# SIMPLE EVALUATION OF GROUND-SOURCE HEAT PUMP SYSTEM INSTALLATION USING SHALLOW SUBSURFACE GEOLOGICAL INFORMATION IN THE AIZU BASIN, NORTHEAST JAPAN

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## ABSTRACT

Shallow subsurface geological structure mapping combined with ground effective thermal conductivity values at the basin scale provide an appropriate method to evaluate the installation potential of ground-source heat pump (GSHP) systems. In the Aizu Basin (Northeast Japan), the geological structure was analyzed using sedimentary cores and boring log and the distribution of average effective thermal conductivity in the range from 10 m to 100 m depth calculated from cores and logs was illustrated. Gravel layers are dominant in alluvial fans of the northern and southern basin areas, which are found to be associated with higher average effective thermal conductivity values, while central and western floodplain areas show lower values due to the existence of thick mud layers in the shallow subsurface. These results suggest that the conventional closed-loop systems are more suitable in northern and southern alluvial fan areas than in the central and western floodplain areas. It is the unique of this study that assessment for the GSHP systems installation potential using depth-based distribution maps of average effective thermal conductivity in the Quaternary sedimentary basin with highly complex geology. This approach is valuable and available for the simple assessment of the system installation in different sedimentary plains and basins in Japan and other countries.

**Keywords**: ground-source heat pump system, Quaternary geological structure, effective thermal conductivity, depth-based distribution map, Aizu Basin

## 1. INTRODUCTION

Ground-source heat pump (GSHP) systems have been spotlighted as one of the most energy efficient systems for providing space-cooling/heating, hot water supply, snow-melting, and more (Omer, 2008). In Japan, GSHP systems has installed increasingly since the year around 2000 (Ministry of Environment, Japan, 2017). The number of their installations, however, is still limited compared with the United States, Europe, and China. The reasons of the limitation are uncertainties regarding subsurface information (e.g. geology, groundwater flow, and thermal temperatures) that is required to plain optimal GSHP systems as well as the higher drilling costs associated with ground heat exchangers (GHEs).

In Japan, the population concentrates in the alluvial plains and basins filled by the Quaternary system with heterogeneous geological structure. The Quaternary system also act as suitable aquifers where groundwater flow occurs. These geological structure and groundwater flow affect effective thermal conductivity of ground and heat advection, respectively, that control the heat exchange rates of GHEs. Therefore, a suitability evaluation based on local hydrogeological information is required for the installation development of GSHP systems (Uchida et al., 2010).

Several studies regarding the installation suitability of GSHP systems (mainly closed-loop systems) in plain/basin scales have been carried out in different regions of Japan (e.g. Fujii et al., 2005, 2007; Uchida et al., 2010; Yoshioka, et al., 2010; Shrestha et al., 2015, 2017, 2018). These studies assessed the installation potential of GSHP systems on the analytical basis of three-dimensional groundwater flow and heat transport models and illustrated suitability maps. On the other hand, only a few studies has been evaluated GSHP system installation suitability using geological information (Hamada et al., 2002; Hamamoto et al., 2014; Takemura et al., 2014; Sakata et al., 2017). As mentioned above, the geological structure (thickness of gravel/mud layers and the three-dimensional continuity of each layer) controls the effective thermal conductivity as well as hydrogeological characteristics. Information of the geological structure can be not only essential input data for the analysis of groundwater flow and heat transport but also a basic evaluation index for the planning of GSHP systems.

From such background, Ishihara et al. (2018) reconstructed the shallow subsurface geological structure of the Aizu Basin, northeast Japan on the basis of coring survey and then prepared a depth-based distribution maps of effective thermal conductivity to simply assess GSHP system installation. This paper explains the above method of simple evaluation of GSHP system installation using geological information in the Aizu Basin (Fig. 1) based on Ishihara et al. (2018).

## 2. STUDY AREA

The Aizu Basin extend N-S for about 30 km and is about 12 km wide. In the north and south, the basin is enclosed by mountains consisting of Cretaceous granites and Neogene rocks (Suzuki et al., 1977). In the west and east, the basin is surrounded by hills mainly composed of Pliocene to middle Pleistocene sediments (Suzuki et al., 1977). The Aga River and its tributaries flow from the basin margin to the central areas of the basin. Alluvial fans formed by the above rivers are distributed in the northern and southern areas as well as the western and eastern margins. In contrast, a floodplain of the Aga River spread in the central and western basin areas.

The Aizu Basin is filled by a Quaternary system consisting of gravels, sands, muds, and tuffs with total over 150 m thickness (Suzuki et al., 1977), although minimal survey work with detailed geological structural information has been reported. Gravel layers of the systes host the main basin aquifers where groundwater flow primarily occurs. Groundwater recharges at the alluvial fan of the basin margin and flows to the central areas of the basin (Akimoto and Suzuki, 1988).

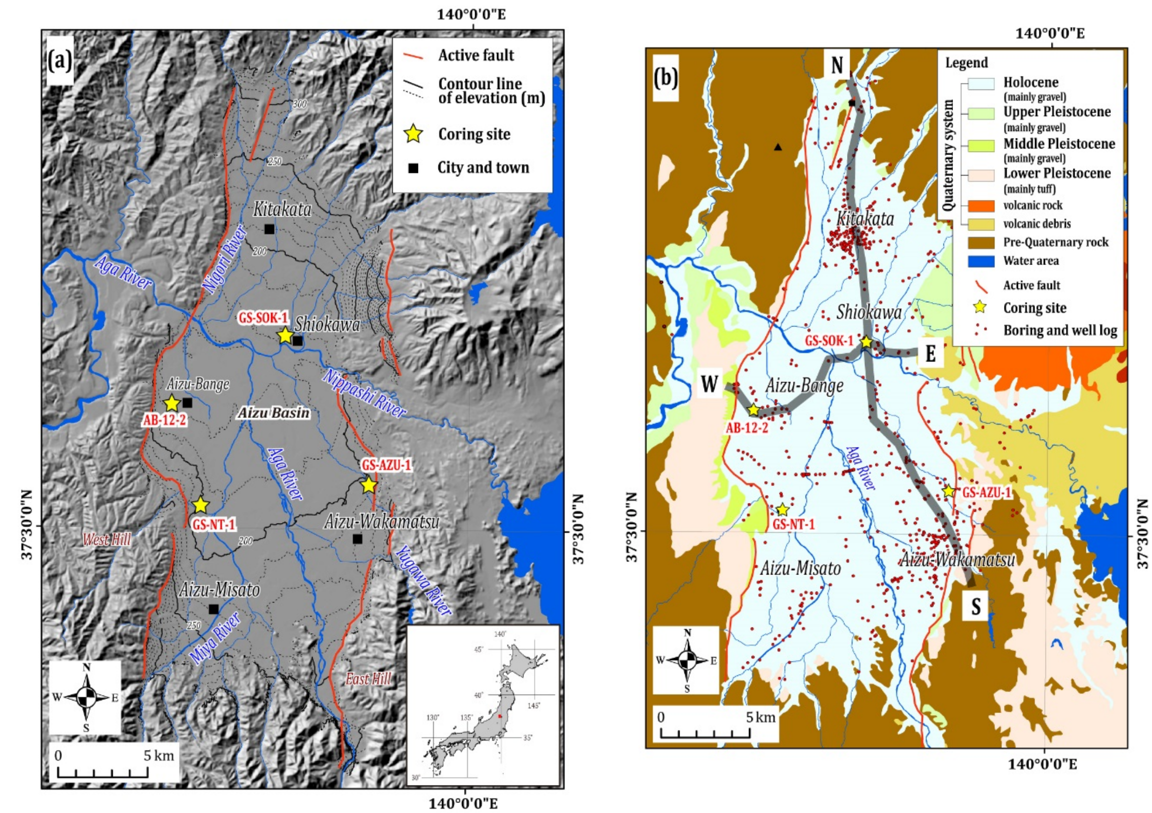


Fig. 1 (a) Location and geography of the Aizu Basin and (b) Geological map of the Aizu Basin (after Ishihara et al., 2018). Relief map and elevation contour lines (10 m interval) are drawn from the 50 m grid digital elevation map of the Geospatial Information Authority of Japan (GSI).

## 3. SHALLOW SUBSURFACE GEOLOGICAL STRUCTURE OF THE AIZU BASIN

To reconstruct the shallow subsurface geological structure of the Aizu Basin, Ishihara et al. (2018) first analyzed four sedimentary core samples (GS-AZU-1, GS-SOK-1, GS-NT-1, and AB-12-2 shown in Fig.1) with around 100 m depths and 790 boring/snow-melting well log data. The stratigraphy of these logs was interpreted in terms of the stratigraphic framework of the cores. Second, a lot of geological cross-sections were illustrated using cores and logs to clarify the three-dimensional continuity of the gravel/mud layers. Representative N-S and W-E geological cross sections are shown in Figs. 2 and 3, respectively. The lateral continuity of gravel/mud layers was examined in each section based on a comparison between facies of cores and log data.

Core analyses showed that all strata consist of Quaternary systems up to ca. 100 m depth in the basin. Based on core and log analyses, the geologica facies of the Quaternary system were classified into five types; gravel, sand, mud, peat, tuff (including pyroclastic flow sediment). Base rock of the system and top soil (artificial fill) were also found.

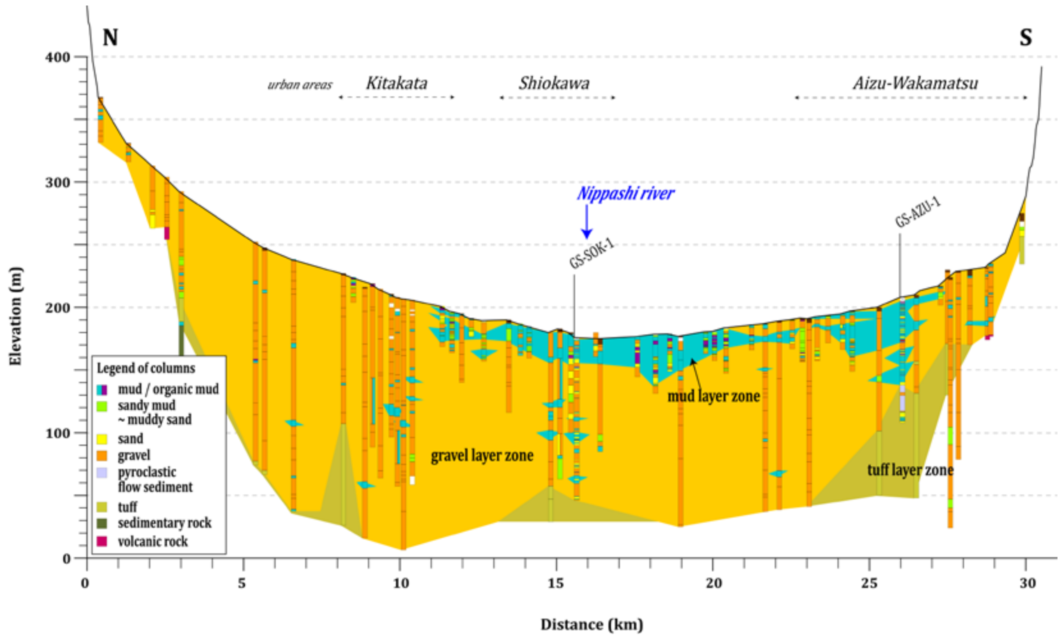


Fig. 2 N-S cross section shown in Figure 1b. Columns show sedimentary cores, boring, and snow melting well logs (after Ishihara et al., 2018).

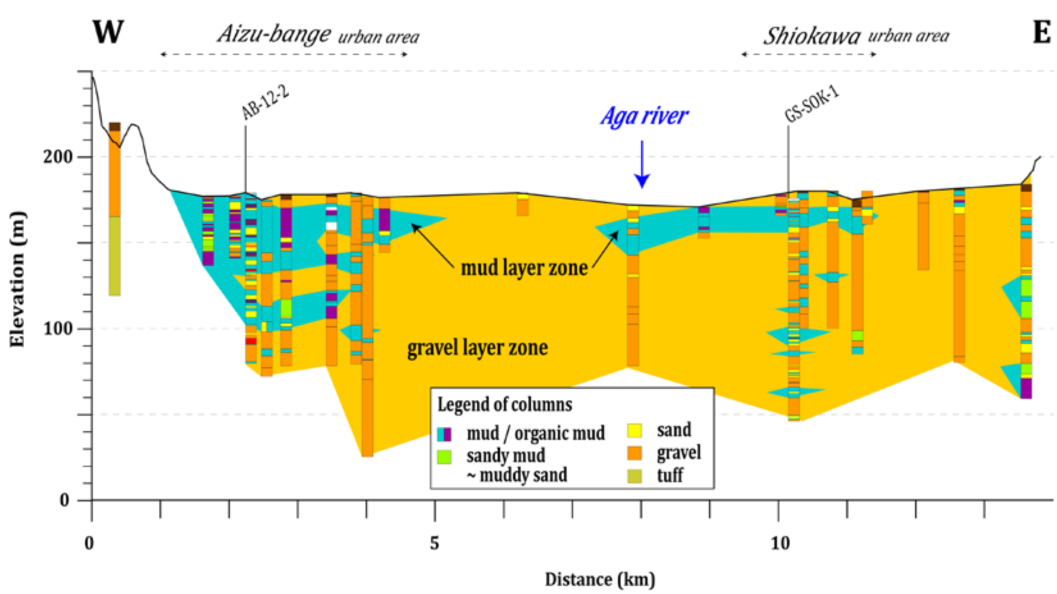


Fig. 3 W-E cross section shown in Figure 1b. Columns show sedimentary cores, boring, and snow melting well logs (after Ishihara et al., 2018).

Geological cross-sections show that gravel layers dominate up to 100 m depth from the ground surface throughout the Aizu Basin, especially in the northern (around Kitakata City) and southern (around Aizu-Wakamatsu City) alluvial fan regions. Mud beds are intercalated between gravel layers with a few-meter thickness in the northern and southern areas although their lateral continuity appears poor since the distribution depth and thickness vary in each log.

On the other hand, thick mud layers exist up to 20 ~ 50 m depth from the ground surface in four cores and many boring\well logs in the central and western regions (around Shiokawa and Aizu-Bange towns). It is indicated that these thick mud layers spread widely under the shallow parts of the central and western floodplain area except a region along the Aga River. Gravel layers become dominant below 40 m depth around a central area while mud layers still extend beneath 50 m around a western area (Fig. 3).

## 4. DISTRIBUTION OF AVERAGE EFFECTIVE THERMAL CONDUCTIVITY IN THE BASIN

For the consideration of suitable areas for the installation of GSHP systems in the Aizu Basin, Ishihara et al. (2018) calculated the effective thermal conductivity of each geological facies classified the previous section. The physical parameter of each facies for calculating effective thermal conductivity are listed in Table 1.

**Table 1.** Physical parameters of geological facies in the Aizu Basin. Geological facies were re-categorized from Shrestha et al. (2017, 2018). Porosity and thermal conductivity after Shrestha et al. (2017, 2018).

| Geological Facies | Porosity | Thermal Conductivity (W/m/K) | Ground Effective Thermal Conductivity (W/m/K) | |
|---|---|---|---|---|
| | | | Saturated | Unsaturated |
| Top soil | 0.2 | 1.4 | 1.25 | 1.12 |
| Mud (Silt) | 0.4 | 1.4 | 1.10 | 0.85 |
| Sand | 0.35 | 1.5 | 1.20 | 0.98 |
| Gravel | 0.25 | 1.6 | 1.36 | 1.21 |
| Peat | 0.5 | 0.7 | 0.68 | 0.36 |
| Tuff (Pyroclastic flow sediments) | 0.2 | 1.0 | 0.93 | 0.80 |
| Rock | 0.15 | 2.5 | 2.22 | - |
| Water | - | 0.65 | - | - |
| Air | - | 0.024 | - | - |

Calculation of effective thermal conductivity ($\lambda_g$) was expressed as follows:

$$\lambda_g = (1 - e)\lambda_s + eS\lambda_f + e(1 - S)\lambda_a \quad (1)$$

where $\lambda_s$, $\lambda_f$ and $\lambda_a$ are thermal conductivity of the solid (sediment/rock), fluid (water) and air, $e$ is the porosity, and S is the moisture saturation. The groundwater level (i.e. boundary between saturated/unsaturated zone) of the basin exists below 0 m to 5 m from the ground surface (Kaneko and Nakagawa, 1969) and its fluctuation ranges are less than 5m (Kaneko et al., 2017), thus in this calculation, the groundwater level was set to 5 m below the surface.

In the case where the effective thermal conductivity (average value) of certain location is obtained from boring log data with geological heterogeneity, the value are estimated by length-weighted average methods using an effective thermal conductivity and thickness of each facies:

$$\lambda_{ave} = \Sigma(\lambda_{gk} \times L_k)/\Sigma L_k \quad (1)$$

where $\lambda_{gk}$ and $L_k$ are the effective thermal conductivity and total thickness of each facies, respectively.

After calculation, distributions of average effective thermal conductivity were mapped in the range from a –10 m to –100 m depth using an inverse distance weighted algorithm in the ArcGIS software package (ESRI Japan Corporation) (Fig. 4).

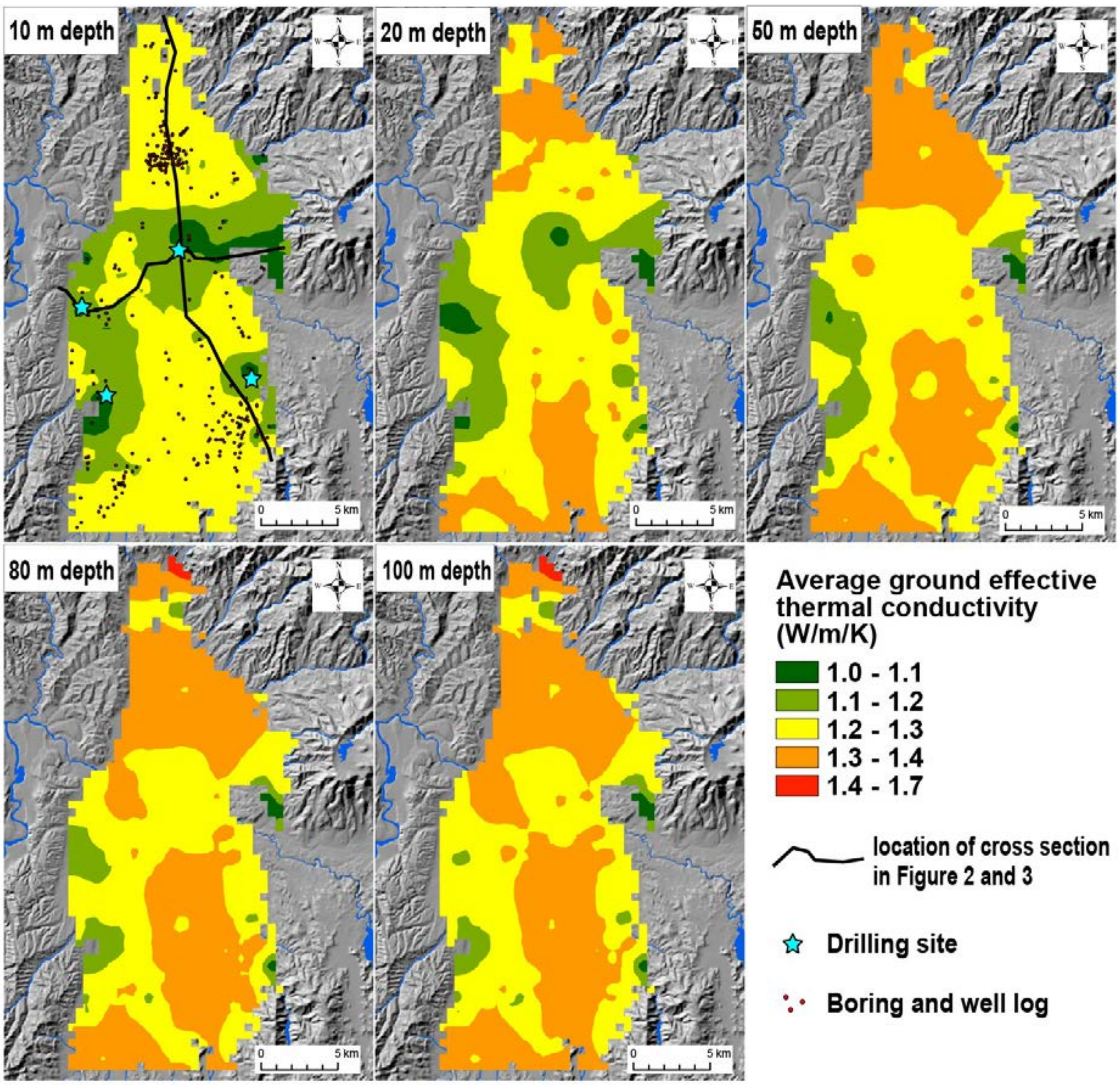


Fig. 4 Distribution map of the average effective thermal conductivity (10 m, 20 m, 50 m and 100 m depth) (modified from Ishihara et al., 2018).

Fig. 4 shows that values of average effective thermal conductivity were higher (1.3-1.4 W/m/K) in the northern and southern basin areas corresponding to gravelly alluvial fan regions. Moreover, these alluvial fans are expected to act as preferable aquifers, thus values of effective thermal conductivity should be higher due to heat advection by groundwater flow (apparent thermal conductivity) in the northern and southern basin areas.

By contrast, lower values of average effective thermal conductivity (1.0-1.3 W/m/K) were estimated for the central and western floodplain areas except along the Aga River because of thick mud layers in the shallow subsurface. The average effective thermal conductivity slightly increase with depth in the central area due to an increase of the ratio of gravel layers below approximately 50 m depth although the values remains low in the western area up to 100 m depth due to existence of thick mud layers (Figs. 2 and 3).

The above information of geological structure and effective thermal conductivity indicates that conventional closed-loop systems are more feasible in the northern and southern basin areas including Kitakata and Aizu-Wakamatsu cities than the central and western basin areas including Shiokawa and Aizu-Bange towns. If a conventional GSHP systems will be installed in the northern and southern areas, the GHE depth of the system is suggested to be shorter (concerning lower initial costs) than in the central and western areas. However, in region with higher groundwater velocity the apparent thermal conductivity should be higher than the effective thermal conductivity, therefore thermal response tests and/or based on three-dimensional groundwater flow and heat transfer analysis are required for more accurate evaluation of the suitability of GSHP system. Geological and effective thermal conductivity data are also available as a reference for such analyses.

In this way, Ishihara et al. (2018) prepared that the installation suitability of GSHP system (conventional closed-loop system) can be simply evaluate using the geological information. The approach of the assessment using depth-based distribution maps of average effective thermal conductivity is unique in the study. The combination of geological cross-sections to the distribution maps may be helpful for considering the system design such as GHE depth. The approach of Ishihara et al. (2018) is proper and valuable for the simple evaluation of GSHP system installation in other sedimentary plains and basins with heterogeneous geology in Japan and other countries.

## REFERENCES

Akimoto, T. and Suzuki, Y. (1988) Water quality of confined groundwater in the Aizu Basin, Fukushima Prefecture (In Japanese with English Abstract). *Jpn. Assoc. Hydrol. Sci.*, *18*, 14–21.

Fujii, H., Inatomi, T., Itoi, R. and Uchida, Y. (2007) Development of suitability maps for ground-coupled heat pump systems using groundwater and heat transport modeling. *Geothermics*, *36*, 459–472.

Hamada, Y., Tanaka, S., Nagano, K., Tamura, H., Takigawa, I., Nakamura, Y., Marutani, K., Takashimizu, Y. and Takada, M. (2009) Feasibility study of underground thermal energy system by using digital national land information (In Japanese with English Abstract). *Trans. Soc. Heat., Air-cond. Sanit. Eng. Jpn.*, *34*, 1–10.

Hamamoto, H., Shiraishi, H., Hachinohe, S., Ishiyama, T., Satake, K. and Miyakoshi, A. (2014) Synthesis of subsurface temperature information and evaluation of potential for setting up ground heat exchangers in Saitama prefecture (In Japanese with English Abstract). *Butsuri-Tansa (Geophys. Explor.)*, *67*, 107–119.

Ishihara, T., Shrestha, G., Kaneko, S. and Uchida, Y. (2018) Analysis of shallow subsurface geological structure and ground effective thermal conductivity for the evaluation of ground-source heat pump system installation in the Aizu Basin, northeast Japan. *Energies* **2018**, *11*, 2098.

Kaneko, R. and Nakagawa, S. (1969) Water balance in Aizu Basin (In Japanese with English Abstract). *Bull. Natl. Res. Inst. Agric. Eng. Japan.*, *7*, 33–51.

Kaneko, S., Shibasaki, N., Shoji, M. and Uchida, Y. (2016) Characteristics of changes in groundwater level and groundwater temperature based on long-term monitoring in the Aizu Basin, Fukushima, Japan (In Japanese with English Abstract). *Bull. Geol. Surv. Japan*., *67*, 183–208.

Omer, A.M. (2008) Ground-source heat pumps systems and applications. *Renew. Sustain. Energy Rev*., *12*, 344–371.

Sakata, Y., Katsura, T. and Nagano, K. (2018) A study on estimation of ground effective thermal conductivity as probability-weighted average (In Japanese with English Abstract). *J. Geotherm. Res. Soc. Jpn*., *40*, 33–44.

Shrestha, G., Uchida, Y., Yoshioka, M., Fujii, H. and Ioka, S. (2015) Assessment of development potential of ground-coupled heat pump system in Tsugaru Plain, Japan. *Renew. Energy*, *76*, 249–257.

Shrestha, G., Uchida, Y., Kuronuma, S., Yamaya, M., Katsuragi, M., Kaneko, S., Shibasaki, N. and Yoshioka, M. (2017) Performance evaluation of a ground-source heat pump system utilizing a flowing well and estimation of suitable areas for its installation in Aizu Basin, Japan. *Hydrogeol. J*., *25*, 1437–1450.

Shrestha, G., Uchida, Y., Ishihara, T., Kaneko, S. and Kuronuma, S. (2018) Assessment of the installation potential of a ground source heat pump system based on the groundwater condition in the Aizu Basin, Japan. *Energies*, *11*, 1178.

Suzuki, K., Manabe, K. and Yoshida, T. (1977) The late Cenozoic stratigraphy and geologic development of the Aizu Basin, Fukushima Prefecture, Japan (In Japanese with English Abstract). *Mem. Geol. Soc. Japan*., *14*, 17–44.

Takemura, T., Nakazato, K., Tajima, T. and Takano, Y. (2014) Extraction of geological conditions for ground heat utilization and the development of an independent source system utilizing heat and water power (In Japanese with English abstract). *Proc. Inst. Nat. Sci*., *Nihon Univ*., *49*, 155–162.

Uchida, Y., Yoda, Y., Fujii, H., Miyamoto, S. and Yoshioka, M. (2010) Adoption of suitability area for ground-coupled heat pump systems 1st paper, Development of suitability maps for ground-coupled heat pump systems using groundwater flow/heat transport modeling and geographic information system (In Japanese with English Abstract). *J. Geotherm. Res. Soc. Jpn*., *32*, 229–239.

Yoshioka, M., Uchida, Y., Yoda, Y., Fujii, H. and Miyamoto, S. (2010) Adoption of suitability area for ground-coupled heat pump systems 2nd paper, Development of heat exchange rate maps using groundwater flow/heat transport modeling (In Japanese with English Abstract). *J. Geotherm. Res. Soc. Jpn*., *32*, 241–251.