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Assessment of groundwater quality based on principal component analysis and pollution source-based examination: a case study in Ho Chi Minh City, Vietnam

Binh Thanh Nguyen · Tham Minh Thi Nguyen · Quang-Vu Bach

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Abstract The current study aimed to assess the quality of apportion pollution sources and examine the impacts of anthropogenic activities on groundwater. The study was implemented in two sequential steps of (1) bulk examination of groundwater quality followed by principal component analysis/factor analysis (PCA/FA) to apportion pollution sources and (2) pollution source-based examination to assess the effects of anthropogenic activities. Well-water samples were taken in Ho Chi Minh City, Vietnam, in 2015 (233 samples) and 2019 (20 samples) and analyzed for 8 and 15 water quality parameters, respectively. The results showed that 99% of studied wells had pH value lower than the permissible limit, and 29, 20, 15, and 14% of studied wells had concentrations of Fe, NH_4^+, COD (chemical oxygen demand), and coliform, respectively, higher than the maximum permissible limit. PCA/FA revealed that three pollution sources, ranked in the order of importance: agricultural, urban, and industrial activities, could mainly contribute to enriching the pollutant concentrations of groundwater. While agricultural activities may contaminate groundwater with organic substances, the urban area may enrich bacterial-pathogen density such as *E. coli* and coliform, and the industrial area may contribute to contaminating groundwater with some inorganic parameters. Groundwater quality index and ANOVA showed that groundwater of the studied area was poor to very poor in quality and that in the agricultural area was the worst of the three land-use types. In brief, the groundwater quality in the studied area was degraded and agricultural activities were the most important factor causing the degradation followed by urban and industrial activities.

Keywords Quality assessment · Anthropogenic activity · Agricultural area · Urban area · Component analysis/factor analysis

Introduction

Water is essential to life and all living organisms on the earth, and thus, its pollution is one of the most concerning issues worldwide. The pollution process is speeding up today due to the fast growth of population, urbanization, and industrialization. There are many water sources on the earth and aquifers are an important one regularly used for various purposes such as drinking water supply, irrigation for agricultural production, and industrial production (Ibrahim 2016; de Graaf et al. 2019). Zektser and Everett (2004) reported that a withdrawal rate of 600–700 km^3 $year^{-1}$ from groundwater was carried out globally, providing potable water for

Corresponding author at Faculty of Environment and Labour Safety, Ton Duc Thang University, Ho Chi Minh City, Vietnam

B. T. Nguyen · T. M. T. Nguyen
Institute of Environmental Science, Engineering, and Management, Industrial University of Ho Chi Minh City, 12 Nguyen Van Bao, Go Vap District, Ho Chi Minh City, Vietnam

Q.-V. Bach (✉)
Sustainable Management of Natural Resources and Environment Research Group, Faculty of Environment and Labour Safety, Ton Duc Thang University, Ho Chi Minh City, Vietnam
e-mail: bachquangvu@tdtu.edu.vn

around 70% of the world's population. Nevertheless, human activities can lead to the deterioration of groundwater, putting the world into a water-crisis situation.

Groundwater is inter-connected with other environmental components, typically those located on the land surface overlying the beneath aquifers. Consequently, groundwater, especially in the shallow aquifers, is recharged frequently from surface water bodies, such as local precipitation, river, and reservoirs (Vinh et al. 2017). This indicates that the quality of groundwater in the shallow aquifers could be affected by various local factors, categorized into natural and anthropogenic groups. The former can be involved in climate factors, such as rainfall, evaporation, and soil factors such as rock type forming the aquifers, soil types, and topography (Burri et al. 2019). The effects of the natural factors could be relatively even over a relatively flat and small-scale area. The anthropogenic factors potentially affecting groundwater quality may include typical activities happening on the land surface such as agricultural, industrial, and urban areas (land-use types) (He et al. 2019). For example, Burri et al. (2019) documented that groundwater can be found with many compounds widely used today. Salman et al. (2018) found that various water quality indexes such as sodium absorption ratio (SAR), soluble sodium percentage (SSP), residual sodium bicarbonate (RSBC), and permeability index (PI) were significantly affected by land-use changes in Bangladesh. Fertilizer application to enhance soil fertility for agricultural production was found to degrade groundwater quality in India (Singh and Singh 2010). These indicate that the status of groundwater quality could be significantly influenced by human activities on the land surface overlying the aquifers.

In general, there are two methodological categories commonly applied to examine the connections between groundwater quality and anthropogenic activities, including experimental methods and statistical methods. The former are known as traditional methods used to assess the effects of independent variables on the dependent variables. It could be involved in the pre-assignment of sampling sites to certain land-use types and analysis for necessary quality parameters of groundwater (Salman et al. 2018; Reyes et al. 2019). Nevertheless, this methodological category may be useless if historical data are of interest to study because information and characteristics of land-use do not exist and thus are not accurately determined. The latter is related to statistical methods, such as principal component analysis/factor (PCA/FA), which can be used to apportion the pollution sources, such as agricultural activities, contributing to degrading groundwater quality (Chenini and Khemiri 2009; Elizabeth et al. 2018). The techniques are involved in reducing the dimensionality (features) of the large dataset and increasing interpretability while minimizing information loss (Jolliffe and Cadima 2016; Yao and Jianjun 2019). Consequently, Li et al. (2019) used the technique to identify and arrange pollution source of groundwater in southwestern China in the order of hydro-geochemical process, agricultural activities, domestic sewage discharges, and industrial sewage discharges. Based on PCA/FA, Zhang et al. (2020) concluded that domestic and industrial sewage was the main pollution source of groundwater in the Hutuo River alluvial-pluvial Fan, China. Nevertheless, the pollution sources identified through PCA/FA could be interpreted with some uncertainty because (1) they are based on the hidden factors representing the similar-dimensional variables measured from water samples collected from mixed pollution-source areas and (2) the different pollution sources may have some similar features. The two methodological categories have their own advantages as well as disadvantages. A combination of the two categories (the experimental methods and statistical methods) could correct the uncertainty of the PCA/PA while accurately assess the effects of anthropogenic activities on groundwater quality of historical data. Nevertheless, this combination is limitedly applied because one study may apply one or the other methodological category.

Therefore, the current study was conducted in district 12, Ho Chi Minh City, as a case study, to apportion the pollution sources based on historical data collected in 2015 using PCA/FA and to assess the effects of anthropogenic activities known as pollution sources identified from PCA/FA using the experimental method on groundwater quality. The study aimed to assess the quality of, identify potential pollution sources, and examine the impacts of anthropogenic activities on groundwater in the studied area.

Materials and methods

The studied area

The current study was conducted in District 12, located in the northwest of Ho Chi Minh City, a megacity in southern Vietnam with a fast growth rate recently. The population of the City was around 8,859,688 (updated in January 2019) with an increasing rate of 2.15%/year for the last 10 years (Tran 2019). District 12 is located on a relatively flat area (elevation varying from 2 to 10 m above the sea) of around 5275 ha, composed of 11 administrative wards (Fig. 1). The hydrological system of the district consists of four main canals and a river, which are the Saigon River (5.6 km), the Van Thuat canal (2 km), Ben Cat canal (3.6 km), Tham Luong canal (10.2 km), and Tran Quang Co canal (2.5 km). The system receives and transports liquid wastes from the urban area, the agricultural area, and the industrial zone in and out of the district. The tropical climatic regime of the studied area is characterized by two distinct seasons, the rainy season from May to November and the dry season from December to April (van Emmerik et al. 2018). The annual rainfall of the studied area is around 1868 mm, more concentrated on the rainy season (80 to 85% of total yearly rainfall) and the average temperature is 27.4 °C. The main soil type in the studied area is acrisols with low pH, sandy to silt loan texture, and high water infiltration.

Sequential experimental-setup

The current study was implemented in two sequential steps. The first one was to do a bulk examination of groundwater quality, followed by principal component analysis/factor analysis (PCA/FA) to apportion pollution sources contributing to polluting groundwater. The second one was to do a pollution source-based examination (field experimental method) to examine the effects of the PCA/FA-apportioned pollution sources on groundwater quality. Consequently, three pollution sources apportioned through the first step by PCA/FA included agricultural area, industrial zone, and urban area. These three land-use types can be characterized by different properties such as high organic carbon content, low pH value, and high density of microbial pathogens such as *E. coli* and coliform for the urban area (Huang et al. 2010; Aguilar-Ascon 2019; Leong et al. 2018), high organic carbon substances from plant residue and inorganic irons of NH_4^+, NO_3^- from inorganic fertilizers for the agricultural area (Li et al. 2017), and high inorganic cations, turbidity, and low pH for the industrial areas (Walakira and Okot-Okumu 2011; Noukeu et al. 2016). In addition, the three areas should be much different in water infiltration-related physical processes, which are surface disturbance by agricultural activities (plowing, harrowing, and weeding) and surface sealing by surface cementation through civil and transportation construction in the urban and industrial areas. These three land-use types are used as an experimental factor for a field experiment, set up as a completely randomized design with varying replicates (5 for the industrial and agricultural areas and 10 for the urban areas).

Sampling and chemical analysis

In Vietnam, groundwater can be stored in seven aquifers of the order from the top to the bottom: the Holocene, upper Pleistocene, middle Pleistocene, lower Pleistocene, upper Pliocene, middle Pliocene, and Miocene (Minderhoud et al. 2017). Because the top two aquifers are recharged frequently from surface water bodies, such as local precipitation, river, and reservoirs (Vinh et al. 2017), the water samples from examined bore wells (average depth equal 40 m) were taken from the top two aquifers for the current study. Water sampling was conducted in two different campaigns, which were in 2015 and 2019. For the 2015 campaign, 233 wells were selected randomly over the studied area for water sampling using a pump. For the 2019 campaign, 20 wells located on or close three land-use types (urban area (10 wells), agricultural area (5 wells), and industrial zone (5 wells)) were selected for water sampling.

There are many quality parameters used to characterize water quality that can be grouped into physical, chemical, and biological properties. For the 2015 sampling campaign, which was for a bulk examination with 233 samples, we reduced water quality parameters measured to save analysis cost. We selected parameters to measure in such a way to represent the three grouped properties. For the physical property, turbidity was selected; for chemical properties, pH, NH_4^+ (nutrient), Fe and As (heavy metal), and COD (chemical oxygen demand, organic matter) were measured; and for the biological properties, coliform and *Escherichia coli* (*E. coli*) were measured from 233 water samples. For the 2019 sampling campaign, 15 parameters were measured from 20 water samples collected from three land-use types, including temperature, pH, turbidity, NH_4^+, F, As, *E. coli*, coliform, Cl, NO_3^-, total Fe, hardness, EC (electrical conductivity), DO (dissolved oxygen), and

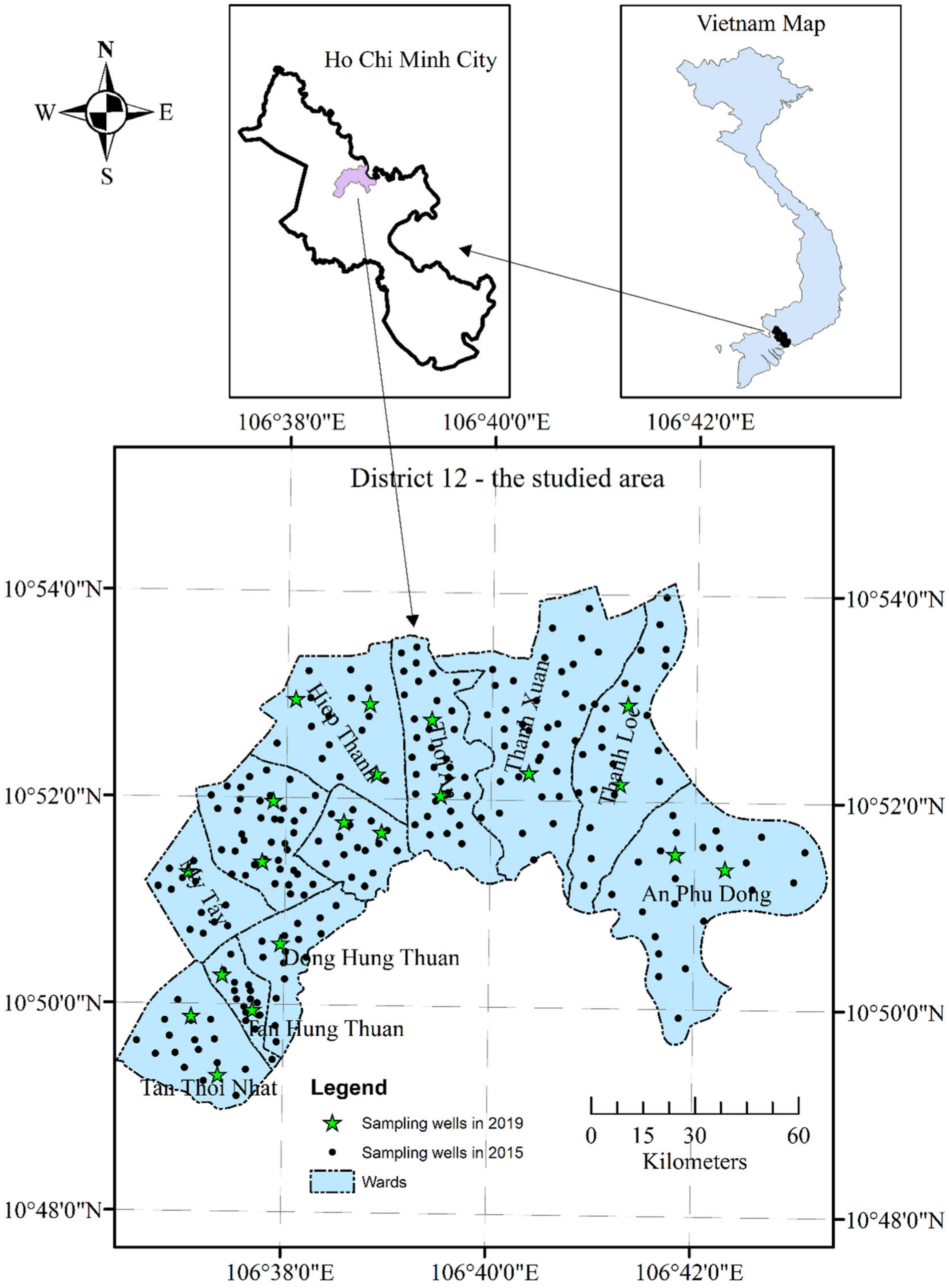

Fig. 1 Sampling sites and map of District 12 in Ho Chi Minh City, Vietnam

COD. Water samples, after being taken, were transferred to a laboratory and measured for these parameters following national standard methods for drinking water quality (QCVN 01:2009/BYT 2009).

Statistical analyses

For the 2015 campaign, data were subjected to descriptive analysis to show mean, the maximum, the minimum, the standard deviation of the mean, number of samples below the maximum permeable limit (MPL), and its percentage. Principal component analysis/factor analysis (PCA/FA) was applied to apportion pollution sources and identify important water quality parameters associated with the sources. The PCA/FA was applied to the whole data to extract varimax factors, corresponding pollution sources, having an eigenvalue greater than 1, following the procedure described by Eqani et al. (2011) and Phung et al. (2015). For the 2019 campaign, Groundwater Quality Index (GWQI) was computed based on the following equation (Nguyen et al. 2019).

$$GWQI = \sum_{i=1}^{n} w_i \times \frac{C_i}{S_i} \times 100 \qquad (1)$$

where n is the number of groundwater parameter; $w_i$is the weightage of the parameter i, taken from Nguyen et al. (2019); C_i is the measured value of the parameter i, and S_i is the maximum permissible limit of the parameter i, taken from MONRE (2015). All data were subjected to analysis of variance (ANOVA) to examine the effects of anthropogenic activities on water quality parameters and GWQI, based on a completely randomized design. A full ANOVA model applied was $\gamma_{ij} = \mu + \propto_j + \varepsilon_{ij}$, where γ_{ij} is the response of individual well, μ is the overall mean, α_j is the fixed effect of the j^{th} anthropogenic activity (pollution source), and $\in_{ij}$ is the random error with mean zero and having normal distribution (Akhtar and Memon 2009). When the ANOVA result indicated significant effect at $P \leq 0.05$, Tukey's honest significant difference test was used to classify treatment means. Statistical analyses were conducted, using JMP pro 13 (SAS Institute Inc., NC, USA). All figures were established using Sigmaplot 12 (Systat Software Inc.).

Results

Bulk examination of groundwater quality

Water samples from bore wells collected in the 2015 sampling campaign were analyzed for eight representative parameters, which are shown in Table 1. The mean concentration of As was very low, around 0.002 (mg L^{-1}), and of the 233 samples, 14 samples equal 6% had As concentration above the MPL. The mean pH value was 4.8, and 231 samples equal 99.1% had pH value lower than the permissible limit. The total Fe concentration in the water samples was high with a mean of 3.3 varying from 0 to 37.8 (mg L^{-1}) and 68 samples equal 29.2% had Fe concentration over the MPL. The NH_4^+ concentration varied from 0 to 22 with a mean of 2 mg L^{-1}. COD content varied from 0.1 to 7 with a mean value of 1.2 mg L^{-1}, and 34 samples had the COD concentration higher than the MPL. Two biological parameters coliform and *E. coli* were found in 32 (13.7%) and 14 (6%) samples, with mean values of 9.3 and 2.6 (most probable number (MPN) 100^{-1} mL), respectively.

Principal component analysis/factor analysis showed that three main pollution sources for groundwater in the studied area, corresponding to three varimax factors (VF), were extracted (Table 2), together explaining 63% of the total variance of eight groundwater parameters. The VF1 was the most important, explaining 31% of the total variance of the eight parameters of groundwater. The second most important varimax factor (VF2) explained 18% and VF3 explained 14% of the total variance. The VF1 had high loading value with total Fe and COD concentration, and VF2 with coliform, *E. coli*, and As concentration, and VF3 with turbidity, pH, and NH_4^+.

Pollution source-based examination of groundwater quality

Of the 15 parameters analyzed from 20 water samples taken from 20 bore wells located close to the three land-use types, eight parameters including T, pH, turbidity, NH_4^+, As, *E. coli*, and coliform were not significantly different among the three pollution-source areas (agricultural, industrial, and urban) (Table 3). As and *E. coli* were not found in the 20 samples; the pH of all 20 samples was lower than the permissible limit. A total of 30, 15, and 20% of the total samples had turbidity, NH_4^+, and coliform, respectively, higher than the MPL.

Figure 2 shows that the groundwater quality index (GWQI) of samples collected from bore wells in the agricultural area (434) was significantly higher than that in the urban area (132) and the industrial area (138). Groundwater in the agricultural area was in very poor quality (GWQI > 200), while that in the other areas was

Table 1 Statistics of quality parameters of groundwater collected from 233 bore wells in the studied area in 2015 (*n* = 233)

Statistics	Turbidity (NTU)	pH	NH_4^+ (mg L^{-1})	Fe (mg L^{-1})	COD (mg L^{-1})	Coliform (MPN 100 mL^{-1})	*E. coli* (MPN 100 mL^{-1})	As (mg L^{-1})
Mean	1.0	4.8	2.0	3.3	1.2	9.3	2.6	0.002
Min	0.0	3.4	0.0	0.0	0.1	0.0	0.0	0.0
Max	5.3	7.4	22.0	37.8	7.0	800.0	180.0	0.017
SE	0.1	0.0	0.2	0.5	0.1	3.8	1.1	0.0
MPL[a]	2	6.5–8.5	3	0.3	2	0	0	0.01
Sample > MPL[b]	24	231	46	68	34	32	14	14
Percentage	10.3	99.1	19.7	29.2	14.6	13.7	6.0	6.0

COD chemical oxygen demand, *SE* standard deviation of the mean, *MPN* most probable number

[a] Maximum permissible limit based on QCVN 01:2009/BYT (2009)

[b] The number of samples having values of associated parameters greater than the MPL

in poor quality (GWQI = 100–200). Figure 3 a shows that Cl^- concentration of groundwater collected in the agricultural area (184) was significantly higher than that from the other two areas (67 in the urban area and 73 mg L^{-1} in the industrial zone). Figure 3 b shows that the industrial zone had NO_3^- concentration (14.5) significantly higher than the other two areas, urban area (4.2) and agricultural area (2.4 mg L^{-1}). Total Fe concentration was significantly higher in the agricultural area (6.9) than in the urban area (0.8) and industrial zone (0.2 mg L^{-1}) (Fig. 3c). The hardness of groundwater was significantly higher in the agricultural area (57) than in the urban area (28), and that in the industrial zone (39 mg L^{-1}) was in between these two zones (Fig. 3d). Compared to the MPL, the mean concentrations of Cl^-, NO_3^-, and hardness were well below the associated limits, 250, 50, and 300 (mg L^{-1}), respectively. Fe concentrations in agricultural and urban areas were higher than the MPL, while that in the industrial zone was lower than the MPL of 0.3 mg L^{-1}.

Table 2 Loading values of eight quality parameters of well water from principal component analysis/factor analysis. Italicized numbers are those greater than 0.75, and bold numbers are those greater than 0.5 and smaller than 0.75

Parameters	VF1	VF2	VF3
Turbidity	0.34	0.15	**0.70**
pH	0.33	0.20	**0.68**
NH_4^+	− 0.07	− 0.10	**0.52**
Fe	*0.91*	− 0.02	0.12
COD	*0.89*	− 0.03	0.22
Coliform	0.44	**0.55**	− 0.38
E.coli	0.09	*0.82*	0.07
As	− 0.19	**0.70**	0.09
Eigenvalue	2.5	1.5	1.1
% total variance	31.0	18.3	13.8
Cumulative percentage variance	31.0	49.3	63.1

VF varimax factor

EC and the concentrations of DO and COD were significantly higher in the agricultural area than the other areas, depending on individual parameters (Fig. 4a, b, and c). The EC value in the agricultural area (700) was significantly higher than that in the urban area (322) and that in the industrial zone (406 μS cm^{-1}) was in between the two areas. Similarly, DO concentration was significantly higher in the agricultural area (3.0) than in the urban area (2.6 mg L^{-1}). The agricultural area also had COD concentration (2.6) significantly higher than the other examined areas (1.0 in the urban area and 0.4 mg L^{-1} in the industrial zone). Compared to the MPL, COD concentration in the agricultural area was higher, while that in the other areas was lower than the regulated limit.

Discussion

Groundwater quality

Groundwater in the studied area was poor in quality with a high percentage of water samples having some parameters such as pH, total Fe, NH_4^+, COD, and coliform higher than the associated MPLs (Table 1). The high concentration of Fe in groundwater is quite a common phenomenon in the Mekong river delta,

Table 3 Statistics of quality parameters of groundwater collected from three land-use types in 2019

Statistics	Temperature (°C)	pH	Turbidity (NTU)	NH_4^+ (mg L^{-1})	F (mg L^{-1})	As (mg L^{-1})	*E. coli* (MPN 100 mL^{-1})	Coliform (MPN 100 mL^{-1})
Mean	31.73	4.65	2.63	1.37	0.07	0.00	0.00	2.45
Min	29.30	3.40	0.20	0.00	0.00	0.00	0.00	0.00
Max	36.20	5.50	14.00	10.40	0.37	0.00	0.00	43.00
SE	0.34	0.11	0.86	0.56	0.02	0.00	0.00	2.14
MPL[a]	N/A	6.5–8.5	2.00	3.00	1.50	0.01	0.00	0.00
Sample > MPL[b]	0.00	20.00	6.00	3.00	0.00	0.00	0.00	4.00
Percentage	0.00	100.00	30.00	15.00	0.00	0.00	0.00	20.00

SE standard deviation of the mean. Note: only parameters not significantly different among three land-use types are shown here

[a] Maximum permissible limit based on QCVN 01:2009/BYT (2009)

[b] The number of samples having values of associated parameters greater than the MPL

Vietnam, ranging from 0.01 to 38 (mg L^{-1}) (Hoang et al. 2010). The concentration of total Fe in the current study varied from 0 to 38 mg L^{-1}, within the range reported by the authors. Some studies found that the extractable concentration of Fe in soil solution and also in groundwater is negatively correlated with pH (Auxtero et al. 2012; Gad et al. 2016) while the other showed no significant relationship (Malik et al. 2017). The current study found that the positive relationship between the two parameters was significant with a correlation coefficient of 0.38 (data not shown). This is because Fe measured in the current study was the total form, which could be associated with suspended sediment and organic matter in aquifer water. This association would be discussed in more detail in “The pollution sources of groundwater”.

High Fe concentration was reported to be accompanied by high As concentration in groundwater (McArthur et al. 2004; Richards et al. 2020). Nevertheless, the current study found that As concentration in groundwater from most of the examined wells was not detected (only 6% of wells examined in the 2015

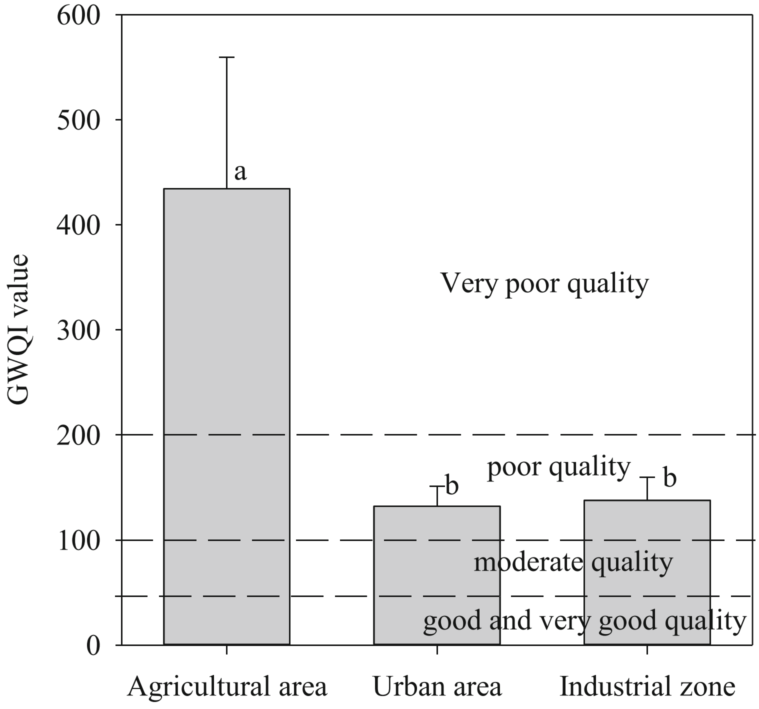

Fig. 2 Groundwater quality index (GWQI) of three examined land use zones. Note: bars attached with the same letter were not significantly different from the other. The error bar indicates standard error

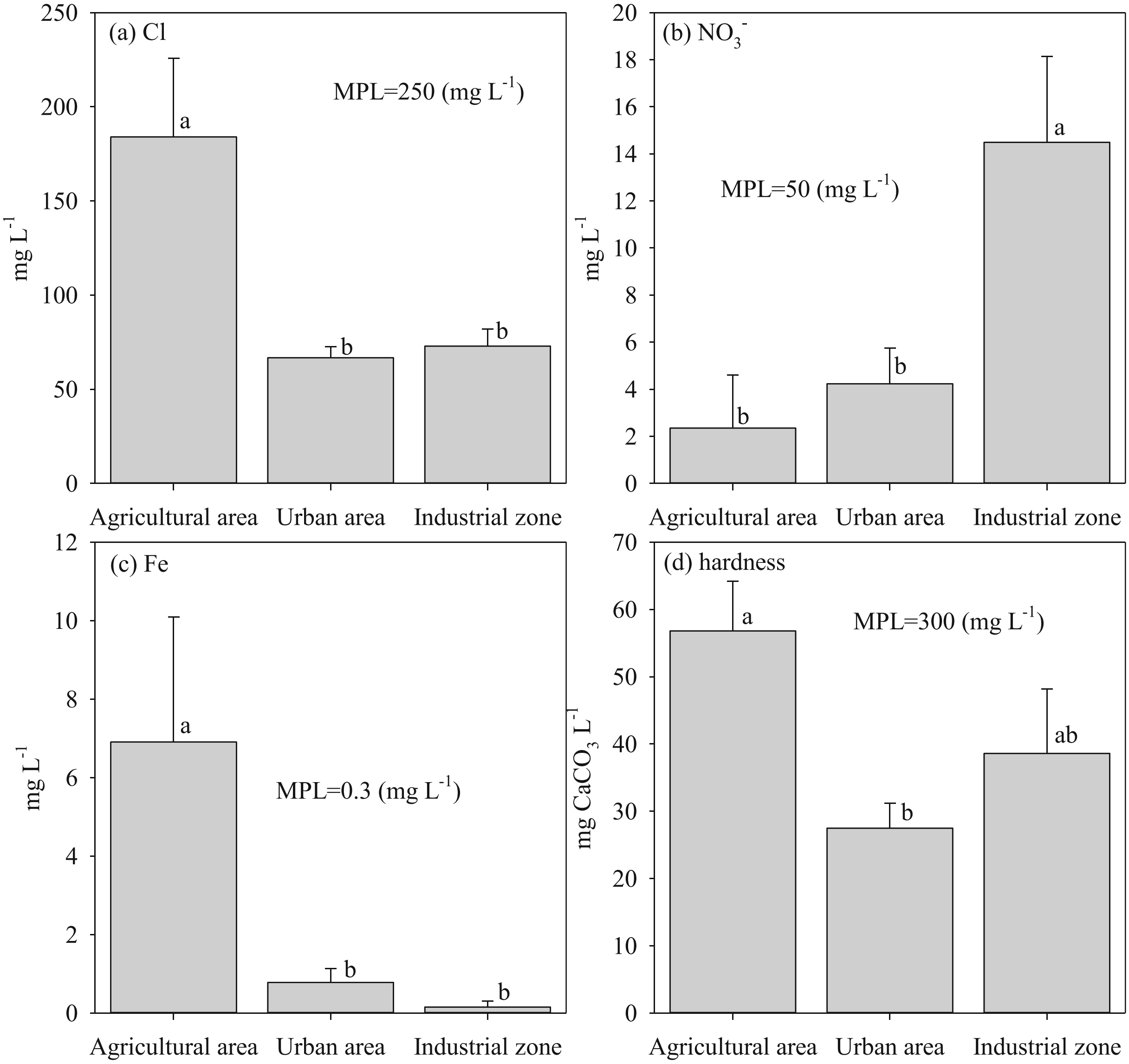

Fig. 3 The concentration of Cl, NO_3^-, Fe, and hardness of three examined zones. MPL = maximum permissible limit based on QCVN 01:2009/BYT (2009). Within a panel, bars attached with the same letter were not significantly different from the other. The error bar indicates standard error

sampling campaign detected to contain some As). The relationship between Fe and As concentration was found insignificant from a study in the Mekong River Delta, Vietnam (Hoang et al. 2010). The low percentage of examined water samples contaminated with As in the current study could be a consequence of low pH of groundwater, because As availability was pH-dependent (Kang et al. 2000). For example, Katsoyiannis and Katsoyiannis (2007) found that as water pH changed from 7.3 to around 8, As concentration increased from around 4 to 130 μg L^{-1}.

Around 15% of water samples in the current study were detected to have the COD, indicating that some wells were more likely to contain some level of organic matter. The concentration of organic matter in groundwater was significantly correlated with surface precipitation (Shen et al. 2014), suggesting that organic matter could enter the aquifer from surface water resources. The decomposition of organic matter in the aquifers could happen (Goldscheider et al. 2006), lowering the pH of well water as found by Vinh et al. (2017) in an area close to the current study area. The low pH in the

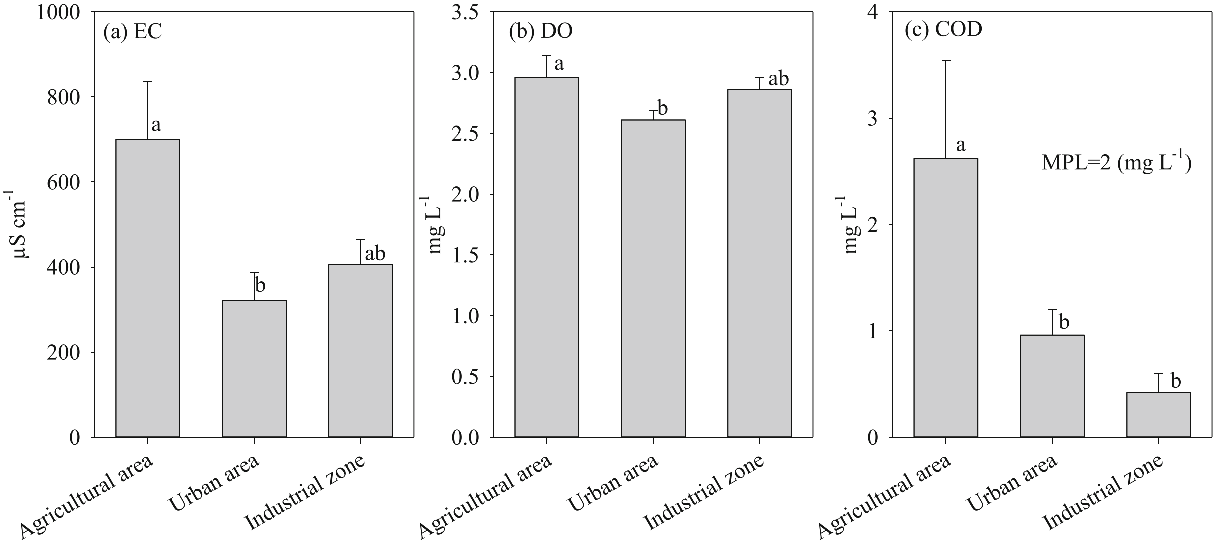

Fig. 4 EC value and the concentration of DO and COD in three examined zones. Line in panel **c** indicates the maximum permissible limit of the parameter based on QCVN 01:2009/BYT (2009). Within a panel, bars attached with the same letter were not significantly different from the other. The error bar indicates standard error

current study could also be due to other reasons, such as low-pH water recharging from local surface water bodies and hydrolysis of pyrite in the aquifer or the overlying soil layer (Zhou et al. 2015). In addition, the low pH could be derived from soil, Acrisols, in the studied area that was characterized by low pH value. The current study also found that the bore wells in the studied area were contaminated with coliform (14% of water samples contaminated) and *E. coli* (6% contaminated). This indicated that the wells in the examined areas were not well protected, making them be contaminated with biological pathogens through the overlying permeable soil layer or direct contact with well water. The microbial-pathogen contamination of groundwater was also reported in different regions in the world (Mahmud et al. 2019; Lutterodt et al. 2018; Macler and Merkle 2000).

The pollution sources of groundwater

Three main pollution sources, corresponding three varimax factors extracted from PCA/FA analysis, contributing to contaminating the groundwater in the studied area were apportioned and shown in Table 2. Having high loading value with Fe and COD, the most important pollution source could be derived from either urban/residential area, discharging a large amount of domestic sewage, oil, and grease, and solid wastes into surface-water bodies or from an agricultural area, on which organic fertilizers/plant residues were applied/left behind (Han et al. 2018). While domestic wastes could be characterized with high organic carbon concentration of main fibers, proteins, and sugars (Huang et al. 2010), the organic fertilizers naturally had high organic carbon content (Li et al. 2017). Nevertheless, the significantly higher concentration of COD in the agricultural area than in the other areas (Fig. 4c) may suggest that the main source of COD in groundwater of the current study could be mainly derived from agricultural activities. Containing a high Fe concentration, organic fertilizers from agricultural production (Isoda and Shinohara 2013) may additionally support this assumption and thus could be the source for total Fe in the groundwater. In addition, Fe could originate from Fe oxides in the aquifer-overlying soil layers that could be leached with the recharge-water flow and reduced by organic matter in an anoxic condition (McArthur et al. 2004). These made the two parameters originating from related sources and significantly correlated with each other with a correlation coefficient of 0.8 (data not shown).

The second source of contaminants, represented by coliform, *E. coli*, and As in the studied area, could come from the urban area, discharging a considerable amount of domestic sewage daily to surface-water bodies in the studied area. The wastewater from this pollution source was characterized by a high concentration of *E. coli* and coliform (Oteng-Peprah et al. 2018; Sunta et al. 2019), which could be leached to the top aquifers from the contaminated water bodies on the land surface (Takal and Quaye-Ballard 2018). Similarly, van Geen et al. (2011) found that local recharge from the surface was likely the reason for the increased frequency of *E. coli* detection from well water. Nevertheless, the domestic sewage may not be the source for As in the groundwater that necessitates more studies to clarify. As could be derived from both natural and anthropogenic sources (Missimer et al. 2018). As was found in different studies in Vietnam (Winkel et al. 2011; Postma et al. 2012) but the low concentration of As in the current study could also need more studies.

The last source for the contaminants represented by turbidity, pH, and NH_4^+ in the well water could be the mixed domestic and industrial effluents. Greywater from the urban area had high values of turbidity and NH_4^+ concentration, and low pH value (Leong et al. 2018). The studied area was located with various industrial enterprises, companies, plants, manufacturers at different scales that could discharge a large amount of both solid and liquid wastes into the environment. Depending on industrial types, their effluents could be high in turbidity and low in pH (Walakira and Okot-Okumu 2011). Some types of industries such as food-processing industries may release much wastewater, characterized by a high content of nitrogen and low pH (Noukeu et al. 2016). Initially, the industrial zones were located outside the residential areas but with a rapid urbanization process, those zones are currently situated on or close the residential areas in the studied area. Consequently, differentiation between the two sources in terms of these few parameters could not be separated through the current study, necessitating more studies. The not-difference in pH, NH_4^+, and turbidity between the industrial and urban areas (Table 3) may additionally suggest that these parameters could originate from similar sources.

Effects of land-use types

For the above discussion, it is clear that anthropogenic activities, such as residential, industrial, and agricultural activities significantly affected groundwater quality. The land-use type may affect groundwater quality through biological/chemical mechanisms and physical mechanisms. While the former were discussed in the above section, the latter could be involved in modifying the recharge rate of water from surface-water bodies to the aquifers. The agricultural area had a groundwater quality index (GWQI) significantly higher than the urban area (Fig. 2), meaning that the groundwater quality was lower in the agricultural area than that in the urban area. This may indicate that agricultural activities could be the most important pollution source for groundwater identified by PCA/FA (Table 2). Compared to the agricultural area, the urban area may have a low annual recharge rate to aquifers because of the sealing of the ground with concrete and buildings (Wakode et al. 2018). Consequently, this may restrict the movement of contaminants from surface-water sources and from the permeable subsoil layer to the aquifers through the recharge current. In addition, the urban area contained pipe networks, which could likely leak to recharge the groundwater resource (Butterfield et al. 2017; Lerner and Harris 2009). The leaking water from the pipe networks is more likely clean water, compared to the surface water, making groundwater in the urban area high in quality than in the agricultural area as found in the current study. Similar reasons, such as ground sealing and pipe network leakage, could be the case for groundwater in the industrial area. In the meantime, some activities in the agricultural area, such as organic-fertilizer application, soil practices (plowing and harrowing), and weeding, may disturb the surface soil layer, creating more chances for water to percolate downward and carry the pollutants to the beneath aquifers.

Conclusions

The combination of PCA/FA to examine historical data and experimental methods to establish a well-controlled field experiment enabled us to come to conclusions on groundwater quality with high confidence. Groundwater in the studied area was degraded in quality with a high percentage of studied wells having pH value under the permissible limit (99% of wells), and Fe (29%), NH_4^+ (19.7%), COD (14.6%), and coliform (13.7%) concentration higher than the maximum permissible limit. The current study revealed that three pollution sources from anthropogenic activities in the urban, agricultural, and industrial areas could mainly contribute to degrading groundwater quality. While agricultural activities may contaminate groundwater with organic matter, the urban area may degrade groundwater quality with bacterial pathogens, and industrial areas may contribute to contaminating groundwater with some inorganic parameters. In addition, physical mechanisms such as ground sealing in the urban and industrial areas and soil practices (plowing and harrowing) and weeding in the agricultural areas may contribute to altering the quality of groundwater. In brief, groundwater quality in the studied area was lowest in the agricultural area, and better in the urban and industrial areas and associated reason could be involved in anthropogenic activities on different land-use types.

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