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Assessment of the Installation Potential of a Ground Source Heat Pump System Based on the Groundwater Condition in the Aizu Basin, Japan

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Abstract: Assessment of suitable locations for a ground source heat pump (GSHP) system based on the groundwater condition of study area is important for its sustainable development. Installation potential of a GSHP system was evaluated for the Aizu Basin, Japan. Firstly, suitability assessment was done for a conventional closed-loop system by preparing a distribution map of heat exchange rates for space heating. Heat exchange rates were higher at the northern and southern areas and lower at the central area, indicating that the northern and southern areas are appropriate for the conventional system. A different type of GSHP system using an artesian well was proposed at the central area because groundwater is flowing in an upward direction and using its heat energy can increase heat exchange rates. Demonstration of this system using an artesian well for space heating resulted in higher heat exchange rates compared to the conventional system. A GSHP system using an artesian well is suitable at the central area, and the conventional one is suitable at the northern and southern areas. Assessment of the installation potential of different types of GSHP system in the same Aizu Basin based on its groundwater condition is unique to this study. It can assist in selecting suitable locations for GSHP system installation and to promote its growth in Japan.

Keywords: ground source heat pump system; installation potential; groundwater; heat exchange rate; artesian well

1. Introduction

The ground source heat pump (GSHP) system is a competent and capable system for energy and environment conservation. Low-enthalpy geothermal energy is used by this system for air conditioning, heating, and so forth [1,2]. Growth of this system is increasing in Japan [3], but it is still behind the expected goals as compared to Europe and America. The major reason for the slow development is the higher capital cost resulting from a bigger design of the system than is needed. Determination of suitable places to construct GSHP systems based on the groundwater condition of the target region is essential for the best-suited design and sustainable growth of the system in Japan.

Temperature structure under the ground is perturbed by groundwater flow due to its advection effect, by which heat is transported with the flow [4–7]. Due to this, the groundwater condition of the region strongly influences the heat exchange efficiency and performance of GSHP systems [8–12]. In the context of Japan, a large percentage of the population lives in urban areas, which are situated on a Quaternary system. This Quaternary system acts as the main aquifers where groundwater flow occurs [13]. Therefore, if the advantage of this groundwater could be effectively taken, the heat exchange rate of a GSHP system can be increased efficiently.

Some researches had evaluated the installation potential of a GSHP system in different areas of Japan. Previous studies [1,14–17] had assessed the installation potential of a GSHP system in plain and basin scales of Japan. In these studies, suitability maps were prepared that illustrate appropriate places for the construction of a GSHP system, based on groundwater flow and heat transport analysis. Fujii et al. [1] and Yoshioka et al. [15] calculated heat exchange rates at different locations and mentioned their importance for suitable places and appropriate design of the system. Uchida et al. [14] integrated the results of numerical analysis and hydrogeological field data to prepare suitability maps for GSHP systems using the geographic information system (GIS). Shrestha et al. [16] prepared the distribution map of effective thermal conductivity based on the results of groundwater flow analysis and field data obtained from thermal response tests. Shrestha et al. [17] evaluated the economic efficiency of GSHP systems by preparing the distribution map of the coefficient of performance (COP) in addition to the distribution map of heat exchange rates. From the COP, the electricity consumption of the system and its operational cost can be predicted, which can be useful to select the suitable locations and optimum design of the system.

These abovementioned studies to assess the installation potential at the regional scale are still limited in Japan. On the basis of the abovementioned studies, suitable locations for GSHP system installation can be evaluated. However, in these studies, only a conventional closed-loop system was considered in their analyses. At the locations which are less suitable for this conventional system, alternative types of systems that can be installed at those less suitable areas were not proposed at all. In the current scenario, studies concerning the conventional system only will not lead to the growth of the GSHP system as a whole. Evaluation of the installation potential of the GSHP system for both suitable as well as less suitable locations is very crucial to enhance its sustainable use, as well as to promote its further development in Japan. This kind of work has not been done until now. As already mentioned, major Japanese cities are situated on alluvial plains and basins, with actively flowing groundwater. Hence, the groundwater condition should be taken into consideration in order to assess the installation potential of the system more accurately in the case of Japan. This study's main objective is to evaluate the installation potential of not only the conventional system, but also an alternative type of system based on the groundwater condition of the target area.

In this study, the installation potential of a GSHP system in the Aizu Basin was evaluated based on the regional groundwater condition. Groundwater condition and underground temperature structure of the Aizu Basin was analyzed by using a groundwater flow and heat transport model and a field survey. Firstly, the assessment was done for the conventional closed-loop system by preparing a distribution map of heat exchange rates for space heating. This map was prepared by using the results of the heat exchange simulations conducted with ground heat exchanger (GHE) models constructed at several locations within the Aizu Basin. The northern and southern areas were found to be more appropriate for the conventional system with higher heat exchange rates. Then, at the less suitable central area with lower heat exchange rates, a different type of GSHP system using an artesian (flowing) well developed by Shrestha et al. [18] was proposed. It is because at these locations, groundwater upflow is occurring, and utilizing its heat can enhance the system's heat exchange performance. Demonstration of this system using an artesian well for space heating resulted in higher heat exchange rates compared to the conventional system at the central area. This kind of suitability assessment and comparison of heat exchange performance of different types of GSHP systems in the same region based on its groundwater condition is unique to this study. Additionally, this study can be effective to select appropriate areas for the suitable types of GSHP systems, as well as to update the present development trend of GSHP systems in the whole of Japan.

2. Study Area

The study area is the Aizu Basin, which is based in Fukushima Prefecture, Japan (Figure 1). Its area is about 324 km^2, with the length of 30 km (N–S) and the width of 12 km (E–W). Elevation of the basin varies from 170 m to 320 m. The Aizu Basin is surrounded by uplands composed of Upper Neogene to Middle Pleistocene sediments, with elevation varying from 300 m to 400 m, and mountains composed of Cretaceous and Middle Miocene rocks, with elevation varying from 1000 m to 2000 m [19]. This basin is formed by Quaternary sediments carried by the Aga River and its tributaries flowing through the basin. The Quaternary system is composed of sand and gravel, which act as aquifers within the basin.

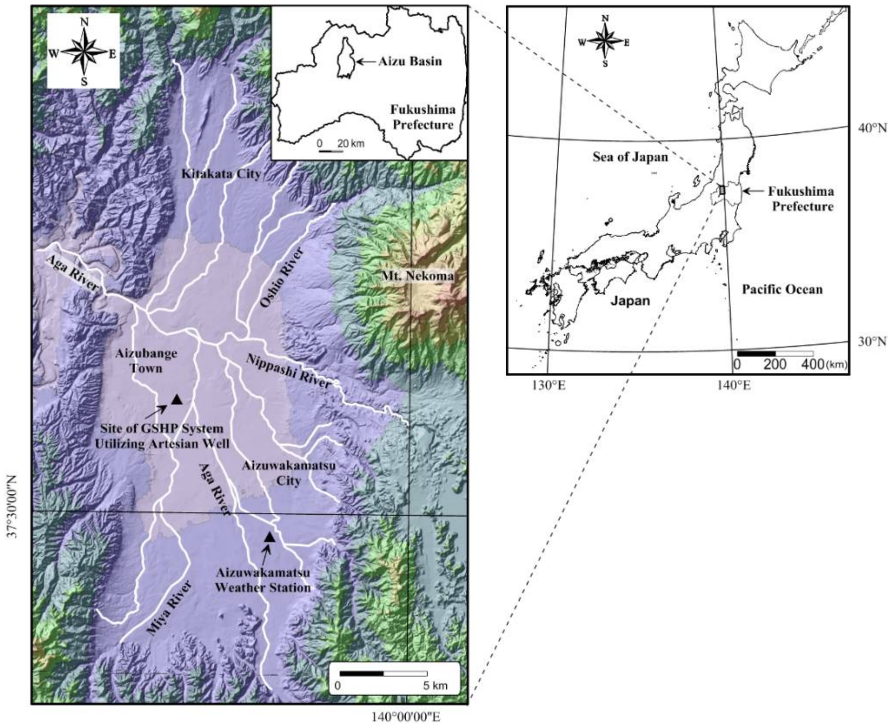

Figure 1. Location of the Aizu Basin.

3. Regional Scale 3D Analysis Model

Analysis of groundwater flow and heat transport must to be done for assessing the installation potential of a GSHP system. For this purpose, an analysis model (Figure 2) developed by Shrestha et al. [18] was used in this paper. The finite element program FEFLOW [20] was used to develop this analysis model. A brief description of the analysis model is presented below.

Layers 1 to 33 are taken as the aquifer system, and layers 34 to 39 are regarded as the bed rock of the Aizu Basin. Horizontal mesh of the model was refined along the rivers and the major area of the basin, and vertical mesh was refined at the upper layers compared to the bottom layers for accuracy in the computations. On the basis of past geological borehole recordings, 10 hydrogeological facies were classified. Table 1 shows these hydrogeological facies and physical parameters of the analysis model. As groundwater aquifers are mainly composed of gravel and sand, their hydraulic conductivities were set in detail with the model depth. Volumetric heat capacity of 2.52 $MJ/m^3/K$ was assigned to the model layers.

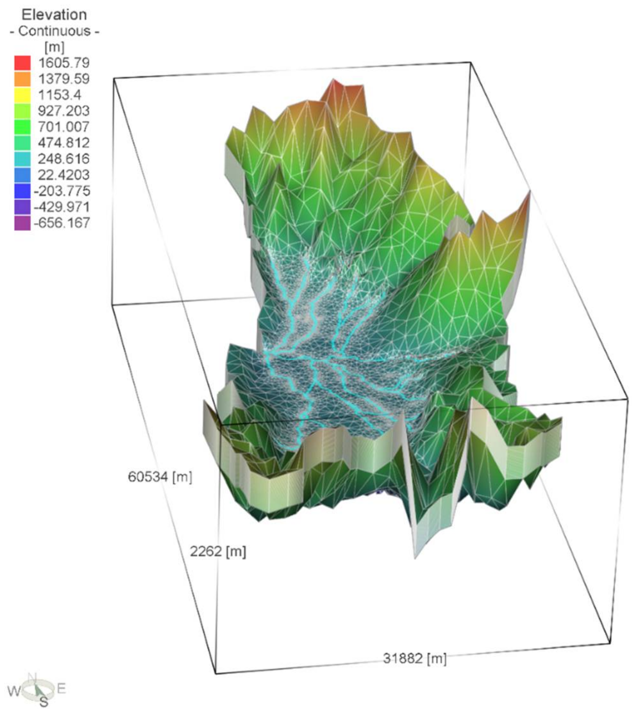

Figure 2. Analysis model of the Aizu Basin. Reprinted by permission from Springer Customer Service Centre GmbH: Springer HYDROGEOLOGY JOURNAL (Performance evaluation of a ground-source heat pump system utilizing a flowing well and estimation of suitable areas for its installation in Aizu Basin, Japan, Shrestha et al., 2017).

Table 1. Parameters of analysis model.

Hydrogeological Facies	Hydraulic Conductivity (m/day)					Porosity (-)	Thermal Conductivity (W/m/K)
	Layers 1 to 5	Layers 6 to 10	Layers 11 to 15	Layers 16 to 20	Layers 21 to 39		
Top Soil	0.5	0.5	0.5	0.5	0.5	0.2	1.4
Clay	1×10^{-4}	1×10^{-4}	1×10^{-4}	1×10^{-4}	1×10^{-4}	0.45	1.3
Silt	0.01	0.01	0.01	0.01	0.01	0.4	1.4
Sand	8.0	4.0	1.6	0.8	0.4	0.35	1.5
Gravel	10.0	5.0	2.0	1.0	0.5	0.25	1.6
Volcanoclastic material	1.0	1.0	1.0	1.0	1.0	0.2	1.0
Loam	0.02	0.02	0.02	0.02	0.02	0.4	0.9
Peat	0.01	0.01	0.01	0.01	0.01	0.5	0.7
Others	0.5	0.5	0.5	0.5	0.5	0.2	1.2
Rock	1×10^{-6}	1×10^{-6}	1×10^{-6}	1×10^{-6}	1×10^{-6}	0.15	2.5

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Boundary Conditions and Validation of Analysis Model

Using the above analysis model, computation was done to elucidate the groundwater system and underground temperature structure. To analyze the groundwater, surroundings of the model were affixed with groundwater levels and rivers with elevations. The model's bottom and vertical sides were assumed as impervious. To analyze the underground temperature regime, the top of the model was set with temperature based on the atmospheric temperature of the Aizu Basin, considering variation in elevation, and the bottom was fixed with temperature calculated by using vertical temperature gradients of 0.036 °C/m for layers 1 to 33 and 0.060 °C/m for layers 34 to 39.

The analysis model had been validated by comparing the calculated results of groundwater levels and vertical distribution of underground temperature with their corresponding measured field data of the existing wells in the basin [18]. Figures 3 and 4 show the verification of calculated hydraulic heads and underground temperature with their measured data. More details about the analysis model and its validation can be referred to in the previous work by Shrestha et al. [18].

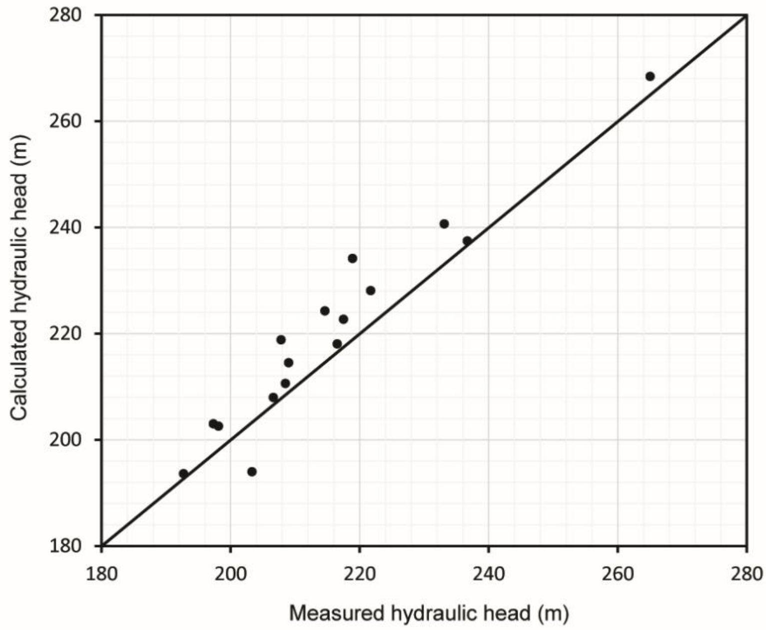

Figure 3. Comparison of calculated hydraulic heads with measured values. Reprinted by permission from Springer Customer Service Centre GmbH: Springer HYDROGEOLOGY JOURNAL (Performance evaluation of a ground-source heat pump system utilizing a flowing well and estimation of suitable areas for its installation in Aizu Basin, Japan, Shrestha et al., 2017).

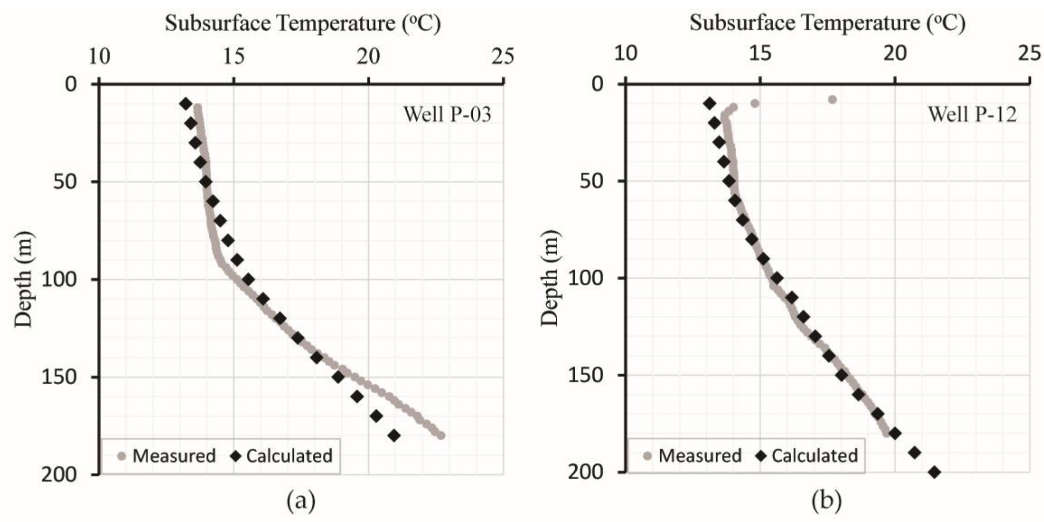

Figure 4. Comparison of calculated underground temperature distribution with measured values. (**a**) Comparison for Well P-03; (**b**) comparison for well P-12. Reprinted by permission from Springer Customer Service Centre GmbH: Springer HYDROGEOLOGY JOURNAL (Performance evaluation of a ground-source heat pump system utilizing a flowing well and estimation of suitable areas for its installation in Aizu Basin, Japan, Shrestha et al., 2017).

4. Ground Heat Exchanger Model

In order to determine suitable areas for the construction of a GSHP system, a suitability map showing a distribution of heat exchange rates is considered to be useful. Assuming a conventional closed-loop system, identical ground heat exchanger (GHE) models (Figure 5) of dimensions 20 m × 20 m × 120 m were constructed at 20 locations (Figure 6) to compute heat exchange rates at these locations. These locations are referred to hereafter as "GHE locations". As the Aizu Basin is situated in a cold-weather region of Japan, computations were done for space heating purposes.

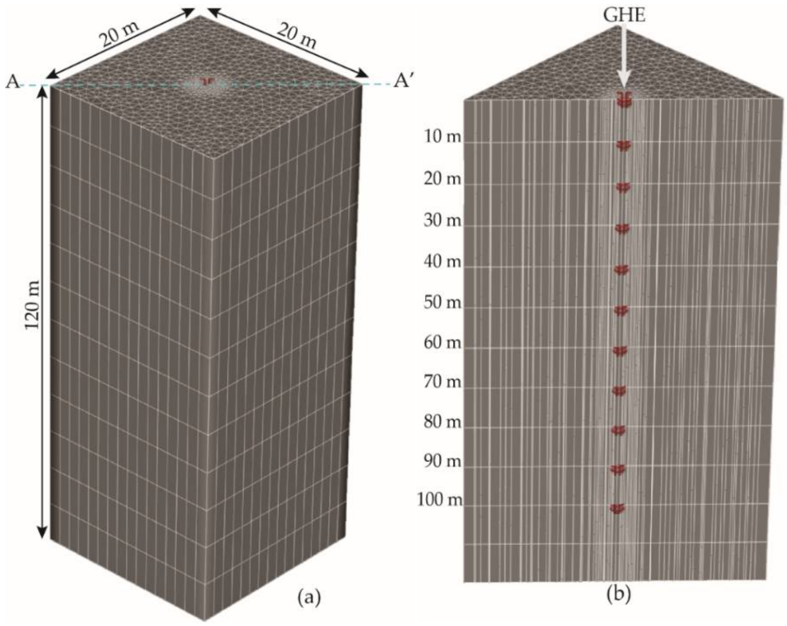

Figure 5. Ground heat exchanger (GHE) model. (**a**) Three-dimensional model; (**b**) cross-sectional view at A–A′.

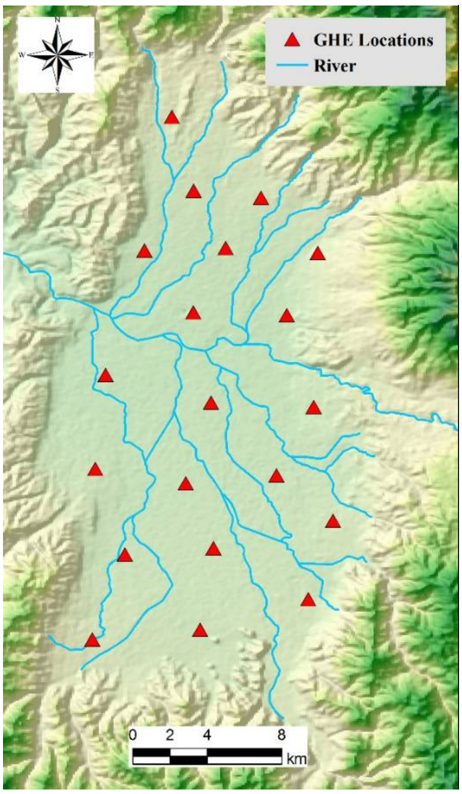

Figure 6. Locations of ground heat exchanger models.

GHE models were constructed using the finite element program FEFLOW [20]. Parameters adopted for the GHE models are the same as those assigned for the analysis model as shown in Table 1. For each GHE model, the same geological data and hydrological and thermal parameters from the same GHE locations in the analysis model were assigned. Similarly, initial and boundary conditions of the GHE models were set based on the groundwater flow velocity, hydraulic head, and underground temperature calculated from the analysis model at each GHE location.

At the center nodes of the GHE models, a ground heat exchanger of 100-m depth was set. A double U-tube of diameter 34 mm and grout of silica sand were considered. For groundwater analysis, the models' top and bottom were assumed as impervious without any flow. Vertical faces were affixed with groundwater levels to obtain the same flow velocities that were computed at the same points from the analysis model. For underground temperature, results gained from the analysis model were assigned to all layers.

Distribution Map of Heat Exchange Rates

For each GHE model at the respective locations, heat exchange simulations were done for space heating. The operating scenario was set as 120 days of space heating per year from December to March, with 24-h operation. The inlet temperature and flow rate of circulation fluid were maintained as 5 °C and 20 L/min, respectively. Water is taken as a circulation fluid. From the simulations, heat exchange rates at GHE locations were estimated. On the basis of estimated values, a distribution map of heat exchange rates (Figure 7) in the Aizu Basin was prepared using ArcGIS.

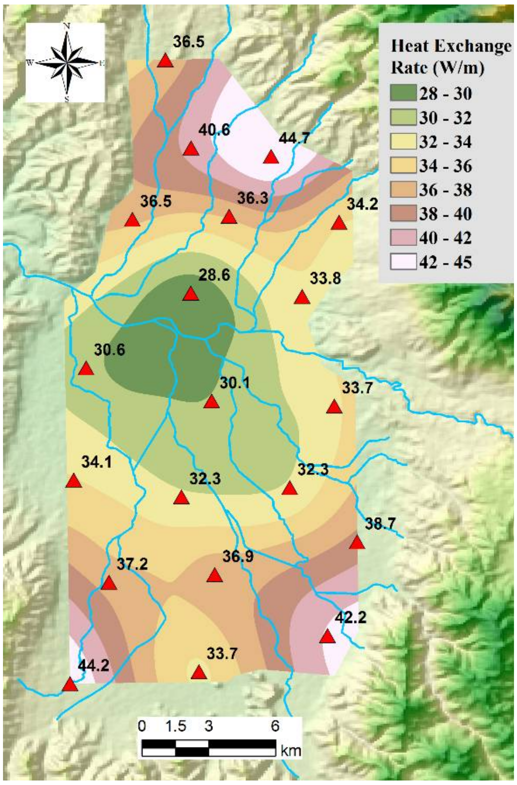

Figure 7. Distribution map of heat exchange rates.

Heat exchange rates were found to be higher at the northern and southern areas of the basin, which are the upstream areas of rivers flowing from the north and south parts, respectively. Heat exchange rates at the central basin were lower compared to these areas. The distribution map of heat exchange rates (Figure 7) indicates that the northern and southern areas are more suitable for installing conventional closed-loop GSHP systems than the central basin. This is because groundwater flow velocities were found to be higher at these upstream northern and southern areas and lower at the central area. Figure 8 shows the distribution map of groundwater flow velocity in the Aizu basin, resulting from the analysis model. Groundwater flow velocities are higher at the northern and southern areas because of higher hydraulic gradients and preferable geology at these areas. When the groundwater flow velocity is higher, the apparent thermal conductivity of the subsurface also increases, caused by heat transfer through groundwater advection [16,21–24]. Higher flow velocity also assists in retrieving the heat energy at the GHE, which thereby improves heat exchange rate of the system by maintaining constant subsurface temperature at and around the GHE. At the central area, there are clay layers in the underground [25]. Presence of these clay layers and small hydraulic gradients at the central area are the main factors influencing the low groundwater flow velocities at this area. Because of these lower groundwater flow velocities, heat exchange rates for the conventional closed-loop system were also lower at the central area.

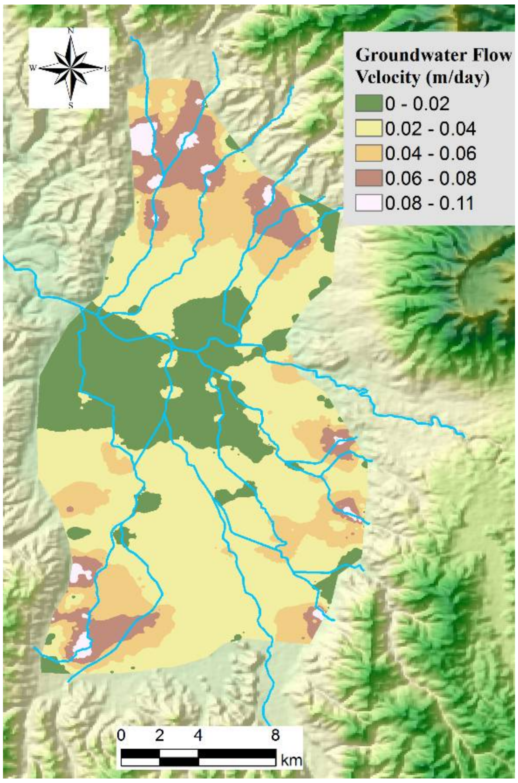

Figure 8. Distribution map of groundwater flow velocity.

5. GSHP System Using an Artesian Well

To use a GSHP system at the central area of the Aizu Basin, an alternative solution to the conventional closed-loop system should be proposed. A different type of GSHP system is necessary that can perform better even at the central area, where the heat exchange rates for the conventional closed-loop system are lower. As already mentioned above, the existence of distributed clay layers at the central area acts as a confining layer, forming an artesian zone. Hence, areas located at the central basin have higher hydraulic potential, and the artesian pressure makes groundwater flow in the upward direction [25]. Also, from the field survey, it was known that existing artesian wells were distributed at the central area, as shown in Figure 9. If the groundwater of this central area can be effectively utilized, heat exchange rates of the system can be enhanced. As groundwater at this central area is flowing in the upward direction, the system using an artesian well is taken as the best possible option to increase heat exchange rates of the system.

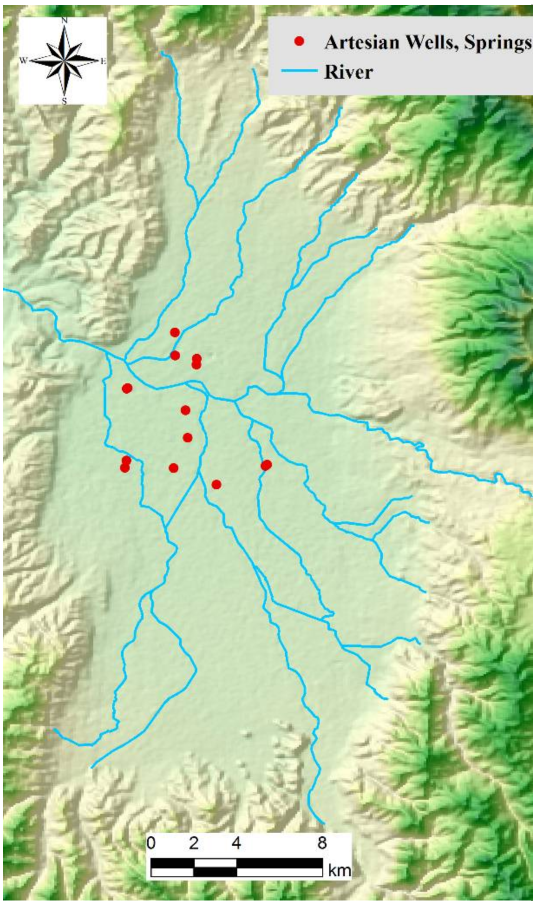

Figure 9. Distribution of existing artesian wells and springs in the Aizu Basin.

In this study, the GSHP system using an artesian well developed by Shrestha et al. [18] is taken into consideration as an alternative system that can be used at the central area. For demonstration purpose, this system was constructed at the central area (Figure 1). In this area, the heat exchange rates for the conventional closed-loop system were found to be lower (Figure 7). The artesian well of 100-m depth with double U-tubes and 10-kW heat pumps were used (Figure 10). More details about this system can be referred to in the previous work by Shrestha et al. [18].

Space heating operation was conducted with this system during the winter season from December 2016 to March 2017. Figure 11 shows the temporal variation of the obtained heat exchange rate during its operational period. The average heat exchange rate was found to be 54.8 W/m, with a maximum value of 72.4 W/m and a minimum value of 34 W/m. These values are higher compared to the heat exchange rates of the conventional closed-loop system at the central area of basin (Figure 7), which ranged from 28 W/m to 31 W/m.

In this system, the source of heat for space heating is the groundwater of the artesian well itself, flowing in the upward direction. For the conservation of groundwater use and keeping the temperature within the well constant, the upflow of groundwater was controlled by the electric valve [18]. Because of maintaining constant temperature, the heat exchange rate of this system was higher, although the heat is continuously taken for space heating.

Specification of this system is briefly explained below, based on the previous work by Shrestha et al. [18]. During space heating operation, once the temperature within the well decreases to 10 °C, the valve opens, substituting the groundwater within the well by new groundwater from the aquifer. When the temperature increases to 12 °C (original temperature of the well), the valve gets closed. This process repeats, keeping the temperature constant within the well. In this way, the heat source of space heating is continuously retained, and the performance of the system is well maintained.

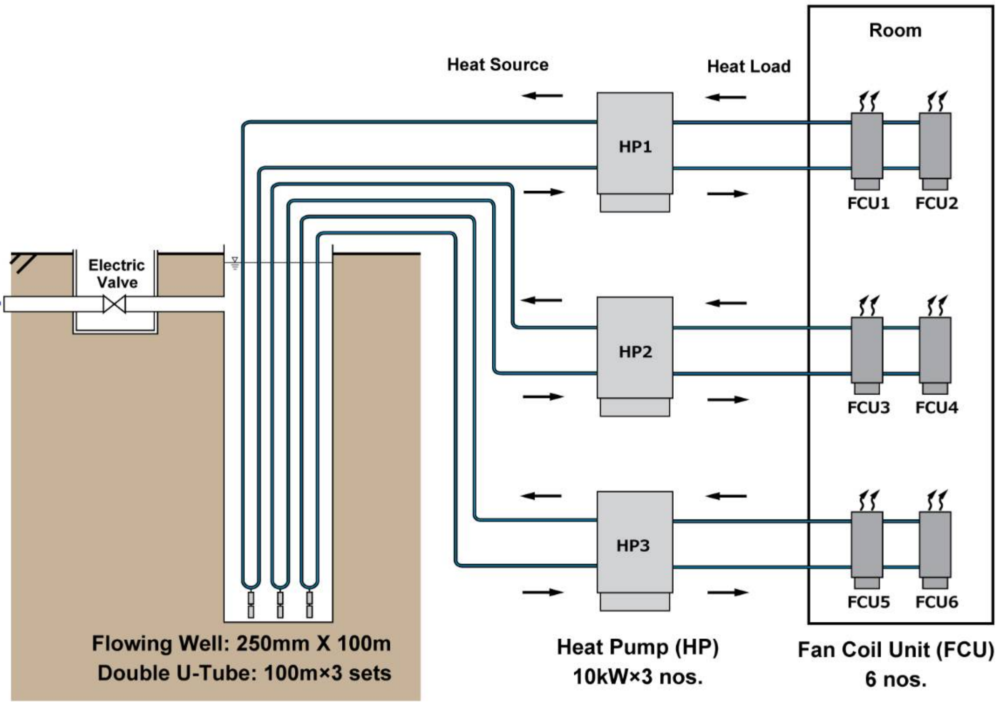

Figure 10. Ground source heat pump (GSHP) system using an artesian well. Reprinted by permission from Springer Customer Service Centre GmbH: Springer HYDROGEOLOGY JOURNAL (Performance evaluation of a ground-source heat pump system utilizing a flowing well and estimation of suitable areas for its installation in Aizu Basin, Japan, Shrestha et al., 2017).

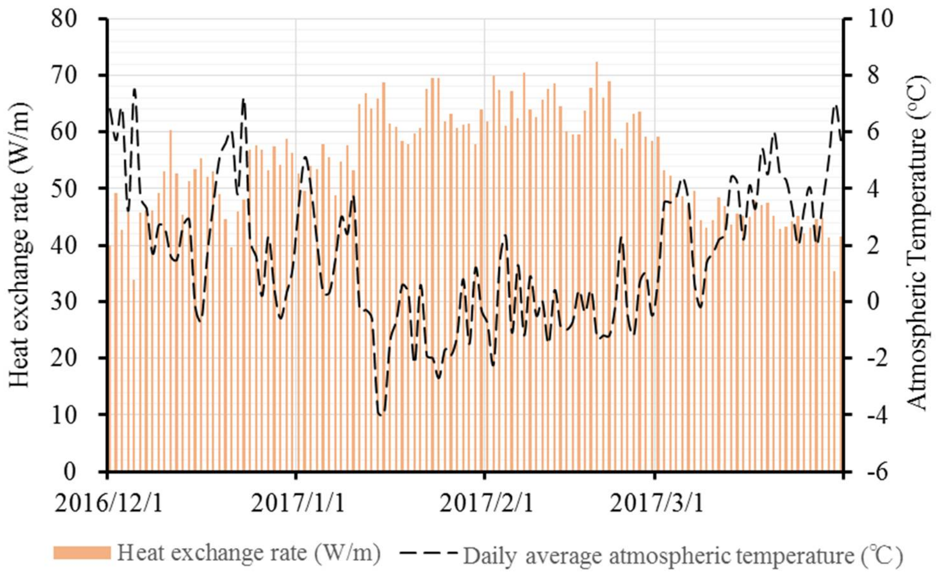

Figure 11. Variation of heat exchange rates of the system using an artesian well for space heating.

Appropriate Locations for a GSHP System Using an Artesian Well

Artesian wells are generally formed by upflowing groundwater driven by artesian pressure [26]. Therefore, groundwater discharge areas are suitable for the construction of the system using an artesian well. Figure 12 shows the distribution map of groundwater discharge areas which are computed from the analysis model (Figure 2) [18]. Computed groundwater discharge areas, except along the river, and existing artesian wells in the field determined from the field survey (Figure 9) were distributed at the central area.

Therefore, the system using an artesian well is suitable for installation at the central area where groundwater is flowing in an upward direction and its velocity is low. On the other hand, the conventional closed-loop system is suitable at the upstream northern and southern parts of the basin, where groundwater flow velocity is higher than at the central area.

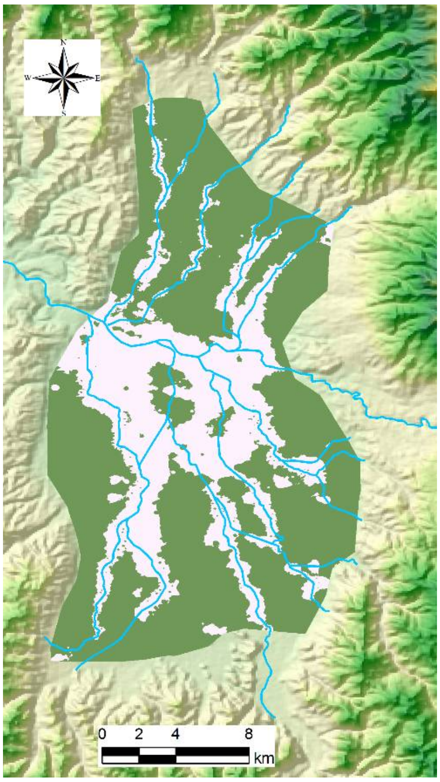

Figure 12. Distribution map of groundwater upflow areas (white areas). Reprinted by permission from Springer Customer Service Centre GmbH: Springer HYDROGEOLOGY JOURNAL (Assessment of installation potential of ground-source heat pump system based on the groundwater condition in Aizu Basin, Japan, Shrestha et al., 2017).

6. Conclusions

In this study, the installation potential of a GSHP system was evaluated for the Aizu Basin, located in Japan, based on its regional groundwater condition. Groundwater condition and underground temperature structure of the basin was analyzed by using a 3D analysis model and a field survey. Firstly, suitability assessment was done for a conventional closed-loop system by preparing a distribution map of heat exchange rates for space heating. For this purpose, identical GHE models were constructed at 20 locations using the finite element program FEFLOW. A 100-m deep ground heat exchanger was set at the center of the GHE models, consisting of a double U-tube with outer diameter of 34 mm. To compute heat exchange rates, heat exchange simulations were conducted with these GHE models. Space heating operations were conducted for 120 days per year from December to March. From the simulations, heat exchange rates were computed at each location, and the distribution map of heat exchange rates was prepared using ArcGIS. Heat exchange rates were found to be higher at the northern and southern areas of the basin, which are the upstream areas of rivers flowing from the north and south parts of the basin; while at the central basin, heat exchange rates were found to be lower. The distribution map of heat exchange rates shows that the northern and southern areas are more suitable for installing the conventional closed-loop GSHP systems than the central area. Higher heat exchange rates are because of higher groundwater flow velocities at the upstream northern and southern areas. Groundwater flow velocities are higher at these areas because of higher hydraulic gradients and preferable geology. Higher flow velocity increases the apparent thermal conductivity of the subsurface because of the advection effect of groundwater flow, and ultimately increases heat exchange rates; while at the central area, the presence of clay and a small hydraulic gradient cause the low groundwater flow velocities. Due to this, heat exchange rates for the conventional closed-loop system are lower at the central area.

For promoting the use of a GSHP system in the Aizu Basin, the development of a different type of GSHP system other than the conventional system that can perform better even at the central area is very essential. At the central area, although the flow velocity is low, groundwater is found to be flowing in an upward direction. Also found from the field survey, artesian wells were distributed at the central basin. Utilizing the heat energy of this upflowing groundwater can increase the heat exchange rate of the system. Hence, in this study, the GSHP system using an artesian well is taken as the best possible option that can produce higher heat exchange rates at the central area. For demonstration purpose, this system was installed at the central area, where the heat exchange rates for the conventional closed-loop system were found to be lower. The artesian well of 100-m depth was used with double U-tubes and 10-kW heat pumps. Space heating operation was conducted with this system during the winter season from December 2016 to March 2017. This system with an artesian well showed a higher heat exchange rate with an average value of 54.8 W/m, which is higher than that estimated for the conventional closed-loop system at the central area. It can be said that an artesian well can be efficiently used to increase the heat exchange rate of a GSHP system.

From this study, it can be said that the system using an artesian well is suitable for installation at the central area with groundwater upflow. On the other hand, the conventional closed-loop system is suitable at the upstream northern and southern parts of the basin, where groundwater flow velocity is higher than in the central area. In this way, the suitability assessment and comparison of heat exchange performance of different types of GSHP systems in the same region based on its groundwater condition is the originality of this study, which had not been performed previously. It can be said that this study and its results are significant to selecting appropriate areas for the accurate design of GSHP systems and also for the widespread growth of the system in Japan.

Regarding limitations of this study, all the specifications of the GSHP system using an artesian well could not be adopted in the heat exchange simulations because of complications in the modelling of ground heat exchangers and for accuracy in calculations. As a further study, heat exchange rates will be computed for space cooling operations as well as for the both conventional closed-loop system and the GSHP system using an artesian well. Furthermore, the results of this study will be compared with those of different study areas in order to upgrade the methodology of the suitability assessment based on inter-regional analysis.

Author Contributions: Gaurav Shrestha is the principal investigator of this work who prepared this manuscript. Youhei Uchida advised on the groundwater flow system and subsurface temperature. Takeshi Ishihara contributed on the hydrogeology. Shohei Kaneko contributed on the analysis of groundwater condition and its temperature distribution. Satoru Kuronuma contributed on the GSHP system using an artesian well. All authors approved the manuscript.

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Conflicts of Interest: Authors declare no conflict of interest.

Nomenclature

COP	Coefficient of performance
GHE	Ground heat exchanger
GSHP	Ground source heat pump
3D	Three-dimensional

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