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Hydrogeochemical and isotopic features of the groundwater flow systems in the central-northern part of Jeju Island (Republic of Korea)

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ABSTRACT

Groundwater from 10 production wells located in lowlands to highlands was investigated from July 2008 to February 2010 for chemical and isotopic compositions ($\delta^{18}O$, $\delta^{2}H$, and $\delta^{13}C_{DIC}$) to understand groundwater recharge processes and to assess geochemical conditions of groundwater in the volcanic aquifers. The groundwater in lowlands had elevated concentrations of Cl and NO_3 with greater seasonality when compared with those from higher areas, indicating that groundwater in the lowlands is affected by contamination. Based on $\delta^{18}O$ values and altitudinal variations, groundwater was classified into two regional flow systems with different flow paths. The regional flow systems are likely connected from highland to lowland areas, considering consistent $\delta^{18}O$ values and major ion contents throughout the seasons. Of the two regional flow systems, the wells clustered in one regional flow system showed low $\delta^{13}C_{DIC}$ values (average −14.3‰) and high P_{CO2} (average 2.04 in -logP_{CO2}), reflecting relatively high contribution of soil CO_2 to groundwater. The other regional flow system with low P_{CO2} (average 2.39 in -logP_{CO2}), however, consisted of two highland wells with enriched $\delta^{13}C_{DIC}$ value, −9.3‰ and two lowland wells with relatively depleted $\delta^{13}C_{DIC}$ value, −13.7‰. These findings indicate that the two regional flow systems were mixed with local recharge from soil layers during recharge. The $\delta^{18}O$ and $\delta^{2}H$ values in groundwater from the regional flow systems were not clearly consistent with the local meteoric water line due to mixing of summer and dry season precipitation. The isotopic variations showed a phase lag and cyclic temporal patterns, suggesting that a considerable portion of groundwater was derived from fast recharge with short residence times on monthly time scales. This study suggests that groundwater in lowland areas in Jeju Island can be significantly contributed from highland areas, which was revealed by chemical and isotopic compositions, especially, altitude effect and seasonal variation of $\delta^{18}O$ value. We expect that the knowledge on the volcanic aquifer system can be useful for management of groundwater resources including projects (e.g. artificial recharge technology) which has been carried out to mitigate water poverty over the world.

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1. Introduction

The water resources shortage has drawn worldwide concern. Recently, Lawrence et al. (2002) reported a water poverty index (WPI) for 140 countries based on factors such as the total amount of water, water management by humans, and evaluation of the environment for water reserves. South Korea ranked as 59th, with a relatively high WPI, suggesting a less severe shortage of water resources. Moreover, the Oxford Centre for Water Research, using a world map classified by WPI (http://ocwr.ouce.ox.ac.uk), determined that South Korea provides water to its residents without severe problems. Nevertheless, these data are not applicable to Jeju Island in South Korea due to regional characteristics of climate, topography, geology, and continuously increasing tourism.

The amount of precipitation on Jeju Island is generally more than that in any other area of South Korea; during the last thirty years (1981–2010), the average annual precipitation on Jeju Island was 1633 mm, whereas that in continental areas was 1333 mm (Korea Meteorological Administration [KMA], www.kma.go.kr). Despite higher amount of precipitation, the water resources have not been efficiently managed due to both the absence of proper structures for a good storage of the water resources and the concentration of precipitation in the summer season. That is, according to precipitation reported in 2000 to 2010, >56% of precipitation on Jeju Island is concentrated in the summer season, i.e., June to September, and perennial streams are lacking because of extensively distributed permeable basaltic rocks. As a result, only 46% of total precipitation infiltrates into groundwater, and 19% is

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washed away to oceans by runoff (KOWACO, 2003). The great increase in Jeju Island's total population (settled and tourist populations), from 4.7 million in 2000 to 8.3 million in 2010 (Jeju Synthesis Data Center [http://jejudb.jejusi.go.kr/content/stat/stat_02_5.php]; Jeju Special Self-Governing Province [http://www.seogwipo.go.kr/contents/index.php?page=4&mid=033112]), demands more sustainable water resources and also underscores the necessity for efficient water management. In similar, many arid and semiarid countries suffer from water resources shortage and thus have interested in how to mitigate water poverty and efficiently manage them, with consideration for a lack of water storage infrastructure. For example, artificial recharge technology, which directly divert precipitation collected into injection wells, was carried out in several countries (Asano and Cotruvo, 2004; Dillon, 2005; Sheng, 2005; Bouri and Dhia, 2010). To do the state-of-the art technique, it is prerequisite to understand aquifer properties (e.g., thickness, linkage of aquifers, flow direction) and to determine whether anthropogenic sources contribute to groundwater chemistry in production well.

In terms of geochemical processes occurring in volcanic aquifer, silica (Si) is regarded as a main constituent to understand recharge and flow system of groundwater. Si is not involved significantly in the reaction such as ion exchange and biological exploitation (Drever and Clow, 1995). Thus, Si concentration becomes higher with increasing residence time and as flowing through bedrock than above it (Mandal et al., 2011). Numerous studies have deciphered groundwater system in volcanic aquifer using the variation of Si concentration and Si related to ions (Koh et al., 2009). According to companion studies of Koh et al. (2006a, 2009), Si concentration rapidly increased in the early stage of reaction and thereafter constant later due to formation of secondary silicate mineral, with comparison of groundwater age and mineralization. In addition, Mandal et al. (2011) inferred, depending on the level of Si concentration, that spring water, groundwater and submarine groundwater discharge would undergo a different flow path, and this was supported by environmental tracers such as CFC-12 and SF_6 and ^3H reported by Asai et al. (2008).

On Jeju Island, high- and low-permeability layers alternate and there is very thick unsaturated zone, approximately 50% of the elevation on which it is (Kim and Kim, 2009). Additionally, pahoehoe, generally including lava tunnels and lava tubes, is widely distributed (Won et al., 2005). The total amount of precipitation per year declines from ca. 3400 mm in the most upland to ca. 1200 mm in coastal regions (Korean Water Resources Corporation [KOWACO] 2003). The geological and meteorological characteristics suggest the possibility that aquifers with high storage capacity at high altitudes would be connected to wells at low altitudes as a form of regional flow. The island can be divided into two regions of coastal area, <200 m above sea level (asl), and high-altitude area, >200 m asl based on topography and land use patterns (Koh et al., 2007b). The high-altitude area contributes 69% of total recharge of the island (Park et al., 2014).

The aim of this study was to determine whether wells at relatively high altitudes, >200 m above sea level (asl), are connected to groundwater at the lower altitudes, <200 m asl, and then to decipher how groundwater in the wells is recharged. For these purposes, groundwater samples were collected from five wells located at low altitude, ca. 150 to 200 m asl, and from the other five wells at high altitude, ca. 200 to 400 m asl, from 2008 to 2010. Chemical and isotopic compositions of the groundwater were determined to understand the geochemical conditions of each groundwater for purposes of classifying groundwater pathways and groundwater recharge processes.

2. Site description

2.1. Description of Jeju Island and study area

Jeju Island, a typical volcano shield with gentle topography and an elliptical shape, is located in southwestern South Korea; it is the largest island in the country, with an area of 1845 km^2 (Fig. 1). Jeju Island is naturally mountainous area dominated by Halla Mountain (1950 m asl), and consists of lowlands in the coastal areas (<200 m asl) and mountainous areas from 200 to 600 m asl. Most residents live in the coastal areas of Seogwipo and Jeju. These cities offer various facilities for tourists such as hotels, restaurants, and rental car service centers in addition to an airport, buildings, orange orchards, and agricultural areas. The mountainous areas are mainly used for agricultural purposes, pastures, forests, and golf courses, whereas the Halla Mountain areas are dominated by forests. Compared with the high areas, the thicker soil layers are developed widely in the lowland areas on Jeju Island (Water Management Information System, WAMIS: www.wamis.go.kr) (Fig. 1).

Jeju Island has a humid subtropical climate that is warmer than that of the rest of South Korea and has clear seasonal variation. The monthly mean air temperature reported by the Korea Meteorological Administration (KMA, www.kma.go.kr) during 1981–2010 ranged from 5.7 to 26.8 °C.

2.2. Geological and hydrological properties of Jeju Island

Jeju Island was formed by volcanism from the Pliocene to Quaternary, and >90% of the island is covered by basaltic rocks (Koh et al., 2006a). The basaltic rocks overlie a hydro-volcanic sedimentary formation, the Seogwipo Formation, which consist of sand, tuffaceous material, and basaltic rock fragments (Sohn et al., 2003). The U Formation, mainly composed of unconsolidated sand and silt, underlies the Seogwipo Formation (Sohn, 1996; Won et al., 2006). The Seogwipo Formation in the northern part of Jeju Island occurs mostly at an altitude of −100 to 50 m asl (Won et al., 2006). The basaltic rocks contain numerous interflow structures that are not filled and are significantly permeable with high storage capacity (Koh et al., 2006a, 2009). The lithology of the Jeju Island aquifers is characterized by thick unsaturated zones, and high- and low-permeable vertically alternated layers (Kim and Kim, 2009). Hydrological properties such as hydraulic conductivity, specific capacity, and groundwater flow were summarized in previous studies (Hagedorn et al., 2011, and references therein). Vertical hydraulic conductivity (K) values for the basaltic aquifers overlying the Seogwipo Formation were estimated to range from 3 to 28 m/d (Kim et al., 2003). According to previous studies, basaltic aquifers distinctly include the higher specific capacities from ca. 1290 to ca. 2410 m^2/day and younger groundwater with ca. 10 to ca. 30 years. These data are comparable to those of sedimentary aquifers with relatively low specific capacity (average 1010 m^2/day) and older groundwater, i.e., 20 to 60 years (Won et al., 2005; Koh et al., 2006a). Groundwater elevations are roughly dependent on topography, and the amount of rainfall increases with altitude (KOWACO, 2003). Water table elevation varies from 180 m asl in high-lying areas to 2 m asl in low-lying areas (Hagedorn et al., 2011), and the N-S-oriented horizontal hydraulic gradient was greater than that of E-W (Koh et al., 2006b). The amount of groundwater use in Jeju city was approximately 73×10^6 m^3/year ($n = 1898$ wells) in 2010, and of the total amount, 62% was for domestic use ($n = 858$ wells) and 36% for agricultural practices ($n = 842$ wells) (WAMIS: www.wamis.go.kr).

2.3. The studied wells: water level and flow direction

10 wells distributed throughout highland to lowland areas were shown in Fig. 1. For all wells, it was hard to obtain the simple information such as the pumping rates, depth to water and screen length during the study period because they were in private. Alternatively, the information on the wells was summarized on the basis of the report written during pumping test period (Table 1). In brief, the length of the wells ranges from 190 m to 350 m. Natural groundwater level (NWL) was measured from 95 m to 185 m in terms of depth to water. By comparison, stable groundwater level (SWL) measured after pumping out approximately 700–800 m^3/d was slightly lowered, 102 m to 190 m. The length and number of screens in each well are dependent on lithological

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