

Temporal changes in the hydrochemical facies of groundwater quality in two main aquifers in Hanoi, Vietnam

Thuy Thanh Nguyen¹ · Akira Kawamura¹ · Naoko Nakagawa¹ · Hideo Amaguchi¹ · Romeo Gilbuena Jr¹

¹ Tokyo Metropolitan University

Abstract

Groundwater is the major source for drinking and domestic water in Hanoi, Vietnam. A clear understanding of the processes that influence its hydrochemical properties would be of invaluable use in management and protection of this important water resource. In this study, the temporal changes in the hydrochemical facies in the confined and unconfined aquifers in Hanoi were investigated using the water quality data from 10 and 16 sampling wells of Holocene unconfined and Pleistocene confined aquifers, respectively, taken in 1993, 2003 and 2011. The hydrochemical type in each aquifer of each well was determined using the Piper diagram method. Results indicate that the two main aquifers in Hanoi are predominated by the calcium cation and bicarbonate anion types. Results also show that the hydrochemical facies remain mostly unchanged not only in the Pleistocene confined aquifer but also in the Holocene unconfined aquifer, in which, the chemical characteristics of the groundwater in the latter are affected directly by precipitation, infiltration of water through soil, and anthropogenic activities. This implies that the hydrochemical facies is controlled by the materials that are naturally occurring in the aquifers.

1. Introduction

In Hanoi, the capital of Vietnam, nearly the entire population depends on groundwater for daily water consumption because of the uneven distribution and contaminated quality of surface water resources. Recently, the combination of rapid population growth, urbanization and industrialization results in overexploitation of the groundwater resources in the region. The continuous high water demand leads to the unmitigated decline of groundwater levels (Bui et al. 2012) and the deterioration of water quality, as a result of the salinisation and contamination processes (Duong et al. 2003; Montaganero et al. 2007). Sustainable management of groundwater is thus necessary to secure its future availability and ecological value.

Hydrochemical facies, an important diagnostic chemical aspect of groundwater solutions occurring in hydrologic systems, is commonly examined in the assessment of groundwater quality. Hydrochemical facies analysis provides information on the distinct zones of cations and anions along different layers of aquifers (Christopher and Robert 2005). Pollutants, such as heavy metals and organic compounds, generally interact with the ions present in groundwater (William 1997). A clear view of the predominant ions can help understand the origin, interaction and mechanisms of contamination process.

There have been quite a few studies on the groundwater in Hanoi reported in literature. Nguyen and Helm (1996) and Trinh and Fredlund (2000), for example, investigated on land subsidence due to excessive groundwater exploitation. Spatial and temporal analyses of groundwater levels in Hanoi were carried out by Bui et al (2012b). Duong et al. (2003) considered groundwater quality, pollution and monitoring system design. Groundwater arsenic contamination was identified in some parts of Hanoi (Berg et al. 2008). However, there is little available information regarding the groundwater hydrochemical properties in Vietnam, including Hanoi.

Various researchers have carried out extensive hydrochemistry studies for assessing groundwater quality. Marghade et al. (2012) assessed the chemistry of major ions of shallow groundwater to understand the groundwater geochemical evolution and water quality in Nagpur city, central India. Baghvand et al. (2010) studied the groundwater quality of the Kashan Basin, central Iran and characterized the groundwater species by using the Piper diagram. Arumugan and Elangovan (2009) assessed the groundwater quality of the Tirupur region in India for drinking and irrigation purposes by using the Piper diagram and sodium percentage values. However, very few studies have looked at the temporal changes in the hydrochemical properties. In fact, evaluation of temporal changes in hydrochemical facies is a difficult issue because groundwater chemistry data commonly have short record length, limited spatial coverage, and high uncertainty. Investigation of temporal changes in the hydrochemical properties may reflect the groundwater hydrodynamics and circulation, which may help improve the data collection programs for groundwater assessment and enable better use of groundwater supplies.

Through implementing a National Hydrogeological Database Project under the support and nomination of the Ministry of Resources and Environment of Vietnam, we have constructed and maintained a costly groundwater monitoring database to gather all the observed groundwater data. To take advantages of our internally- available data sets, the main objective of this study was to investigate temporal changes in the groundwater hydrochemical properties in Hanoi and to deduce a hydrochemical evaluation of the

aquifer system based on the ionic constituents, water types, and factors controlling groundwater quality. To achieve the expected goals, groundwater quality data of the unconfined and confined aquifers in three years, 1993, 2003 and 2011 during dry and rainy seasons were collected and analyzed. The Piper diagram was used to investigate the hydrochemical facies. Decades of studies have already proven the efficacy and robustness of the Piper diagram method in classifying the ions in the groundwater into various hydrochemical types (Jamshidzadeh and Mirbagheri 2011; Joshi and Seth 2011; Arumugan and Elangovan 2009; Tatawat and Chandel 2008; Raji and Alagbe 1997). This study will provide valuable insights in understanding the temporal changes in the groundwater hydrochemical properties in Hanoi, especially under the looming effects of climate change

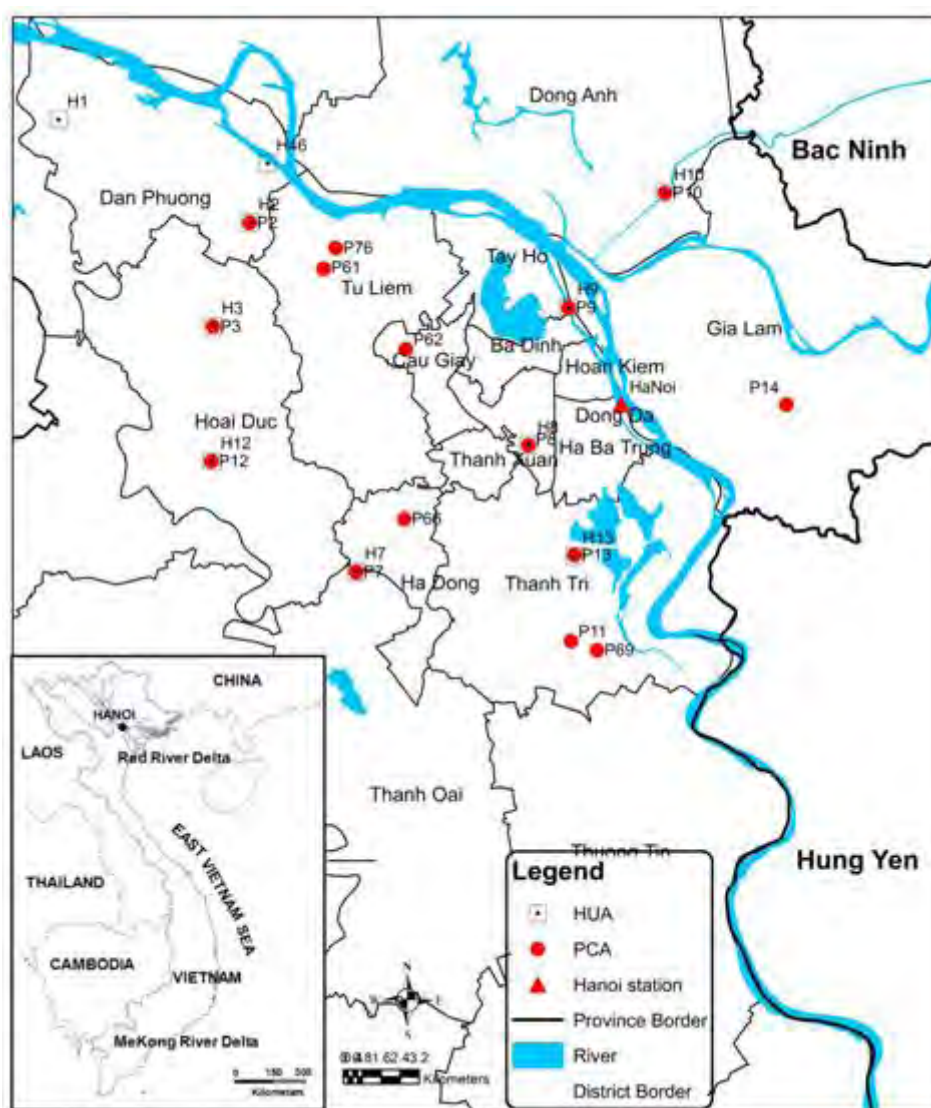


Figure 1 Study area and distribution of sampling points

2. Study area

Figure 1 shows the geographical locations of Hanoi and the 10 and 15 sampling wells in HUA and PCA, respectively, used in this study. Hanoi is located at north-eastern Vietnam. It covers a total area of about 3400 km² and has a population of about 7 million (in 2011), which comprises approximately 7.5% of the total population of Vietnam. Hanoi is situated in the tropical monsoonal region with two distinct dry and rainy seasons. The rainy season starts in May and ends in October, while the dry season lasts from November until April. The annual average rainfall is about 1,600 mm, but in 2011, it was measured at 1,795 mm. The annual average humidity is about 80%, and the average temperature is around 24°C. The annual evaporation average is around 900 mm. The river network is quite extensive, with a network density of about 0.7 km/km². More than 100 lakes can be found in Hanoi, with a total surface area of more than 21.8 km². In 2011, the recorded average discharge of the Red River at the Hanoi station, shown by the triangle in **Figure 1**, was 2182 m³/s during the flood season, and 927 m³/s during the dry season; both are lower than the average discharge in the past (3970 m³/s and 1160 m³/s, respectively). High concentration of suspended solids is always present in the Red River. The lakes, ponds and canals in Hanoi are highly polluted because of untreated domestic and industrial wastewater. Because groundwater is relatively cleaner, and remains generally unaffected by the surface environmental problems, it has become the most trusted water source (Bui et al. 2011).

In terms of regional geology, Hanoi is underlain by the Pleistocene and Holocene sediments, with the latter being partly derived from postglacial marine transgressions and tectonic activity. From our previous studies (Bui et al. 2011, 2012a), HUA consists of silty clay and various sands mixed with gravel. The thickness of this layer varies greatly up to more than 35m with an average of about 15 m. The transmissivity in HUA is from 20 to 1,788 m²/day. PCA consists of sands mixed with cobbles and pebbles, and is situated lower in the stratigraphic sequence. The thickness of PCA fluctuates over a large range with an average of about 35m, and gradually increases from north to south. The transmissivity ranges from 700 to 2900 m²/day and indicates a very high potential of groundwater resources. Within the 5 km zone of the Red River, HUA and PCA are mainly recharged by the river. Outside the 5 km zone, PCA is predominantly recharged by the vertical percolation of water coming from HUA through hydrogeological windows (borders between two aquifers where the two aquifers are directly connected without any impermeable layer).

3. Data used

Groundwater samples were collected from the two major aquifers (HUA and PCA) in Hanoi using 10 and 15 observation wells for HUA and PCA, respectively (**Figure 1**). The samples were collected in February (dry season) and August (rainy season) of three years (1993, 2003 and 2011) and were analyzed according to ISO standard test methods (National technical regulation on underground water quality, 2008) for the following physico-chemical parameters: TDS, pH, major cations (Ca^{2+} , Mg^{2+} , Na^+ , K^+), major anions (HCO_3^- , Cl^- and SO_4^{2-}), NH_4^+ , NO_2^- , and NO_3^- . The water analyses were conducted in the laboratories of the Ministry of Natural Resources and Environment. The carbonate ion (CO_3^{2-}) was calculated from the observed bicarbonate (HCO_3^-) and pH data (James 1982). The total hardness (TH) in ppm was calculated from the data of Ca^{2+} and Mg^{2+} data (Todd 1980).

4. Results and discussion

The term "hydrochemical facies" is used to describe the occurrence modes of groundwater in an aquifer with respect to chemical composition. To determine the hydrochemical facies of groundwater, the percentages of the equivalents of each physico-chemical parameter are plotted on a Piper diagram. This diagram is then used to identify the dominant cation and anion in each well by using the left and right ternary diagrams, respectively. The left ternary diagram is divided into three cationic classification regions, namely the [Ca^{2+}], [Mg^{2+}], and [Na^+] types, whereas the right ternary diagram is divided into three anionic classification regions, namely the [HCO_3^-], [Cl^-], and [SO_4^{2-}] types. Each observation has a dominant cation and anion type. The combination of these predominant ion types is the hydrochemical facies of the aquifer at a specific observation well. After plotting the data, the hydrochemical facies of each well was investigated for temporal changes by comparing the dominant ions.

Figures 2 and **3** show the Piper diagram plot for HUA in dry and rainy season, respectively. The number symbols and their color in this figure correspond to the locations of the observation wells in **Figure 1** and the observation year, respectively. As indicated in the left ternary diagram of these figures, the water samples identified as the [Ca^{2+}], [Na^+], and [Mg^{2+}] types are 25, 2 and 3 during dry season and 20, 7 and 3 during rainy season, respectively. The right ternary diagram shows 29 out of the 30 water samples to be of the [HCO_3^-] type in both seasons. Thus, HUA is mostly of the [Ca^{2+} - HCO_3^-] type (calcium ion-bicarbonate ion type). In general, it is observed from Figs 2 and 3 that the temporal

changes in the hydrochemical facies of the HUA groundwater are not significant except for well H3 and H13. Note that three groundwater samples from well H3 show an obvious difference of water type from other wells, especially anion type. In addition, the temporal changes in the hydrochemical facies are also identified in this well. The water type of groundwater in well H3 in 1993 was $[Ca^{2+}-SO_4^{2-}]$, but became $[Ca^{2+}-HCO_3^-]$ in 2003 and $[Na^+-HCO_3^-]$ in 2011 during both seasons (**Figures 2 and 3**). With closer inspection of land use, this well is located in an agricultural area of intensive irrigation (Nguyen 2010). Therefore, it is reasonable to infer that agricultural activities cause the groundwater samples of H3 to differ from other wells and change the hydrochemical facies over time.

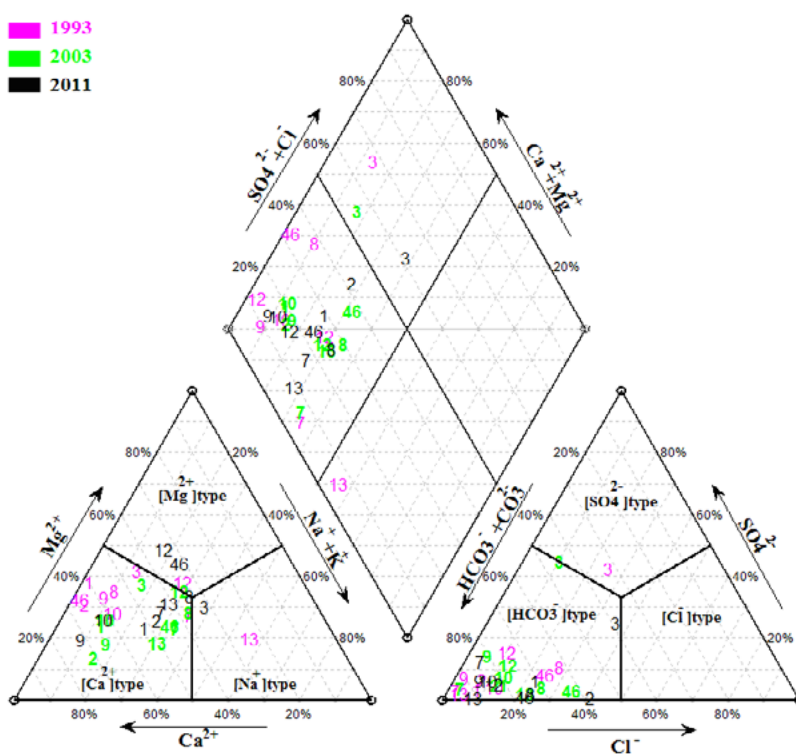


Figure 2 Piper diagram for HUA in dry season in 1993, 2003, 2011

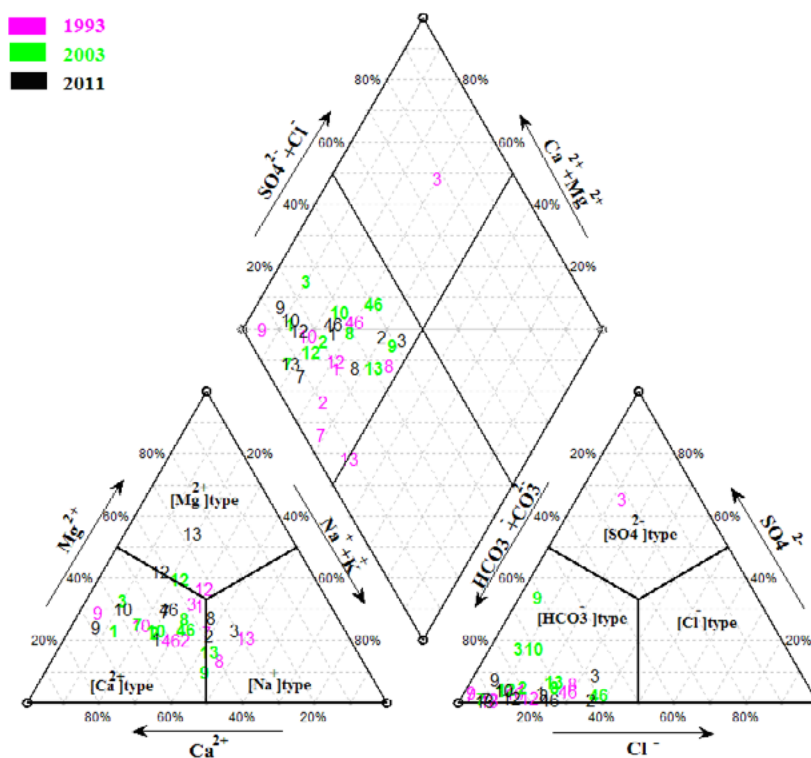


Figure 3 Piper diagram for HUA in rainy season in 1993, 2003, 2011

It is also observed that water type of groundwater in well H13 changed from $[\text{Na}^+\text{-HCO}_3^-]$ to $[\text{Ca}^{2+}\text{-HCO}_3^-]$ in dry season during the period of 1993-2003 (**Figure 2**) and recently changed from $[\text{Na}^+\text{-HCO}_3^-]$ to $[\text{Mg}^{2+}\text{-HCO}_3^-]$ in rainy season (**Figure 3**). These changes may be due to recharge from surface water such as lake, river and rainfall.

The Piper diagrams for PCA were also created to examine the temporal changes in the hydrochemical facies during dry and rainy seasons as shown in **Figures 4** and **5**, respectively. From the left ternary diagrams, the numbers of the $[\text{Ca}^{2+}]$, $[\text{Na}^+]$, and $[\text{Mg}^{2+}]$ types are 27, 15 and 3 during dry season and 29, 14 and 3 during rainy season, respectively. The right ternary diagrams indicate that all water samples during dry season and 44 out of 45 during rainy season are dominated by the $[\text{HCO}_3^-]$ type. Thus, like HUA, the groundwater in PCA is primarily of the $[\text{Ca}^{2+}\text{-HCO}_3^-]$ type. **Figures 4** and **5** indicate that there are no significant temporal changes in the hydrochemical facies for the groundwater samples in PCA.

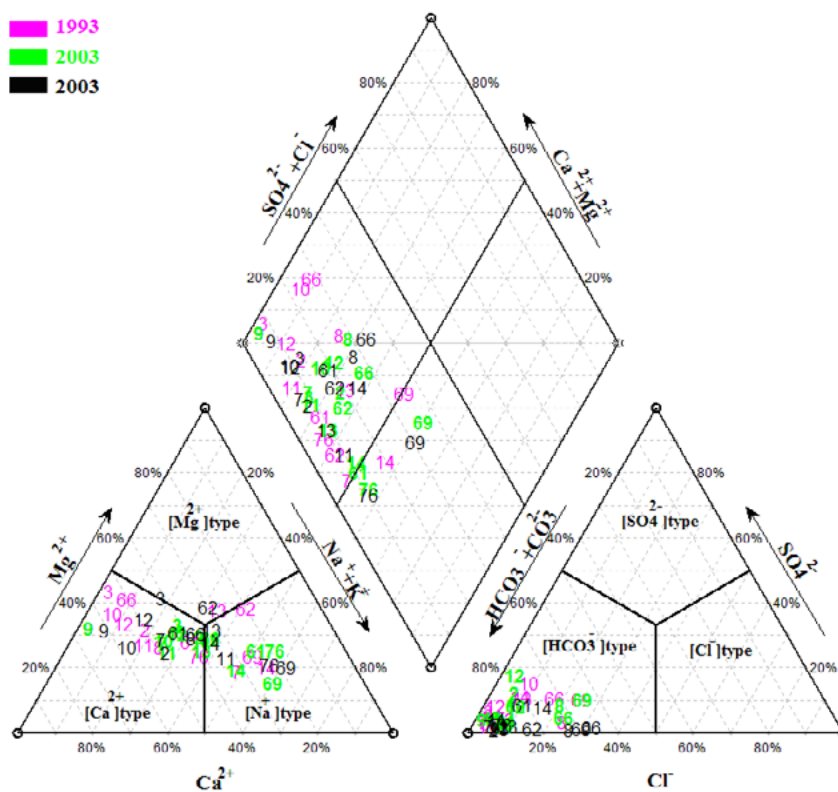


Figure 4 Piper diagram for PCA in dry season in 1993, 2003, 2011

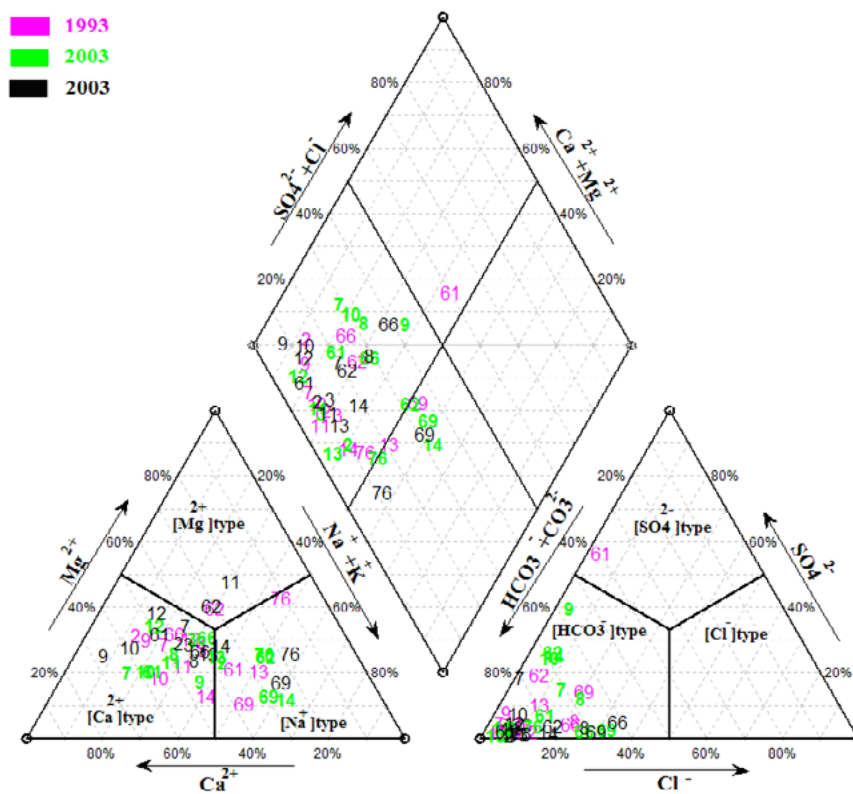


Figure 5 Piper diagram for PCA in rainy season in 1993, 2003, 2011

To have a better view of the temporal changes, the hydrochemical facies of all observation wells in **Figures 2, 3, 4, and 5** are summarized and tabulated as shown in **Tables 1 and 2** for HUA and PCA, respectively. As shown in **Table 1**, the hydrochemical facies of 4 and 6 out of the 10 HUA wells during dry and rainy seasons, respectively, exhibited temporal changes, particularly of the cation type. In rainy season, H2 changed from the $[Ca^{2+}]$ to $[Na^+]$ type during the period of 2003-2011, while H7 changed from the $[Na^+]$ to $[Ca^{2+}]$ type during the period of 1993-2003. Water type in the well H8 changed from the $[Na^+]$ to $[Ca^{2+}]$ type during the period of 1993-2003 and changed again to the $[Na^+]$ type in 2011 in rainy season. H12 changed from the $[Mg^{2+}]$ to $[Ca^{2+}]$ type during the period of 1993-2003 and changed again to the $[Mg^{2+}]$ type in 2011 in dry season, whereas in rainy season, it changed from the $[Ca^{2+}]$ to $[Mg^{2+}]$ type during the period of 1993-2003 and changed again to the $[Ca^{2+}]$ type in 2011. H13 and H46 also show the temporal changes in the cation type (e.g from the $[Na^+]$ to $[Ca^{2+}]$ or $[Mg^{2+}]$ type or from the $[Ca^{2+}]$ to $[Na^+]$). Regarding PCA, 8 and 6 out of the 15 observation wells showed temporal changes in the cation type during the dry and rainy seasons, respectively (**Table 2**). Changes from the $[Na^+]$ to $[Ca^{2+}]$ were observed in P7, P61 during the period of 1993-2003, P2, P13 and P61 during 2003-2011. Changed from the $[Ca^{2+}]$ to $[Na^+]$ were observed in P2, P61, P66 and P76 during 1993-2003, in P11 and P13. Change from the $[Mg^{2+}]$ to $[Ca^{2+}]$ or $[Na^+]$ type or from the $[Ca^{2+}]$ or $[Na^+]$ to $[Mg^{2+}]$ type were also observed in P3, P11, P13 and P63. These changes perhaps result from great heterogeneities of groundwater abstraction, recharge from surface water, infiltration of rainfall and characteristic of the aquifers.

Table 1: Water type of groundwater samples in HUA

Sampling Well	Dry season			Rainy season		
	1993	2003	2011	1993	2003	2011
H1	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$
H2	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Na^+-HCO_3^-]$
H3	$[Ca^{2+}-SO_4^{2-}]$	$[Ca^{2+}-HCO_3^-]$	$[Na^+-HCO_3^-]$	$[Ca^{2+}-SO_4^{2-}]$	$[Ca^{2+}-HCO_3^-]$	$[Na^+-HCO_3^-]$
H7	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Na^+-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$
H8	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Na^+-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Na^+-HCO_3^-]$
H9	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$
H10	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$
H12	$[Mg^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Mg^{2+}-HCO_3^-]$	$[Mg^{2+}-HCO_3^-]$	$[Mg^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$
H13	$[Na^+-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Na^+-HCO_3^-]$	$[Na^+-HCO_3^-]$	$[Mg^{2+}-HCO_3^-]$
H46	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Mg^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$	$[Ca^{2+}-HCO_3^-]$

Table 2: Water type of groundwater samples in PCA

Sampling Well	Dry season			Rainy season		
	1993	2003	2011	1993	2003	2011
P2	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Na ⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]
P3	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Mg ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]
P7	[Na ⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]
P8	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]
P9	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]
P10	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]
P11	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Na ⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Mg ²⁺ -HCO ₃ ⁻]
P12	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]
P13	[Mg ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Na ⁺ -HCO ₃ ⁻]	[Na ⁺ -HCO ₃ ⁻]	[Na ⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]
P14	[Na ⁺ -HCO ₃ ⁻]	[Na ⁺ -HCO ₃ ⁻]	[Na ⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Na ⁺ -HCO ₃ ⁻]	[Na ⁺ -HCO ₃ ⁻]
P61	[Ca ²⁺ -HCO ₃ ⁻]	[Na ⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Na ⁺ -SO ₄ ²⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]
P62	[Na ⁺ -HCO ₃ ⁻]	[Na ⁺ -HCO ₃ ⁻]	[Mg ²⁺ -HCO ₃ ⁻]	[Mg ²⁺ -HCO ₃ ⁻]	[Na ⁺ -HCO ₃ ⁻]	[Mg ²⁺ -HCO ₃ ⁻]
P66	[Ca ²⁺ -HCO ₃ ⁻]	[Na ⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]	[Ca ²⁺ -HCO ₃ ⁻]
P69	[Na ⁺ -HCO ₃ ⁻]	[Na ⁺ -HCO ₃ ⁻]	[Na ⁺ -HCO ₃ ⁻]	[Na ⁺ -HCO ₃ ⁻]	[Na ⁺ -HCO ₃ ⁻]	[Na ⁺ -HCO ₃ ⁻]
P76	[Ca ²⁺ -HCO ₃ ⁻]	[Na ⁺ -HCO ₃ ⁻]	[Na ⁺ -HCO ₃ ⁻]	[Na ⁺ -HCO ₃ ⁻]	[Na ⁺ -HCO ₃ ⁻]	[Na ⁺ -HCO ₃ ⁻]

One interesting finding from **Tables 1** and **2** was that there are more HUA groundwater samples showing the temporal changes in the hydrochemical facies during rainy season than during dry season. This may be due to the HUA groundwater affected directly by precipitation, surface water, and anthropogenic activities during rainy season. By contrast, in PCA groundwater samples having the temporal changes during dry season were observed more than during rainy season. This phenomenon could be due to the lag time for rainwater and recharge from surface water to be infiltrated in to the deeper aquifer (PCA).

It is worth to note that in rainy season, 6 out of 25 HUA and PCA samples show the changes in the hydrochemical facies during the period of 1993- 2003, whereas 9 out of 25 show the changes during the period of 2003-2011. This is perhaps due to the effect of contemporary anthropogenic activities such as irrigation, industrialization and urbanization on the chemical characteristics of the groundwater.

5. Conclusion

The main objectives of this study are to investigate the temporal changes in hydrochemical facies and to deduce a hydrochemical evaluation of the aquifer system based on the ionic constituents and water type not only in HUA but also in PCA. In this paper, taking advantage of the unique database, hydrochemical parameters from 10 sampling wells for HUA and 15 for PCA in Hanoi acquired during dry and rainy season in 1993, 2003 and 2011 were comprehensively analyzed.

From analysis of the Piper diagrams for HUA and PCA, the following generalizations were obtained as the groundwater properties in Hanoi: the $[Ca^{2+}]$ type groundwater is quite abundant in both aquifers; almost all groundwater in the 10 HUA and 15 PCA observation wells is of the $[HCO_3^-]$ type during the dry and rainy seasons in both aquifers. The results from the Piper diagrams also show temporal changes in hydrochemical facies in 50% of the HUA wells and 46.7% of the PCA wells during both seasons. The change particularly occurs in the cation type (i.e., $[Ca^{2+}]$ to $[Mg^{2+}]$ or $[Na^+]$, $[Mg^{2+}]$ to $[Ca^{2+}]$, $[Na^+]$ to $[Ca^{2+}]$ or $[Mg^{2+}]$), whereas the anion type almost unchanged. It is also observed that there are more groundwater samples showing the changes in the hydrochemical facies during the period of 1993 – 2003 than during the period of 2003 – 2011 in rainy season. This implies that contemporary anthropogenic activities such as irrigation, industrialization and urbanization on the chemical characteristics of the groundwater perhaps affect groundwater chemistry in the study area. The findings of this study provide valuable information regarding the groundwater hydrochemical properties and hydrodynamics in Hanoi, Vietnam.

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References

- Arumugan K, Elangovan K (2009) Hydrochemical characteristics and groundwater quality assessment in Tirupur region, Coimbatore District, Tami Nadu, India. *Environment Geology*, 58, 1509-1520
- Baghvand A, Nasrabadi T, Bidhend, NG, Vosoogh A, Karbassi A, Mehrdadi N (2010) Groundwater quality degradation of an aquifer in Iran central desert. *Desalination*, 260, 264-275

- Berg M, Pham TKT, Stengel C, Buschamana J, Pham HV, Nguyen VD, Giger W (2008) Hydrological and sedimentary controls leading to arsenic contamination of groundwater in the Hanoi area, Vietnam: the impact of iron-arsenic ratios, peat, river bank deposits, and excessive groundwater abstraction. *Chemical geology*, 249, 91-112
- Bui DD, Kawamura A, Tong TN, Amaguchi H, Nakagawa N, Iseri Y (2011). Identification of aquifer system in the whole Red River Delta, Vietnam. *Geosciences Journal*, 15(3), 323-338
- Bui DD, Kawamura A, Tong TN, Amaguchi H (2012a) Aquifer system characterization for potential groundwater resources in Hanoi, Vietnam. *Hydrological Processes*, 26(6), 932-946
- Bui DD, Kawamura A, Tong TN, Amaguchi H, Nakagawa N (2012b) Spatio-temporal analysis of recent groundwater-level trends in the Red River Delta, Vietnam. *Hydrogeology Journal*, 20, 1635-1650
- Bullukraya PN, Ravi R (1999) Characterization of groundwater in the unconfined aquifers of Chennai City, India; Part I: Hydrogeochemistry. *Journal of Geology Science, India*, 54, 1-11
- Christopher JD, Robert RR (2005). Definition of hydrochemical facies in the New Zealand National groundwater Monitoring Programme, *Journal of Hydrology (NZ)*, 44(2), 105-130
- Duong HA, Berg M, Hoang MH, Pham HV, Gallard H, Giger W, von Gunten U. (2003) Trihalomethane formation by chlorination of ammonium- and bromide- containing groundwater in water supplies of Hanoi, Vietnam. *Water Resources*, 37 (13), 3242-3252
- Gibbs RJ (1970). Mechanisms controlling world water chemistry. *Science*, 17, 1088-1090
- Gurugnanam B, Suresh M, Vinoth M, Prabhakaran N, Kumaravel S (2009) GIS based microlevel approach for hydrochemical studies in upper Manimuktha sub basin, Vellar, South India. *Indian Journal of Science and Technology*, 2(11), 5-10
- James ID (1982) *The Geochemistry of Natural Waters*, Prentice-Hall, p36
- Jamshidzadeh Z, Mirbagheri SA (2011) Evaluation of groundwater quantity and quality in the Kashan Basin, Central Iran. *Desalination*, 2070, 23-30
- Joshi A, Seth G (2011) Hydrochemical profile for assessing the groundwater quality of Sambhar lake City and its Adjoining area. *Environmental Monitoring and Assessment*, 174, 547-554
- Keith ES (2002) Occurrence and Distribution of Ammonium in Iowa groundwater. *Water Environment Research*, 74, 177-187
- Kumar SK, Rammodan V, Sahayam JD, Jeevanandam M (2009) Assessment of groundwater quality and hydrogeochemistry of Manimuktha River basin, Tamil Nadu, India. *Environmental Monitoring and Assessment*, 159, 341-351

- Laluraj CM, Gopinath G, Dineshkumar PK (2005) Groundwater chemistry of shallow aquifers in the coastal zones of Cochin, India. *Applied Ecology and Environmental Research*, 3(1), 133-139
- Magesh NS, Krishnakumar S, Chandrasekar N, Soundranayagam JP (2012) Groundwater quality assessment using WQI and GIS techniques, Dindigul district, Tamil Nadu, India. *Arabian Journal of Geosciences*. DOI 10.1007/s12517-012-0673-8
- Marghade D, Malpe DB & Zade AB (2012) Major ion chemistry of shallow groundwater of a fast growing city of Central India, *Environmental Monitoring and Assessment*, 184, 2405-2418
- Montangero A, Le NC, Nguyen VA, Vu DT, Pham TN, Belevi H (2007) Optimising and phosphorus management in the urban environmental sanitation system of Hanoi, Vietnam. *Science of the Total Environment*, 384, 55-66
- Nagarajan R, Rajmohan N, Mahendran U, Senthamilkumar S (2010) Evaluation of groundwater quality and its suitability for drinking and agricultural use in Thanjavur city, Tamil Nadu, India. *Environmental Monitoring and Assessment*, 171, 289-308
- National technical regulation on underground water quality, 2008 (in Vietnamese)
- Nguyen TL (2010). Assessment of land use planning in Hoai Duc, Hanoi during 2006-2010. Ms. thesis, National economics university, 63p. (In Vietnamese)
- Nguyen TT, Helm DC (1996) Land subsidence due to groundwater withdrawal in Hanoi, Vietnam. *International Journal of Rock Mechanics and Mining Sciences and Geomechanics*, 33(7), 298A-298A
- Piper AM (1994) A graphical interpretation of water analysis. *Transactions-American Geophysical Union*, 25m 914-928
- Raji B, Alagbe S (1997) Hydrochemical facies in parts of the Nigerian basement complex, *Environmental Geology*, 29, 46-49
- Raju NJ, Shukla UK, Ram P (2011) Hydrogeochemistry for the assessment of groundwater quality in Varanasi: a fast-urbanizing center in Uttar Pradesh, India. *Environmental Monitoring and Assessment*, 173, 279-300
- Ravikumar P, Venkatesharaju K, Prakash KL, Somashekar RK (2011) Geochemistry of groundwater and groundwater prospects evaluation, Anekal Taluk, Bangalore Urban District, Karnataka, India. *Environmental Monitoring and Assessment*, 179, 93-112
- Tatawat RK, Chandel CPS (2008) A hydrochemical profile for assessing the groundwater quality of Jaipur City. *Environment Monitoring and Assessment*, 143, 337-343
- Todd DK (1980) *Groundwater hydrology*. NewYork: Wiley
- Tong TN (2007) Groundwater level change in the Red River Delta. Ph.D. thesis, University of Geology and Mining, Hanoi, 150 p. (In Vietnamese)

- Umar R. & Alam F (2012) Assessment of hydrochemical characteristics of groundwater in parts of Hindon-Yamuna interfluvial region, Badhpat District, Western Uttar Pradesh Environmental Monitoring and Assessment, 184, 2321-2336
- William JD (1997) Groundwater geochemistry: Fundamentals and application to contamination, Lewis publishers
- Yidana SM, Bruce BY, Thomas MA (2010) Analysis of groundwater quality using multivariate and spatial analyses in the Keta basin, Ghana. Journal of African Earth Sciences, 58, 220-234