Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 9, No. 03, March, 2023

Seasonal Variations in Groundwater Quality under Different Impacts Using Statistical Approaches

Giao Thanh Nguyen [1*], Nhien Thi Hong Huynh [1]

[1] *College of Environment and Natural Resources, Can Tho University, Can Tho City 900000, Vietnam.*

Received 19 December 2022; Revised 12 February 2023; Accepted 21 February 2023; Published 01 March 2023

Abstract

The objective of this study was to evaluate seasonal fluctuations in groundwater quality, determine the effects of different stressors on this resource, and recognize the potential pollution sources in a coastal region of southern Vietnam. Eleven samples collected in Ben Tre province during the dry and wet seasons were then analyzed for sixteen parameters, including pH, total dissolved solids (TDS), salinity, total hardness (TH), ammonium (NH_4^+-N), nitrite (NO_2^--N), nitrate (NO_3^--N), sulfate (SO_4^{2-}), chloride (Cl^-), iron (Fe), manganese (Mn), lead (Pb), mercury (Hg), arsenic (As), coliforms, and Escherichia coli (*E. coli*). Pearson correlation analysis, principal component analysis (PCA), and cluster analysis (CA) were employed. The results indicated that total dissolved solids, salinity, total hardness, Cl^-, *E. coli* and coliform were detected as contaminants in groundwater samples. The trend of fluctuations in the parameters was mostly higher in the dry season. Which Mn and coliform significantly fluctuated between the dry and wet seasons. Activities in industrial-craft areas, landfills and seawater-intruded areas negatively impacted groundwater quality, typically TDS in industrial-craft areas, coliform and *E.coli* at the landfill area. Six principal components obtained from PCA could explain 93.6% of the variance, and all parameters are responsible for variations in groundwater quality. Geology, discharged wastewater, landfill leachate, agricultural activities, and saltwater intrusion can be considered representative factors. CA grouped the collected samples into four clusters based on the similarity in water properties. The analysis results showed that the locations in each cluster have outstanding water quality characteristics, clusters I and III have high TDS characteristics, cluster II has coliforms, and cluster IV sets of locations with high salinity. This study is promised to partially fill the gap in comprehensive information on groundwater quality in the coastal province so that policymakers can develop sustainable water management strategies in the future.

Keywords: Ben Tre; Coastal Area; Coliform; Groundwater; Seasonal Variation.

1. Introduction

Groundwater is indeed a crucial freshwater source in coastal areas [1]. Unfortunately, anthropogenic activities have significantly contributed to the deterioration of groundwater sources [2, 3]. Besides, the physicochemical properties of groundwater are controlled by natural factors such as weathering of rock and precipitation [4-6]. The groundwater source in the coastal region of the Mekong Delta is deemed vulnerable to anthropogenic activities, including agricultural production, dam construction, as well as the effects of climate change [1, 7-9]. In addition, the report of Xiao et al. (2021) [10] has shown that groundwater quality degradation due to saline intrusion is an important problem in the Mekong Delta. According to Zhang et al. (2017) [11], seawater intrusion in the south-eastern Arabian Peninsula has caused the degradation of groundwater quality, which is predicted to be even more serious with global warming. Groundwater contamination has recently attracted more attention due to its serious impacts on the ecosystem and human health [12, 13]. In which groundwater quality (specifically the chemical composition of water) is considered the standard showing the suitability of groundwater for different purposes [14]. For example, nitrate

* Corresponding author: ntgiao@ctu.edu.vn

http://dx.doi.org/10.28991/CEJ-2023-09-03-01

(NO_3^--N) is one of the common pollutants in groundwater, which enters groundwater through diffusion, absorption of liquids from on-site sanitation systems, sludge treatment operations, waste, and agriculture [15-17]. Another problem reported in the research of Le Luu (2019) [18] was the high level of total coliform in groundwater samples in urban areas of the Mekong Delta. Nevertheless, the previous studies only focused on assessing quality by comparing with Vietnamese standards or evaluating certain parameters, typically heavy metals [19, 20]. In addition, studies are almost exclusively aimed at assessing reserves, vulnerability [21], or predictive models of saline intrusion [10, 22, 23]. The research by Nguyen et al. (2015) [22] performed cluster analysis based on hydrogeochemical data. However, this analysis is only done in different aspects of hydrology. In addition, the approach to multivariate statistical analysis methods is mainly carried out for the surface water environment [24–26]. Up to now, there has been a lack of comprehensive studies on seasonal variations in groundwater quality in coastal provinces of the Mekong Delta, Vietnam.

Ben Tre, a coastal province, is situated in the Mekong Delta of southern Vietnam. The topography of Ben Tre province has an average elevation of 1-2 m above sea level. The lowland part is less than 0.5m, concentrated in coastal districts such as Binh Dai, Ba Tri, and Thanh Phu. The province has four main soil groups: sandy (accounting for 6.4% of the total area), alluvial (26.9%), alkaline (6.74%), and saline (about 43.11%). Local water resources include rainfall, surface water, and groundwater. An interlaced river system in the province has facilitated sufficient water supply for domestic, agricultural, industrial, and aquaculture activities [27]. However, the surface water quality of the province is gradually polluted [28]. The majority of wastewater from urban areas and industrial parks has not been collected and treated thoroughly before being discharged into the environment. Moreover, under the impacts of climate change, such as sea-level rise and salinization, freshwater resources in the province are increasingly depleted [29]. Due to the inadequate supply of surface water, the demand for groundwater has sharply increased to ensure domestic and production activities (over 80% freshwater demand). The total quantity of groundwater exploited reached approximately 2.5 million m^3 day^{-1} in the Mekong Delta [10]. However, the groundwater reserve is limited, with only about 32,640 m^3 day^{-1} in Ben Tre Province, most of which are distributed at depths above 200 m [29]. The Mekong Delta has about 9,650 wells with a scale of over 10 m^3 day^{-1}. In addition, there are about one million individual wells with household scales. In which, there are more than 15% of privately dug wells cannot be used because of improper drilling in the Mekong Delta [30]. On the other hand, in the coastal districts of the Ben Tre province, saline water from the sea easily penetrates into the aquifer, causing salinization of the groundwater. It can be seen that these groundwater sources are facing many threats to deteriorate their quality, especially in the coastal areas.

Based on the above, it is very important to analyze and evaluate groundwater quality to protect the groundwater environment from pollution. In addition, each area has its own causal factors for variation in groundwater quality, and it is essential to assess groundwater quality in each area. Moreover, the application of multivariate statistical approaches promises to provide more useful information about groundwater quality, consequently supporting general water management strategies. Therefore, this study focuses on (1) evaluating the seasonal variations in groundwater quality, (2) analyzing the different impacts on water quality, and (3) recognizing the potential pollution sources in a southern coastal province.

2. Materials and Methods

2.1. Description of the Study Area

Ben Tre province is located in the Mekong Delta region. Because of low precipitation, the primary freshwater sources for domestic and production activities are surface water and groundwater. The province has been characterized by abundant surface water sources from >100 rivers and canals that are distributed throughout the mainland. However, it is seriously affected by salinity in the dry-season months. Ben Tre province has a tropical monsoon climate with two distinct seasons: the rainy season (from May to October) and the dry season (from November to April). According to the Vietnamese nomenclature, the aquifer system includes 8 hydrogeological units: Holocene (qh), Upper Pleistocene (qp_3), Middle-Upper Pleistocene ($qp_{2\ 3}$), Lower Pleistocene (qp_1), Middle Pliocene ($n_{2\ 2}$), Lower Pliocene ($n_{2\ 1}$), Upper Miocene ($n_{1\ 3}$), and Upper-Middle Miocene ($n_{2\ 3}$) [31].

2.2. Groundwater Sampling and Analysis

Data on physicochemical, microbial, and heavy metal parameters in 2020 at 11 groundwater monitoring locations were collected from the Department of Natural Resources and Environment of Ben Tre province. Eleven groundwater samples were collected twice in March (dry season) and September (wet season). The groundwater parameters measured for this study are pH, total dissolved solids (TDS, mg L^{-1}), salinity (‰), total hardness (TH, mg L^{-1}), ammonium (NH_4^+-N, mg L^{-1}), nitrite (NO_2^--N, mg L^{-1}), nitrate (NO_3^--N, mg L^{-1}), sulfate (SO_4^{2-}, mg L^{-1}), chloride (Cl^-, mg L^{-1}), iron (Fe, µg L^{-1}), manganese (Mn, µg L^{-1}), lead (Pb, µg L^{-1}), mercury (Hg, µg L^{-1}), arsenic (As, µg L^{-1}), coliform (MPN 100mL^{-1}), and *Escherichia coli* (*E. coli*, MPN 100mL^{-1}). Samples were collected in the areas of industrial clusters and craft villages (denoted as GW1-GW3), in the waste dump areas (GW4-GW8), and in saline-intruded areas (GW9-GW11) (Figure 1). Groundwater samples at the wells were collected after pumping for 5-10 minutes to remove all impurities in the pipes. Samples from GW1-8 were measured for all parameters except salinity, which these locations are not directly and permanently affected by seawater. Meanwhile, sampling locations to observe the impacts of seawater intrusion were analyzed for pH, salinity, TH, NH_4^+-N, and coliforms. pH and salinity were measured directly in the field using hand-held meters. The remaining parameters were analyzed in the laboratory of the Center of Natural Resources and Environment Survey in Ben Tre province according to standard methods [32]. The heavy metal was analyzed by Atomic Absorption Spectroscopy (GTA 120 Graphite Tube Atomizer). These methods are clearly presented in Table 1. All methods and materials were certified by the Ministry of Natural Resources and Environment (2020) [33]. Moreover, the system of bio-chemistry laboratories is also ISO/IEC 17025:2005-VILAS 1000 accredited by the Ministry of Science and Technology.

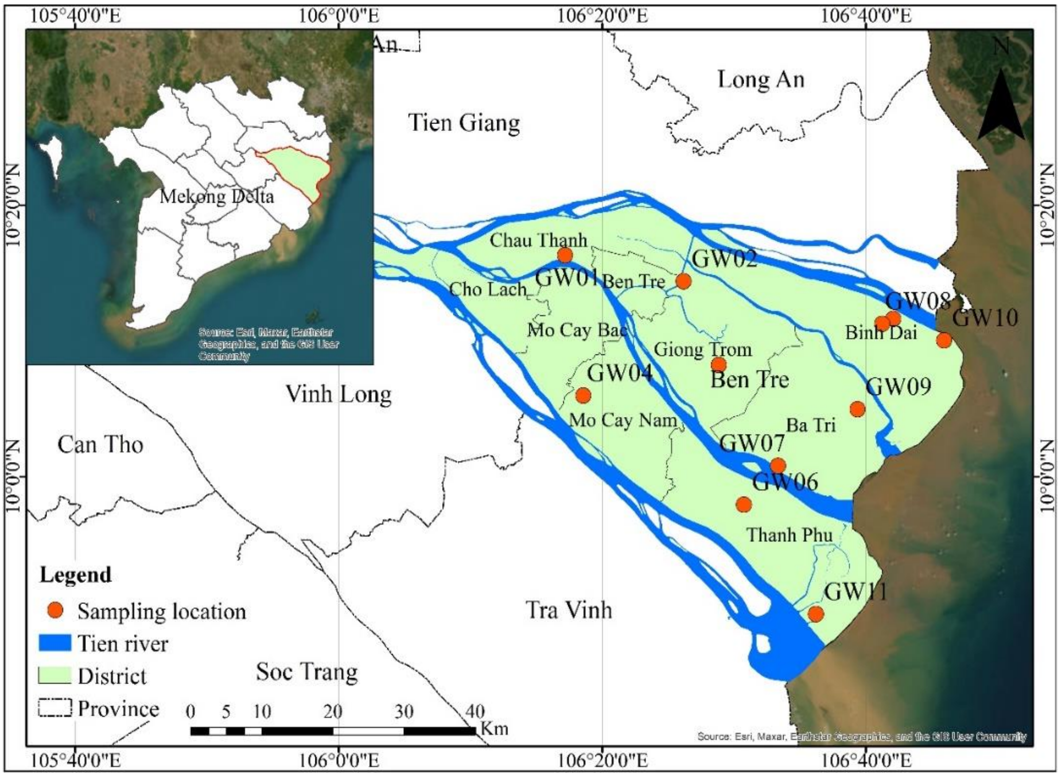

Figure 1. Map showing the sampling locations in Ben Tre province

Table 1. Methods of analyzing parameters

No.	Par.	Unit	Methods	Detection limit	Permissible limit in Vietnamese standard
1	pH	-	TCVN 6492:2011	2-12	5.5-8.5
2	TDS	mg L^{-1}	SOP-HT-05	0-199900	1500
3	Salinity	‰	SMEWW 2520B:2017	0-36	-
4	TH	mg L^{-1}	SMEWW 2340C:2017	3	500
5	NH_4^+ -N	mg L^{-1}	SMEWW 4500- NH_3.B&F:2017	0.03	1
6	NO_2^--N	mg L^{-1}	TCVN 6178:1996	0.02	1
7	NO_3^--N	mg L^{-1}	SMEWW 4500-NO_3^-.E:2017	0.03	15
8	SO_4^{2-}	mg L^{-1}	SMEWW 4500-SO_4^{2-}.E:2017	1	400
9	Cl^-	mg L^{-1}	SMEWW 4500.Cl^-.B:2017	2	250
10	Fe	µg L^{-1}	SMEWW 3111B:2017	30	5000
11	Mn	µg L^{-1}	SMEWW 3111B:2017	30	500
12	Pb	µg L^{-1}	SMEWW 3113B:2017	2	10
13	Hg	µg L^{-1}	SMEWW 3112B:2017	0.3	1
14	As	µg L^{-1}	SMEWW 3114B:2017	0.1	50
15	Coliform	MPN $100mL^{-1}$	TCVN 6187-2:1996	3	3
16	*E.coli*	MPN $100mL^{-1}$	TCVN 6187-2:1996	3	No detected

2.3. Data Analysis

One-way ANOVA analysis was done to determine the statistically significant difference in groundwater parameters between seasons and different impacts ($p<0.05$). Pearson correlation analysis was performed to determine the relationship between physicochemical parameters, microorganisms, and heavy metals in groundwater. The statistical analyses were performed using IBM SPSS Statistics ver. 20 software. The groundwater quality was also compared with QCVN 09-MT:2015/BTNMT–Technical regulation on groundwater quality in Vietnam [34].

The average values of groundwater quality parameters were used for the principal component analysis (PCA) and cluster analysis (CA). PCA is widely used to reduce data and extract a small number of latent factors to analyze the relationship between observed variables to identify the main variables affecting groundwater quality and other factors. Factors with eigenvalues of 1 or more are considered important [35]. CA is a clustering method based on the similarity of groundwater properties at each location. It is often illustrated with dendrograms, providing a visual summary of the intuitive relationship between any positions [36, 37]. PCA and CA analysis were performed using STATISTICA software ver. 10. A summary of the data analysis method was shown in Figure 2.

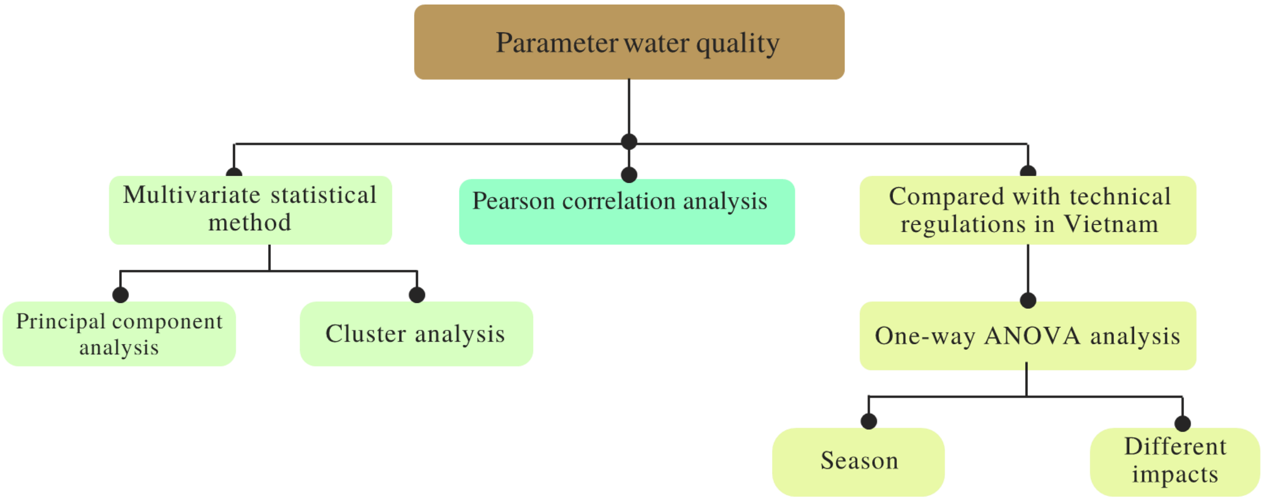

Figure 2. Summarize the process of the methodology

3. Results and Discussion

3.1. Seasonal Variation in Groundwater Quality

The fluctuation of analyzed groundwater quality parameters by season is illustrated in Figure 3. pH is a critical parameter that determines the solubility and bioavailability of nutrients, heavy metals, and other substances in water [38]. In Ben Tre province, the pH of groundwater ranged from 6.25-7.68, with a fluctuation in the dry season of 6.07-7.99 and the wet season of 6.42-7.62. pH values measured in the study area fluctuated from acidic to slightly alkaline, which is within the limits of QCVN 09-MT:2015/BTNMT (5.5–8.5) [34]. The analysis results show that the pH value in the rainy season tended to be higher than that in the dry season. This result was in contrast to the previous study by Giao et al. (2022) [39]. According to Giao et al. (2022) [39], the average groundwater pH in the dry and rainy seasons was 7.37±0.14 and 7.33±0.34 in Can Tho city, respectively.

TDS is deemed a salinity index of groundwater: TDS<200 mg L^{-1} is low salinity, 200-500 mg L^{-1} is medium salinity, 500–1500 is high salinity, and >1500 is very high salinity [40]. According to WHO (2017) [41], drinking water supplies containing more than 500 mg L^{-1} TDS are considered undesirable. TDS of groundwater in Ben Tre province greatly ranged from 709–20,250 mg L^{-1}. The findings of TDS in the dry and wet seasons varied from 696–20,500 mg L^{-1} and 722-20,000 mg L^{-1}, respectively. According to the Vietnamese standard on groundwater quality, the value of TDS is set to be lower than 1,500 mg L^{-1}. Only the TDS concentration at station GW03 was within this permissible limit. High TDS indicates high mineralization in the region and may distort the taste of the water [40, 41]. This indicated that dissolved substances (such as inorganic salts) from industrial activities may have contributed to the increased TDS. Based on the salinity classification, most groundwater samples collected in this coastal area were very high salinity. This is consistent with the study of Tran et al. (2021) [1]. That reported seawater intrusion has been found in both inland and coastal areas in Soc Trang province, with TDS of 82–12,950 mg L^{-1}, where Ben Tre is bordered. However, the lower TDS value in another neighboring province (Bac Lieu) was 286-715 mg L^{-1} [42].

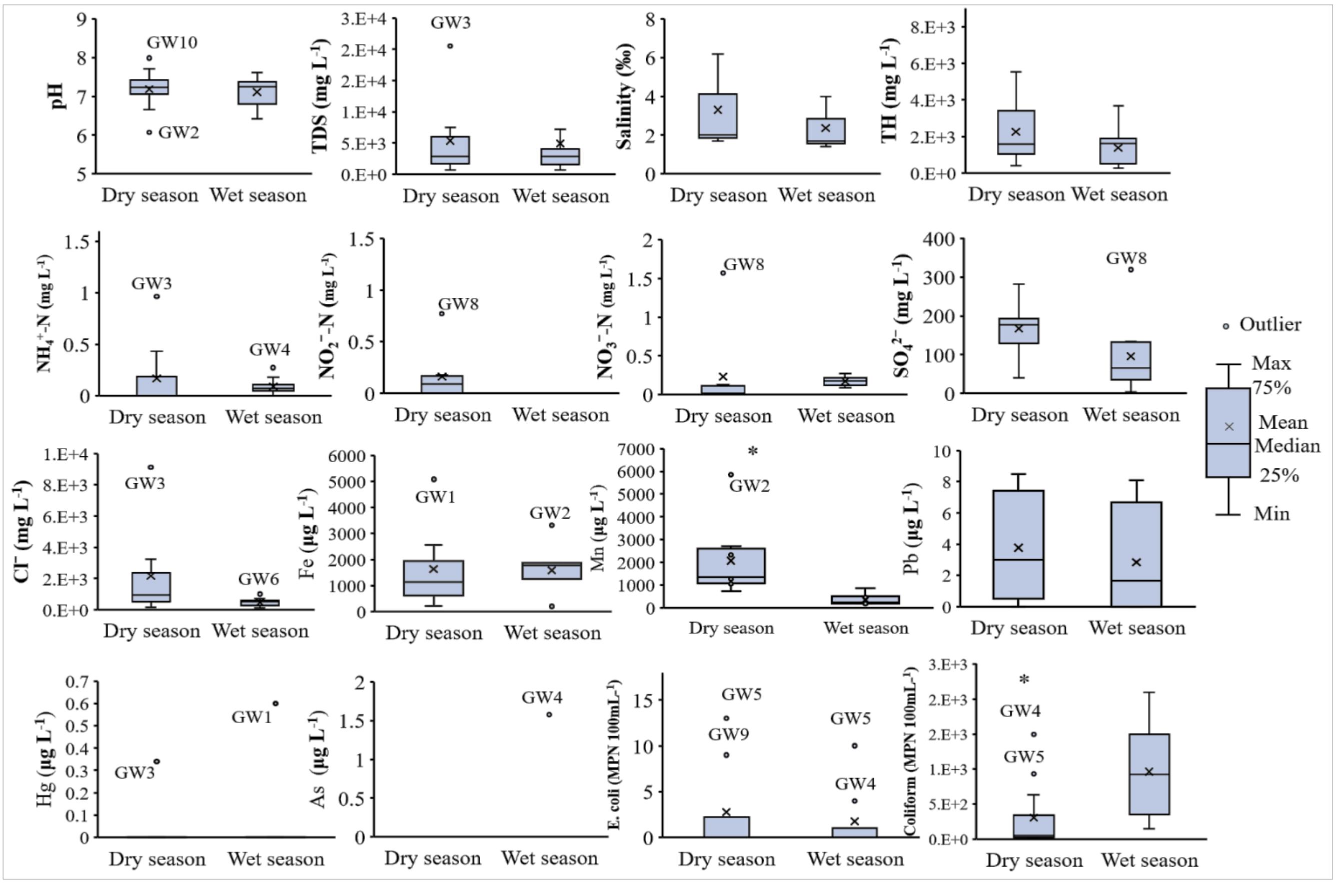

Figure 3. Seasonal variations in groundwater quality in Ben Tre province (*represents the statistically significant difference between seasons ($p<0.05$))

The salinity parameter was measured in observation wells nearby the coastline. The value found in the dry and wet seasons ranged from 1.70-6.20 ‰ and 1.40-4.00 ‰, respectively. It is in agreement with a previous study showing that saline intrusion during the dry season is a major concern in the Mekong Delta [43]. Nguyen and Vo (2022) [28] reported that the salinity in surface water during the dry season was remarkably high, ranging from 0.20-25.5 ‰. The percolation of surface water into aquifers can cause high saline groundwater. In addition, the weathering process can release high salt-contained minerals into the groundwater, such as granite, rhyme, and marine sediments. Common diseases associated with the consumption of saline groundwater are cardiovascular disease, diarrhea, hypertension, infant mortality and skin and respiratory diseases [44, 45].

TH in groundwater is due to the presence of calcium and magnesium cations and anions such as carbonate, bicarbonate, chloride and sulfate in the water [46]. The average of TH in groundwater ranged from 337.5-4,064 mg L^{-1}, which mostly exceeded the Vietnamese standard (500 mg L^{-1}). This figure in the dry season was 390-5,520 mg L^{-1}, which was relatively higher than in the wet season of 285-3,688 mg L^{-1}. This is similar to the results found in Shagamu industrial area [47] and in coastal aquifers of Kavaratti Island, Lakshadweep Archipelago (India) [48], where TH values were higher in the dry season. In the downstream Kotri area, the TH value in groundwater only fluctuates from 110-1,476 mg L^{-1} [49]. According to Alamdar et al. [50], TH is classified as follows: from 0-75 mg L^{-1} as soft, 75-150 mg L^{-1} as moderately hard, 150-300 mg L^{-1} as hard, and >300 mg L^{-1} as very hard. Thus, groundwater in the study area is graded as hard to very hard, which shows deteriorating groundwater quality situations for drinking purposes. High TH may be due to the process of percolating wastewater into groundwater [49]. Using water with high hardness can lead to cardiovascular diseases and reduce the quality of detergent, soap, and cleaning products [40].

The average concentrations of NH_4^+-N, NO_2^--N and NO_3^--N detected in Ben Tre province were within the Vietnamese limits (1 mg L^{-1}, 1 mg L^{-1}, and 10 mg L^{-1}, respectively). These N-containing compounds in the dry season were up to 0.96 mg L^{-1}, 0.77 mg L^{-1}, and 1.57 mg L^{-1}, respectively. Meanwhile, these values in the wet season were lower, especially the concentration of NO_2^--N which was below the detection limit. The results of this analysis are almost in contrast to previous studies [19, 51], which suggested that in the rainy season, there will be an increase in the release of nitrogenous compounds into groundwater. Overexploitation in the dry season can increase NH_4^+-N and NO_3^--N concentrations in groundwater and degrade water quality leading to the penetration of chemical fertilizers in agricultural areas.

The findings of SO_4^{2-} were within the standard (400 mg L^{-1}), ranging from 21.33-271.55 mg L^{-1}. While SO_4^{2-} concentration in the dry season varied from 39.42-281.86 mg L^{-1}, which was slightly higher than in the wet season (3.24-319.73 mg L^{-1}). This can be seen as an indication that SO_4^{2-} has been contributed from seawater because of the low rainfall and low water flow from upstream in the dry season, which facilitates the process of seawater intrusion. Cl^- concentration in Ben Tre province was in the range of 133.38-4,823 mg L^{-1}, which exceeded the permissible limit (250 mg L^{-1}). That ranged from 147.12-9,128.40 mg L^{-1} in the dry season and 119.64-1,006 mg L^{-1} in the wet season. Higher Cl^- concentration in the dry season is observed in the previous study [39, 48]. That concentration in the rainy season in Can Tho city was 15.30-146.60 mg L^{-1} lower than in the dry season (25.20-382.30 mg L^{-1}). Overexploitation of groundwater in the dry season could lead to the encroachment of seawater into aquifers, which partially increases Cl^- concentration. Another reason for less Cl^- concentration in the wet season can be an increase in dilution due to higher precipitation infiltration. Great variations in Cl^- concentration were detected in Soc Trang province, with the range of 2.9-15,883 mg L^{-1} [1]. High Cl^- and SO_4^{2-} content in groundwater in the study area has not only affected the quality of irrigation water but also the corrosion phenomenon and water distribution system.

The concentrations of Fe and Mn ranged from 700-3480 μg L^{-1} and 490-3030 μg L^{-1}, which was within the Vietnamese standard (5000 and 500 μg L^{-1}), respectively. However, Fe and Mn concentrations were estimated to exceed WHO drinking water guidelines (WHO) [41]; this finding was similar to the study by El-Nagdy and Abdel-Hameed (2022) [52] for Mn and Fe in groundwater in Mekong Delta. These concentrations in the dry season were in the range of 210-5080 μg L^{-1} and 720-5850 μg L^{-1}, respectively. Meanwhile, lower values of these metals were reported in the wet season by 200-3320 μg L^{-1} and 190-870 μg L^{-1}, respectively. This result was in contrast to the previous study in Can Tho city, where the average concentration of Fe in the dry season (690 μg L^{-1}) was lower than in the rainy season (2710 μg L^{-1}) [39]. Fluctuations of Mn and Fe concentrations in groundwater were found to be related to the pH value, mainly because heavy metal concentrations increase when the pH becomes acidic [53].

According to the Vietnamese standard, the permissible limits of Pb, Hg and As in groundwater are 10, 1 and 50 μg L^{-1}, respectively. In Ben Tre province, the concentrations of these heavy metals were within this standard. Pb and Hg in the dry season were detected up to 8.5 and 0.84 μg L^{-1}, respectively. These values in the wet season reached 8.1 and 0.06 μg L^{-1}, respectively. In the study period, As was only detected in the wet season in GW04 (1.58 μg L^{-1}), which is located near the landfill area. The increase of As in the wet season at the location near the landfill can be explained by the seepage of leachate. Compared with the groundwater quality in Can Tho city and Soc Trang province, the average concentrations of Pb in both seasons in this area were significantly higher [39, 51]. Although the concentrations of these metals were within the permissible limits, their presence can pose a threat to human health, especially Hg and As – carcinogenic substances [54, 55].

Coliform and *E. coli* are commonly used as indicators of bacterial and pathogen activity. Coliform density in the study area ranged from 165.5-1,933.1 MPN 100mL^{-1}, which far exceeded the standard (3 MPN 100mL^{-1}). Higher coliform densities were found in the wet season, ranging from 150-2,100 MPN 100mL^{-1}. The density of coliform in the dry season was in the range of 17-1,500 MPN 100mL^{-1}. According to the Vietnamese standard, groundwater should not have *E. coli*. However, GW04 and GW05 were detected *E. coli* ranging from 6.5-11.5 MPN 100mL^{-1}. The maximum densities of *E. coli* in the dry and wet seasons were 13 and 10 MPN 100mL^{-1}, respectively. The presence of Coliform and *E. coli* in groundwater indicated that surface impacts have negatively affected water quality through extraction sites. Microbial contamination in groundwater is widely observed in many regions in the Mekong Delta [39, 42, 56]. However, this problem has not been solved effectively, consequently putting local health in peril.

There were statistically significant differences in Mn and coliform between the dry and wet seasons ($p=0.01$ and $p=0.02$, respectively), while other differences were considered to be insignificant. However, it is urgent to deal with high TDS, salinity, TH and microorganisms in groundwater to ensure this freshwater source for human activities.

3.2. Spatial Variation in Groundwater Quality

Groundwater quality in three typical regions of Bac Lieu province is presented in Table 2. The average pH value measured in the saline-intruded areas (7.28±0.41) was slightly higher than in industrial and craft areas (7.07±0.67) and landfills (7.11±0.36). However, this difference was statistically insignificant ($p=0.69$). This result is consistent with previous studies because this is typical of coastal aquifers. For example, in Lai Chau Bay, China, groundwater under the influence of seawater intrusion is also relatively high and ranges from neutral to alkaline (7-8.83) [57]. Similarly, according to Satheeskumar et al. (2021) [58], pH was most concentrated in seawater intrusion. This value is similar to some other coastal provinces in the Mekong Delta, such as Ca Mau (7.93) [26], Bac Lieu (7.16-8.20) [42] and Soc Trang (6.64-7.83) [51]. The pH fluctuation can be explained by the terrain elevation above sea level. For example, a previous study by Ha et al. (2022) [20] reported that pH in groundwater is commonly observed in the high-altitude area (elevation > 5m above mean sea level).

Table 2. Spatial variations in groundwater quality

Parameters	Industrial-craft areas	Landfill	Saline-intruded areas
pH	7.07±0.67[a]	7.11±0.36[a]	7.28±0.41[a]
TDS	9770±8501.48[a]	2425.1±1424.38[b]	-
Salinity	-	-	1.4±1.9[a]
TH	2795.5±2069.62[a]	1210.5±972.64[a]	1864.17±897.68[a]
NH_4^+-N	0.24±0.36[a]	0.13±0.14[a]	0.02±0.03[a]
NO_2^--N	0.04±0.07[a]	0.11±0.24[a]	-
NO_3^--N	0.11±0.11[a]	0.26±0.47[a]	-
SO_4^{2-}	78.94±63.91[a]	163.2±96.80[a]	-
Cl^-	2406.27±3466.4[a]	682.33±617.94[a]	-
Coliform	165.5±160.01[a]	933.1±795.18[a]	607±648.20[a]
E. coli	ND	3.6±5.13	-
Fe	2220±1730[a]	1240±800[a]	-
Mn	1470±2180[a]	1060±890[a]	-
Pb	4.1±3[a]	2.8±4[a]	-
Hg	0.02±0.03	ND	-
As	ND	0.02±0.05	-

ND: Not detected. Different superscript letters indicate statistically significant differences between the areas affected by different activities at a significance level of 5% ($p<0.05$).

The findings of TDS in the industrial and craft regions were far higher than in the landfill sites and this difference was statistically significant ($p=0.01$). Only GW04 and GW05 in the landfill area were within the standard. It can be deduced that the impact of solid waste and wastewater from industrial zones and craft villages on groundwater TDS is very large. These activities primarily include the processing industry of agricultural products, seafood, garments, mechanics, and packaging. In addition, high TDS concentrations can be attributed to the presence of bicarbonates (HCO_3^-), carbonates (CO_3^-), SO_4^{2-} and Cl^-. Therefore, the difference in TDS content in spatial was also reflected through geological structures. Similar studies in coastal aquifers in other countries suggest high TDS with proximity to the coast [13]. High TDS in water can affect the taste, hardness, and corrosive properties of water and cause gastrointestinal irritation [49].

Salinity changes at three monitoring locations ranged from 1.4-6.2 ‰, with an average of 1.4±1.9 ‰. The highest salinity found at GW10 is very close to the sea, so it is easily affected by the influence of seawater infiltration into the groundwater. Saline intrusion is a significant threat to freshwater resources in coastal aquifers worldwide [29]. The situation of the saline water supply has affected the operation of businesses in industrial areas and craft villages, notably in several stages, such as domestic water for workers, factory sanitation, and washing water in the production stage. It is more serious in some factories with high water demand, including brewing, food, boiler, and fabric dyeing. Table 2 shows that TH is highest in industrial zones and craft villages (2,795.5±2,069.62 mg L^{-1}) and lowest in landfills (1210.5±972.64 mg L^{-1}). TH content has no statistically significant difference between these three areas ($p=0.10$). The value of TH found in the vicinity of Zhoukou landfill (China) ranged from 234-2,045 mg L^{-1}, depending on the sampling depth and distance from the landfill [59].

The NH_4^+-N content fluctuated in the range of 0.02-0.24 mg L^{-1}, the lowest in the area affected by saline intrusion and the highest in the industrial parks and craft villages. Statistical analysis showed that the NH_4^+-N concentration in groundwater in three different areas was statistically insignificant ($p=0.23$). NO_2^--N concentration was highly concentrated in the landfill areas with 0.11±0.24 mg L^{-1} and 2.75 times higher than in the industrial cluster and craft villages. However, this difference was statistically insignificant ($p=0.48$). The NO_3^--N concentration ranged from 0.11-0.26 mg L^{-1}, the lowest in the industrial and craft areas and the highest in the landfill areas. However, this difference was statistically insignificant ($p=0.47$). In another study, the concentration of NO_3^--N in the groundwater in the landfill area was very large, ranging from 20.4-60.5 mg L^{-1}, formed from leachate and landfill sanitation accumulated over time and entering groundwater [60]. Compared with several provinces in Mekong Delta, the concentrations of NH_4^+-N, NO_2^--N and NO_3^--N in the study area were significantly lower than in Soc Trang [51] and Bac Lieu provinces [42]. NH_4^+-N is formed mainly by wastewater from seafood processing, dried fish in the study area and the decomposition of various N-containing organic compounds like proteins [61]. High levels of NH_4^+-N in water can lead to unpleasant odors and reduce the effectiveness of chlorine and other halogens in disinfection. Moreover, it is contributed to the enrichment of nitrite that can be converted to ammonia and increase the hazard in water treatment processes [62, 63]. Furthermore, the consumption of NO_2^--N-contaminated groundwater is likely to lead to serious diseases because it can react with secondary or tertiary amines to form nitrosamines that are considered carcinogens [64]. High NO_3^--N in groundwater is associated with poor septic tanks, untreated industrial and domestic wastewater, improper treatment, and indiscriminately littering. In addition, the variation of nitrogen compounds in the study area may be related to agricultural activities through irrigation water and fertilizer applications [20, 65]. Because the characteristics of agricultural development in Ben Tre are much lower than in Soc Trang and Can Tho sources [66-68], the risk of contamination in groundwater may be lower from this source.

The average SO_4^{2-} concentration ranged from 78.94-163.2 mg L^{-1}, and the landfill area with the presence of SO_4^{2-} is higher than the rest. However, the SO_4^{2-} content between the two regions was not statistically significant (p=0.08). In the surrounding area of Zhoukou landfill, SO_4^{2-} concentration varied from 46.9-380.0 mg L^{-1} [59]. This indicates leaching from landfills are a source of significant increase in SO_4^{2-} and cause of groundwater contamination. Compared with some other coastal provinces in the Mekong Delta [42, 51]. SO_4^{2-}concentration in the study area was found to be significantly lower. In the study of Adimalla (2019) [69], SO_4^{2-} content in groundwater in the coastal area of South India also ranged from 21-328 mg L^{-1}. The average concentration of Cl^- in the industrial areas and craft villages was 2,406.27 mg L^{-1}, which was higher than in the landfill sites. This difference was statistically insignificant (p=0.14). An increase in chloride ion concentrations in groundwater is caused by leaks from sewers and industrial wastewater.

The results also revealed that Fe, Mn, Pb and Hg concentrations were relatively high in the groundwater samples affected by industrial clusters, craft villages, and As affected by landfill sites. In Bac Lieu province, the concentrations of Fe and Mn were significantly lower than that of the study area, within the range of 40-120 μg L^{-1} and 10-60 μg L^{-1}, respectively [42]. Meanwhile, the As content in groundwater in Soc Trang, Long An and Tien Giang were found to be higher than in the study area [51, 70]. On the other hand, the As analysis results were similar to previous studies in Bac Lieu province [42], which did not detect As in groundwater. The difference in geological conditions can explain the variation in As concentration; for example, the soil in Long An has been recorded with a sulfuric horizon, and sulfuric acid is extracted from the soil leading to the release of As [70].

Coliform density found in the landfill areas was higher than in other regions. The average density in landfill, industrial-craft, and saline intruded areas was 165.5±160.01, 933.1±795.2, and 607±648.2 MPN $100mL^{-1}$, respectively. This difference was statistically insignificant (p=0.10). Sampling locations in the landfill areas detected *E. coli* in groundwater, ranging from 6.5-11.5 MPN $100mL^{-1}$. It can be seen that human activities in the industrial areas and craft villages have rather impacts on groundwater quality with TDS, TH, NH_4^+-N, Cl^-, and some heavy metals. In addition, uncontrolled landfills have greatly caused microbial contamination in groundwater.

3.3. Correlation between Groundwater Quality Parameters

A Pearson correlation matrix between groundwater quality parameters is presented in Figure 4. The correlation coefficient (r) is close to 1; that is, two parameters are related in a positive linear. In contrast, if it is close to -1, it means a negative linear correlation. When two parameters show a positive correlation, they have the same source. On the contrary, a negative correlation indicates different sources. The strong positive correlations are observed in TDS and Cl^- (r=0.71), NH_4^+-N and Cl^- (r=0.84), and NO_3^--N and NO_2^--N (r=0.91). The correlation between TDS and Cl^- was also found in the study of Ghimire et al. (2023) [71]. Moreover, total hardness had the moderate positive correlations with TDS (r=0.62), Cl^- (r=0.58), and Mn (r=0.42). The moderate negative correlations are observed in salinity with SO_4^{2-} (r=-0.49) and Fe (r=-0.46). In addition, other moderate correlations include TDS and Pb (r=0.46), TDS and NH_4^+-N (r=0.59), NH_4^+-N and Hg (r=0.43), SO_4^{2-} and Mn (r=0.44), and Cl^- and Pb (r=0.56). However, the relationship between SO_4^{2-} and Cl^- was not recorded; this was also reported in the previous study by Ha et al (2019) [53]. These strong correlations represent the impacts of anthropogenic sources on groundwater quality in the study area. This contamination is associated with the releases of domestic and industrial sewages, the leachate from improperly operated landfills, and seawater intrusion.

Par.	pH	TH	Sal.	TDS	NH_4^+	NO_2^-	NO_3^-	SO_4^{2-}	Cl^-	Fe	Mn	Pb	Hg	As	Coliform	*E. coli*
pH	1															
TH	-0.28	1														
Sal.	0.37	0.17	1													
TDS	-0.08	0.62**	-0.33	1												
NH_4^+	-0.19	0.38	-0.28	0.59**	1											
NO_2^-	0.03	-0.1	-0.18	-0.05	0.23	1										
NO_3^-	0	-0.13	-0.23	0	0.28	0.91**	1									
SO_4^{2-}	-0.06	-0.09	-0.49*	-0.05	0.04	0.42	0.31	1								
Cl^-	-0.12	0.58**	-0.25	0.71**	0.84**	0	-0.06	0.09	1							
Fe	-0.02	-0.22	-0.46*	0.09	0	0.4	0.35	0.25	-0.09	1						
Mn	-0.41	0.42*	-0.33	0.21	0.16	0.13	-0.03	0.44*	0.35	0.09	1					
Pb	0.22	0.18	-0.38	0.46*	0.39	0.1	0.11	0.17	0.56**	0.34	0.24	1				
Hg	0.23	0.03	-0.15	0.25	0.43*	-0.11	0.02	-0.09	0.41	0.03	-0.06	0.27	1			
As	-0.31	-0.24	-0.11	-0.12	0.15	-0.08	-0.01	0.08	-0.1	0.12	-0.11	-0.17	-0.07	1		
Coliform	-0.07	-0.42	-0.12	-0.29	-0.21	-0.26	-0.14	-0.22	-0.27	-0.21	-0.11	-0.03	-0.19	-0.14	1	
E. coli	0.09	-0.41	-0.22	-0.2	-0.06	0	-0.07	0.25	-0.17	0.12	0.31	0.08	-0.13	0.14	0.33	1

-1
0
1

Figure 4. Correlation matrix of 16 groundwater quality parameters in Ben Tre province (: correlations is significant at the 0.01 level, *: correlation is significant at the 0.05 level)**

3.4. Investigation of Important Parameters on Groundwater Quality and Potential Pollution Sources

The percentage variability of the data ranged from 6.9-29.5%, with 6 principal components (PC) explaining 93.6% of the total variance of the dataset (Table 3).

Table 3. Identification of key groundwater parameters

Variable	PC1	PC2	PC3	PC4	PC5	PC6
pH	0.061	-0.032	**-0.422**	**0.444**	-0.179	0.207
TDS	**-0.416**	-0.169	0.068	-0.023	-0.118	0.181
Sal.	0.264	**-0.320**	-0.197	-0.062	0.018	0.026
TH	-0.258	**-0.325**	0.060	**-0.316**	-0.087	-0.165
NH_4^+-N	**-0.388**	-0.050	0.056	-0.091	-0.035	**0.453**
NO_2^--N	-0.078	**0.369**	**-0.373**	-0.248	-0.103	0.048
NO_3^--N	-0.121	**0.348**	-0.352	-0.282	-0.088	0.133
SO_4^{2-}	-0.091	**0.491**	-0.059	-0.152	-0.104	-0.007
Cl^-	**-0.420**	-0.164	0.065	-0.035	-0.134	0.141
Coliform	0.230	0.119	**0.308**	0.158	**-0.526**	0.008
E. coli	0.081	0.270	**0.304**	0.275	-0.127	0.253
Fe	-0.221	0.287	0.002	0.259	**0.381**	**-0.363**
Mn	-0.195	0.192	**0.406**	-0.114	0.089	**-0.325**
Pb	**-0.322**	0.061	0.042	**0.394**	**-0.369**	-0.131
Hg	-0.266	-0.063	-0.229	**0.436**	**0.347**	-0.013
As	0.097	0.142	**0.307**	-0.001	**0.441**	**0.576**
Eigenvalues	4.7	3.6	2.5	1.9	1.2	1.1
%Variation	29.5	22.2	15.6	11.8	7.6	6.9
Cum. %Variation	29.5	51.7	67.2	79.1	86.7	93.6

The first component (PC1), which represents the highest percentage of variants (29.5%), had a weak negative correlation with TDS (-0.416), NH_4^+-N (-0.388), Cl^- (-0.420) and Pb (-0.322). In addition to the influence of natural factors like geogenic sources, this PC is also affected by anthropogenic sources such as wastewater with high detergent properties, rich in nutrients, and solid waste disposal. PC2 explained 22.2% of the variability of the original data set, was negatively correlated with salinity (-0.320) and TH (-0.325) and positively correlated with NO_2^--N (0.369), NO_3^--N (0.348) and SO_4^{2-} (0.491). All of them were weakly correlated. This factor can indicate the source of saltwater intrusion into the groundwater, and the source of nutrients can arise from leachate, septic tanks, and poor sanitary conditions. PC3 with a variance of 15.6%, had a negative correlation with pH (-0.422) and NO_2^--N (-0.373) and a weak positive relationship with coliform (0.308), *E. coli* (0.304), Mn (0.406) and As (0.307). These contaminants can also arise from septic tanks and breeding microorganisms in landfills; this was also reported in a previous analysis by Ghimire et al. (2023) [71]. PC4 displayed 11.8% of the total variance, with a significant relationship at a weak correlation with pH (0.444), Pb (0.394) and Hg (0.436) and TH (-0.316). PC5 explained 7.6% of the total variance, which correlated significantly with coliform (-0.526) and some heavy metals (Fe, Pb, Hg and As) at a weak level. Finally, PC6, with a variance of 6.9%, has a weak correlation with NH_4^+-N, Fe and Mn and a moderate correlation with As. Heavy metals can be from landfill waste, industrial sources, and the overuse of fertilizers in agriculture. Furthermore, previous research by Tweed et al. (2022) [72] demonstrated that As concentrations in the Mekong Delta region of Cambodia are mainly influenced by natural processes rather than by irrigation. In addition, several other studies in the Mekong Delta of Vietnam have also reported that As is mostly derived from soil weathering [56, 73]. In general, the environmental parameters contributing to the groundwater quality variation are from weak to moderate.

3.5. Cluster Analysis of Groundwater Sampling Locations

The results of cluster analysis using Ward's linkage method to group the sampling locations are illustrated in Figure 5. Eleven locations are classified into four clusters. Cluster I comprises GW3, which is located in Binh Thang commune, Binh Dai district, Ben Tre province. Cluster II includes three locations GW6, GW7, and GW8 are located in Thanh Phu, Ba Tri, and Binh Dai districts, respectively. These locations are located near the landfills of these districts. GW2 is classified into Cluster III that is close to Phong Nam industrial areas. The remaining locations (GW1, GW4, GW5, GW9-11) are grouped into Cluster IV, including saline-intruded areas, landfills, and industrial parks.

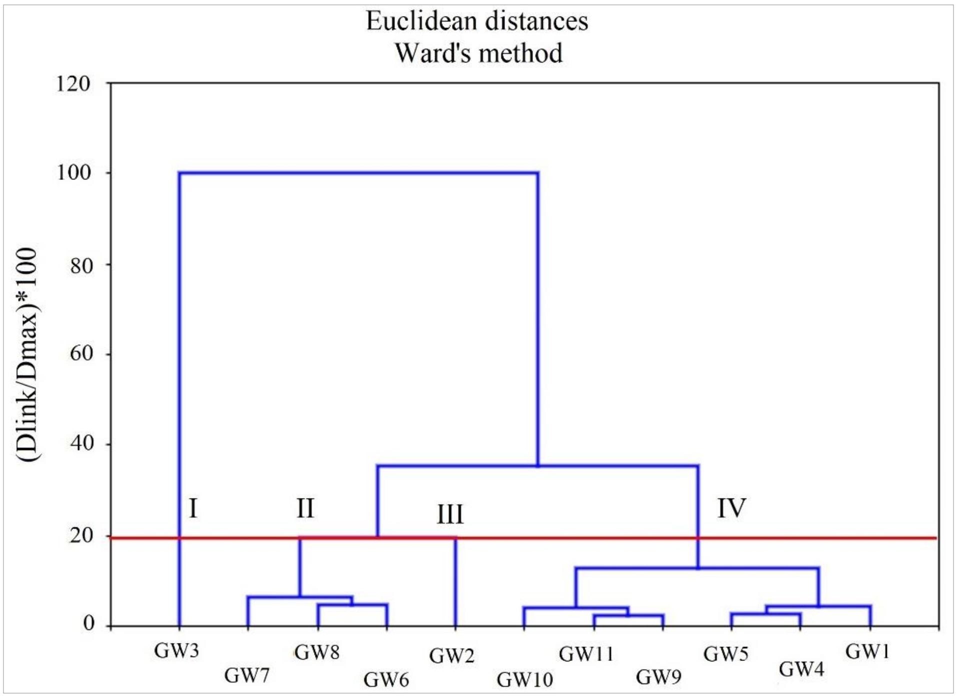

Figure 5. Dendrogram grouping the sampling locations based on their characteristics

The characteristics of groundwater quality in four clusters are described in Table 4. Cluster I is highly polluted by TDS, TH, Cl^- and coliform. Wastewater from seafood processing and dried fish activities can percolate into aquifers, which significantly contributes to this contamination in groundwater. Moreover, due to its coastal location, this has led to the enrichment of Cl^- via seawater intrusion. Cluster II is characterized by extreme pollution with coliform. The operation of uncontrolled landfills is the primary source of coliform contamination in groundwater. Besides, TDS, TH, and Cl^- problems in groundwater are also found in this cluster. Cluster III shared the groundwater pollution problems with Cluster I, but to a different extent. The contamination is associated with the activities of Phong Nam industrial areas. Groundwater sampling locations in Cluster IV detected an average salinity of 2.83% and *E. coli* of 6 MPN $100mL^{-1}$. Slight Cl^- pollution was also observed in Cluster IV. Seawater intrusion is responsible for the salinity in this cluster. Moreover, leachate from landfills containing *E. coli* can move into aquifers.

Table 4. Groundwater characteristics in four Clusters

Characteristics	I	II	III	IV
pH	7.31	7.1	6.25	7.30
TDS	20,250	3,326	7,345	1,286.8
Salinity	ND	ND	ND	2.83
TH	4,064	1,716	3,740	1,180
NH_4^+-N	0.52	0.13	0.14	0.06
NO_2^--N	0	0.16	0.02	0.06
NO_3^--N	0.1	0.36	0.05	0.13
SO_4^{2-}	21.33	175.38	111.52	131.28
Cl^-	4,823	1,011.1	1,876.5	299.11
Fe	960	1060	2220	2180
Mn	890	750	3030	1180
Pb	6.1	3.1	1.9	3
Hg	0.02	0	0	0.01
As	0	0	0	0.03
Coliform	104.5	866.83	240	673
E. coli	ND	ND	ND	6

4. Conclusion

The results of this study revealed seasonal variations, most significantly in Mn and coliform. Heavy metals and N-containing compounds in water tend to be higher in the dry season, while microorganisms tend to be higher in the rainy season. The problem of TDS, salinity, TH, Cl^- and microorganism contamination was detected in groundwater in Ben Tre province. TDS pollution was observed in the industrial and craft villages; coliform and *E.coli* contamination were most appreciated near the landfill site. Correlation analysis and PCA described the relationship between parameters and recognized the six potential pollution sources that can explain approximately 94% of the total variance. In which factors including geology, discharged wastewater, landfill leachate, agricultural activities, and saltwater intrusion are the main factors affecting most of the variation in water quality parameters. Based on the groundwater properties, 4 clusters were obtained from 11 sampling locations, with each cluster representing a prominent pollution problem. Clusters I and III represent TDS, Cl^-, Fe, and Pb pollution problems; clusters II and IV represent sites with high levels of coliform contamination and high salinity, respectively. This helps in the identification of problematic zones in the area where remedial actions need to be focused; therefore, the usefulness of using statistics in interpreting analytical results is also illustrated. The findings of this study have provided general information related to groundwater problems in a coastal province of southern Vietnam. It is essential to conduct studies on seawater intrusion into inland areas, and appropriate treatments should be installed at home to ensure human health.

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.

6. References

[1] Tran, D. A., Tsujimura, M., Loc, H. H., Dang, D. H., Le Vo, P., Thu Ha, D., Thu Trang, N. T., Chinh, L. C., Bich Thuc, P. T., Dang, T. D., Batdelger, O., & V. Nguyen, T. (2021). Groundwater quality evaluation and health risk assessment in coastal lowland areas of the Mekong Delta, Vietnam. Groundwater for Sustainable Development, 15, 100679. doi:10.1016/j.gsd.2021.100679.

[2] Sohrabi, N., Kalantari, N., Amiri, V., Saha, N., Berndtsson, R., Bhattacharya, P., & Ahmad, A. (2021). A probabilistic-deterministic analysis of human health risk related to the exposure to potentially toxic elements in groundwater of Urmia coastal aquifer (NW of Iran) with a special focus on arsenic speciation and temporal variation. Stochastic Environmental Research and Risk Assessment, 35(7), 1509–1528. doi:10.1007/s00477-020-01934-6.

[3] Bauer, J., Börsig, N., Pham, V. C., Hoan, T. V., Nguyen, H. T., & Norra, S. (2022). Geochemistry and evolution of groundwater resources in the context of salinization and freshening in the southernmost Mekong Delta, Vietnam. Journal of Hydrology: Regional Studies, 40, 101010. doi:10.1016/j.ejrh.2022.101010.

[4] Taiwo, A.M., Adeogun, A.O., Olatunde, K.A., Adegbite, K.I. (2011). Analysis of Groundwater Quality of Hand-Dug Wells in Peri-Urban Area of Obantoko, Abeokuta, Nigeria for Selected Physico-Chemical Parameters. The Pacific Journal of Science and Technology, 12(1), 527-534.

[5] Krishan G, C. R. (2014). Assessment of Ground Water Quality in Punjab, India. Journal of Earth Science & Climatic Change, 05(10), 243. doi:10.4172/2157-7617.1000243.

[6] Tamura, T., Nguyen, V. L., Ta, T. K. O., Bateman, M. D., Gugliotta, M., Anthony, E. J., Nakashima, R., & Saito, Y. (2020). Long-term sediment decline causes ongoing shrinkage of the Mekong Megadelta, Vietnam. Scientific Reports, 10(1), 1–7. doi:10.1038/s41598-020-64630-z.

[7] Long, P. N., & Phan, L. T. (2021). Impacts of climate change on groundwater resources in Vietnam: a short review. VNUHCM Journal of Earth Science and Environment, 5(SI2), 34-44. doi:10.32508/stdjsee.v5iSI2.596.

[8] Tran, T. A., Dang, T. D., Nguyen, T. H., & Pham, V. H. T. (2021). Moving towards sustainable coastal adaptation: Analysis of hydrological drivers of saltwater intrusion in the Vietnamese Mekong Delta. Science of the Total Environment, 770, 145125. doi:10.1016/j.scitotenv.2021.145125.

[9] Park, E., Loc, H. H., Van Binh, D., & Kantoush, S. (2022). The worst 2020 saline water intrusion disaster of the past century in the Mekong Delta: Impacts, causes, and management implications. Ambio, 51(3), 691–699. doi:10.1007/s13280-021-01577-z.

[10] Xiao, H., Tang, Y., Li, H., Zhang, L., Ngo-Duc, T., Chen, D., & Tang, Q. (2021). Saltwater intrusion into groundwater systems in the Mekong Delta and links to global change. Advances in Climate Change Research, 12(3), 342–352. doi:10.1016/j.accre.2021.04.005.

[11] Zhang, H. W., Sun, Y. Q., Li, Y., Zhou, X. D., Tang, X. Z., Yi, P., Murad, A., Hussein, S., Alshamsi, D., Aldahan, A., Yu, Z. B., Chen, X. G., & Mugwaneza, V. P. (2017). Quality assessment of groundwater from the south-eastern Arabian Peninsula. Environmental Monitoring and Assessment, 189(8), 1–14. doi:10.1007/s10661-017-6092-2.

[12] Li, Y., Li, P., Cui, X., & He, S. (2021). Groundwater quality, health risk, and major influencing factors in the lower Beiluo River watershed of northwest China. Human and Ecological Risk Assessment, 27(7), 1987–2013. doi:10.1080/10807039.2021.1940834.

[13] Rakib, M. A., Quraishi, S. B., Newaz, M. A., Sultana, J., Bodrud-Doza, M., Rahman, M. A., Patwary, M. A., & Bhuiyan, M. A. H. (2022). Groundwater quality and human health risk assessment in selected coastal and floodplain areas of Bangladesh. Journal of Contaminant Hydrology, 249, 104041. doi:10.1016/j.jconhyd.2022.104041.

[14] Nguyen, H. G., Tran, D. H., Hoang, N. T. Do, & Nguyen, T. T. (2022). Predictive modelling physico-chemical properties groundwater in coastal plain area of Vinh Linh and Gio Linh districts of Quang Tri Province, Vietnam. Water Practice and Technology, 17(10), 2100–2112. doi:10.2166/wpt.2022.120.

[15] Wolf, L., Nick, A., & Cronin, A. (2015). How to keep your groundwater drinkable: Safer siting of sanitation systems–Working Group 11 Publication. Sustainable Sanitation Alliance, 1-7.

[16] African Groundwater Network (2016). Integration of Groundwater Management into Transboundary Basin Organizations in Africa. Groundwater Hazards - A Training Manual. African Groundwater Network (AGW-Net). Available online: https://www.gwp.org/globalassets/global/toolbox/references/trainingsmanual.pdf (accessed on January 2023).

[17] Cui, R., Zhang, D., Wang, H., Fu, B., Yan, H., Hu, W., Liu, G., & Chen, A. (2023). Shifts in the sources and fates of nitrate in shallow groundwater caused by agricultural intensification intensity: Revealed by hydrochemistry, stable isotopic composition and source contribution. Agriculture, Ecosystems and Environment, 345. doi:10.1016/j.agee.2022.108337.

[18] Le Luu, T. (2019). Remarks on the current quality of groundwater in Vietnam. Environmental Science and Pollution Research, 26(2), 1163–1169. doi:10.1007/s11356-017-9631-z.

[19] Vinh, D. C., & Lam, T. H. (2018). Level of nitrate on shallow groundwater in Pleiku City, Gia Lai. Journal of Science and Technology - University of Danang, 116-118. (In Vietnamese).

[20] Ha, Q. K., Tran Ngoc, T. D., Le Vo, P., Nguyen, H. Q., & Dang, D. H. (2022). Groundwater in Southern Vietnam: Understanding geochemical processes to better preserve the critical water resource. Science of the Total Environment, 807(2), 151345. doi:10.1016/j.scitotenv.2021.151345. (In Vietnamese).

[21] Zhao, X., Wang, D., Xu, H., Ding, Z., Shi, Y., Lu, Z., & Cheng, Z. (2022). Groundwater pollution risk assessment based on groundwater vulnerability and pollution load on an isolated island. Chemosphere, 289, 133134. doi:10.1016/j.chemosphere.2021.133134.

[22] Nguyen, T. T., Kawamura, A., Tong, T. N., Nakagawa, N., Amaguchi, H., & Gilbuena, R. (2015). Clustering spatio-seasonal hydrogeochemical data using self-organizing maps for groundwater quality assessment in the Red River Delta, Vietnam. Journal of Hydrology, 522, 661–673. doi:10.1016/j.jhydrol.2015.01.023.

[23] Dieu, L. P., Cong-Thi, D., Segers, T., Ho, H. H., Nguyen, F., & Hermans, T. (2022). Groundwater Salinization and Freshening Processes in the Luy River Coastal Aquifer, Vietnam. Water (Switzerland), 14(15), 2358. doi:10.3390/w14152358.

[24] Nguyen, T. G., Phan, K. A., & Huynh, T. H. N. (2022). Major concerns of surface water quality in south-west coastal regions of Vietnamese Mekong Delta. Sustainable Environment Research, 32(1), 1–14. doi:10.1186/s42834-022-00156-5.

[25] Hong, T. T. K., & Giao, N. T. (2022). Analysis of Surface Water Quality in Upstream Province of Vietnamese Mekong Delta Using Multivariate Statistics. Water (Switzerland), 14(12). doi:10.3390/w14121975.

[26] Muoi, L. Van, Srilert, C., Dang Tri, V. P., & Pham Van, T. (2022). Spatial and temporal variabilities of surface water and sediment pollution at the main tidal-influenced river in Ca Mau Peninsular, Vietnamese Mekong Delta. Journal of Hydrology: Regional Studies, 41. doi:10.1016/j.ejrh.2022.101082.

[27] Vân, L. T. H., & My, T. N. D. (2020). The Zooplankton composition and surface water quality in some watershed around the aquaculture areas at the Ben Tre province. Science and Technology Development Journal - Natural Sciences, 4(1), First. doi:10.32508/stdjns.v4i1.768.

[28] Nguyen, T. G., & Vo, Q. M. (2022). The Categorized of Surface Water Quality Variation using Multivariate Statistical Approaches: A Case Study of Ben Tre Province, Vietnam. Trends in Sciences, 19(8), 3468–3468. doi:10.48048/tis.2022.3468.

[29] Ministry of Natural Resources and Environment. (2015). Solutions for Sustainable Development of Water Resources in Ben Tre. Ministry of Natural Resources and Environment (MNRE), Hanoi, Vietnam. Available online: http://dwrm.gov.vn/index.php?language=vi&nv=news&op=Hoat-dong-cua-dia-phuong/Giai-phap-phat-trien-ben-vung-nguon-nuoc-o-Ben-Tre-4318 (Accessed on January 2023). (In Vietnamese).

[30] Vo, D. T., & Huynh, K. V. (2017). Estimating residents' willingness to pay for groundwater protection in the Vietnamese Mekong Delta. Applied Water Science, 7(1), 421–431. doi:10.1007/s13201-014-0257-8.

[31] Duy, N. Le, Nguyen, T. V. K., Nguyen, D. V., Tran, A. T., Nguyen, H. T., Heidbüchel, I., Merz, B., & Apel, H. (2021). Groundwater dynamics in the Vietnamese Mekong Delta: Trends, memory effects, and response times. Journal of Hydrology: Regional Studies, 33, 100746. doi:10.1016/j.ejrh.2020.100746.

[32] American Public Health Association. (2017). Standard Methods for the Examination of Water and Wastewater (23rd Ed.). American Water Works Association, American Public Health Association (APHA), Water Environment Federation, Washington, United States.

[33] Ministry of Natural Resources and Environment. (2020). Decision No. 100/QD-BTNMT dated January 14, 2020 of the Ministry of Natural Resources and Environment on certification of eligibility for environmental monitoring services. Ministry of Natural Resources and Environment, Hanoi, Vietnam.

[34] Ministry of Natural Resources and Environment. (2015). National technical regulation on groundwater quality. Ministry of Natural Resources and Environment, Hanoi, Vietnam. Available online: https://vanbanphapluat.co/qcvn-09-mt-2015-btnmt-chat-luong-nuoc-duoi-dat (accessed on January 2023). (In Vietnamese).

[35] Usman, U. N., Toriman, M. E., & Juahir, H. (2014). Assessment of Groundwater Quality Using Multivariate Statistical Techniques in Terengganu. Science and Technology, 4(3), 42–49. doi:10.5923/j.scit.20140403.02.

[36] Suleiman, A., Ibrahim, A., & Abdullahi, U. (2020). Statistical Explanatory Assessment of Groundwater Quality in Gwale LGA, Kano State, Northwest Nigeria. Hydrospatial Analysis, 4(1), 1–13. doi:10.21523/gcj3.2020040101.

[37] Awomeso, J. A., Ahmad, S. M., & Taiwo, A. M. (2020). Multivariate assessment of groundwater quality in the basement rocks of Osun State, Southwest, Nigeria. Environmental Earth Sciences, 79(5), 1–9. doi:10.1007/s12665-020-8858-z.

[38] Gunarathna, M. H. J. P., Kumari, M. K. N., & Nirmanee, K. G. S. (2016). Evaluation of interpolation methods for mapping pH of groundwater. International Journal of Latest Technology in Engineering, Management & Applied Science, 3, 1-5.

[39] Giao, N. T., Nhien, H. T. H., & Anh, P. K. (2022). Groundwater Quality Assessment Using Classification and Multi-Criteria Methods: A Case Study of Can Tho City, Vietnam. Environment and Natural Resources Journal, 20(2), 179–191. doi:10.32526/ennrj/20/202100183.

[40] Aleem, M., Shun, C. J., Li, C., Aslam, A. M., Yang, W., Nawaz, M. I., Ahmed, W. S., & Buttar, N. A. (2018). Evaluation of groundwater quality in the vicinity of Khurrianwala industrial zone, Pakistan. Water (Switzerland), 10(10), 1321. doi:10.3390/w10101321.

[41] World Health organization. (2017). Guidelines for drinking-water quality: Fourth Edition incorporation the first addendum. World Health Organization (WHO), Geneva, Switzerland. Available online: https://www.who.int/publications-detail-redirect/9789241549950 (accessed on January 2023).

[42] Giao, N. T., Anh, P. K., & Nhien, H. T. H. (2021). Evaluating groundwater quality in Bac Lieu province using multivariate statistical method and groundwater quality index. Indonesian Journal of Environmental Management and Sustainability, 5(4), 129–135. doi:10.26554/ijems.2021.5.4.129-135.

[43] Karila, K., Nevalainen, O., Krooks, A., Karjalainen, M., & Kaasalainen, S. (2014). Monitoring changes in rice cultivated area from SAR and optical satellite images in Ben Tre and Tra Vinh provinces in Mekong delta, Vietnam. Remote Sensing, 6(5), 4090–4108. doi:10.3390/rs6054090.

[44] Chakraborty, R., Khan, K. M., Dibaba, D. T., Khan, M. A., Ahmed, A., & Islam, M. Z. (2019). Health implications of drinking water salinity in coastal areas of Bangladesh. International Journal of Environmental Research and Public Health, 16(19), 1–10. doi:10.3390/ijerph16193746.

[45] Rahaman, M.A., Rahman, M.M., Nazimuzzaman, M. (2020). Impact of Salinity on Infectious Disease Outbreaks: Experiences from the Global Coastal Region. Good Health and Well-Being. Encyclopedia of the UN Sustainable Development Goals, Springer, Cham, Switzerland. doi:10.1007/978-3-319-95681-7_106.

[46] Aragaw, T. T., & Gnanachandrasamy, G. (2021). Evaluation of groundwater quality for drinking and irrigation purposes using GIS-based water quality index in urban area of Abaya-Chemo sub-basin of Great Rift Valley, Ethiopia. Applied Water Science, 11(9), 148. doi:10.1007/s13201-021-01482-6.

[47] Ojekunle, Z. O., Adeyemi, A. A., Taiwo, A. M., Ganiyu, S. A., & Balogun, M. A. (2020). Assessment of physicochemical characteristics of groundwater within selected industrial areas in Ogun State, Nigeria. Environmental Pollutants and Bioavailability, 32(1), 100–113. doi:10.1080/26395940.2020.1780157.

[48] Antony, S., Dev, V. V., Kaliraj, S., Ambili, M. S., & Krishnan, K. A. (2020). Seasonal variability of groundwater quality in coastal aquifers of Kavaratti Island, Lakshadweep Archipelago, India. Groundwater for Sustainable Development, 11, 100377. doi:10.1016/j.gsd.2020.100377.

[49] Memon, Y. I., Qureshi, S. S., Kandhar, I. A., Qureshi, N. A., Saeed, S., Mubarak, N. ., Ullah Khan, S., & Saleh, T. A. (2021). Statistical analysis and physicochemical characteristics of groundwater quality parameters: a case study. International Journal of Environmental Analytical Chemistry, 1–22. doi:10.1080/03067319.2021.1890064.

[50] Alamdar, R., Kumar, V., Moghtaderi, T., & Naghibi, S. J. (2019). Groundwater quality evaluation of Shiraz City, Iran using multivariate and geostatistical techniques. SN Applied Sciences, 1(11), 1–16. doi:10.1007/s42452-019-1108-x.

[51] Giao, N. T., Anh, P. K., & Nhien, H. T. H. (2022). Groundwater Quality Assessment Using Groundwater Quality Index and Multivariate Statistical Methods and Human Health Risk Assessment in a Coastal Region of the Vietnamese Mekong Delta. Applied Environmental Research, 44(2), 68–85. doi:10.35762/AER.2022.44.2.6.

[52] El-Nagdy, I., & Abdel- Hameed, I. (2022). a Review of Study on Heavy Metal Concentrations in Source of Water in Vietnam. Zagazig Journal of Agricultural Research, 49(2), 209–219. doi:10.21608/zjar.2022.237617.

[53] Ha, Q. K., Choi, S., Phan, N. L., Kim, K., Phan, C. N., Nguyen, V. K., & Ko, K. S. (2019). Occurrence of metal-rich acidic groundwaters around the Mekong Delta (Vietnam): A phenomenon linked to well installation. Science of the Total Environment, 654, 1100–1109. doi:10.1016/j.scitotenv.2018.11.200.

[54] United States Environmental Protection Agency (EPA). Mercury. United States Environmental Protection Agency (EPA), Pennsylvania, United States. Available online: https://www.epa.gov/mercury (accessed on January 2023).

[55] United States Environmental Protection Agency (2023). Chemical Contaminant Rules. EPA, Washington, D.C., United States. Available online: https://www.epa.gov/dwreginfo/chemical-contaminant-rules (accessed on January 2023).

[56] Phan, K. A., & Nguyen, T. G. (2018). Groundwater quality and human health risk assessment related to groundwater consumption in An Giang province, Viet Nam. Journal of Vietnamese Environment, 10(2), 85–91. doi:10.13141/jve.vol10.no2.pp85-91.

[57] Wen, X., Lu, J., Wu, J., Lin, Y., & Luo, Y. (2019). Influence of coastal groundwater salinization on the distribution and risks of heavy metals. Science of the Total Environment, 652, 267–277. doi:10.1016/j.scitotenv.2018.10.250.

[58] Satheeskumar, V., Subramani, T., Lakshumanan, C., Roy, P. D., & Karunanidhi, D. (2021). Groundwater chemistry and demarcation of seawater intrusion zones in the Thamirabarani delta of south India based on geochemical signatures. Environmental Geochemistry and Health, 43(2), 757–770. doi:10.1007/s10653-020-00536-z.

[59] Han, D., Tong, X., Currell, M. J., Cao, G., Jin, M., & Tong, C. (2014). Evaluation of the impact of an uncontrolled landfill on surrounding groundwater quality, Zhoukou, China. Journal of Geochemical Exploration, 136, 24–39. doi:10.1016/j.gexplo.2013.09.008.

[60] Longe, E. O., & Balogun, M. R. (2010). Groundwater quality assessment near a municipal landfill, Lagos, Nigeria. Research Journal of Applied Sciences, Engineering and Technology, 2(1), 39–44.

[61] Patroescu, V., Jinescu, C., Cosma, C., Cristea, I., Badescu, V., & Stefan, C. S. (2015). Influence of ammonium ions on the treatment process selection of groundwater supplies intended to human consumption. Revista de Chimie, 66(4), 537–541.

[62] Du, Y., Ma, T., Deng, Y., Shen, S., & Lu, Z. (2017). Sources and fate of high levels of ammonium in surface water and shallow groundwater of the Jianghan Plain, Central China. Environmental Science: Processes and Impacts, 19(2), 161–172. doi:10.1039/c6em00531d.

[63] Maharjan, A. K., Kamei, T., Amatya, I. M., Mori, K., Kazama, F., & Toyama, T. (2020). Ammonium-Nitrogen (NH4+-N) Removal from Groundwater by a Dropping Nitrification Reactor: Characterization of NH4+-N Transformation and Bacterial Community in the Reactor. Water (Switzerland), 12(2), 1–13. doi:10.3390/w12020599.

[64] Brandao, G. C., Matos, G. D., Pereira, R. N., & Ferreira, S. L. C. (2014). Development of a simple method for the determination of nitrite and nitrate in groundwater by high-resolution continuum source electrothermal molecular absorption spectrometry. Analytica Chimica Acta, 806, 101–106. doi:10.1016/j.aca.2013.11.031.

[65] Tu, T. A., Tweed, S., Dan, N. P., Descloitres, M., Quang, K. H., Nemery, J., Nguyen, A., Leblanc, M., & Baduel, C. (2022). Localized recharge processes in the NE Mekong Delta and implications for groundwater quality. Science of the Total Environment, 845, 157118. doi:10.1016/j.scitotenv.2022.157118.

[66] Ben Tre Statistics Office. (2020). Ben Tre Statistical Yearbook 2019. Statistical Publishing House, Hanoi, Vietnam.

[67] Can Tho Statistics Office. (2020). Can Tho Statistical Yearbook 2019. Statistical Publishing House, Hanoi, Vietnam.

[68] Soc Trang Statistics Office. (2020). Soc Trang Statistical Yearbook 2019. Statistical Publishing House, Hanoi, Vietnam.

[69] Adimalla, N. (2019). Groundwater Quality for Drinking and Irrigation Purposes and Potential Health Risks Assessment: A Case Study from Semi-Arid Region of South India. Exposure and Health, 11(2), 109–123. doi:10.1007/s12403-018-0288-8.

[70] Nguyen, V. T., Vo, T. D. H., Tran, T. D., Nguyen, T. N. K., Nguyen, T. B., Dang, B. T., & Bui, X. T. (2021). Arsenic-contaminated groundwater and its potential health risk: A case study in Long An and Tien Giang provinces of the Mekong Delta, Vietnam. Environmental Science and Pollution Research, 28(45), 63558–63571. doi:10.1007/s11356-020-10837-6.

[71] Ghimire, M., Kayastha, S. P., Regmi, T., & Bhuiyan, C. (2023). Hydro-chemical characterisation and quality assessment of shallow groundwater in parts of the Kathmandu Valley, Nepal. Physics and Chemistry of the Earth, 129, 103349. doi:10.1016/j.pce.2022.103349.

[72] Tweed, S., Massuel, S., Seidel, J. L., Chhuon, K., Lun, S., Eang, K. E., Venot, J. P., Belaud, G., Babic, M., & Leblanc, M. (2020). Seasonal influences on groundwater arsenic concentrations in the irrigated region of the Cambodian Mekong Delta. Science of the Total Environment, 728, 138598. doi:10.1016/j.scitotenv.2020.138598.

[73] Minh, H. V. T., Avtar, R., Kumar, P., Tran, D. Q., Van Ty, T., Behera, H. C., & Kurasaki, M. (2019). Groundwater quality assessment using Fuzzy-AHP in a Giang Province of Vietnam. Geosciences (Switzerland), 9(8), 330. doi:10.3390/geosciences9080330.