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Changes of groundwater conditions on Jeju volcanic island, Korea: implications for sustainable agriculture

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Groundwater is the sole source of fresh water in the volcanic Jeju Island due to the absence of any perennial streams. Groundwater exploitation has been extensive and intensive for agricultural, domestic consumption, including drinking, and industrial purposes. In addition, ground source heat pumps (GSHPs; open, closed and underground air types) are now gaining popularity. The conservation of groundwater quantity and quality is therefore crucial to the sustainable development of the island. Groundwater use has continuously increased over the last decade (1999 to 2008) from 110 to 195 M m^3/year, in line with the increasing number of groundwater wells, despite the introduction of many efforts for groundwater protection such as the banning of illegal groundwater well installation and the instigation of artificial groundwater recharge using harvested rainwater. Analysis of the long-term groundwater monitoring data showed a substantial waterlevel decline and corresponding electrical conductivity (EC) rise, which indicated enhanced seawater intrusion and groundwater quality deterioration. In this paper, the current status of groundwater conditions on the island is examined and some implications for its sustainable use are drawn.

Key words: Groundwater, artificial groundwater recharge, ground source heat pumps, seawater intrusion, Jeju volcanic island.

INTRODUCTION

Increasing population and agricultural productivity require an expanded freshwater supply and global climate change adds further stress to the challenge of meeting the increasing freshwater demand worldwide (Vörösmarty et al., 2000; Arnell, 2004; Kundzewicz et al., 2008). Especially, the many islands in the world are the most vulnerable to the adverse effects of the climate change (Barnett, 2001; Uyarra et al., 2005; Ebi et al., 2006). Excessive groundwater pumping in coastal areas can reduce available freshwater quantity due to accelerated seawater intrusion. In addition, sea level rise caused by the global warming further threatens the groundwater resources and ecosystems in the coastal aquifers of many islands (Sherif and Singh, 1999; Bobba, 2002; Baker et al., 2006; Craft et al., 2009).

Jeju Island (latitude of 33°06'-34°00' and longitude of 126°08-126°58') is located 450 km south of Seoul, capital of the Republic of Korea (South Korea), and is the largest island off the Korean peninsular (inset map in Figure 1). The volcanic island was formed 0.7 to 1.2 million years ago through multiple eruptions (Won et al., 2006). The island is 32 km long and 74 km in wide, with a total area of 1,828 km^2 and its peak, Mt. Halla (elevation 1,950 m), is located in the center (Figure 1). The topographic slopes are relatively steep (~5°) in the north and east directions but gentle (~3°) in the south and west directions. Most residential housing is situated in the low elevation coastal areas (0 to 300 m elevations). In the middle and high elevation areas, various agricultural activities such as the growing of many subtropical fruits, vegetables and flowers and raising of cattle, pigs, horses and fowl have been conducted (Lee and Choi, 2012). The very peculiar geologic features such as pillar-shaped joints and mild weather attract tourists worldwide and the tourism services account for 51.6% of the gross regional domestic products (Lee and Choi, 2012).

The island has a mild oceanic climate with an annual mean air temperature of 15.5°C for three decades (1971-2000) but the mean monthly air temperature ranges from

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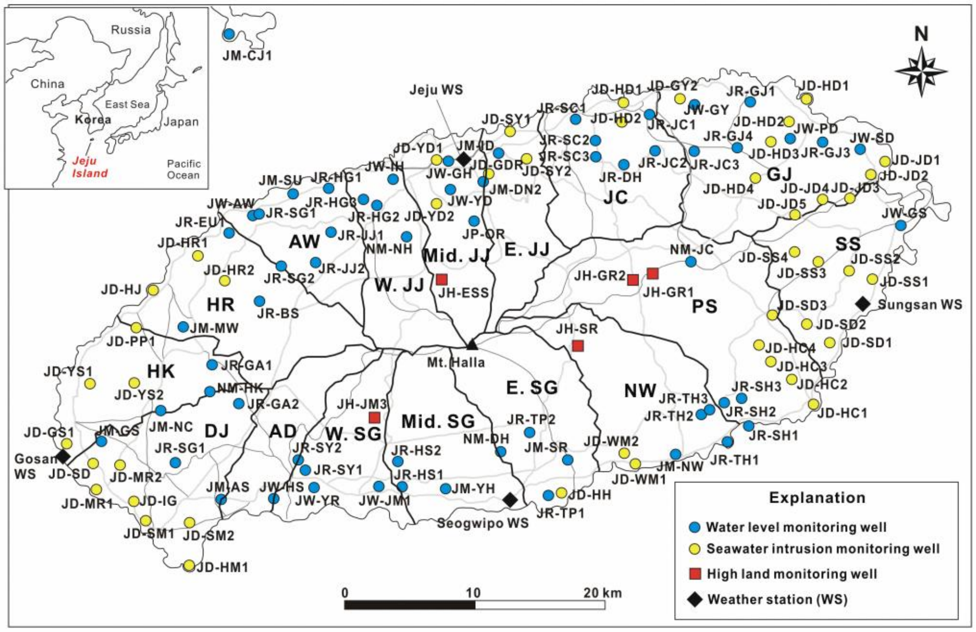

Figure 1. Location of the Jeju Island showing the groundwater monitoring wells. Abbreviation of each region is also noted in capital character.

a low of 4.8°C in February to a high of 29.2°C in August (Figure 2). The air temperature shows a distinctive seasonal variation but the mean annual air temperature increased by 1.6°C for 1924 to 2009 (NIMR and JRMA, 2010). The mean annual precipitation for the three decades is 1,975 mm but the inter-annual variation is very large (Figure 2b). In addition, the precipitation varies greatly with topographic elevation over the range of 1,000 to 3,500 mm: increasing with elevation rise at a rate of 150 to 250 mm/100 m (Won et al., 2006). Due to the monsoon weather characteristics of eastern Asia, about 60% of the total annual precipitation occurs in June-September. The amount of precipitation gradually increased by a rate of 0.11 mm/yr for 1924 to 2009 (NIMR and JRMA 2010). The increased air temperature and precipitation may be attributed to the global climate change (Lee, 2011).

The surface geology of the island is comprised of basalts, trachytic rocks, volcanic sediments and sand dune (Won, 1976; Park et al., 2000). The basalts cover most of the low elevation lands and coastal areas, especially in eastern and western regions, and are the most permeable (mean K = 234.3 m/day), while the trachytic rocks are mainly distributed in the central mountainous parts of the island and show intermediate permeability (mean K = 124.9 m/day) (JPG and KOWACO, 2003; Won et al., 2006). The volcanic sediments show the lowest permeability with a mean hydraulic conductivity of 10.5 m/day and they sporadically occur in coastal areas (Lee and Choi, 2012). The subsurface geology at typical locations in the middle mountainous and coastal areas exhibits basalts (100 to 600 m thickness), sedimentary rocks (50 to 250 m thickness), trachytic rocks and Jurassic granite from the top (Lee, 1982; Kim et al., 2002). As described earlier, the high permeability of the basalts allows the rainfalls to infiltrate readily into subsurface meaning that streams only run during torrential rainfall. The sedimentary rocks below the basalts consist of sandstone and mudstone (Koh and Yoon, 1997), with very low permeability, and form the bottom of the upper permeable basaltic aquifer (Won et al., 2006). The basement Jurassic granites are generally situated at 500 m below mean sea level (Lee et al., 2007a).

Due to these unique geological features, Jeju Island has been almost entirely dependent on groundwater as a fresh water source and thus groundwater conservation and its sustainable use are crucial for the island. To date, despite the many local studies related to groundwater quality and quantity that have been conducted, little overall review of the whole island has been performed (Hahn et al., 1997; KOWACO, 2003; Hamm et al., 2005). The objective of this study is therefore to evaluate groundwater conditions in this peculiar volcanic island. For this purpose, groundwater monitoring data for the period 2001-2009, such as water level, electrical conductivity (EC) and water temperature, were collected from the provincial groundwater monitoring network. We investigated any indications of change in the groundwater conditions, compared with those of a previous period (2001-2005), which may have been affected by changes of groundwater pumping amount, and weather conditions such as precipitation and sea level. The study results can be used to build up a sustainable management plan of

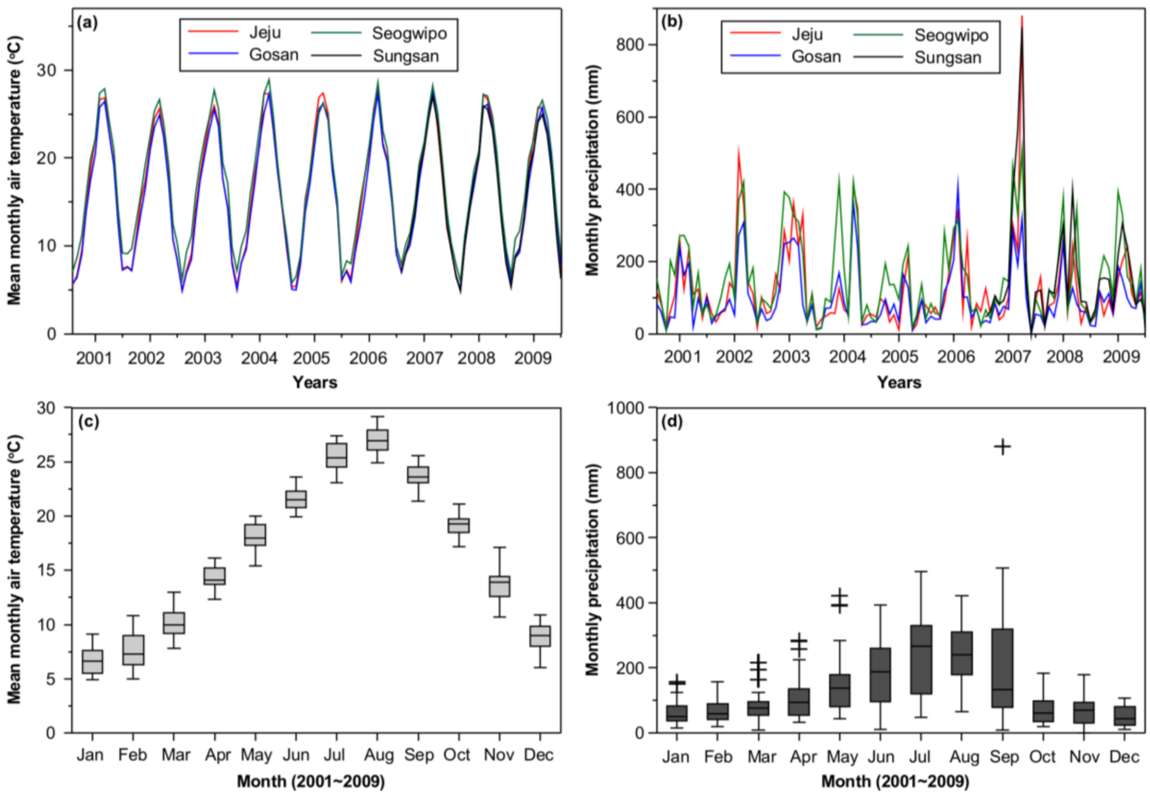

Figure 2. Air temperature and precipitation measured at 4 weather stations (Jeju, Seogwipo, Gosan and Sungsan): (a) monthly mean air temperature, (b) monthly precipitation and box plots of (c) monthly mean air temperature and (d) monthly precipitation.

the groundwater resources.

GROUNDWATER USE AND GROUND SOURCE HEAT PUMPS (GSHPs)

Groundwater is nearly the sole source of freshwater in the volcanic Jeju Island because there are no truly perennial streams (Won et al., 2005). Before 1961, the fresh water supply had been mostly dependent on harvested rainwater, naturally flowing springs and hand-dug shallow wells (Lee et al., 2007a). However, since 1961, many deep groundwater wells equipped with submersible pumps were installed, especially in the low elevation lands, with the help of the United States Operations Mission (IER, 2010). According to national statistics from Statistics Korea, groundwater use in the whole country for the last decade (1999 to 2008) increased from 3,083 to 3,784 million (M) m^3/yr and the number of wells from 988,973 to 1,344,594, which indicated annual mean increasing rates of 85.4 M m^3 and 37,090 wells every year, respectively (Figure 3a). However, if the saline groundwater pumped for aquacultures in coastal areas of Jeju Island is included, the annual domestic groundwater pumping was 6,119 M m^3 in 2008 and its corresponding number of wells was 1,345,841.

In accordance with the increase of national groundwater use, the annual groundwater use in Jeju Island also increased from 113 to 195 M m^3/yr for 1999 to 2008 and the number of wells increased from 4,406 to 5,419 (Figure 3b). Over this decade, the provincial groundwater pumping nearly doubled (mean increasing rate = 10.3 M m^3/yr) and the number of wells increased by 23% (mean increasing rate = 76 wells/yr). The saline groundwater pumping in the coastal areas (which was approximately an order of magnitude larger than the fresh groundwater pumping) showed a most striking increase from 875 M m^3 in 1999 to 2,334 M m^3 in 2008, which was an increase of 167% for the decade. The groundwater pumping occupies 3.7 to 5.2% of total national groundwater pumping and the proportion in increasing annually. If the saline groundwater is included, the proportion reaches up to 25 to 41.3%.

Groundwater usage in Jeju Island also differs markedly from that of the whole country (Figure 4). Agricultural groundwater use has been the most dominant, ranging from 55.4 to 67%, and it had gradually increased annually. The secondly dominant groundwater use is for domestic purpose (29.5 to 38.4%), which includes food preparation, dishes washing, bathing and laundry. The industrial groundwater use has gradually decreased from 4.5 to 3%. However, agricultural groundwater use has consistently taken most (93 to 94.4%) of the total provincial groundwater use (Figure 4b). The domestic and industrial uses have been only 5.2 to 6.4 and 0.4 to 0.7%, respectively. There have been few industrial facilities and the island's main economic development has been dependent on tourisms and agriculture (67.1%; Kang, 2009). Many kinds of vegetable and tropical fruit are being cultivated in the fields and greenhouses of low elevation lands to middle mountainous areas with the extensive pumping of groundwater for irrigation of these agricultural crops (Koh et al., 2007).

Ground source heat pumps (GSHPs) are gaining popularity in Korea for space heating and cooling and have been used especially in agricultural facilities such as greenhouses and livestock farms in Jeju Island (Lee, 2009). As shown in Figure 5a, the number of GSHP installations of Korea has dramatically increased, reaching 131.8 MWt in 2008 and those of Jeju Island also largely increased to 0.46 MWt in 2008 from only 21.1 kWt in 2004 (Figure 5b; KEMCO, 2009). Unlike the mainland where the closed (ground

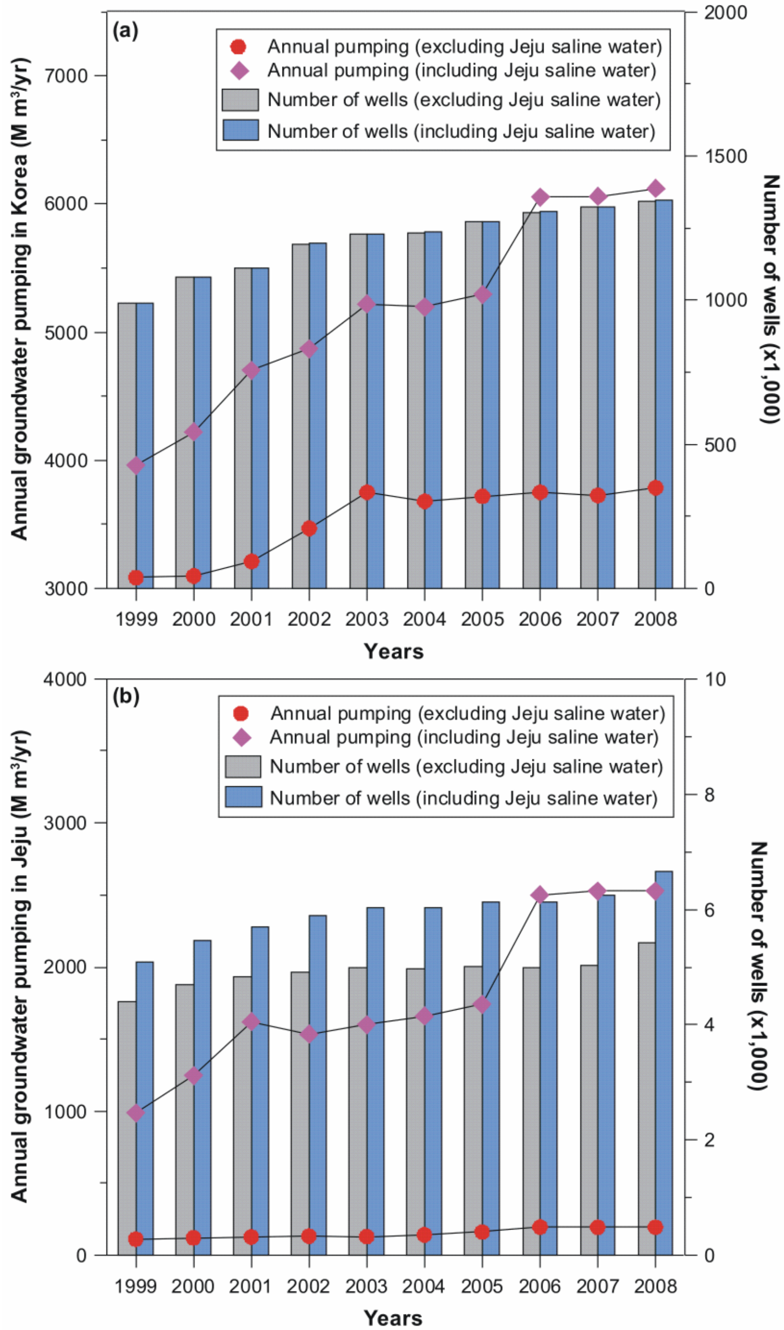

Figure 3. Variations of number of groundwater wells and groundwater pumping amount for 1999-2008 in (a) Korea (whole country) and (b) Jeju Island.

coupled) types are dominant (Lee, 2009), the underground air is dominantly used for the GSHPs in the island (Lee and Choi, 2012). The stable underground air (15-19°C) is extracted from a borehole (~50 m depth) using a blower, delivered to greenhouses and livestock farms, so that the indoor air can be maintained cool in the summer and warm in the winter (Lee and Choi, 2012). However, groundwater pumping (although the groundwater type is few) and the imprudent installation of boreholes for GSHPs have raised public concern about potential groundwater contamination through the boreholes (Jo et al., 2009; Lee and Choi, 2012).

Groundwater monitoring network

The Jeju provincial government has operated various groundwater monitoring wells since 2001, including 57 waterlevel monitoring wells, 47 seawater intrusion wells, 5 high elevation monitoring wells and 4 national groundwater monitoring (installed and operated by K-Water) wells, as of 2009 (see well locations in Figure 1). They are distributed to cover the whole island except for the very elevated area near Mt. Halla. At each monitoring well, groundwater level, water temperature and EC are automatically measured every hour

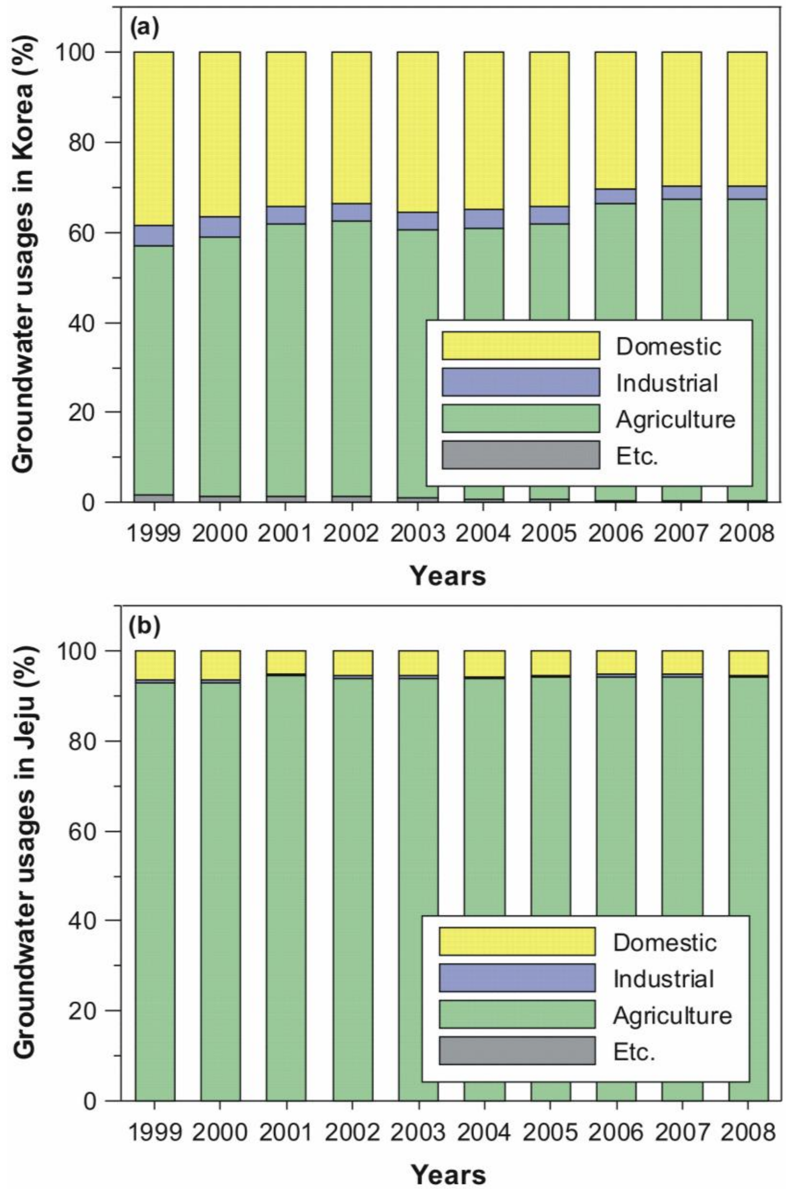

Figure 4. Groundwater usage for 1999 to 2008 in (a) Korea (whole country) and (b) Jeju Island.

using submersed standard sensors. The measured parameters are automatically transferred online in real time to a host computer at the Water Supply and Drainage Management Headquarter. The daily averaged data are available to the public on the web.

Among 113 monitoring wells, 98 (86.7%) had a monitoring period of greater than 2 years and 74 (65.5%) of 6 to 10 years (Figure 6a). Elevations of the monitoring well locations ranged from 5.6 to 620 m and 99 wells (87.6%) were located in areas of elevation below 200 m (Figure 6b), which was 1.6 times larger than the spatial area (55.3%, < 200 m). Because of the increased groundwater pumping due to heavy agricultural activities and expanded residential housing in these low elevation lands, many more monitoring wells were allocated. The well depths ranged between 26 and 550 m and they showed a good linear correlation with topographic elevation ($r = 0.84$, $p<0.001$).

In this study, the monitored groundwater data obtained from the 113 groundwater monitoring wells over a 10-year period were analyzed in order to examine the groundwater condition and its potential change. For trend analyses, only the 98 wells with monitoring data over a period more than 2 years were used. We interpreted any changes found in these trend analyses in the context of changes of groundwater pumping, sea level, regional precipitation and air temperature during the same period.

RESULTS AND DISCUSSION

Distributions of groundwater level, temperature and EC

Figure 7 shows the distribution of annual mean

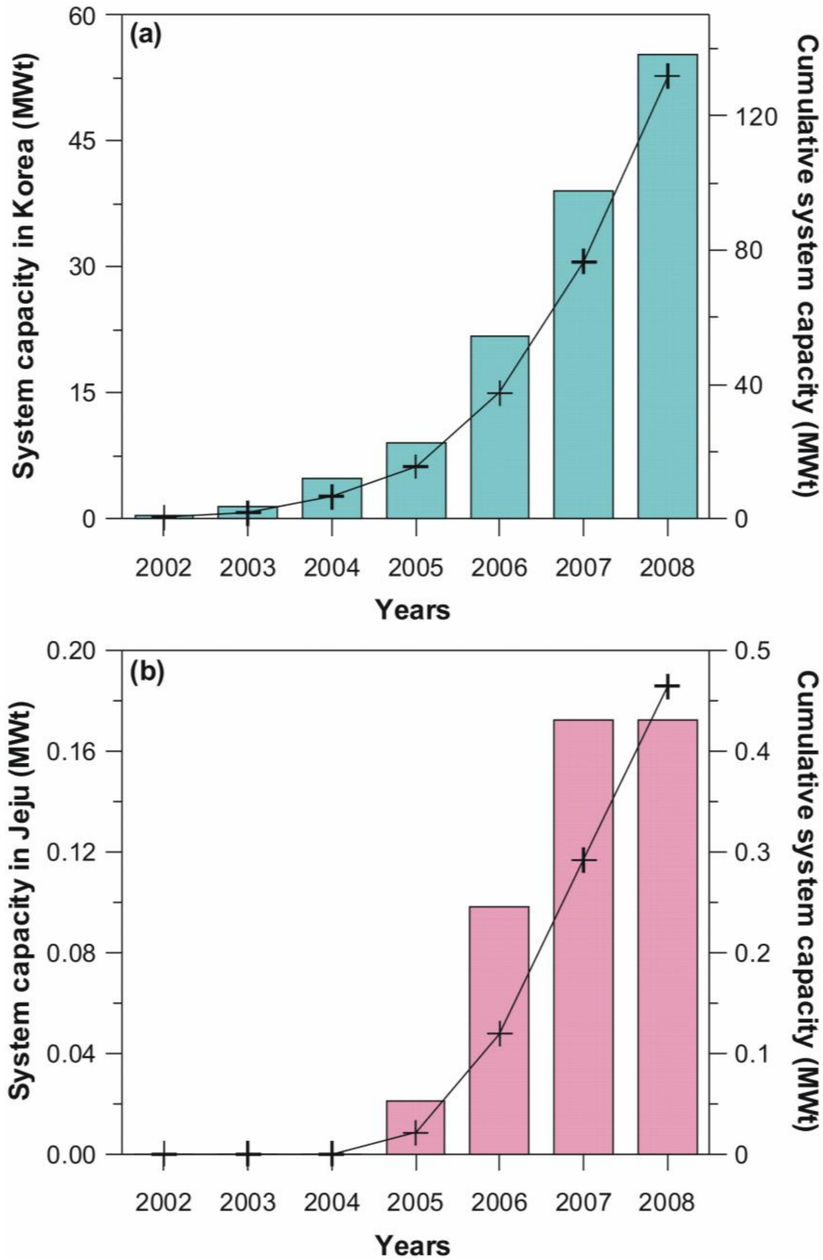

Figure 5. Use of ground source heat pumps for 2002-2008 in (a) Korea (whole country) and (b) Jeju Island. Data are from KEMCO (2009).

groundwater levels and annual water level variation (maximum-minimum) in 2008. The water levels ranged between 7.03 and 343.66 m with an average of 76.1 m and generally showed a good linear correlation with elevation ($r = 0.93$, $p < 0.001$). The hydraulic gradients were steep in the north and south regions but relatively gentle in the east and west regions (Figure 7a). The annual waterlevel variation ranged from 0.42 to 38.06 m (mean = 3.9 m), and was generally larger in the elevated lands (recharge area) but smaller in the low elevation lands (discharge area) ($r = 0.46$, $p < 0.001$) (Lee et al., 2005). The larger waterlevel fluctuations found locally in the low elevation lands (western region) and big cities (Jeju and Seogwipo cities) can be partly attributed to heavy pumping for agricultural irrigation or domestic use (Figure 7b).

The distributions of annual mean EC and annual EC variation (maximum-minimum) are shown in Figure 8. The mean EC ranged from 33 to 37,592 µS/cm with an average of 3,573 µS/cm. Generally, EC was higher in coastal areas and lower inland and was negatively correlated with topographic elevation ($r = -0.22$, $p = 0.02$).

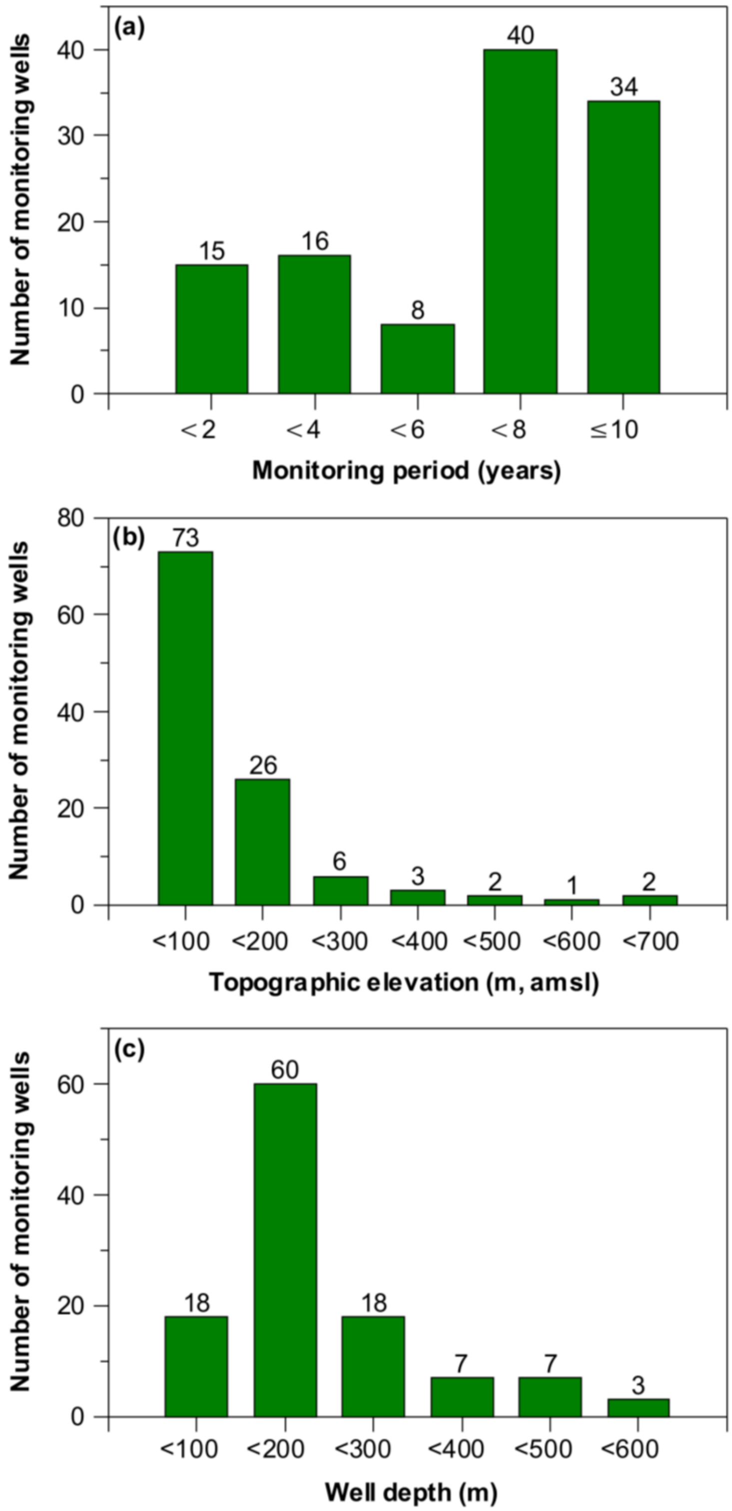

Figure 6. Specifications of the groundwater monitoring wells in the Jeju Island.

Higher values over 1,500 µS/cm generally indicate the effects of seawater intrusion (Mondal et al., 2010; Park et al., 2011). The annual EC variation showed a similar distribution to that of mean EC (Figure 8b) and was also negatively correlated with topographic elevation ($r = -0.25$, $p = 0.01$), which indicated that the larger variation

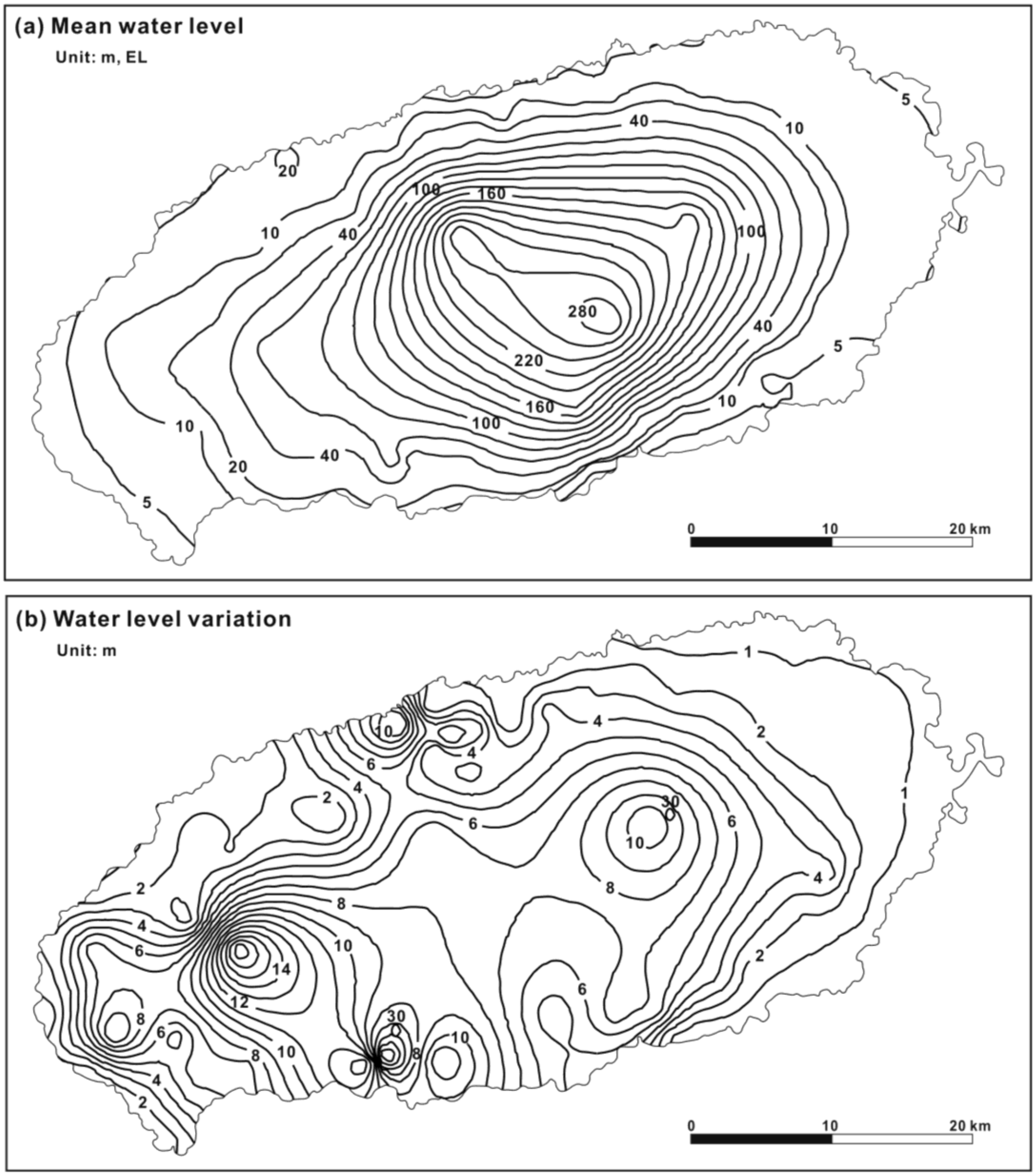

Figure 7. Distributions of (a) groundwater levels (elevation, m) and (b) annual waterlevel fluctuation.

occurred in low elevation coastal areas.

The annual mean groundwater temperature ranged from 13.3 to 19.4°C, with an average of 15.9°C (Figure 9a). Generally, the groundwater temperature was higher in coastal areas and lower in mountainous area and was negatively correlated with elevation ($r = -0.27$, $p = 0.007$). The annual temperature variation was between 0.1 and 7.5°C (average = 1.4°C; Figure 9b), which indicated that the groundwater temperature was relatively stable throughout the year. In general, the annual stability of the groundwater temperature, which also represents the subsurface temperature, supports the potential application of GSHPs with respect to efficient system design and maintenance (Shonder, 2002; Lee and Hahn, 2006).

Trends of groundwater level, temperature and EC

We examined the variation trends of the groundwater levels, water temperature and EC using simple linear regressions or non-parametric trend tests such as Mann-Kendall test (Mann, 1945; Kendall, 1975). Figure 10a shows the distribution of water level changing trends for the monitoring period. The changing rates ranged from -7.14 to +11.58 m/yr with a mean of -0.1 m/yr. Most (72.4%) of the groundwater level data, especially in the coastal areas showed, a decreasing trend, while only

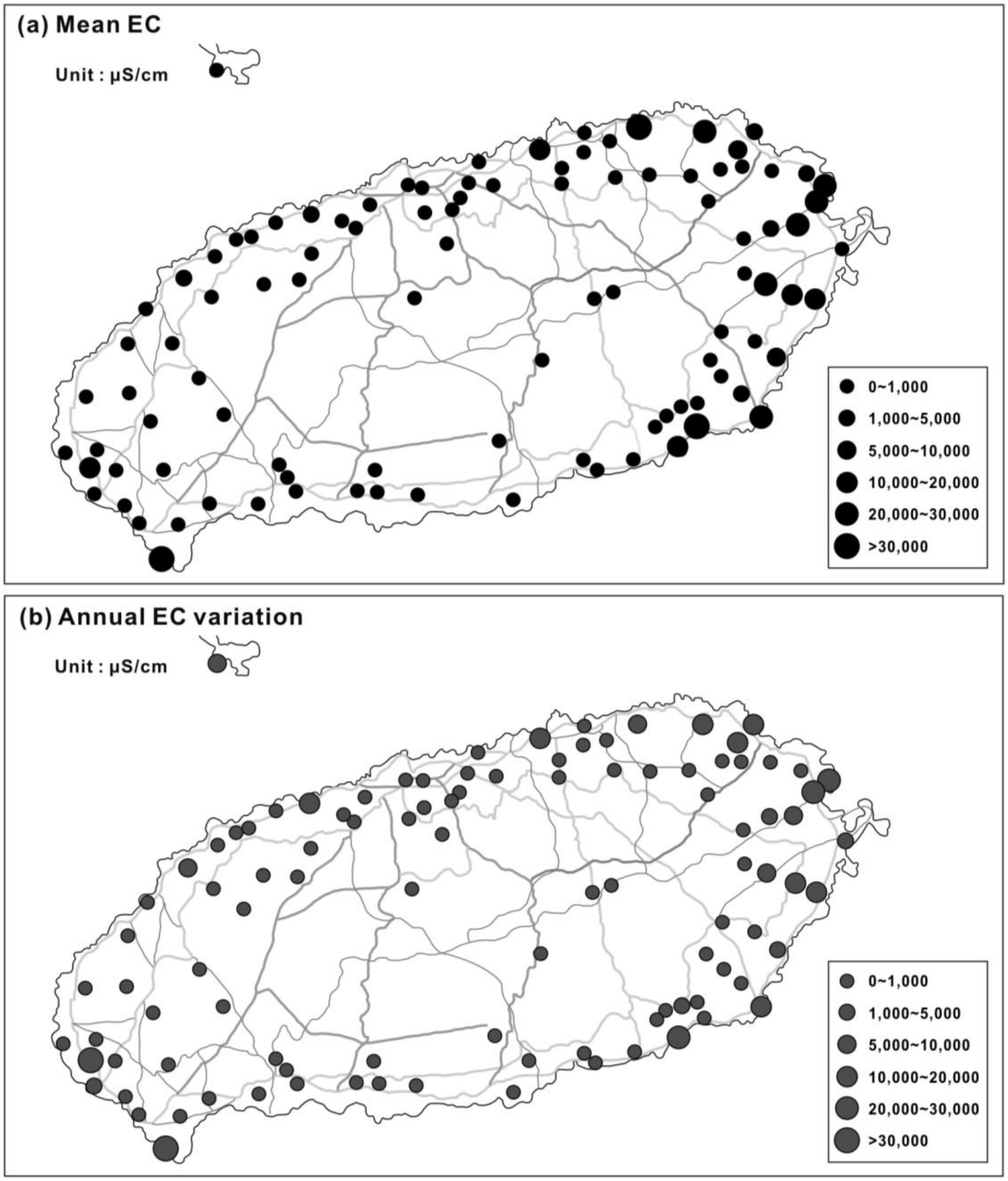

Figure 8. Distributions of (a) electrical conductivity (µS/cm) (b) annual EC variation.

27.6% showed an increasing trend. The proportion of the decreasing trends greatly increased from 74.0% for the previous data of 2001 to 2005 (Lee et al., 2007a). Mann-Kendall trend tests for monthly precipitation showed that amount of precipitation was not changed for the same period ($p = 0.01$). Thus, precipitation does not appear to be one of the driving factors for the changes. As previously shown in Figure 3b, the groundwater pumping, mostly for agricultural irrigation, continuously increased. The distinctive decreasing trend and larger magnitude were found especially in the western region where agricultural groundwater was heavier. The Hankyung (HK) and Daejung (DJ) areas of the western region (see locations in Figure 1) had the largest total groundwater pumping and pumping per unit area for agriculture (Table 1). Therefore, the increased of groundwater pumping was one of main reasons for the decreasing groundwater levels.

The sea level around Jeju Island has been gradually increasing at rates of 5.23 to 5.65 mm/yr (Table 2), which are much higher than those of other seas around the Korean peninsula (3.86 to 4.66 mm/yr) and the global

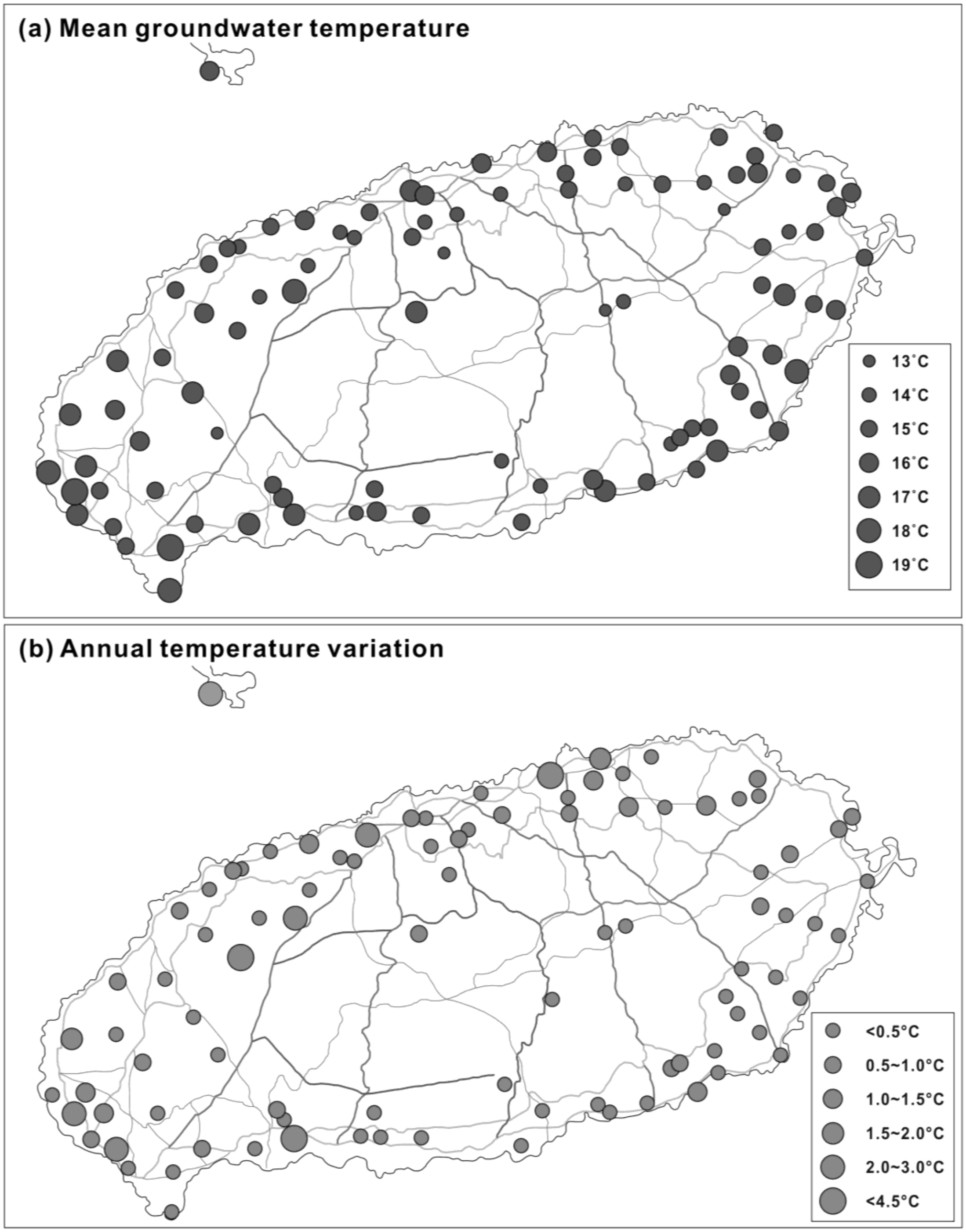

Figure 9. Distributions of (a) groundwater temperature (°C) and (b) annual temperature variation.

mean (3.16 mm/yr). This sea level rise raises the groundwater level and, to a certain extent, increases the seawater intrusion in coastal aquifers (Sherif and Singh, 1999; Werner and Simmons, 2009, Choi et al., 2011). Thus, the approximate 5 cm sea level rise over the groundwater monitoring period would have elevated the groundwater level in the island's coastal aquifers. However, the effect of the sea level rise appeared to be mostly masked by heavy groundwater pumping. Interestingly, some groundwater wells in coastal areas showed increasing water level trends with increasing EC and water temperature, which may have been due to the effects of the sea level rise.

Figure 10b shows the distribution of EC changing rates for the monitored period. The changing rates ranged between -4,558 µS/cm and +11,161 µS/cm (mean = +18

Table 1. Groundwater pumping in 2007 for each region of Jeju Island (data from IER 2010; see locations in Figure 1).

Region	Area (km^2)	Pumping rate (m^2/day)	No. of wells	Pumping per unit area (m^2/day/km^2)
Gujwa (GJ)	156.6	78,500	121	501
Jocheon (JC)	119.6	145,400	270	1,216
East Jeju (E. JJ)	72.5	54,300	151	749
Middle Jeju (Mid. JJ)	85.2	148,400	581	1,742
West Jeju (W. JJ)	87.4	41,600	75	476
Aewol (AW)	79.0	101,300	165	1,282
Hankyung (HK)	94.7	156,100	261	1,648
Hanrim (HR)	134.4	105,100	204	782
Daejung (DJ)	120.3	239,900	782	1,994
Anduk (AD)	60.1	29,700	68	494
West Seogwi (W. SG)	76.2	61,200	212	803
Middle Seogwi (Mid. SG)	100.4	109,900	505	1,095
East Seogwi (E. SG)	103.1	114,800	522	1,113
Namwon (NW)	126.4	187,100	649	1,480
Pyosun (PS)	202.1	90,600	255	448
Total	1,719.0	1,707,100	4,934	993

Table 2. Sea level and seawater temperature rises around the Korean Peninsular (data are from IPCC, 2007; BRMA, 2009; Cho and Kim, 2009; Kim et al., 2009).

Region	Sea level rise		Seawater temperature rise	
	Rate (mm/yr)	Period	Rise (°C)	Period
East Sea	3.86	1993-2008	0.90	1968-2007
West Sea	4.18	1993-2008	1.09	1968-2007
South Sea	4.66	1993-2008	1.14	1968-2007
Jeju island (north)	5.23	1964-2008	1.94	1924-2009
Jeju island (south)	5.65	1964-2008	0.70	2000-2009
Korean mean	4.02	1993-2008	1.04	1968-2007
Global mean	3.16	1993-2008	0.74	1906-2005

µS/cm). About half of the groundwater wells, mostly distributed in coastal areas, (49.5%) showed increasing trends. The proportion of the increasing EC trends was elevated from 39.4% for 2001 to 2005 data of a previous study (Lee et al., 2007a). The locations showing the increasing EC trend were similar to those of the decreasing water levels. In particular, the extensive EC increase in the western region such as Daejung (DJ) was well consistent with the decreasing water level due to heavy groundwater for agricultural activities (Table 1). Furthermore, many of the increasing EC trends at the groundwater wells of coastal areas accompanied with decreasing water level and increasing water temperature were indicative of the effects of enhanced seawater intrusion.

Figure 10c shows the distribution of groundwater temperature changing rates. The changing rates ranged between -0.80 and +0.19°C/yr with a mean of -0.03°C/yr. About 36% of the groundwater wells showed increasing temperature trends. The increased groundwater temperature may have been caused by the elevated air temperature (Park et al., 2010) or intrusion of warmer seawater. The increasing trends were especially distinctive in the western region where groundwater pumping is heavy. The temperature of the surrounding seawater was also generally increased over time (Table 2). Thus, the intrusion of this warmer seawater due to excessive groundwater pumping may have elevated the groundwater temperature. However, the increased groundwater temperature in the inland areas was mainly attributed to the elevated air temperature. The smaller proportion of the increasing groundwater temperature trends was unexpected because the groundwaters of the Korean mainland showed dominantly increasing trends (82.8% for shallow groundwater and 68.8% for deep groundwater) for period of 1996 to 2008 (Park et al., 2010). The smaller proportion may be partly due to the shorter monitoring period in this island (2001 to 2008) because the longer period (1996 to 2008) would have reflected more distinctively the effects of climate change.

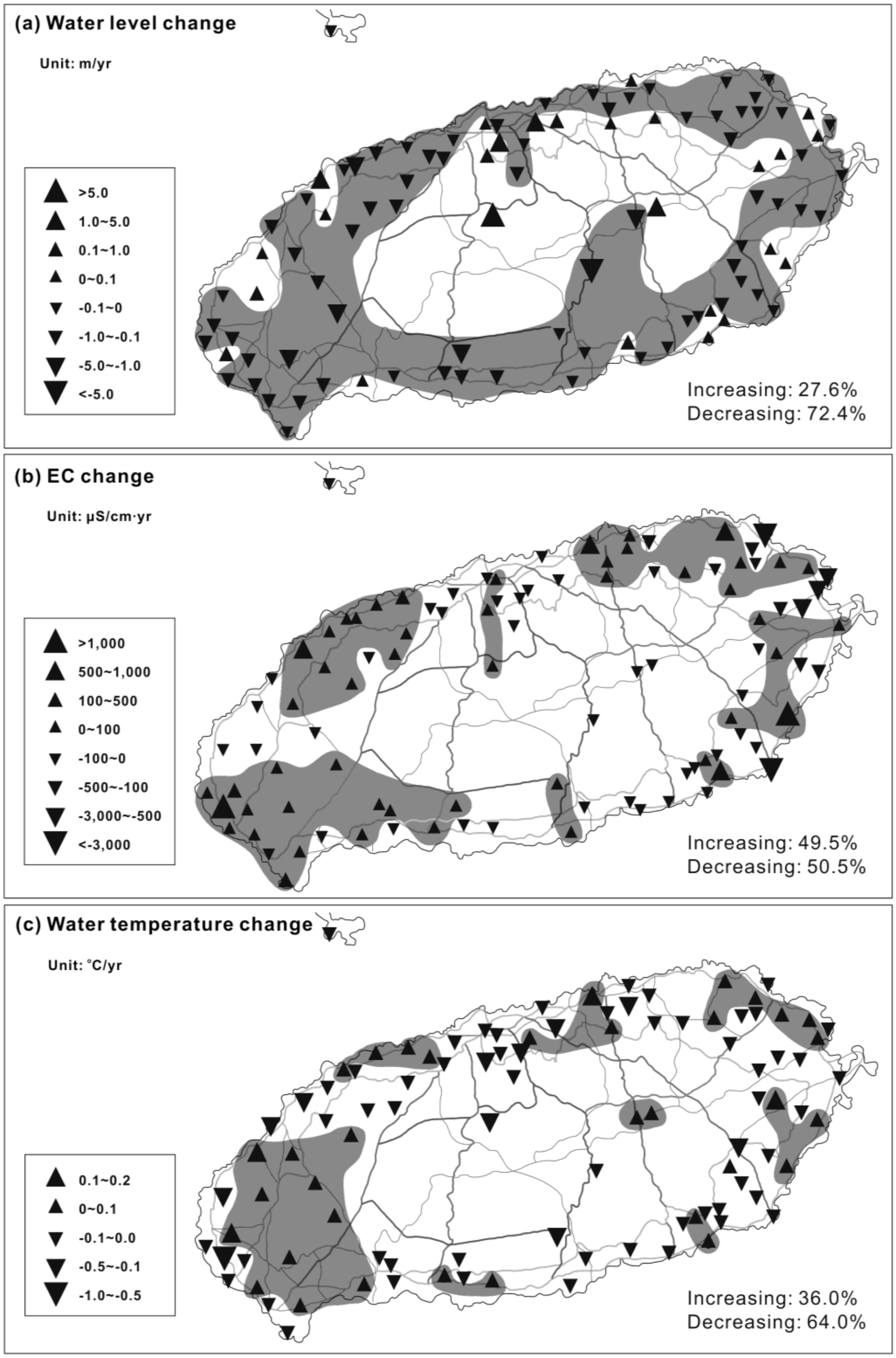

Figure 10. Long-term variation trends of (a) groundwater levels, (b) EC and (c) groundwater temperature.

Groundwater conservation efforts for sustainable use

The Jeju provincial government has endeavored to secure groundwater resources for sustainable development under the influence of climate change. While the "Groundwater Law" established in 1994 regulates all kinds of groundwater development activities in mainland (Kim et al., 1995; Lee et al., 2007b), the "Special Law of the Jeju Special Self-Governing Province” established in 2006 controls more strictly all the groundwater development activities (Lee and Choi, 2012). According to Chapter 2 (Groundwater Conservation and Management: articles 310 to 323) of the law, the provincial government can ban any groundwater development activities at certain areas and lay a tax on groundwater users. Despite these rigorous regulations, the provincial groundwater use has continuously increased due to increasing freshwater demand (Figure 3b).

Besides implementing groundwater regulations, the Jeju government started an artificial recharge program (Jeju-friendly Artificial Recharge Technology) in 2007 to meet the growing freshwater demand (Kim et al., 2008). For this, 10 injection wells (50 m depth and 400 mm diameter) were installed at a middle elevation in a mountainous area. Rainwater harvested from the roofs of many greenhouses or stream water especially in the wet monsoon season (August to October), was injected into these wells (Lee et al., 2008). The provincial government plans to inject 15,000 m^3 of rainwater per well. A second artificial recharge site is additionally under construction. As of 2009, 695,000 m^3 of rainwater was being injected annually through 81 injection wells, including the clustered artificial recharge wells, which is equivalent to the annual water use of 5,600 people.

Nevertheless, despite these efforts exerted by the provincial government, the groundwater condition has progressively worsened with respect to both quantity and quality. As discussed above, most of the groundwaters, especially in coastal areas, have experienced a gradual waterlevel decline and rising EC, which indicates a reduction of fresh groundwater resources. This degradation can be aggravated over time due to accelerated sea level rise induced by global warming. The effect of the agricultural activities in increasing groundwater usage may necessitate reforming the industrial structure through transformation to lower water-consuming industries. Heavy agricultural activities can also cause severe groundwater contamination due to the application of fertilizers and pesticides (Koh et al., 2007).

Although precipitation was unchanged over the monitoring period of this study (Figure 2a), it did increase over a longer past period, and is predicted to increase in the future due to climate change (NIMR, 2010). In particular, the precipitation in the summer monsoon (wet season) greatly increased and has become frequently torrential (Lee, 2011). Such changes lead to quicker draining of precipitation into the sea and reduced groundwater recharge, which will further complicate an appropriate water use and management strategy. More artificial recharge wells are needed to collect the wasted rainwater and stream water in the summer flood season. Underground dams can be constructed in coastal areas to constrict and retain flood flows (Dillon, 2005). These will also be beneficial in mitigating the seawater intrusion. Underground dams have been constructed for various purposes in many countries, including India, Ethiopia, China, Brazil and Kenya (Hanson and Nilsson, 1986; Ishida et al., 2011). In Korea including Jeju island, many studies have been conducted since 1990 to investigate the efficient storage of plentiful precipitation and the prevention of seawater intrusion (Kim and Kim, 2010). Practical studies of the underground dams in Japan, which are located in geological environments similar to that of Jeju Island, are very active. Many underground dams have been constructed since the first mega underground dam storing over 1 million m^3 of groundwater was constructed on Miyako island in 1993 (Ishida et al., 2011). In addition to these mega underground dams, some small to medium sized dams were also constructed in Okinawa for agricultural irrigation (Nawa et al., 2006; Ishida et al., 2011). Hawaii is comprised of volcanic islands of geological conditions similar to those of Jeju Island and 80% of the residents are dependent on groundwater for drinking water. Therefore, securing drinking water is very crucial and many efforts have been exerted to collect flooded water occurring in heavy rains using underground dams (Muirhead, 2008).

The increased use of underground air type GSHPs can be a potential source of groundwater contamination (Lee and Choi, 2012). Unlike conventional groundwater wells equipped with contamination protection systems, the boreholes for underground air type GSHPs do not have appropriate contamination protection facilities. Therefore, surface contaminants in water from heavy rains can easily enter the boreholes. However, no regulation related to environmental protection has yet been specified for such boreholes, and is urgently required.

Conclusion

We examined some of the most important aspects of the groundwater conditions on the volcanic Jeju Island, Korea. Groundwater is the most important source of freshwater and its conservation is therefore crucial for the sustainable development of this island. Analysis results of the monitored groundwater data indicated that most of the groundwater levels are decreasing and that substantial proportions of EC are increasing. These deteriorating groundwater conditions are mainly due to increased groundwater pumping, especially in the coastal areas. The decline of the water level and rise of EC will further reduce the fresh groundwater supply.

Rainwater harvest, artificial recharge and underground dams should be more rigorously implemented in order to secure more water resources. In addition, the prevention of groundwater contamination and sea water intrusion is also very important, and this therefore necessitates intensive and continuous monitoring. Even though the Jeju provincial government has endeavored to conserve and protect the groundwater resources, more active and urgent measures are needed to meet the increasing freshwater demand and cope with the negative effects of climate change. Because the agricultural sector is the driving force for the increasingly heavy groundwater pumping, the agriculture-dependent industrial structure must be transformed as soon as possible.

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