Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Seasonal Change of Underground Temperature and the Use of Geothermal in Gifu City, Japan

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Keywords: Seasonal change of underground temperature, Gifu, Japan

ABSTRACT

Seasonal change of underground temperature has been measured in the alluvial fan of the Nagara River, central Japan. Underground temperature of most boreholes are fluctuated not only near-surface but also in the aquifers. The maximum differences of seasonal temperature of each borehole generally become larger toward the apex of the fan. The maximum temperature of each borehole is generally not during the summer season, and is not coincident with the temperature change of river water. These suggest that the groundwater in the alluvial fan recharge from the river water, and that the seasonal change of the underground temperature results from the lateral flow of the recharged groundwater. For the low temperature geothermal use such as ground-coupled heat pumps, annual change of underground temperature has a possibility that underground temperature becomes lower in the summer and higher in the winter.

1. INTRODUCTION

Generally, the underground temperature is constant except near-surface. The temperature in the near-surface (e.g. above 10 m depth) is annually changed due to the effect of seasonal change of ground surface temperature. As the thermal conductivity of rocks and soils are quite low, this seasonal change of ground temperature cannot reach below a certain depth. This depth is dependent on not only the thermal conductivity of rocks or soils but also the groundwater flow in a vertical direction. The constant temperature in a certain depth is consistent with the average of ground surface temperature. The underground temperature below a certain depth is dependent on a long-term climate change (Miyakoshi et al., 2003) and a geothermal gradient.

Low temperature geothermal uses such as ground-coupled heat pumps and groundwater heat pumps apply the temperature difference between surface and underground to thermal energy. As the underground temperature is constant, the underground becomes a heat source in winter and a heat sink in summer.

Alluvial fans are recharge areas of groundwater and rapid groundwater flows are expected. The underground temperature in alluvial fans is influenced by rapid groundwater flow recharged from a river (Gifu Prefecture et al, 2011). In this paper, we clarify the distribution of the underground temperature and the velocity of groundwater flow in an alluvial fan to understand the potential of low temperature geothermal energy.

2. DISTRIBUTION OF UNDERGROUND TEMPERATURE OF ALLUVIAL FAN OF NAGARA RIVER

2.1 Study Area

The study area is an alluvial fan of the Nagara River, central Japan. This alluvial fan is located in the marginal area of the Nobi plain (Figure 1). The underground of this alluvial fan mostly consists of sands and gravels and often intercalate thin fine sand and silt layers. The aquifers are divided by these sand and silt layers. But these aquifers would be partly connected, as water table changes in these aquifers are related each other.

2.2 Measurements of underground temperature

The underground temperature of this area had been measured from May 2013 to May 2014. The temperature is measured in 17 boreholes with the length of 30 m. The measurement is performed once a month by a thermistor thermometer with the interval of 1 m depth.

2.3 Results of temperature measurements

The results of ground temperature measurements are shown in Figure 2. Well-1 is located near the apex of the alluvial fan. The underground temperature is almost constant from 15 m depth to the bottom of the borehole in each month. The temperature is greatly changed according to seasons, and the lowest and the highest temperatures are in May and November, respectively. As the outside air temperature is highest in August, the phase difference between outside air and underground temperature is 3 months. The temperature difference between May and November is 13.5 °C.

Well-3 is 1.5 km away from Well-1. The underground temperature above 10 m depth is influenced by surface temperature change. The depth range from 10 to 20 m shows different characteristics from that above 10 m depth, and is affected by a lateral groundwater flow. Below 20 m depth is constant through all seasons. This indicates that aquifers are separated at 20 m depth. This is also supported by the existence of a thin sand layer at 20 m depth. The lowest and highest temperatures from 10 to 20 m depth are in August and March, respectively. The phase difference is six months. The temperature difference between the lowest and the highest is 5.7 °C.

Well-7 is 3.7 km away from Well-1. The underground temperature above 11 m depth is influenced by surface temperature change. The depth range from 11 to 19 m shows different characteristics from that above 11 m depth and is affected by a lateral groundwater flow. Below 19 m depth is constant through all seasons. This suggests that the aquifers are divided at 19 m depth. The lowest and highest temperatures from 11 to 19 m depth are in February and June, respectively. The phase difference is almost zero. The temperature difference between the lowest and the highest is 0.3 °C.

2.4 Annual ground temperature change at 15 m depth

Ground temperature change at 15 m depth in each well can be fit well using a sine curve. Average temperature, phase difference and temperature fluctuation between minimum and maximum in each well are calculated from the fitted sine curves (Figure 3).

Figure 4 shows the ground temperature change in the study area. The phase difference of ground temperature against the river temperature (Figure 4a) basically increases from north to south in the southern side of the river. Although some wells far from the river seem to be out of sequence, the travel times of the groundwater from the river to these wells would be more than one year. The value of the phase differences of these wells should be added 365 or 730 days. The recharge area is estimated from this distribution at the yellow circle of Figure 4a. The phase differences in the northern side of the river show different and complicated characteristics relative to the southern side. This suggests the existence of several recharge area. This difference of northern and southern side results from the distribution of basement rocks such as chert. As the permeability of basement rocks is lower, the river water cannot infiltrate the aquifer of the southern side in the upper stream side of the yellow circle in Figure 4a.

Figure 4b shows the distribution of the annual average ground temperature. The wells near the river show lower temperatures, as the average temperature of the river water is lower than the average air temperature of study area. In the southern side of the river, the average ground temperature become higher toward south. Figure 4c shows the annual fluctuation of ground temperature. In the southern side of the river, this fluctuation becomes smaller toward the south.

3. DISCUSSIONS AND CONCLUSIONS

The maximum differences of seasonal temperature of each borehole generally become larger toward the apex of the fan. The maximum temperatures of most boreholes are generally not in the summer season, and this is not coincident with the temperature change of the river water. These suggest that the groundwater in the alluvial fan recharge from the river, and that the annual change of the underground temperature results from the lateral flow of the recharged groundwater.

For the low temperature geothermal use, the natural change of the underground temperature is important for the efficiency of the heat pumps. The area where the phase difference is 6 months is best, because the underground temperature in the summer becomes lower than the average outside air temperature. The potential study of the low temperature geothermal uses should contain the annual temperature change in the alluvial fans.

Ground temperature change at 15 m depth of each well can be fit by a sine curve. Distribution of phase differences shows that the average velocity of ground water flow is 8.5 x 10^{-3} cm/s (Figure 5a). The velocity of ground water flow is faster than the average value in the area less than 4 km from the recharge area, and slower more than 4 km. Generally, the permeability of the aquifer is higher near the top of the alluvial fan, and lower near the base. This difference of the permeability causes the difference of the velocity of ground water flow.

The velocity of ground water flow can be estimated by not only the distribution of phase differences but also that of annual temperature fluctuation. Stallman (1965) represents the following mathematical formula representing a steady one-dimensional fluid flow with sinusoidal surface temperature.

$$T - T_{AX} = \Delta T e^{ax} \sin(2\pi t/\tau - bx) \qquad (1)$$

where T is temperature, T_{AX} is temperature at $x = \infty$, x is distance along the direction of flow, t is time, τ is period of oscillation of temperature at $x = 0$. The parameters a and b are assumed to be constants, and are represented by the following equations:

$$a = \left[(K^2 + V^4/4)^{1/2} + V^2/2\right]^{1/2} - V \qquad (2)$$

and

$$b = \left[(K^2 + V^4/4)^{1/2} - V^2/2\right]^{1/2} \qquad (3)$$

where

$$K = \pi c \rho / k\tau \qquad (4)$$

and

$$V = v c_0 \rho_0 / 2k \qquad (5)$$

Here, c is specific heat of the fluid and rock in combination, c_0 is specific heat of the fluid, ρ is density of fluid and rock in combination, ρ_0 is density of fluid, and k is heat conductivity of fluid and solid in combination.

From Eq. 1, the annual temperature fluctuation at x is represented by the following equation (Yang et al, 2011):

$$ax = -\ln(\Delta T_x / \Delta T_0) \qquad (6)$$

The velocity of ground water flow is estimated to be 2.3 x 10^{-4} cm/s based on the distribution of the annual temperature fluctuation and Eq. 6 (Figure 5b). This estimated velocity is quite slow compared to what is expected from the phase differences of ground temperature. This difference would result from the pumping-up and leakage of ground water from the aquifer. Ground water is well pumped up in the study area, and the ground water in the studied aquifer should leak to the deeper aquifer. These pumping-up and leakage of ground water causes heat loss from the aquifer. This results in the extreme decrease of the annual temperature fluctuation as it is apart from the recharge area. Therefore, the estimated velocity from the annual temperature fluctuation is apparent, and the true velocity is that estimated from the phase differences of ground temperature.

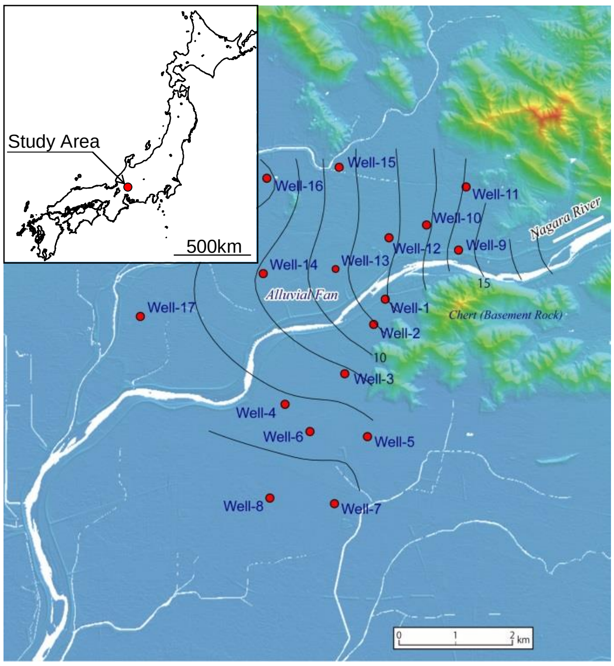
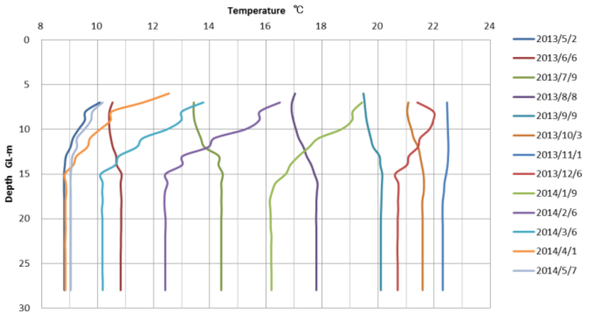
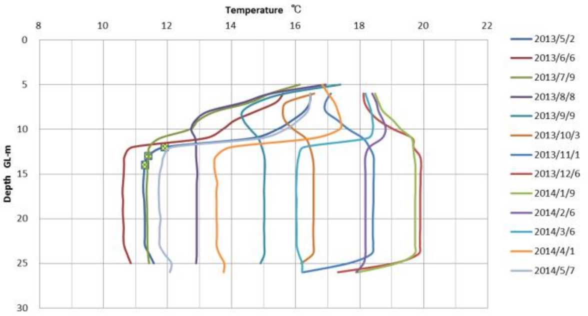


Figure 1. Distribution of the observation wells in the alluvial fan of the Nagara River. Contour lines indicate the distribution of hydraulic head with an interval of 1 m in May 2014.

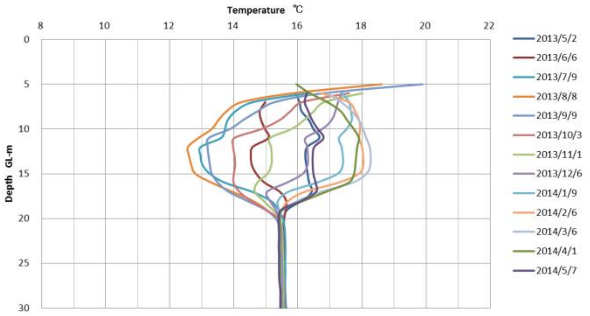
(a) Well-1



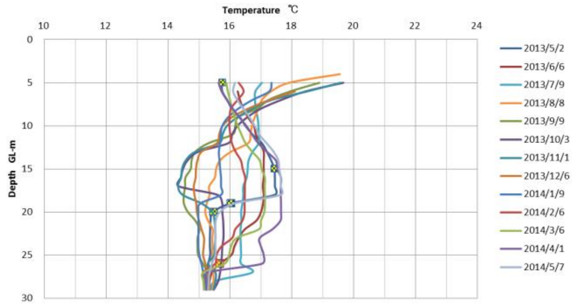
(b) Well-2



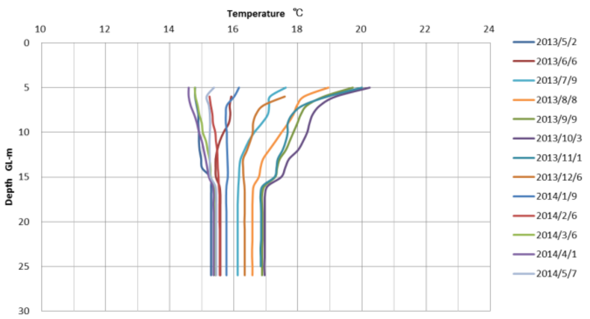
(c) Well-3



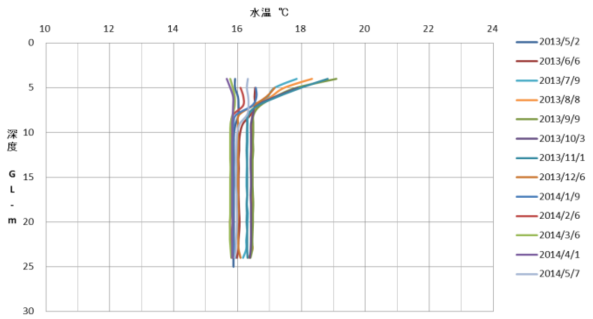
(d) Well-4



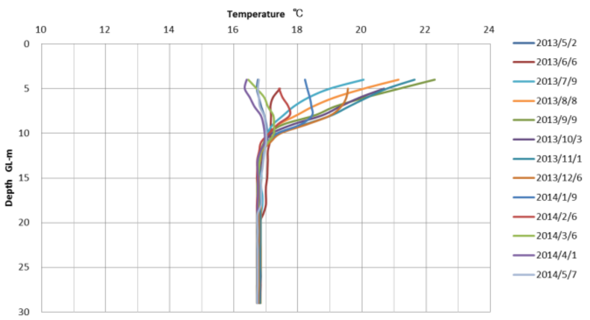
(e) Well-5



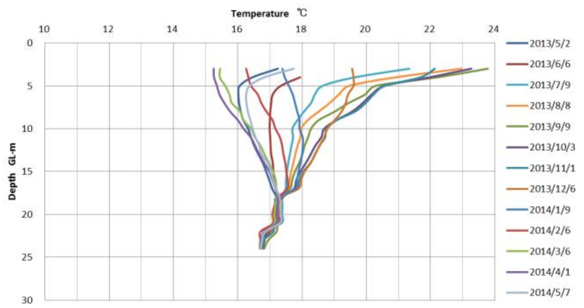
(f) Well-6



(g) Well-7



(h) Well-8



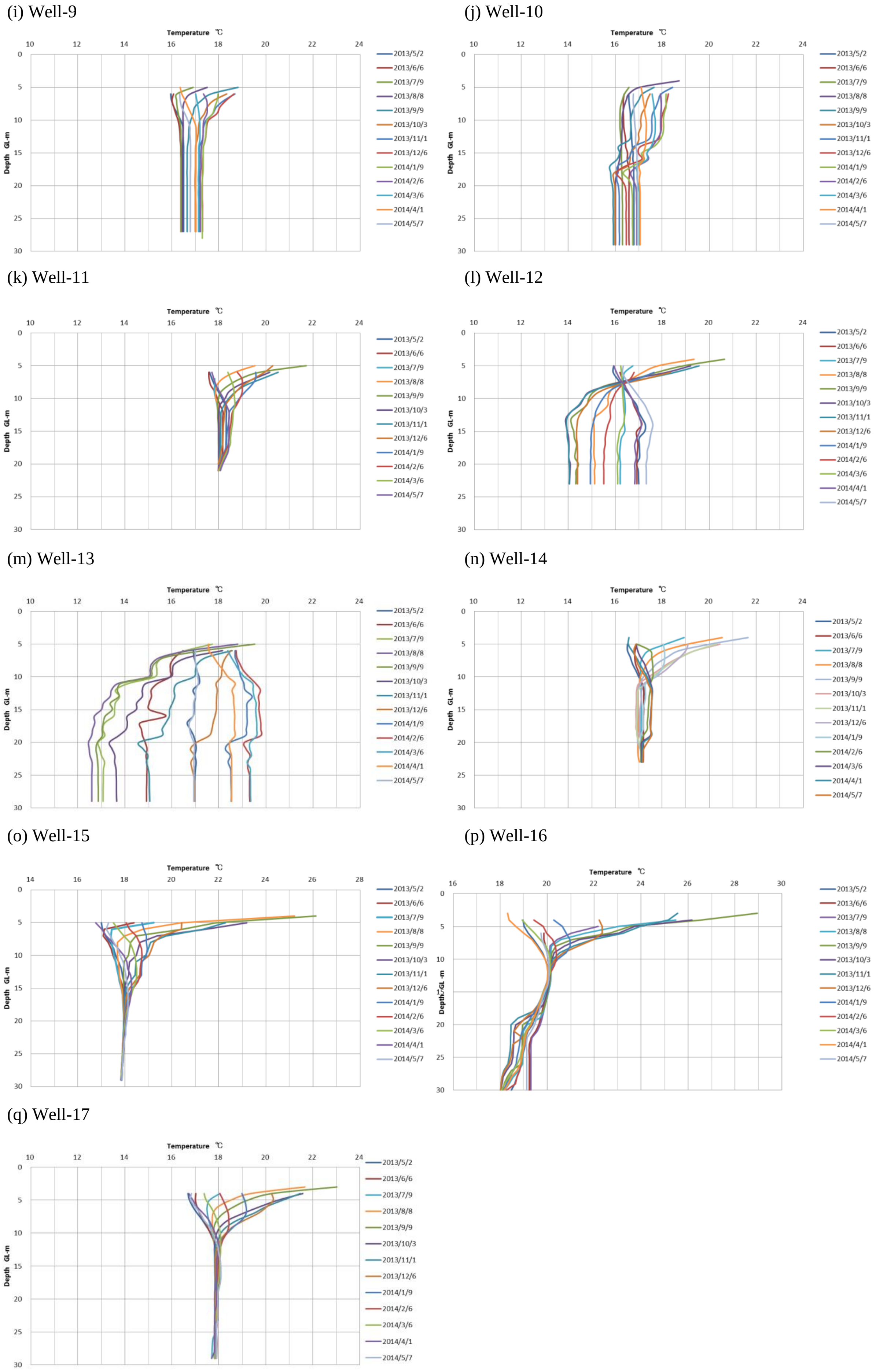


Figure 2. Underground temperature distribution of each observation well.

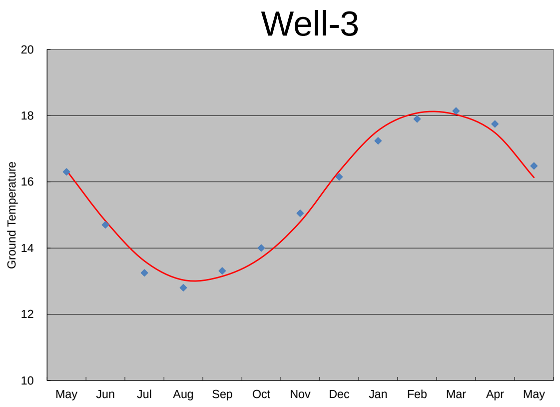


Figure 3. Observed ground temperature in 15 m depth and the result of the sine curve fitting.

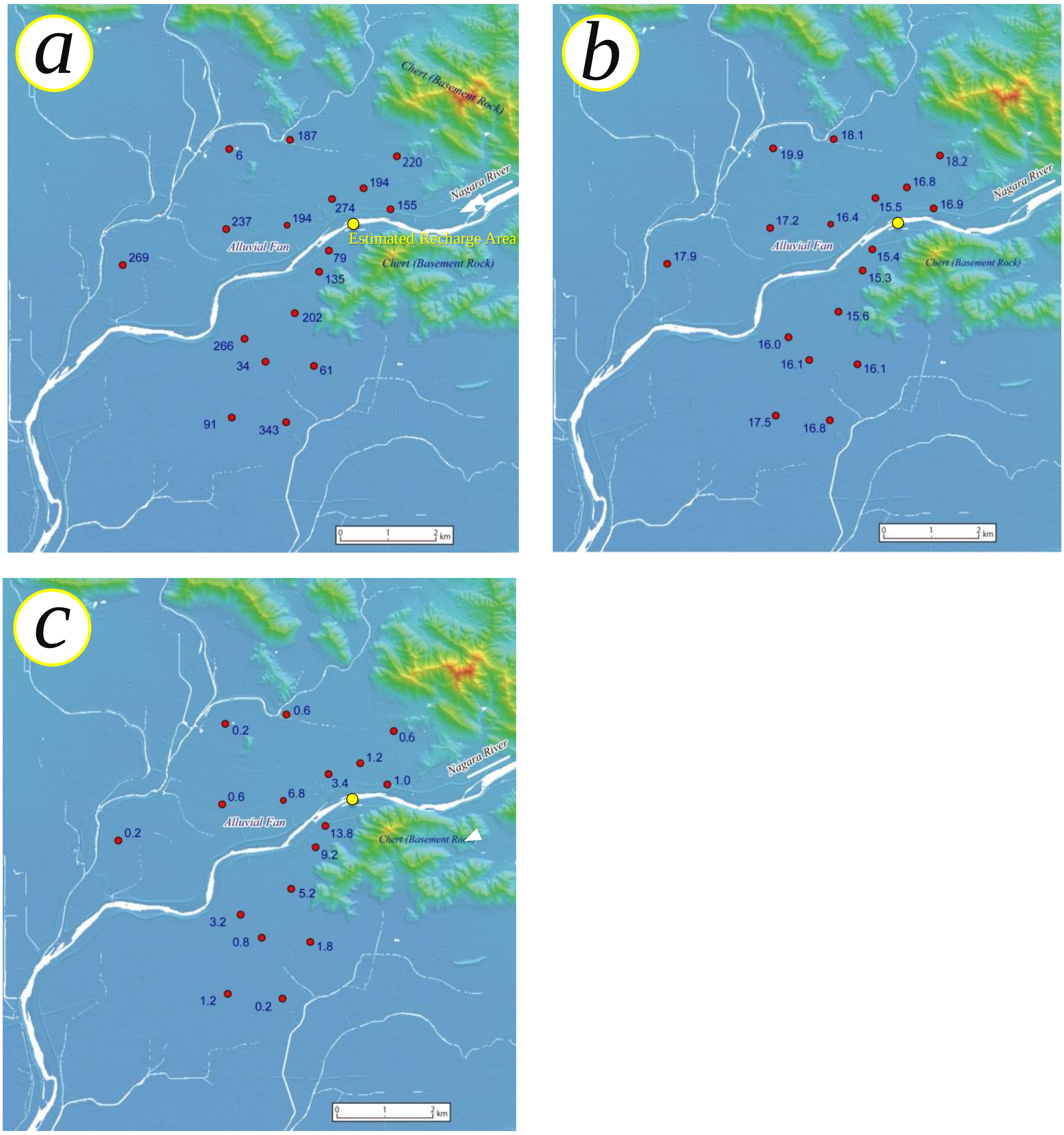


Figure 4. Ground temperature change in the alluvial fan of the Nagara River. Yellow circle is the estimated recharge area. (a) Phase difference (day) of ground temperature against the river temperature. (b) Annual average ground temperature. (c) Annual fluctuation of ground temperature.

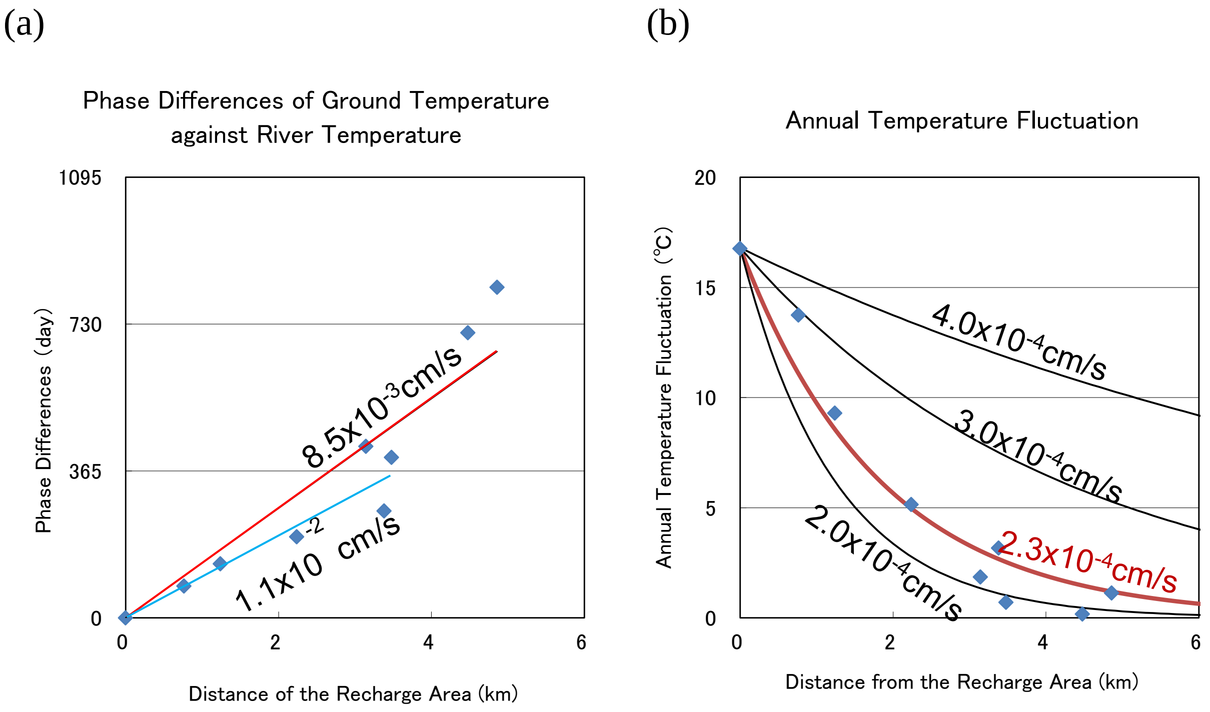


Figure 5. (a) Phase differences of ground temperature. Red line is estimated average velocity of ground water flow based on all data. Blue line is estimated velocity based on less than 4 km away from the recharge area. (b) Annual fluctuations of ground temperature. Red line is estimated velocity of ground water flow. Three black lines show the relation of annual temperature fluctuation and distance in the case of 2.0 x 10^{-4} cm/s, 3.0 x 10^{-4} cm/s and 4.0 x 10^{-4} cm/s.

ACKNOWLEDGMENT

I thank Gifu city government for permission to use the boreholes for measurements.

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