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Hydrogeochemical characteristics of groundwater from the two main aquifers in the Red River Delta, Vietnam

Thuy Thanh Nguyen [a,*], Akira Kawamura [a], Thanh Ngoc Tong [b], Naoko Nakagawa [a], Hideo Amaguchi [a], Romeo Gilbuena Jr. [a]

[a] Department of Civil and Environmental Engineering, Tokyo Metropolitan University, 1-1 Minami-Ohsawa, Hachioji, Tokyo 192-0397, Japan
[b] Center of Water Resources Planning and Investigation, Ministry of Natural Resources and Environment, Hanoi, Viet Nam

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ABSTRACT

In the Red River Delta, situated in the northern part of Vietnam, nearly its entire population depends solely on groundwater for daily water consumptions. For this reason, groundwater quality assessments must be carefully carried out using hydrogeochemical properties, to ensure effective groundwater resource planning for the Delta's present and future groundwater use. In this study, the spatial and seasonal changes in the hydrogeochemical characteristics of groundwater in the two main aquifers of the RRD were investigated by analyzing the physicochemical data obtained in 2011 from 31 conjunctive wells in the Delta's Holocene unconfined aquifer (HUA) and Pleistocene confined aquifer (PCA) using the Piper diagram and the Gibbs diagram. Results of the data analysis show that the groundwater in both aquifers in the upstream area of the delta is dominated by the [Ca^{2+}–HCO_3^-] water-type, while the [Na^+–Cl^-] dominates along the middle-stream and downstream areas. Seasonal changes in the hydrogeochemical facies in both aquifers, comparing the results for the dry and the rainy seasons, were detected in about one third of the sampling wells, which were mainly located at the upstream portion of the Delta. The hydrogeochemical facies of HUA were different from that of PCA by about 45% of the sampling wells in both the dry and the rainy seasons, which were found mostly in the upstream and middle-stream areas.

1. Introduction

The Red River Delta (RRD) is the second largest delta in Vietnam with an area of about 13,000 km^2 which encompasses the Vietnamese capital, Hanoi. The RRD has a population of around 20.2 million people in 2012 (around 23% of Vietnam's total population), making it one of Vietnam's most densely populated regions (Vietnam General Statistic Office, 2013). In terms of groundwater uses, almost all of the residents of the RRD depend entirely on groundwater for their domestic water supply. In recent years, due to the rapid population growth in the RRD, alongside industrial and agricultural developments, the groundwater resources in the region were overexploited, leading to the unmitigated decline of groundwater levels (Bui et al., 2012) and deterioration of groundwater quality (Duong et al., 2003; Montangero et al., 2007), which threatens its future availability and/or suitability for succeeding generations. Sustainable management of groundwater in the RRD is thus necessary to secure its availability and ecological value.

In the past, a few RRD's groundwater–related studies were carried out, covering only a small part of the delta, specifically in Hanoi (Vietnam's capital). For instance, Trinh and Fredlund (2000) investigated the occurrence of land subsidence in the Hanoi area as caused by excessive groundwater exploitation. Duong et al. (2003) investigated the prevalence of water pollution in the groundwater supplies of Hanoi. However, in recent years several studies on groundwater have been accomplished in the whole RRD due to the region's importance in the development of Vietnam. For example, Tran et al. (2012) investigated the origin and extent of fresh groundwater, salty paleowaters and saltwater from recent seawater intrusions in the RRD by using geological observations, geophysical borehole logging and transient electromagnetic methods. Arsenic pollution of groundwater in the entire RRD has been studied by Winkel et al. (2011) based on a complete geo-referenced database with 37 chemical parameters from several hundred wells. In our earlier studies, the authors investigated the spatial characteristics of the aquifer system (Bui et al., 2011) as well as groundwater level trends in the whole RRD (Bui et al., 2012). So far, there has been no study carried out in the RRD that focused on analysis of the hydrogeochemical parameters (major

* Corresponding author. Tel.: +81 42 677 4542; fax: +81 42 677 2772.
E-mail address: nguyen-thanhthuy@ed.tmu.ac.jp (T.T. Nguyen).

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cations and anions) such as hydrogeochemical facies, which is fundamental and could serve as reference to future groundwater research works in Vietnam.

The chemical composition of groundwater is controlled by many factors, including the mineralogy of aquifers, the chemical composition of the precipitation and surface water, climate, topography, and anthropogenic activities (Edmunds et al., 1982). The interaction of groundwater with these factors leads to the formation of different hydrogeochemical facies (Clark and Fritz, 1997). Hydrogeochemical facies is one of the most effective tools used to differentiate various forms of geochemical reaction and can be used to infer environmental factors that affect groundwater quality and its flow. Identification and analysis of the hydrogeochemical facies can help further understand the geochemical processes, hydrodynamics and origin of groundwater, as well as its interaction with the aquifer materials (Furi et al., 2011).

The chemistry of groundwater has been extensively studied by many researchers in the past. For instance, 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 in India. Baghvand et al. (2010) studied the groundwater quality of the Kashan Basin in Iran, and characterized the groundwater species using the Piper diagram. Al-Shaibani (2008) evaluated the groundwater chemistry of a shallow alluvial aquifer in western Saudi Arabia. Most of the earlier studies focused only on the hydrogeochemical properties of shallow (unconfined) aquifers. In Vietnam, there is no study on the hydrogeochemical facies of either unconfined or confined aquifers as far as the authors know. Groundwater in the RRD mainly exists in the Holocene unconfined aquifer (HUA) and Pleistocene confined aquifer (PCA) with the latter serving as the highest groundwater potential and most important aquifer for water supply (Bui et al., 2011). In addition, excessive groundwater abstraction from PCA causes vertical percolation of water from HUA, which may lead to changes in groundwater chemistry. Therefore, the investigation of the differences in hydrogeochemical characteristics between HUA and PCA is important in understanding the interaction between the two aquifers.

Groundwater interacts with surface hydrologic systems, such as rivers, lakes and oceans, and is indirectly influenced by seasonal changes during recharge and discharge. The change in seasons can potentially affect the hydrogeochemical properties of groundwater, especially in areas that have distinct dry and rainy seasons, like Vietnam. The hydrogeochemical characteristics in the RRD can also be affected by the change in seasons, hence, investigation of the seasonal changes in the hydrochemistry of groundwater may reflect the groundwater hydrodynamics and circulation that may help improve the data collection programs for groundwater assessment and enable better use of groundwater supplies in the RRD.

The aim of this study is to investigate the seasonal changes and spatial hydrogeochemical characteristics of groundwater in not only HUA but also PCA in the RRD. Through the initiative of the national government (National Hydrogeological Database Project), groundwater quality data of the HUA and PCA in the RRD were collected in 2011 during the dry and rainy seasons. The Piper diagram was used to investigate and identify the hydrogeochemical facies. Decades of studies (e.g. Back, 1966; Raji and Alagbe, 1997; Kagabu et al., 2011) have already proven the efficacy and robustness of the Piper diagram method in classifying the ions in the groundwater into various hydrogeochemical types. Gibbs (1970) proposed chemical diagram for the assessment of functional sources of dissolved chemical constituents and to infer the mechanism controlling the chemistry of surface water. Various researchers have already demonstrated the usefulness of Gibbs diagram for groundwater of shallow (unconfined) aquifers (Xiao et al., 2012; Oinam et al., 2012; Raju et al., 2011). In this study, the Gibbs diagram was used as reference to determine the factors that govern groundwater composition, not only in the unconfined aquifer, but also in the confined aquifer of the RRD. This study will provide valuable insights in understanding the changes from the dry to rainy seasons, the differences between two aquifers, and the spatial distribution of the groundwater hydrogeochemical properties in the RRD.

2. Study area

Fig. 1 shows the geographical locations of the RRD and the 31 conjunctive groundwater sampling wells for both HUA and PCA. For convenient investigation of the study area, the RRD is divided into 3 parts: upstream, middle-stream and downstream areas by two hydrogeological cross-sections (lines A-A′ and B-B′) as shown in Fig. 1. Well Nos. 1–15 are in the upstream area, Well Nos. 16–24 are in the middle-stream area, and Well Nos. 25–31 are in the downstream area. The RRD is the most developed region in Vietnam and is comprised of 11 provinces/cities (Fig. 1). Two of Vietnam's major economic centers, Hanoi and Hai Phong, are located in the RRD (Bui et al., 2012).

The RRD is situated in the tropical monsoonal region with two distinct seasons: the rainy (May to October) and the dry (November to April) seasons. The annual average rainfall is about 1,600 mm, 75% of which occurs during the rainy season. The annual average humidity is about 80%, and the average temperature is 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/km^2 (Bui et al., 2011). The average discharge of the Red River at the Hanoi station (indicated by a triangle in Fig. 1) is 1160 m^3/s during the dry season and 3970 m^3/s during the rainy season (IMHE-MONRE, 2011). In the Red River, high concentration of suspended solids is always present that actually give it its "reddish" color. The tidal range along the coast is approximately 4 m. The lakes, ponds and canals in highly urbanized areas are seriously polluted with untreated domestic and industrial wastewater. The groundwater, being relatively cleaner and generally unaffected by the surface environmental problems, has become the most trusted freshwater source in the RRD (Bui et al., 2011).

In terms of regional geology, the RRD is composed of Quaternary-aged unconsolidated sediments with the thickness ranging from a few meters in the northwest to 150–200 m at the coastline in the southeast (Tran et al., 2012). In our previous studies (Bui et al., 2011), five hydrogeological cross-sections were identified by hydrostratigraphically interpolating strata data from a number of well logs in order to demonstrate the vertical framework of the aquifer system. Fig. 2 shows two out of the five cross-sections along the A-A′ and B-B′ lines shown in Fig. 1. The groundwater mostly exists as porous water that forms the topmost HUA and the shallow PCA, sandwiching the Holocene–Pleistocene aquitard. This aquitard however is completely missing in some places, thus creating hydrogeological windows that directly connect the two aquifer systems. HUA consists of silty clay and various sands mixed with gravel. The thickness of this layer varies greatly up to more than 60 m, which increases from the northwest to the southeast of the delta, whereas there exists a thin area with the thickness of less than 30 m in the middle of the delta. The transmissivities in HUA vary up to 2200 m^2/day. PCA consists of sands mixed with cobbles and pebbles, and is situated below HUA in the stratigraphic sequence. The thickness of PCA fluctuates over a large range with an average of about 80 m, and gradually increases from the northwest to southeast of the delta. The transmissivity ranges from 700 to 3000 m^2/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