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Evaluation of Groundwater Monitoring Data in Four Megacities of Korea: Implication for Sustainable Use

Jin-Yong Lee[1,3] and Jiwon Han[2]

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The objective of this study was to evaluate groundwater conditions in the four greatest megacities (Seoul, Busan, Daegu, and Incheon) of Korea using 5-year (2006–2010) monitoring data obtained from the Korean National Groundwater Monitoring Stations. With decreasing of groundwater draft, groundwater levels for the 5-year period were not substantially decreasing but they responded differently to outer stress like rainfall according to degree of urbanization or pavement of surrounding areas. However, groundwater and air temperatures were gradually increasing due to the widespread climate change. Coastal groundwaters (Seoul, Busan, and Incheon) have suffered from seawater intrusion, which can be aggravated by sea level rise in the future. Some monitoring stations of the megacities observed a drastic decrease of groundwater level for a specific period and the marked increasing of electrical conductivity; thus, detailed investigations revealing the causes and appropriate mitigation measures are required. Urban groundwater did not uniformly respond to outer anthropogenic and natural stresses because a variety of human interventions are differently involved.

KEY WORDS: Metropolitan city, urbanization, groundwater level, seawater intrusion.

INTRODUCTION

The Republic of Korea (Korea hereafter) is one of the most rapidly developing countries in the world. Thus, water demand for various purposes has been gradually growing, especially in urban areas. Groundwater is an important water source in Korea, comprising about 13% of the total annual water use in the country (Moon et al. 2012). As of 2010, there were 1.38 million groundwater wells in the country and total groundwater use was 3,806 million m^3 per year, of which about 6.35% was used in seven metropolitan cities (MLTM 2011).

Urbanization generally causes many groundwater problems including groundwater level decline due to increase of groundwater pumping for domestic and industrial uses and lessening of recharge due to impermeable pavement (Lawrence et al. 1998; Booth et al. 2002; Lee and Koo 2007). In addition, construction of deep grounded buildings and subways aggravates the decline of groundwater levels (Lee et al. 2007a). Furthermore, the urban sprawl causes groundwater contamination with various pollutants including petroleum hydrocarbons, chlorinated solvents, and heavy metals (Ellis and Rivett 2007; Chae et al. 2008). In urban groundwater of Korea, chlorinated solvents including TCE and PCE are the most frequently detected pollutants (Baek and Lee 2011; Lee 2011).

However, recently some metropolitan cities like London (UK) and Tokyo (Japan) have experienced an interesting phenomenon of suffering from groundwater flood largely due to increased groundwater

[1]Department of Geology, College of Natural Sciences, Kangwon National University, Chuncheon 200-701, Republic of Korea.
[2]Department of Early Childhood Education, Yeungjin College, Daegu 702-721, Republic of Korea.
[3]To whom correspondence should be addressed; e-mail: hydrolee@kangwon.ac.kr

levels, which threat the stability of many underground buildings and facilities in the cities (UKDoE 1992; Lawrence et al. 1998; Galloway 2001). In fully developed old cities, net gain (surplus) of groundwater budget occurs due to lessened groundwater pumping for industrial use, leakage of urban water works (water supplied from outside of the cities) and sewer lines, and excess urban irrigation (Kim et al. 2001; Lee and Koo 2007).

Regular groundwater monitoring is essential for examining variations of its quantity and quality. The Korean government (MLTM and K-water) first constructed in 1995 a groundwater monitoring system called National Groundwater Monitoring Stations for collecting data on groundwater level, water temperature, and electrical conductivity (EC) (Lee et al. 2007b; Park et al. 2011) and now (as of 2012) the number of monitoring stations reached 320, covering the whole country including the Jeju volcanic island. In many cases, each station has two monitoring wells, one for shallow groundwater (mean well depth = 20 m) and the other for deep bedrock groundwater (mean well depth = 70 m) (Lee et al. 2007b). A submersed sensor in each well measures water level, temperature, and EC every hour and the data are automatically transmitted into the host server in real time and they (daily averaged data) are open to the public on the Korean official website (http://www.gims.go.kr) for free of charge.

The objectives of this study are (i) to evaluate the groundwater monitoring data obtained from the Korean National Groundwater Monitoring Stations especially in the four largest megacities of Korea and (ii) to draw some implications from the evaluation results for sustainable groundwater use in the metropolitan cities.

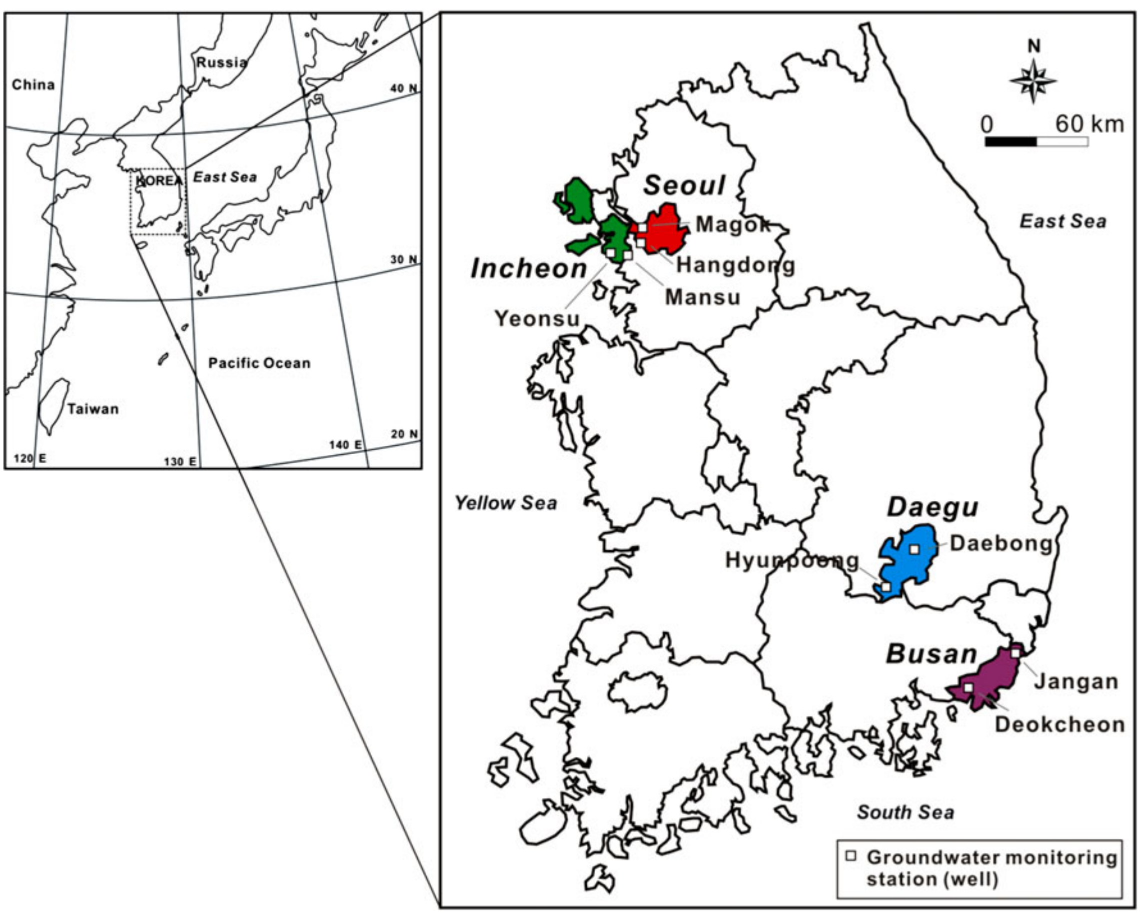

Figure 1. The four studied metropolitan cities (Seoul, Busan, Daegu, Incheon) and locations of groundwater monitoring stations (wells).

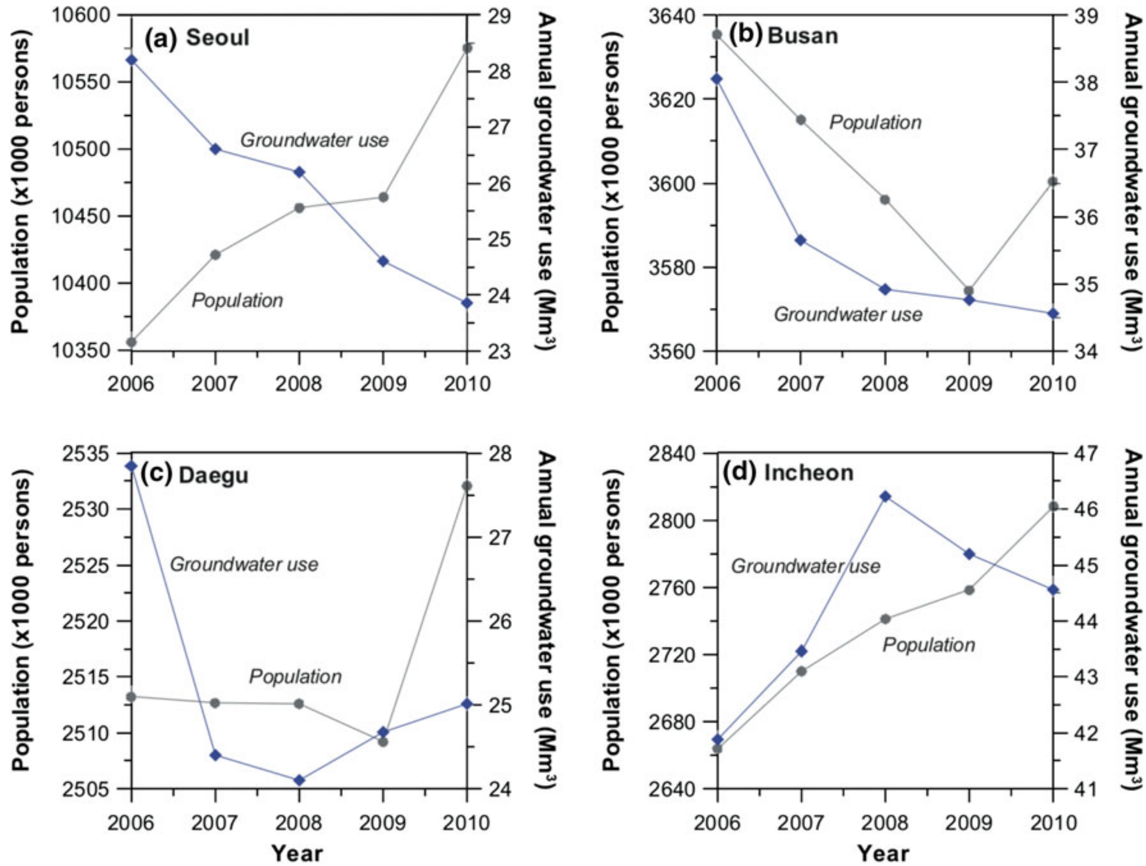

Figure 2. Populations and annual groundwater use of the four studied cities for 2006–2010.

MATERIALS AND METHODS

The selected megacities for this study are Seoul, Busan, Daegu, and Incheon in Korea (Fig. 1), which are the four greatest cities in terms of population. Seoul is the capital city (area = 605 km^2 in 2010) of the country and its population was 10.35 million (M) in 2006, and continuously increased to 10.57 M in 2010 (one-fourth of total national population) (Fig. 2a). Unlike its population, annual groundwater use in Seoul gradually decreased from 28.19 M m^3 in 2006 to 23.85 M m^3 in 2010, which is mainly due to gradual relocation of many industrial companies in the city to rural areas or overseas and strict banning of groundwater development by the metropolitan government (Kim et al. 2011).

The second largest city, Busan (area = 767 km^2 in 2010), is located in the south-east coastal area of the country, facing the South Sea (Fig. 1). Its population was 3.63 M in 2006, 3.57 M in 2009, and 3.60 M in 2010. With its decreasing population, the annual groundwater use of the city gradually decreased from 38.06 M m^3 in 2006 to 34.56 M m^3 in 2010 (Fig. 2b). The third largest city, Daegu (area = 884 km^2 in 2010), is located 230 km south-east of Seoul (Fig. 1). Its population was 2.51 M in 2006, 2.50 M in 2009, but it increased to 2.53 M in 2010 (Fig. 2c). The annual groundwater use in Daegu was 27.84 M m^3 in 2006 and then it decreased. However, with its increasing population, the groundwater use in Daegu increased in 2008 (24.10 M m^3) and it reached 25.02 M m^3 in 2010. The last city, Incheon (area = 1,029 km^2 in 2010), is located in the proximity of Seoul and it faces the Yellow Sea. Its total population including the main city area and many islands (see Fig. 1) was 2.66 M in 2006 and it increased to 2.80 M in 2010 (Fig. 2d). With increasing population, the annual groundwater use in Incheon also increased from 41.87 M m^3 in 2006 to 44.55 M m^3 in 2010.

The use and development of groundwater in this country, including the studied megacities, have been regulated by the Groundwater Law since 1994 (Lee et al. 2007b). Under this law, if anyone wants to

Table 1. Specifications of Groundwater Monitoring Stations for This Study

City	Station (Well)	Elevation (EL, m)	Well Depth (m)	Screen Interval (m)	Sensor Depth (m)	Geology	Hydraulic Conductivity (cm/s)
Seoul (SL)	Magok	9.866	70	50–70	20	Granitic gneiss	3.34×10^{-5}
	Hangdong	19.49	64	32–64	20	Biotite gneiss	6.55×10^{-5}
Busan (BU)	Deokcheon	5.42	70	24–44	30	Amphibole granite	1.08×10^{-5}
	Jangan	58.903	70	56–70	20	Andesitic porphyry	3.82×10^{-5}
Daegu (DG)	Daebong	38.26	55	32–52	20	Shale	1.51×10^{-5}
	Hyunpoong	18.46	70	24–44	20	Black shale	–
Incheon (IN)	Yeonsu	10.03	70	20–56	20	Biotite granite	1.52×10^{-5}
	Mansu	7.85	70	20–56	20	Biotite schist	9.49×10^{-5}

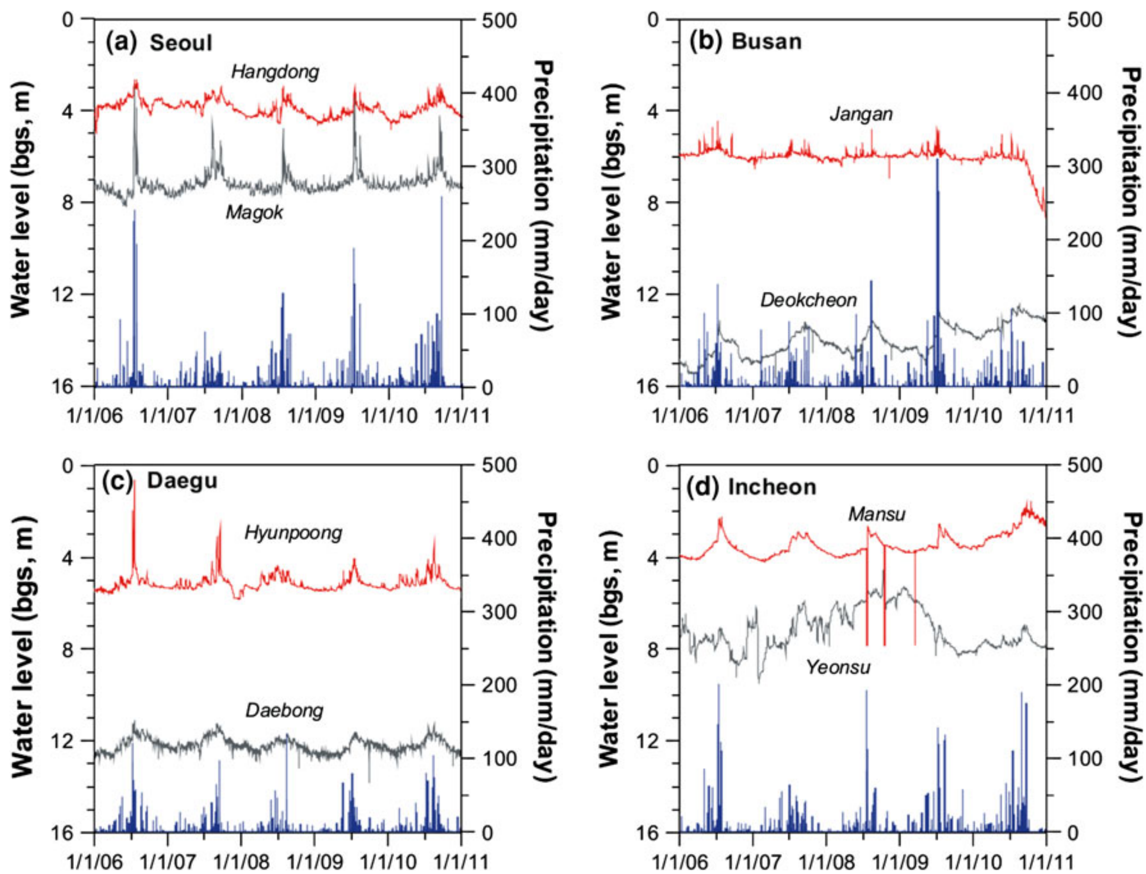

Figure 3. Groundwater levels (depth to water) with daily precipitation for 2006–2010 at the groundwater monitoring wells.

develop new groundwater wells, the owner should report the development to a relevant authority. If the amount of the groundwater development is greater than a regulated value (100 m^3/day for living and 150 m^3/day for agriculture), the user should obtain an official permit from the relevant authority. The law also enforces the operation of the national groundwater monitoring stations, from which the groundwater management plan is drawn on a national and/or local scale. In spite of the strict law, there have been many illegal (not officially reported) groundwater wells in the cities and rural areas (Park et al. 2011).

Groundwater data [daily averaged water level (compensated for barometric pressure change), water temperature and EC] for 5 years (2006–2010) were obtained from the national groundwater

Table 2. Statistical Summary of Groundwater Parameters and Weather Characteristics for 2006–2010

Parameter	City	Station (Well)	Mean	Max	Min	SD	Coeff. of Variation
Water level (bgs, m)	Seoul	Magok	7.17	8.17	2.81	0.49	0.07
		Hangdong	3.90	5.04	2.63	0.35	0.09
	Busan	Deokcheon	14.03	15.66	12.44	0.68	0.05
		Jangan	6.03	8.69	4.43	0.43	0.07
	Daegu	Daebong	12.19	13.82	11.09	0.31	0.03
		Hyunpoong	5.13	5.82	0.63	0.38	0.07
	Incheon	Yeonsu	7.17	9.50	4.54	0.91	0.13
		Mansu	3.45	7.85	1.52	0.60	0.17
Water temp. (°C)	Seoul	Magok	14.1	15.8	12.2	0.57	0.04
		Hangdong	14.0	14.9	13.2	0.37	0.03
	Busan	Deokcheon	17.9	18.7	17.1	0.28	0.02
		Jangan	14.9	16.0	13.0	0.65	0.04
	Daegu	Daebong	17.6	18.1	17.2	0.26	0.01
		Hyunpoong	16.5	18.2	13.6	0.58	0.04
	Incheon	Yeonsu	14.9	15.2	14.7	0.09	0.01
		Mansu	14.3	14.8	14.2	0.15	0.01
EC (μS/cm)	Seoul	Magok	2,873	5,058	819	831	0.29
		Hangdong	713	744	664	23	0.03
	Busan	Deokcheon	17,821	24,671	5,071	5,689	0.32
		Jangan	361	577	216	67	0.19
	Daegu	Daebong	611	721	557	47	0.08
		Hyunpoong	775	970	224	172	0.22
	Incheon	Yeonsu	729	883	684	26	0.04
		Mansu	7,492	27,118	5,035	1,412	0.19
Daily precipitation (mm/day)	Seoul	–	4.3	259.5	0.0	17.23	4.00
	Busan	–	3.9	310.0	0.0	15.65	3.97
	Daegu	–	2.7	135.0	0.0	10.02	3.73
	Incheon	–	3.7	202.5	0.0	15.17	4.12
Air/soil temp. (°C)	Seoul	Air	12.9	30.1	−13.2	10.19	0.79
		Soil (z = 5 m)	15.6	20.5	11.7	2.07	0.13
	Busan	Air	15.1	30.1	−4.3	7.94	0.53
		Soil (z = 5 m)	16.9	20.1	14.5	1.32	0.08
	Daegu	Air	14.7	31.1	−6.3	9.35	0.63
		Soil (z = 5 m)	–	–	–	–	–
	Incheon	Air	12.7	29.4	−11.2	9.54	0.75
		Soil (z = 5 m)	15.0	18.3	12.2	1.57	0.10

monitoring stations. We selected two representative monitoring stations (one for heavily urbanized area and the other for less or partly urbanized area) from each city, and the monitoring wells (for monitoring bedrock groundwater) in different cities have very similar specifications (Table 1). The well depth ranges from 55 to 70 m and sensor depth is mostly 20 m. While the geology around the monitoring well is somewhat different, varying from sedimentary rocks to metamorphosed rocks, the hydraulic conductivity is all in the order of 10^{-5} cm/s. Weather data for the city including daily precipitation, air temperature, and soil (depth = 5 m) temperature (this was not available for Daegu) were obtained from the Korea Meteorological Administration (KMA).

Time series analysis has been widely used to identify periodicity of consecutive hydrologic data and inter-dependency between hydrologic parameters (Larocque et al. 1998; Lee and Lee 2000; Panagopoulos and Lambrakis 2006; Jo and Lee 2010). In this study, we used auto-correlation, spectral density, and cross-correlation functions for the daily basis data. In order to eradicate the effect of very long-term trends in the times series data or to feature relatively short-term variation in the cities, we first detrended them using the linear trend best fit (Matsoukas et al. 2000; Hanson et al. 2004). The detrended data were used for the time series analysis using PAST (Hammer et al. 2001), except for the linear regression identifying the long-term variation trends.

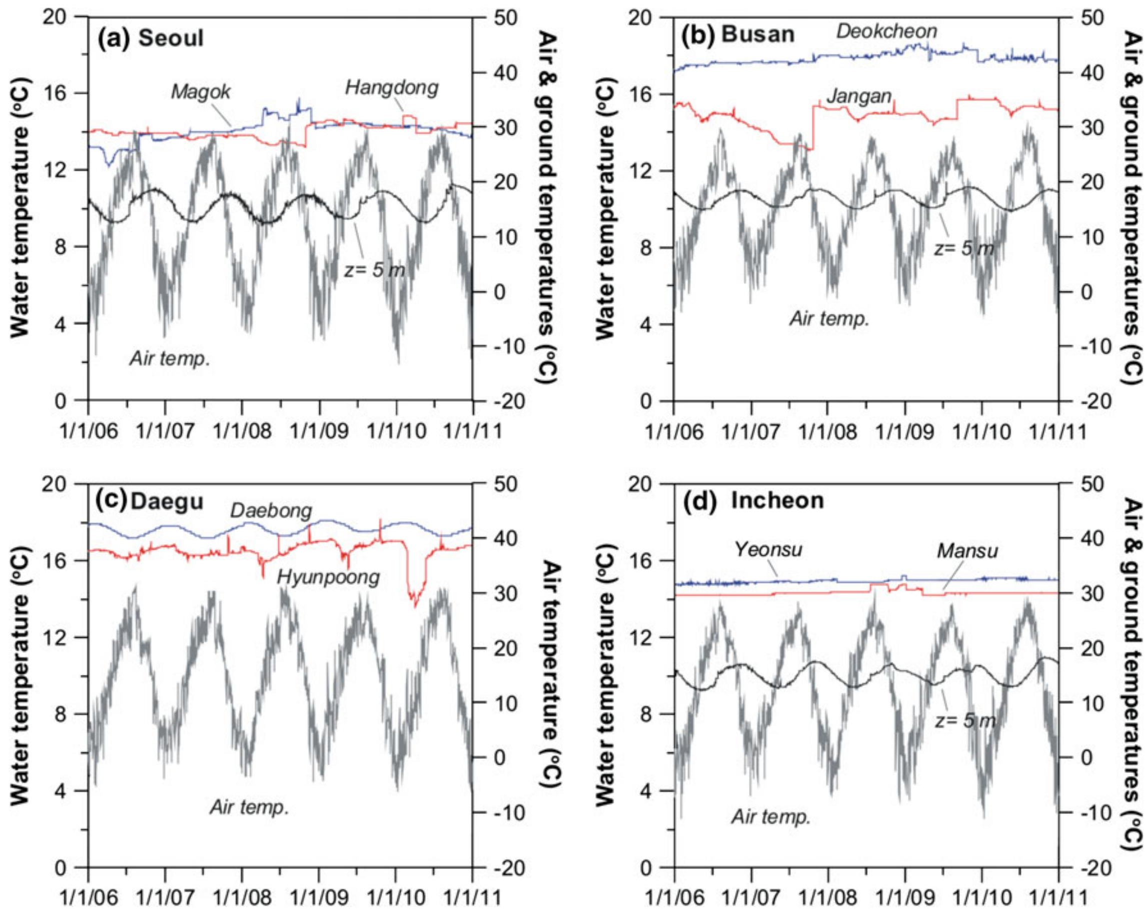

Figure 4. Groundwater temperatures with air and soil (depth = 5 m) temperatures at the studied metropolitan cities for 2000–2006.

RESULTS AND DISCUSSION

Groundwater Levels

Figure 3 shows groundwater levels [depth to water (DTW) below ground surface; not-detrended data] with daily precipitation for 2006–2010 at the monitoring wells in the four studied megacities. Groundwater level of Magok station (in proximity of the Han River) of Seoul showed a frequent and sensitive fluctuating response to rainfall while that of Hangdong station showed a less sensitive response with smaller amplitudes to the same rainfall stress (Fig. 3a), probably because the surroundings of the latter area is mostly covered by impervious pavement (Lee et al. 2005). Groundwater level of Deokcheon station (in proximity of the Nakdong River) of Busan also showed a typical but less sensitive response to rainfall (Fig. 3b). Groundwater level at this station showed a distinctive inter-annual increasing trend for the last five years and the increasing water levels may be due to increased annual precipitation and less groundwater pumping around the station. However, groundwater levels of Jangan station (Busan), whose surrounding area was paved, showed very different erratic behavior and they did not markedly respond to rainfall. In addition, the annual repetition phenomenon was also not distinctive, which indicates that groundwater around the Jangan station is largely affected by anthropogenic factors. The drastic decrease of the groundwater levels in 2010 also implies anthropogenic effects including artificial groundwater pumping.

Groundwater levels of the two stations in Daegu exhibited similar behaviors (Fig. 3c). Groundwater levels of Daebong station, located in the central part of the city, showed a good response with rainfall but with comparatively smaller amplitudes. The relatively lower groundwater levels, about 12 m below ground surface (Table 2), can be attributed to the nearby subway (Kim and Lee 2003; Lee et al. 2007a). However, groundwater levels of Hyunpoong station, located in the proximity of a stream, showed a markedly sharp relation with rainfall. Groundwater levels in Incheon showed the most irregular variations (Fig. 3d; their coefficients of variation are the largest in Table 2). Groundwater levels of Mansu station showed seasonal or annual variation but not distinctive short-term sensitive response with rainfall. The sharp drops of groundwater levels for a short period were due to artificial pumping for maintenance of the monitoring well and the gradual increase of groundwater level may be related to increased annual rainfall. The most erratic groundwater level changes of Yeonsu station indicate anthropogenic effects including subway groundwater pumping.

Groundwater Temperatures

Figure 4 shows groundwater, air and soil (depth = 5 m) temperatures for the studied 5-year period. Groundwater temperatures of Seoul showed neither systematic nor seasonal patterns and the variation ranges were only 1.7°C for Hangdong station and 3.6°C for Magok station (Table 2), which indicate they did not shortly respond to outdoor air temperature. Air temperatures showed annual repetition with very large amplitude (maximum = 30.1°C, minimum = −13.2°C). Soil temperatures at depths of 5 m showed excellent annual repetitive behavior with relatively smaller amplitudes (8.8°C; Table 2) and showed substantial lag times compared with air temperatures (discussed later in correlations). Groundwater temperatures of Busan were generally higher than those of Seoul (Fig. 4b), which are largely attributed to latitude effect (Lee and Hahn 2006). However, they also exhibited irregular variation without distinctive response to air temperature. Air and soil temperatures at this city showed repetitive seasonal and annual fluctuations with smaller amplitudes.

Groundwater temperatures at Daegu were, on average, the highest (16–17°C) (Fig. 4c). Groundwater temperature of Daebong station showed distinctive seasonal and annual variation with a range of 0.9°C, while that of Hyunpoong station showed most frequent and irregular fluctuations, which may be partly due to quick infiltration of rainfall as evidenced by very sensitive groundwater level rise response to rainfall (Fig. 3c). Air temperatures showed typical annual variation with a mean of 14.7°C (Table 2). Groundwater temperatures of Incheon were the most stable (ranges = 0.5–0.6°C; Table 2) while air and soil temperatures showed the typical seasonal and annual variations (Fig. 4d). Consequently, groundwater temperatures at Incheon were the least varying compared with the groundwater levels in response to outer stress.

Groundwater Electrical Conductivities

Figure 5 shows groundwater electrical conductivities (ECs) for the period of 2006–2010. The average EC of Magok (Seoul) station was 2,873 μS/cm (Table 2), which is much greater than that of uncontaminated bedrock groundwater (457 μS/cm) in the country (Park et al. 2011). The high values of ECs can be attributed to the effects of seawater encroachment from the Yellow Sea through the Han River (Park et al. 2005; Park et al. 2012). However, they showed very large fluctuation (maximum–minimum = 4,239 μS/cm), which is likely related with dilution due to rapid infiltration of rainfall and partly with tidal fluctuation (Fig. 3a). The EC values of groundwater at Hangdong station were the most stable (Fig. 5a) and their average was 713 μS/cm. This is, however, somewhat elevated EC compared with background values, indicating that groundwater was affected by anthropogenic factors.

The ECs of Busan groundwater showed quite a similar behavior with those of Seoul (Fig. 5b). Groundwater of Deokcheon station had very high ECs, ranging from 5,071 to 24,671 μS/cm (mean = 17,821 μS/cm), which are also the effect of seawater intrusion through the Nakdong River, connecting to the South Sea. However, EC values of groundwater at Jangan station were low (216–577 μS/cm) and showed substantial inverse correlation with rainfall. The EC values of groundwater at Daebong station were relatively low (557–721 μS/cm) (Fig. 5c) but they gradually increased with time, indicating that the groundwater was affected with some anthropogenic contaminants (Lee et al. 2007a). Most interestingly, the ECs of groundwater at Hyunpoong station revealed very frequent fluctuation with large amplitudes. Relatively high groundwater EC values can be attributed to contamination in this industrial area and the frequent variation may be caused by quick mixing or dilution due to rapid rainfall infiltration (Fig. 3c). Direct rainfall intrusion into the monitoring well due to imperfect completion of the surrounding surface was suspected.

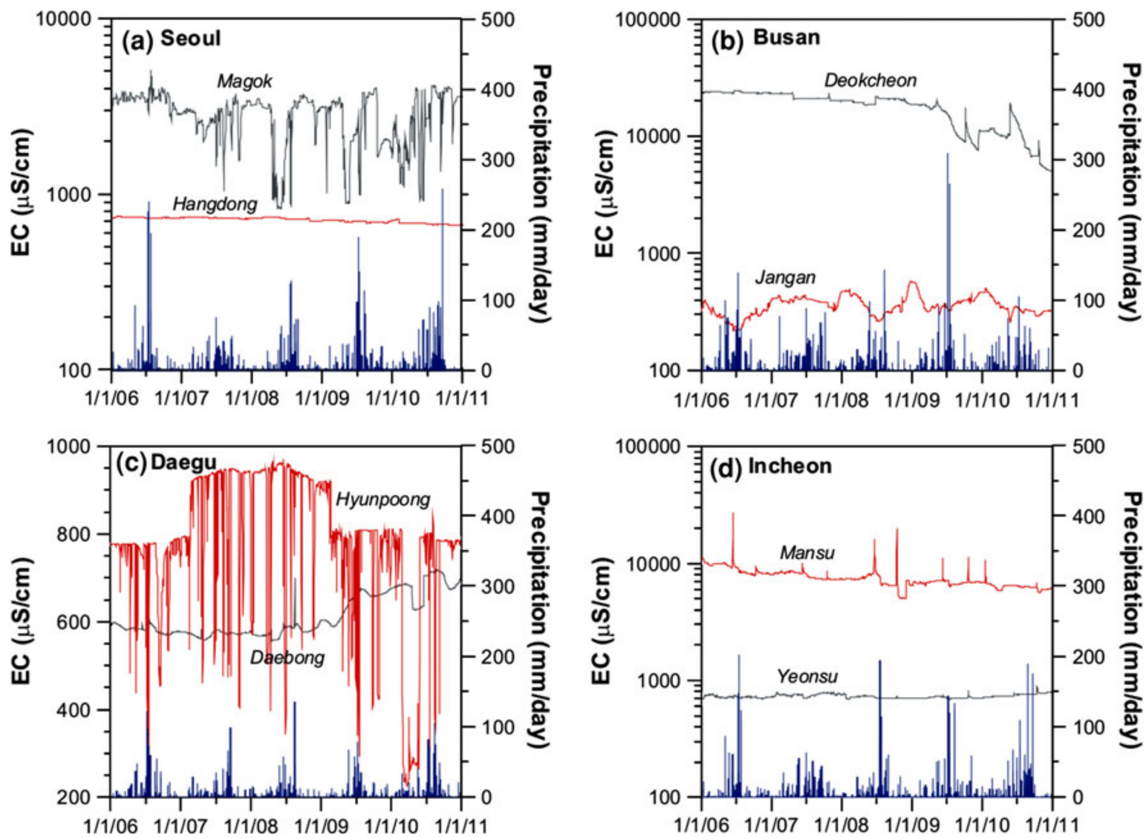

Figure 5. Electrical conductivities of groundwater at the monitoring wells in the studied cities for 2000–2006.

The EC values of groundwater at Mansu station were very high (mean = 7,492 μS/cm) (Fig. 5d) and they were highly affected by seawater intrusion through a stream in this coastal area (Park et al. 2012), but they were gradually decreasing after 2006. Groundwater EC values of Yeonsu station were comparatively low (mean = 729 μS/cm), indicating little impact by seawater intrusion but they showed a gradual increase of EC.

Response of Groundwater Parameters to Weather Parameters

Table 3 shows the linear regression results for groundwater and weather parameters. For groundwater levels, variation rates ranged from −0.347 to +0.121 m/year. Interestingly, groundwater levels in heavily urbanized areas (Hangdong, Jangan, Daebong) generally showed increasing trends while those in less or partly urbanized areas (Magok, Deokcheon, Hyunpoong, and Mansu) showed the decreasing trends. Even though groundwater levels of Yeonsu (heavily urbanized) showed decreasing trend, their rate was much smaller than those of Mansu. These trends appear, however, to be closely related with decreasing of groundwater pumping at the metropolitan cities (Fig. 2), especially in the heavily urbanized areas. In the last decade, many industrial companies in the urban area moved to outskirts or overseas, which caused less groundwater pumping (Lee and Koo 2007).

Groundwater temperatures showed the most striking increasing trends and most of all (except for Hyunpoong) showed positive increasing trends, ranging between +0.024 and +0.220°C/year. The increasing trends of groundwater temperatures were well consistent with those of air temperatures (+0.146–0.407°C/year). Thus, the increase of groundwater temperatures were probably caused by that of air temperatures even though the heat island effect also likely contributed to air temperature rise (Taniguchi and Uemura 2005; Park et al. 2011). Like air and groundwater temperatures, soil temperatures at the cities also showed distinctive increasing trends, ranging from +0.099 to +0.271°C/year. All

Table 3. Results of Linear Regression Analyses of Groundwater Parameters and Weather Characteristics for 2006–2010

Parameter	City	Station (Well)	Linear Fit (Daily Data)	Annual Trend
Water level (WL)	Seoul	Magok	$Y = -0.000196X + 14.94$ ($r^2 = 0.044$)	−0.072 m/year
		Hangdong	$Y = 0.000233X - 5.36$ ($r^2 = 0.120$)	+0.085 m/year
	Busan	Deokcheon	$Y = -0.000950X + 51.69$ ($r^2 = 0.543$)	−0.347 m/year
		Jangan	$Y = 0.000331X - 7.09$ ($r^2 = 0.166$)	+0.121 m/year
	Daegu	Daebong	$Y = 0.000055X + 9.98$ ($r^2 = 0.009$)	+0.020 m/year
		Hyunpoong	$Y = -0.000049X + 7.09$ ($r^2 = 0.005$)	−0.018 m/year
	Incheon	Yeonsu	$Y = -0.000083X + 10.47$ ($r^2 = 0.002$)	−0.030 m/year
		Mansu	$Y = -0.000578X + 26.36$ ($r^2 = 0.259$)	−0.211 m/year
Water temp. (WT)	Seoul	Magok	$Y = 0.000603X - 9.85$ ($r^2 = 0.314$)	+0.220°C/year
		Hangdong	$Y = 0.000335X + 0.73$ ($r^2 = 0.231$)	+0.122°C/year
	Busan	Deokcheon	$Y = 0.000314X + 5.41$ ($r^2 = 0.339$)	+0.115°C/year
		Jangan	$Y = 0.000517X - 5.61$ ($r^2 = 0.175$)	+0.189°C/year
	Daegu	Daebong	$Y = 0.000066X + 15.01$ ($r^2 = 0.018$)	+0.024°C/year
		Hyunpoong	$Y = -0.000032X + 17.73$ ($r^2 = 0.001$)	−0.012°C/year
	Incheon	Yeonsu	$Y = 0.000147X + 9.13$ ($r^2 = 0.697$)	+0.054°C/year
		Mansu	$Y = 0.000073X + 11.41$ ($r^2 = 0.067$)	+0.027°C/year
EC	Seoul	Magok	$Y = -0.329915X + 15948$ ($r^2 = 0.044$)	−120 μS/year
		Hangdong	$Y = -0.040114X + 2303$ ($r^2 = 0.839$)	−15 μS/year
	Busan	Deokcheon	$Y = -9.861284X + 408629$ ($r^2 = 0.835$)	−3599 μS/year
		Jangan	$Y = 0.020558X - 453$ ($r^2 = 0.026$)	+8 μS/year
	Daegu	Daebong	$Y = 0.073120X - 2286$ ($r^2 = 0.659$)	+27 μS/year
		Hyunpoong	$Y = -0.066504X + 3410$ ($r^2 = 0.042$)	−24 μS/year
	Incheon	Yeonsu	$Y = 0.005465X + 512$ ($r^2 = 0.012$)	+2 μS/year
		Mansu	$Y = -1.915101X + 83388$ ($r^2 = 0.511$)	−699 μS/year
Annual precipitation	Seoul	–	$Y = 107.49X - 214268.3$ ($r^2 = 0.282$)	+107 mm/year
	Busan	–	$Y = 32.36X - 63541.3$ ($r^2 = 0.048$)	+32 mm/year
	Daegu	–	$Y = 0.46X + 57.1$ ($r^2 = 0.001$)	+0.5 mm/year
	Incheon	–	$Y = 121.73X - 243090.4$ ($r^2 = 0.521$)	+122 mm/year
Air/soil temp.	Seoul	Air	$Y = 0.000401X - 3.01$ ($r^2 = 0.001$)	+0.146°C/year
		Soil (z = 5 m)	$Y = 0.000741X - 13.80$ ($r^2 = 0.036$)	+0.271°C/year
	Busan	Air	$Y = 0.001116X - 29.17$ ($r^2 = 0.005$)	+0.407°C/year
		Soil (z = 5 m)	$Y = 0.000272X + 6.10$ ($r^2 = 0.012$)	+0.099°C/year
	Daegu	Air	$Y = 0.000664X - 11.59$ ($r^2 = 0.001$)	+0.242°C/year
		Soil (z = 5 m)	Not available	–
	Incheon	Air	$Y = 0.000740X - 16.65$ ($r^2 = 0.002$)	+0.270°C/year
		Soil (z = 5 m)	$Y = 0.000699X - 12.71$ ($r^2 = 0.055$)	+0.255°C/year

these three parameters clearly indicate warming of the country. Interestingly, accompanying these increases, the annual precipitation for this period also showed increasing trends (Table 2), which are consistent with results of climate change scenarios for the country (Ho et al. 2003; Wentz et al. 2007).

The ECs of groundwater showed very mixed variation trends (Table 3). In areas affected by seawater encroachment (Magok, Deokcheon, Mansu), the ECs of groundwater showed large decreasing trends, which can be related with lessened groundwater pumping or increased annual rainfall. However, in heavily urbanized areas (Jangan, Daebong, Yeonsu), they showed increasing trends with small rates (not distinctive) even though groundwater pumping in these areas was expected to decrease.

Auto-correlation Analyses of Groundwater and Weather Parameters

Figure 6 shows auto-correlation and spectral density functions of weather parameters including daily precipitation, air temperature, and soil temperature. The daily precipitation revealed a quick decrease of auto-correlation with very short lag times (Fig. 6a), indicating that it is an uncorrelated random variable (Angelini 1997; Lee and Lee 2000). The spectral density of the precipitation exihibits a prominent periodicity of annual repetition (f = 0.00274 cpd). The relatively high spectrum values even at high frequencies also indicate the random characteristic of daily precipitation. Air and soil temperatures show very high auto-correlations at

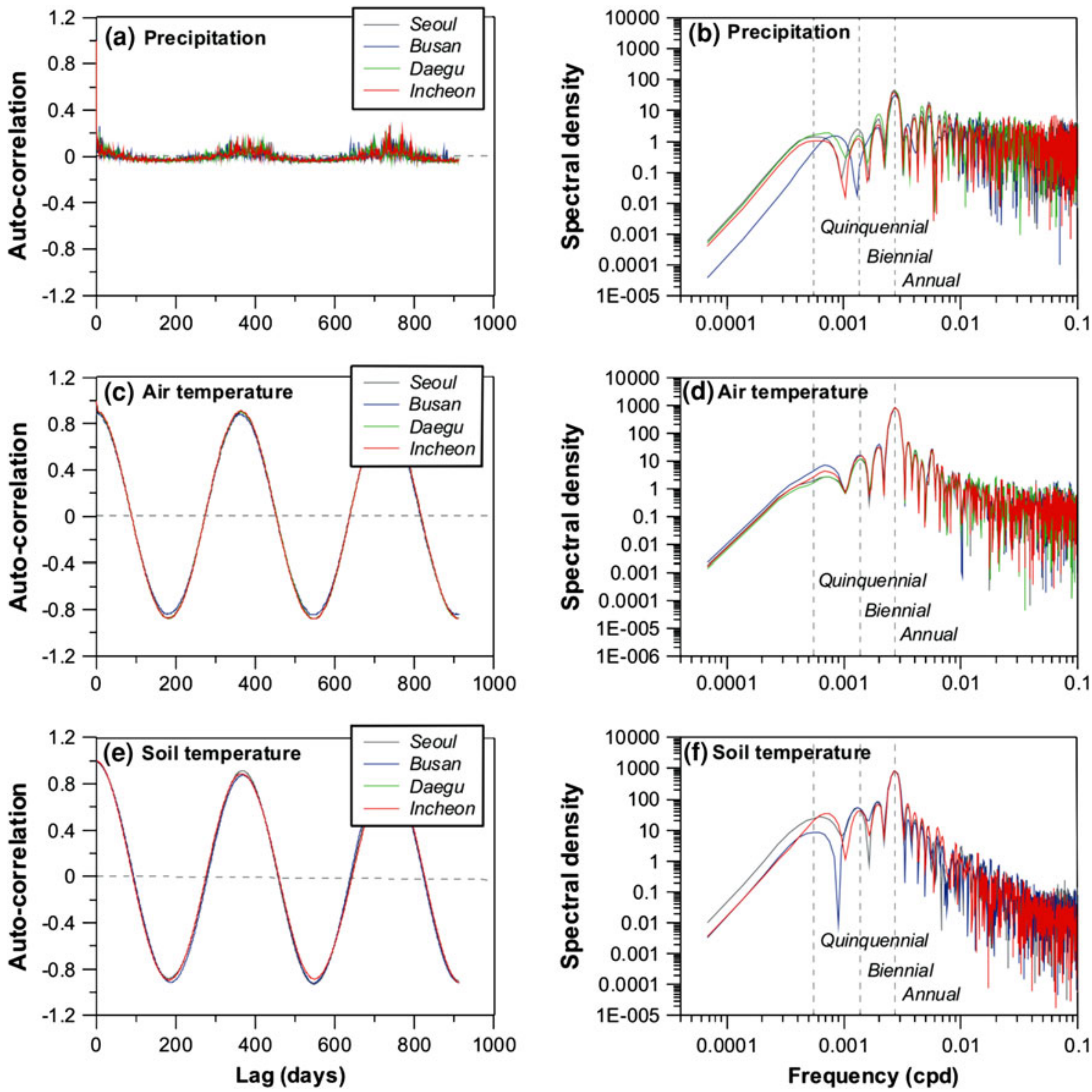

Figure 6. Auto-correlation and spectral density functions of daily precipitation, air temperature and soil temperature (depth = 5 m) in the four studied cities.

very long lag times (Fig. 6c, e), revealing their strong inter-dependency of their successive values. In addition, the most peculiar peaks of the spectral densities at $f = 0.00274$ cpd also indicate strong annual repetition.

Figure 7 shows auto-correlation and spectral density functions of groundwater level, temperature, and EC. Compared with daily precipitation, groundwater levels show longer memory effect at long lag times (Fig. 7a), indicating strong self-dependency. The spectral density functions mostly show the annual cyclic behaviors but groundwater levels of Yeonsu station did show much longer duration than annual repetition (absence of annual repetition), implying that they were strongly affected by some artificial factor like impermeable pavements. The auto-correlation of groundwater temperatures show stable and stronger self-dependency (longer memory effect) and thus the spectral density showed relatively higher spectrum at lower frequencies such as biennial and quinquennial frequencies (Fig. 7d). Only groundwater temperatures at the Daebong station showed the

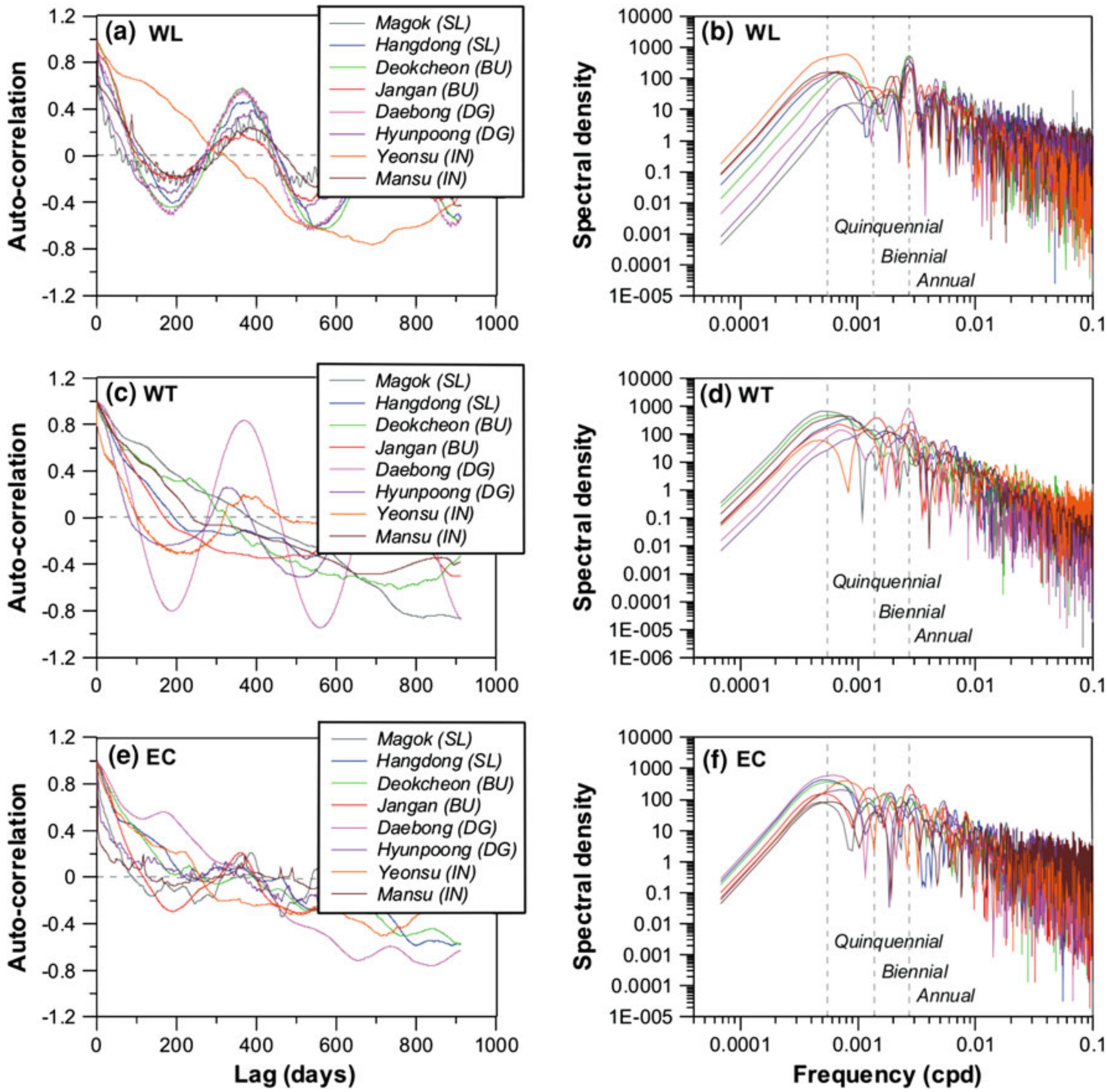

Figure 7. Auto-correlation and spectral density functions of groundwater levels (WL), groundwater temperatures (WT) and electrical conductivities (EC).

annual cycle. The ECs of groundwater showed the most irregular self-dependency with a weak annual repetition (Fig. 7e, f).

Correlation Analyses of Groundwater and Weather Parameters

Figure 8 shows correlation between groundwater levels (output) and daily precipitation (input). Groundwater levels of Magok station (Seoul) showed a quick and high response to precipitation (r = 0.524 at a lag time of one day) while those of Hangdong showed attenuated response (r = 0.352) at the same lag time (Fig. 8a), and this difference can be attributed to degree of urbanization or proportion of impermeable pavements of surrounding areas (Lee and Koo, 2007). Groundwater levels of Busan showed much lowered correlations (r = 0.174 at 11 days for Deokcheon; r = 0.254 at 1 day for Jangan) with precipitation, compared with those of Seoul (Fig. 8b). Very delayed response to precipitation at the Deokcheon

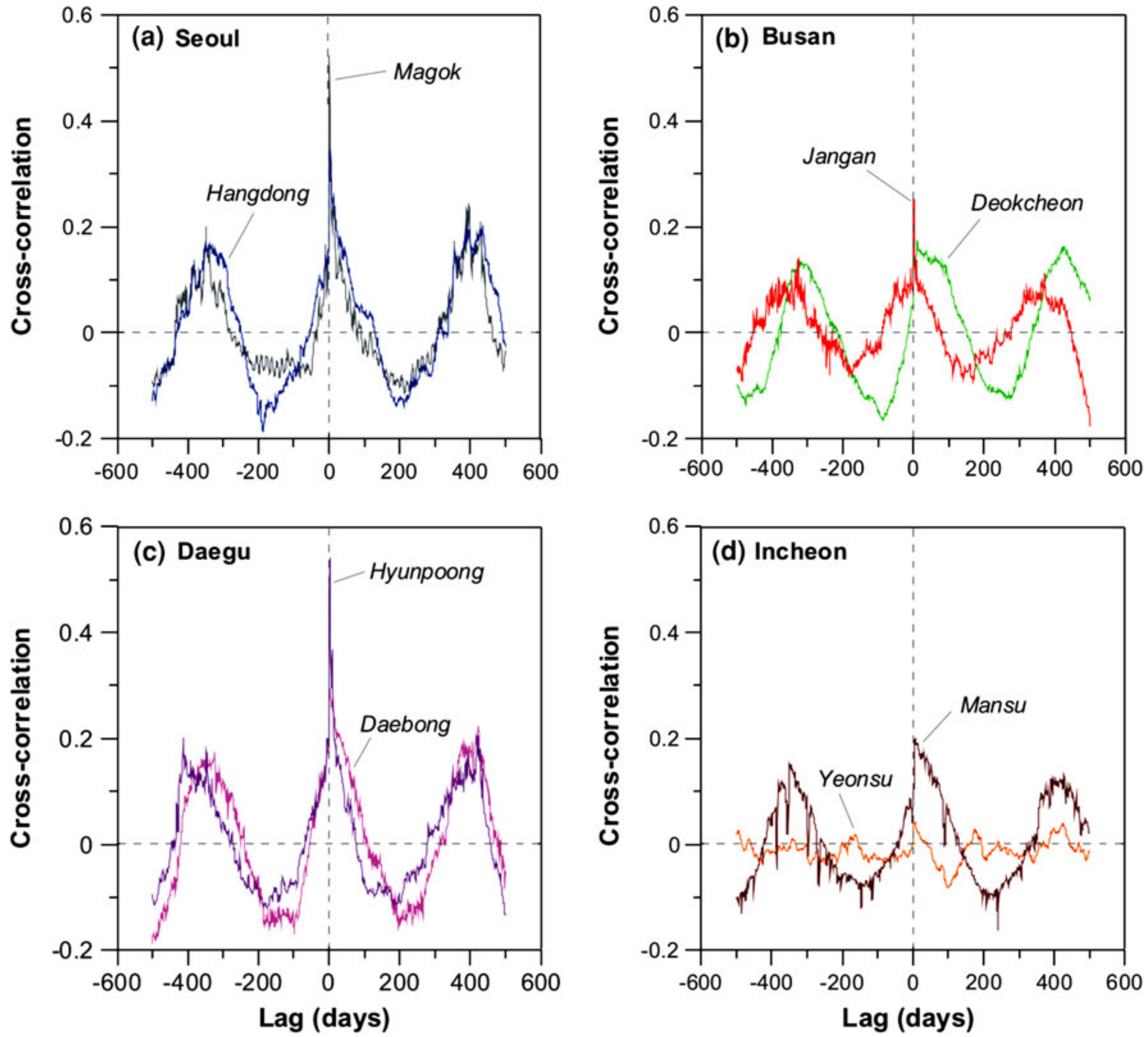

Figure 8. Cross-correlation of groundwater levels with daily precipitation (truncation = 500 days).

station can be attributed to the lowest groundwater levels (mean depth to water = 14.03 m; Table 2).

The response of groundwater levels at Daegu is very similar to that at Seoul (Fig. 8c). Groundwater levels at a highly urbanized area (Daebong station) showed somewhat delayed and attenuated response (r = 0.294 at lag time of 3 days) due to lowered groundwater levels (mean depth to water = 12.19 m; Table 2) and pavement. However, the Hyunpoong station showed a quick and excellent response to precipitation (r = 0.541 at lag time of 2 days). Response of groundwater levels at Incheon to precipitation was the weakest (Fig. 8d). However, the Mansu station near a stream showed a relatively fast and higher response to precipitation (r = 0.199 at 7 days) but the Yeonsu station showed nearly negligible response to precipitation (r = 0.041 at 7 days). Thus, it is again confirmed that groundwater levels of Yeonsu station (more urbanized) were not controlled by natural factors like precipitation.

Figure 9 shows cross-correlations of groundwater and soil temperatures with air temperatures. Groundwater temperatures of Seoul showed low and intermediate correlations at much delayed lag times (r = 0.130 at 31 days for Magok; r = 0.303 at 181 days for Hangdong) (Fig. 9a). These large phase differences between air and groundwater temperatures indicate slow propagation of air temperature waves into the subsurface (Bundschuh 1993; Lee and Hahn 2006). Soil temperature showed an excellent

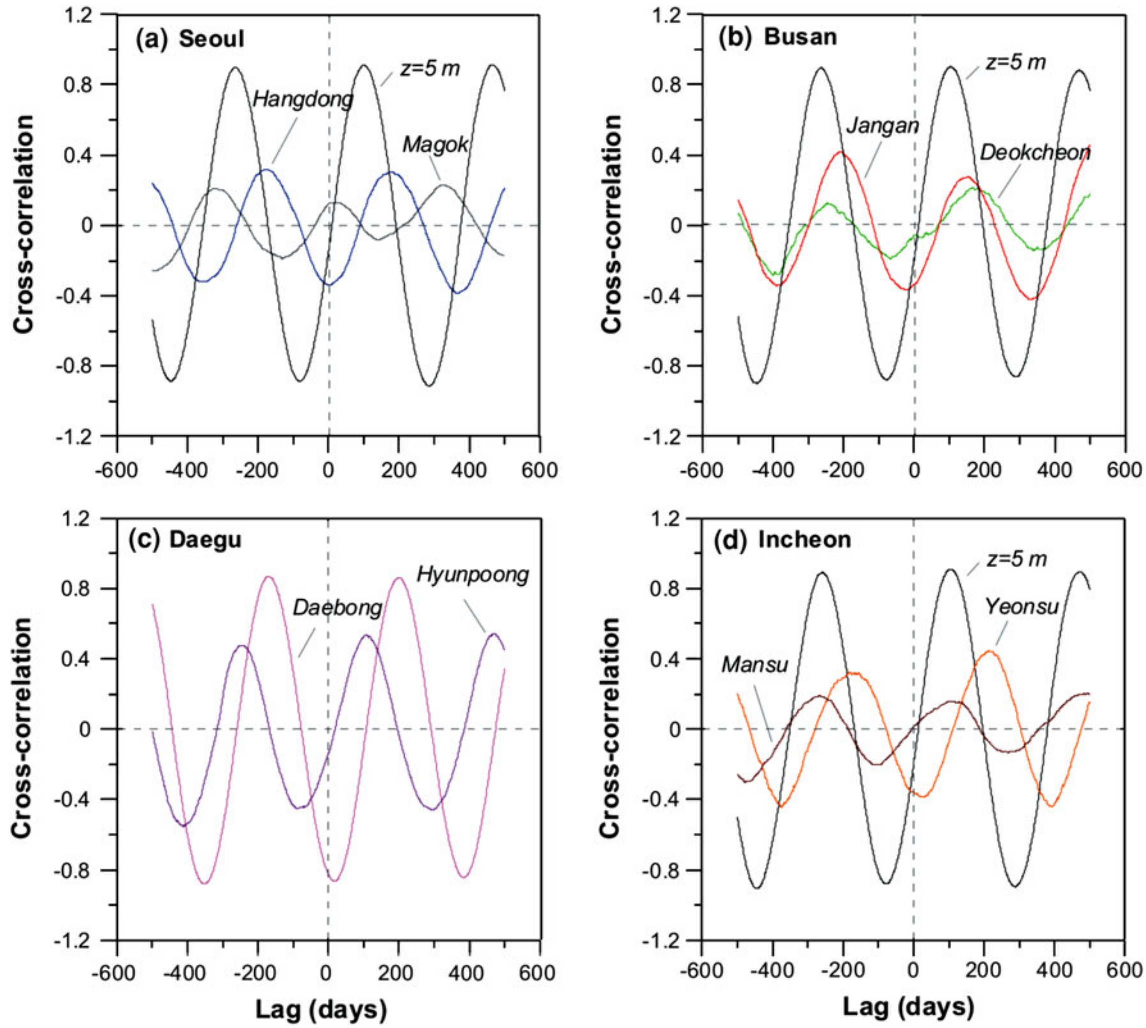

Figure 9. Cross-correlation of groundwater and soil temperatures with air temperature (truncation = 500 days).

response (r = 0.913) with air temperature at lag time of 99 days and an annual cyclic behavior. Groundwater temperatures of two stations of Busan showed very similar correlations with those of Seoul (Fig. 9b). However, the Deokcheon station showed relatively lower peak correlation at a longer lag time (r = 0.215 at 167 days) while the Jangan station showed somewhat higher peak correlation with a shorter lag time (r = 0.276 at 154 days), which can be attributed to the difference in the thickness of unsaturated (soil) zone, that is, mean depth to water of Deokcheon was 14.3 m but that of Jangan was 6.03 m (see Table 2). Soil temperatures of Busan showed the peak correlation with the air temperature (r = 0.902 at 102 days) at nearly the same lag time of Seoul.

Groundwater temperatures of Daegu showed the most excellent response with air temperature (Fig. 9c). The Daebong station shows high peak correlation (r = 0.859) at 202 days and the Hyunpoong station shows intermediate correlation (r = 0.535) at 106 days. The phase difference of the peak times can be also attributed to the difference of water levels (mean DTW of Daebong = 12. 19 m and Hyunpoong = 5.13 m). Groundwater temperatures of Incheon show the most similar correlation behaviors with those of Seoul (Fig. 9d). The two stations showed low to intermediate peak correlations (r = 0.159 at 109 days for Mansu; r = 0.445 at 212 days for Yeonsu). The marked phase difference of the peak times can also be attributed to the difference of groundwater level depth. The mean DTW of Yeonsu station was over two times greater than that of Mansu and, thus, the propagation of heat waves would take more time. Most similarly with the

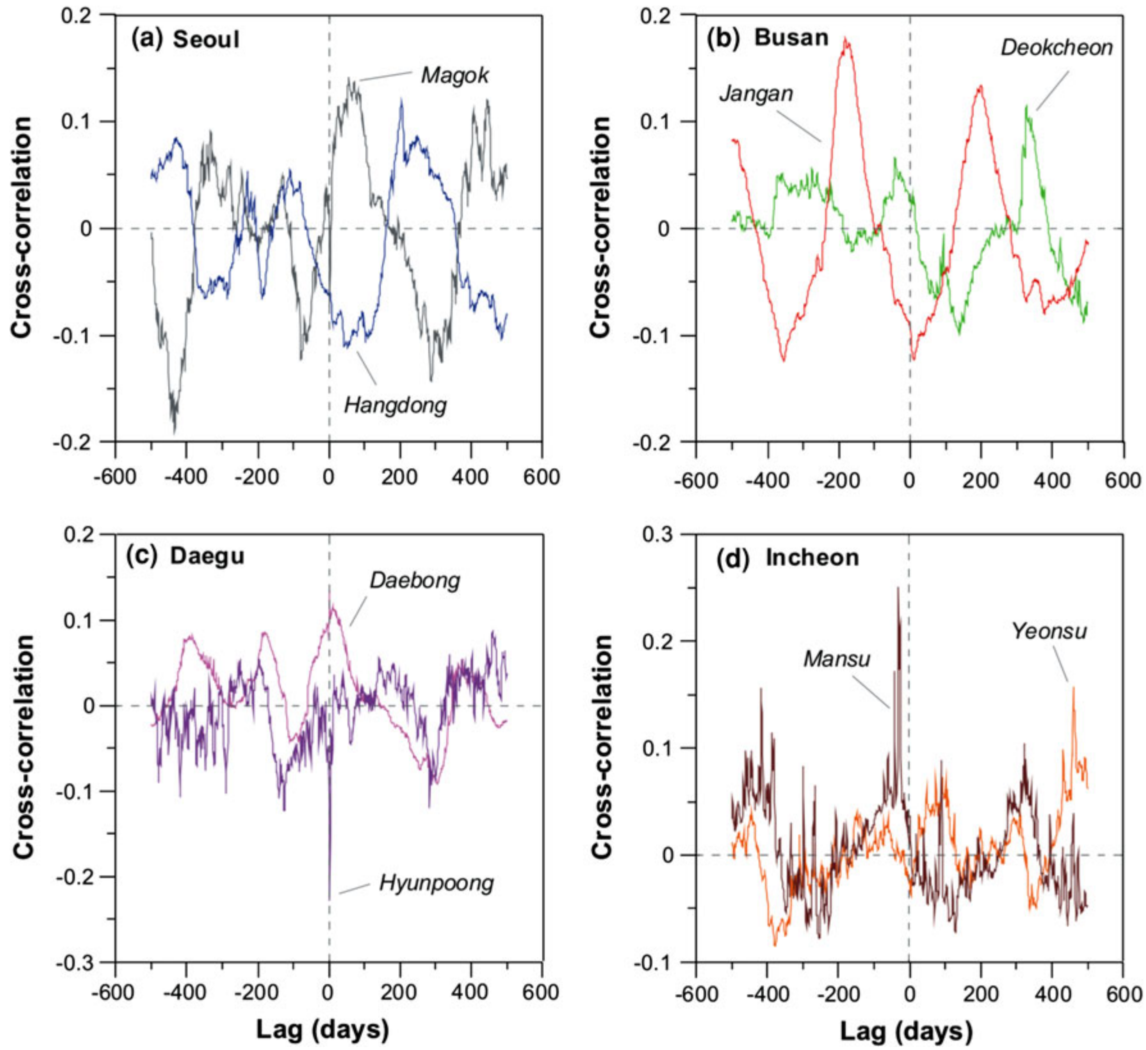

Figure 10. Cross-correlation of groundwater EC with precipitation (truncation = 500 days).

other cities, soil temperatures of Incheon showed high peak correlation (r = 0.908) at 105 days.

Figure 10 shows the correlation between groundwater EC and precipitation. The correlations of groundwater with precipitation were marked but generally much lower ($r < 0.2$) compared with those of groundwater levels. The Magok station showed a fairly fast negative relation ($r = -0.073$ at 1 day) but the response was quickly recovered (Fig. 10a). The influence of incoming rainfall (lowering of EC) was quickly dissipated due to high values of background ECs (see Fig. 5a). The Hangdong station showed some delayed response ($r = -0.111$ at 53 days) with the outer (rainfall) stress but the influence was sustained much longer. Like responses of groundwater levels with precipitation, the different responses of groundwater ECs can also be attributed to degree of pavement or urbanization of surrounding areas. The ECs of groundwater at the two stations of Busan showed very different correlations (Fig. 10b). The Jangan station with shallower groundwater levels (mean DTW = 6.03 m) showed a fast EC decrease with rainfall ($r = -0.123$ at 11 days) but the Deokcheon station revealed a prolonged response with rainfall ($r = -0.066$ at 69 days or $r = -0.100$ at 138 days).

The ECs of groundwater at the Daebong station in Daegu showed an erratic correlation with precipitation, that is, a positive correlation (r = 0.135) at a short lag time (1 day), which is contrary to our expectation that precipitation would lower groundwater EC like other stations. Considering a quick

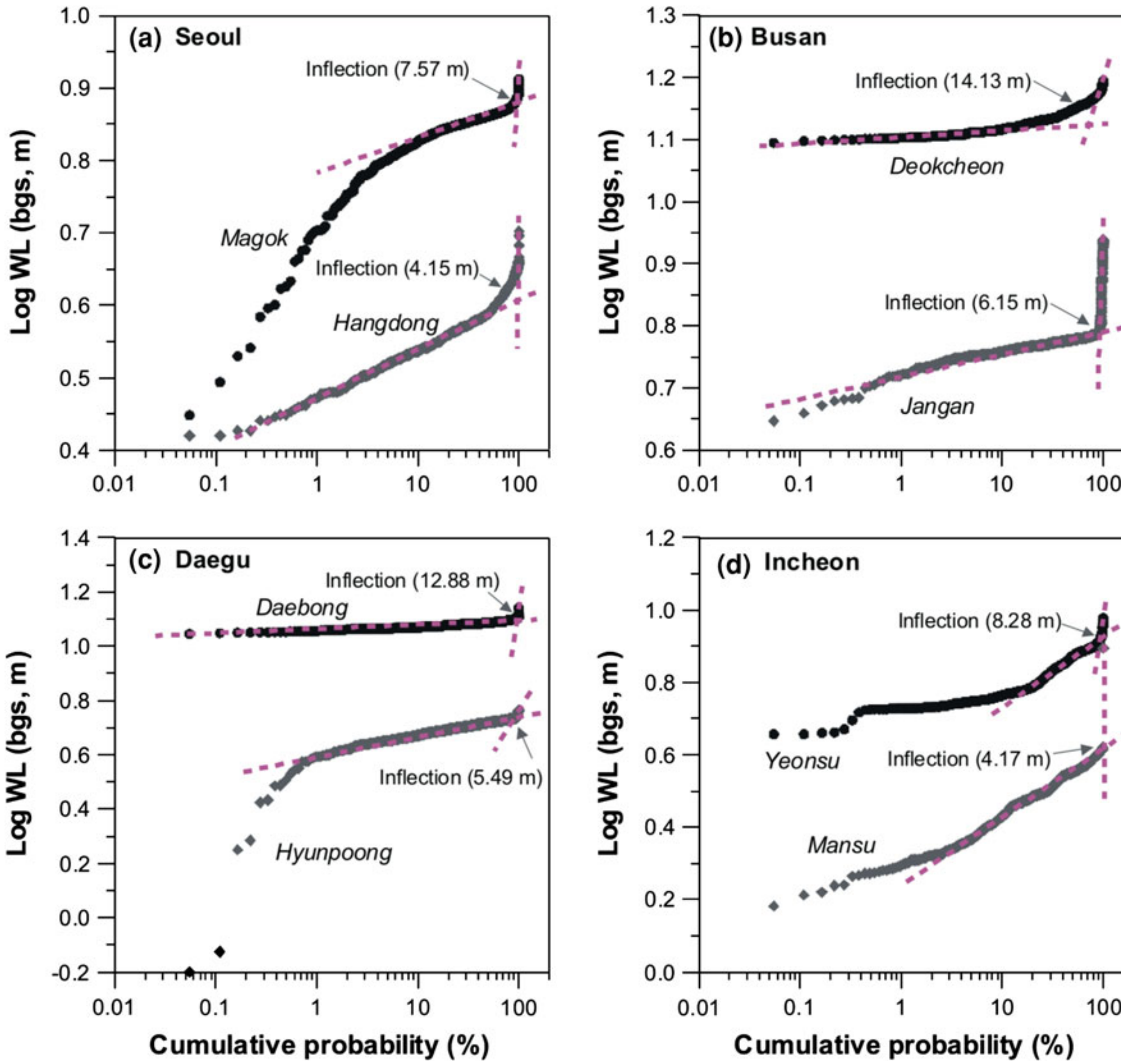

Figure 11. Cumulative probability plots of groundwater levels.

and substantial response of groundwater levels at this station (see Fig. 8c), this positive correlation may be derived from incoming surface contaminants through rainfall infiltration (Pacheco and Cabrera 1997; Yi et al. 2007). However, the Hyunpoong station showed the most striking quick and greatest negative response ($r = -0.228$ at 1 day), whose influence was also quickly recovered within 10 days. The quick response was very similar to that of groundwater level (Figs. 3c, 8c). The ECs of groundwater at the Mansu station in Incheon did not show any discernible and substantial correlation with precipitation, rather they did show an annual cyclic behavior. The erratic and indistinctive correlation can be derived from very high background values (see Fig. 5d). The Yeonsu station showed a negligible correlation ($r = -0.038$ at 3 days). Like groundwater levels of Incheon, groundwater ECs were not expected to be influenced by rainfall in a short and fast manner.

Analysis of Abnormal Values of Groundwater Parameters

Identification of abnormal values of groundwater parameters, indicating any significant variation due to anthropogenic or natural factors, is essential for appropriate groundwater management (Park et al. 2005; Hinsby et al. 2008). Here we used

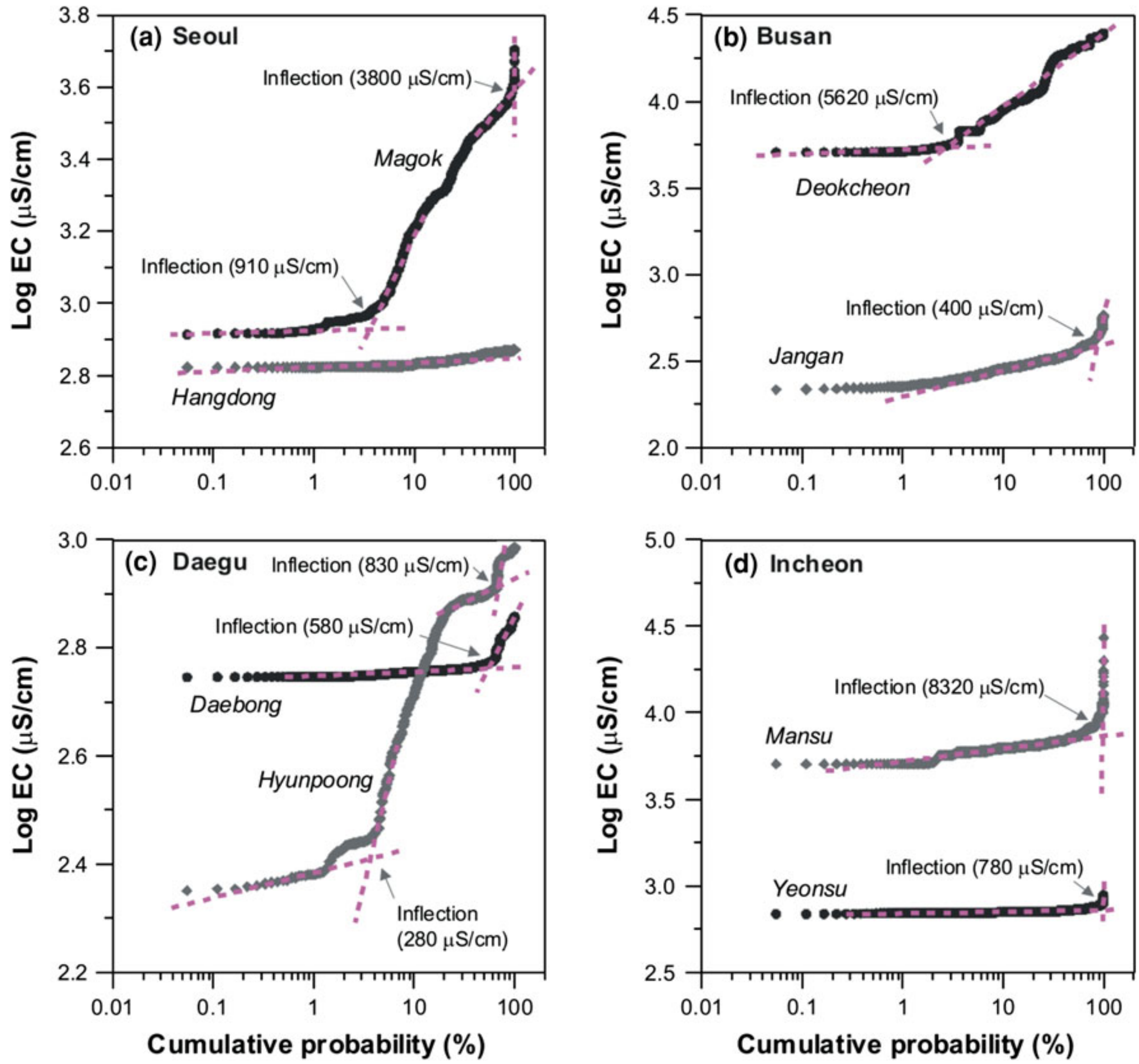

Figure 12. Cumulative probability plots of groundwater ECs.

cumulative probability plots like in many studies (Sinclair 1974, 1991; Park et al. 2005; Panno et al. 2006; Koh et al. 2009) to discriminate values of groundwater parameters into normal or background and affected or abnormal values.

Figure 11 shows cumulative plots of the groundwater levels for the four megacities. Groundwater levels of Magok station show an inflection point of 7.57 m bgs (Fig. 11a), which was statistically formed due to many high groundwater levels by heavy rainfall in the monsoon season (Fig. 3a), thus lowered groundwater levels larger than those values are not problematic considering the annual cyclic rebounds. The Hangdong station showed an inflection point of 4.15 m (bgs), and many groundwater levels larger than that value, actually lowered groundwater levels, were repeatedly observed for a short period. This is related to an artificial pumping for maintenance (cleaning, not regular) of the monitoring well (Lee et al. 2007b). Considering the annual cycle of groundwater levels and the maintenance activity, those lowered water levels also are not problematic.

Groundwater levels of Deokcheon station in Busan revealed an inflection point (14.13 m bgs) (Fig. 11b) but this high groundwater level was calculated as the inflection due to gradual increasing groundwater levels with year (Fig. 3b). Consequently, groundwater levels are not problematic with respect to groundwater depletion. However, at the Jangan station, all groundwater levels after October 15 of

2010 were lower than the threshold value (inflection = 6.15 m bgs) and they were still decreasing. Thus detailed investigations on the causes of the decline and mitigation measures are essentially equired. The Daebong station in Daegu revealed a threshold of 12.88 m (Fig. 11c), but the lowered groundwater levels below the threshold values were only observed at the time of well maintenance (Fig. 3c), which is not problematic. The inflection point (5.49 m bgs) of the Hyunpoong station and only some values in the dry season were below the threshold value. Therefore, considering annual recovery, those groundwater levels are not causing any problem.

Groundwater levels of Yeonsu station showed an inflection point of 8.28 m (Fig. 11d) and lowered groundwater levels than that value were only observed in the late of 2006 and in the early of 2007 (see Fig. 3d). In addition, at the Mansu station, groundwater levels, affected by the artificial pumping for well cleaning, were only lowered than the inflection value of 4.17 m (see Fig. 3d). Therefore, the current groundwater level conditions at the stations are good.

Figure 12 shows the cumulative probability plots of groundwater ECs. The ECs of groundwater at the Magok station revealed two inflection points (910 and 3,800 μS/cm) (Fig. 12a). The mean EC values of groundwater at this station, which is affected by seawater intrusion from the Yellow Sea, is 2,873 μS/cm and thus lower than the first threshold value (910 μS/cm), indicating that very saline groundwater was affected by heavy rainfall infiltration. The second high threshold value (3,800 μS/cm) was occasionally exceeded, which meant that seawater intrusion was aggravated for the periods due to enhanced groundwater pumping and/or high tides. However, because continuous exceeding of the high threshold value or distinctive increasing trends of EC were not observed, only the regular monitoring appears to be appropriate at this time. The Hangdong station did not reveal a meaningful inflection value and ECs of groundwater were in a nominal or a slightly elevated range (664–744 μS/cm) of urban groundwater. The decreasing trend (Table 2; Fig. 5a) of groundwater ECs did not cause any concern on aggravation of groundwater quality.

The Deokcheon station, highly affected by seawater intrusion through the Nakdong River, showed a high inflection point of 5,620 μS/cm (Fig. 12b), but this is a very low value considering the much higher background values (mean EC = 17,821 μS/cm) (Table 2). However, the distinctively decreasing trend of EC of groundwater at this station requires only continuous monitoring. The Jangan station showed an intermediate threshold value of 400 μS/cm (Fig. 12b). The higher values over the threshold were repeatedly observed mainly in the low groundwater season (dry season) but the EC values of groundwater were recovered to low normal levels in the wet season (Fig. 5b). Thus, the EC of groundwater appears to be under stable condition.

The Daebong station in Daegu revealed an intermediate groundwater EC threshold (580 μS/cm) and all EC values of groundwater after December 2008 exceeded the threshold value (see Fig. 5c). This condition with the markedly increasing trend (see Table 2) strongly indicates groundwater contamination was progressing around this station and thus detailed investigation and mitigation measure are urgently needed. The Hyunpoong station showed two inflection points (280 and 830 μS/cm) (Fig. 12c). The first very low threshold value (280 μS/cm) was derived from many low groundwater EC values due to direct or quick mixing of rainfall with more contaminated groundwater (see Fig. 5c). The highly elevated groundwater EC values greater than the second threshold value (830 μS/cm) were observed from March 2007 to February 2009 and, after that period, the EC values of groundwater were below 800 μS/cm without any increasing trend (see Fig. 5c). However, the most frequent groundwater EC fluctuations require inspection and maintenance of the monitoring well.

The Mansu station in Incheon showed a very high inflection point of 8,320 μS/cm (Fig. 12d). After June 2006, EC values of groundwater only occasionally exceeded the threshold value and they showed a gradual decreasing trend. Therefore, the high EC values of groundwater at this station are not problematic at this stage. The drastically high peaks of groundwater ECs before heavy rainfall events (Fig. 5d) cannot be explained for the present. The inflection value of the Yeonsu station is 780 μS/cm, which has been exceeded only since October 2010. Thus, additional monitoring is essential to determine further continuous exceeding or any trend.

CONCLUSION

We examined groundwater conditions in the four largest metropolitan cities in Korea using monitored data (2006–2010) obtained from Korean national groundwater monitoring stations. Groundwater use in the megacities generally decreased while the population mostly increased for the period, which was due to strict banning of further groundwater pumping and movement of many industrial companies in the cities to overseas or outskirts. Due to the lessened groundwater pumping, the groundwater levels were not substantially decreasing. Rather rise of groundwater levels was observed mainly in the central part of the cities, which can cause a stability problem of many buildings with deep foundations or subway flooding. The unexpected groundwater level rise may be attributed to enhanced rainfall infiltration due to increased precipitation and leakage of waterworks and sewer lines, which deserves a water budget study.

Groundwater levels responded sensitively to rainfall events in less developed areas, while those in the highly urbanized areas showed delayed or attenuated responses. Groundwater temperatures mostly showed increasing trends, which were associated with increasing air temperatures, representing the effects of climate changes. Some groundwater monitoring stations, especially in the coastal cities (including Seoul, Busan, and Incheon) have suffered from seawater intrusion. The Jangan station of Busan recently experienced a drastic decrease of the groundwater level; thus, a detailed investigation revealing the causes and appropriate mitigation measures are required. In addition, the Daebong station in Daegu showed marked increasing trends of ECs, indicating gradual groundwater contamination possibly from anthropogenic origin; therefore, field examination is also needed.

Urban groundwater does not uniformly respond to anthropogenic and natural stresses because the variety of human interventions like pavement, building construction, and artificial irrigation affect the cities in different ways. In particular, the highly populated megacities can be largely affected by rising groundwater levels, which threatens the stability of many deep based facilities and buildings. Enhanced urban groundwater recharge due to increase of precipitation can result in frequent urban flooding. In the era of climate change, a preparatory groundwater monitoring and necessary mitigation measure for relevant groundwater problems should be continued, thus ensuring use of groundwater resources and securing citizens and buildings from possible groundwater hazards.

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