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Application of Integrated-Weight Water Quality Index in Groundwater Quality Evaluation

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Abstract

Groundwater is one of the most crucial freshwater resources in many parts of the world. However, the growth of the population and different economic activities have negatively impacted groundwater quality. This study aims to assess the groundwater quality in An-Giang province, Vietnam, from 2017–2020 and investigate its suitability for drinking via a new integrated-weight water quality index (IWQI). The samples were collected at thirteen wells in dry and rainy seasons and analyzed for eleven physicochemical parameters, including pH, total dissolved solids (TDS), total hardness, nitrate (NO_3^-), ammonium (NH_4^+), iron (Fe), manganese (Mn), arsenic (As), mercury (Hg), lead (Pb), and coliform. These values were compared to the Vietnamese standard. The entropy weight method and the Criteria Importance Though Inter-criteria The correlation weighting method was integrated to compute the weights in IWQI. The results showed that NH_4^+ and coliform concentrations were consecutively higher than the standard over the study period. No detection of As, Hg, and Pb concentrations in groundwater was in 2019 – 2020. There were significant statistical differences between parameters from 2017–2020 in the dry and rainy seasons. The results of IWQI revealed that about 40% of the total samples in 2020 were categorized as unsuitable for drinking. IWQI values range from 72 to 7973 in 2020, 12 to 3020 in 2019, 21 to 1115 in 2018, and 53 to 2246 in 2017. Most samples with high IWQI values are located near the burial pits of African fever-infected swine. The findings of this study could provide further information about the changes in groundwater quality from 2017–2020 in An Giang province, Vietnam, and the IWQI method can be proposed for other studies to evaluate groundwater quality effectively.

Keywords: Coliform; Groundwater; Integrated-Weight Water Quality Index (IWQI); An-Giang (Vietnam).

1. Introduction

Billions of people around the world depend on groundwater as an indispensable freshwater source [1–4]. In fact, half of drinking water sources are groundwater [5], and it also provides approximately 20% of total irrigation water [6]. Groundwater has been used in Vietnam as a reliable source of high-quality potable water for over a century [7, 8]. Its important role is even more emphasized in the context of widespread surface water pollution caused by human activities, such as industrial and agricultural wastewater, over-application of fertilizers, and domestic wastewater. However, the quantity and quality of groundwater are threatened to deteriorate seriously. Groundwater in Burdur plain in Turkey had Mn, NO_3^-, and total hardness concentrations exceeded the permissible limits of WHO, which prevented this water source from drinking and household activities. The degradation of groundwater is attributed to natural processes and anthropogenic activities [7–9]. There were 20% of the total groundwater samples in Ojoto with high heavy metal contamination, hence unsuitable for human consumption [10]. Groundwater in Soc Trang province, a coastal region of Vietnam, was reported with high levels of NO_3^- (>50 mg/L) and Cl^- (1000 mg/L) [11]. In several provinces in Vietnam,

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high coliform and Cl^- concentrations were found in groundwater [7, 12]. As a result, 80% of human diseases, such as diarrhea, typhoid, and skin infections, are associated with long-term water consumption [10, 13, 14]. Therefore, it is required to a deeper understanding of groundwater quality status and its suitability for drinking or other purposes.

Groundwater quality assessment has been studied by different methods. The conventional approach compares individual parameters to the national or international standard, which is considered ineffective for large data sets, consumes time and effort, and misses important information [15, 16]. Many studies have introduced the water quality index (WQI) as an effective method to overcome these aforementioned limitations. It is a dimensionless number based on the composite effects of various parameters, which classify water quality into different classes [2, 15-17]. Based on the results of WQI, groundwater in Can Tho, Vietnam, was determined to have excellent status [18], and some parts of the coastal area were classified as unsuitable for any purpose [11]. Previous studies have applied this index to assess groundwater quality; however, the results are considered subjective since the weights are commonly assigned by experts or scientists [19]. The weights determine the importance of each analyzed parameter in overall water quality [15-17]. Thus, even small changes in these values will significantly affect the final WQI values and explain the water quality status.

Further methods have been developed and applied to enhance the objectivity of the weights in WQI and the overall groundwater quality assessment accuracy. Several studies suggest that information entropy is deemed an alternative method to calculate the weights. Entropy-weight water quality index (EWQI) classified groundwater quality in southeast North China Plain into 2 main groups (good and poor quality) [20] and determined over 50% of the groundwater samples in south India to be medium quality [21]. The results obtained from EWQI are promised to be more objective and accurate. However, they are affected by the changes in the size and value of data and do not examine the conflict between water parameters [22-24]. To tackle these limitations of EWQI, the Criteria Importance Though Inter-criteria Correlation (CRITIC) weighting method has been employed in many studies [25]. This weighing calculation is based on two rudimentary concepts: contrast intensity is demonstrated in the form of standard deviation that can reveal the value variation between the different assessment schemes of the similar parameter, and the conflict between the parameters is expressed by the correlation between these parameters [23, 24]. Over 94% of groundwater samples in a semi-arid area of China were considered suitable for drinking using WQI with the CRITIC weighing method. However, only a few studies have employed the CRITIC theory in WQI to evaluate groundwater assessment. The strengths of these two weighing theories (i.e., entropy and CRITIC) were combined in the study of Zhang et al. (2021). The effectiveness of an integrated-weight water quality index (IWQI) in terms of objectivity and accuracy is confirmed in interpreting and assessing groundwater quality [21]. Thus, it is necessary to apply this approach to further groundwater quality assessment in different regions rather than using a separate weighting method.

An Giang province is situated in Mekong Delta, Vietnam, where people depend on groundwater resource to serve domestic demand, irrigation, or other production activities. Due to the degradation of surface water quality, the demand of using groundwater is especially increasing in the study area [26-28]. According to Minh et al. (2019), groundwater extracted from the shallow aquifers in An Giang province was considered poor quality, which are associated with high As concentration from 2009 – 2018 [8]. Consuming As-contaminated groundwater in this area can pose a medium to high cancer risk for both local children and adults [28]. Giao (2021) reported that groundwater in An Giang was seriously contaminated by NH_4^+, coliform, and *E. coli* due to burying swine that infected African swine fever in 2019 [12]. To the best of our knowledge, there is no study in the region that has applied the IWQI to assess groundwater quality comprehensively. The evidence suggests that it is necessary to have practical studies on seasonal variations in groundwater quality assessment, which helps to develop solutions to preserve this water resource for future use. The primary objectives of this study are to evaluate seasonal changes in groundwater quality in the four years and assess the overall suitability of groundwater quality for drinking using IWQI based on entropy and CRITIC weighing in An Giang province, Vietnam.

2. Materials and Methods

2.1. Study Area

An Giang is the southwestern upstream province of the country and the Lower Mekong River, and also one of four provinces in the key economic region of the Mekong Delta. The total natural area is 353,668.02 ha. The province has 11 administrative units: Long Xuyen city, Chau Doc city, Tan Chau town, An Phu, Phu Tan, Cho Moi, Chau Phu, Chau Thanh, Thoai Son, Tinh Bien, Tan Chau, and Tri Ton districts. The plains occupy about 87% of the provincial natural area including alluvial plains and montane plains. About 89% of the province's population lives in these plains. The elevation gradually lowers from the northeast to the southwest with a height difference of 0.5 - 1 cm/km. Land in mountainous areas is mainly gray soil, poor in nutrients, poor in water retention, and prone to drought and erosion. An Giang is located in the tropical monsoon area, with steamy weather all year round. There are rainy and dry seasons, relatively high and stable temperatures, abundant rainfall, and seasonal distribution.

In addition to the integration process of the country, the free trade agreements have created many opportunities for the economic development of An Giang province. Accordingly, An Giang province can access export markets, and advantageous local products are facilitated for development, especially agriculture, fisheries, industry, and tourism services. Implementing the socio-economic development plan for the year 2016-2020, the total product in the area is estimated in 2020 (at 2010 constant prices) to increase by 2.69% over the same period last year, much lower than the increase of the previous year (in the same period in 2019 increased by 7.04%). A primary reason is the negative impact of the Covid-19 epidemic, which is also the lowest increase in recent years. The agriculture, forestry, and fishery sector increased by 2.46% and contributed 0.92% to the overall growth. Industry-construction sector increased by 6.54% and accounted for 0.96% of the overall growth. The service sector increased by only 1.65% (in 2019 increased by 7.10%) and contributed 0.732% to the total growth [29]. Therefore, at this rate of economic development, this has led to an increased demand for water and affects the quality of the environment, especially groundwater.

2.2. Sampling Locations and Analyzing Groundwater Quality Parameters

Groundwater samples in An Giang were collected in 13 monitoring wells from 2017 – 2020, as presented in Figure 1. These samples were collected in March and September, representing the dry and rainy seasons, respectively. Each groundwater sample was analyzed for eleven parameters, including pH, total dissolved solids (TDS), total hardness, nitrate (NO_3^-), ammonium (NH_4^+), iron (Fe), manganese (Mn), arsenic (As), mercury (Hg), lead (Pb), and coliform. Only pH parameter was measured on-site, while other parameters were analyzed at the Environmental Monitoring Center of An Giang province according to the standard methods [30]. In addition, one-way analysis of variance (ANOVA) was applied to determine the significant difference in seasonal variations of groundwater parameters with the Ducan test using SPSS software (version 20.0, USA).

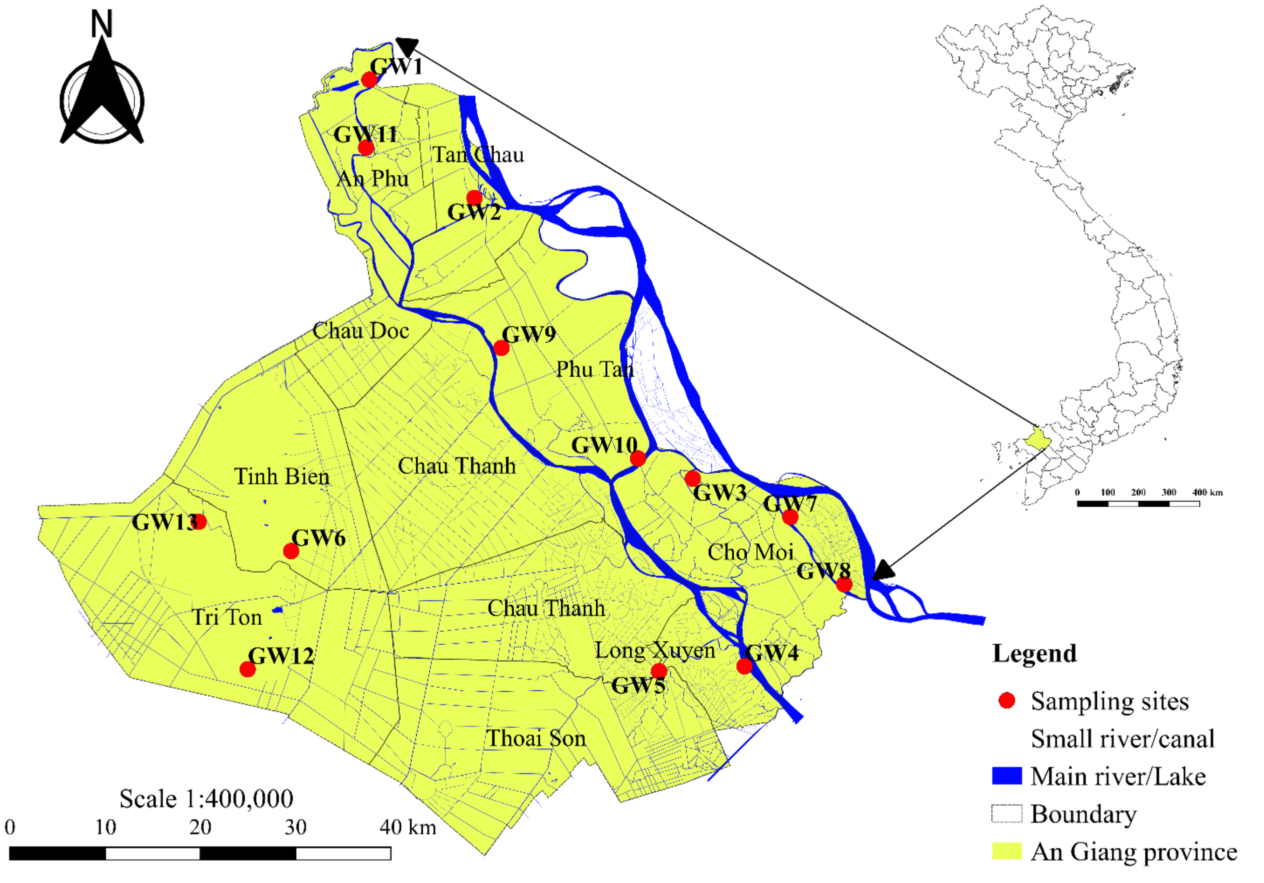

Figure 1. Sampling locations in An Giang province

2.3. Integrated-Weight Water Quality Index (IWQI)

The calculation of IWQI in this study is generally divided into 5 steps: entropy weighting calculation, CRITIC-based weighting calculation, computation of integrated weights, integrated-weight water quality index, and groundwater quality assessment based on the results of WQI. The general framework of this process is illustrated in Figure 2.

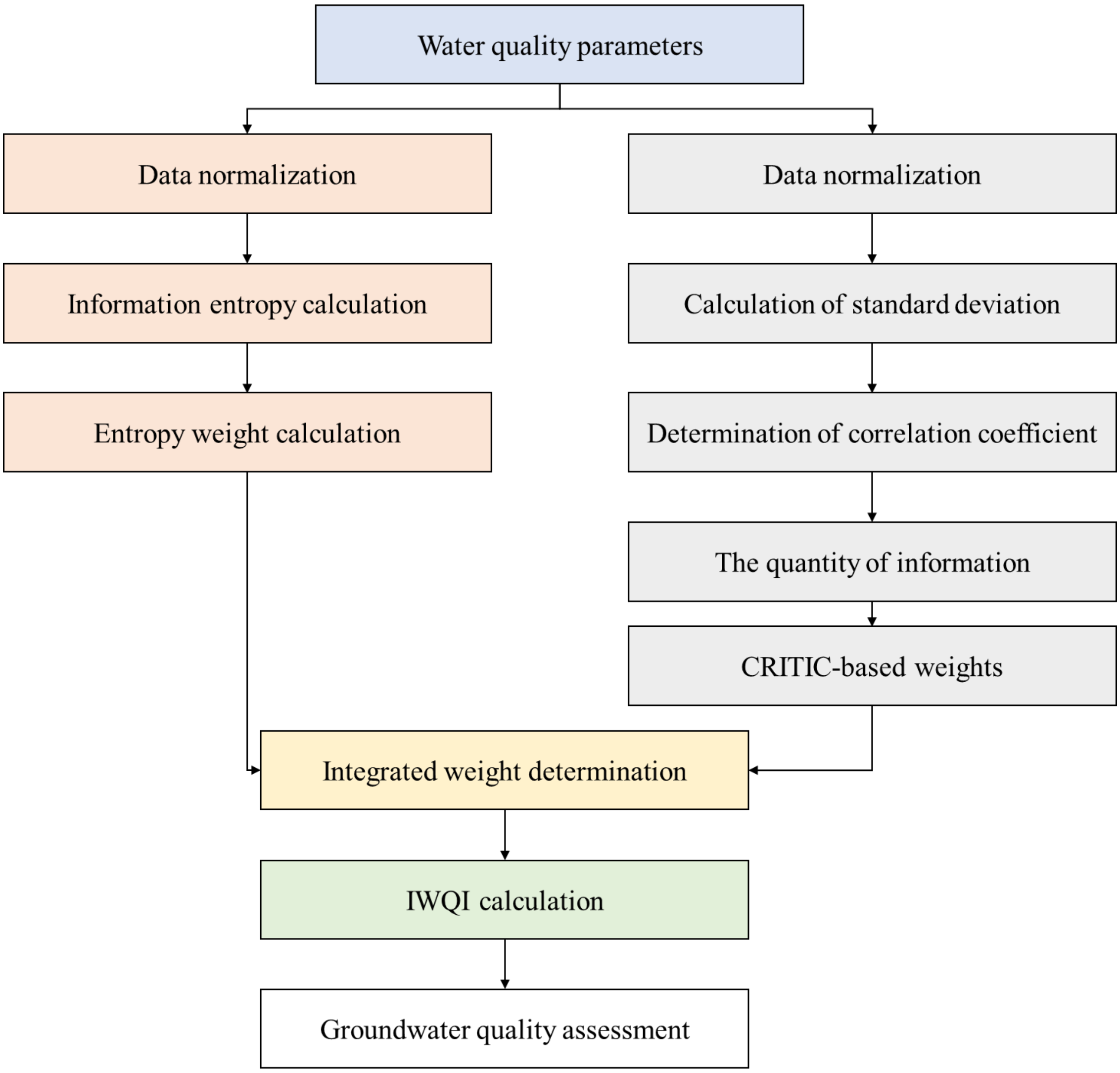

Figure 2. The general framework of groundwater quality assessment based on IWQI

2.3.1. Weight Calculation based on the Entropy-Weighted Method

Entropy was introduced by Shannon to objectively show important information on the basis of original data [31]. The entropy weight (wj_1) is calculated based on the following steps:

Step 1: Normalize the initial matrix (X) using as Equation 1:

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \tag{1}$$

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

The standardized value (y_{ij}) is calculated using Equation 2:

$$y_{ij} = \frac{x_{ij} - (x_{ij})_{min}}{(x_{ij})_{max} - (x_{ij})_{min}} \tag{2}$$

After that, the standard matrix is presented in Equation 3:

$$Y = \begin{bmatrix} y_{11} & \cdots & y_{1n} \\ \vdots & \ddots & \vdots \\ y_{m1} & \cdots & y_{mn} \end{bmatrix} \tag{3}$$

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

Step 2: Compute the information entropy (e_j) using Equations 4 and 5:

$$e_j = -\frac{1}{lnm}\sum_{i=1}^{m} y_j lny_j \quad (4)$$

$$y_j = \frac{y_{ij} + 10^{-4}}{\sum_{i=1}^{m}(y_{ij}+10^{-4})} \quad (5)$$

Step 3: Obtain entropy weight (w_{j1}) using Equation 6:

$$w_{j1} = \frac{1-e_j}{\sum_{j=1}^{n}(1-e_j)} \quad (6)$$

2.3.2. Weight Computation using CRITIC Method

Criteria importance through inter-criteria correlation (CRITIC) approach was employed to calculate the relative weights of parameters objectively. The weights of parameters are calculated [22], as follows:

$$w_{j2} = \frac{s_j}{\sum_{j=1}^{m} s_j} \quad (7)$$

$$s_j = \delta_j \sum_{j=1}^{m}(1 - r_{ij}) \quad (8)$$

$$r_{ij} = \frac{\sum(x_{ij}-\overline{x_{ij}})(y_{ij}-\overline{y_{ij}})}{\sqrt{\sum(x_{ij}-\overline{x_{ij}})^2 \sum(y_{ij}-\overline{y_{ij}})^2}} \quad (9)$$

where, w_{j2} is the weight of the j^{th} parameter, s_j is the quantity of data for the jth parameter, δ_j is the standard deviation of j^{th} parameter after normalizing, r_{ij} is the correlation coefficient, $\overline{x_{ij}}$ is the average value of x_{ij}, and $\overline{y_{ij}}$ is the mean value of y_{ij}.

2.3.3. Calculation of Integrated Weight

The integrated weight (W_j) is computed according to the study of Zhang et al. (2021) [22], as shown in Equations 10 to 12:

$$W_j = pw_{j1} + (1-p)w_{j2} \quad (10)$$

$$p = \sum_{j=1}^{m}\left[\left(w_j - w_{j1}\right)^2 + \left(w_j - w_{j2}\right)^2\right] \quad (11)$$

$$w_j = \frac{w_{j1} \times w_{j2}}{\sum_{j=1}^{m} w_{j1} \times w_{j2}} \quad (12)$$

where, p is considered the preference coefficient.

2.3.4. Integrated-Weight Water Quality Index (IWQI)

IWQI values are calculated using the integrated weights as follows:

$$IWQI = \sum_{i=1}^{n} W_j Q_j \quad (13)$$

$$Q_j = 100 \times \frac{V_o - V_j}{S_n - V_j} \quad (14)$$

where, n: the number of parameters, W_j: unit weight for the j^{th} parameter, Q_j: the quality rating of the j^{th} parameter, V_o: the observed value of j^{th} parameter at a certain monitoring site; V_j: the ideal values which are considered "0" for drinking water except pH. In the case of pH, V_j is 7.0 (neutral pH) and S_n is 8.5.

The groundwater quality is categorized into five classes based on the results of IWQI computation [7, 22], as listed in Table 1. The spatial variation of IWQI is presented using the Arcgis version 10.2 software. It is based on interpolation with the inverse distance weighted method.

Table 1. The classification of groundwater quality using IWQI values

IWQI	Classification	Class
0 – 50	Excellent	I
50 – 100	Good	II
100 – 200	Poor	III
200 – 300	Very poor	IV
>300	Unsuitable for drinking	V

3. Results and Discussion

3.1. General Groundwater Characteristics from 2017 – 2020

The analysis results of parameters to evaluate groundwater quality in An Giang province in the period of 2017 – 2020 are presented in Table 2. These values are compared to the Vietnamese technical regulation of groundwater quality (QCVN 09-MT:2015/BTNMT). The average pH values of thirteen sampling wells in 2017 and 2018 were 2.97 ± 0.15 and 6.92 ± 0.16, respectively. These values slightly increased in the following years, by 7.04 ± 0.12 in 2019 and 7.20 ± 0.11 in 2020. The average pH values of groundwater in this study area during this period were within the permissible ranges of Vietnamese regulation (5.5 – 8.5). The current results are in agreement with the previous studies in other provinces nearby: Soc Trang province ranged from 6.64 – 7.83, with an average of 7.18 ± 0.34 [7], and Can Tho city had pH values of 6.69 - 8.22 in the rainy season and 7.14 – 7.64 in the dry season [18]. These pH variations are suitable for human activities.

Table 2. Groundwater quality parameters in An Giang province from 2017 – 2020

Parameter	Unit	2017		2018		2019		2020		Vietnamese standard*
		Mean±SD	Range	Mean±SD	Range	Mean±SD	Range	Mean±SD	Range	
pH	mg/L	6.97±0.15	6.8-7.3	6.92±0.16	6.7-7.2	7.04±0.12	6.9-7.3	7.20±0.11	7.0-7.4	5.5-8.5
TDS	mg/L	1302±868	265-2975	1870±1175	611-3487	1184±663	544-2668	678±139	463-925	1500
Hardness	mg/L	433±222	138-814	706±357	306-1278	423±276	78-1000	557±291	241-1323	500
NO_3^-	mg N/L	0.17±0.20	ND-0.6	0.20±0.44	ND-1.6	0.38±0.51	ND-1.32	0.75±1.16	ND-2.9	15
NH_4^+	mg N/L	1.04±1.23	0.07-4.6	1.70±1.90	0.03-4.9	4.38±3.70	0.15-15	2.95±2.43	0.04-6.4	1
Fe	mg/L	0.85±1.75	ND-6.2	1.17±1.59	0.2-4.9	1.31±2.42	ND-7.63	0.45±0.64	ND-2.3	5
Mn	mg/L	1.19±1.52	ND-5.3	1.68±2.29	ND-7.8	1.06±1.15	ND-351	0.38±0.55	ND-1.5	0.5
As	mg/L	0.04±0.12	ND-0.4	0.03±0.03	ND-0.1	ND	ND	ND	ND	0.05
Hg	mg/L	ND	ND	ND	ND	ND	ND	ND	ND	0.001
Pb	mg/L	ND	ND	0.02±0.03	ND-0.1	ND	ND	ND	ND	0.01
Coliform	MPN/100 mL	108±163	5.7-465	48±72	ND-230	108±206	ND-762	224±585	ND-2150	3

* Vietnamese technical regulation of groundwater quality (QCVN 09-MT:2015/BTNMT)

The average value of TDS in 2018 was 1870 ± 1175 mg/L, which is higher than in 2017 (1302 ± 868 mg/L), 2019 (1184 ± 663 mg/L) and 2020 (678 ± 139 mg/L) and over the permissible limit of TDS in groundwater (1500 mg/L). Although the average values of TDS in the remaining years are within this permissible level, about 23.1% and 30.8% of total sampling wells exceeded the limit in 2017 and 2019, respectively. The TDS values in groundwater were significantly reduced in 2020, ranging from 463 – 925 mg/L. TDS concentration of groundwater in the study area tends to decrease over time. Several studies showed that high TDS values in groundwater could be attributed to different sources, such as percolating domestic and industrial wastewater, agricultural runoff, dissolution, and leading of mineral-bearing rocks and soils [32, 33]. TDS concentration in groundwater in Soc Trang province, a coastal area in the Mekong Delta, was from 82 – 12,950 mg/L in 2017 – 2018 due to the effects of saltwater intrusion [34]. It is consistent with high values of TDS found in Ca Mau Peninsula from 300 – 24,750 mg/L since groundwater extracted from the $qp_{2\text{-}3}$ aquifers contains a lot of dissolved substances, such as Ca^{2+}, Mg^{2+}, Cl^-, HCO_3^-, SO_4^{2-}, and Na^+ [16].

The average value of hardness in groundwater was 433 ± 222 mg/L in 2017 and then increased to 706 ± 357 mg/L in 2018. In the next two years, this value dropped to 423 ± 276 mg/L in 2019 and 557 ± 291 mg/L in 2020. The percentages of groundwater samples exceeding the permissible limit (500 mg/L) were 23.1% in 2017, 61.5% in 2018, 38.5% in 2019, and 46.2% in 2020. Although the hardness of groundwater has reduced, it is still higher than the permissible limit in 2020. During 2009 – 2018, the average hardness of groundwater in An Giang province was reported from 234 – 958 mg/L in the dry seasons and 270 – 1763 mg/L in the rainy season [8]. In Soc Trang province, the total hardness ranged from 13 – 3080 mg/L in 2017 – 2018, and locations with high total hardness values were detected in shallow aquifers [11]. The precipitation of minerals in rocks and soils can be responsible for releasing calcium and magnesium salts into groundwater, which leads to high total hardness concentration [2, 11].

The average concentrations of NO_3^- from 2017 – 2020 were within the limited point of the regulation for groundwater (15 mg N/L). There was a slight increase in the average NO_3^- concentrations between monitoring wells over time. These values were 0.17 ± 0.20 mg N/L in 2017, 0.20 ± 0.44 mg N/L in 2018, 0.38 ± 0.51 mg N/L in 2019, and 0.75 ± 1.16 mg N/L in 2020. NO_3^- concentration was found during 2017 – 2020 to be lower than the permissible limit. It is consistent with the results of previous studies in this area. For example, according to Giao (2021), NO_3^- concentration of monitoring wells in An Giang province ranged from 0.01- 2.96 mg N/L in 2020 [12]. From 2009 to 2018, the average NO_3^- concentration of groundwater samples in An Giang province fluctuated from 0.08 – 3.96 mg

N/L in the dry seasons and 0.03 ‑ 10 mg N/L in the wet seasons [8]. However, a very high NO_3^- concentration in groundwater was reported in Soc Trang province ranging from 0.1 ‑ 260 mg/L, which is the result of anthropogenic activities, such as aquacultural wastes, landfill leachates, and agricultural wastes [11]. Moreover, NO_3^- concentration in Ca Mau Peninsula was in the range of 0.24 ‑ 12.16 mg/L [16]. It can be seen that NO_3^- concentration in this study area is generally lower than in other regions in the Mekong Delta.

The average NH_4^+ concentrations were found to be increased from 2017 – 2019 and exceeded the permissible limits of NH_4^+ in groundwater (1 mg N/L). It includes 1.04 ± 1.23 mg N/L in 2017, 1.70 ± 1.90 mg N/L in 2018, and 4.38 ± 12.18 mg/L in 2019. Although the average NH_4^+ concentrations in 2020 (2.95 ± 2.43 mg/L) were lower than in 2019, it was still higher than the permissible limit. There were about 23.1%, 46.2%, 69.2%, and 61.5% of total sampling wells with average NH_4^+ concentrations that exceeded the limited point for groundwater from 2017 – 2020, respectively. Notably, NH_4^+ concentrations in 2019 between monitoring wells greatly fluctuated from 0.15 mg N/L (at GW13) to 12.18 mg N/L (at GW1). High NH_4^+ concentrations of groundwater in An Giang province were also reported by Giao (2021), with the range of 0.05 – 10.4 mg N/L [12]. According to Minh et al. (2019), average NH_4^+ concentrations were ranged from 0.43 – 3.17 mg N/L in the dry seasons and 0.23 – 2.83 mg N/L in the wet seasons from 2009 to 2018 [8]. It is prevalent that NH_4^+ concentration is lower than 0.2 mg/L in groundwater under aerobic conditions, whereas this concentration can be increased over ten times under anoxic conditions [8]. Therefore, high NH_4^+ concentration in groundwater is caused by anthropogenic activities, including the excessive application of fertilizer, septic tank leakage, domestic and livestock wastewater, and aquacultural waste [12, 13].

The average concentrations of Fe between sampling wells from 2017 – 2020 were generally complied with the regulation of Fe concentration in groundwater (5 mg/L). However, this concentration was detected as higher than the limit in some wells, including GW11 (6.22 mg/L) in 2017, and GW1 (5.55 mg/L) and GW11 (7.63 mg/L) in 2019. It is similar to the findings of Minh et al. (2019) that Fe concentrations of groundwater in An Giang province from 2009 to 2018 were within the permissible limits [8]. In 2016 – 2018, Fe concentration in groundwater tended to rise from 0.81 – 2.19 in Soc Trang province, but it is still within the permissible limit [35]. In addition to artificial sources, the dissolution of iron-bearing rocks is also another primary source of Fe in groundwater [2].

The average concentration of Mn in 2017, 2018, and 2019 were 1.19 ± 1.52, 1.68 ± 2.29, and 1.06 ± 1.15 mg/L, respectively, which exceeded the permissible limit of Mn in groundwater (0.5 mg/L). Meanwhile, the average Mn concentration in 2020 was 0.38 ± 0.55 mg/L that was lower than the permissible limit. The highest percentage of sampling wells exceeding Mn limit in groundwater was found in 2017, with the rate of 69.2%. Only 5 out of 13 sampling wells, accounting for 38.5%, had Mn concentration in 2020 higher than the limit. Similar to Fe, Mn is also present in different types of rocks; therefore, the fact is that water passes through these mineral-bearing rocks and dissolute Mn into groundwater [2]. Moreover, other sources such as industrial effluent, landfill leachate, and sewage leakage also contribute to Mn in groundwater.

There was no detection of As concentration in groundwater at all sampling wells from 2019 – 2020. Before that period, As concentrations were found to be below the detection limit of 0.44 mg/L in 2017 and 0.09 mg/L in 2018. However, the concentrations of As were over the permissible limit (0.05 mg/L) found at GW11 (0.44 mg/L) in 2017, and GW1 (0.09 mg/L) and GW11 (0.08 mg/L) in 2018. As concentration in this study was only detected in 2017 – 2018. It is consistent with the results of Minh et al. (2019) that As concentration detected in groundwater in An Giang province during 2009 – 2018, ranging from 0.01 – 0.06 mg/L in the dry seasons and from 0.002 – 0.84 mg/L in the wet seasons [8]. Also, there was a decrease in As concentrations over time in that study [8]. The average As concentration in the period of 2009 – 2016 varied from 0.004 – 0.55 mg/L in An Giang province [28]. As, a toxic metalloid, can cause adverse effects on humans, particularly cancer for humans [34, 36]. Due to the characteristic of the Mekong Delta that is young and naturally rich sediments, it created anaerobic conditions, which resulted in the release of Fe, Mn, and As concentrations in groundwater [37, 38]. However, in recent years, there was a decrease in As concentration in groundwater associated with reduced sediment deposition in the Mekong Delta [8]. Young Quaternary deltaic and alluvial sediments can contain As, and the building of hydropower plants in the upper Mekong River has prevented these sediments from flowing down to the lower areas [8, 39].

The concentrations of Hg and Pb were below the detection limits from 2017 – 2020, with the exception of Pb in 2018. The average concentration of Pb in that year was 0.02 ± 0.10 mg/L, which was higher than the permissible limit (0.01 mg/L). There were 6 out of 13 monitoring wells having Pb concentrations that exceeded the limit in 2018, accounting for 46.2%. Previous studies in the region have not analyzed Hg [8, 11, 12]. The maximum concentration of Pb was detected in Soc Trang province by 2.50 μg/L [2]. The presence of Pb in groundwater is attributed to improper treatments for domestic and industrial effluents and combustion of fossil fuels of machine engines; that is, Pb particles can be released into the air and then follow raindrops falling into the groundwater [40].

Coliform concentrations in sampling wells were extremely high during 2017 – 2020 and higher than the permissible limit of coliform in groundwater (3 MPN/100mL). All analyzed groundwater samples in 2017 had coliform concentrations exceeding the limit, with the range of 5.70 – 465 MPN/100mL. After that, the percentage of sampling well with a higher limit of coliform was about 69.2% in 2018, with the range of no detection to 230 MPN/100mL. However, the number of wells contaminated by coliform increased to 12 and 11 out of 13 wells in 2019 and 2020, respectively. The highest coliform concentration in groundwater (2,150 MPN/100mL) was found at GW2 in 2020, which was over 700 times higher than the permissible limit. Heavily polluted groundwater by coliform in An Giang was also reported in former studies. For instance, the average coliform concentration in groundwater from 2009 – 2016 was 693.6 ± 543 MPN/100mL in An Giang province [28]. The presence of coliform in groundwater may indicate this water source is contaminated by septic tank leakage, livestock wastewater, and wild animal droppings via unprotected wells. This is because these wells were improperly covered or abandoned wells did not cap correctly. High coliform in groundwater was detected where wells located in the swine buried areas due to African swine fever in An Giang was also reported ranging from 9 – 9300 MPN/100mL [12]. In addition, burying pigs during the 2019 epidemic led to a higher concentration of coliforms in groundwater in 2019 - 2020 than in previous years.

3.2. Temporal Variation of Groundwater Quality during 2017 – 2020

Box-and-Whisker plots for the variation of groundwater quality in the dry season are presented in Figure 3. In the dry season, the variations of pH, hardness, NO_3^-, Fe, Mn, As, Pb, and coliform during the period of 4 years were not a significant difference ($p>0.05$). There were significant statistical differences over time in terms of TDS and NH_4^+ ($p<0.05$). The data range of TDS was significantly wider in 2018 than other years, with the range of 327.4 – 6078 mg/L. Also, a significant difference of NH_4^+ was found in 2019, with a wide range of data from 0.08 – 23.1 mg N/L. The seasonal variations in As, NO_3^-, pH, NH_4^+, and Fe was previously described [8].

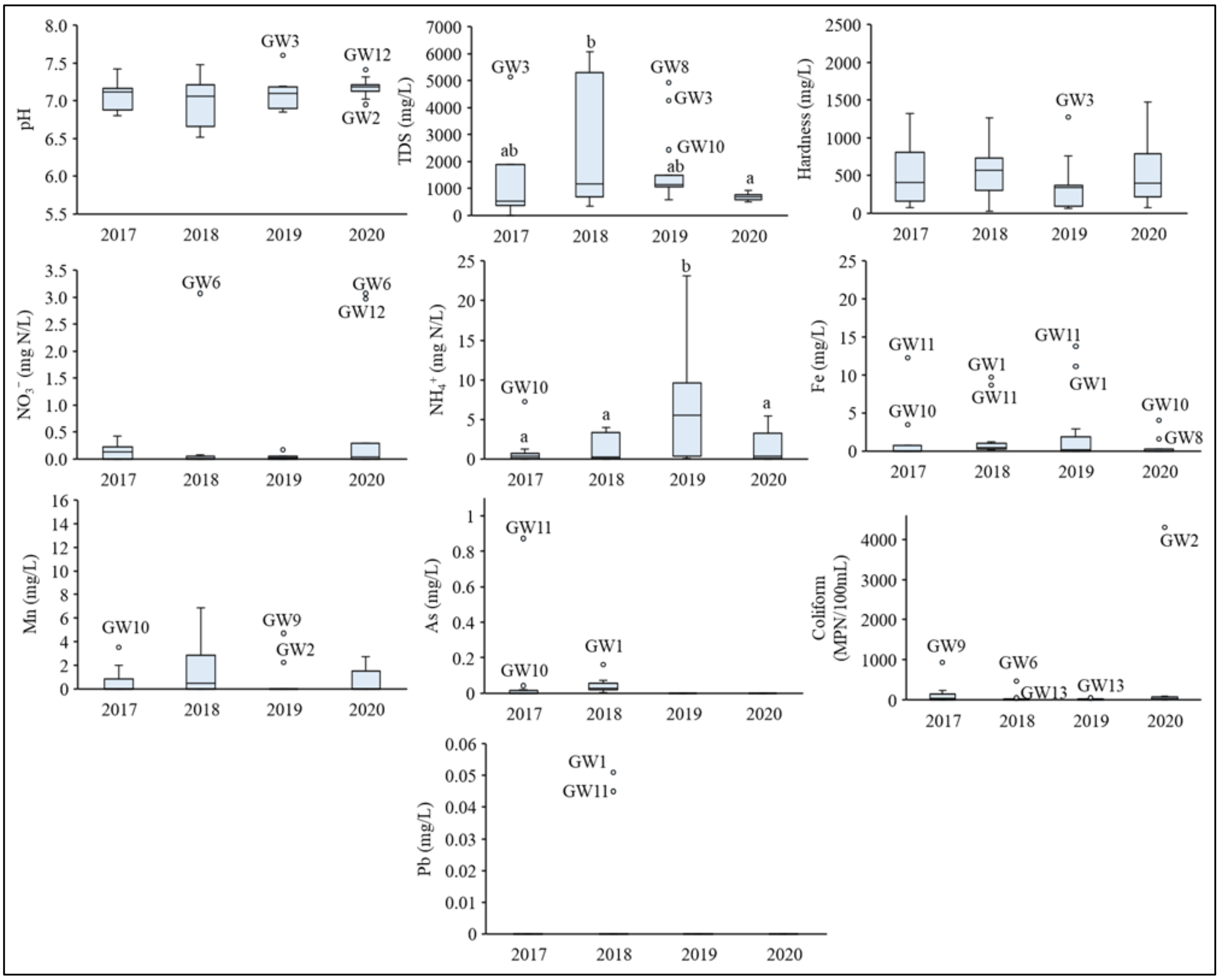

Figure 3. Box-plot graph for the variation of groundwater quality parameters in the dry season during 2017 – 2020. Different letters (a, b, c) represent significant differences at a significant level of 5%

The variations of groundwater quality parameters in the rainy season 2017 – 2020 using the Box-and-Whiskers graphs are illustrated in Figure 4. These variations of pH, TDS, hardness, NH_4^+, and Pb were significantly different. The wider data range of pH was found in 2019 ranging from 6.80 – 7.38, while this higher data range was observed in 2020 from 6.87 – 7.58. The data range of TDS was significantly wider in 2017 than in other years, ranging from 1.46 – 2634 mg/L. Following that year, the data range of hardness in groundwater was considerably greater, with the range of 218.8 – 1290 mg/L. It is similar to the dry season that the data range of NH_4^+ in the rainy season was detected wider in 2019. Another significant difference between years in the rainy season was found in terms of Pb in 2018 since there was no detection of Pb in other years.

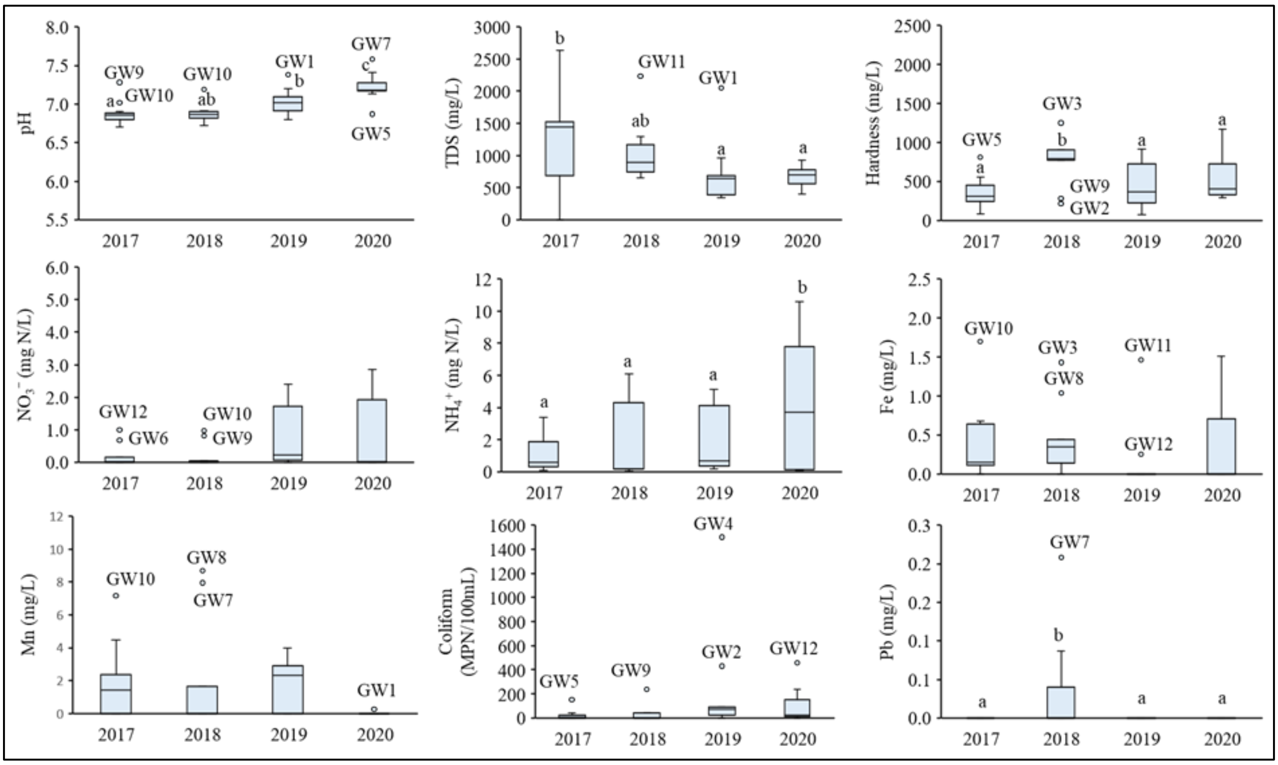

Figure 4. Box-plot graph for the variation of groundwater quality parameters in the rainy season during 2017 – 2020. Different letters (a, b, c) represent significant differences at a significant level of 5%

Furthermore, it is notable that the groundwater quality parameters seasonally fluctuated during 2017 – 2020. TDS and hardness tend to be higher in the dry season during this period of time, except for 2020 that TDS values were seemed to be stable between dry and rainy seasons. In contrast, greater NO_3^- and NH_4^+ concentrations in groundwater were detected in the rainy season from 2017 – 2020, excluding the concentration of NH_4^+ in 2019. Fe and As concentrations were higher in the dry season, but there was no detection of As in 2019 and 2020. In addition, Mn can be found throughout the year. The detection of coliforms in both dry and rainy seasons was also observed, especially in some monitoring wells having very high coliform in the dry season.

It can be seen that groundwater quality in this study was seasonally fluctuated in the period of 4 years. While TDS, hardness, Fe, and As concentration tends to be higher than in the dry season, NO_3^- and NH_4^+ concentrations are lower in this season. The study of Giao (2021) showed that very high NO_3^- and NH_4^+ concentrations of some wells in An Giang province were found in June and September which are in the rainy season of this area [12]. It is also similar to the results of Minh et al. (2019) conducted in An Giang from 2009 – 2018 [8]. During the rainy season, the amount of runoff increases, which brings nitrogen compounds from fertilizer residues and other nitrogen sources into the groundwater. Although high coliform in groundwater can be detected throughout a year, some wells had a very high coliform concentration in the dry season. According to Anh and Giao (2018), there was no great seasonal fluctuation of coliforms in groundwater from 2009 – 2016 [28]. However, Giao (2021) reported the coliform density of groundwater in An Giang province in the dry season (15 – 2,300 MPN/100mL) was significantly more than that in the rainy season (9 – 230 MPN/100mL) [12]. The primary source of coliform in groundwater is related to human activities such as livestock and aquacultural wastes, leakage of septic tanks, degradation of deceased animals. Thus, it can cause consecutive impacts on groundwater quality during a year.

3.3. Integrated-Weight Water Quality Index

The IWQI values of each monitoring well and its rank from 2017 – 2020 are listed in Table 3. The results of IWQI calculation in 2020 are higher than previous years in this study area, ranging from 72 – 7973 with an average of 893. It includes 7.7, 38.5, and 15.4% of the total sampling wells categorized as good, poor, and very poor groundwater quality, respectively. There were 5 out of 13 sampling wells accounting for 38.5% that were considered unsuitable for drinking purposes. The IWQI values were ranged from 12 – 3020 in 2019, 21 – 1115 in 2018, and 53 – 2246 in 2017. According to Minh et al. (2019), high As concentration is the reason for the classification of poor groundwater quality in An Giang province during 2009 – 2018 [8]. However, it is inconsistent with the results of this study that could not detect As concentration in groundwater in 2019 – 2020, but the IWQI values of these years are very high. High coliform density is a decisive factor for higher IWQI values of groundwater in this study area. It is observed that coliform density has significantly increased over time. For example, the range of coliform density in 2017 was 5.70 – 465 MPN/100mL, which was accelerated to 2150 MPN/100mL in 2020. The evidence suggests that coliform contamination is a new rising problem for groundwater, which has resulted in the deterioration of groundwater and is unsuitable for drinking purposes. The results of IWQI in the study area are higher than in other regions. The entropy-weight water quality index calculated in Soc Trang ranges from 20 to 739 [7]. According to Zhang et al. (2020), the values of WQI of groundwater in a semi-arid area of China ranged from 21 to 967 [24]. In another study, the IWQI were calculated from thirteen parameters in the Jiaokou Irrigation District, China, ranging from 17 to 553 [22].

Table 3. IWQI values of monitoring wells from 2017 – 2020

Location	2017		2018		2019		2020	
	IWQI	Rank	IWQI	Rank	IWQI	Rank	IWQI	Rank
GW1	2211	V	194	III	239	IV	221	IV
GW2	290	IV	680	V	1003	V	7973	V
GW3	422	V	220	IV	332	V	101	III
GW4	138	III	60	II	3020	V	72	II
GW5	454	V	56	II	12	I	428	V
GW6	239	IV	1115	V	146	III	374	V
GW7	138	III	337	V	153	III	141	III
GW8	656	V	311	V	302	V	104	III
GW9	2246	V	684	V	255	IV	136	III
GW10	189	III	437	V	117	III	223	IV
GW11	227	IV	191	III	261	IV	169	III
GW12	53	II	21	I	506	V	1036	V
GW13	87	II	120	III	278	IV	632	V

Groundwater quality in this study area has changed over time based on the results of IWQI computation. Several sampling wells showed better groundwater quality, such as GW9 (reducing from 2246 in 2017 to 136 in 2020), GW6 (reducing from 1115 in 2018 to 374 in 2020), GW4 (reducing from 3020 in 2019 to 72 in 2020), and GW1 (reducing from 2211 in 2017 to 221 in 2020). One reason for this improvement is the effective policy of An Giang "Environmental Protection Planning of An Giang province to 2020" (Decision 1566/QĐ-UBND, 2011) about reducing the application of fertilizers in the agricultural practices and applying wastewater treatment systems for livestock and aquacultural activities [8]. In contrast with this trend, groundwater quality in some areas was deteriorated, seriously in GW2, GW12, GW13, and GW5. The IWQI values of these points in 2020 were 7973 (GW2), 1036 (GW12), 632 (GW13), and 428 (GW5), which constitutes an undrinkable water source. These sampling sites are located in Tan Chau and Tri Ton districts, and Long Xuyen city, where there were swine burial pits that appeared in 2019 due to African swine fever. It is not only groundwater but also surface water in An Giang province polluted by coliform and *E. coli* [12]. It can be seen that groundwater quality changes over time and encounter new rising problems; therefore, monitoring program should be conducted annually to promptly detect groundwater problems and then alleviate its impacts on human health and other groundwater-related activities.

The spatial distribution of groundwater classification based on the results of the IWQI calculation in the dry and rainy seasons from 2017–2020 is shown in Figure 5. It can be seen that there was a greatly seasonal variation in groundwater quality in the study area. In 2017–2018, groundwater in the rainy season tended to be better than in the dry season. A number of good and excellent groundwater samples were recorded in the southwest (GW6, GW12, GW13), southeast (GW4), and north (GW1) parts of the study area. The sampling points are located in mountainous areas (such as Tri Ton and Tinh Bien districts), An Phu district, and Long Xuyen city, where there are fewer human impacts. In 2019, only GW1 was recorded with groundwater quality that was unsuitable for drinking in the dry season. However, in the rainy season 2019, 7 out of 13 sampling sites with groundwater quality were classified as unsuitable for consumption, accounting for approximately 54% of total samples. There was only GW5 with excellent groundwater quality, and others were identified as good to unsuitable for drinking in this season. A wide geographical spread of undrinkable groundwater quality in the rainy season 2019 was continued until the dry season 2020. However, a small part of the southeast region was recorded with better water quality classified as excellent to poor. Then, this part was gradually extended to the north of the province, along with the Mekong River and the Bassac River. Many sampling wells (GW12, GW13, GW6, GW5, GW1) are located in An Phu, Tri Ton, and Tinh Bien districts, and Long Xuyen city is still classified as unsuitable for drinking purposes. It is because these wells are situated near the swine burial pits, thus being heavily contaminated by coliforms.

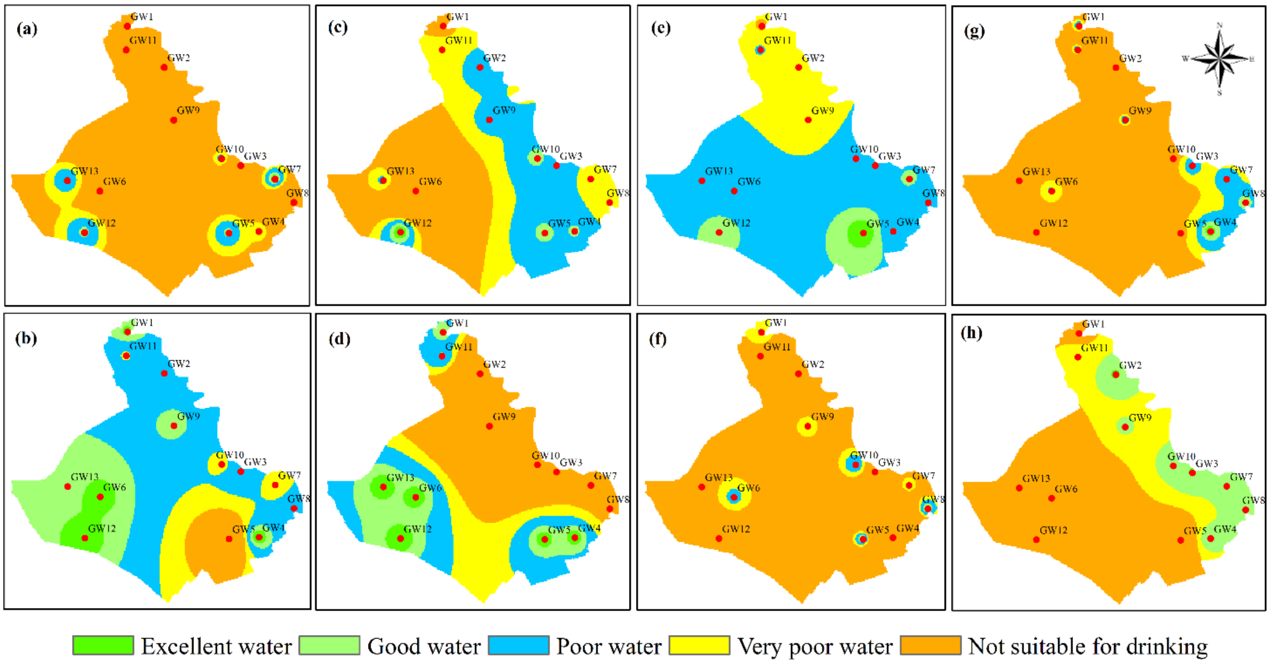

Figure 5. Spatial distribution map of groundwater categories based on the computed IWQI value in (a) dry season in 2017, (b) rainy season in 2017, (c) dry season in 2018, (d) rainy season in 2018, (e) dry season in 2019, (f) rainy season in 2019, (g) dry season in 2020, and (h) rainy season 2020.

4. Conclusion

This present study evaluated the groundwater quality in An Giang province from 2017 – 2020 by comparing to the Vietnamese standard and investigated the suitability of this water source for drinking purposes using a new integrated-weight water quality index (IWQI). The concentrations of NO_3^-, TDS, Fe, Mn in groundwater decreased gradually from 2017 – 2020 and within the permissible limits. There were no detections of As, Hg, and Pb in the last two years. However, NH_4^+ and coliform concentrations recorded in the study area were higher than the permissible limits during this time. Seasonal water quality fluctuations observed in the area: TDS and NH_4^+ variations had significant statistical differences over time in the dry season, and it happened to pH, TDS, hardness, NH_4^+, Pb in the rainy season. The results of the IWQI calculation showed that approximately 40% of total groundwater samples in 2020 were classified as unsuitable for drinking, and the IWQI values of this year were ranged from 72 – 7,973 and greatly higher than previous years. Although groundwater in some wells tends to be improved, such as GW9, GW6, GW4, and GW1, other wells (seriously in GW2, GW12, GW13, and GW5) become heavily polluted. This is associated with the rapid increase in the concentration of coliforms in groundwater during this period. In addition to the conventional reasons as septic tank leakage, wastewater of livestock, and aquacultural activities, burying African fever-infected swine in the province was the major reason for this spike. Groundwater plays an important role in local domestic and production activities, so it is essential to have timely and practical solutions to overcome this pollution.

5. Declarations

5.1. Author Contributions

Conceptualization, N.T.G. and P.K.A.; methodology, N.T.G.; software, H.T.H.N. and P.K.A.; validation, N.T.G., H.T.H.N. and P.K.A; formal analysis, P.K.A.; investigation, N.T.G.; resources, N.T.G.; writing-original draft preparation, N.T.G., P.K.A. and H.T.H.N.; writing-review and editing, N.T.G. and P.K.A.; visualization, H.T.H.N.; supervision, N.T.G.; project administration, N.T.G. 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 in the article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

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