Groundwater Quality Assessment Using Classification and Multi-Criteria Methods: A Case Study of Can Tho City, Vietnam

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ABSTRACT

This study aimed to classify groundwater quality in Can Tho City, Vietnam using groundwater quality index (GWQI), principal component analysis (PCA), and cluster analysis (CA). Groundwater samples were collected in April (dry season) and October (rainy season) in 2019 and then analyzed for thirteen parameters including pH, color, total hardness, chloride, sulfate, chemical oxygen demand, magnesium, total iron, nitrate, arsenic, lead, mercury, and coliforms. The results showed that groundwater quality in Can Tho City was contaminated with coliforms in both seasons. COD and Cl^- was found exceeded the allowable limits in several wells in the dry season. The other groundwater parameters were within the permissible limits. GWQI values indicated that groundwater quality was in excellent state. The CA results revealed that groundwater quality in the dry season was more spatially varied than that in the wet season. In addition, CA revealed that groundwater monitoring sites could be reduced by 9 sites and 12 sites in the dry and wet seasons, respectively. The PCA results showed that 63.4% and 73.9% of the groundwater variation in the dry and wet seasons were explained by four PCs and three PCs, respectively. All the groundwater quality monitoring parameters were significantly and influenced by geological factors, domestic wastes, industrial and agricultural activities. Coliform should be completely treated before domestic use of groundwater in the study area. Future study should focus on investigating contribution of specific polluting sources for appropriate management measures.

1. INTRODUCTION

In Vietnam, groundwater has been exploited for different usage purposes for more than a century and has continuously expanded (Berg et al., 2007; Erban et al., 2014). Especially, in the Mekong delta, surface water has been strongly polluted by agricultural and aquaculture activities, salinity intrusion, domestic and industrial contaminants. Therefore, this water resource is unsuitable for human use and places more importance on alternative freshwater resources such as groundwater (Dao et al., 2016). However, the availability and quality of groundwater are currently affected by both natural processes and anthropogenic activities (Ha et al., 2019a). The natural processes are all related to the geology and climate of the area. Typically, arsenic is naturally released into groundwater through biological reactions or decomposition of iron oxides (Fendorf, 2010) and the solubility of fluoride-containing minerals. In addition, seasonal variation in groundwater quality and geochemical mobility of ions have been documented in previous studies (Gaikwad et al., 2020; Kadam et al., 2021a; Kadam et al., 2021b); which may limit the use of water resources during certain periods. Particularly, the Mekong Delta area has low topography, acid sulfate soil, and two distinct seasons (dry season and rainy season); therefore, groundwater quality has seasonal fluctuations and limited use in the dry season due to the impact of climate and seawater. The anthropogenic activities that could influence on groundwater quality including intensive groundwater abstraction, improper waste treatments in industrial, domestic and agricultural sectors, and excessive fertilizer application (Nguyen and Tran, 2007; Erban et al., 2014; Huang et al., 2016; Kadam et al., 2021a). According to the World Health Organization (WHO), 80% of all human diseases were

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associated with waterborne (WHO, 2017). Thus, it is necessary to assess the current groundwater quality in the study area.

Because of the complexity of the influencing factors on groundwater quality, a comprehensive assessment method is required. Recently, multivariate statistical analyses such as principal component analysis (PCA) and cluster analysis (CA), have been widely applied to recognize the key parameters in the variation of the data and to group the monitoring sites based on similar properties (Abou and Hafez, 2015; Misi et al., 2018). PCA is used to reduce the size of the dataset (i.e., physicochemical parameters) by explaining the correlation matrix and avoiding the loss of important information (Jackson, 2005). Additionally, this allows identifying the main parameters that control groundwater quality in the variation of the original dataset and determining the potential pollution sources (Nguyen et al., 2021a). Abou and Hafez (2015) studied the sources and distribution of nitrate pollution in groundwater in Damascus Oasis using PCA. The results of PCA could explain up to 84% of the cumulative variance and reveal the complication of pollutants causing groundwater pollution in Zimbabwe (Misi et al., 2018). In terms of water quality assessment, CA is also one of the effective methods in order to group samples on the basis of their similar properties (Egbueri, 2020; Nguyen et al., 2021a). For example, CA classified all groundwater monitoring sites into two clusters based on the pollution index and ecological risk index, supporting the selection of areas for groundwater treatment before use (Egbueri, 2020). In Mekong Delta, the groundwater quality index (GWQI) has been applied in previous studies to evaluate groundwater quality (Dao et al., 2016; Huynh et al., 2019). This tool can combine several different water parameters into only one index, which allows recognizing the composite impact of these parameters on groundwater in a particular area. For example, Huynh et al. (2019) and Dao et al. (2016) reported that the groundwater quality in An Giang and Ca Mau were classified as "bad water" and 50% of total samples in the good quality group based on the results of GWQI, respectively.

In the Mekong Delta Region, Can Tho is a city directly under the central government of Vietnam and also the economic and industrial center of the region. Most local economic activities strongly depend on freshwater resources including groundwater, rainwater, and surface water (DoNRE, 2009). According to Hang (2019), the total amount of groundwater being exploited in the Can Tho City has about 127,956 m^3/day at 50,673 exploited wells. In which, there are about 510 self-exploited wells with a capacity of about 75,982 m^3/day serving family activities, concentrated residential areas or producing industrial crops and vegetables, the service activities and industrial production facilities. Due to rapid industrialization and urbanization, the increasing human demand for freshwater was associated with surface water and groundwater in the city decreasing over time (Tran and Huynh, 2017; Tran et al., 2021). The research by Tran et al. (2021) reported that there was a significant decrease in groundwater levels during the period 2000-2018; especially the Upper-Pleistocence (qp_3) và Middle-Upper Pleistocene aquifers (qp_{2-3}). Lower groundwater levels in Can Tho City have been reported because of the combined effects of low recharge rates and high abstraction (Nuber et al., 2008). Therefore, it can be seen that groundwater resources play an important role in the region and are facing many threats to their quality and availability. Recently, several studies in Can Tho City and surrounding areas have also been conducted; however, these studies only focused on assessing the variability of water reserves (Tran et al., 2021) or specific pollutants (such as arsenic) in An Giang, Tien Giang, and Long An (Phan and Nguyen, 2018; Nguyen et al., 2021b). There are no comprehensive studies that assess groundwater quality using the WQI, PCA and CA in Can Tho City. Therefore, the primary purpose of this study was; (1) evaluated the seasonal groundwater variations and assess its suitability for human consumption; (2) assess the spatial distribution and groundwater quality variability of the sampling sites by using GWQI and multivariate statistical methods; (3) identify the key factors influencing groundwater quality. The results of this study provide the status and potential sources of groundwater quality variations, supporting scientific information for appropriate groundwater management strategies.

2. METHODOLOGY

2.1 Study area

This study was conducted to evaluate groundwater quality in Can Tho City belonging to the Mekong delta, Vietnam, has 1,439.2 km^2 and a population of 1,235,171 people. In terms of land use, agricultural land is dominant (79.66%), concentrated in Co Do, Vinh Thanh and Thoi Lai Districts; while non-agricultural land is representing most of the land area of Ninh Kieu and Binh Thuy Districts (Can Tho City Statistics Office, 2020). Can Tho City has a tropical monsoon climate with two seasons in the year, including the rainy season (from May to November) and the dry season (from December to April next year). The average temperature fluctuated from 26.2ºC to 29.8ºC in 2019. Total rainfall accounts for about 90% of the annual rainfall during the rainy season (1,406.6 mm/rainy season), while dry season accounts for only about 10% (179.9 mm/dry season). The terrain is relatively flat with an average height of about 1-2 m, sloping from the plains along the Hau and Can Tho Rivers and gradually lowering from the northeast to southwest (DoNRE, 2015). The geology in the city is mainly formed through the marine and alluvial Mekong River deposits. There are two main types of soil groups, including alluvial soil and acid sulfate soil. In which, alluvial soil accounts for 84% of the natural area, which is distributed along the Hau River and from 8-12 km from the river; acid sulfate soil accounts for 16% of the natural area (DoNRE, 2015). The density of rivers and canals in Can Tho City is quite large 1.8 km/km^2 with more than 158 rivers and canals (DoNRE, 2015; Nguyen, 2020). Although the network of rivers and canals is crisscrossed, only exploiting surface water for economic development and basic daily demands is not sufficient. At the same time, due to the rapid population growth, surface water quality is degraded over time because of mass domestic and industrial wastes. Therefore, groundwater has become one of the alternative water resources to serve local demands.

Can Tho City has seven water-bearing units in the order from top to bottom, namely Holocene (qh), Upper Pleistocene (qp_3), Middle-Upper Pleistocene ($qp_{2\text{-}3}$), Lower Pleistocene (qp_1), Upper Pliocene (n_2^2), Lower Pliocene (n_2^1), Upper Miocene aquifer (n_1^3) (Le et al., 2017). On the surface at a depth of 50 m, there are two types of sediments: Holocene (new alluvium) and Pleistocene (ancient alluvium) (DoNRE, 2015; Le et al., 2017). In which, aquifers are mainly in Pleistocene, Pliocene, Miocene at depths of 80-400 m, some places have been recorded at depths of 18-35 m. The aquifer that has the largest number of boreholes exploited and used in Can Tho City is the Pleistocene ($qp_{2\text{-}3}$) (Le et al., 2017).

2.2 Groundwater monitoring sites and analyses

Groundwater samples were collected from 27 monitoring locations in 2019 labeled from GW1 to GW27, shown in Figure 1. This were collected and preserved according to the national standards on guidelines for sampling and preserving groundwater of the Ministry of Science and Technology of Vietnam (2011) and Ministry of Science and Technology of Vietnam (2008). Each collected sample was analyzed for 13 parameters including pH, color, total hardness, chloride (Cl^-), sulfate (SO_4^{2-}), chemical oxygen demand (COD), magnesium (Mg), total iron (Fe), nitrate (NO_3^-), arsenic (As), lead (Pb), mercury (Hg), and coliforms. These parameters have been selected based on the characteristics of the area and national technical regulations in the assessment and monitoring of groundwater quality to guide different water use purposes (MoNRE, 2015). In addition, many previous studies have noted that As, Fe, and Pb were frequently presented in groundwater of provinces in the Mekong Delta (Huang et al., 2016; Ha et al., 2019a; Nguyen et al., 2021b). While the Ni, Cd in the Mekong River Delta exceeded (less than 1%) the WHO standards (2008) and did not have the ability to affect public health. In addition, cations were not mentioned in national technical regulation on groundwater quality in Vietnam, which is applied as the basis to guide for the different water uses (MoNRE, 2015). Therefore, these parameters are of less interest in the study area (Tran, 2019). The temporal variation of groundwater was evaluated in the dry season (April) and the rainy season (October). The pH was measured directly in the field, and other parameters were analyzed in the laboratory at the Can Tho City Environmental and Natural Resources Monitoring Center using standard methods (APHA, 1998).

2.3 Groundwater quality index (GWQI)

The groundwater quality index (GWQI) was used to evaluate overall groundwater quality. GWQI was calculated using the formula (1) (Dao et al., 2016; Li et al., 2021):

$$\mathrm{GWQI} = \sum_{n=1}^{10}(q_n \times W_n) \tag{1}$$

$$W_n = \frac{w_n}{\sum_n^{10} w_n} \tag{2}$$

Where; W_n is the relative weight of the nth parameter; q_n is sub-assessment quality index corresponding to the nth parameter. The q_n values was calculated by the formula (3):

$$q_n = 100 \times \frac{(V_n - V_i)}{S_n - V_i} \tag{3}$$

Where; S_n is the limit values of groundwater quality specified in the Vietnamese regulation on groundwater quality (QCVN 09-MT:2015/BTNMT) (MoNRE, 2015); V_n was the content of parameter n in the study area; V_i was ideal values (with pH=7, the rest of parameters were equal to 0). The weight factor of groundwater parameters is presented in Table 1.

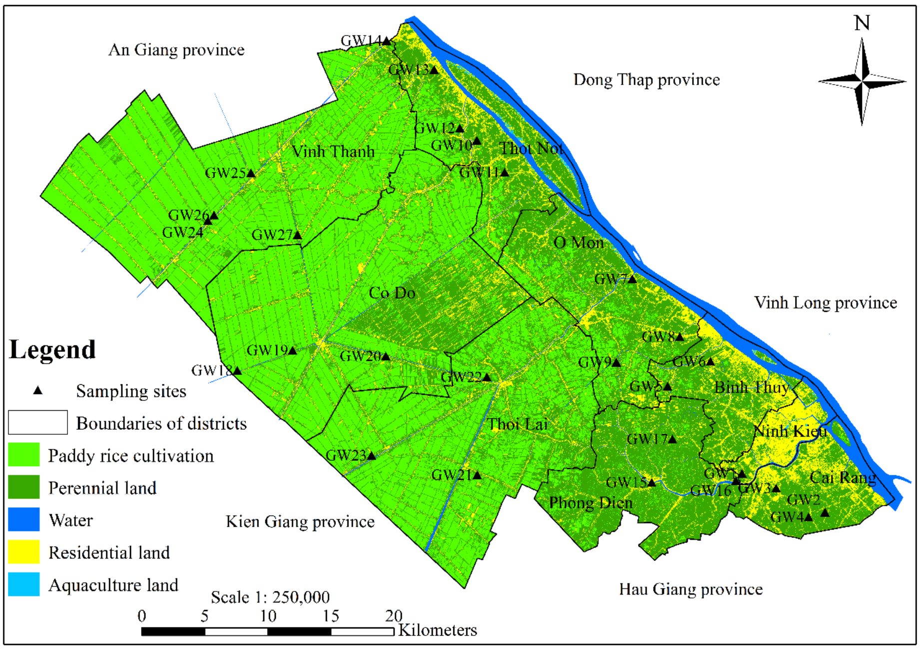

Figure 1. Location map of Can Tho City groundwater monitoring point

Table 1. The weight factor of groundwater parameters

Parameter	S_n	w_n ($1/S_n$)	W_n
pH	5.5-8.5	1.18E-01	1.05E-04
Hardness	500	2.00E-03	1.78E-06
Cl^-	250	4.00E-03	3.57E-06
SO_4^{2-}	400	2.50E-03	2.23E-06
Fe	5	2.00E-01	1.78E-04
NO_3^-	15	6.67E-02	5.95E-05
As	50	2.00E+01	1.78E-02
Pb	10	1.00E+02	8.92E-02
Hg	1	1.00E+03	8.92E-01
Coliforms	3	3.33E-01	2.97E-04

The groundwater quality is classified into 5 levels based on the computed GWQI values, as shown in Table 2. This calculated data was used to create a spatial distribution map of GWQI. The GWQI distribution map was performed using the interpolation with inverse distance weighted (IDW) method. The IDW method would estimate the GWQI values at the unsampled locations using a linear function of the sampled locations. The GWQI values of the predicted locations would decrease with the distance from the sampling site (Huynh et al., 2019; Hasan and Rai, 2020). The study used Arcgis version 10.2 software to perform the spatial interpolation. Besides that, cluster analysis (CA) and principal component analysis (PCA) were used to group the wells with similar groundwater quality and to identify key variables resulting in variation of groundwater quality (Wagh et al., 2019; Kadam et al., 2021c). CA and PCA analysis were performed using Primer 5.2 software (PRIMER-E Ltd, Plymouth, UK).

Table 2. Water quality classification based on the calculated GWQI

GWQI	<50	50-100	100-200	200-300	>300
Water quality	Excellent	Good	Poor	Very poor	Unsuitable for drinking

(Dao et al., 2016; Li et al., 2021; Huynh et al., 2019)

3. RESULTS AND DISCUSSION

3.1 Groundwater quality assessment

The seasonal changes of physicochemical properties in groundwater quality in Can Tho City are presents in Table 3. The values of the monitoring parameters were compared to the Vietnamese technical regulation on groundwater quality (QCVN09-MT:2015/BTNMT).

pH values were found to vary from 7.14-7.64 in the dry season and 6.69-8.22 in the rainy season, which are within the allowable limit (5.5-8.5). There was a little spatiotemporal variation in pH values, and alkalinity was predominant. In the dry season, the groundwater color in all monitoring sites ranged from 1 to 143 Pt-Co, with an average of 23.33±29.87 Pt-Co. This value was much lower in the rainy season which varied from 1 to 21 Pt-Co, with an average of 7.15±5.06 Pt-Co.

The results showed that there was a significant spatiotemporal variation of total hardness. The average values of total hardness at the monitoring sites were in the range of 25.20-168.50 mg/L. In the rainy season, the average hardness value was 150.19±58.69 mg/L, which was over four times higher than that in the dry season (35.50±14.77 mg/L). The reason for this fluctuation is an increase in water volume into aquifers that contain high dissolved mineral contents such as calcium and magnesium because of moving through soil and rock (Ram et al., 2021). In addition, Fe could also increase the hardness in groundwater in this study; because the study area has about 16% iron or aluminum acid soil (Hua, 2019). The detected hardness values of groundwater in the study area are within the allowable limit of the Vietnamese standard. Several studies of groundwater quality in the Mekong Delta reported that total hardness values were found in the range of 220.15 to 1,262.50 mg/L in An Giang Province (Nguyen, 2021a), 52.50 to 7,355.36 mg/L in Ca Mau peninsula (Dao et al., 2016) and 125 to 138 mg/L in Dong Thap Province (Pham, 2019). High total hardness in groundwater not only reduces the water quality for domestic and production usage but also causes adverse effects on human health (Li et al., 2021; Ram et al., 2021).

Table 3. Seasonal variation of groundwater quality

Variables	Units	Dry season	Rainy season	Vietnamese standard
pH	-	7.37±0.14	7.33±0.34	5.5-8.5
Color	Pt-Co	23.33±29.87	7.15±5.06	-
Hardness	mg $CaCO_3$/L	35.50±14.77	150.19±58.69	500
Cl^-	mg/L	138.66±118.33	24.91±25.91	250
SO_4^{2-}	mg/L	67.41±43.76	22.07±21.48	400
COD	mg/L	4.84±2.30	2.76±2.37	4
Mg	mg/L	0.12±0.08	0.20±0.36	-
Fe	mg/L	0.69±0.52	2.71±13.45	5
NO_3^-	mg N/L	0.32±0.36	0.90±3.72	15
As	µg/L	0.7±0.9	ND	50
Pb	µg/L	2.09±1.77	ND	10
Hg	µg/L	ND	ND	1
Coliforms	MPN/100 mL	8.63±6.65	4.96±3.89	3

ND: Not detected

The Cl^- concentrations in the dry and rainy seasons were found in the range of 25.20-382.30 mg/L and 15.30-146.60 mg/L, respectively. Also, there was a spatial variation of the Cl^- concentration (15.3-382.3 mg/L). Most monitoring sites had the Cl^- concentration within the permissible limit (250 mg/L), with the exception of GW2, GW3, GW4, GW7, GW15, GW16, GW17, and GW27. High Cl^- concentration could result from overexploitation of groundwater, leading the saline boundary to encroach into the aquifer

(Nguyen et al., 2017). The seasonal fluctuation of the Cl^- concentration has been reported in previous studies in which Cl^- tended to be higher in the dry season (Nguyen et al., 2017; Li et al., 2021). As a result of higher precipitation infiltration, salt concentration is diluted, which in turn reduces the Cl^- concentration in groundwater in the wet season. The presence of high Cl^- concentration is also a major concern to crop productivity and human health (Nguyen et al., 2021b; Pius et al., 2012).

Similarly, the average SO_4^{2-} concentration in the rainy season (22.07±21.48 mg/L) was lower than that in the dry season (67.41±43.76 mg/L). The spatial variation of SO_4^{2-} concentration was in the range of 2.0-181.7 mg/L, which was within the national permissible limit. SO_4^{2-} in groundwater is the result of dissolving rocks containing gypsum, iron sulfides, and other sulfur compounds (Dao et al., 2016; Ram et al., 2021). Moreover, leaching sulfate in fertilizer application in agriculture and other human activities is also responsible for SO_4^{2-} in groundwater (Al-Ahmadi, 2013).

The average value of COD in the dry season (4.84±2.30 mg/L) was found to be higher than that in the rainy season (2.76±2.37 mg/L), and the COD concentration in the monitoring sites ranged from below detection limit to 10.6 mg/L. COD at seven out of 27 monitoring sites (25% of the monitoring sites) in the rainy season exceeded the permissible limit of groundwater quality standard. Meanwhile, this ratio increased up to nearly 63% in the dry season. The seasonal variation of COD in groundwater was also reported in the previous study (Huynh et al., 2016). High COD in groundwater could be caused by anthropogenic sources such as leachates and industrial wastewater (Nguyen et al., 2019).

Mg^{2+} concentrations were ranged from below the detection limit to 0.29 mg/L in the dry season and from 0 to 2 mg/L in the rainy season (Table 3). Nguyen et al. (2017) also reported a great Mg^{2+} concentration in groundwater in Ba Ria Vung Tau, Vietnam, with the range of 0.24-118.56 mg/L in the rainy season. Higher Mg^{2+} concentrations are responsible for the higher hardness of groundwater in the rainy season, which is the result of the dissolution of magnesium-contained rocks.

The average of total Fe concentration was 0.69±0.52 mg/L in the dry season and 2.71±13.45 mg/L in the rainy season (Table 3). Total Fe concentration also considerably fluctuated among monitoring sites from 0.05 to 70.00 mg/L. While total Fe concentration found in most of the monitoring sites was within the permissible limit (5 mg/L), it was detected at very higher levels in the GW9 site which was 14-time greater than the limit. Several studies have shown a relatively lower total Fe concentration in groundwater in the Mekong Delta such as from 0.81-2.19 mg/L in Soc Trang Province (Nguyen et al., 2021b) and 0.07-2.16 mg/L in An Giang (Phan and Nguyen, 2018). When water contains higher than 0.5 mg/L of total Fe, it has an unpleasant fishy odour and yellow color, which adversely affects the quality of drinking water for domestic use and production.

The NO_3^- concentration was ranged from no detection to 1.09 mg N/L in the dry season and 19.50 mg N/L in the rainy season (Table 3). Only GW9 site in the rainy season had NO_3^- concentration exceeded the permissible limits (15 mg N/L). NO_3^--contaminated groundwater is attributed to anthropogenic sources such as fertilizer practices, domestic and industrial wastewater (Li et al., 2021; Li et al., 2016). NO_3^- concentration in groundwater was found to be varied among the study areas in the Mekong Delta. Nguyen et al. (2021b) reported that this concentration ranged from 0.008-0.047 mg/L in Soc Trang Province, while it was found over 30 mg/L in Tra Vinh Province (Nguyen and Tran, 2007). The NO_3^- groundwater contamination not only occurred in the Mekong Delta but also in other areas in Vietnam. Duong and Lam (2018) found the NO_3^- concentration greatly fluctuated from 0.09 to 95.96 mg/L in Pleiku City.

The concentration of As in groundwater was only detected in the dry season, with an average of 0.7±0.9 µg/L (Table 3). This concentration was within the permissible limit of the Vietnamese standard. As-contaminated groundwater is a major concern in the Mekong Delta because it is a carcinogenic substance (Berg et al., 2007; Huang et al., 2016). Several studies reported that As concentration in the groundwater was up to 60 µg/L in Tra Vinh Province (Nguyen and Tran, 2007) and 0.55±1.21 mg/L in An Giang Province (Phan and Nguyen, 2018). The use of As-contaminated groundwater without appropriate treatment could cause potential life time cancer risk from medium to high level (Phan and Nguyen, 2018).

The Pb concentration was only detected in the dry season with an average of 2.09±1.77 µg/L and varied from below the detection limit to 6.0 µg/L at different monitoring sites (Table 3). This is within the permissible limit of Pb in groundwater. According to Ha et al. (2019b), Pb-contaminated groundwater in Mekong delta (4 µg/L) higher than that in Can Tho

City. The presence of Pb in groundwater in Can Tho City may be due to its natural availability or runoff through agricultural areas, where there is accumulation of lead in the soil by the use of fertilizer. The accumulation of Pb in agricultural land in Thoi Lai District, Can Tho was also recorded by Nguyen (2021b). There was no detection of Hg in groundwater in the study area during the study period.

Coliforms in groundwater had a considerable spatiotemporal variation which ranged from below the detection limit to 23 MPN/100 mL (Table 3). The average density of coliforms in the dry season (8.63±6.65 MPN/100 mL) was higher than that in the rainy season (4.96±3.89 MPN/100 mL). Coliform density in most of the monitoring sites (24/27 sites) exceeded the permissible limit. The problem of coliform contamination was also previously reported in the study area in 1999-2002 (Huynh et al., 2016). This could be indicative of pollution from inadequate sanitation systems and infiltration of polluted urban runoff entering groundwater wells. Microbial contamination of groundwater in the Mekong Delta has been reported in several previous studies (Phan and Nguyen, 2018; Nguyen, 2021a). As a result of poor well protection and maintenance, microbial contaminants from septic tank leakage, agricultural runoff, wild animals, and cattle faecal matter can enter aquifers.

3.2 Groundwater quality index (GWQI)

The results of computed GWQI showed that there was a little variation between the dry season and rainy season in the study area, as presented in Figure 2. The GWQI values in the dry season were varied from 0.04 to 5.68, which was slightly higher than that in the rainy season (0.00-0.35). This difference was associated with the high concentration of Cl^-, SO_4^{2-}, COD, As, Pb, and coliforms in the dry season. In general, the groundwater quality in the study area is at an excellent level on the basis of calculated GWQI values and is potable for human consumption.

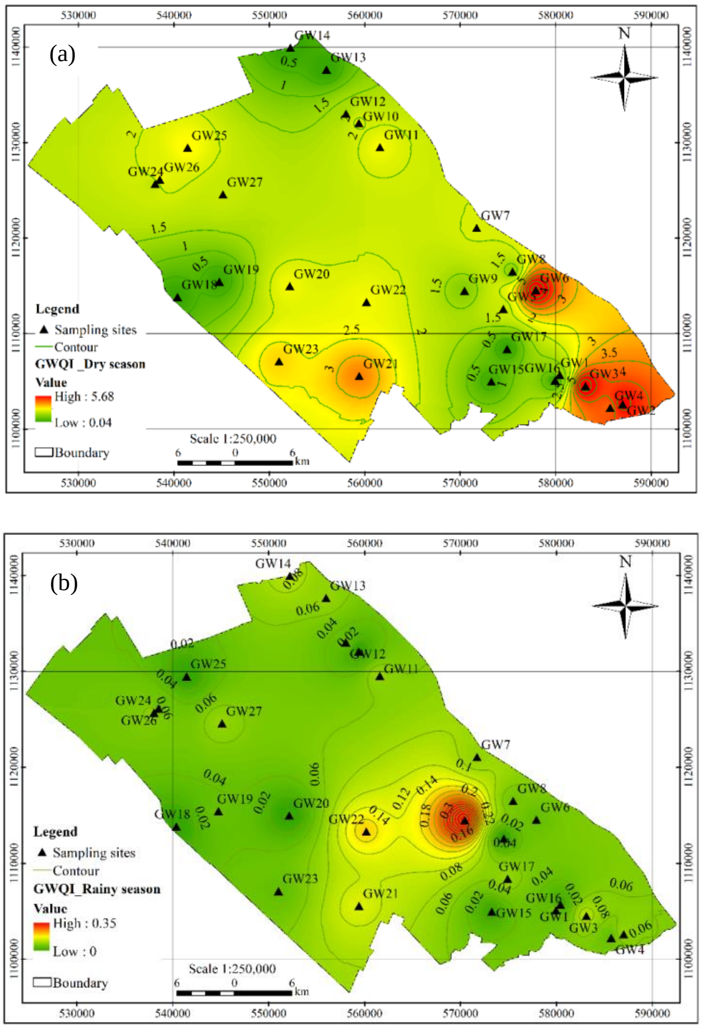

Figure 2. GWQI distribution map in (a) the dry season and (b) the rainy season

As illustrated in Figure 2, groundwater in the southeast of Can Tho City including GW2, GW3, GW4, and GW6 tended to be more polluted than the other wells in the dry season. These monitoring sites were in Ninh Kieu, Binh Thuy, and Cai Rang Districts where there are several residential areas and industrial areas as well as diverse economic activities (Vo et al., 2020). Moreover, overexploitation of groundwater in the dry season could cause the depletion of the water table and increase saline water intrusion into these areas (MoNRE, 2021). Only GW9 had slightly higher GWQI value in the study area in the rainy season because of considerable higher coliform density, NO_3^- and total Fe concentration. It means that wells in this area were not adequately protected, which caused the contamination from human sewage, livestock wastewater, or animal droppings. Thus, comminated groundwater could be the result of overexploitation, improper waste disposal or improper well maintenance in the long-term use.

3.3 Cluster analysis (CA)

Two dendrograms were created using the results of groundwater quality at different monitoring sites in the dry and rainy seasons, as showed in Figure 3. In the same distance (D_{link}/D_{max}<30), while the groundwater monitoring sites were divided into 9 clusters in the dry season, those sites were into 5 clusters in the rainy season.

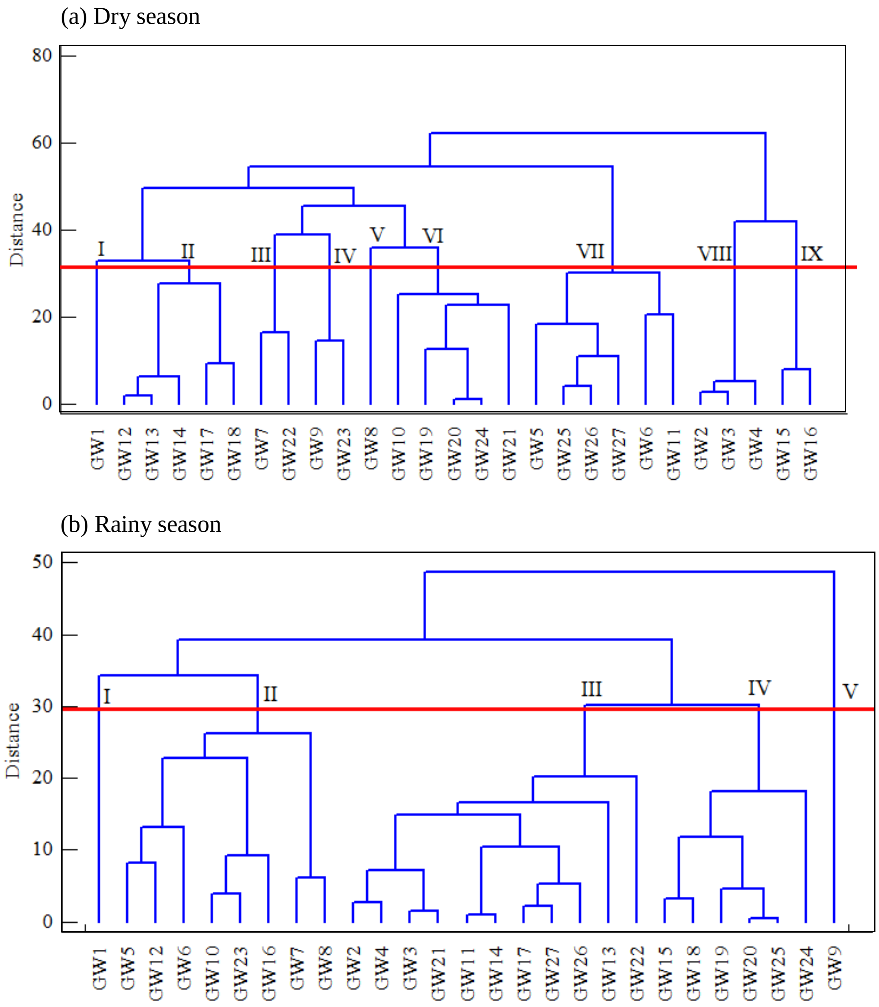

Figure 3. Water quality clustering based on seasonal parameters

The groundwater quality characteristics of each cluster are presented in Table 4. It can be seen that there was a more significant spatial variation in groundwater quality in the dry season than that in the rainy season.

In the dry season, the cluster II comprised of five monitoring sites (GW12, GW13, GW14, GW17, and GW18) located at high terrain in two districts of Co Do and Thot Not. The groundwater of these monitoring sites was polluted by coliforms, which could be the result of domestic waste leakages, animal fecal matters, and improper well protection. The monitoring sites in the cluster III, IV, and V are located in O Mon and Thoi Lai Districts, with similar economic development and land-use types. The presence of metalic compounds containing Fe, Mg, As, and Pb in these clusters could be attributed to mineral dissolution from industrial and agricultural areas into the aquifers. High Cl^- concentration was found in the cluster III, which means that saltwater intrusion strongly affects groundwater quality in GW7 and GW22. Coliform density in groundwater was extremely high the cluster IV and VI. Cluster VII included GW5, GW6, GW11, GW25, GW26, and GW27 belong to rural areas with the majority of agricultural practices and intensive fertilizer uses that resulted in high SO_4^{2-} in this cluster. The cluster VIII are located in the urban and industrial production areas facing the chloride pollution in groundwater caused by saltwater intrusion in the dry season. Very high coliform density was detected in groundwater in the cluster IX (GW15 and GW16), which belongs to the perennial crop area in Phong Dien District. The presence of coliforms in the groundwater indicated the protection and manitenance of groundwater wells are not appropriate.

Table 4. Mean values of water quality parameters for each cluster

Season	Cluster	pH	Color	Hardness	Cl^-	SO_4^{2-}	COD	Mg	Fe	NO_3^-	As	Pb	Coliform
Dry	I	7.20	10.00	57.60	62.80	36.90	2.10	0.29	0.27	0.10	0.00	1.60	4.00
	II	7.35	12.00	32.12	92.92	55.04	5.74	0.06	0.58	0.03	0.26	0.32	7.40
	III	7.52	6.50	12.00	222.20	95.45	8.50	0.20	0.96	0.00	0.00	2.35	5.50
	IV	7.60	11.00	22.90	28.05	43.30	4.25	0.22	0.56	0.63	1.65	1.95	15.00
	V	7.47	143.00	32.00	91.90	51.40	6.40	0.10	1.34	0.00	0.00	1.40	4.00
	VI	7.39	32.80	30.68	81.58	68.42	5.74	0.11	1.51	0.58	0.00	2.02	13.20
	VII	7.40	24.50	33.93	105.55	121.62	3.18	0.12	0.21	0.62	0.98	3.00	4.17
	VIII	7.14	18.33	55.87	310.63	19.93	4.97	0.11	0.43	0.13	1.33	5.07	7.33
	IX	7.24	8.00	56.90	325.50	23.70	2.65	0.06	0.48	0.06	2.15	0.00	17.00
Rainy	I	7.20	2.00	240.00	146.60	28.40	-	0.13	0.06	0.00	-	-	0.00
	II	7.39	10.00	105.00	23.00	43.29	1.33	0.13	0.12	0.09	-	-	3.38
	III	7.22	6.64	138.64	18.95	12.05	2.79	0.12	0.13	0.20	-	-	7.91
	IV	7.46	5.17	216.67	18.10	14.45	4.25	0.15	0.13	0.32	-	-	1.83
	V	-	-	-	-	2.00	7.81	2.00	70.00	19.50	-	-	9.00

Only five clusters were obtained on the basis of groundwater quality parameters in the rainy season. The cluster IV was an assemblage of monitoring sites (GW15, GW18, GW19, GW20, GW24, and GW25) located in low terrain and far from large rivers; thus, this limits the movement of pollutants from surface water into aquifers. This cluster is considered insignificant pollution in groundwater. The cluster II was comprised of eight monitoring sites (GW5, GW12, GW6, GW10, GW23, GW16, GW7, and GW8) located along the Hau River. Groundwater in this cluster was polluted by coliforms. The GW1 location was categorized into a separate cluster in both seasons, with relatively good groundwater quality but slightly contaminated with coliforms in the dry season. Nevertheless, in the rainy season, the hardness of groundwater became higher than in other clusters. Industrial waste and subsurface geological structure could be the souces calcium and magnesium that directly contributed to the hardness of groundwater.

Besides, CA analysis also showed that groundwater characteristics are similar for the districts in Can Tho City; this can be applied to reduce the number of samples to save budget and time. For example, a sampling sites may be removed when the location has the same grouping and the same district. Specifically, Cluster II included five locations in Thot Not, Phong Dien and Co Do Districts in the dry season; this cluster can be reduced to three samples in the next groundwater quality monitoring. Cluster III and cluster IV had two locations in each cluster, namely GW7 and GW22 (cluster III), GW9 and GW23 (cluster IV); however, GW7 and GW22 are located in two separate districts (O Mon and Thoi Lai Districts). Therefore, these four sampling sites will still be retained for future monitoring. The removal of samples was performed similarly for the remaining clusters. Thereby, the number of samples can be reduced from 27 to 18 (dry season) and 15 (rainy season) samples; which can save about 33.3% and 44.4% of the total budget, respectively.

3.4 Principal component analysis (PCA)

The PCA results showed that 4 PCs and 3 PCs contributed significantly to groundwater quality variation in the dry and rainy season, respectively, presented in Table 5. In the dry season, 4 PCs could explain 63.4% of total groundwater quality groundwater variation in the study area. PC1 explains 24.8% of the variance and has weak correlations with pH (-0.469), Cl^- (0.415), and As (0.309) and moderate correlation with total hardness (0.52). Groundwater hardness is associated with the dissolution of calcium or magnesium-bearing rock, industrial effluent or agricultural activities. The presence of Cl^- in groundwater could be the result of both natural and anthropogenic sources such as seawater intrusion and excessive application of inorganic fertilizers (Nguyen et al., 2017). The alkalinity of groundwater could be affected by agricultural leachate, detergents and industrial wastes (Hoko, 2008).

PC2 accounted for 17.5% of the total variation and had a weak correlation with groundwater parameters. It had a negative coefficient with COD (-0.443) and total Fe (-0.365), and a positive coefficient with Mg (0.302), NO_3^- (0.424), As (0.312), and Pb (0.335). The presence of metallic compounds in groundwater could be from mineral dissolution from industrial sites. Because as reported by Tran et al. (2021), overexploitation of groundwater has resulted in land subsidence (4.28 cm/year) as well as the release of As and possibly other heavy metals.

PC3 explained 10.7% of total variation and had weak correlations with Fe (0.352) and NO_3^- (0.430) and medium correlation with coliforms (0.678). The high positive loading coliform is due to the feces of warm-blood animals and humans; especially residential area. In addition, nitrate has shown the use of nitrogen-based fertilizers in the study area; which has been converted into nitrite and nitrate by microorganisms for the growth of plants. The contribution of nitrogen from agricultural sources has also been reported in previous studies (Wagh et al., 2019; Kadam et al., 2021c). PC4 accounted for 10.3% of total variation and was correlated with color (0.539) at medium and SO_4^{2-} (0.310) at weak.

Table 5. Key variables influencing groundwater quality in Can Tho City

Variables	Dry season				Rainy season		
	PC1	PC2	PC3	PC4	PC1	PC2	PC3
pH	**-0.469**	-0.028	-0.129	-0.244	**-0.443**	-0.041	-0.139
Color	-0.107	-0.256	0.236	**0.539**	-0.153	**0.588**	0.02
Hardness	**0.520**	-0.014	0.19	0.249	-0.231	**-0.467**	-0.06
Cl^-	**0.415**	-0.175	-0.081	0.105	-0.14	**-0.354**	**0.607**
SO_4^{2-}	-0.287	0.277	0.032	**0.31**	-0.122	**0.391**	**0.325**
COD	-0.119	**-0.443**	-0.279	**-0.317**	0.246	**-0.342**	**-0.397**
Mg	-0.108	**0.302**	-0.068	0.209	**0.449**	0.023	0.173
Fe	-0.232	**-0.365**	**0.352**	0.187	**0.451**	0.011	0.17
NO_3^-	-0.239	**0.424**	**0.43**	-0.072	**0.451**	0.002	0.165
As	**0.309**	**0.312**	0.073	**-0.349**	-	-	-
Pb	0.082	**0.335**	-0.164	0.051	-	-	-
Coliforms	0.064	-0.131	**0.678**	**-0.416**	0.154	0.197	**-0.509**
Eigenvalues	2.98	2.11	1.29	1.23	4.67	1.46	1.26
%Variation	24.8	17.5	10.7	10.3	46.7	14.6	12.6
Cum.%Variation	24.8	42.4	53.1	63.4	46.7	61.3	73.9

In the rainy season, the results of PCA could explain 73.9% of the variation in groundwater quality in the study area with 3 PCs. PC1 accounts for 46.7% of the total variation obtained with a weak correlation to groundwater parameters. It had a positive coefficient with Mg (0.449), total Fe (0.451), NO_3^- (0.451), and a negative coefficient with pH (-0.443). NO_3^- indicated the groundwater pollution sources could be from excessive application of fertilizers in the agricultural areas. Before reaching the aquifer, water can pass through limestone or gypsum and dissolve magnesium and iron, hence carrying it into groundwater. Moreover, industrial effluent and sewage can also be sources of magnesium and iron pollution. PC2 explains 14.6% of the total variation including color (0.588) with moderate correlation and weak correlation with hardness (-0.467), Cl^- (-0.354), SO_4^{2-} (0.391), and COD (-0.342). PC3 was weakly correlated with SO_4^{2-} (0.325), COD (-0.397), and correlated at medium with Cl^- (0.607) and coliforms (-0.509). Many sources can be contributed to the Cl^- and SO_4^{2-} groundwater pollution including industrial effluent, fertilizer application, and other anthropogenic activities.

It can be deduced that groundwater quality in the study area was influenced by different sources such as geological conditions (specifically the problem of serious land subsidence), agricultural activities in Thoi Lai, Co Do and Phong Dien District. While sources from industrial zones and residential areas are identified as potential sources of Binh Thuy (GW5 and GW6), Ninh Kieu (GW1), and Cai Rang (GW2-GW3) Districts. In addition, all analyzed parameters play an important role in evaluating groundwater quality and should be remained in the later monitoring program.

4. CONCLUSION

The groundwater in Can Tho City in 2019 was polluted by coliforms at all sampling sites in both seasons and by COD and Cl^- in several monitoring sites in the dry season. Groundwater quality in all monitoring sites was classified at the excellent level and groundwater in the southeast area of Can Tho tended to be more polluted in the dry season. CA results divided 27 monitoring sites into 9 clusters in the dry season and 5 clusters in the rainy season, which also confirmed more spatial variation of groundwater in the dry season. The result of CA could be used for considering reduction of the monitoring site by 9 sites (dry season) and 12 sites (rainy season). The results of PCA revealed that four PCs and three PCs could explain 63.4% in the dry season and 73.9% in the rainy season, respectively. All analyzed parameters were significantly contributed to the groundwater variations due to the influence of subsurface geological characteristics, industrial effluent, domestic waste, and agricultural practices. The findings in the current study could provide useful information for future groundwater monitoring and management.

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