Geosciences Journal
Vol. 10, No. 1, p. 91 − 99, March 2006

Evaluation of hydrogeologic conditions for groundwater heat pumps: analysis with data from national groundwater monitoring stations

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ABSTRACT: Groundwater can be used as an alternative renewable and clean energy source for space heating and cooling. Hydrogeologic conditions of Korea were evaluated for application of groundwater heat pumps (GWHPs), especially for open-loop system. Groundwater data obtained from the national groundwater monitoring stations (NGMSs) were used for the purpose. Temperatures of shallow and deep groundwaters are between 1.2–25.8°C and their annual variations are mostly within 10°C. Especially the small amplitude of variation for deep groundwaters can facilitate design and maintenance of groundwater heat pumps. Groundwater levels for shallow and deep wells are located at average 4.79–6.07 m below ground surface. The shallow water levels are most promising for groundwater heat pumps, which reduces pumping costs. A large number of monitoring wells showed a good well yield exceeding a requirement for 3 RT heat pumps for small residential purposes but a limited application is expected for large commercial uses with the single well. Some proportions of shallow and deep groundwaters exhibited scaling and corrosion potentials in respect to hardness, pH, electrical conductivity, total dissolved solids, bicarbonate and chloride. Each relevant parameter was separately evaluated in this study but the parameters are closely correlated. Thus for more detailed and quantitative examination of water quality conditions for GWHPs, integrated and extensive chemical analysis of groundwaters are essentially required.

Key words: Groundwater temperature, hydraulic conductivity, heat pumps, open-loop, national groundwater monitoring stations, Korea

1. INTRODUCTION

Recently renewable energy sources are one of main interests of environmental community and relevant governmental authorities in Korea. Drastic increase in energy demands resulted in consumption of a large quantity of fossil fuels and their progressive depletion. The energy crisis urges the country to search and develop alternative energy sources and furthermore they should be environment-friendly. Effects of global warming mainly derived from CO_2 emission are ubiquitous in the world. So reduction in emission of the greenhouse gases is inevitable (USEPA, 1993; Houghton et al., 1996). Emerging alternative energy sources include solar energy, wind power energy, biomass energy and ground source heat energy and the renewable energy sources become one of intensive and extensive R & D areas in the country (Lee and Hahn, 2005).

The subsurface (ground) is a great reservoir of heat energy. Unlike the air, it has very stable temperatures. Consequently, the ground is warmer than the ambient air in winter and cooler than the summer air. Ground source heat pump (GSHP) systems have become increasingly popular for both residential and commercial heating and cooling applications mainly due to their higher energy efficiency compared with conventional systems (Chiasson et al., 2000). In the winter, a geothermal heat pump transfers heat from the ground or groundwater to provide space heating and in the summer, the heat transfer process is reversed; the ground or groundwater absorbs heat from the living or working space and cools the air (DOE, 1999). There are two basic ground source heat pump systems: an earth coupled (closed-loop) type and a groundwater (open-loop) type. In the residential sectors, closed-loop GSHP tends to be installed in homes in the upper cost end of the market (Rafferty, 2000).

The open-loop GSHP, also known as groundwater heat pump (GWHP), typically depends upon groundwater to supply or accept heat. Three types of commonly used open-loop systems are shown in Figure 1. Direct open-loop heat pumps are largely used for residential and small commercial applications (Rafferty, 2001). This system is most suitably applied where a chemically pure groundwater is available because the direct use of the groundwater can cause scaling, deposition of mineral precipitates in pipes, valves or heat exchangers (PDEP, 1996). The standing column systems are used in locations where groundwater wells do not produce sufficient water for conventional open-loop system and where water quality is also good (Rafferty, 2001). The single well system can reduce initial costs of extra injection well installation (Lee and Hahn, 2005). The indirect open-loop systems generally involve a heat exchanger between the building loop and the groundwater, by which eliminates exposure of any building components to the groundwater (Rafferty, 2001). Details of the groundwater heat pumps including principles, system design, and well installation were described in Hahn et al. (2004).

Especially in the groundwater heat pumps, it is basically most important to obtain a plentiful amount of groundwater with a stable temperature (Koo et al., 2003). Therefore, the

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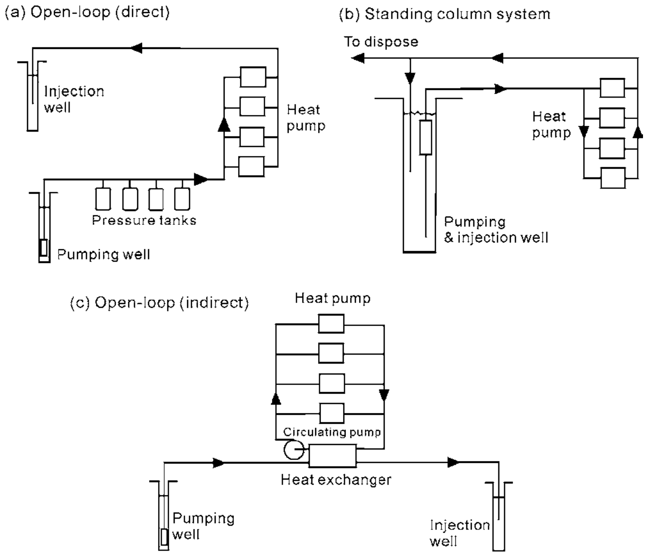

Fig. 1. Open-loop groundwater heat pump systems. The figure was from Rafferty (2001). With kind permission of the Geo-Heat Center, Oregon Institute Technology.

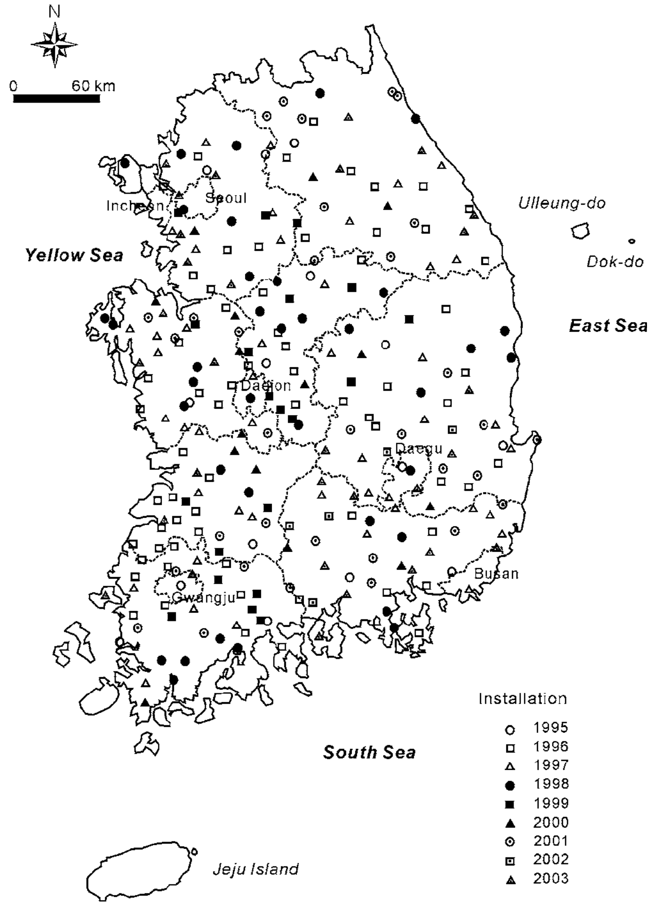

Fig. 2. Locations of the national groundwater monitoring stations.

groundwater supply well must yield enough water of good chemical quality to transport the required amount of heat (PDEP, 1996). In this point of view, this study evaluated groundwater conditions of this country using the hydrogeologic data obtained from the national groundwater monitoring stations (NGMSs). Lee and Hahn (2005) and Hahn et al. (2004) intensively analyzed the groundwater temperature data from the NGMSs in consideration of the heat pump system. They analyzed distribution of groundwater temperature throughout half of the peninsular, classified patterns of groundwater temperature variation and clarified months of highest and lowest temperature occurrence. So in this study, other very important parameters such as water levels, hydraulic conductivity, well yield, hardness, electrical conductivity, and other general water qualities were extensively examined.

2. METHODS AND MATERIALS

Main parameters considered in the groundwater heat pump system design can be classified into two groups: physical or hydrologic factors (groundwater temperatures, water levels, well yield, hydraulic conductivity) affecting system or energy efficiency (i.e., EER or COP) and chemical factors (groundwater chemistry) affecting maintenance or life span of the system by scaling, corrosion or both. In order to analyze general groundwater conditions for this purpose, data of the NGMSs were used.

KOWACO (Korea Water Resources Corporation), an affiliated organization of the MOCT (Ministry of Construction and Transportation), is in charge of the establishment, operation, and maintenance of the NGMSs (Lee et al., 2005). The construction of the stations has been performed by step by step since 1995 (Fig. 2). By 2004, 293 stations were completed. Mostly for each monitoring station, two separate groundwater wells were newly installed (some of stations have only single monitoring well). One well, with an average well depth of 11.7 m, is used to monitor shallow groundwater (alluvial aquifer) and the other, with an average depth of 69.8 m, is used to monitor deep groundwater (bedrock aquifer) (Lee and Hahn, 2005). At each monitoring well, an integrated probe measuring water levels, water temperatures and electrical conductivity (EC) was installed.

Groundwater level, water temperature, and electrical conductivity are measured every 6 hours using the integrated probe and these data are stored in the data logger. The measured groundwater data are automatically transmitted to a host server at KOWACO once a day at a designated time. In addition, periodic analyses of groundwater quality are performed twice per year for all the monitoring wells including analyses of general water chemistry during the well installation. For maintenance of the facilities and the monitoring devices, a field inspection/maintenance team regularly visits each station at least 6 times per year. All the data obtained from the groundwater monitoring stations are managed by the NGMN management system on the web. The data are safely stored in an Oracle DB at KOWACO. In this paper, groundwater data obtained from the 266 NGMSs (including 128 shallow monitoring wells and 236 deep monitoring wells) were analyzed and relevant hydrogeologic tests data gathered during the station installation were examined.

3. RESULTS AND DISCUSSION

3.1. Groundwater Temperature

Figure 3 shows spatial distribution of maximum and minimum groundwater temperatures for shallow and deep aquifers recorded during 1995-2003. The maximum groundwater temperatures ranged between 11.9 and 25.8°C with a mean of 16.8°C for shallow groundwaters (Fig. 3a) while they were between 9.9 and 25.6°C with a mean of 15.3°C for deep groundwaters (Fig. 3b). The highest groundwater temperatures were observed in Daegu metropolitan city, which is one of the hottest (highest air temperatures) areas in summer in the country (Kim and Min, 2001). In general, groundwater temperatures in western half of the country were relatively lower than those in eastern half, which were mainly derived from higher air temperatures at the latter region due to high elevations topography (Taebaek mountains blocking cold winds in winter) and a warm current of the East Sea (Donghan Current; Min, 1979; Lee and Hahn, 2005).

The minimum groundwater temperatures for shallow groundwaters ranged from 3 to 16.1°C (Fig. 3c) with a mean of 11.2°C while they ranged from 1.2 to 16.9°C with a mean of 12.9°C for deep groundwaters (Fig. 3d). Except for the highest latitude areas (upper Gyeonggi province), the lowest groundwater temperatures occurred in Yeongyang, Gyeongbuk province. Maximum groundwater temperatures are mostly observed in coldest months (November-February) and minimum temperatures occur in March-June, immediately before the hottest months (July-August). Phase differences compared with air temperatures wave are within 5 months (Lee and Hahn, 2005). The longer phase delays were generally related to thicker upper soils or lower water levels. The phase difference and amplitude attenuation occur during transport of air heat through upper soils or rocks, which depends on various subsurface properties such as soil density, specific heat, thermal conductivity, porosity, organic content and moisture content (Lee et al., 2000; Koo et al., 2003). The phase differences are quite a favorable to operation of GWHPs for space heating and cooling in the country.

Variations of groundwater temperatures are summarized in Table 1. Most of shallow wells (85.2%) showed relatively small temperature change within 10°C. Only 14.8% of the wells showed rather large variation greater than 10°C (maximum variation=20.8°C). In the deeper wells, stable groundwater temperatures were most prominent. Nearly all of the wells (97.4%) showed a variation within 10°C while 2.6% exhibited a large variation over 10°C. Compared with mean air temperature variation of over 30°C for the same period in the country (half of the peninsular), these very stable groundwater temperatures have an advantage for system design and maintenance of groundwater (ground source) heat pumps (Koo et al., 2003; Hahn et al., 2004; Lee and Hahn, 2005). Especially, the bedrock aquifers are most promising for groundwater heat pumps in respect to temperature stability (Lee and Han, 2001; Lee and Hahn, 2005). Groundwaters with temperatures of 10−20°C are most suitable for open-loop groundwater heat pumps (Hahn et al., 2004).

3.2. Water Levels and Hydraulic Properties

Groundwater level is one of important parameters determining efficiency (COP or EER) of GWHPs. The deeper is the groundwater level, the more power is need to extract the groundwater, thus which results in reducing the efficiency. Actually pumping level (original static water level + pumping drawdown) instead of static groundwater level is most important and the pumping level is a function of pumping rate (Rafferty, 1998). In the open-loop system, a submersible pump of about 0.75 HP (horse power) is required to provide a groundwater enough for 1 RT (refrigeration ton or simply ton) heat pump in case pumping level is 60 m below ground surface (Hahn et al., 2004). When the pumping level is about 30 m (bgs), a pump of less than 0.56 HP is enough to complete the same purpose (Rafferty, 1998). Commonly 3 RT heat pump is necessary for space heating and cooling of a house with 4 peoples and 57 pyeongs (174 m^2). Higher groundwater levels (within 30 m) are most suitable for open-loop groundwater heat pumps or single well groundwater heat pumps (Heng and Rybach, 2005).

Mean groundwater levels (depths to water) for 2003 are presented in Figure 4. Groundwater levels for shallow wells were located at 1.29−32.42 m below ground surface with a mean of 4.79 m (Table 2). The deepest mean water levels were observed at Jeongsun area, Kangwon province, which was derived from higher topographic elevation (EL=347.054 m). Lower groundwater levels at other areas are mostly related to heavy groundwater withdrawals for various purposes (MOCT and KOWACO, 2004). The water levels of deep wells (depths to water but strictly speaking potentiometric surface if confined) ranged from 0.57 to 51.04 m with a mean of 6.07 m below ground surface. Also lowest water levels were observed at Jeongsun, Ulsan and Munan areas. Interestingly most of lowest water levels were found at coastal areas of the country rather than at inner land areas. Meanwhile, recently relevant authorities (MOCT and KOWACO) undertook a detailed investigation project revealing exact causes of large decline of the water levels for some of the areas and devising attenuation measures.

To supply enough and stable amounts of groundwaters, hydraulic properties are very important. Transmissivity, hydrau-

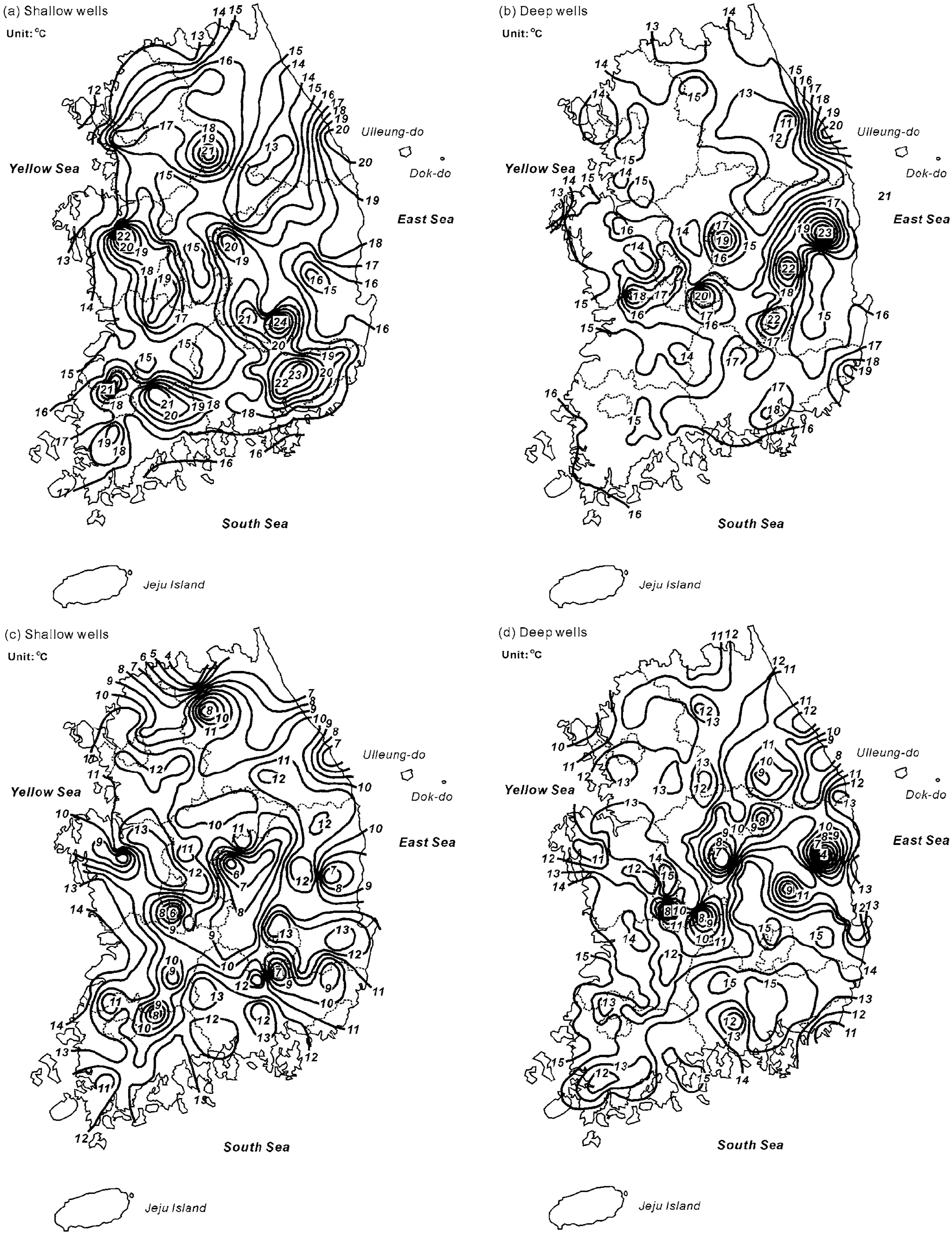

Fig. 3. Distribution of maximum (a, b) and minimum (c, d) groundwater temperatures recorded during 1995-2003.

Table 1. Summary of groundwater temperatures variation (1995-2003).

Maximum-minimum	Shallow wells		Deep wells	
	Proportion	Cumulative	Proportion	Cumulative
<2°C	16.4%	16.4%	53.4%	53.4%
2–4°C	26.6%	43.0%	28.8%	82.2%
4–6°C	17.2%	60.2%	11.4%	93.6%
6–8°C	16.4%	76.6%	3.4%	97.0%
8–10°C	8.6%	85.2%	0.4%	97.4%
>10°C	14.8%	100%	2.6%	100%

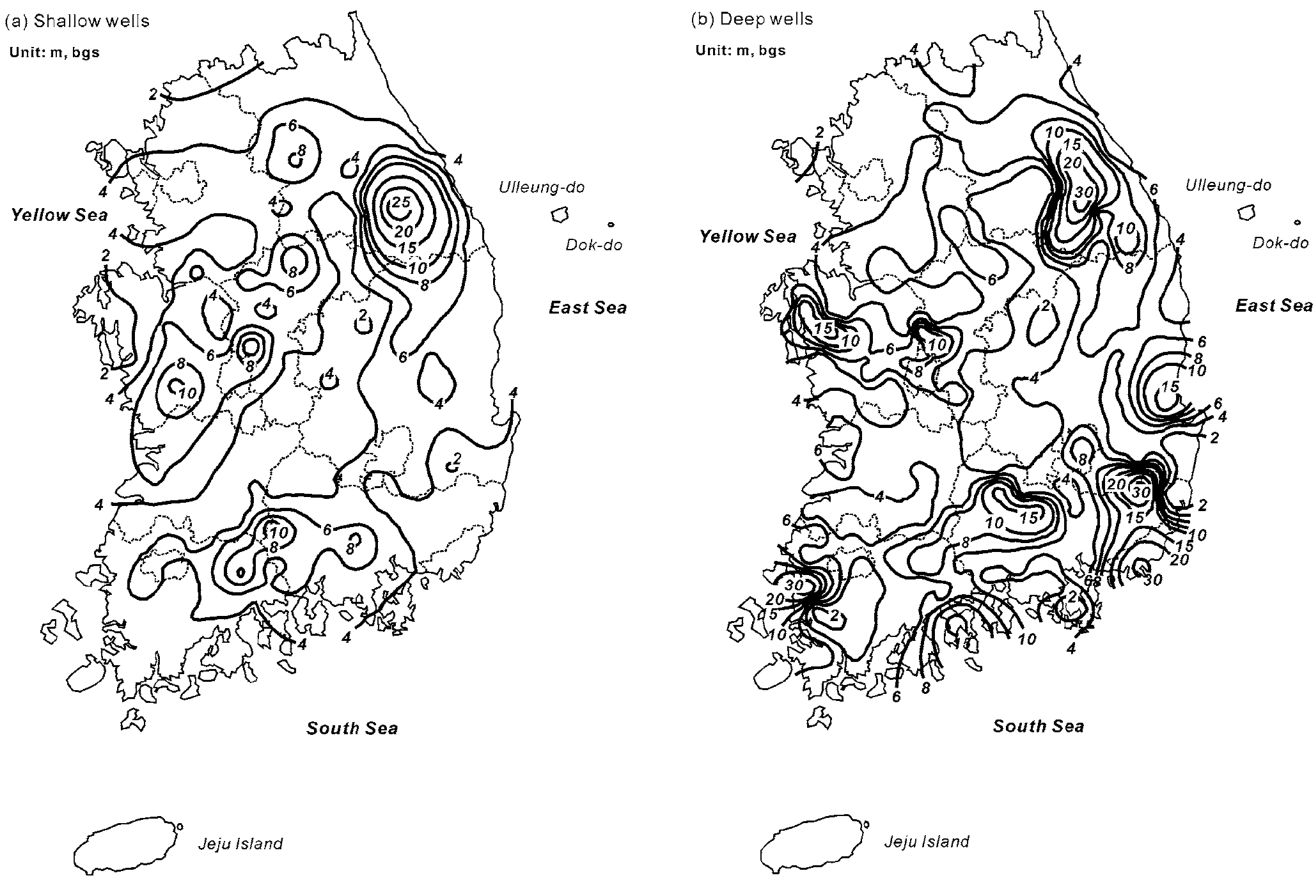

Fig. 4. Distribution of mean water levels (depth to water) of (a) shallow and (b) deep monitoring wells for 2003.

Table 2. Statistics of groundwater levels for shallow and deep monitoring wells.

Statistics	Shallow wells (m, below ground surface)	Deep wells (m, below ground surface)
Number of data	127	232
Maximum	32.42	51.04
Minimum	1.29	0.57
Mean	4.79	6.07
Median	4.02	4.37
Standard deviation	3.29	6.30

lic conductivity and well yields for shallow and deep wells of NGMN are summarized in Table 3. Geometric mean of transmissivity of shallow wells is two times larger than that of deep wells. And corresponding hydraulic conductivity shows much larger difference (15 times). Generally higher hydraulic conductivity (on the order of 10^{-3} cm/sec or higher) is favorable for successful and efficient functioning of the groundwater heat pumps (open-loop). Most of all, well yield is very important. For small residential purpose (3 RT), at least well yield of 16 m^3/day is required and in large (>50 tons) commercial GWHP systems, minimum well yield of 274 m^3/day is needed (Rafferty, 1998; Hahn et al., 2004). Well yields for shallow wells range 3.40–1,440 m^3/day with a mean of 103.57 m^3/day (see Table 3). And 70.3% and 7.6% of the well yields of shallow wells (single well) are greater

Table 3. Summary of transmissivity (T), hydraulic conductivity (K) and well yields of the monitoring wells in the national groundwater monitoring stations.

Parameters	T (m^2/day)		K (cm/sec)		Well yield (m^3/day)	
	Shallow	Deep	Shallow	Deep	Shallow	Deep
No. of data	128	236	128	236	118	228
Maximum	1,681	1,289	3.55×10^{-1}	2.55×10^{-2}	1,440	2,931
Minimum	0.12	0.08	1.88×10^{-5}	1.50×10^{-6}	3.40	6
Mean	67.20	24.96	1.26×10^{-2}	6.81×10^{-4}	103.57	169.64
Geometric mean	7.08	3.32	1.25×10^{-3}	8.32×10^{-5}	41.80	89.56

than 16 274 m^3/day and 274 m^3/day, respectively. Well yields for deep wells are between 6 m^3/day and 2,931 m^3/day (mean=169.64 m^3/day). And 91.7% and 14.9% of single well yields are over 16 m^3/day and 274 m^3/day, respectively. Thus most of single wells for both shallow and deep aquifers are suitable for groundwater heat pumps with small residential purposes but for large commercial purposes, single well has limited applications.

3.3. Water Chemistry

Open-loop groundwater heat pumps are susceptible to water quality induced problems (Rafferty, 2001) and corrosion and scaling caused by unique chemistry of groundwaters, may lead to operating problems with equipment components exposed to flowing water and steam (Lund, 1996). Water quality is also a consideration for closed-loop ground source heat pumps and in the closed-loop system, the concern is not the main refrigerant to water heat exchanger but the desuperheater (Rafferty, 2000). Water quality components relevant to corrosion and scaling include hardness (as $CaCO_3$), pH, EC (electrical conductivity), TDS (total dissolved solids), chloride (Cl^-), and bicarbonate (HCO_3^-) (Rafferty, 2000; Hahn et al., 2004).

Scaling problems may occur above levels of 100 mg/L hardness and become serious above 200 mg/L (Rafferty,

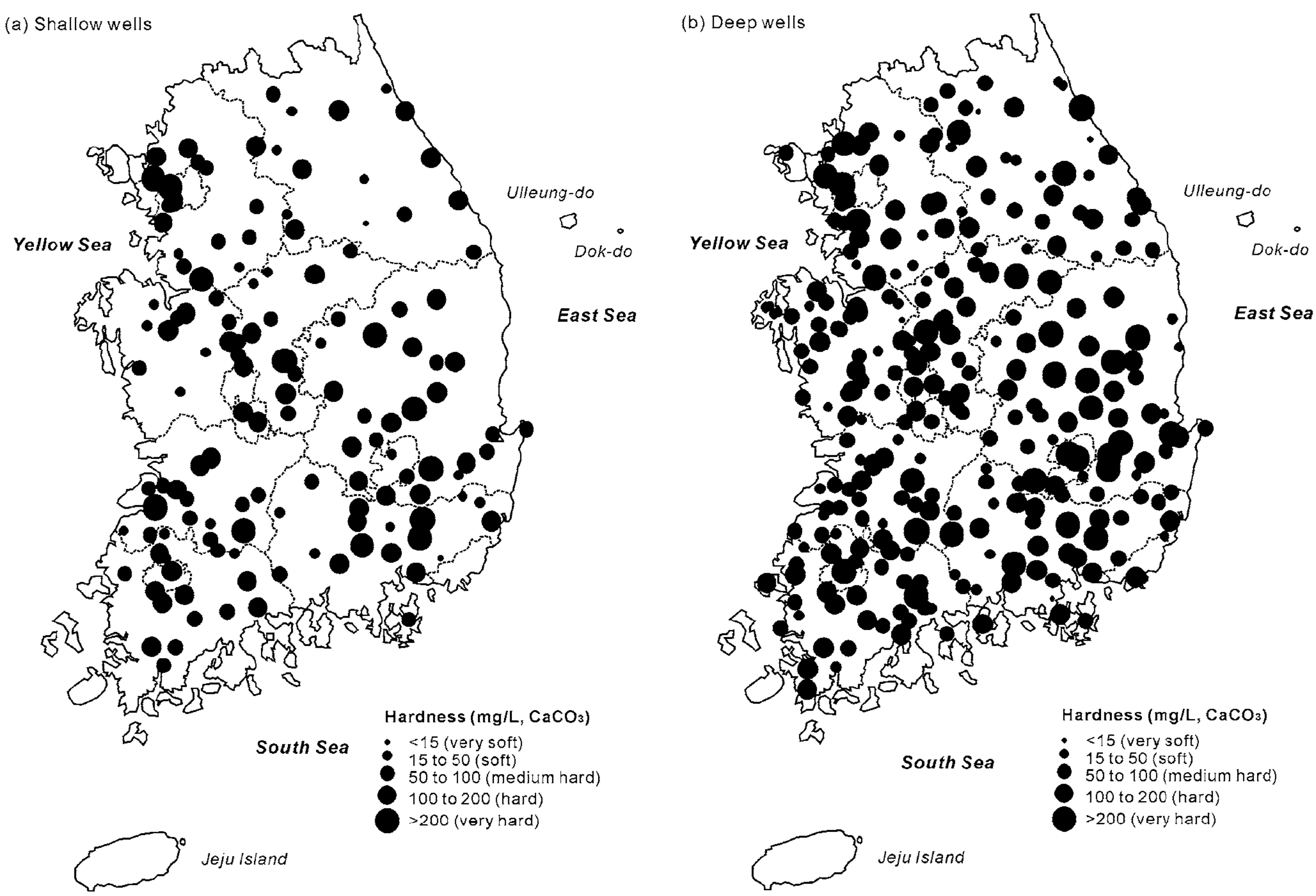

Fig. 5. Distribution of groundwater hardness (mg/L, $CaCO_3$) for shallow and deep groundwaters.

2000). Scaling generally increases with increasing calcium concentration, hardness, alkalinity, pH and groundwater temperature. Groundwater scaling potentials can be classified according to hardness as low (< 100 mg/L), moderate (100–200 mg/L), and high (> 200 mg/L) (Rafferty, 1999). Figure 5 shows groundwater hardness for shallow and deep wells. Hardness of shallow wells ranged from 4 to 822 mg/L as $CaCO_3$ (mean=115 mg/L). Of these, 54.9, 36.1, 9.0% are classified as low, moderate, and high scaling potentials, respectively. For deep wells, hardness is between 8 and 1,490 mg/L as $CaCO_3$ (mean=127 mg/L), of which, 55.8, 32.1, and 12.1% involved low, moderate and high scaling potentials, respectively. Deep groundwaters showed slightly larger scaling potential than shallow groundwaters.

The pH values of most fresh groundwaters are in the range of 5.0 and 9.0 (Hem, 1985). Scaling and corrosion problems are common at pH values above 8.0 and below 6.5, respectively (Hahn et al., 2004). The pHs of groundwaters in the country exhibited normal distributions (Fig. 6). For shallow groundwaters, 11.95 and 11.2% showed pH values below 6.5 and above 8.0, respectively. And for deep groundwaters, pH values below 6.5 and above 8.0 account for 9.9 and 11.4% of total values, respectively. The abnormal pH values do not always accompany corrosion and scaling problems. However, they can affect long maintenance of the heat pump system. Because scaling or corrosion is a slow process occurring over months or years, the slow erosion of the savings by the system may be imperceptible to the system user (Rafferty, 2000).

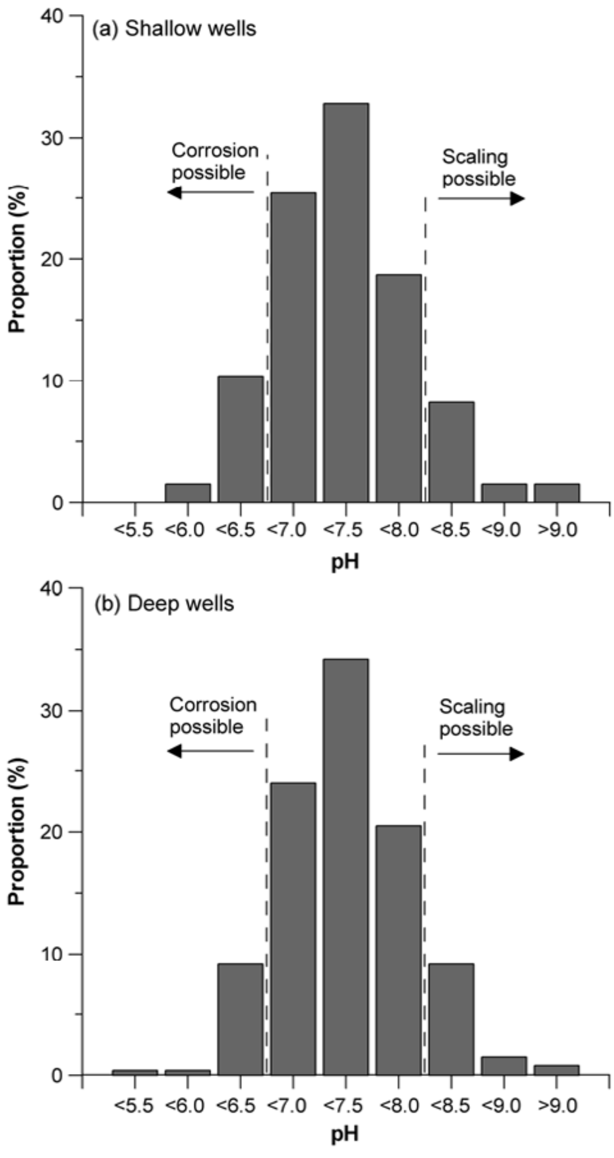

Fig. 6. Distribution of pH values for shallow and deep groundwaters.

Electrical conductivity (EC) of fresh groundwaters ranges from 50 to 500 μS/cm. The ECs of groundwaters increase with dissolved constituents concentrations. Thus high EC (>500 μS/cm) waters readily conduct the electrical currents and accelerate the corrosion, which increase maintenance costs of the heat pump systems. In this study, ECs of shallow groundwaters ranged from 15 to 2,300 μS/cm with a mean of 339 μS/cm (Table 4). Most (88.8%) of the shallow groundwaters have EC values less than 500 μS/cm. The EC values of deep groundwaters ranged between 13 and 15,800 μS/cm (mean=378 μS/cm). Also a large proportion (86.3%) showed proper EC values (<500 μS/cm). Higher EC values directly related to levels of total dissolved solids (TDS).

TDS levels of groundwaters suitable for general purposes range between 200 and 1,000 mg/L. As TDS increases, water quality problems are more likely to occur. Detailed investigation of water chemistry is essentially required for groundwaters with high levels of TDS (>500 mg/L). TDSs above 500 mg/L may cause corrosion problems. Levels of TDS for shallow groundwaters are between 37.9 and 4078.2 mg/L while those for deep groundwaters range between 31.7 and 11,421.0 mg/L. Only 4.1 and 4.2% of shallow and deep groundwaters exceeded TDS of 500 mg/L, respectively. Meanwhile TDS generally has a linear relationship with EC level (slope=0.45–0.67). Also in this study, reasonable slope ranges were observed; 0.47 (r^2=0.84) for shallow groundwaters, and 0.60 (r^2=0.97) for deep groundwaters. It is known that higher slope is obtained for higher dissolved concentrations (Hem, 1985).

Alkalinity is a measure of the buffering capacity of water, or the capacity of bases to neutralize acids. In the range of normal groundwater chemistry, alkalinity is the result of the bicarbonate (HCO_3^-) content of the groundwater (Rafferty, 2000). If alkalinity is too low, pH will be easily impacted and abrupt changes in pH can cause scaling or corrosion of metal equipment (AHP, 2001; Lund et al., 2003). But when the alkalinity is too high, the pH may drift upward, causing scale to form (AHP, 2001). Appropriate range of alkalinity is between 30 and 180 mg/L. Concentrations of bicarbonate (indicative of alkalinity) for shallow wells are between 0.0 and 230.3 mg/L (mean=69.1 mg/L). Of shallow groundwa-

Table 4. Some water quality parameters related to scaling potential of groundwaters.

Parameters		No. of data	Maximum	Minimum	Mean	Median	Standard deviation
EC (μS/cm)	SG[a]	134	2,300	15	339	276	303
	DG[b]	263	15,800	13	378	261	989
TDS[c] (mg/L)	SG	97	4078.2	37.9	206.1	129.0	429.6
	DG	215	11,421.0	31.7	287.0	150.1	1,017.0
HCO_3^- (mg/L)	SG	97	230.3	0.0	69.1	52.1	45.6
	DG	215	613.5	0.0	83.0	67.5	65.3
Cl^- (mg/L)	SG	123	2,219	1.0	50.6	16	208.2
	DG	232	7,380	0.0	92.1	17	648.1

[a]Shallow groundwaters.
[b]Deep groundwaters.
[c]Total dissolved solids calculated from water chemistry data.

ters, 17.5% are out of the range. Levels of bicarbonate of deep groundwaters range from 0.0 to 613.5 mg/L (mean=83.0 mg/L) and 13.0% are out of the appropriate range.

High chloride concentrations may cause corrosion (Knipe and Rafferty, 1985). Chloride concentrations over 100 mg/L in groundwaters indicate a risk of corrosion in transport pipes. Concentrations of chloride for shallow wells are between 1.0 and 2,219 mg/L (mean=50.6 mg/L) while those for deep wells range between 0.0 and 7,380 mg/L (mean=92.1 mg/L). Higher concentrations over 200 mg/L were mostly observed at coastal areas and are indicative of effects of seawater intrusion (Kim et al., 2003). Of chloride concentrations, 7.3% for shallow groundwaters and 5.6% for deep groundwaters exceeded 100 mg/L chloride.

4. SUMMARY AND CONCLUSION

In this study, hydrogeologic conditions of groundwaters of Korea were basically examined for application of GWHPs. For theses purposes, groundwater data obtained from NGMN were used. From the various evaluations, some major conclusions were drawn.

1. Temperatures of shallow and deep groundwaters are between 1.2–25.8°C and their annual variations are mostly within 10°C. Especially the small amplitude of variation for deep groundwaters can facilitate design and maintenance of groundwater heat pumps.

2. Groundwater levels (depths to water for shallow and deep wells) are located at average 4.79–6.07 m below ground surface. The shallow water levels are most suitable for groundwater heat pumps, which reduces pumping costs.

3. Large number of monitoring wells showed a good well yield exceeding a requirement for 3 RT heat pumps (for small residential purposes) but a limited application is expected for large commercial uses with the single well.

4. Some proportions of shallow and deep groundwaters exhibited scaling and corrosion potentials. Each relevant parameter was basically and separately evaluated in this study. But the parameters are closely correlated. Thus for more detailed and quantitative examination of water quality conditions for GWHPs (e.g., Langelier Saturation Index and Ryznar Stability Index), integrated and extensive chemical analysis of groundwaters are essentially required.

ACKNOWLEDGEMENT: The authors wish to thank Prof. Chang-Eob Baag at Seoul National University and two anonymous reviewers for their critical and helpful comments improving the initial manuscript.

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Manuscript received July 22, 2005
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