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An Interpretation of Changes in Groundwater Level and Electrical Conductivity in Monitoring Wells in Jeju Island

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제주도의 지하수 관측망 자료를 이용한 지하수위 및 전기전도도 변화 해석

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Abstract: Water sources in volcanic Jeju Island are almost entirely dependent on groundwater because there are actually no perennial streams or rivers due to the permeable nature of surface soils derived from basaltic or trachytic rocks. Uncontrolled development of groundwater resulted in substantial water-level decline, groundwater pollution, and seawater intrusion in several places of the island. To maintain its sustainable groundwater, the provincial government has declared some parts of the island as the Special Groundwater Conservation/Management Area since 1994. Hence, all the activities for the groundwater development in the area should obtain official permit from relevant authorities. Furthermore, to acquire information on groundwater status, a network of groundwater monitoring was established to cover most of the low land and coastal areas with the installation of automatic monitoring systems since 2001. The analysis of the groundwater monitoring data indicated that the water levels had decreased at coastal area, especially in northern part of the island. Moreover, very high electrical conductivity (EC) levels and their increasing trends were observed in the eastern part, which was ascribable to seawater intrusion by intensive pumping in recent years. Water level decline and EC rise in the coastal area are expected to continue despite the present strict control on additional groundwater development.

Keywords: groundwater, basalt, Jeju Island, electrical conductivity, a network of groundwater monitoring

요 약: 제주도는 현무암과 조면암으로부터 기원한 투수성 높은 토양으로 인하여 지표수 유입에 따른 상시하천 발달이 어려워, 용수의 대부분을 지하수에 의존하고 있다. 이에 따른 무분별한 지하수 개발은 지하수위 강하로 이어져, 제주도 내 많은 지역에서 지하수 오염과 해수침투 현상이 나타나고 있다. 제주특별자치도는 제주도의 항구적인 지하수자원 보전을 위하여 1994년 이래 일부 지역을 지하수 보전구역으로 지정하였으며, 이 지역내의 모든 지하수 개발은 허가를 받도록 지정한 바 있다. 또한 지하수 수문과 관련된 수리지질 정보 획득을 위하여, 2001년 이래로 제주도 내 해안지역 및 저지대 전체를 대상으로 지하수 관측망을 설치 · 운영 중이다. 본 연구에서 이러한 지하수 관측망으로부터 얻어진 지하수위, 수온, 전기전도도 등 장기 관측자료를 분석한 결과, 북부 해안지역의 경우 지하수위가 지속적으로 하강하는 것으로 나타났다. 또한 동부 해안지역의 경우는 최근 취수량의 급격한 증가에 따른 해수침투의 영향으로, 대부분의 관측정에서 전기전도도가 높게 나타나며 지속적으로 증가하고 있는 추세로 분석되었다. 이러한 문제점들은 지하수 개발과 관련하여 제주특별자치도의 강력한 통제로 인하여 최근들어 감소하는 추세이지만, 본 연구 결과에 의하면 해안지역의 경우에는 지하수위 하강 및 전기전도도 상승 현상이 지속될 것으로 판단된다.

주요어: 지하수, 현무암, 제주도, 전기전도도, 지하수 관측망

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Introduction

Being 400 km distant from south of Seoul, the capital of Korea, the Jeju Island is the largest volcanic island in the country (Fig. 1a). The island is 73 km in length and 32 km in width. With the location of the Halla Mountain (1,950 m) in the center of the island, its topographic elevations exhibit a centric shape (Fig. 1b). In addition, the island is topographically steep in N-S direction, while it is relatively gentle in E-W direction. Ephemeral streams are mostly developed in N-S direction (Fig. 1c). The island is almost entirely dependent on groundwater as water source for various uses because there exist practically no perennial streams or rivers (Won et al., 2006). The streams run only in the wet season or in the heavy rain period. Rainfalls easily and rapidly infiltrate into the subsurface due to high permeability and large porosity of land surface originating from volcanic rocks.

Before 1994, groundwater was developed without any proper or administrative control, similar to the condition seen in the mainland of the country. Uncontrolled groundwater development resulted in various groundwater hazards such as substantial water-level decline, anthropogenic groundwater contamination, and seawater intrusion (Lee et al., 2007a). Especially in coastal areas, a large increase in salinity (or EC) of groundwaters led to the abandonment of many wells (Kim et al., 2003) and encroachment of the seawater (saline water) has aggravated the conditions of water supply in the island. The "Groundwater Law" was enacted in 1994 to regulate the groundwater development and to establish the national plan of sustainable conservation of the groundwater resources throughout the country. Since then, the Jeju provincial government established an action plan consisting of groundwater monitoring and strict local regulations on the groundwater development.

Focusing on the coastal areas, where substantial seawater intrusion was observed, the local government declared them as the "Special Groundwater Conservation/Management Area". According to this declaration,

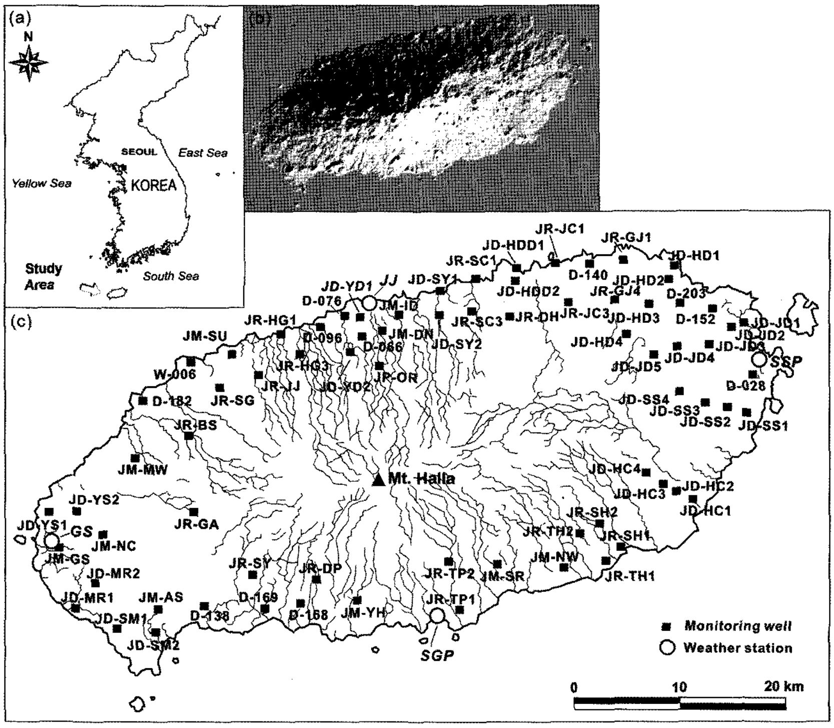

Fig. 1. Location of the Jeju Island (a) and locations of the monitoring wells (b and c). Open circles are the location of 4 weather stations (JJ: Jeju station, GS: Gosan station, SGP: Seogwipo station, and SSP: Seongsanpo station).

activities of all groundwater development and construction of potential contamination facilities (landfills, municipal and livestock wastewaters production facilities) were prohibited strictly without the special and official permit of the local administrative authority. Furthermore, in 2004, the local government designated 20 automatic monitoring wells as the "Reference Wells". Based on the monitoring of groundwater levels, step-wise administrative measures will be undertaken to reduce compulsorily groundwater pumping and its use as a counter-measure of possible drought (Kim et al., 2005). As a management strategy of water resources and water supply, sustainable development of the groundwater resource is the most important in the island.

The objective of this study is to evaluate the recent groundwater development and the variation of groundwater parameters related to seawater intrusion including water level, electrical conductivity and water temperature. All of this information was obtained from a groundwater monitoring network in the island consisting of 73 wells. These parameters have been made automatically at hourly intervals since 2001.

General Geology and Hydrogeology of the Jeju Island

The Jeju Island is a shield volcano, lying on a continental shelf off the Korean Peninsula and it is mainly composed of basaltic lava flows, pyroclastic, and sedimentary rocks (Fig. 2a). The island was formed from 1.20 to 0.025 Ma through multiple volcanic activities (Won et al., 1986). There exist more than 360 pyroclastic cones in the island. Most of them are scoria cones and they are mostly distributed in the inland area. Granite, tuff (mainly, trachytic rocks), sedimentary rocks, and basalt are distributed in the subsurface or surface of the island. The basement granite was formed in Jurassic and Cretaceous periods (Kim et al., 2002) and it occurs at 500 m below sea level (Fig. 2b). The welded tuff formed in the late Cretaceous to early Tertiary periods sits on the basement of granite and it occupies a large portion of the surface of the island. The sedimentary rocks are stratigraphically located between the tuff and the basalts (Yoon et al., 1994). The formations are exposed at a few sites but they are widely distributed in the subsurface as identified by deep borehole data (Oh et al., 2000). They consist of gravelly sandstone, sandstone, sandy mudstone and mudstone which are characterized by abundant bioclastic shells (Koh and Yoon, 1997). The geologic ages of the formations were estimated to be late Pliocene to middle Pleistocene (Yi et al., 1998) and they were regarded as aquitards or aquicludes because of the relatively low permeability (Won et al., 2005, 2006). Upper part of the sedimentary rocks is practically the bottom of the upper very permeable basaltic aquifer.

The basalts predominantly outcropped in east and west parts of the island and it sporadically appears in the central region, mostly adjacent to the coast (see Fig. 2a). Thickness of the basalt is largely varying from 100 to 600 m, with topographic elevations. The basalts are the most permeable. Due to the high permeability of the basalts originated from vesicles and cavities, the rainwater rapidly infiltrates into subsurface. Average values of transmissivity and hydraulic conductivity of the formations are 6,904 m^2/day and 234 m/day, respectively (Won et al., 2006). The most efficient and productive wells on the island have been drilled into the basalts. The trachytic rocks mainly composed of crystalline tuff are inferior to the basalts in permeability but can make adequate aquifers. Average values of transmissivity and corresponding hydraulic conductivity of the formations are 4,369 m^2/day and 125 m/day, respectively. The sedimentary rocks are usually very poorly permeable and values of transmissivity and hydraulic conductivity are 100-1,000 times less than those of the basalts.

The island has a mild oceanic climate and its mean annual air temperature is 15°C. The annual average precipitation is 1,975 mm and local variation and orographic rain effects are very great (Won et al., 2005). Fig. 3 shows precipitation records at four selected weather stations (see Fig. 1 for localities) for 2001-2005. As shown in the figure, patterns of precipitation are very similar even at different

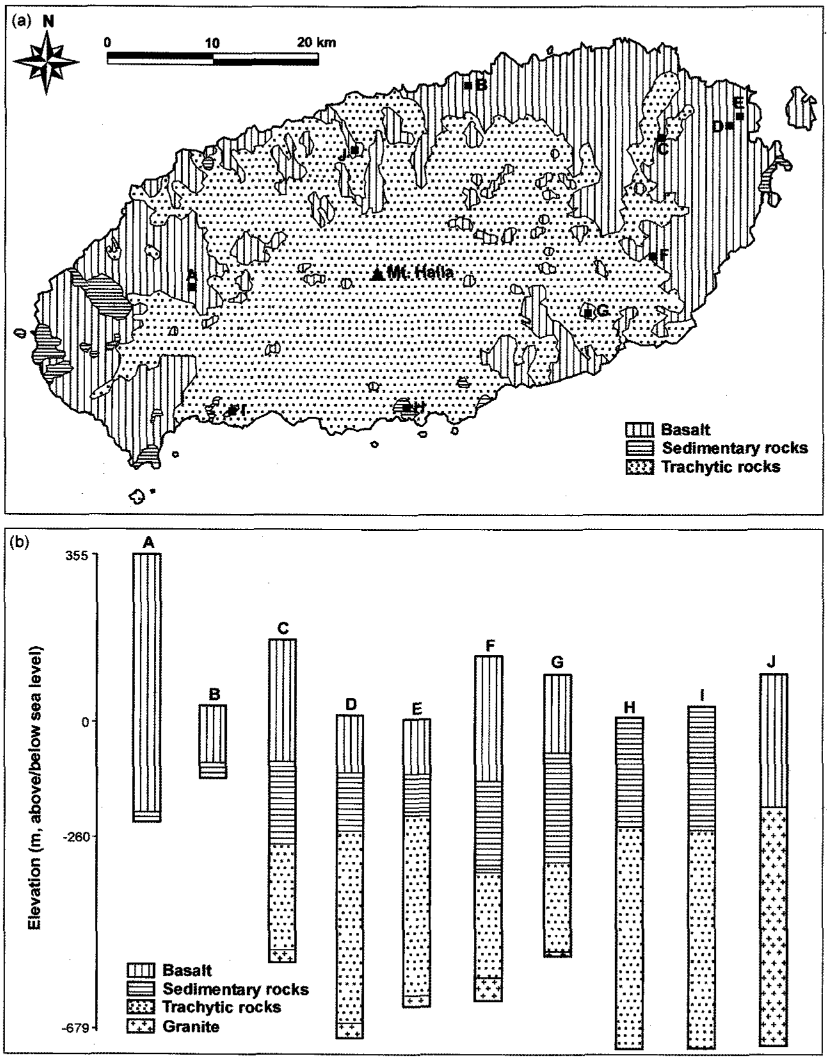

Fig. 2. Geologic map of the Jeju Island (a) and the simplified geologic sections at some locations (b). Data are from Lee (1982), Lee et al. (1994), Kim et al. (2002) and Won et al. (2006).

locations but its intensity is very different. Magnitudes of annual precipitation are different by factors of 1.53-1.92 with location. Furthermore, amount of the precipitation is also very different with topographic elevation (1,100-3,600 mm/year) and it increases as the land elevation becomes higher (Won et al., 2006). In the mean time, over about 60 percent of the annual rainfall occurs during the monsoon season from June to September, which is a characteristic of eastern Asia (Lee and Lee, 2000). According to water budget analyses, groundwater recharge is averagely 46% of the total amount of precipitation in an ordinary year (Won, 2004). The remainder corresponds to the evapotranspiration.

Groundwater Development

Historically the surface water resource is very scarce in the island. Before 1900, most of water was obtained from natural springs or rain harvesting. There were 12 hand-dug shallow wells in 1935. The first drilled well (depth = 73 m and well yield = 395 m^3/day) was constructed in 1961 with an aid of USOM (United States Operations Mission). Number of drilled

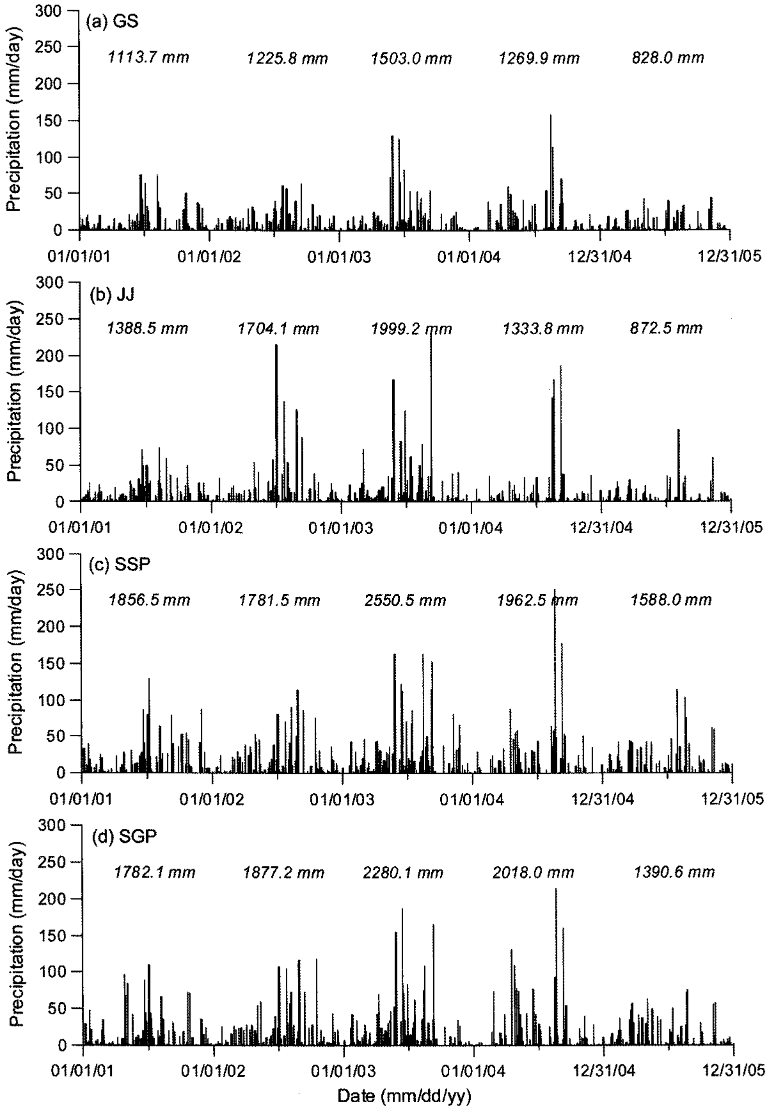

Fig. 3. Daily precipitations measured at four weather stations in Fig. 1 from 2001 to 2005. Annual mean precipitations are also shown.

wells was 15 in 1965 and it increased to 19 in 1969 and to 124 in 1979. It is known that most intensive groundwater development in the island occurred in a large number of private wells that were constructed without any control (JPWRMO, 2006).

Variations of the number of groundwater wells and the amount of groundwater pumping for 13 years (1993-2005) are shown in Fig. 4. Most groundwater data have been officially collected in the island since 1993, one year before the "Groundwater Law" was formally enacted throughout South Korea (Lee et al., 2007a). Starting with 2,712 wells and corresponding pumping amount of 230.4×10^6 m^3/year in 1993, the total pumping amount was decreased to 46.0×10^6 m^3/year in 1998 as a result of strict administrative control of new further groundwater development on the island. After 2001, there was no practically large new groundwater development and therefore total pumping amount was maintained around 550×10^6 m^3/year.

The total number of groundwater wells in the island reached 4,976 in 2005 and its corresponding total pumping was 587.4×10^6 m^3/year. Among the 4,976

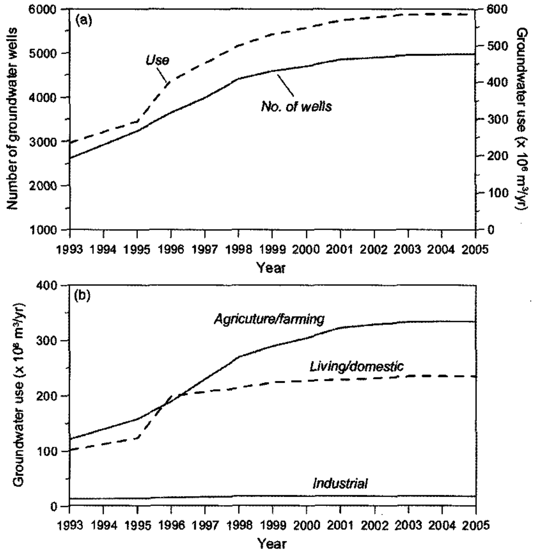

Fig. 4. Number of groundwater wells and the amount of groundwater use in 1993-2004 in the Jeju Island.

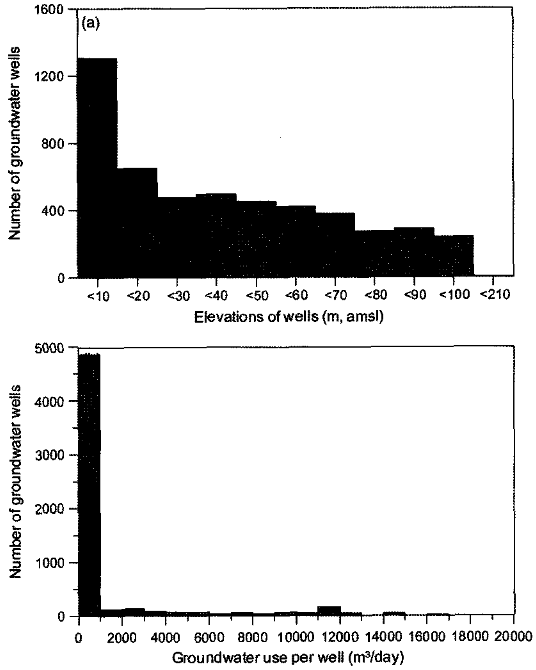

Fig. 5. Distribution of the elevation of groundwater wells and the amount of groundwater use per well (data in 2005).

wells, about 68% are located in area where the topographic elevations are less than 50 m (asl), and 99.9% are within 100 m elevation (Fig. 5a). It means that most of the groundwater wells were concentrated in very low lands. The coastal area (whose elevation is less than 200 m) occupies 54.3% of the total island (1,828.3 km^2; Jeju Province and KOWACO, 2003). Excessive groundwater pumping in some wells results in seawater intrusion (Won et al., 2006). Amount of groundwater use in each well ranged from 5 to 18,720 m^3/day (mean = 1,407 m^3/day). But most (82%) of the wells produce groundwater less than 1,000 m^3/day (Fig. 5b) and about 56% less than 200 m^3/day.

Among the total groundwater wells, about 82% are privately owned and they have been mainly used for agricultural activity or livestock farming (Table 1). In respect to number of wells, the order of decreasing number is agricultural/livestock (66.5%) > living (domestic) (27.7%) > industrial (3.6%) > monitoring (2.2%). The 27.7% of the groundwater wells for domestic use accounted for 40.0% of the total groundwater use, which indicates that pumping rate of each domestic well is relatively larger. Proportion of groundwater use (3.1%) for industrial purpose is relatively small in the island (Fig. 5b), compared with 6% of inland area (Lee et al., 2007a) because main business areas of the island are agriculture, farming, and tourism.

Groundwater Monitoring Network

Official groundwater monitoring in the island to evaluate seawater intrusion started in 1991 but automatic monitoring was initiated in 2001. Installation of monitoring well (station) has been done step by step

Table 1. Summary of groundwater development in the Jeju Island (data in 2005)

Ownership		Public well (896; 18.0%), private well (4,080; 82.0%)
Usage	Number of wells	Agricultural/livestock (3,306; 66.5%) living/domestic (1,380; 27.7%), industrial (180; 3.6%), monitoring (110; 2.2%)
	Quantity of groundwater use (m^3/day)	Agricultural/livestock (915,723; 56.9%) living/domestic (644,364; 40.0%), industrial (49,353; 3.1%), monitoring (0; 0.0%)

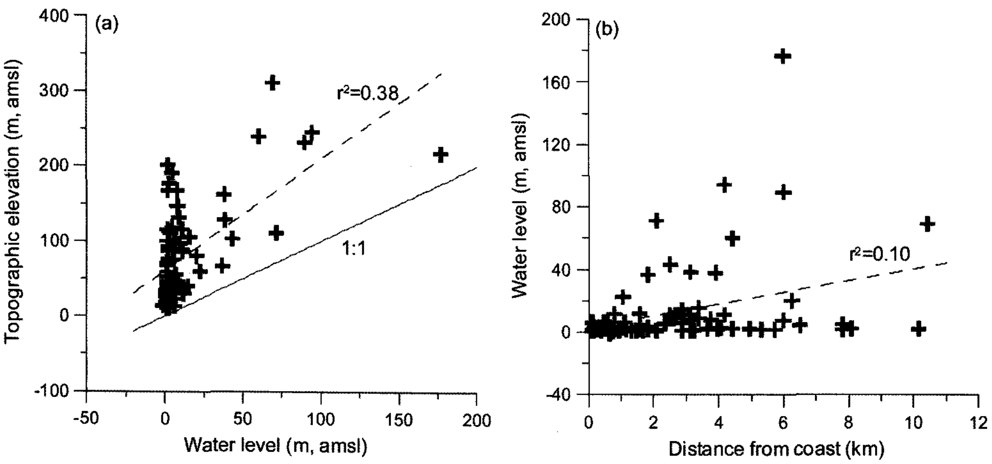

Fig. 6. Relationship between groundwater levels and elevations (a) and distances from the coast (b) for monitoring wells.

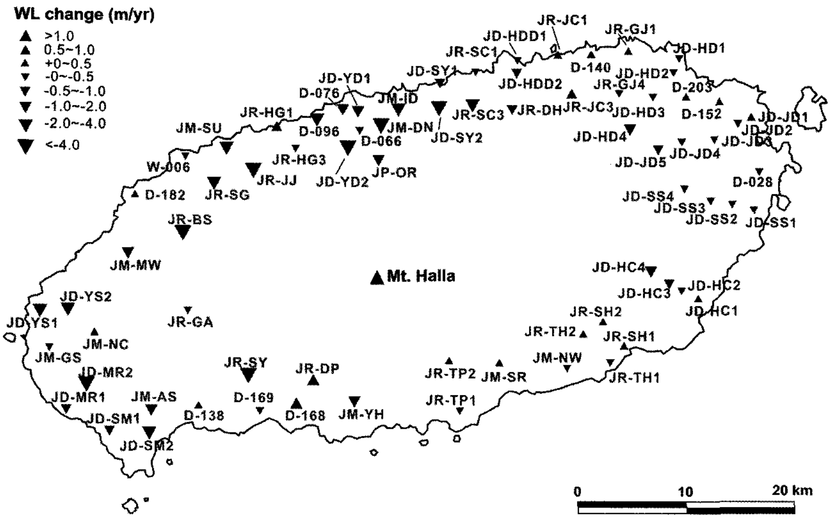

Fig. 7. Distribution of the calculated rates of groundwater level change.

and the number of the automatic monitoring wells mainly covering low lands and coastal areas reached 73 in 2004 (see Fig. 1c). Depths of the monitoring wells range between 26 and 408 m (average = 161 m) and their topographic elevations are between 10.53 and 311.54 m above sea level (average = 82.03 m). Monitoring wells at higher elevations (>500 m) are under construction. Distances from the coast range between 0.1 and 10.4 km with an average of 2.9 km. Except for grouting of upper a few meters, lower portion of the monitoring well is left open. The monitoring wells mostly tapped the basalt or the trachytic rocks (mostly crystalline tuff).

An automatic probe equipped with a data logger measures water level, electrical conductivity, and water temperature every hour. Daily averaged values of them are available to the public on the web (http://www.jejuwater.go.kr/index.html), which were used for this study. In addition, in this database, pertinent information of all the groundwater wells in the island is provided, which includes permission date of well installation, well location and depth, elevation and amount of daily groundwater use, and initial water level measured at the time of the well installation.

Variation and Distribution of Groundwater Parameters

To identify the trend of groundwater parameters (water level, electrical conductivity, and groundwater temperature) in the island, the groundwater monitoring data (2001-2005) obtained from the provincial groundwater monitoring network (see Fig. 1c) managed by the Jeju government (Jeju Provincial Water Resources Management Office) were analyzed.

Groundwater levels of the monitoring wells ranged between 7.43 and 242.31 m below ground surface (mean = 67.73 m). The water levels showed a slightly linear relationship with the topographic elevation ($r^2 = 0.38$; Fig. 6a). In addition, they showed a slight increase along with distances from the coast (Fig. 6b), especially in the north and south parts of the island where the topographic gradients are relatively steep (see Fig. 1b). The result of linear regression analysis for multi-year water level data is presented in Fig. 7. A large proportion (74%) of the monitoring wells (water levels) showed negative correlation slopes with pumping rates. The largest decline rates of water levels (<-4 m/year) were detected mainly at the northern part which is most populated and heavily urbanized in the island. The large and continuous

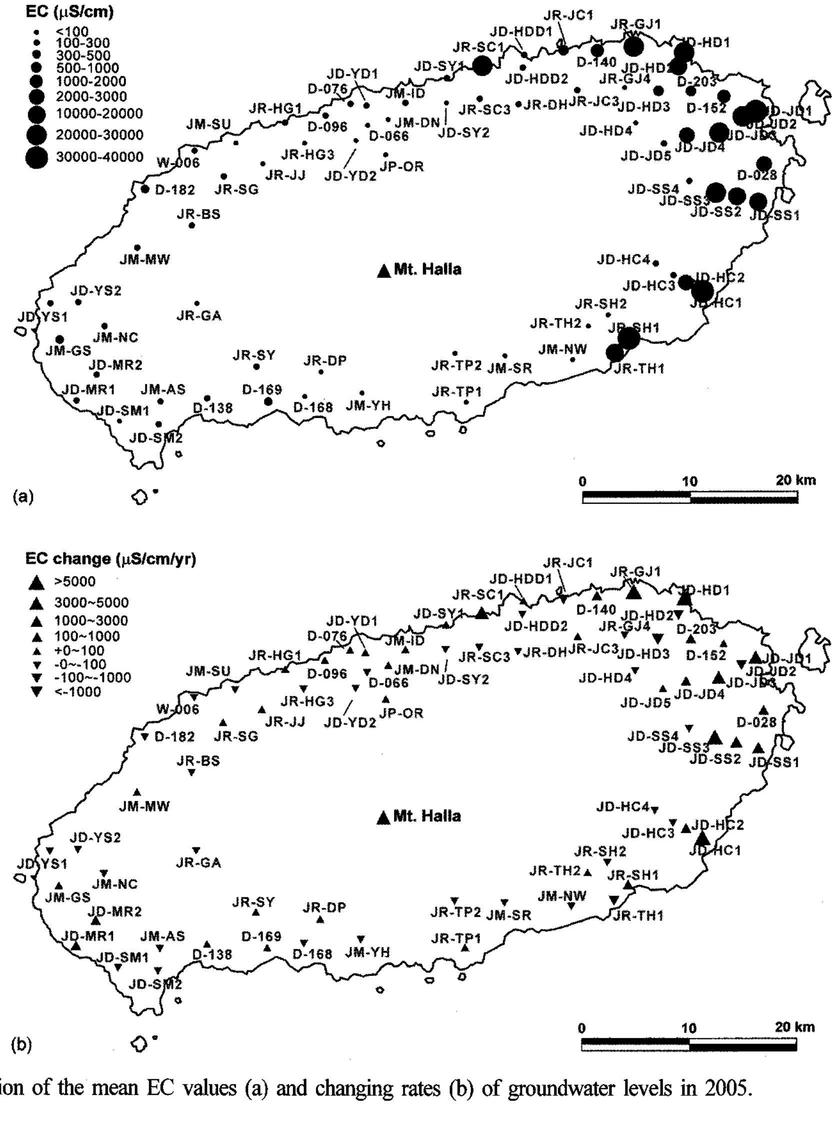

Fig. 8. Distribution of the mean EC values (a) and changing rates (b) of groundwater levels in 2005.

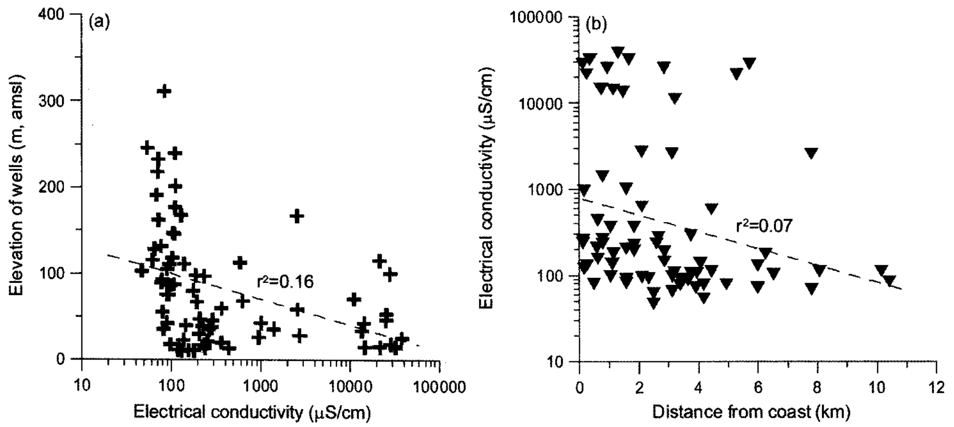

Fig. 9. Relation between EC and elevations (a) and distances from the coast (b) for monitoring wells.

decrease of the water levels is closely related to the increased pumping for domestic uses in urban area.

Distribution of mean EC in 2005 is presented in Fig. 8a. The highest EC levels (30,000-40,000 μS/cm) were observed at eastern part of the island, where large groundwater pumping had occurred for various agricultural activities including cultivation of fruits and vegetables and livestock farming. The large EC values along the coast line indicate gradual encroachment of seawater. In this area, a large increase of EC was also found. Interestingly, areas with high levels or high increasing rates of EC values are not identical to those with high decreasing rates of water levels. The present EC levels are actually the results of intensive pumping in preceding years. Therefore, the substantial EC increase is expected in the northern part of the island in near future. Even though the magnitude of the decreasing water levels was relatively small, the water levels in the eastern part of the island were still decreasing (see Fig. 7).

In the mean time, electrical conductivity showed an inverse relationship with topographic elevation, that is, the lower the elevation the larger the EC (Fig. 9a). This indicates seawater intrusion in coastal low lands. Actually the encroachment of the saline water was also identified from a bivariate plot of EC versus distance from the coast (Fig. 9b). Even in the distance of 5 km from the coast line, very high EC (>20,000 μS/cm) was observed in the eastern part of the island. Along with large amount of groundwater pumping, another main reason of the high EC levels or seawater intrusion is the relatively low hydraulic gradients in this area. Also in the mainland of South Korea, substantial seawater intrusion was observed only in coastal areas having gentle hydraulic gradients (Lee et al., 2007b), adjacent to Yellow Sea and the coastal aquifers are characterized by low recharge rate and high hydraulic conductivity (Kim et al., 2003).

Fig. 10 shows the distribution of mean groundwater temperature and its variation with well depth. The mean temperature ranged from 13.6 to 18.9°C (average = 15.8°C). Annual variation was within 2°C. Compared with mean groundwater temperatures of 14.1°C (for shallow alluvial wells) and 14.2°C (for deep bedrock wells) in the main land area, the groundwater temperatures were slightly higher because of higher ambient air temperatures in Jeju Island, which is the warmest place in the whole country. Interestingly, groundwater temperatures generally increased with well depth (Fig. 10b) even though we rather expected the opposite trend. This indicated that the groundwater temperatures might be affected by the geothermal heat flow from deeper subsurface as well as the solar radiation (Lee, 2006).

Summary and Conclusions

Groundwater is the unique source of water supply

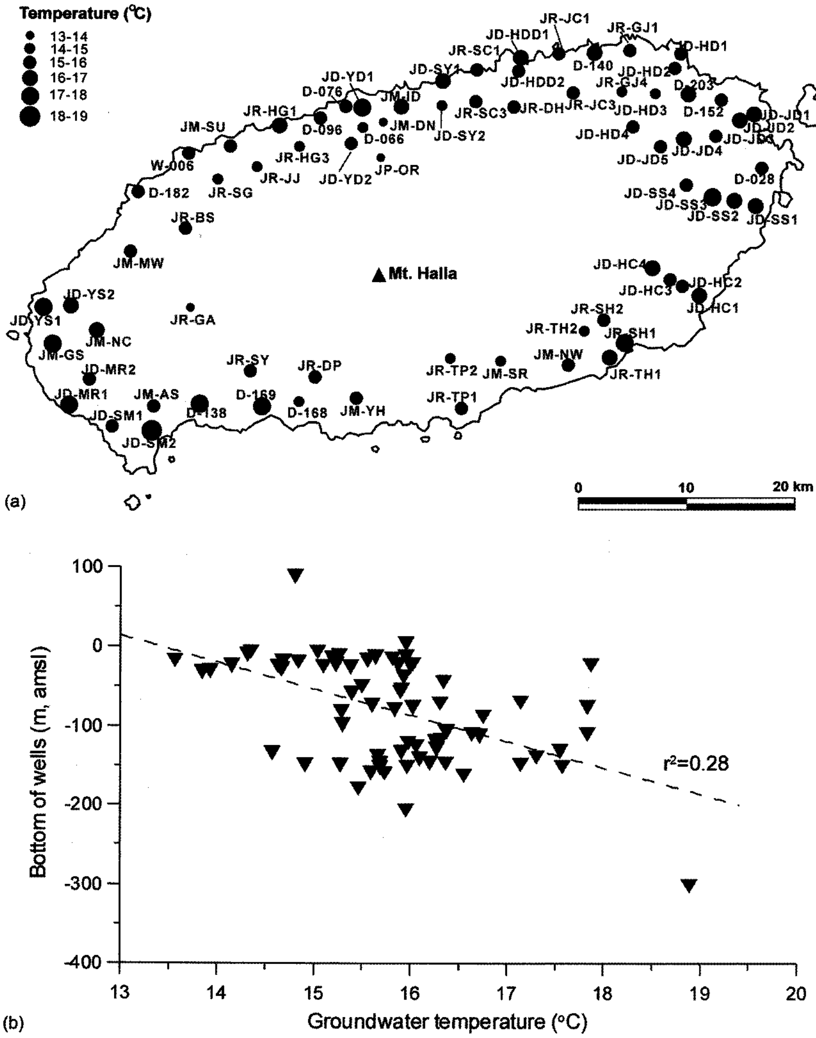

Fig. 10. Distribution of mean groundwater temperatures (a) and the relation between groundwater temperatures and bottom elevation of the monitoring wells (b).

in the Jeju volcanic Island. In the past, peoples in the island were entirely dependent on natural spring waters or rainwater harvestings. But after the drilling technology was used in the island, a large number of groundwater wells were constructed without any proper control especially during a period of 1985-1993. However, after the "Groundwater Act" was enacted in 1994, a proper control or legal regulation on the indiscreet groundwater development became possible. The Jeju provincial government has designated many areas of the whole island as "Special Groundwater Conservation/Management Area" in which additional groundwater development is strictly prohibited. In addition, to monitor groundwater conditions of the island, the government has established the groundwater monitoring network composed of 73 automatic measuring stations, whose number is steadily increasing. From the monitoring network, water level, electrical conductivity, and water temperature data are gained in real time.

Analysis of the monitoring data (2001-2005) from the local groundwater monitoring network revealed that the groundwater levels were still decreasing in many parts of the island and the EC levels showed substantial increasing trend although new groundwater development has been strictly regulated. Consequently further water level decline or EC increase should be carefully monitored in the near future.

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