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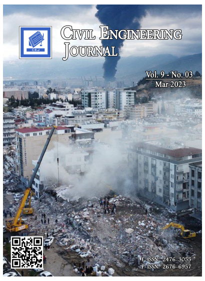

Characterization of Groundwater Quality and Human Health Risk Assessment

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Abstract

The study aimed to appraise groundwater quality in the Mekong Delta using a groundwater quality index (GWQI) and estimate human health risks associated with groundwater consumption. Groundwater samples were collected at sixty wells distributed in An Giang, Kien Giang, Hau Giang and Dong Thap provinces. Twelve water quality parameters were measured, including pH, total dissolved solids (TDS), hardness, coliform, nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), sulfate (SO_4^{2-}), iron (Fe), manganese (Mn), arsenic (As) and cadmium (Cd). The results were compared with the national regulation on groundwater quality. The findings of this study indicated that groundwater in the Mekong Delta was contaminated with microorganisms and some heavy metals (Fe, Mn, and As). This was related to anthropogenic activities, such as improperly treated domestic wastewater and agricultural and industrial wastes. Based on the results of GWQI, 30% of the total groundwater samples in the Mekong Delta were classified as very good for drinking purposes. However, over 26% of all samples were unsuitable for drinking. In terms of risk assessment, children were rather susceptible to cancer risks and adverse health effects through drinking As-contaminated groundwater than adults. The cancer risks of consuming As-contaminated groundwater for children and adults were up to 4.28×10^{-3} that is higher than the acceptable risk. The highest aggregate hazard quotient of heavy metal-contaminated groundwater for children and adults was 9.54, which means that they could suffer adverse health effects. Groundwater is an indispensable source of freshwater in the Mekong Delta; thus, home water treatments are recommended to protect public health, and an in-depth groundwater quality and health risk assessment should be conducted.

Keywords: Arsenic; Groundwater Quality Index; Health Risk Assessment; Mekong Delta; Microbiological Pollution.

1. Introduction

Groundwater is important for human use because of its abundance and high quality. In recent decades, it has been considered a main freshwater source, especially where surface water is polluted [1–3]. Moreover, it is a reliable and accessible source in arid, semi-arid, and coastal regions [4]. Previous studies have estimated that more than 50% of the population relies on groundwater to meet their daily needs [4, 5]. However, due to the impacts of overexploitation and anthropogenic activities, the quantity and quality of groundwater have been seriously impaired [4, 6]. The study by Idrees et al. indicated that heavy metal contamination of groundwater is alarming in some West U.P. regions of India [7]. The high concentrations of nitrate (NO_3^-) and zinc (Zn) in groundwater in North China were linked to human activities such as agricultural runoff and industrial wastewater [5]. In addition, climate change also negatively impacts groundwater [8]. The level of salinity in groundwater has increased due to seawater intrusion [9]. This degradation of groundwater quality seriously affects public health. Using unsafe water sources has caused serious waterborne diseases, including cholera, dysentery, and cancer [1, 3, 6]. In the UN World Water Day 2022, UNESCO introduced a campaign on "Groundwater: Making the invisible visible" to enlighten the roles of this hidden resource, which also

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contributes to achieving Sustainable Development Goal 6 (SDG) on water and sanitation [10]. Thus, assessing groundwater quality and associated health risks are necessary tasks in order to accomplish the worldwide water management strategy.

Water quality index (WQI), which was first introduced by Horton (1965), has been widely employed as an environmental tool to assess the suitability of groundwater for drinking [11–13]. The method allows large quantities of hydrochemical data to be combined into a single number in order to evaluate the overall groundwater quality. Many studies have effectively applied WQI to assess groundwater quality for drinking purposes in India [7] and China [12]. Moreover, only one dimensionless number obtained from WQI also helps to communicate groundwater quality to the public. The study of Adimalla & Venkatayogi (2020) categorized 60% of groundwater samples in central Telangana using WQI [13]. In India, the findings of the WQI ranging from 4.75 to 115.9 mean that the groundwater in this area is generally safe for drinking [7]. The results of the WQI are useful in supporting decision-making in the management of groundwater quality [12]. Hence, in this study, the WQI was applied to evaluate overall groundwater quality in the Mekong Delta.

The Mekong Delta is home to over 20 million people with a high demand for groundwater [14]. Local people have long exploited groundwater for drinking, irrigation, and other activities because of its good quality and availability. Moreover, groundwater does not require advanced treatments before use. As a result, the decline of groundwater levels for all aquifers in the Mekong Delta was reported at the rate of 0.01-0.55 m/year [15]. In An Giang province, groundwater is one of the primary water supplies for domestic activities and partly for irrigation; nevertheless, groundwater exploited from shallow wells in the north and south-east of An Giang during 2009–2018 was classified as "bad water" for drinking [16]. Aquifers in the lowland areas of the delta are susceptible to seawater intrusion [17]. In the coastal areas of the Vietnamese Mekong delta, serious coliform and NH_4^+ contamination was observed all year round [18]. Moreover, alum and toxic metal pollution have threatened groundwater in other parts because of human impacts [18–21]. Consuming polluted groundwater has posed human health risks for local people, especially arsenic. About 100 million people in south and Southeast Asia are constantly exposed to arsenic via its natural presence in groundwater [22]. The arsenic concentration found in groundwater in An Giang province ranged from 4.71-538.35 µg/L. As a result, the cancer risks calculated for adults and children ranging from 8.66×10^{-4} to 8.26×10^{-2} were far higher than the acceptable limit (10^{-6}) [20]. Another study reported the highest arsenic concentration in the region was up to 0.84±2.6 mg/L [16]. It can be seen that groundwater in the Mekong Delta is facing different stressors. However, the number of studies in the field is limited, which makes it difficult to make decisions in developing regional water management strategies. Therefore, this study is conducted to evaluate groundwater quality using GWQI and human health risks associated with groundwater consumption in the Mekong Delta. The findings can be used to understand groundwater sources and develop solutions for the sustainable management of water resources.

2. Materials and Methods

2.1. Site Description

The Mekong Delta, one of the two biggest deltas in Vietnam, is located in the southern part. It covers an area of about 40,547 km^2, accounting for 13% of the national area. The region has a tropical monsoon climate with two distinct seasons: rainy (April to November) and dry (December to March). An average temperature ranged from 27-30°C. Groundwater in the Mekong Delta is exploited in seven aquifers, including 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 Upper Miocene (n_{1-3}). The amount of groundwater in the area is relatively rich in shallow and deep layers, with a total potential exploitation reserve of pale groundwater of 22,512,989 m^3/day [15, 23]. The static gravity reserve is 21,283,182 m^3/day, and the elastic static reserve is 1,229,807 m^3/day. The safe reserve is 4,502,598 m^3/day. Currently, the qp_{2-3} layer is the most exploited and is considered to have a very large reserve [23]. The qp_{2-3} and qp_1 layers have up to 60% of exploiting wells. This floor also supplies water for most domestic and industrial water supply projects. Domestic supply wells are mainly at depths of 70 to 120 m, while ones for water supply plants are from 100 to 250 m deep [23, 24]. Nevertheless, overexploitation has negatively influenced the groundwater level and quality in the Mekong Delta.

An Giang, Dong Thap, Kien Giang, and Hau Giang provinces are the most populous provinces in the Mekong Delta. According to the General Statistics Office of Vietnam, the population of these provinces in 2022 was: 1,864,65 people in An Giang, 1,730,117 people in Kien Giang, 1,586,438 people in Dong Thap, and 728,255 people in Hau Giang. In addition, An Giang and Kien Giang are two of four provinces in the key economic region of the Mekong Delta. An Giang is the southwestern, upstream province of the country and the lower Mekong River. Its geographic coordinates are determined from 10°12’ to 10°57’ north latitude and 104°46’ - 105°35’ east longitude, with an area of 353,668.02 ha [16, 18]. Kien Giang has a natural area of 634,878 ha, from 9°32'20" to 10°32'26" north latitude and from 101°30’07" to 105°32’06" east longitude [25]. Dong Thap has a natural area of 338,380 ha. Hau Giang lies within the limits of 105°19’39" - 105°53’49" East longitude and 9°34’59" - 9°59’39" North latitude, with an area of 160,058.69 ha [26]. These provinces have long exploited groundwater for domestic activities and irrigation. Therefore, it is necessary to assess groundwater quality in the region and the human health risks associated with groundwater consumption.

2.2. Groundwater Sampling and Analysis

The flowchart shows one process by which the research is conducted (Figure 1).

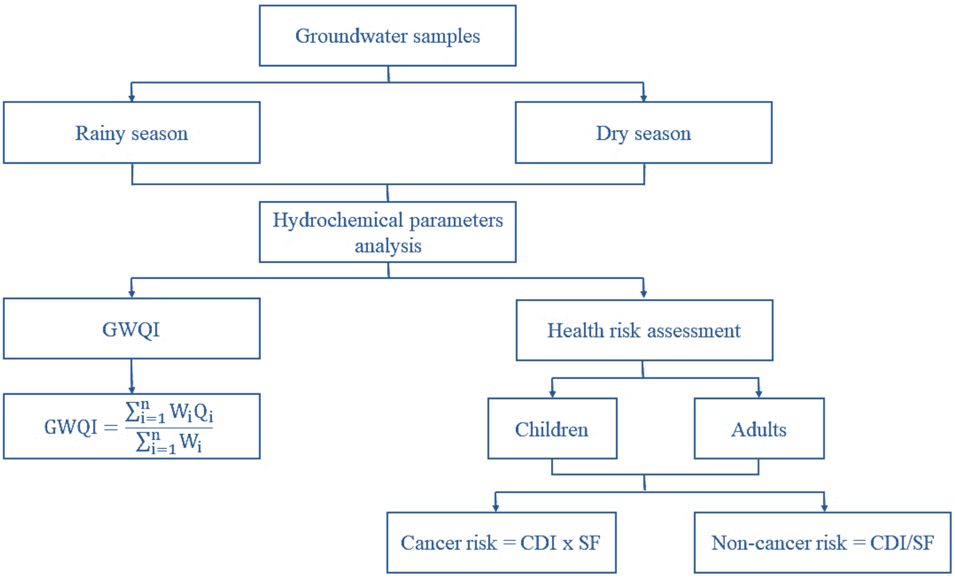

Figure 1. Flowchart of the study procedure in groundwater quality and human health risk assessment

Groundwater quality monitoring data in 2019 was collected in 4 provinces of the Mekong Delta: An Giang, Dong Thap, Hau Giang, and Kien Giang. The sampling locations are presented in Figure 2. The sample collection was conducted twice, in March–April (the dry season) and September (the rainy season). The sampling technique was carried out according to the national standard TCVN 6663-1:2011 (ISO 5667-1) [27]. The collected samples from 60 well observations were stored and preserved according to TCVN 6663-3:2003 (ISO 5667-3) [28]. Twelve physicochemical and biological parameters were analyzed, including pH, total dissolved solids (TDS), hardness, total coliform, nitrate (N-NO_3^-), nitrite (N-NO_2^-), ammonium (N-NH_4^+), sulfate (SO_4^{2-}), iron (Fe), manganese (Mn), arsenic (As), and cadmium (Cd). The pH and TDS parameters were measured in the field using PCD 650 (Eutech, Singapore), while the others were analyzed in the laboratory by standard methods [29]. The criteria, units, analytical methods, and allowable limits are presented in Table 1.

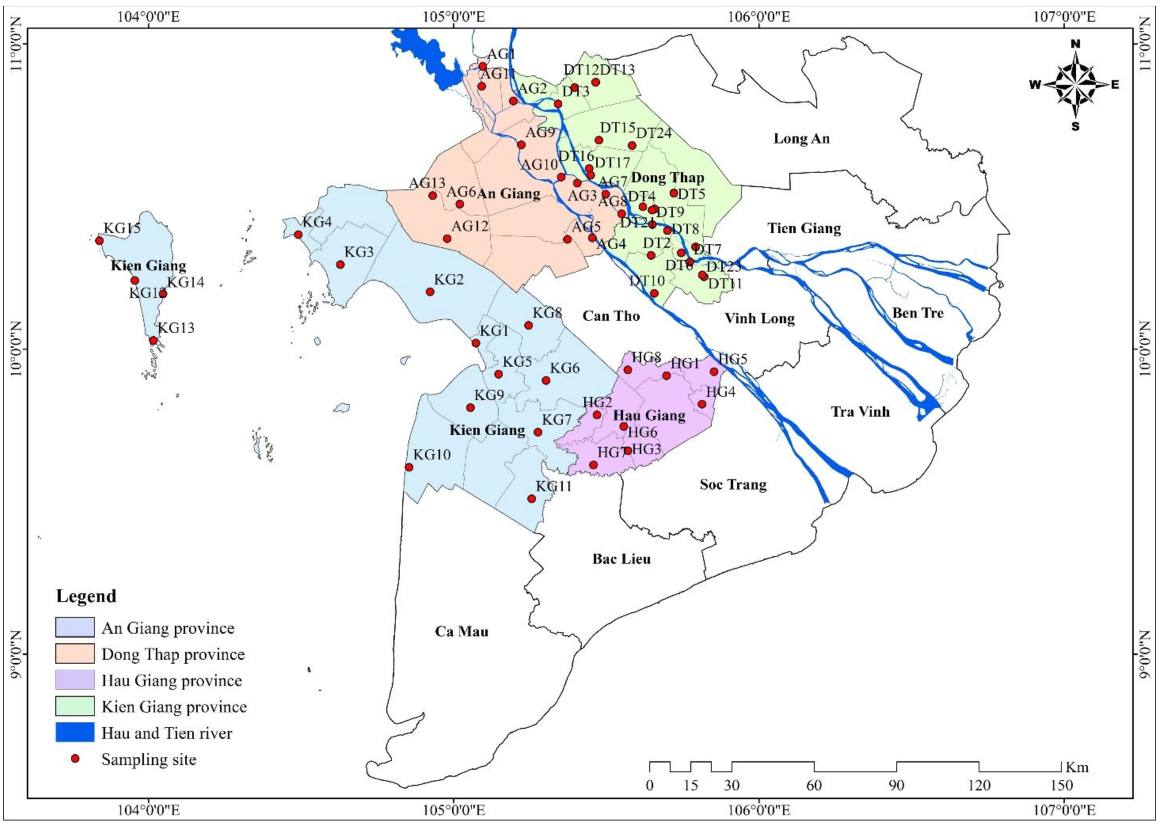

Figure 2. Map of the sampling locations

Table 1. Analytical methods of groundwater quality parameters

Parameters	Unit	Analytical methods	Vietnamese standard*
pH	-	SMEMW 4500.H-B:2012	5.5-8.5
Hardness	mg/L	TCVN 6224:1996	500
TDS	mg/L	SMEWW 2540.C:2012	1500
NO_3^--N	mg/L	SMEWW 4500.NO_3^- E:2012	15
NO_2^--N	mg/L	TCVN 6178:1996	1
NH_4^+-N	mg/L	SMEWW 4500 NH_3.F:2012	1
SO_4^{2-}	mg/L	SMEWW 4500-SO_4^{2-}.E:2012	400
Mn	mg/L	SMEWW 500-MnB:2012	0.5
Fe	mg/L	TCVN 6177:1996	5
Coliform	MPN/100mL	TCVN 6178-2:1996	3
As	mg/L	TCVN 6626:2000	0.05
Cd	mg/L	SMEWW 3120.B:2012	0.005

* Source: [30]

2.3. Groundwater Quality Index (GWQI)

It is an assessment technique that provides the aggregate influence of each quality parameter on the overall water quality, which in turn gives a quantitative description of water quality and usability [8, 18, 21]. Moreover, it is an important index for zoning groundwater quality and is calculated as follows:

$$WQI = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i} \tag{1}$$

Each groundwater quality parameter is assigned a weight (W_i) using the Equation 2:

$$W_i = \frac{K}{S_n} \tag{2}$$

where W_i is the weight of each parameter, S_n is the standard value of the n^{th} parameter specified in the national regulation [30], and K is equal to 1.

The sub-assessment quality index (Q_i) is calculated:

$$Q_i = 100 \times \frac{(V_o - V_i)}{(S_n - V_i)} \tag{3}$$

where V_o is the observed value of the i^{th} parameter, V_i is the ideal value of the n^{th} parameter. $V_i = 0$ for all parameters (except pH). Q_i for pH is calculated by the Equation 4:

$$Q_{pH} = 100 \times \frac{(V_{pH} - 7.0)}{(8.5 - 7.0)} \tag{4}$$

The GWQI values are classified and evaluated according to 5 levels. Level A ($0<GWQI\leq 25$) is excellent water; level B ($26<GWQI\leq 50$) is good water; level C ($51<GWQI\leq 75$) is poor water; level D ($76<GWQI\leq 100$) is very poor; and level E ($GWQI>100$) is unsuitable for drinking. The distribution of GWQI values on the map was displayed using Arcgis 10.2.

2.4. Human Health Risk Assessment

This assessment was conducted based on the United States Environmental Protection Agency [31]. In the study area, people are primarily exposed to contaminants in groundwater through dermal and oral. Since groundwater exposure via the skin, such as showering and washing, is negligible, only oral exposure was considered in this study. There were two subjects: children and adults (20-55 years old). It was computed as follows:

$$CDI = \frac{C \times IR \times EF \times ED}{BW \times AT} \tag{5}$$

where CDI is the chronic daily dose (mg/kg/day), C is the average concentration of Fe, Mn, As and Cd (mg/L), IR is the exposure rate (L/day), EF is the frequency of exposure (day/year), ED is the duration of exposure (years), BW is body weight (kg), AT is the average time of exposure (day). Reference dose (RfD) and slope factor (SF) were determined based on the United States Environmental Protection Agency's Integrated Risk Information System (USEPA IRIS) (http://www.epa.gov/iris/). The values of the parameters are given in Table 2.

Table 2. Health risk calculation parameters

	IR	EF	ED	BW	AT	RfD (mg/kg-day)*				SF of As (mg/kg-day)$^{-1}$*
						Fe	Mn	Cd	As	
Children	1	365	70	10	25,550	0.7	0.14	0.0005	0.0003	1.5
Adults	3	365	70	55	25,550	0.7	0.14	0.0005	0.0003	1.5

* Source: [32]

Hazard Quotient (HQ) for non-carcinogenic pollutants (Equation 6) and risk index for carcinogenic pollutants (Equation 7):

$$HQ = \frac{CDI}{RfD} \tag{6}$$

$$Risk = CDI \times SF \tag{7}$$

The aggregate risks of adverse health impacts owing to Fe, Mn, Cd, and As in groundwater are computed as follows:

$$HQ = HQ_{Fe} + HQ_{Mn} + HQ_{Cd} + HQ_{As} \tag{8}$$

3. Results and Discussion

3.1. Groundwater Quality in Four Provinces in the Mekong Delta

The characteristics of groundwater quality in the Mekong Delta are illustrated in Figure 3. pH values measured in the study areas fluctuated within the permissible limit (5.5–8.5) according to the national regulation on groundwater quality [30]. The average pH value of An Giang, Dong Thap, Kien Giang, and Hau Giang provinces ranged from 6.88 to 7.25, 6.98–7.76, 6.54–7.36, and 6.84–7.32, respectively. This is in agreement with the results of the previous studies in the region: 6.64–7.83 in Soc Trang [33] and 6.5–7.2 in An Giang province [16]. Giao et al. (2022) reported that pH variations in Can Tho city between the dry and rainy seasons were 7.14–7.64 and 6.69–8.22, respectively [3]. The fluctuation of pH in groundwater in this study area is considered safe for use [8].

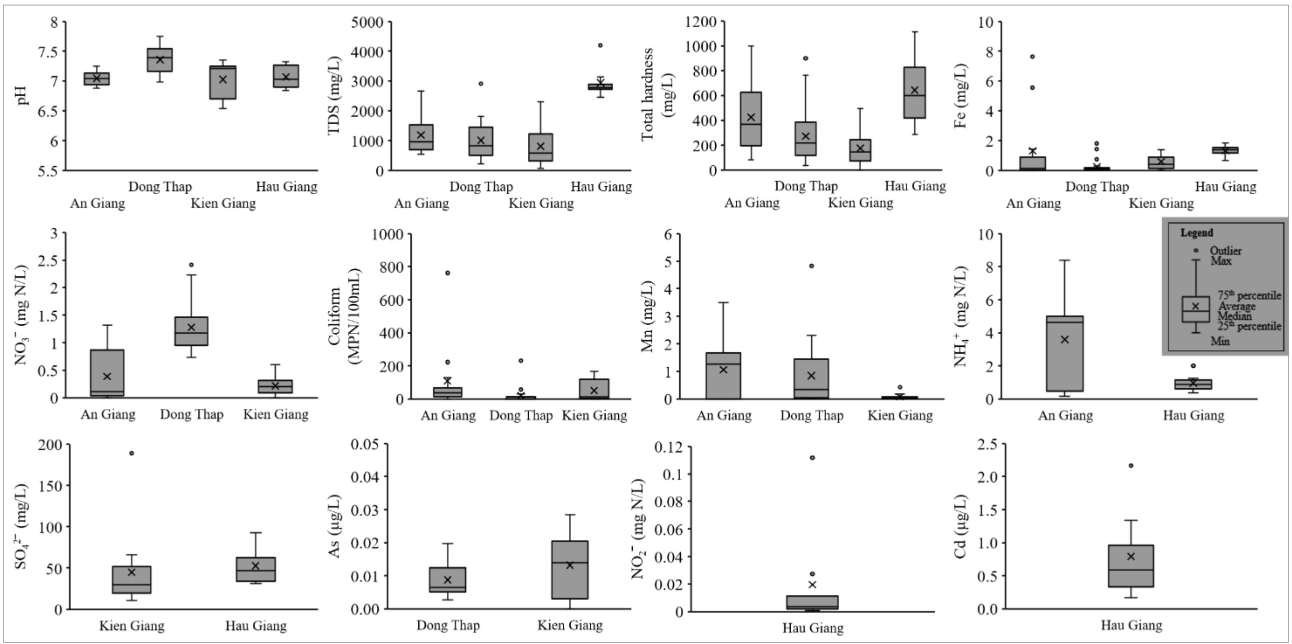

Figure 3. Boxplots of groundwater quality parameters in the Mekong Delta

The findings of TDS in the Mekong Delta exceeded the Vietnamese standard (1,500 mg/L). Especially, all samples collected in Hau Giang province were higher than the standard, ranging from 2462–4194 mg/L. The values of TDS in An Giang, Dong Thap, and Kien Giang provinces were lower than in Hau Giang province, varying from 544 to 2668 mg/L, 227–2907 mg/L, and 77–1307 mg/L, respectively. The ratios of samples with TDS higher than the standard in An Giang, Dong Thap, and Kien Giang were about 31, 25, and 27% of the total samples in each province, respectively. Higher TDS values were reported in the south of Vietnam, by 4.1±7.8 g/L in the rainy season and

3.2±6.7 g/L in the dry season [17]. Similarly, TDS in Soc Trang, a coastal province of the Mekong Delta, was greater than the limit, ranging from 281–8055 mg/L [33]. Meanwhile, lower TDS values were reported in Bac Lieu province, ranging from 286–715 mg/L [24]. According to the study of Giao et al. [33], high TDS in groundwater was associated with natural processes (e.g., water-rock interaction to release salts) and anthropogenic activities (e.g., domestic sewage, industrial, and domestic wastewater). Moreover, high TDS concentrations are usually observed in agricultural and residential areas [5]. Based on the TDS concentration, groundwater in the study area is classified into freshwater hard water and medium salt hard water [32].

The average hardness values in An Giang, Dong Thap, and Kien Giang provinces showed remarkable fluctuation, ranging from 78.3 to 999.7 mg/L, 34.8–897.5 mg/L and 0–494 mg/L, respectively. In Hau Giang province, the qp_3 aquifer of the HG2 site recorded the highest value at 1411.50±1615.74 mg/L, and the lowest at the qp_1 aquifer at the HG7 site reached 206.50±60.10 mg/L. All samples in Kien Giang province with hardness were within the limit (500 mg/L). Meanwhile, 5 out of 13 positions in An Giang, 3 out of 24 samples in Dong Thap, and 12 out of 24 sites in Hau Giang province exceeded the standard. The reason may be that Hau Giang province monitors groundwater by depth, so the TDS content and hardness in the groundwater have the highest concentration. High hardness could degrade the quality of groundwater, which is costly for water treatment and causes heart disease and kidney stones [21]. In Bac Lieu province, total hardness in groundwater varied from 98-172 mg/L [34]. Total hardness found in Can Tho city seasonally fluctuated from 35.50±14.77 mg/L (dry season) to 150.19±58.69 mg/L (rainy season) [3]. These contents are lower than in Soc Trang province, ranging from 13 – 3080 mg/L [9]. The greater hardness of groundwater is related to the release of calcium and magnesium via water-rock interaction, seawater intrusion, and anthropogenic activities [3, 9].

The Fe fluctuations in Dong Thap, Kien Giang, and Hau Giang provinces were low, ranging from 0.02±0.02 to 3.38±1.09 mg/L. The highest Fe value recorded in An Giang province at position AG11 reached 7.63±8.73 mg/L. Only two sampling locations (AG1 and AG11) in An Giang province showed Fe content exceeding the limit (5 mg/L). This low Fe concentration in this study site is consistent with other provinces in the delta: 0.69±0.52 mg/L (dry season) and 2.71±13.45 mg/L (rainy season) in Can Tho city [3], 0.09-2.28 mg/L in An Giang province [16], and 0.04-0.12 mg/L in Bac Lieu province [34]. The study by Khan et al. in India showed that Fe was a dominant contaminant in groundwater [35]. Due to the natural existence of Fe in the environment, the enrichment of Fe can be related to untreated wastewater from residential areas, industrial sites and agricultural activities [36]. Moreover, using age-corroded pipes in groundwater extraction is also a common source of Fe [35].

The findings of NO_3^- and NO_2^- min the study area was within the limits (15 mg N/L). The average NO_3^- in An Giang, Dong Thap, and Kien Giang ranged from 0 to 1.32 mg N/L, 0.73–2.23 mg N/L and 0–0.60 mg N/L, respectively. The study by Tran et al. (2021) showed that NO_3^- in Soc Trang province was high, ranging from 0.1-260 mg/L [9]. The NO_2^- concentration in groundwater was up to 0.14±0.18 mg/L in Dong Thap province, which was below the limit in all samples (1 mg/L). Besides, the findings of NH_4^+ in An Giang and Hau Giang ranged from 0.15–8.39 mg/L and 0.21–2.55 mg/L, respectively. Most samples in An Giang province exceeded the limit (1 mg N/L). During 2009–2018, the average ammonium concentrations in An Giang province were reported to be higher than the limit [16]. It means that ammonium contamination of groundwater is a pressing problem in the province. In addition, in Hau Giang province, the aquifers qp_1 and qp_3 at the HG2 site, the qp_1 and qp_3 layers at the HG3 position, and qp_1, qp_3 layers at the HG5 and HG4 locations exceeded the limit. This is associated with agricultural runoff containing chemical fertilizers and pesticides and the river and canal systems polluted by garbage, waste, and domestic wastewater from residential areas [3, 16, 18]. Thus, there has been the movement of nitrate, nitrite, and ammonium from the soil and surface water environments into groundwater in the study area.

The average sulfate content in Hau Giang province ranged from 19.00 to 112.50 mg/L, which was within the allowable limit (400 mg/L). In the Mekong Delta, the concentrations of sulfate relatively fluctuated: Soc Trang province (0.02-3239 mg/L) [9], Can Tho city (22.1-67.4 mg/L) [3], and Bac Lieu province (36.9-137.6 mg/L) [34]. However, sulfate minerals can cause scale buildup in water pipes similar to other minerals and a bitter taste in water, possibly leading to shortness of breath, dehydration, and diarrhea [37]. In addition to anthropogenic activities, sulfate may be naturally released from sulfide-bearing minerals, such as pyrite and gypsum [35].

The average coliform concentration varied significantly between the observation wells, ranging from 0 to 761.50 MPN/100mL. Most samples from An Giang, Dong Thap and Kien Giang provinces had coliform concentrations that far exceeded the standard (3 MPN/100mL). The results are generally consistent with previous studies showing that groundwater in the Mekong Delta has high microbial contamination: 693.9 MPN/100mL during 2006-2016 in An Giang province [20], 154 ± 359 MPN/100 mL in Soc Trang province and 152-1315 MPN/100mL in Ben Tre province [18]. It has shown that human and animal wastes that have not been treated properly can seep into aquifers and degrade groundwater quality. Pathogen contamination in groundwater has long been a serious issue in the Mekong Delta; therefore, it is required to eradicate pathogens before use to protect local people.

The average Mn content in An Giang, Dong Thap, and Kien Giang provinces ranged from 0-1.69 mg/L, 0.01-4.82 mg/L, and 0-0.43 mg/L, respectively. Approximately half of the collected groundwater samples in An Giang and Dong Thap with Mn concentrations exceeding the national limit (0.5 mg/L). Meanwhile, all samples in Kien Giang province were below the limit. Mn makes up the majority of soils and aquifers and is prevalent in food. However, humans will be poisoned by chronic Mn exposure, consequently causing adverse health effects [38, 39]. Several studies showed that the Mn concentrations varied from 0.01-0.06 mg/L in Bac Lieu province [34] and 0.03-2.03 mg/L in Soc Trang province [33]. The presence of Mn in groundwater is the result of the leaching of Mn-bearing rocks and industrial wastewater. In Bangladesh, 87% of groundwater samples had Mn concentrations greater than the standard [40].

The average As concentration in Dong Thap and Kien Giang provinces ranged from 0–28.5 µg/L, which was within the limit (50 µg/L). The highest As concentration was recorded at location KG11, Kien Giang province. In this study, the As concentrations in An Giang and Hau Giang provinces were below the detection limit. In the period of 2009-2018, As concentrations in An Giang ranged from 0.002-0.84 mg/L [16]. There was no detection of As in groundwater in Bac Lieu province [34]. In Pakistan, arsenic in groundwater ranged from 11 to 828 µg/L, and they also reported that high arsenic was found near the Sutlet River [41]. Arsenic is present in groundwater through many natural sources (e.g., water-rock interaction) and human activities (e.g., solid waste, wastewater from agricultural activities, and industries (manufacturing paper, glass, dyeing, textiles, tanning, and pharmaceuticals)) [6]. Other studies suggest that areas with high arsenic are associated with high iron, ammonium, and phosphate concentrations and low oxygen, nitrate, manganese, and sulfate concentrations [22]. Long-term exposure to arsenic can cause skin, bladder, and lung cancer [16, 20].

The average Cd concentration in groundwater recorded in Hau Giang province was low, ranging from 0.00–0.005±0.007 mg/L. Most monitoring sites have Cd content within the limit (0.005 mg/L). Cadmium is a less absorbed substance in the soil but is more mobile than other metals and is derived from fertilizers and pesticides [39]. This shows that agricultural activities in the province are gradually affecting groundwater resources. As a result, cadmium often accumulates in the liver and kidneys, causing human health effects such as bronchitis, anemia, kidney and bone damage [7]. However, monitoring Cd concentrations in groundwater still attract little interest in the Mekong Delta.

3.2. Groundwater Quality Index

The appropriateness of groundwater in An Giang, Dong Thap, Hau Giang, and Kien Giang provinces for drinking obtained by GWQI is presented in Figure 4. It can be seen that the groundwater quality in these four provinces is only 30% of level A (very good quality), and more than 26% of locations are at level E (unsuitable for drinking). Approximately 92% of samples in An Giang are considered inappropriate for consumption. This is completely consistent with the results discussed above, which show that most of the water quality parameters in An Giang Province are above the allowable limits. The highest GWQI (GWQI = 2500) was found in position AG4, and the lowest (GWQI = 12.7) was in AG5. Previous studies showed groundwater deterioration is associated with high As and coliform concentrations [16, 20]. The study of Minh et al. (2019) revealed that groundwater in some northeast and southeast areas of An Giang was considered unsuitable for drinking according to the WQI calculation [16]. Thus, groundwater in this province is urgently treated before being used.

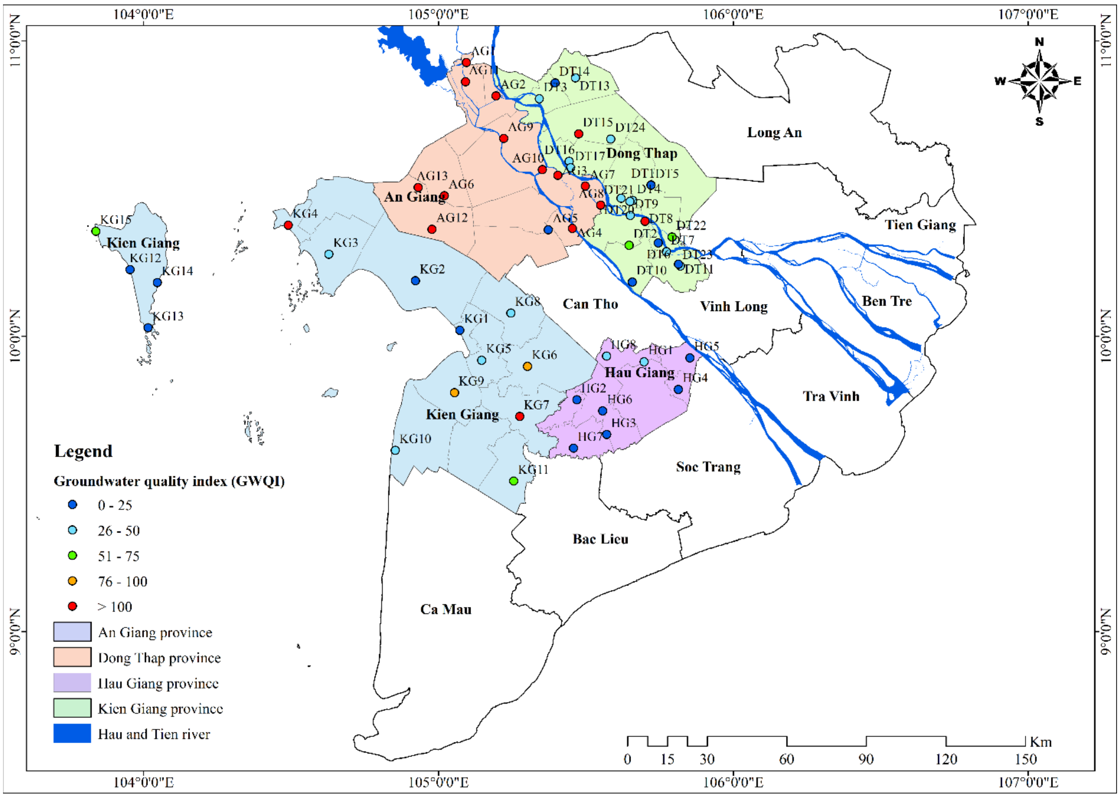

Figure 4. Spatial distribution of GWQI in the Mekong delta provinces

Dong Thap province has fairly uniform GWQI values among monitored wells. About 25% of wells have GWQI ≤ 25, which are considered areas with very good water quality. Besides, over 58% of total wells are of good quality. DT2 and DT22 fall into areas with poor quality, and DT8 and DT15 are unsuitable for domestic use. The GWQI of Hau Giang province ranges from 7.25 to 43.11, with an average of 16.17. The results indicated that 75% of the total samples achieved very good quality. HG1 and HG8 are classified as a good quality group, accounting for 25% of samples. The GWQI values found in Kien Giang Province are relatively uniform, ranging from 0 to 114.60. There are about 33% of wells with GWQI≤25, which means very good water quality. In addition, more than 26% of the total wells have GWQI values in the range of 26–50. The remaining six wells are in equal proportions, with about 13% of the quality monitoring wells being of bad quality, very bad, and unsuitable for use. In the Ca Mau Peninsula, WQI values calculated for groundwater quality ranged from 36 to 1344, with approximately half of the groundwater samples being of good quality [42]. In Soc Trang province, the WQI values of the groundwater samples varied from 8.5 to 285 [9]. In the study of Giao et al. (2022) in Can Tho city, groundwater quality was assessed to be very good for drinking using the GWQI [3]. GWQI has effectively presented the overall groundwater quality in the Mekong Delta. Moreover, it was also noticed that groundwater quality was unevenly distributed. Therefore, GWQI is suggested as a simple and effective tool to assess groundwater quality in the region in order to support the decision-making process.

3.3. Human Health Risks Associated with Groundwater Use

The cancer risks for drinking As-contaminated groundwater among children and adults in Dong Thap and Kien Giang provinces are depicted in Figure 5-a. Since there was no detection of As concentrations in An Giang and Hau Giang, the cancer risks were not involved. According to the regulation of the USEPA, the acceptable limit for cancer risks is defined as lower than 10^{-6}. As presented in Figure 5-a, the calculated cancer risks in these two provinces are higher than the acceptable level. In Dong Thap province, the highest cancer risks for children and adults were 2.96×10^{-3} and 1.62×10^{-3} at DT19, respectively; that is, about 3 children and 2 adults for a thousand people are at cancer risk due to drinking As-contaminated groundwater, respectively. The cancer risks for these two subjects found in Kien Giang are higher than those in Dong Thap. The highest risks were 4.28×10^{-3} for children and 2.33×10^{-3} for adults at KG11. It means 4 children and 20 adults in a thousand people could be at risk of cancer. The results of this study are consistent with previous studies showing that children have a higher cancer risk index than adults over the same average exposure period of 70 years [9, 20]. This may be associated with immature immune systems and the ability to eliminate arsenic from the body compared to adults. Therefore, it can be deduced that drinking groundwater with a high arsenic concentration long-term will cause a higher cancer risk for both children and adults. According to the study by Anh and Giao (2018), the consumption of As-contaminated groundwater in An Giang province could cause a cancer risk of 8.66×10^{-4} to 8.26×10^{-2} to both adults and children [20]. Previous studies reported that high carcinogenic risks are associated with a high arsenic concentration in groundwater [35, 39, 43]. According to the Vietnamese standard, the limit of As concentration in groundwater is 50 µg/L [30]. Cancer risk for children and adults with that As concentration was 7.50×10^{-3} and 4.09×10^{-3}, respectively; that is, for every 1,000 people, there will be 7 children and 4 adults facing cancer risk. According to WHO regulations, the maximum arsenic concentration in drinking water has been reduced from 50 to 10 µg/L. With this concentration, the cancer risk in both study subjects was significantly reduced. Specifically, of 10,000 people, 15 children and 8 adults are at risk of cancer. Thus, the limit of As concentration in Vietnam should be considered to lower the risk of cancer.

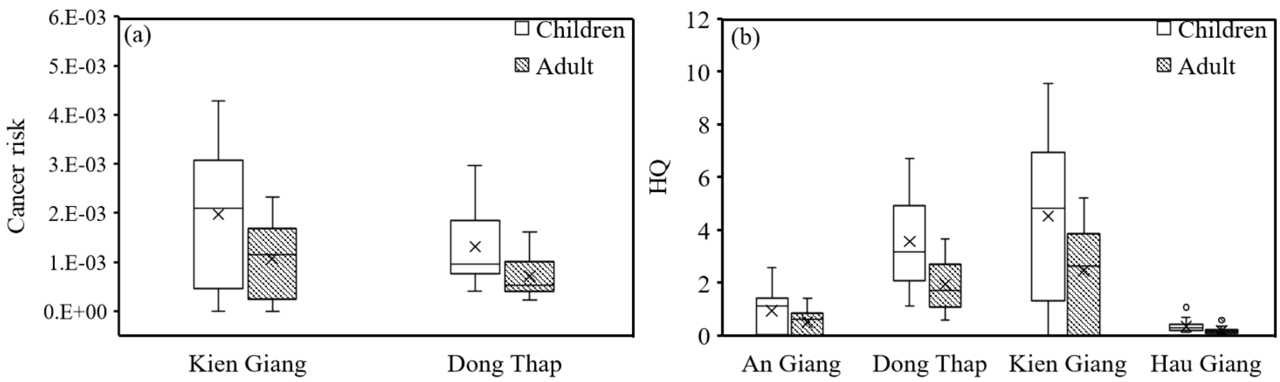

Figure 5. Health risk assessment for adults and children: (a) cancer risk of arsenic contamination in Kien Giang and Dong Thap provinces and (b) non-cancer risk of heavy metal contamination in the study area

The aggregate non-carcinogenic risks for children and adults due to heavy metals (Fe, As, Mn, and Cd) in groundwater are illustrated in Figure 5-b. If HQ is greater than 1, there will be a risk of adverse health effects. Children and adults in Kien Giang province face the highest risks of adverse health effects due to consuming this groundwater source, with HQs of 0.002-9.54. There were 11 out of 15 samples in this province, with HQs>1, accounting for approximately 74%. In Dong Thap, the calculated HQs for children and adults ranged from 1.11-6.69

and 0.61-3.65, respectively. All collected groundwater samples in this province cause serious health effects on children once consumed over the long term. Meanwhile, this ratio was lower for adults, with approximately 80% of the total (19 out of 24 samples). Lower risks of serious diseases were found in An Giang and Hau Giang because only two heavy metals were detected here. The HQs values in An Giang varied from 0-2.58, which has about 61% and 8% of total samples causing serious effects on children and adults, respectively. There was only one sample in Hau Giang with HQs for children larger than 1; it is considered a safe water source for adults. The study by Ghosh et al. (2020) in Bangladesh concluded that the HQ of manganese was up to 2.5 (adults) and 1 (children); the HQ of iron in adults and children was up to 1.5 and 0.6, respectively [40]. The aggerate HQs of heavy metals in groundwater in India for adults ranged from 0.1 to 12.5 [35]. The risks of adverse human health effects due to long-term groundwater consumption in the Mekong Delta have not been comprehensively studied. The study by Tran et al. (2021) reported that 15% of groundwater samples in Soc Trang province potentially cause serious health effects to the population associated with nitrate and salt contamination [9]. Nevertheless, the calculated risks presented in this study did not consider at-home water treatments; therefore, the predicted risks can be higher. It is necessary to take into consideration the risks of groundwater consumption in decision-making to protect public health.

4. Conclusion

This study assessed groundwater quality using GWQI in the Mekong Delta, namely An Giang, Dong Thap, Hau Giang, and Kien Giang provinces, where the population primarily depends on this freshwater source. Cancer and non-cancer risks associated with groundwater consumption in the region were studied. By comparing with the national regulation of groundwater, the results of this study illustrated that coliforms continued to be a serious problem in groundwater because operating wells have been properly protected to prevent the transport of pathogens. Moreover, the noticeable occurrence of heavy metals, including Fe, Mn, and As, is related to anthropogenic sources such as industrial and domestic wastewater. Besides common issues in these four provinces, groundwater in Hau Giang and Kien Giang had high TDS, while An Giang and Dong Thap showed high total hardness in water. The GWQI method effectively presents the large groundwater monitoring data into a single index. The results determined that 30% of the total samples were classified as very good quality for drinking, while the ratio of samples with undrinkable quality was 26%. The result of the health risk assessment showed that the long-term consumption of As-contaminated groundwater causes an unacceptable risk of cancer in adults and children. In addition, the ratio of adverse health risks to the population due to Fe, Mn, Cd, and As was highest in Dong Thap and Kien Giang. Accordingly, the groundwater in the study area should be treated before use. Due to the limited data in this study, it is recommended to conduct further studies to determine the pollution sources to improve groundwater quality. This study only calculated the risk of cancer and non-cancer through the ingestion pathway; thus, other exposure routes need to be considered in future studies.

5. Declarations

5.1. Author Contributions

N.T.G. and H.T.H.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 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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