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Development of Resource Map with the Total Energy Consumption for Open-Loop Type Geothermal Heat Pump System

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ABSTRACT

The resource map of open-loop type of ground source heat pump (GSHP) system is developed based on the annual total energy consumption. The annual total energy consumption is estimated from groundwater temperature, level and heating / cooling demand patterns. The study area of the resource map is the Nobi Plain, central Japan. This plain includes some alluvial fans, where the underground temperature in aquifers is fluctuated with an annual cycle. This temperature change is reflected in the estimation of the total energy consumption.

A heating / cooling experiment at a public hall in the area with the annual underground temperature change is performed to construct the calculation method of the total energy consumption of the open-loop system. The calculation method on coefficient of performance (COP) of the heat pump is constructed from the multiple regression analysis on the monitoring data of groundwater temperature and the ratio of the produced heat to the heating/cooling capacity of the heat pump. The calculation method of the energy consumption of the water pump is constructed from the combination of monitoring results and the characteristic charts of the water pump.

The distribution of the estimated annual total energy consumption of the open-loop system in an office building shows that the total energy consumption is lower in the northwestern part of the study area. This results from the shallower water table and lower groundwater temperature, because the cooling demand is higher than the heating one in an office building of the study area. Some areas of the alluvial fan also exhibit the lower annual power consumption, because the phase difference of the annual underground temperature change is almost 6 months from the ambient temperature change due to a lateral groundwater flow.

1. INTRODUCTION

Total installation number of the GSHP systems in Japan is still limited, and it is 2,662 at the end of March in 2018 (Ministry of the Environment, 2019). Creating a resource map on the GSHP system would help to increase the GSHP. Subsurface geology at the shallower depth in the plain areas of Japan is mainly unconsolidated sediments, such as clay, silt, sand and gravel. Gravels are important for the groundwater aquifer, and they are mainly distributed in the alluvial fans. The groundwater in the alluvial fans are characterized to the faster flow, lower dissolved components and annual temperature change.

Although underground temperature below a certain depth is constant in the most area, that in the alluvial fans often fluctuates due to the faster flow groundwater from the recharge area. The river water infiltrates underground from the river bed to the aquifer in the apex of the alluvial fan. The temperature of the river water fluctuates as same as the ambient temperature. The groundwater keeps the temperature when the river water was infiltrated. It flows rapidly toward the downstream, and the temperature of groundwater is almost preserved to a certain degree. For example, the groundwater recharged in summer forms a warm water mass, and this migrates due to the groundwater flow after summer. This warm water mass is preserved with a slight temperature decrease in winter, and it is expected to be a good heat source of GSHPs.

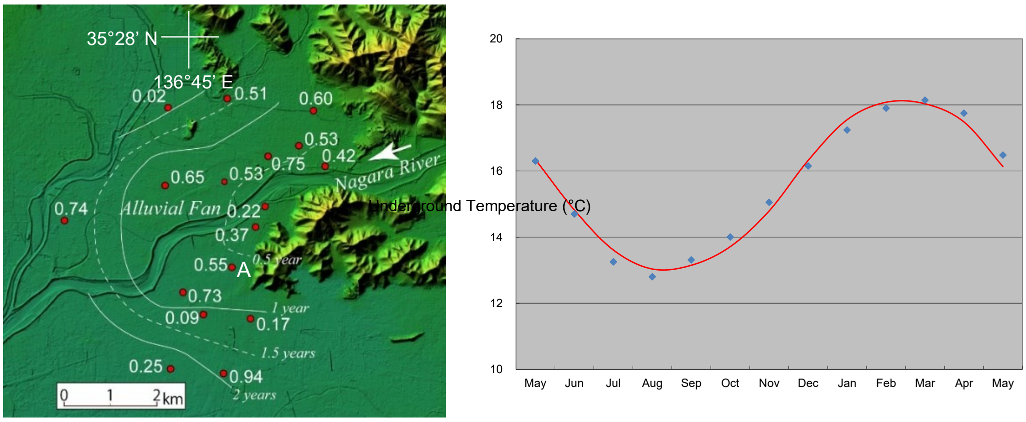

Figure 1: (Left) Phase difference distribution of underground temperature against river water temperature in the alluvial fan of the Nagara River, central Japan. (Right) Underground temperature change at 15 m depth of the observation well A with 0.55 year of phase difference. Both are referred from Ohtani *et al.* (2015).

Underground temperature measurements in the alluvial fan of the Nagara River clarified that the rapid groundwater flow is strongly reflected in the temperature distribution in the shallow aquifer (Figure 1; Ohtani *et al*., 2015; Ohtani *et al*., in press). The open-loop GSHPs would work with a higher COP in the areas with a half year phase difference of underground temperature change against the ambient one. However, the parameters which influence the system COP (SCOP) of open-loop GSHP system is not only underground temperature but also groundwater level and the ratio of the produced heat to the heating / cooling capacity of the heat pump. We clarify the effects of groundwater temperature, level and the ratio of the produced heat to the heating / cooling capacity of the heat pump on the SCOP of GSHPs through the heating/cooling experiment in the area with a half year phase difference of groundwater temperature change. Based on the result of the heating / cooling experiment at a public hall, the calculation method on the SCOP of GSHPs is constructed. Finally, the resource map is created by the combination of the groundwater temperature / level distributions and the above calculation method.

2. ESTIMATION OF ANNUAL TOTAL ENERGY CONSUMPTION

2.1 Outline of heating / cooling experiments

A Heating / cooling experiment had been performed at a public hall in Gifu City, Japan (Figure 2). This is located near the well A in Figure 1. The installed system is consistent with 2 water wells, a water seepage pit, a groundwater heat exchanger unit, a heat pump and 18 indoor units. Two water wells consists of one pumping well and one injection well. The pumping well is located at the upstream side of the groundwater flow. A water seepage pit is experimentally used for water infiltration. A groundwater heat exchange unit is consistent with a heat exchanger between groundwater and antifreeze fluid, a pump unit for the antifreeze fluid circuit and control units of the groundwater circuit and the antifreeze fluid circuit. The rated shaft power of the groundwater pump is 2.2 kW. The rotation speed of the shaft is controlled by the inverter unit depending on the heating / cooling demands. The heat pump is based on ZP-3-XS504T produced by Zeneral Heatpump Industry Co. Ltd and partially remodeled for this experiment. Heating and cooling capacity of the heat pump are 56.5 kW and 50.4 kW, respectively. The heat source of the heat pump can be switched between air and water. Users of the public hall operate each indoor unit freely.

Figure 2: (Left) Heating/cooling experiment site. (Right) Enlarged image of the groundwater heat exchanger unit and the heat pump.

Data monitoring is performed on inlet / outlet groundwater temperatures, pumping rate of groundwater and power consumption of the heat pump and the groundwater pump in an interval of 1 minute from April 2017 to December 2018. Inlet groundwater temperature shows a seasonal change which is assumed to be a sine curve. The highest temperature of the groundwater is 20 °C in January (winter), and the lowest is 13 °C in July (summer; Figure 3). The temperature difference between the inlet and outlet groundwater is set to be constant in a day. This temperature difference is changed to be 3 ºC, 5 ºC, 7 ºC, 8 ºC and 10 ºC as each day comes. Produced heat for heating and cooling are dependent on the user's demands.

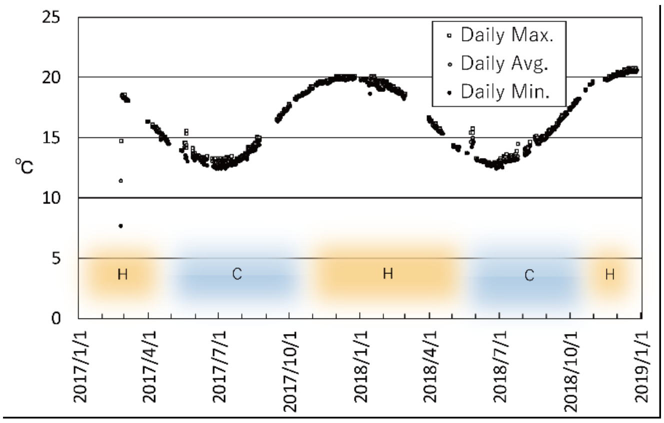

Figure 3: Inlet groundwater temperature of the groundwater heat exchange unit. H: Heating. C: Cooling.

2.2 Energy consumption estimation of heat pump and water pump

A calculation method of the annual total energy consumption of the open-loop system is needed to create a resource map. The distributions of the groundwater temperature and level are already clarified by the previous studies (e.g. Ohtani *et al*., 2015; Ohtani *et al*., in press). Heating / cooling demand patterns of an office building are shown by the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan (2015). If the annual total energy consumption at an arbitrary site is able to be calculated from the groundwater temperature, level and the heating / cooling demand patterns, the resource map can be created.

At the heating / cooling experiment site, the groundwater temperature is fluctuated from 13 °C to 20 °C in a year, and the temperature difference setting between inlet and outlet groundwater is attempted in 5 cases as described above. Although the groundwater level is not so fluctuated, the actual head of the water pump is attempted in 2 cases depending on the way of groundwater injection. Groundwater after heat exchange is injected to the aquifer through the injection well or the water seepage pit (Figure 4). A water injection pipe in the injection well is reached below the water table. When using the injection well, groundwater in the pipe is not released to the atmospheric pressure from the pumping well to the injection well, and the actual head which is the height difference of water table between pumping and injection wells becomes almost zero due to the siphon principle. On the other hand, when using the water seepage pit, groundwater in the pipe is opened to the atmospheric pressure in the water seepage pit. In this case, the actual head is the height between the water table in the pumping well and the water seepage pit that is almost ground surface. Based on this difference of the actual head and the characteristic charts of the water pump, the relationship between the actual head and the energy consumption of a water pump is estimated using the monitoring data.

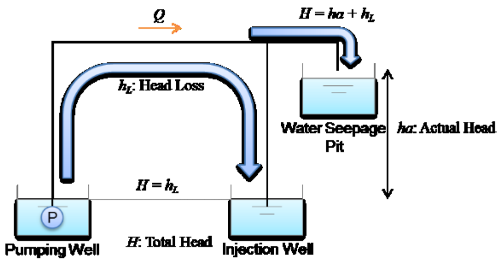

Figure 4: Total head, actual head and head loss of the groundwater circuit from a pumping well to an injection well or a water seepage pit.

A calculation method of energy consumption of the heat pump at an arbitrary site is developed based on the relationship between the monitoring data and COP. That of the water pump at an arbitrary site is based on the relationship between the pumping rate of groundwater and the energy consumption. The annual total energy consumption at an arbitrary site is calculated from the combination of the annual energy consumption of the heat pump and water pump.

To estimate the annual energy consumption of the heat pump, the relationship between the measured inlet temperature of groundwater, the temperature difference between the inlet / outlet groundwater of the groundwater heat exchange unit, the ratio of the produced heat to the heating / cooling capacity of the heat pump and COP is evaluated. This allows to estimate the COP at an arbitrary site from the known data of the groundwater temperature, the temperature difference between the inlet / outlet groundwater and the ratio of the produced heat to the heating / cooling capacity of the heat pump. The annual energy consumption of the heat pump is calculated from the estimated COP and heating / cooling demand patterns.

The COP of the heat pump per minute in the experiment is calculated from the measured inlet / outlet temperature of groundwater and power consumption of the heat pump. The COP during heating and cooling is expressed from the equation (1) and (2), respectively.

$$COP_{\mathrm{heating}} = \frac{Q_{\mathrm{gw}} + 60W_{\mathrm{hp}}}{60W_{\mathrm{hp}}} \quad (1)$$

$$COP_{\mathrm{cooling}} = \frac{-Q_{\mathrm{gw}} - 60W_{\mathrm{hp}}}{60W_{\mathrm{hp}}} \quad (2)$$

where COP_{heating} and COP_{cooling}: COP during heating and cooling, respectively, Q_{gw}: extracted heat from groundwater (kJ/min), W_{hp}: power consumption of heat pump (kWh/min).

The values of extracted heat from groundwater Q_{gw} during heating and cooling are given as positive and negative by the following equation (3), respectively.

$$Q_{\mathrm{gw}} = q\rho c(T_{\mathrm{in}} - T_{\mathrm{out}}) \quad (3)$$

where q: pumping rate of groundwater (L/min), ρ: density of groundwater (kg/L), c: specific heat of groundwater (kJ/kgK), T_{in} and T_{out}: inlet and outlet temperature of groundwater (°C).

The relationship between the measured groundwater temperature, the temperature difference between the inlet / outlet groundwater, the ratio of the produced heat to the heating / cooling capacity of the heat pump and COP is evaluated by the multiple regression analysis. The estimated equation is described as follows;

$$COP_{\mathrm{heating}} = 0.07969T_{\mathrm{in}} - 0.1310\Delta T - 0.0002572Q'^2 + 0.03301Q' + 1.879 \tag{4}$$

$$COP_{\mathrm{cooling}} = -0.1721T_{\mathrm{in}} - 0.4220\Delta T - 0.001194Q'^2 + 0.1167Q'^2 + 10.06 \tag{5}$$

where *ΔT*: temperature difference between the inlet / outlet groundwater (°C), Q': the ratio of the produced heat to the heating / cooling capacity of the heat pump.

The effect of groundwater temperature for the COP is an increase of 0.07969 / °C for heating and a decrease of 0.1721 / °C for cooling. The equations (4) and (5) is consistent with the relationships between the inlet temperature of groundwater (Figure 4a), the temperature difference of inlet/outlet groundwater (Figure 4b), the ratio of produced heat to the heating/cooling capacity of the heat pump (Figure 4c) and the COP. This indicates that the equations deduced from multiple regression analysis enable to estimate the COP of the heat pump from any inlet temperature of groundwater, any temperature difference between inlet / outlet groundwater and any ratio of produced heat to the heating/cooling capacity of the heat pump.

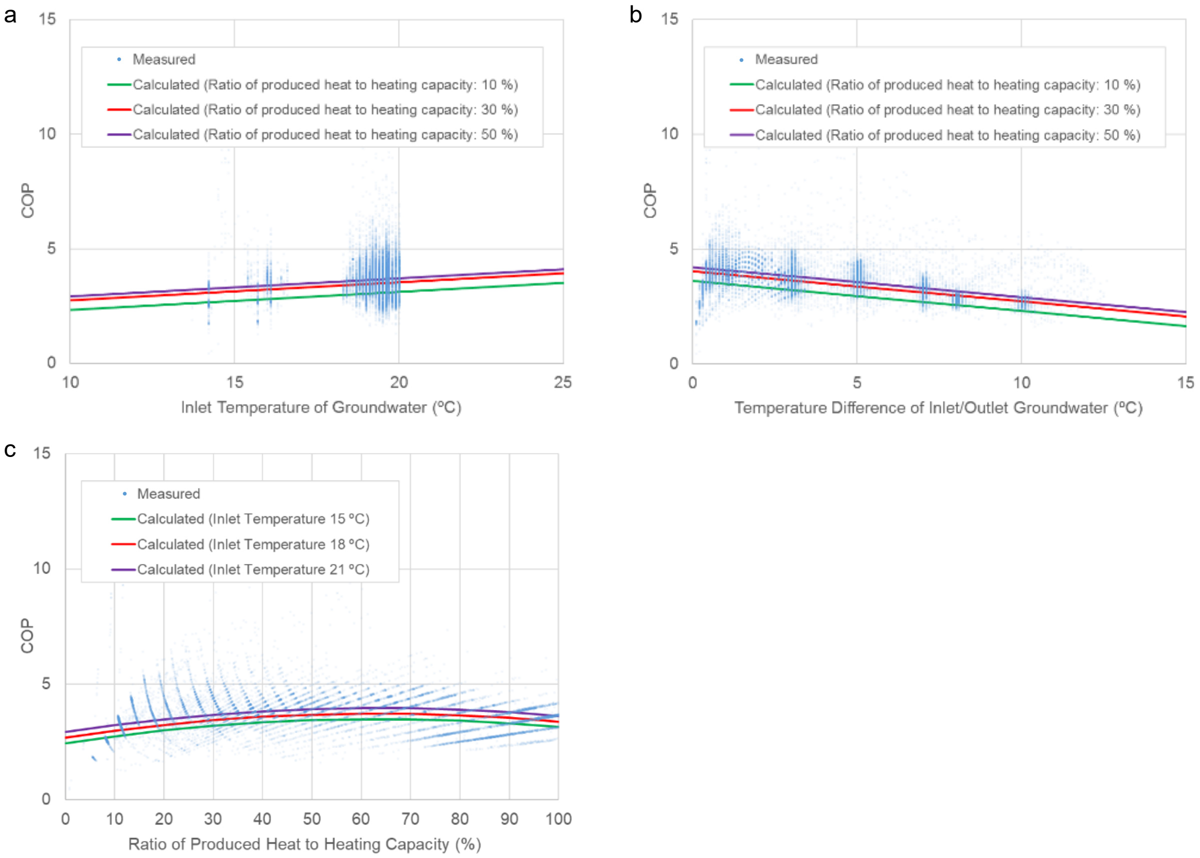

Figure 4: Relationships between (a) the inlet temperature of groundwater, (b) the temperature difference of inlet/outlet groundwater and (c) the ratio of produced heat to the heating capacity of the heat pump and COP.

To estimate the annual energy consumption of the water pump, the relationship between the pumping rate of groundwater, energy consumption of the water pump and injection way (an injection well or a water seepage pit) is evaluated from monitoring data. Based on this evaluation, characteristic chart of water pump and heating / cooling demand pattern, the annual energy consumption of the water pump at an arbitrary site is estimated from the known groundwater level.

To calculate the energy consumption of the water pump per minute, the pumping rate of groundwater *q* (L/min) is calculated by the following equation (6).

$$q = \frac{1}{4.184}\frac{Q_{\mathrm{gw}}}{\Delta T} \tag{6}$$

Power consumption of water pump is calculated by the following empirical formula (modified from Sotoyama, 2016).

$$W_{\mathrm{wp}} = 0.1634 \frac{\eta_{\mathrm{inv}}}{100} \frac{\eta_{\mathrm{mot}}}{100} \frac{\rho \frac{q}{1000} H_m}{\frac{\eta_m}{100}} \tag{7}$$

where W_{wp}: power consumption of a water pump (kW), η_{inv}: inverter efficiency (%), η_{mot}: motor efficiency (%), H_m and η_m: total head (m) and efficiency of a water pump when the rotational speed of the motor shaft is m (%) of the rated one.

In equation (7), inverter efficiency η_{inv}, motor efficiency η_{mot} and density of groundwater ρ are constant, q is calculated by equation (6), H_m and η_m are functions of the rotational speed ratio m.

Total head H is the sum of actual head h and head loss h_{L}.

$$H = h + h_{\mathrm{L}} \tag{8}$$

Head loss h_{L} is expressd by the following equation.

$$h_{\mathrm{L}} = f \frac{L}{D} \frac{v^2}{2g} \tag{9}$$

where f: frictional coefficient of pipe, L: length of pipe (m), D: inner diameter of pipe (m), v: flow velocity (m/s), g: gravitational acceleration (m/s^2).

When the groundwater after heat exchange is recharged into the injection well, the actual head h is regarded to be zero. In this case, the total head H is nearly equal to the head loss h_{L}. The following constant value is calculated from the relationship of the total head and flow rate obtained from the characteristic chart of the water pump.

$$f \frac{L}{D} = 212.336 \tag{10}$$

When the rotational speed of the motor shaft is m (%) of the rated one, flow rate q_m,(L/min), total head H_m (m) and efficient of a water pump η_m are represented as follows (Sotoyama, 2016).

$$q_m = \frac{m}{100} \times q_{100} \tag{11}$$

$$H_m = \left(\frac{m}{100}\right)^2 \times H_{100} \tag{12}$$

$$\eta_m = \frac{1 - \eta_{100}}{\left(\frac{m}{100}\right)^{\frac{1}{5}}} \tag{13}$$

where q_{100} (L/min), H_{100} (m) and η_{100} are flow rate, total head and efficiency of a water pump at the rated rotational speed of m_{100} (%), respectively.

The relationship between the ratio of the rotational speed, flow rate and total head is evaluated by multiple regression analysis.

$$m = 0.002061 q_m^{\frac{1}{3}} - 0.03416 q_m^{\frac{1}{2}} + 0.04485 q_m + 0.001820 H_m^{\frac{1}{3}} + 0.09791 H_m^{\frac{1}{2}} + 0.06703 H_m \tag{15}$$

This equation (15) means that the ratio of the rotational speed ratio m is calculated from flow rate q_m, total head H_m. Flow rate and total head are calculated from equation (6) and (8), respectively. Actual head is almost equal to the depth of groundwater level in a pumping well. Using the ratio of the rotational speed m calculated by the equation (15), η_m are calculated from the equation (13), and power consumption of a water pump W_{wp} (kW) at the rotational speed of m is estimated from η_m using equation (7).

2.3 Calculation of heating / cooling demand pattern

To estimate the annual total energy consumption of the open-loop GSHP system including a water pump, heating / cooling demand pattern of an office building is calculated. The heating / cooling demand is referred from the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan (2015). The period of heating is from December to March, while that of cooling is from April to November. Target room temperature is 22 °C for heating and 26 °C for cooling. Annual heat demand is 56 MJ/m^2 for heating and 295 MJ/m^2 for cooling. Necessary heating and cooling capacities are 268 kJ/m^2 and 357 kJ/m^2, respectively.

Heat demands for heating and cooling is calculated every hour through a year, and the distribution of the ratio of the heat demand to the heating/cooling capacity (heat demand ratio) is shown in Figure 6.

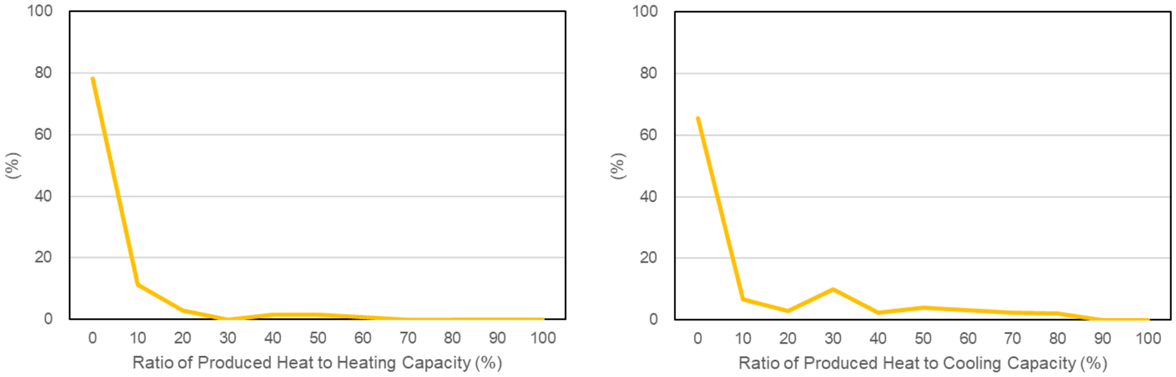

Figure 6: Distribution of the ratio of the heat demand to the heating/cooling capacity. Left: heating. Right: cooling.

The ratio of the produced heat to the heating/cooling capacity is mostly distributed less than 30 % for heating and 40 % for cooling. Especially, the ratio less than 10 % is more than 50 % both for heating and cooling. These indicate that the total energy consumption of the open-loop GSHP system at the lower ratio has a great effect on the annual one.

Annual total energy consumption of an open-loop GSHP system is calculated by multiplying the energy consumption of a system and operation hours in a year. The ratio of produced heat to heating / cooling capacity is divided into intervals with 10 % of ratio, and the annual total energy consumption of each interval is calculated by multiplying the energy consumption of an open-loop GSHP system and operation hours of each interval. The energy consumption of a system is a combination of those of a heat pump and water pump, and these are calculated using the calculation methods described in the chapter 2.2. The ratio of the produced heat to the heating / cooling capacity is equal to Q' in equations (4) and (5) and extracted heat from groundwater $Q_{\rm gw}$ in equation (6) is calculated from Q'. The annual total power consumption in an office building at an arbitrary groundwater temperature and level can be calculated, and its ratio to that with 17 °C and 15 m is shown in Figure 7. The deeper the groundwater level is, the higher the annual total energy consumption is, because the higher energy consumption is needed to pump groundwater up at a certain flow rate from the deeper groundwater level. The line of 100 % shows a downward convex curve. When the groundwater temperature is lower, the total energy consumption becomes lower, because the heat demand of an office building for cooling is higher than that for heating.

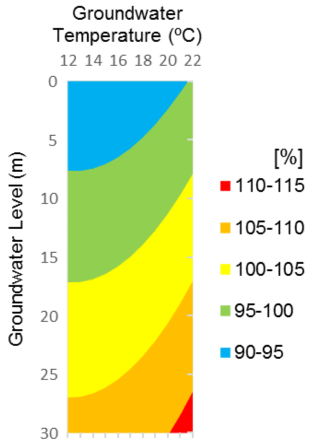

Figure 7: Ratio of the annual total energy consumption with an arbitrary groundwater temperature and level to that with 17 °C and 15 m.

3. DISTRIBUTION OF TOTAL ENERGY CONSUMPTION IN THE NOBI PLAIN, CENTRAL JAPAN

Plenty of previous studies on geology and hydrogeology are accumulated in this area due to the serious land subsidence from 1960s in the Nobi Plain, central Japan. The distribution of groundwater temperature and level is obtained from the previous studies (Uchida and Sakura, 1999; Uchida and Hayashi, 2005; Ohtani *et al*., 2015; Ohtani *et al*., in press), and the distribution of the annual total energy consumption is calculated from the calculation method developed above. The resource map of the annual total energy consumption is created in the Nobi Plain, central Japan (Figure 8).

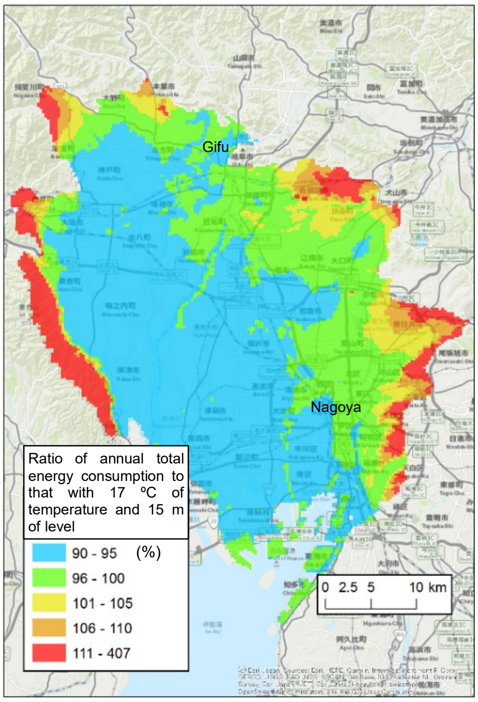

Figure 8: Distribution of the total energy consumption in the Nobi Plain, central Japan.

The Nobi plain are surrounded by mountains and hills except the southern side. The west side of the plain is lower altitude due to the fault movements along the western boundary of the plain. The distribution of the annual total energy consumption is higher along the marginal areas of the plain. The alluvial fans are located in these areas, and the surface elevation is higher than the other areas. Except the marginal areas, the annual total energy consumption in the western area is lower, because the surface elevation of this area is lower and the energy consumption of a water pump is estimated to be lower. The annual total energy consumption in the northwestern area is lower due to the lower groundwater temperature. That in the alluvial fan of Gifu is also lower, because this area exhibits the groundwater temperature fluctuation with a phase difference of 0.5 year against the river water temperature.

4. CONCLUSION

Detailed monitoring of the heating / cooling experiment at a public hall in the Gifu City, Japan is performed on inlet / outlet groundwater temperature, pumping rate of groundwater and power consumption of the heat pump and the water pump. The relationship between the inlet temperature of groundwater, the temperature difference of the inlet / outlet temperature of groundwater and the ratio of produced heat to the heating / cooling capacity of the heat pump and COP is evaluated by the multiple regression analysis. The effect of groundwater temperature for the COP is an increase of 0.07969 / °C for heating and a decrease of 0.1721 / °C for cooling. Combining the energy consumption of a water pump, a calculation method of the annual total energy consumption is developed, and this allows to estimate the annual total energy consumption of an open-loop system at a site with an arbitrary groundwater temperature and level. The energy consumption becomes lower where groundwater temperature is lower in the case of an office building. A resource map based on the annual total energy consumption is created in the Nobi Plain, central Japan. This shows that the total energy consumption is lower in the northwestern area due to lower groundwater temperature except the marginal areas.

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