

Characteristics of ground and groundwater temperatures in a metropolitan city, Korea: considerations for geothermal heat pumps

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ABSTRACT: As a basic feasibility study for geothermal heat pumps, characteristics of ground and groundwater temperatures in a metropolitan city, Seoul, were examined. For the purpose, groundwater data obtained from the subsidiary groundwater monitoring wells of the city and data of ground temperatures at depths of 0.05-5.0 m were analyzed. The annual ground temperature variations decreased exponentially with ground depths and the corresponding phase differences compared with the ambient air temperatures increased linearly with them. The ground temperatures were very stable below 3.0-5.0 m depth with minimal annual variation and they were averagely 15°C. The annual mean groundwater temperatures were 15°C and the groundwaters of most monitoring wells showed the annual variation within 3°C. All these temperature conditions are very promising for the application of the geothermal heat pumps. But the limitation of available space for the buried pipes and the thin unconsolidated soil layer in the metropolitan area would restrict the practical wide application of the closed loop systems. So open systems can be beneficial. A large number of the existing groundwater wells and the shallow water levels may enhance efficiency of the open system maintenance. Some relevant engineering considerations for the groundwater heat pumps were suggested for the metropolitan city.

Key words: ground and groundwater temperature, subsidiary groundwater monitoring wells, open-loop, Seoul, Korea

1. INTRODUCTION

There are numerous methodologies to use abundant natural resource as a renewable energy source in an efficient and environmentally friendly manner for heating and air conditioning industrial, commercial, institutional and residential structures (Boyce and Fitzsimmons, 2003). Ground and groundwater temperatures are ones of the alternative sources for the space heating and cooling (Lund, 1996; Zeng et al., 2003; Hahn et al., 2004; Lee et al., 2006). In some advanced countries, commercial and industrial use of this type energy can be traced up to early 1970s (Bloomquist, 1999). In January 2000, U.S. EPA (Environmental Protection Agency) announced that the geothermal heat pump (GHP or GSHP) is the most efficient and comfortable facility among all devices developed for spacing heating and cooling of residential houses and buildings (Hahn et al., 2004). However, earnest interest, research, commercial application

of the geothermal energy including groundwater heat, and financial incentive scheme have been initiated most recently in Korea (Hahn et al., 2004; Lee et al., 2006).

The ground and groundwater temperatures are substantially dependent on solar radiation (Rybach and Sanner, 2000). The radiated solar energy warms the near surface ground and this in turn warms the atmosphere and the underground (BSDUD, 1999). The surface temperatures penetrate into the ground with decreasing intensity and the penetration depth depends on thermal diffusivity of the ground (Koo et al., 2003). There is another form of surface heating originated from interior of the earth (decay of radioactive isotopes) but this form of heating is much weaker than the sun (BSDUD, 1999). Therefore, the near surface ground and shallow groundwater temperatures are dominantly affected by the exchange of heat between the sun, the earth's surface and the atmosphere, with a much smaller extent from the earth heat flow directed at the surface (BSDUD, 1999; Lee and Hahn, 2006). But below 15-20 m ground depth, atmospheric influences (solar radiation) are clearly negligible (Rybach and Sanner, 2000).

Lee and Hahn (2006) and Hahn et al. (2004) intensively analyzed the groundwater temperature data obtained from the Korean national groundwater monitoring stations (NGMSs). They analyzed distribution of groundwater temperature throughout the country, classified patterns of groundwater temperature variation and clarified months of highest and lowest temperature occurrence. They also asserted that stable groundwater temperatures, substantial phase difference compared with the air temperatures, and the shallow water tables are very attractive for application of the groundwater heat pumps (GWHPs) in the country. In addition, Lee et al. (2006) extensively examined other very important parameters of the NGMSs such as water levels, hydraulic conductivity, well yield, hardness, electrical conductivity, and other general water qualities influencing efficiency and maintenance of the groundwater heat pumps. From the study, they concluded that chemistries of most groundwaters in the country are suitable for water quality conditions for GWHPs although some proportions of the shallow and deep groundwaters exhibited scaling and corrosion potentials.

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This study focused on detailed examination of ground and groundwater temperature characteristics including spatial and temporal distribution, vertical variation with well depth and relationship between air and groundwater temperatures in the metropolitan city, Seoul, Korea. Based on this examination, some implications for practical application of the geothermal heat pumps in the urban area were drawn. For this study, groundwater data were obtained from 119 subsidiary groundwater monitoring stations (wells), installed and managed by the metropolitan government since 1997. In addition, ground and air temperatures data from KMA (Korea Meteorological Administration) for the city were examined. In the country, except for some mountainous areas, mean annual air temperatures ranged between 10 and 16°C for past 30 years (1971–2000) and it was the hottest (23–27°C) in August while it was the coldest (-6 – -7°C) in January (KMA, 2006). Therefore, space cooling is needed in the months of July–August and space heating is required for December–February (Song, 2004).

2. METHODS AND MATERIALS

The Seoul metropolitan government installed a subsidiary groundwater monitoring network composed of 119 monitoring wells in 1997, to monitor changes in quantity and quality of groundwater resources throughout the metropolitan city (Fig. 1). The locations of the monitoring wells were initially determined mainly considering groundwater use, recharge/discharge areas, reported water level declines and potential groundwater contamination sources (SMG, 1996; Lee et al., 2005). The subsidiary groundwater monitoring network supplements the national groundwater monitoring network managed by MOCT (Ministry of Construction and Transportation) and KOWACO (Korea Water Resources Corporation) since 1995 (Lee et al., 2005). Some of the monitoring wells (6.7%) were newly constructed but most of the wells (93.3%) is existing wells developed for emergency (SDI, 2000).

From each monitoring well, water level, water temperature and electrical conductivity are measured every hour

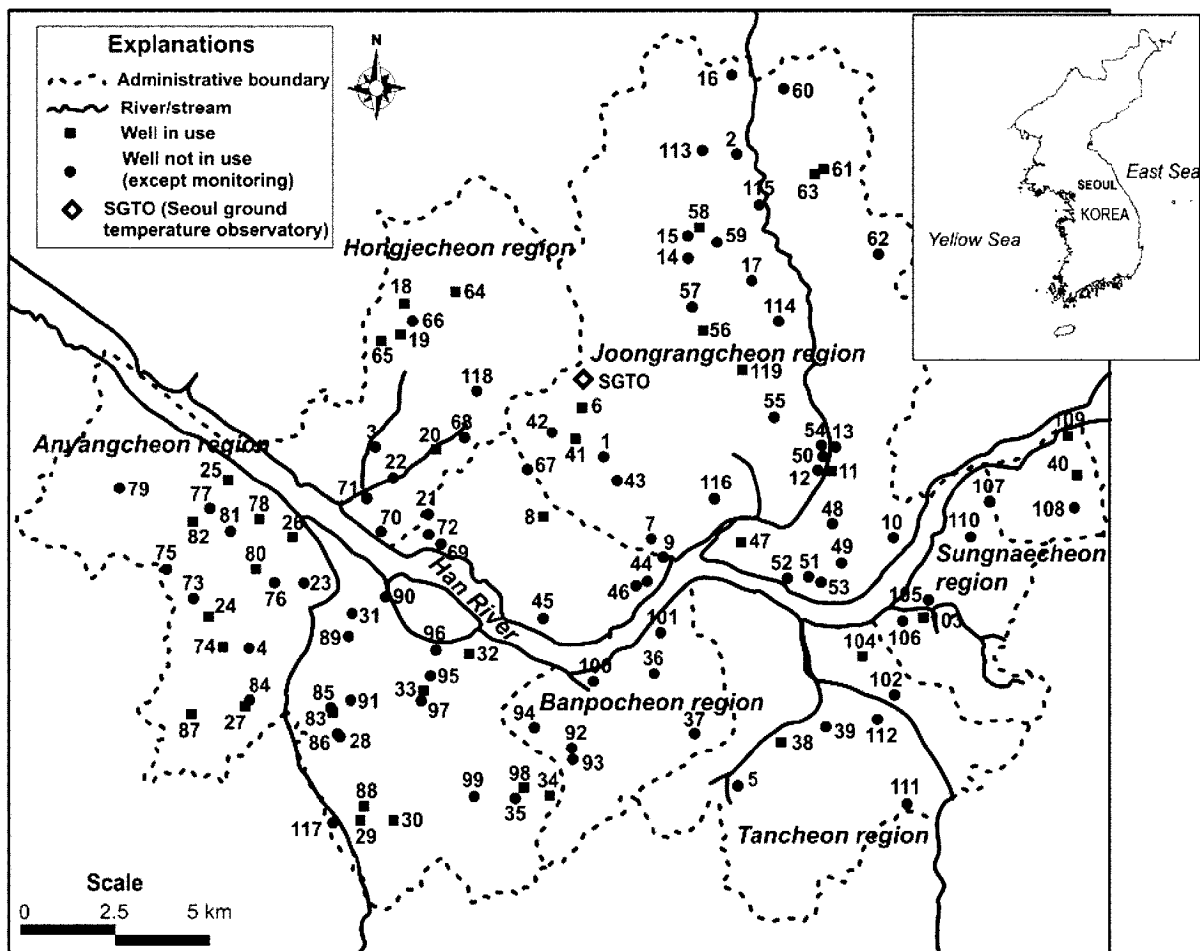


Fig. 1. Locations of groundwater monitoring wells in the Seoul metropolitan city. Numeric near the symbol indicates well identification number.

using an automatic measuring device. The collected data are automatically transferred to a host computer in the city hall by a modem. For accurate data acquisition and optimum maintenance, the monitoring station is regularly visited. The depths of the wells are much varying from 13 m to 150 m. The measurement depths (points) are also much varying between 12 m and 116.5 m below ground surface. For this study, groundwater data (especially groundwater temperatures and groundwater levels) for a period of 1 January to 31 December, 2001 were used. In addition, for the same period, data of air temperature and ground temperature (see measuring location, SGTO in Figure 1) at depths of 0.05, 0.1, 0.2, 0.3, 0.5, 1.0, 1.5, 3.0 and 5.0 m obtained from KMA were analyzed. To identify relationship between the air temperature and ground/groundwater temperature, a cross-correlation analysis was used (Lee and Lee, 2000).

3. RESULTS AND DISCUSSION

3.1. Ground Temperatures

Ground temperatures in the shallow subsurface are dominantly affected by the solar radiation (Lee et al., 2000). The solar energy entered into the unit area is large in the summer while it is small in the winter. Daily and seasonal variation of the ground temperatures generally occurs during the transport of the ground surface heat energy into the deeper subsurface (Kim et al., 2005). Because a basic mechanism of the heat transport in the subsurface is the conduction and its rate is much slow, phase difference (time shift) compared with the daily and seasonal variation of the air temperature will occur (Lachenbruch and Marshall, 1986; Beltrami, 2001; Smerdon et al., 2003; Kim et al., 2005).

Figure 2a shows daily ambient air temperatures and ground temperatures measured at depths of 0.05, 0.1, 0.2,

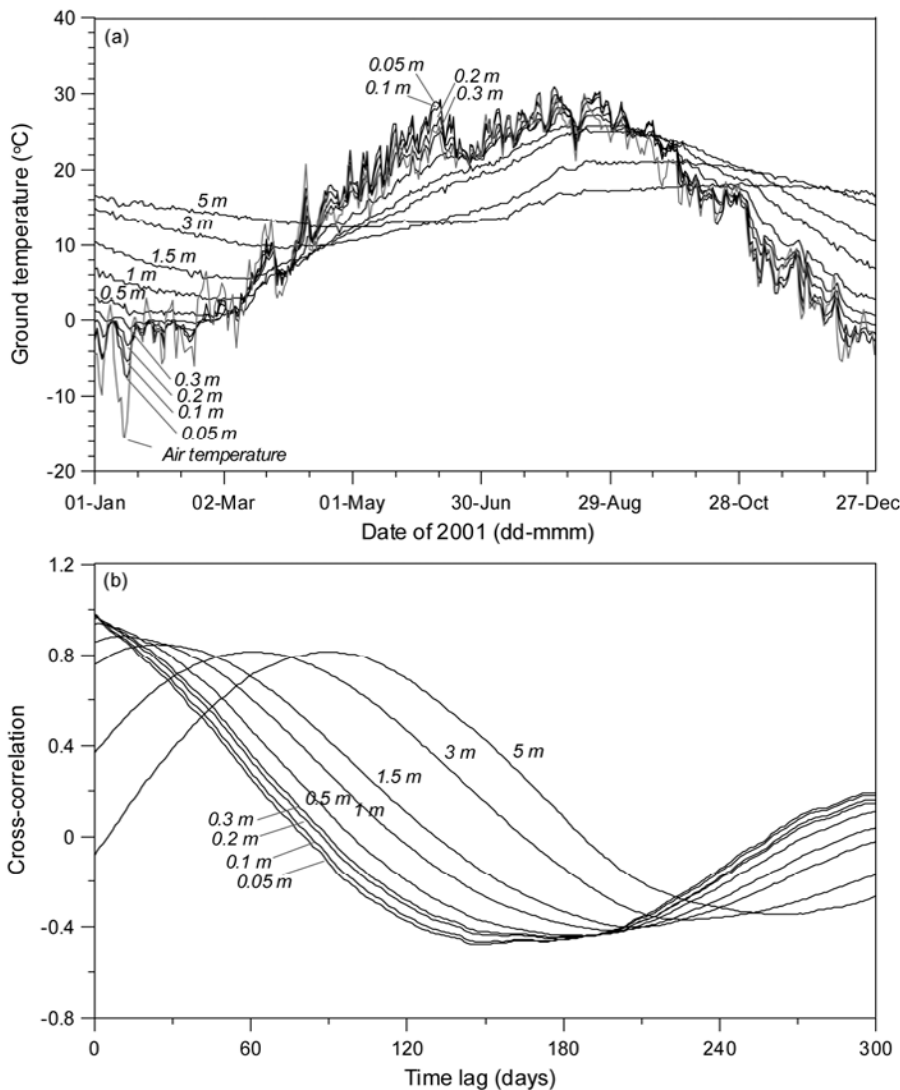


Fig. 2. Variation of ground temperatures with depth (a) and cross-correlation between air temperature and ground temperature (b).

Table 1. Summary of ground temperatures measured at the Seoul observatory (SGTO).

Ground depth (m)	Mean \pm SD	Highest temp. (a)	Date _{highest}	Lowest temp. (b)	Date _{lowest}	$\Delta T(a-b)$
Air	12.9 \pm 11.0	30.0°C	17-Aug	-15.5°C	15-Jan	45.5°C
0.05	13.7 \pm 11.4	30.9°C	03-Aug	-7.5°C	16-Jan	38.4°C
0.1	13.8 \pm 11.1	30.3°C	24-Aug	-5.5°C	16-Jan	35.8°C
0.2	13.8 \pm 10.5	29.6°C	24-Aug	-3.3°C	16-Jan	32.9°C
0.3	13.8 \pm 9.8	28.2°C	04, 23, 24-Aug	-1.1°C	17-Jan	29.3°C
0.5	13.9 \pm 9.2	27.6°C	05, 07-Aug	0.3°C	25-Feb	27.3°C
1.0	14.5 \pm 7.9	26.0°C	11-Aug	1.9°C	28-Feb	24.1°C
1.5	15.4 \pm 6.6	25.4°C	18-Aug	5.4°C	13-Mar	20.0°C
3.0	15.4 \pm 4.1	21.2°C	18, 21, 22-Aug	9.5°C	28, 30, 31-Mar, 01-Apr	11.7°C
5.0	15.3 \pm 2.1	18.3°C	29-Oct	11.5°C	25-Apr	6.8°C

0.3, 0.5, 1.0, 1.5, 3.0 and 5.0 m in the Seoul ground temperature observatory (see the measurement location, SGTO in Fig. 1). The very shallow ground (0.05–0.3 m) and air temperatures showed fluctuations with a high frequency and a large amplitude. The amplitude (maximum–minimum) of the annual temperature variation ranged between 29.3°C (0.3 m) and 45.5°C (air) (Table 1). Like the air temperature, the ground temperatures at these depths were the highest in August and they were the lowest in January. Mean annual ground temperatures (13.7–13.8°C) were slightly greater than the mean air temperature (12.9°C). Below the depth of 0.5 m, the ground temperature fluctuation and its amplitude were largely decreased. As the ground depth increases, the ground temperatures in the cold seasons (October–March) increase while those decrease in the hot seasons (May–September). At the depth of 5 m, the ground temperature is higher than the air temperature by 19.8°C in January while the former is lower than the latter by 9.5°C in August. Furthermore, dates when the lowest temperatures occurring are shifted from February to April. As the ground depth increases, the mean annual ground temperatures gradually increase and the annual variations are greatly reduced (see Table 1). The phase difference between the ambient air temperature and the ground temperatures can be identified using a cross-correlation analysis between them (Fig. 2b). As the ground depth increases, the cross-correlations were not largely reduced but the phase difference significantly increased. To the depth of 0.3 m, no substantial phase difference (lag time) was observed and it indicated nearly simultaneous synchronization of the ground temperatures in association with the variation of the air temperature. Below the depth of 0.5 m, noticeable time lags were found and they range between 11 days (1.0 m) and 89 days (5 m).

Auto-correlation and spectral density can give information on degrees of inter-dependency of successive values and duration of a preceding signal (Angelini, 1997; Larocque et al., 1998). The quantitative values used in this study are the time lag (time at zero auto-correlation is attained) and the regulation time (see Lee and Lee, 2000). The regulation

Table 2. Results of auto-correlation analysis of air and ground temperatures at SGTO.

Ground depth (m)	Time lag (auto-correlation=0)	Regulation time (days)
Precipitation ^a	4 days	2.6
Air temp.	84 days	24.1
0.05	81 days	22.6
0.1	82 days	23.9
0.2	83 days	26.6
0.3	84 days	28.3
0.5	87 days	33.9
1.0	93 days	45.2
1.5	97 days	54.1
3.0	104 days	66.2
5.0	98 days	55.5

^aData of daily precipitation is for comparison and reference purpose

time, obtained from the spectral density function defines the duration of the influence of the input signal and gives an indication of the length of the impulse response of the concerned system (Larocque et al., 1998). Table 2 shows the time lags and the regulation times of the air and the ground temperatures signals. As expected, the temperatures showed excellent inter-dependency among the successive values, which resulted in substantial lag times ranging from 81 to 104 days. Compared with data of precipitation generally regarded as random variable, the air and ground temperatures showed much longer memory effects.

The annual temperature variation exponentially decreases with depth (Smerdon et al., 2003). From the simple regression of the exponential function (actually the inverse of it in this figure, logarithmic function; Fig. 3a), a depth showing practically no variation was estimated as about 15 m. The variation of the solar radiation does not affect the ground temperatures below this depth. As previously described, the phase difference would occur with ground depth. The time shift estimated from the cross-correlation is linearly propor-

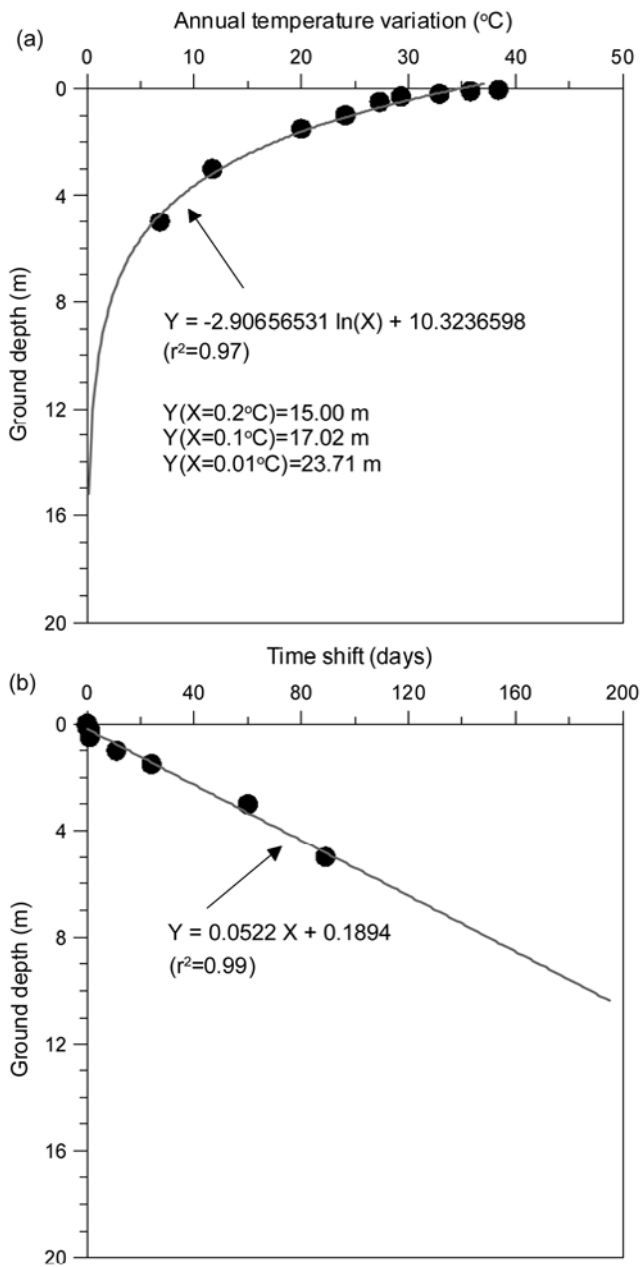


Fig. 3. Vertical profile of annual ground temperatures variation (maximum-minimum temperatures) (a) and time shift with depth (b).

tional to the ground depth (Koo et al., 2003). According to the linear regression (Fig. 3b), the time shift increases by 19.2 days with unit increase (1 m) of the ground depth. The phase difference of about 180 days (half a year) implies completely inverse relationship between the air temperature and the ground temperature, which would be attained at a depth of 9.6 m in this case. At this depth, the annual temperature variation would be 0.78°C (see Fig. 3a). Intuitively, the complete inverse relationship between the air temperature and the ground temperature appears the most promising for application of the geothermal heat pumps

(especially ground-coupled types; Lee and Hahn, 2006) because the higher is the ground temperature, the better is the efficiency of the system in the winter and vice versa in the summer (i.e., COP; Hahn et al., 2004; Yasukawa et al., 2004; Lee et al., 2006). However, the minimum annual temperature variation (in this case 0.78°C) would mask the benefit of the attained lag times. But the stable ground temperature would maximize efficiency of the system maintenance because the system is initially optimized to a certain specific ground or groundwater temperature (Lee and Hahn, 2006).

3.2. Groundwater Temperatures

Figure 4 shows spatial distribution of mean annual groundwater temperatures in the metropolitan city. The mean temperatures ranged between 12°C and 19°C (average = 15°C). In the Joongrancheon region, some higher mean temperatures were found. Superficially the mean temperatures in the upper half of the city (above the Han River) appear higher than those in the lower half region but the difference is not statistically significant ($p < 0.05$). Consequently the spatial distribution does not show any interpretable geographical implication.

Monthly mean groundwater temperatures are presented in Figure 5. Apparently the monthly mean temperatures are much similar to the ambient air temperatures without any significant lag time. The temperatures are the highest in the summer (August–September) and they are the lowest in the winter (December–February). This is very different from the variation behavior of the groundwater temperatures obtained from the Korean NGMSs (Lee and Hahn, 2006; Lee et al., 2006). In the NGMSs, a large proportion of the shallow and deep monitoring wells showed substantial phase differences of 4–8 months compared with the air temperatures. The objective of the NGMSs was to monitor long-term variation of groundwater quantity (water level) and quality throughout the whole country. Consequently, substantial numbers of the NGMSs are located in areas where artificial or anthropogenic effects are hardly to reach and corresponding proportion of them showed natural and typical groundwater temperature variation with season (Lee and Hahn, 2006). However, the groundwater (or groundwater temperature) of the Seoul metropolitan city is expected to be influenced by various human activities with varying degree (e.g., BSDUD, 1999; Kinouchi, 2003; Ferguson and Woodbury, 2004). Somewhat elevated groundwater temperatures of the city may reflect effects of artificial origin including air temperatures or warm water leaked from various sources in the metropolitan city (i.e., heat island effect; Song, 2004). Nevertheless, the median values (15.0°C) and ranges of the first (14.5°C) and third quartiles (around 15.7°C) were nearly the same throughout the year (2001). The most stable temperatures are very beneficial for extracting heat from the

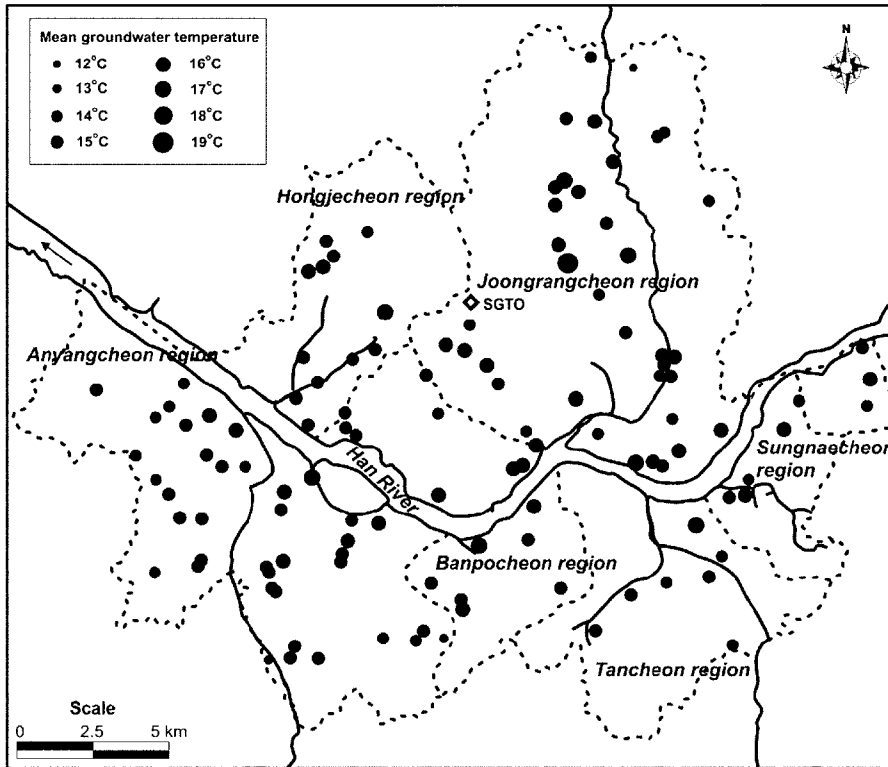


Fig. 4. Spatial distribution of annual mean groundwater temperatures for 2001.

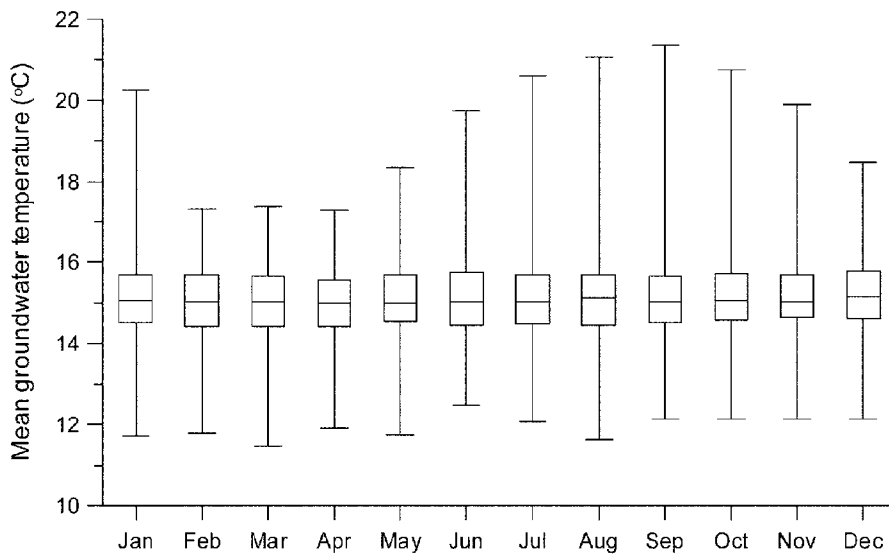


Fig. 5. Variation of monthly mean groundwater temperatures.

groundwaters (Woo, 2003).

Temperatures of most groundwater wells are very stable showing minimal annual amplitude of variation (Table 3). Over 70% of the wells showed an annual temperature variation less than 1°C and about 80% showed the variation within 2°C. Only 6% showed the variation greater than 5°C. Figure 6 shows temperature time series at some selected wells showing noticeable seasonal variation. Although the variation appeared very different each other and somewhat irregular or even erratic, some general trends may be observed.

The groundwater temperatures were low in March-July (warm or hot season) while they were high in September-December (cool or cold season). This means some phase differences of a few months compared with the air temperatures. The groundwater temperatures of these wells showed high correlation with the air temperatures with some lag times (Table 4) while the other wells did not any substantial correlation (data not shown).

Considering the phase differences (time shifts) observed from the cross-correlation between the air temperature and

Table 3. Annual variation (maximum-minimum) of groundwater temperatures.

Annual variation	No. of wells	Proportion (%)	Cumulative (%)
<1°C	84	70.6	70.6
1–2°C	10	8.4	79.0
2–3°C	7	5.9	84.9
3–5°C	11	9.2	94.1
>5°C	7	5.9	100.0

the ground temperature (see Fig. 3b), rather small time shifts (21–84 days) of the groundwater temperatures at the monitoring wells (Nos.: 8, 28, 56, 106) appeared unexpected. Some longer time shifts were initially expected because the monitoring depths are relatively deep (average=36.2 m), the mean water levels (depths to water) were not very shallow (average=17.2 m, bgs) except for the well, no. 8, and the time shift of the ground temperature was 89 days at the depth of 5 m (see Fig. 3b). As expected, the values of the

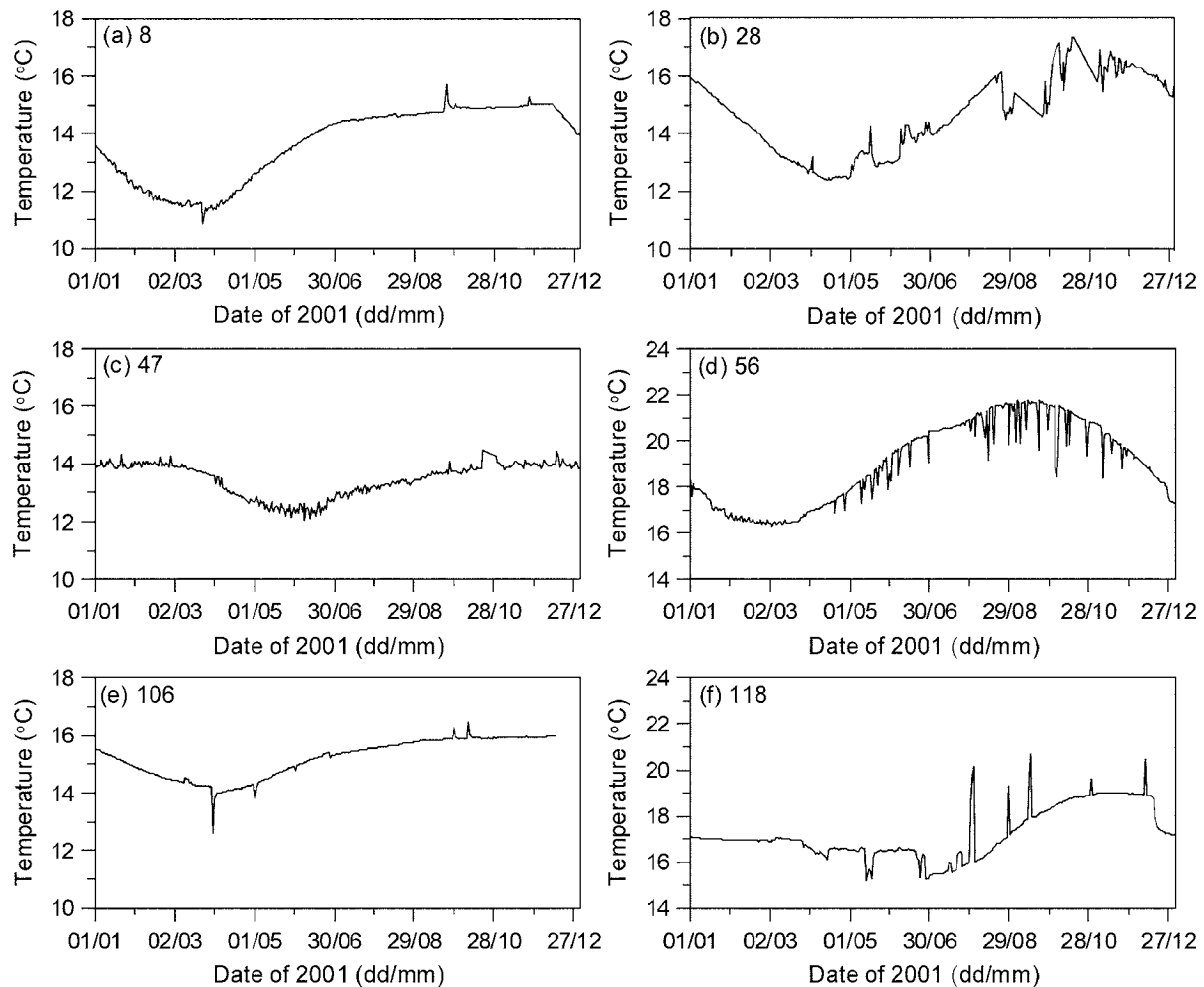


Fig. 6. Groundwater temperature variation at some selected wells (see Table 4 for detailed information on the stations).

Table 4. Cross-correlation between air temperature and groundwater temperature for some selected monitoring wells.

Well no.	Peak correlation	Time shift* (days)	Mean W.L. (m, bgs)	Monitoring depth (m)	Mean water column (m)
8	0.780	50	2.38	21.0	18.62
28	0.777	84	10.15	34.5	24.35
47	0.704	111	6.21	71.1	64.89
56	0.816	21	34.49	44.95	10.46
106	0.789	63	7.10	44.2	37.10
118	0.682	114	3.90	30.5	26.60

*Phase difference at which the peak cross-correlation is attained

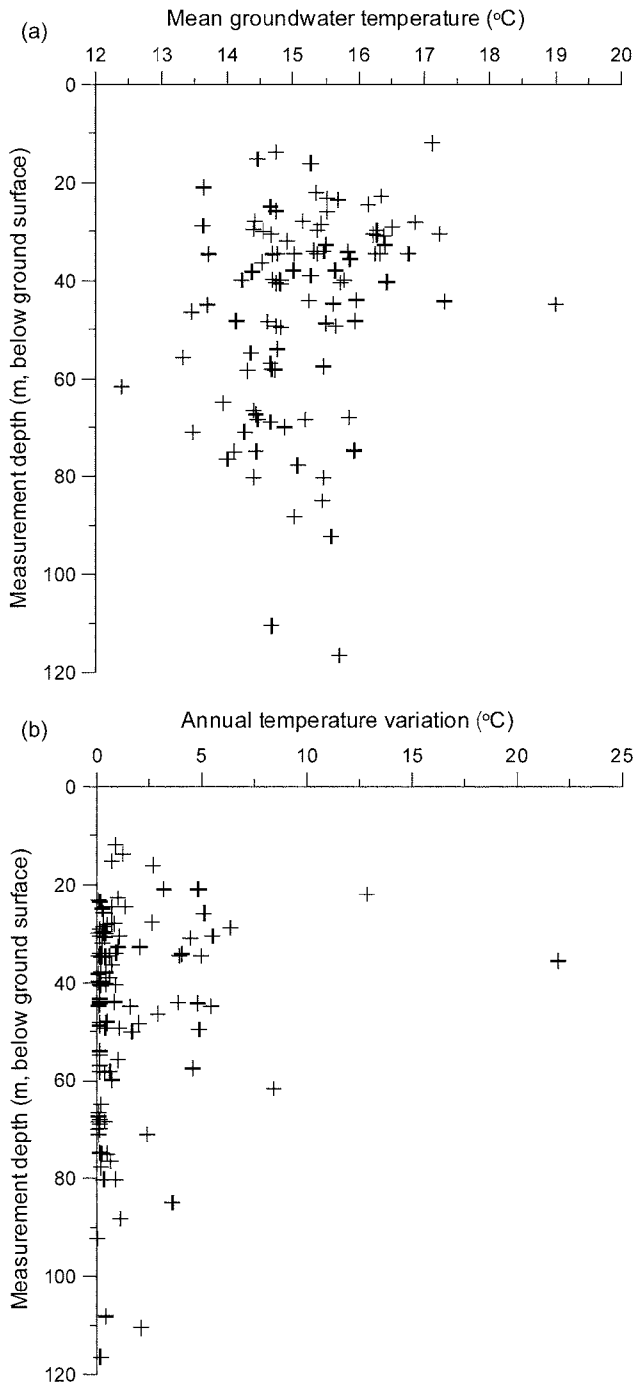


Fig. 7. Mean groundwater temperatures (a) and annual variation (b) with measuring depth.

peak correlation are closely negatively related to the time shifts ($r^2=0.85$; see Table 4). The peak correlations ($r^2=0.05$) and the time shifts ($r^2=0.08$) are not considerably related to the measuring depths (probe locations below ground surface). Both the correlations and the time shifts are meaningfully related to the mean water levels and the lengths of water column above the measuring probe ($r^2=0.33-0.46$).

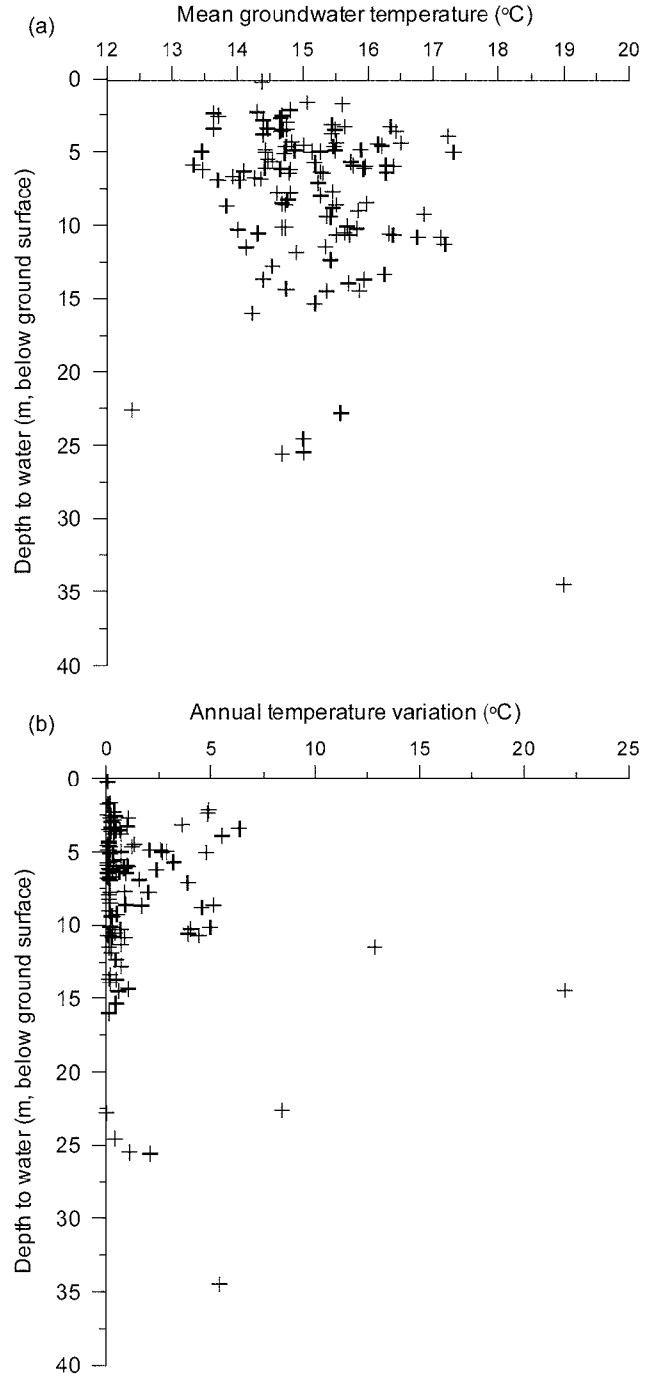


Fig. 8. Relationship between depth to water and groundwater temperatures (a) and annual variation (b).

The examination was extended to all the monitoring wells. Figure 7 shows distribution of the annual mean groundwater temperatures and the annual temperature variation with the measurement depths. The mean groundwater temperatures show a slightly decreasing trend with the measuring depth but the negative correlation is not statistically large ($r=-0.21$, $p=0.009$). Also the annual variation of the

groundwater temperatures was not largely correlated with the measuring depth ($r=-0.14$, $p=0.146$). Figure 8 shows relation between the water levels (depth to water below ground surface), and the mean groundwater temperature and annual temperature variation. The water levels showed some erratic positive correlation with the mean temperatures although the relation is not statistically significant ($r=0.19$, $p=0.038$). In addition, the water levels do not show any sub-

stantial correlation with the annual temperature variation ($r=0.15$, $p=0.028$). Figure 9 shows correlation of the mean lengths of the water column above the measuring point with the mean groundwater temperatures and the annual variation. The mean groundwater temperature is negatively correlated with the water column length ($r=-0.30$, $p=0.001$) and the annual variation is also negatively correlated to the water column length ($r=-0.24$, $p=0.035$).

Among the three variables (the measuring depth, the water level, and the water column length), the water column length appeared the most important factor influencing the annual mean groundwater temperatures and the annual variation. It may reflect relatively fast heat transfer from the ambient air in the monitoring well to the groundwater near the water table instead of heat conduction through the surrounding soil, which is also evidenced by the smaller phase differences with the air temperature (see Table 4). So the previous spatial distribution of the mean groundwater temperatures may be also related to this water column length and so the observed groundwater temperatures in the monitoring wells may be only apparent temperatures.

3.3. Engineering Implications for Geothermal Heat Pumps

In the above, some characteristics of the ground and groundwater temperatures in the metropolitan city were examined. With minimal variations, the ground temperatures at the depth of 3.0-5.0 m are stably maintained around 15°C throughout the year. Below 15 m, the ground temperature would not be affected by the air or near surface temperature. Furthermore, the groundwater levels are very shallow (average±standard deviation=7.91±5.49 m) and the groundwater temperatures are also very stable near 15°C. All these hydrogeologic conditions are promising for the geothermal heat pumps.

In densely populated metropolitan area like Seoul, there does not exist sufficient space for horizontal ground-coupled (close loop) system (Meng, 2003). Even in the vertical loop system, 1 ton (3,517 W) requires 0.0254 m (1 inch) vertical hole of 50 m depth, in which U shape or coaxial typed heat exchange pipe is installed (Hahn et al., 2004). 1 RT (simply ton) is can be the power required to cool 1 short ton of water by 1°F every 10 minutes. In consideration of long maintenance of the system, the distance of 5 m between the vertical pipes should be maintained and consequently in case of 5 tons building (17,585 W), at least ground surface area of 5 m × 25 m is required (Woo, 2003). Furthermore thickness of unconsolidated soil layers in most metropolitan area is less than 5 m except for the surroundings of the Han River (Kim, 2000; Lee et al., 2005), which increase the installation costs. These practical limitations would restrict widespread installation of the ground-coupled systems in the metropolitan area.

Under some conditions, groundwater (open loop) systems

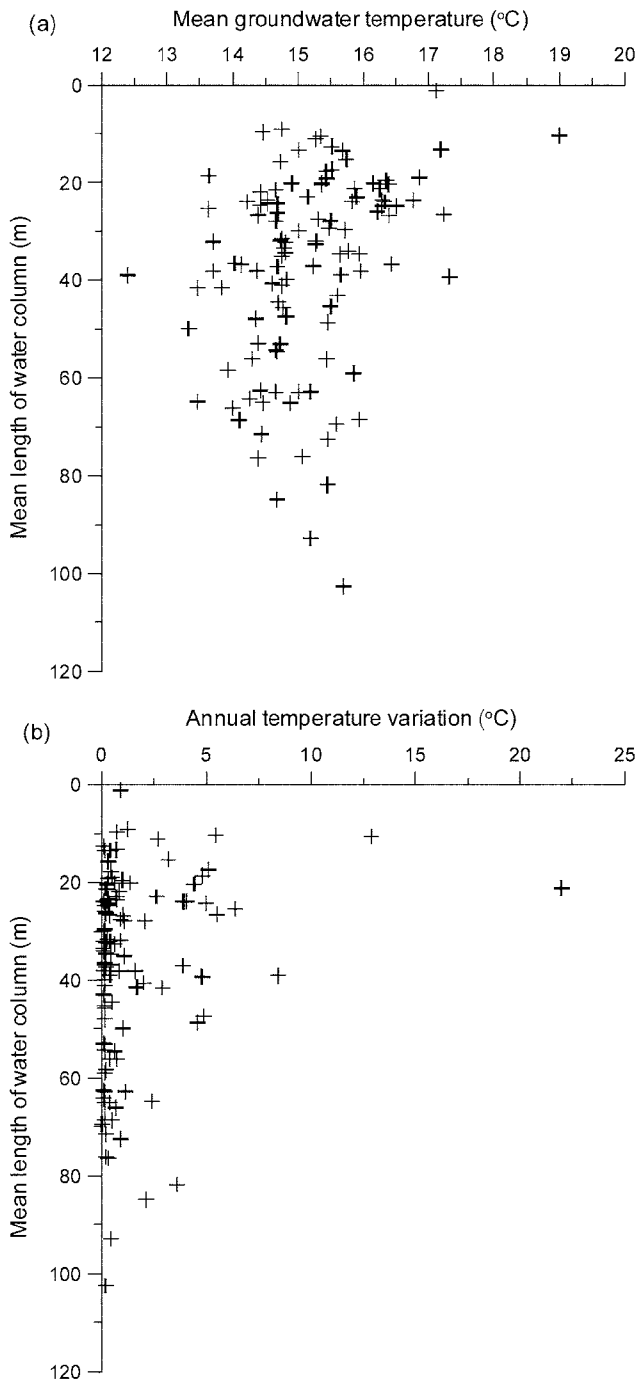


Fig. 9. Relationship between length of water column and groundwater temperatures (a) and annual variation (b).

can offer system performance superior to the ground-coupled systems (Rafferty, 1998). The number of groundwater wells was 18,840 in 1995 in the metropolitan city (SDI, 1995; Kim, 2000), which corresponds to 31 wells/km². Therefore, new construction for the production well of the open loop system would be limited by using the existing wells. The average production rate of all these wells was over 30 m³/day (Kim, 2000). But for deeper wells (average depth=96.1 m), the average pumping rate was 148.2 m³/day (Hahn, 1997). Groundwater would yield 36,479 BTU/hr (10,688 W) from groundwater of 15°C (59°F for the metropolitan city) with a rate of 4.5 gpm by lowering 9°C (16.2°F×8.34 BTU/gal×4.5 gpm×60 min). In case of a general residential house with a target area of 223–316 m² (67–96 pyeong) and a heat loss of 60,000 BTU/hr (17,580 W) (under intermediate insulation condition), a geothermal heat pump of 5 tons is generally required (NowBatu, 2004; Polar Bear Geo Thermal Systems, 2006). For the heat gain from the groundwater of 15°C (in this case), a pumping rate of 7.4 gpm (20.1 m³/12 hrs/day) is enough for the heat pump (generally assuming heat pump operation for 12 hrs per day). This pumping rate does not produce any substantial drawdown in the production well. In consideration of the specific capacity (average=18.6 m³/day, estimated from transmissivity data (Kim, 2000) using Jeon et al. (2005)'s equation ($T=0.52(Q/s)^{0.953}$) of the wells in the city, the pumping drawdown will be restricted within 4 m. This pumping depth (static water level 7.91 m+the drawdown 2.17 m=10.08 m) requires only a groundwater pump of less than 0.20 hp (149 W) (Rafferty, 1998; Lee et al. 2006). Furthermore, during the time of the day in which groundwater is not used for the heat pump, the groundwater may be used for other purpose (waters for living). Or the groundwater used for the heat pump (6°C) can be additionally used.

4. SUMMARY AND CONCLUSION

Characteristics of ground and groundwater temperatures in the metropolitan city, Seoul, were examined. The ground temperatures were stable below 3.0 m depth with annual minimal variation and they were averagely 15°C. The annual mean groundwater temperatures were 15°C and most of the wells showed the annual variation within 3°C. All these temperature conditions appeared very promising for the application of the geothermal heat pumps. But the limitation of available space for the buried pipes (loops) and the thin unconsolidated soil layer in the metropolitan area would restrict the practical application of the closed loop systems. Consequently the open systems can be beneficial. A large number of the existing wells and the shallow water levels may enhance efficiency of the system maintenance.

In this study, various natural and artificial factors affecting the ground and groundwater temperatures were neglected. They include rainfall, soil moisture, soil particle size, and

artificial heat sources in the metropolitan city (Koo et al., 2003; Kim et al., 2005). More quantitative analysis of the effects of these factors on the ground/groundwater temperatures deserves a further study. For practical application of the groundwater heat pumps in the metropolitan city, some pilot operations for some years are essentially required.

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