Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

Suitable Areas for Geothermal Heat Pumps Inferred from Geological and Hydrological Features: a Case Study in the Nobi Plains, Central Japan

Tomoyuki Ohtani, Kohji Kamiya and Satoru Kojima

Dept. Civil Engineering, Gifu University, 1-1 Yanagido, Gifu 501-1193 Japan

tmohtani@gifu-u.ac.jp

Keywords: Geothermal heat pumps, suitable areas, geology, hydrology

ABSTRACT

Distribution of the suitable areas of the Geothermal Heat Pump system is studied. For the closed loop system, the distribution of the Darcy velocity of groundwater flow in aquifers in the Nobi plain is estimated. The velocity of groundwater flow is calculated from hydraulic gradient and permeability coefficient of aquifers. Distribution of hydraulic gradient is estimated from interpolated distribution of water table of wells using kriging. In the most part of the alluvial fan area, the gravel is dominant in the formation and the velocity is $>10^{-6}$m/s. In the southwestern area, the velocity is $\leq 6.3\times10^{-7}$m/s. This difference of groundwater velocity would affect effective heat conductivity of formations and heat transfer under the ground. For the open loop system, distributions of aquifers and groundwater yields are studied using a well database to evaluate the potential installation of the open loop systems in the Nobi plain of Gifu prefecture. The distribution of two aquifers is deduced from that of well screens, and these are getting deep gradually toward the south. The distribution of the groundwater yields indicates that the open loop systems using pre-existing wells have a potential installation in the whole of the study area. The distribution of the groundwater yields drawn from the aquifers shallower than 50m depth shows that the northern part of the study area is a suitable area for the installation of the open loop systems with a well drilling. The potential installation of the open loop systems using the groundwater drawn from the total depth and shallower than 50m depth are 52.9% and 26.0% for the houses in the study area, respectively. These results suggest that the study area has a large potential for the installation of the groundwater heat pump systems.

1. INTRODUCTION

The geothermal heat pump systems (GeoHP) are largely divided into two types; open loop systems which exchange heat from pumped up groundwater and closed loop systems which exchange heat in the heat exchanger(s) installed in the underground. Since the most of urban areas in Japan have experienced severe land subsidence, groundwater use is regulated and open loop systems must not be installed in these areas. As the horizontal type, heat exchange(s) is installed horizontally in the shallow depth, needs large space for their installation, it is difficult in Japan. Therefore, the vertical type of the closed loop systems is possible to install in the most of urban areas in Japan.

Shortening the length of heat exchanger is important in the economical aspect, as the initial installation cost, especially drilling cost, is high in Japan. Niibori *et al*. (2002) clarified that the length of heat exchanger can be shortened due to heat convection in the area of $>10^{-5}$m/s of groundwater flow. Niibori and Nakagome (2005) reported that the length of heat exchanger can be shortened in the area of $>10^{-6}$m/s of groundwater flow, because the underground thermal condition returns to the initial condition after one year in the area of $>10^{-6}$m/s. In contrast, it is estimated that > 50% of stored heat energy will be recoverable in the area of $\leq 6.3\times10^{-7}$m/s of groundwater flow (New Energy and Industrial Technology Development Organization, 2000). As described above, the groundwater flow effect on heat extraction has been understood by previous studies. Therefore, it is possible to study where is good areas for the GeoHP use based on these understandings.

Although the pumping up of groundwater is regulated in most of large cities as mentioned above, it is allowed in some cities where are little risk for a land subsidence. To install the open loop system economically, shallower aquifers enable us to decrease the length of boreholes and initial cost of GeoHPs. Many well information is stocked in the areas where plenty of groundwater is pumped up, and this information can be used for understanding the aquifer structure. Groundwater yields of well information can be used for estimating a potential of the open loop systems.

In this paper, the distribution of groundwater velocity based on geological and hydrological data and suitable area selection for the closed loop system of GeoHP are described. To examine suitable area selection for the open loop system, depth distribution of the shallowest aquifer and groundwater yields from pre-existent wells are also described.

2. CHARACTERICTICS OF STUDY AREA

The Nobi Plain, one of the largest plain in Japan, is selected as a study area for this study. As this area has been experienced severe land subsidence from the 1950s to 1970s, the geological and hydrological data are well collected. The southern area of the Nobi Plain is that the groundwater use is strictly regulated, while the northern area is basically not.

Geology and hydrology in the Nobi Plain is well described by Subsidence Survey Committee in Tokai Region (1985). The pre-Tertiary basement rocks have subsided deeper than 2 km, and younger sedimentary layers cover the basement (Figure 1). The basement consists of the Jurassic accretional complex and the late Cretaceous to early Paleogene granitic rocks. These are displaced vertically along the Yoro-Isewan fault, which is along the western margin of the plain, and the top of the basements is very deep in the eastern side of the fault. The deeper sedimentary layers covering on the basements are more inclined, while the shallower layers are less. The deeper and shallower sedimentary layers contact with the basement in the western margin of the plain and their boundary is the Yori-Isewan fault. This suggests that the basements of the plain have been inclined during the sedimentation.

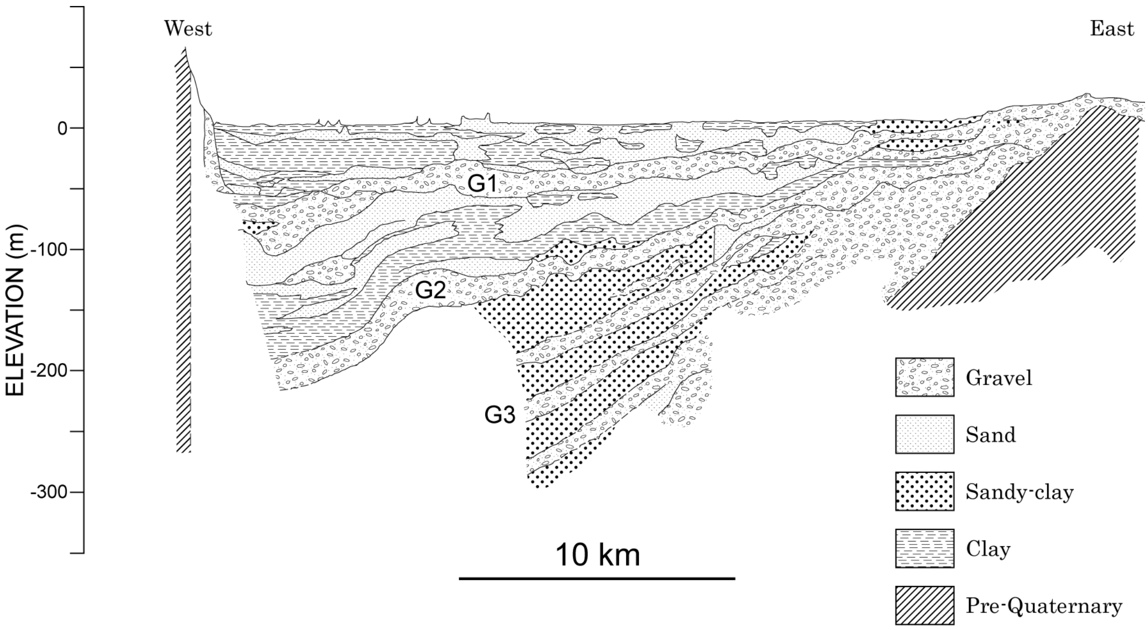

Figure 1: Hydrogeological cross section of the Nobi plain (revised from Subsidence Survey Committee in Tokai Region, 1985). G1, G2 and G3 are aquifers.

Most of the top of the Nobi plain is comprised of the Quaternary layers,and the urban areas are generally located on these layers. Therefore, the shallower depth of the urban areas mainly consist of the Quaternary and unconsolidated layers.

Main aquifers of the Nobi plain are the G1, G2 and G3 aquifers; the G1 aquifer is the shallowest, and the G3 is the deepest (Figure 1). The upper depth and layer thickness distributions are already clarified by Subsidence Survey Committee in Tokai Region (1985). The top depth of the basement rocks is shallower in the northern and eastern areas and deeper in the southern and western areas. Each aquifer also becomes deeper from northeast to southwest. The top depth of the G1 aquifer, the shallowest one, is shallower than 10 m in the northern and eastern areas, while it is deeper than 50 m in the southwestern area (Figure 2a). Its layer thickness is more than 20 m below the large rivers in the western area, and more than 40 m in a part of the northern area (Figure 2b). The rate of gravel layers is more in the northern area (Figure 2c).

3. ESTIMATION OF GROUNDWATER VELOCITY BASED ON WELL INFORMATION

The distribution of groundwater velocity in the study area is estimated from geological and hydrological data. To estimate it, the distributions of hydraulic head and Darcy velocity of groundwater on each aquifer are calculated from water tables of wells. A geographical information system (GIS) software ESRI ArcGIS 9.1 is used for calculation, and altitude data is from the digital map 50m grid (elevation) published by the Geographycal Survey Institute. Geological and hydrological data is input in the GIS software, and unknown values for any geographic point data is predicted by interpolation. The Darcy velocity of groundwater is calculated from the slope of hydraulic head distribution on the assumption of permeability coefficient, which is presumed as a constant value 10^{-3}m/s in each aquifer based on the results of pumping test (Figure 3). In this study, groundwater flow is supposed to be horizontal and limited only within the aquifers.

Two kinds of well information are used; one is that of the wells monitoring water table and the other is the wells registered to the database of the ministry of Land, Infrastructure, Transport and Tourism. The wells monitoring water table are well spread in the study area, and monitor the water table continuously. But the number of the monitoring wells is limited and those are very few in the alluvial fans. The number of the wells registered to the database of the ministry of Land, Infrastructure, Transport and Tourism is enough to study, although the data quality of well information registered the database is not accurate rather than that of the monitoring wells. The well data registrated to the database in the northwestern part are added to supplement the well information in the alluvial fan area.

The hydraulic head distribution is estimated from interpolation of hydraulic head data using ArcGIS 9.1. Kriging is used for this interpolation. Kriging is one of the geostatistical methods, and it is based on statistical models that include autocorrelation – the statistical relationship among the measured points. Because of this, not only do these techniques have the capability of producing a prediction surface, but they can also provide some measure of the certainty or accuracy of the predictions.

Kriging is weights the surrounding measured values to derive a prediction for an unmeasured location. The general formula for both interpolators is formed as a weighted sum of the data:

$$\hat{Z}(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i) \tag{1}$$

where $Z(s_i)$, λ_i, s_0, N are the measured value at the *i*th location, an unknown weight for the measured value at the *i*th location, the prediction location, the number of measured values, respectively.

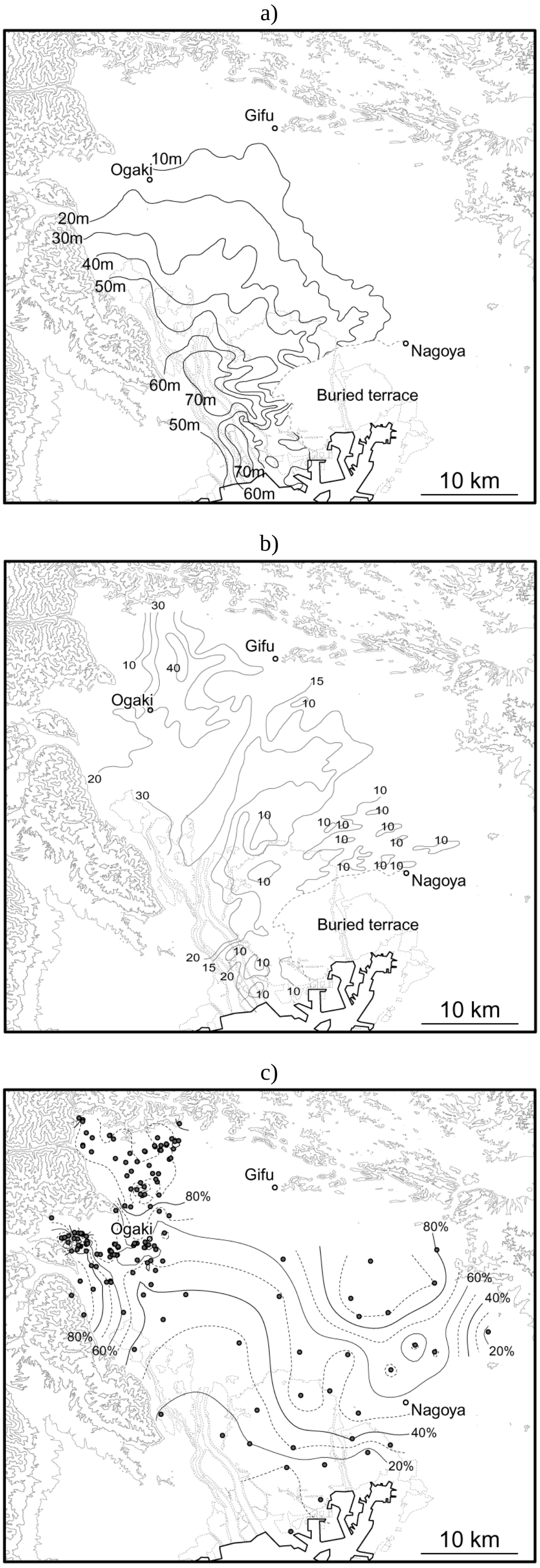

Figure 2: a) Upper depth and b) layer thickness of the G1 aquifer (revised from Subsidence Survey Committee in Tokai Region, 1985). The numbers in b) indicate layer thickness (meter). c) The ratio of gravel thickness to borehole length. Gray broken and thin lines indicate altitude of 0 and 100m, respectively. Gray bold lines are altitude of 200 m interval. Solid circles are studied boreholes.

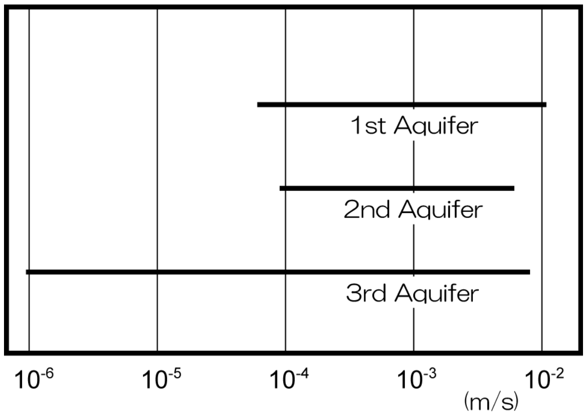

Figure 3: Permeability coefficient calculated from pumping tests (Subsidence Survey Committee in Tokai Region, 1985).

In spatial modeling of the structure of the measured points, we begin with a graph of the empirical semivariogram $\hat{\gamma}(h)$, computed as:

$$\hat{\gamma}(h) = \frac{1}{2|N(h)|}\sum_{N(h)}(\mathrm{Z}(\mathrm{s}_i) - \mathrm{Z}(\mathrm{s}_j))^2 \qquad (2)$$

where h, $|N(h)|$ are distance, the number of all parts of locations separated by distance h, respectively.

The next step is to fit a model to the points forming the empirical semivariogram. This study chooses the following functions to model the empirical semivariogram: Spherical, Exponential and Gaussian. These models are as follows:

The Spherical model

$$\gamma(h) = c_0 + c\left\{\frac{3}{2}\left(\frac{h}{a}\right) - \frac{1}{2}\left(\frac{h}{a}\right)^3\right\} \quad (h \le a)$$

$$= c_0 + c \qquad (h > a) \; (3)$$

The Exponential model

$$\gamma(h) = c_0 + c\left\{1 - \exp\left(-\frac{h}{a}\right)\right\} \qquad (4)$$

The Gaussian model

$$\gamma(h) = c_0 + c\left[1 - \exp\left\{-\left(\frac{h}{a}\right)^2\right\}\right] \qquad (5)$$

where $c_0 + c$, a, c_0 are sill, range and nugget, respectively. To compare these models, the root-mean-square prediction errors on the differences between the measured value at a location and the value predicted from the surrounding measured values if no measured value is at same location is calculated:

$$\left(\hat{Z}(s_i) - z(s_i)\right)_{\mathrm{rms}} = \sqrt{\frac{\sum_{i=1}^{n}\left(\hat{Z}(s_i) - z(s_i)\right)^2}{n}} \qquad (6)$$

The result of the above calculation shows that the Gaussian model is minimum on the root-mean-square errors, and this is applied to fit a model to the points forming the empirical semivariogram.

Table 1. Root-mean-square prediction errors of Spherical, Exponential and Gaussian models for each aquifer.

	Spherical	Exponential	Gaussian
G1 aquifer	3.01	3.22	2.59
G2 aquifer	3.01	3.25	2.12
G3 aquifer	1.29	1.53	1.39
NW area	2.88	2.88	3.50
Average	2.55	2.72	2.40

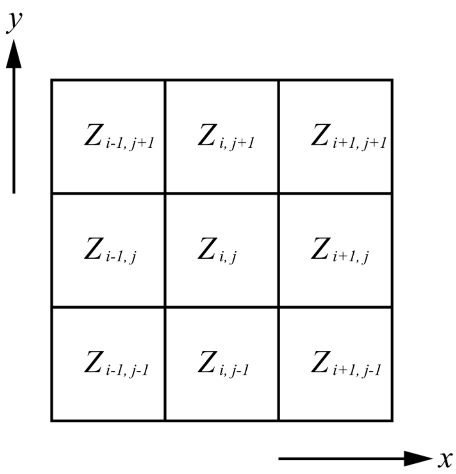

Figure 4: Cells to be used for the calculation of slope of hydraulic head distribution (Burrough, 1990).

The predicted values of the hydraulic head are in cells in raster. When cells are arranged in Figure 4, the slope G (%) on cell (*i,j*) is as follows:

$$G(i, j) = \sqrt{\left(\frac{\delta z}{\delta x}\right)^2 + \left(\frac{\delta z}{\delta y}\right)^2} \quad (7)$$

$$\left[\frac{\delta z}{\delta x}\right]_{i,j} = \frac{Z_{i+1,j+1} + 2Z_{i+1,j} + Z_{i+1,j-1}}{8\delta x} - \frac{Z_{i-1,j+1} + 2Z_{i-1,j} + Z_{i-1,j-1}}{8\delta x} \quad (8)$$

$$\left[\frac{\delta z}{\delta y}\right]_{i,j} = \frac{Z_{i+1,j+1} + 2Z_{i,j+1} + Z_{i-1,j+1}}{8\delta y} - \frac{Z_{i+1,j-1} + 2Z_{i,j-1} + Z_{i-1,j-1}}{8\delta y} \quad (9)$$

where δx, δy are intervals of cells along x- and y- axes, respectively.

The estimated hydraulic head distributions of each aquifer are shown in Figure 5. That of the G1 aquifer is a range of –5m to 10m in most of the study area, and it becomes higher toward the northeastern area (Figure 5a). That of the northeastern area is from 0m to 35m, and it becomes higher toward the upstream area of the alluvial fan. That of the G2 aquifer is a range of –5 to 15m, and it also becomes higher toward the northeastern part (Figure 5b). That of the G3 aquifer is from –5m to 10m, and it becomes higher gently toward the northern part (Figure 5c).

The estimated Darcy velocity distributions of groundwater of each aquifer are shown in Figure 6. That of the G1 aquifer is $\leq 6.3\times10^{-7}$m/s in most area of the southwestern part, and $>10^{-6}$m/s in some area of the northwestern and northeastern parts (Figure 6a). That of the G2 aquifer is also $\leq 6.3\times10^{-7}$m/s in most area of the southwestern part, and $>10^{-6}$m/s in some area of the northwestern and northeastern parts (Figure 6b). That of the G3 aquifer is $\leq 6.3\times10^{-7}$m/s in most area of the southwestern part.

4. EXAMINATION OF AQUIFER DISTRIBUTION BASED ON SCREEN DEPTH

The area where the pumping up of groundwater is not regulated is only the northern and northwestern parts of the study area. The examinations of aquifer distribution and groundwater yields (next chapter) are limited in these parts. The aquifer distribution is estimated from screen depth of wells. The top and bottom depths of screens are recorded in the well database. These depths are assumed to be consistent with those of aquifers in this study.

Spatial and height distribution of the well screens is shown in Figure 6. Solid circles are plotted when wells have screens within the height range shown at the lower left of each figure in Figure 6. Screens > –10m height is in the northern area. The figures above –60m above sea level (a.s.l.) show that shallower screens are in the northern area and screen distribution moves to southwest toward –60m a.s.l. The figure from –50m to –60m a.s.l. shows two clusters of well screens in the northern and southwestern areas. The cluster in the northern area moves again to southwest toward –140m a.s.l. Two aquifers are recognized from the screen distribution. One is at a depth of about –10m in the northern area, becomes deeper toward southwest, and at a depth of about –60m in the southwestern area. The other is at a depth of about –60m in the northern area, becomes deeper toward southwest, and at a depth of about –140m in the southwestern area.

Spatial and depth distribution of the well screens is shown in Figure 7. This distribution is similar to that of height distribution.

5. POTENTIAL INSTALLATION OF OPEN LOOP SYSTEM BASED ON GROUNDWATER YIELDS

The potential installation of the open loop systems is examined based on the groundwater yields of pre-existing wells. The study area is divided into 1030 meshes, and the ratio of potential installation of the open loop systems to private household is calculated in each mesh. Two kinds of groundwater yields are examined; one is the groundwater yields from all depth of screens, the other is those from <50m depth.

Assumptions for this examination are as follows. The open loop systems are used for air conditioning and hot water supply in each house. The amount of floor space for air-conditioning is $32m^2$ in each house. The power of water-source heat pumps is 6kW, its COP is 5, the temperature difference of inlet and outlet for groundwater is 5°C, and the amount of groundwater yields for the operation of

GeoHPs is 20L/min. The number of hours that the GeoHPs are worked is assumed as follows. Ishida (1997) shows the energy consumption per household in study area (Table 2). Electric energy consumption using GeoHPs can be calculated from primary and secondary energy consumptions of Table 2. Total electric energy consumption using GeoHP is 3.4MWh/(year · household). Therefore, the operation time of the GeoHP is 1700h per year and groundwater yield per household is 2040m^3/year, when electricity consumption of the GeoHP is 2kW.

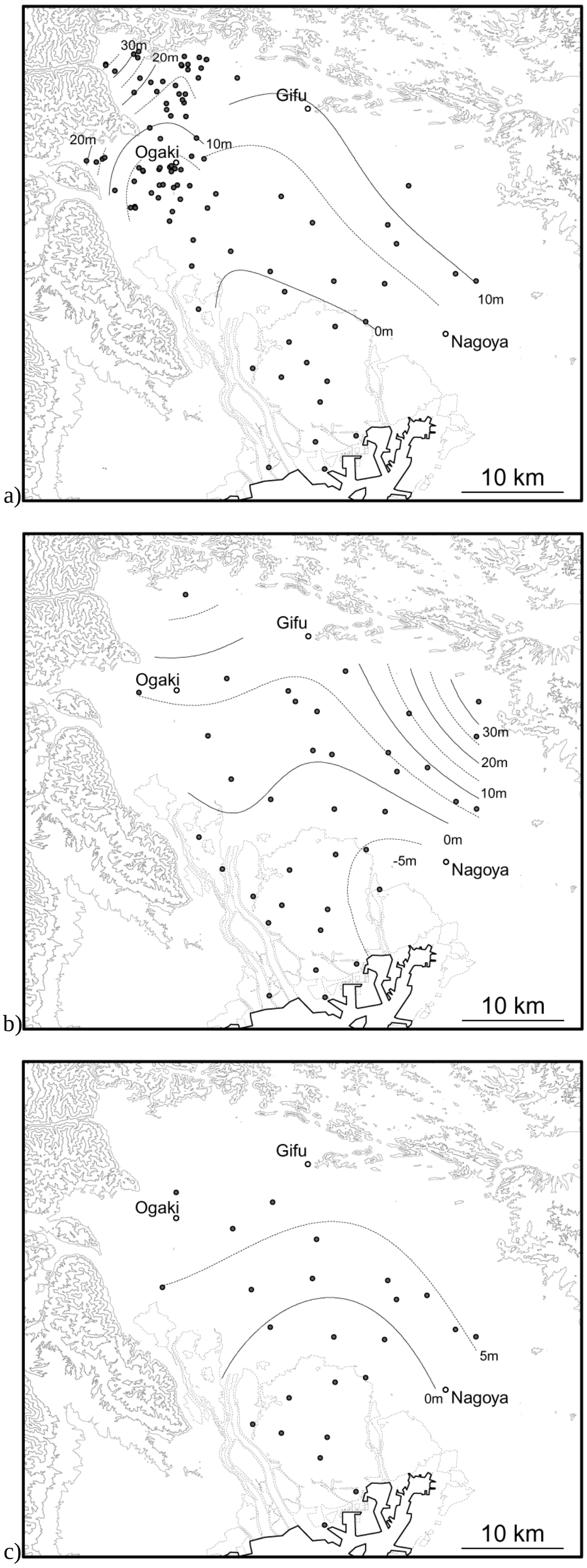

Figure 5. Distribution of hydraulic heads (m) above sea level of a) G1 aquifer and the northwest area of the Nobi plain, b) G2, c) G3 aquifers.

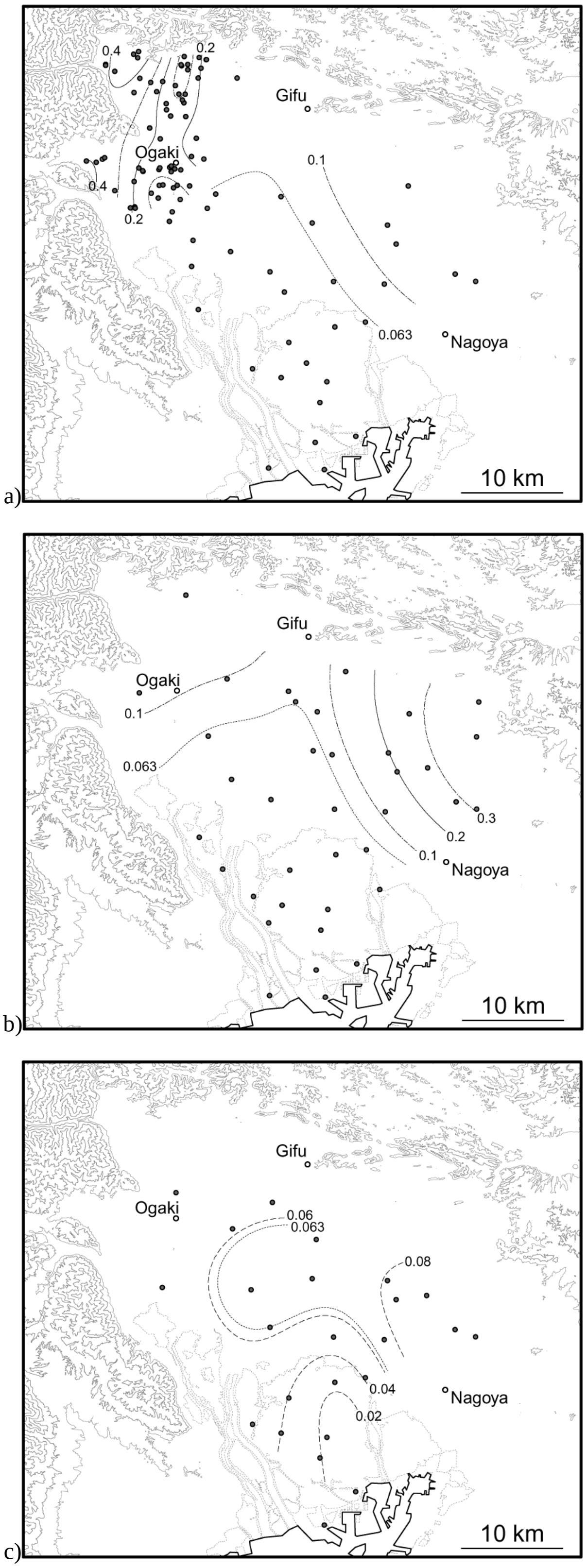

Figure 6. Estimated Darcy velocity of groundwater (×10^{-5} m/s) in the a) G1 aquifer and the northwest area of the Nobi plain, b) G2, c) G3 aquifers.

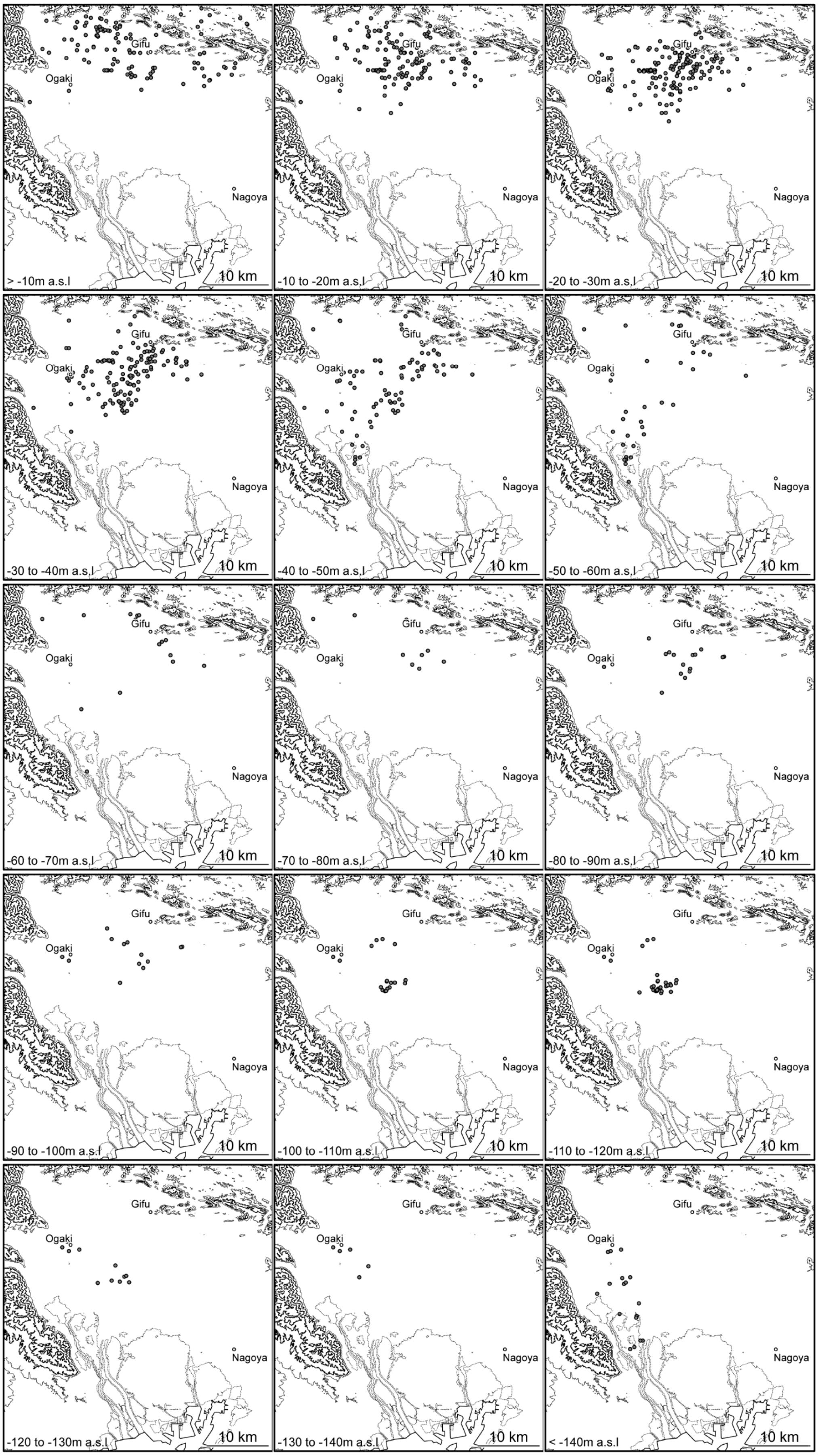

Figure 6: Distribution maps of well screens on the Nobi plain in Gifu prefecture. Solid circles are wells having screens within the altitude range shown at the lower left of each figure. Gray broken and thin lines indicate altitude of 0 and 100m, respectively. Gray bold lines are altitude of 200 m interval. a.s.l: above see level.

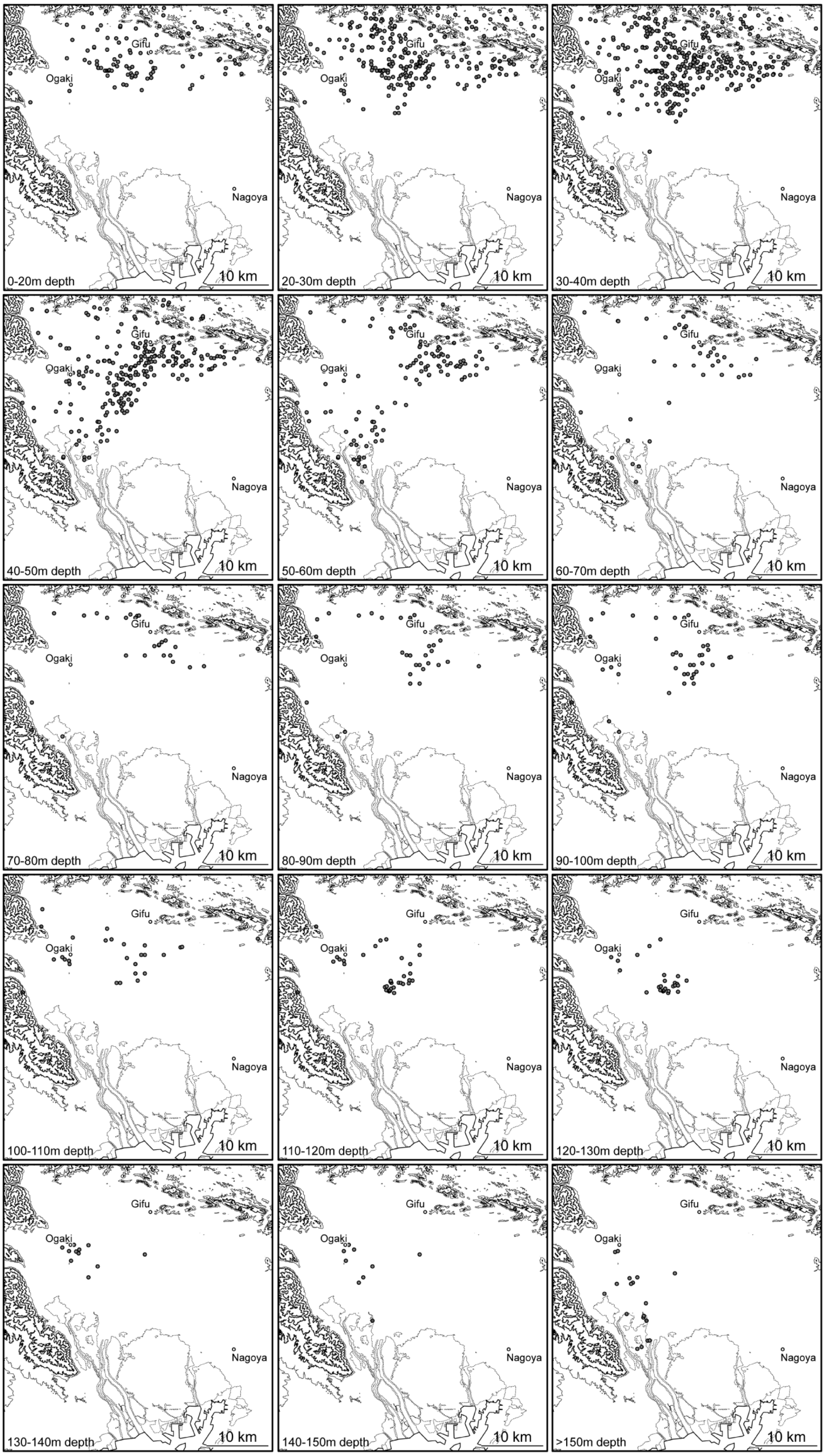

Figure 7: Distribution maps of well screens on the Nobi plain in Gifu prefecture. Solid circles are wells having a screen within the depth range shown at the lower left of each figure.

Table 2: Energy consumption per household in Tokai region. * from Ishida (1997).

	Cooling	Heating	Hot Water Supply	Total	
Secondary Energy Consumption (MWh/year)	0.44	2.95	5.82	9.21	*
Primary Energy Consumption (MWh/year)	1.15	3.75	6.05	10.95	*
Electric Energy Consumption in Secondary Energy Consumption (%)	100	16.8	2.45		
Electric Energy Consumption using GeoHP (MWh/year)	0.44	1.2	1.76	3.4	

Table 3: Groundwater yield, and number and ratio of houses in which can install a groundwater heat pump system on the Nobi plain in Gifu prefecture. 1) Estimation based on the whole groundwater yield. 2) Estimation based on the groundwater yield shallower than 50m depth.

	1	2
Groundwater yield (m^3/day)	1,216,648	597,795
Number of houses in which can install a groundwater heat pump system	217,685	106,959
Ratio of houses in which can install a groundwater heat pump system	52.9%	26.0%

Figure 8 shows distribution of household in the area where groundwater pumping up is not regulated in study area. Population is concentrated in city area; Gifu and Ogaki.

Most of presently pumped up groundwater is used for water resources, not for heat energy resources. The number of houses in which can install a open loop system is calculated based on present groundwater yield, when pumped up groundwater is presumed to be used for heat energy resources and then for water resources (Figure 8). Two types of the number of houses in which can install an open loop system are calculated. Number of houses in which can install an open loop system (1) is that groundwater yields from all depth are considered, and (2) is from <50m depth. The ratio of houses in which can install an open loop system is also calculated on above two types.

The distributions (above 1 and 2) of number of houses in which can install an open loop system are shown in Figure 9a and 9b, respectively. In Figure 9a, the meshes with >500 houses for possible installation are sparsely distributed, and there are some meshes with >1000 houses. In Figure 9b, no distribution is in the southern area of study area, and the mesh distribution is similar to that of Figure 9a in the northern area.

The ratios (1 and 2) of houses in which can install an open loop system are shown in Figure 10a and 10b, respectively. In Figure 10a, the meshes with >100% houses for possible installation are sparsely distributed. Comparing Figure 10b with Figure 10a, meshes with > 100% markedly decrease in Figure10b.

In the whole study area, totals of groundwater yield, number and ratio of houses in which can install an open loop system are described in Table 3. In the case of groundwater from all depths, 52.9% of houses can install this system. From <50m depth, 26.0% is possible.

6. DISCUSSION

6.1 Potential for Installation of Closed Loop System

The area with Darcy groundwater velocity of $>10^{-5}$m/s is not recognized in each aquifer in the study area. This indicates that the area where the efficient heat extraction is expected due to faster groundwater flow is not found in this study. The area with Darcy velocity of $>10^{-6}$m/s is widely spread in the northeastern and northwestern parts. This groundwater velocity is only limited in aquifers, and it should be slower except aquifers. As heat extraction by the vertical heat exchanger of the closed loop system is performed not only aquifers but also other formations, groundwater flow except aquifers should also be considered for heat extraction of the closed loop system. But the groundwater flow in the northeastern and northwestern areas, where faster Darcy velocity is expected, would be faster most of depths along the vertical heat exchanger, because underground in these areas consists of largely gravel layers due to alluvial fan. This suggests that these areas are suitable for the closed loop systems due to faster groundwater flow.

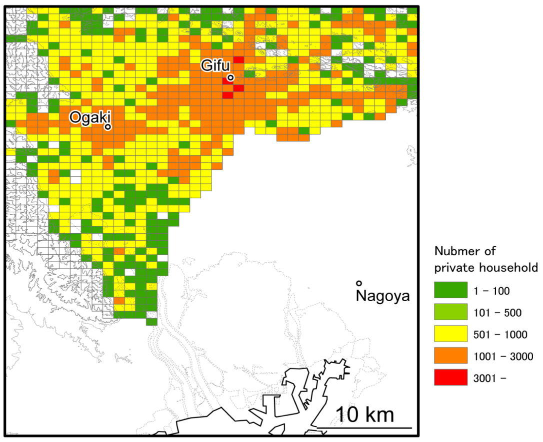

Figure 8: A distribution map of the number of private households on the Nobi plain in Gifu prefecture.

The area with Darcy groundwater velocity of $\leq 6.3\times10^{-7}$m/s is recognized in each aquifer in the southwestern part of the study area, and this suggests that the seasonal heat storage can be expected in this area. Although estimated slower groundwater flow is only limited in aquifers in this study, permeability coefficient of formations except aquifers should be less than that of aquifers, and the groundwater velocity of these layers is slower than that of aquifers. Therefore, the groundwater velocity in all depths would be expected to be slower. This suggests that this area is suitable for the underground heat energy storage.

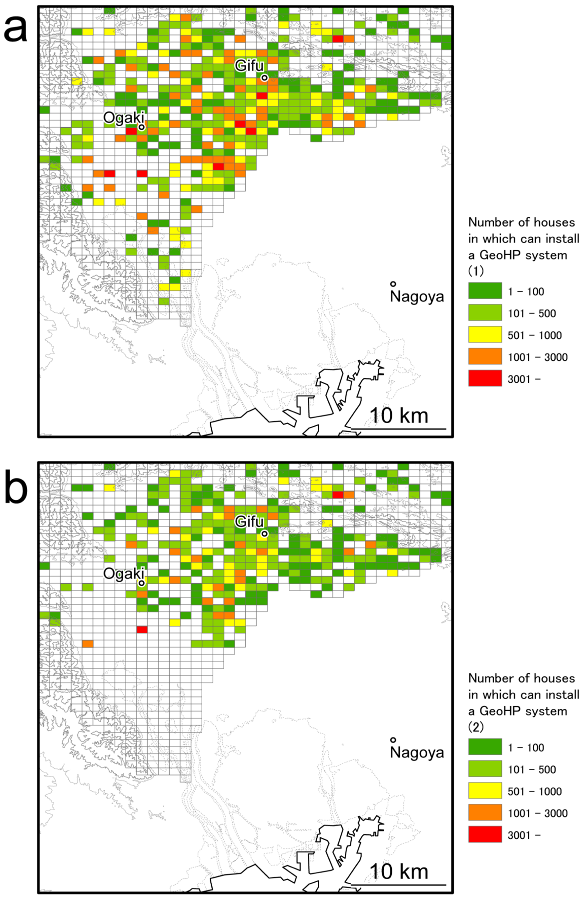

Figure 9: Distribution maps of the number of houses in which can install a groundwater heat pump system on the Nobi plain in Gifu prefecture. a) Estimation based on the whole groundwater yield. b) Estimation based on the groundwater yield shallower than 50m depth.

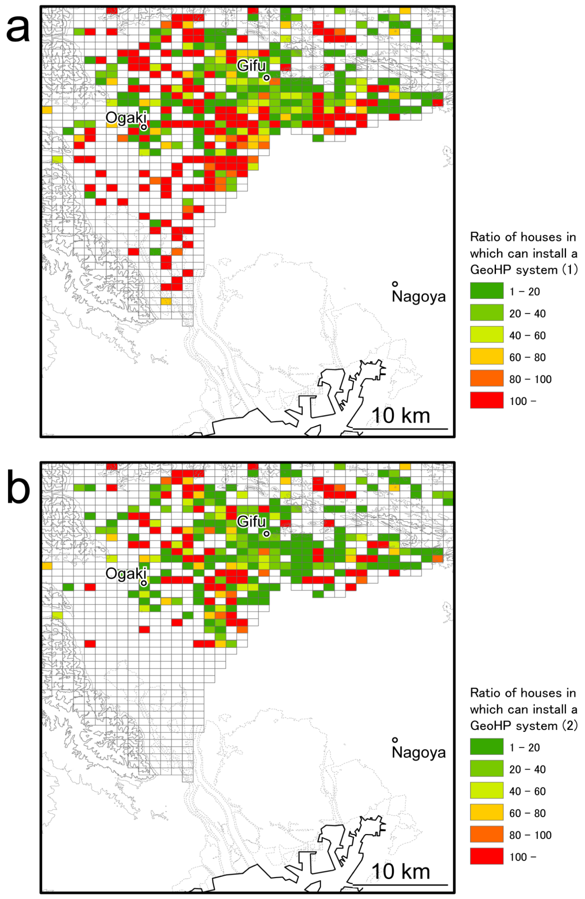

Figure 10: Distribution maps of the ratio of houses in which can install a groundwater heat pump system on the Nobi plain in Gifu prefecture. a) Estimation based on the whole groundwater yield. b) Estimation based on the groundwater yield shallower than 50m depth.

6.2 Potential for Installation of Open Loop System

Two aquifers are recognized from the distribution of screen depth, and these are shallower in the northern area. For drilling production wells or injection wells, a shallower aquifer is preferable. From this point of view, the northern part of study area is suitable for the open loop system.

The open loop systems using pre-existing wells should be distinguished from that with new well drilling, when the potential for installation of open loop system is examined. They do not need to drill production and injection wells, and the depth of aquifers is not important. In contrast, those with new well drilling should consider the depth of aquifers for potential installation.

Figures 9a and 10a show that many meshes both in the northern and southern parts of study area are appropriate for the open loop systems using pre-existing wells. Figures 9b and 10b indicate that the meshes with possible installation for the open loop systems with new well drillings are only in the northern part. This difference results from the aquifer depth distribution. The aquifers become deeper toward southwest. It is difficult to pump up groundwater from shallower depth due to this aquifer distribution. This suggests that enough amount of groundwater can be produced in the shallower aquifer of the northern part, and that there is a suitable area for the installation of the open loop systems.

7. CONCLUSIONS

Distribution of the Darcy velocity of groundwater flow in aquifers in the Nobi plain is estimated to understand suitable area for installation of the closed loop systems of the GeoHPs. In any area of the Nobi plain, the velocity of groundwater flow in the aquifer is not expected to be $>10^{-5}$m/s. In the most part of the alluvial fan area, the gravel is dominant in the formation and the velocity is $>10^{-6}$m/s. In the southwestern area, the velocity is $\leq 6.3\times10^{-7}$m/s. This difference of groundwater velocity would affect effective heat conductivity of formations and heat transfer under the ground, and northeastern and northwestern areas of the study area are suitable for the closed loop systems due to faster groundwater flow, while southwestern area is for the underground heat energy storage due to slower groundwater flow.

The distribution of two aquifers is deduced from that of well screens that are getting deeper gradually toward the southwest. The distribution of the groundwater yields indicates that the open loop systems using pre-existing wells have a potential installation in the whole of the study area. The distribution of the groundwater yields drawn from the aquifers shallower than 50m depth shows that the northern part of the study area is a suitable area for the installation of the open loop systems with new well drillings. The potential installation of the open loop systems using the groundwater drawn from the total depth and shallower than 50m depth are 52.9% and 26.0% for the houses in the study area, respectively. These results suggest that the study area has a large potential for the installation of the open loop systems.

REFERENCES

Burrough, P. A.: Principles of Geographical Information Systems for Land Resources Assessment, Oxford University Press (1986), 220p.

Ishida, K.: Energy Consumption of Detached Houses, Jour. Archit. Plann. Environ. Eng. AIJ, **501,** (1997), 29-36.

New Energy and Industrial Technology Development Organization: Preparatory Study for the Undergournd Thermal Energy Storage System, (2000)，619p.

Niibori, Y., Iwata, Y., Mori, F., and Fukaya, G.: A Study on Relation between Groundwater Flow and the Design of Ground-Coupled HP system with Borehole, *Jour. Geotherm. Res. Soc. Japan*, **24**, (2002), 339-348.

Niibori, Y., and Nakagome, O.: A Design Method of GeoHP System Considering the Relatively Low Flow-velocity of Groundwater, *Abst. w. Prog*. 2005 Annual Meeting Geotherm. Res. Soc. Japan, (2005), A35.

Subsidence Survey Committee in Tokai Region: Land Subsidence and Groundwater in the Nobi Plain, Nagoya University Press, (1985), 245p.