} aquifer increased from 18-1,823 mg/L in May to 12.76-3,155 mg/L in October, resulting in an increase of the average value from 731.40±806.74 to 1,212.34±133.27 mg/L. Even though the difference of the average Cl^- concentrations was not statistically significant between both periods (p>0.05), 60% of groundwater samples (GW2, GW3 and GW5) from both sampling times had Cl^- concentrations higher than the safe recommendation of 250 mg/L. As observed in previous parameters, the Cl^- concentration in the qp_{2-3} aquifer in Hau Giang province tended to increase over time 40]. Status of high Cl^- concentration in groundwater has been reported in some other study areas, such as Pallavaram area in Chennai Metropolitan City (Cl^- up to 6747 mg/L) [4], Chota Nagpur plateau (Cl^- 347 mg/L) [11] and Can Tho city (Cl^- 382.30 mg/L) [38]. Cl^- contamination can originate from detergent-containing wastewater, soil leaching and seawater intrusion [4, 22, 41]. Therefore, consuming groundwater with high Cl^- in the study area can result in some negative effects on humans, such as increased blood pressure, especially the increased risk of stroke and kidney failure in patients with heart and kidney disease [4]. In addition, if used for irrigation, water with a high Cl^- content can be harmful to plants [22].

Fe concentration in qp_{2-3} aquifer in the study area ranged from 0.86-2.65 mg/L (1.74±0.69 mg/L as an average) and 0-5.21 mg/L (1.91±2.14 mg/L as an average) during the May and October, respectively. Statistical analysis results showed no difference in the Fe content between both months (p>0.05). The Fe content of the qp_{2-3} groundwater samples in Hau Giang province did not exceed the Vietnamese allowable limit; however, it was up to 17 times higher than the WHO standard, suggesting bad water quality. Using water with this high Fe content could decrease lung function and affect reproduction [41, 50]. In water supply and distribution systems, high Fe oxidation causes unpleasant water, pipe rust and well blockage [50]. Similar to other analyzed parameters in this study, the Fe content is higher than that observed from 2017-2019 [40]. However, the groundwater in this study has a relatively lower Fe concentration than other areas including Chota Nagpur plateau (6.32±5.18-7.69±5.12 mg/L) [11], Can Tho city (0.69±0.52-2.71±13.45 mg/L) [38], Ba Ria-Vung Tau (1.7±1.5-3.0±4.8 mg/L) [37].

3.2. WPI for Groundwater Quality Evaluation

On the basis of WPI, the water pollution index in this study area has shown a gradual decrease from May to October at all locations (Figure 3). In particular, the water quality of GW1 and GW4 was ranked as excellent to good in both monitoring periods. On the other hand, GW2 and GW3 were heavily polluted and unsuitable for drinking purposes during this time. In May, GW5 was classified as moderate water quality; however, the quality level of GW5 had dramatically declined to a value of 2.58 in October. Cl^- and TH were causes of the variation of WPI at all monitoring locations. Therefore, the quality of groundwater in most of the areas of Hau Giang province (i.e., GW2 and GW3) was heavily contaminated and unsuitable for domestic purposes.

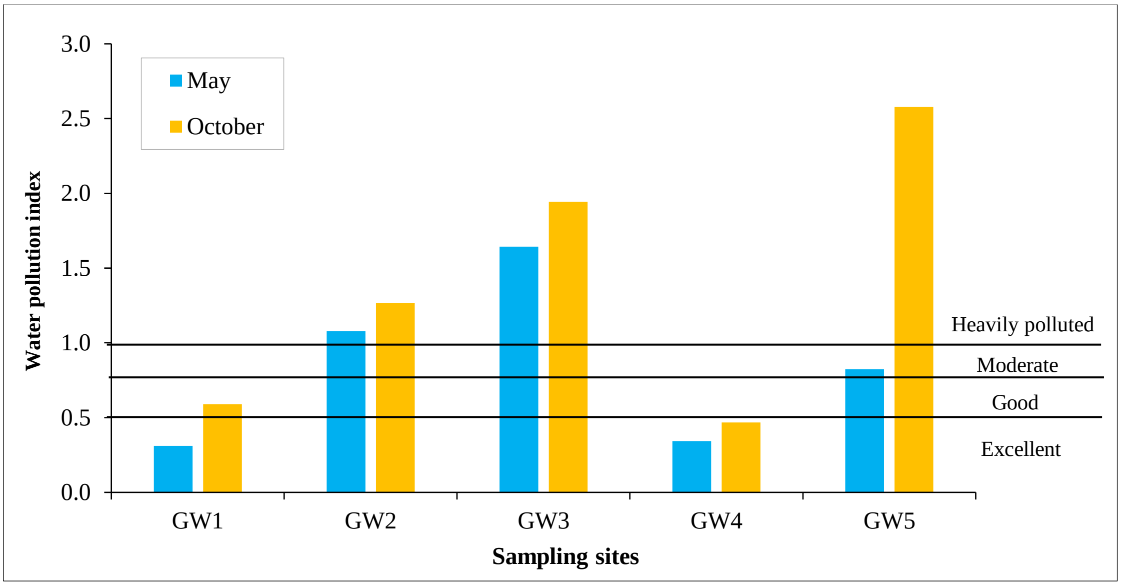

Figure 3. Variation of water pollution index (WPI) in Hau Giang province

3.3. Evaluating Groundwater Quality Using GWQI

The groundwater quality index is an assessment that reflects the cumulative effects of water quality parameters, which is useful for assessing groundwater quality for drinking purposes [22]. The calculation of GWQI considers each parameter's weight, thus minimizing errors in calculation. The general map of groundwater quality according to the calculated GWQI is presented in Figure 4. In May, the groundwater quality was classified as excellent (GW1 and GW4), poor (GW2), and unsuitable for drinking (GW3 and GW5). GW1 showed the lowest GWQI value 10, which means that the groundwater at this location has the best quality. On the other hand, both GW3 and GW5 locations showed the highest GWQI value of 114. In October, the GWQI at groundwater monitoring stations fluctuated between 39-101, dividing groundwater quality into four categories: good (GW4), poor (GW3 and GW5), very poor (GW1) and unsuitable for drinking (GW2). According to Elemile et al. (2021) [13], GWQI with "excellent" quality is suitable for drinking purposes, while "good" quality can be suitable for drinking purposes with appropriate treatment measures. From the GWQI analysis, the quality of groundwater in the $qp_{2\text{-}3}$ aquifer in Hau Giang province tended to decrease over time of monitoring. This can be clearly observed by the decrease in groundwater quality at GW1 (from excellent to very poor quality) and GW4 (from excellent to good), in which only the groundwater at the GW4 borehole had the quality suitable for drinking purposes in October. For other locations, the decrease in GWQI at GW2 was from poor to unsuitable for drinking, and the groundwater quality at GW3 and GW5 tended to be slightly improved in October (from unsuitable for drinking to poor quality). However, the groundwater quality at these two locations was assessed as unsuitable for drinking purposes throughout the monitoring period. This was similar to the study of Minh et al. (2023) [14] in Can Tho City, which found that the GWQI was usually at a high level (>100). Likely to WPI, the fluctuation of groundwater quality from GWQI was also suggested by the variations of TH, PI, NH_4^+-N and Cl^- in high concentrations over the monitoring period, which should be the pollutants of concern for groundwater resource management in this area. In general, the results of the indices' calculation illustrate that GW3 was the most contaminated and GW5 showed considerable fluctuation in the year.

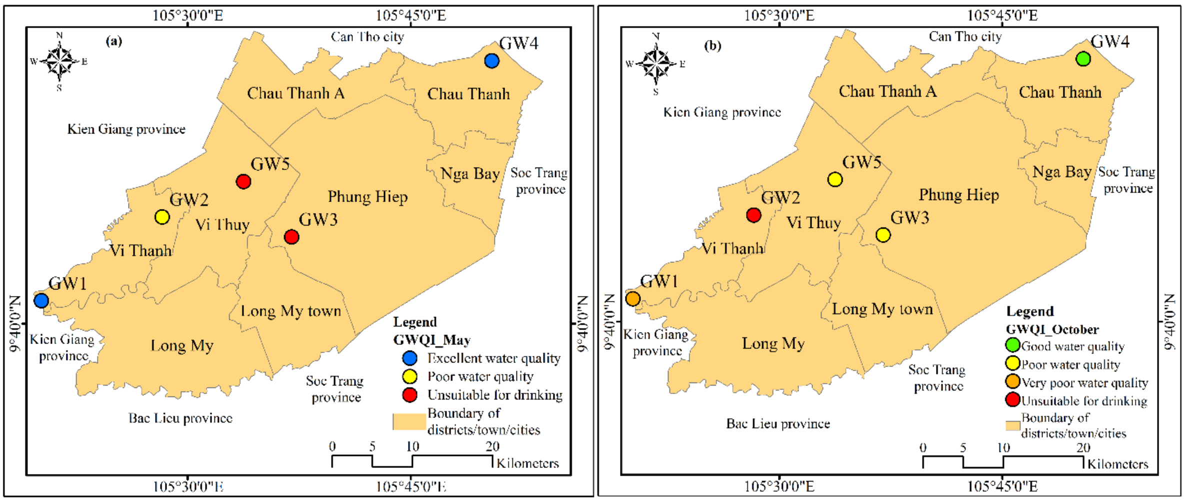

Figure 4. Demonstration of change of GWQI in (a) May and (b) October

The results of cluster analysis of groundwater monitoring stations at the time of monitoring in May and October were presented in the form of dendrogram (Figure 5). Groundwater samples with similar water quality were grouped into the same cluster and differed in separate groups [5, 6, 36]. From the CA results, four water quality groups were classified in May and October, but the difference of samples in each group for both months could be observed. In May, Group IV was considered the group with the most polluted groundwater quality, the same as the GWQI of GW3, which showed the highest value this month. GW2 was characterized with GW5 into group III, which both have poor and unsuitable for drinking quality, respectively. Consists of GW2 and GW5 with concentrations of some pollutants higher than the recommended limit of QCVN 09-MT:2015/BTNMT. It should be noted that the groundwater samples in these two groups had higher TH, PI, NH_4^+-N and Cl^- than the standards of Vietnam. Lastly, groups I and II had the best groundwater quality, comprising GW1 and GW4, respectively. Groups I and II had relatively low concentrations of pollutants and were still within the allowable limit of Vietnam standards. In October, group II represented the best groundwater quality at the GW4 location. Group I comprises the samples at GW1 and GW2, which showed high contamination of Cl^-, NH_4^+-N and TH. Groups III and IV represent a separate position of GW3 and GW5, respectively. This is slightly different from the GWQI that showed the same water quality for both locations in October. This could be due to the difference in contaminant contribution in both groups. Group III was contributed by TDS, TH, PI and Cl^-, whereas group IV was contaminated by the contribution of TH, PI, SO_4^{2-} and Cl^-. From the CA results, it can be seen that some groundwater locations could be considered in the same group according to their water quality parameters. This information can be useful for considering the area for groundwater resource management during different times of the year in the future.

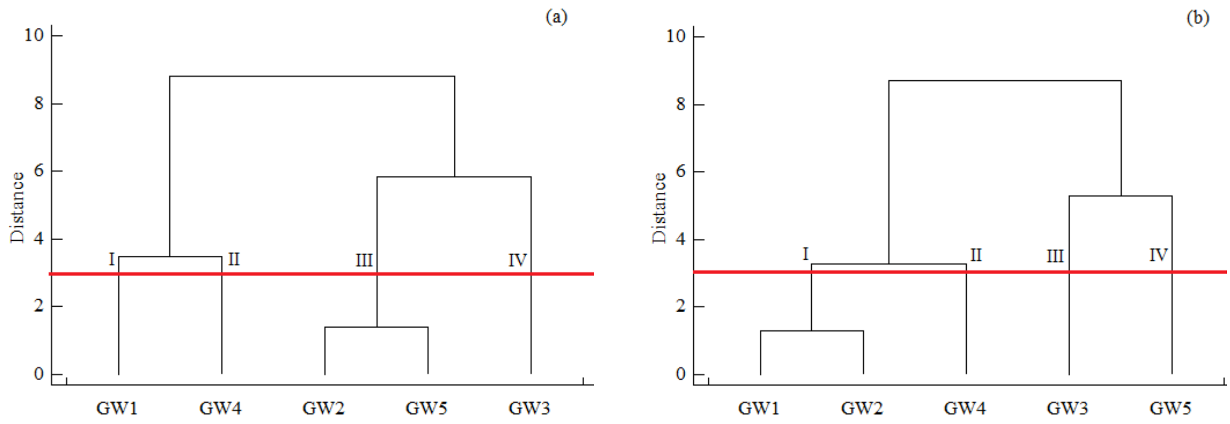

Figure 5. Clustering groundwater quality in May (a) and October (b)

3.4. Potential Sources of Groundwater Variations

In this study, the principal component analysis method was performed based on the data of nine groundwater parameters, including pH, TDS, TH, permanganate index, NH_4^+-N, NO_2^--N, SO_4^{2-}, Cl^-, and Fe. The results of PCA analysis extracted the main components (PCs) of the set of environmental variables that had the most significant impact on groundwater quality [5]. Typically, PCs with Eigenvalues greater than 1 are retained to explain the variability of environmental quality datasets [5, 6, 12]. According to the Scree plots (Figure 6), three PCs were significant and explained about 79.55% of the total variance of groundwater quality variation. It can be seen that the first PC set the most critical environmental variables with a high correlation coefficient with PC. The subsequent PCs explain other important environment variables that were not shown in the previous PC. According to Elemile et al. (2021) [13], the correlation between environmental quality variables and the main component is based on factor load and is divided into three levels, namely strong (0.75), medium (0.75-0.5), and weak (0.5-0.3). In this study, factor loads greater than 0.5 were considered important [51]. From there, it helps to identify pollution sources in the study area that can change groundwater quality.

Since three PCs could explain most of the total variance (about 79.55%), it is indicated that there are at least three main pollution sources affecting the qp_{2-3} groundwater quality in the study area (Table 3). The observed variances for PC1, PC2 and PC3 were 46.11%, 20.17%, and 13.27%, respectively. The study results showed that PC1 positively correlated with groundwater variables TDS, TH, PI, NO_2^--N and Cl^- with the factor loading of 0.533, 0.968, 0.930, 0.682 and 0.955, respectively. Agricultural, industrial and domestic waste discharge activities and landfilling in the study area may contribute to contaminating these pollutants [36, 52]. Besides that, the impact of saline intrusion leads to the formation of large amounts of Cl^- in groundwater [8, 52, 53]. This could be explained by the fact that saltwater intrusion was complicated in Hau Giang province; the highest salinity was 6‰ in surface water [54]. High TDS concentration in groundwater was closely related to Cl^- concentration, which was strongly influenced by saline intrusion [8, 42]. PC2 was positively correlated with SO_4^{2-} (0.590), whereas NH_4^+-N and Fe are negatively correlated with PC2, with factor loading coefficients of -0.944 and -0.628, respectively. The source of SO_4^{2-} has been widely detected in natural water and contamination was found from the oxidation of SO_4^{2-} in fertilizers and wastewater [49, 52]. PC3 was positively correlated with pH (0.840). Nevertheless, the pH value in groundwater in the study area was mainly neutral. The PCA results showed that the observed groundwater variables pH, TDS, TH, permanganate index, NH_4^+-N, NO_2^--N, SO_4^{2-}, Cl^- and Fe significantly influenced the change of groundwater quality in qp_{2-3} aquifer. The source of groundwater pollution in the study area could derive from manufactured sources, such as domestic, agricultural and industrial wastewater, landfilling and some natural factors, such as saline intrusion. Therefore, it is necessary to limit the generation of artificial pollution sources to minimize groundwater pollution in the study area in the future.

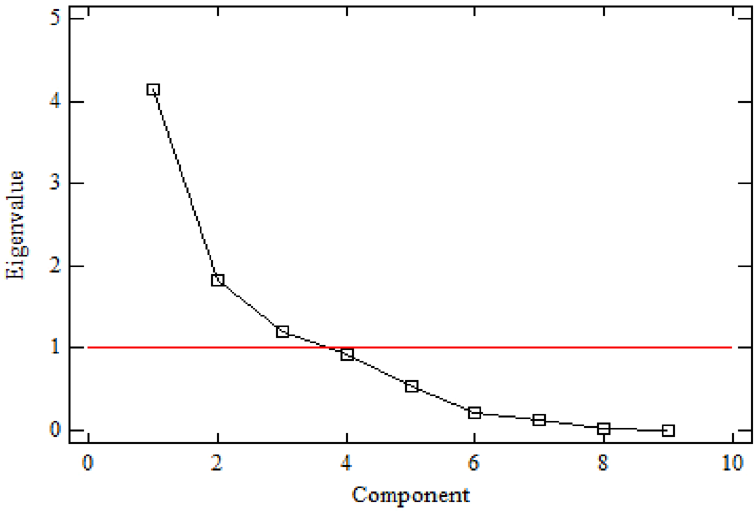

Figure 6. Scree plots with PCs having Eigenvalues > 1

Table 3. Potential sources and key parameters influencing groundwater

Variables	PC1	PC2	PC3
pH	0.107	0.267	**0.840**
TDS	0.533	0.259	-0.743
Total hardness	0.968	0.067	-0.124
Permanganate index	0.930	0.258	-0.098
NH_4^+-N	0.018	-0.944	0.107
NO_2^--N	0.682	0.408	0.424
SO_4^{2-}	0.196	0.590	0.084
Cl^-	0.955	0.108	0.067
Fe	-0.246	-0.628	-0.282
Eigenvalues	4.15	1.82	1.19
% Variance	46.11	20.17	13.27
Cum. %Variance	46.11	66.28	79.55

4. Conclusion

The groundwater of the qp_{2-3} aquifer in Hau Giang province has been contaminated with TDS, NH_4^+-N, PI, and Fe. According to WPI, around 40% of the total groundwater samples were of excellent quality. However, based on GWQI, the groundwater quality deteriorated over sampling time, and not more than 20% of the groundwater had good quality for drinking. Groundwater quality was classified into four categories by CA. PCA could extract 3 PCs, which explains 79.55% of the total variations in groundwater quality. PCA revealed that three potential sources of pollution could affect groundwater quality, including wastewater, landfilling, and seawater intrusion, in which nutrients have contaminated groundwater resources. It was suggested that appropriate actions should be taken to improve groundwater quality.

5. Declarations

5.1. Author Contributions

L.D.K. and P.Q.N. contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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