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ARTICLE

Prediction of Groundwater Temperature Variation in Riverine Well for the Safe Operation of Groundwater Heat Pump (GWHP) System

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ABSTRACT

Riverbank filtration is used for producing a large amount of groundwater for a long time. The surface water infiltration is accompanied with riverbank filtration and may significantly affect the quality and temperature of pumping water if the pumping well is located nearby the river. A coupled groundwater flow and heat transport model was developed to estimate the influence of surface water on the temperature in pumping well for groundwater heat pump system at the riverbank. The model included the aquifers under river and considered the variation of surface water temperature with season and depth to simulate accurately pumping water temperature. To depict in detail the aquifers and riverbed sediment in contact with the river, the 3D geological model was developed by Geomodeller, and the numerical model was completed by FEFLOW. For model calibration, the simulation results were compared to the measured groundwater level and temperature data in pumping well during 2 years. The result showed high accuracy with the coefficient of determination (R^2) of 0.971, root mean square error (RMSE) of 0.211 °C. Using calibrated model, the groundwater temperature changes in pumping well were predicted for 15 years. The proposed modeling method can be used to estimate the groundwater flow, quality, and temperature change by the surface water infiltration in riverine aquifer.

Keywords: Numerical Modeling; Groundwater Flow; Heat Transport; Riverbank Filtration; River-Aquifer Interaction; GWHP

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1. Introduction

Today, due to the depletion of fossil fuels and the acceleration of global warming, the exploitation of clean energy is an important issue for the future of mankind.

The groundwater pumping in riverine aquifer has the history of about 200 years [1]. It is being applied for producing groundwater as not only water resources but also shallow geothermal energy resources in many countries. In case of pumping groundwater in riverbank, a lot of groundwater can be pumped continuously because of the infiltration of river water, at the same time water quality is improved by filtration and adsorption in porous aquifer. But unplanned and excessive groundwater mining may generate serious problems. So a lot of theoretical and practical studies were performed to investigate groundwater flow and accompanying heat and mass transfers during riverbank filtration.

Several authors studied the river-aquifer flow exchange in regional scale. Epting et al. investigated the sensitivity of future groundwater temperature development of Swiss alluvial aquifers and supposed that groundwater recharge and the associated temperature variation of aquifers was primarily determined by infiltrating surface waters [2]. Mas-Pla et al. developed a stream–aquifer numerical flow model to assess river water management under water scarcity in a Mediterranean basin [3]. Generally, the dimensions of the river are smaller than the mesh spacing of the model in the case of large scale groundwater models. Rushton applied the conception of river coefficients to include River-aquifer interaction in regional groundwater model [4]. Doppler et al. applied dynamic leakage coefficient to simplify modeling of interaction between rivers and aquifers [5].

Some studies indicated the significance of heat transport to understand the behavior of river-aquifer interface and developed exchange flux model using water level and temperature data. Maharjan and Donovan indicated that river water infiltration was a major component of pumped water and the temperature of pumped water could be tracer for identifying source water [6]. Gerecht et al. showed that heat in conjunction with water level measurement might do an important role for investigating temporal and spatial distribution of exchange flux [7]. Also, Ebrahim et al. studied the effect of temporal resolution of water level and temperature data on numerical simulation of groundwater-surface water flux exchange [8]. Hassen et al. studied the influence of regional faults on groundwater flow and regional impact of current and future groundwater use in the aquifer system as an example for 3D numerical flow model of using coupled FEFLOW and Geomodeller software [9].

Some modeling methods considered the detailed configuration of river-aquifer interface were studied. As an example the numerical approach using MODFLOW and MT3DMS, the fate and behavior of a range of organic compounds or temperature during riverbank filtration were investigated using numerical flow and transport model [10,11]. Matusiak et al. investigated the groundwater flow path and the travel time from the river to individual wells and calculated the parameters describing the conditions of surface water infiltration [12]. Wang et al. implemented a transient flow and heat transport to quantify the spatial and temporal variation in the bank filtration of reconstructed canal area [13].

Due to the importance of entering water temperature of GWHP, the coupled models of groundwater flow and heat transport were used to estimate local and regional thermal distribution of groundwater for heat pump system [14,15]. Li et al. and Wu et al. conducted laboratory and field experiments to evaluate the impact of hydrogeological and thermal factors on groundwater flow field variation such as groundwater velocity and recharge rate changes for heat transfer characteristics [16,17]. Sezer et al. and Permanda and Ohtani developed a numerical model of open-loop geothermal heat exchanger installed in fractured chalk and alluvial aquifers using FEFLOW respectively, and analyzed the thermal impacts created due to the heating and cooling operation, offering insights into system performance [18,19]. Baquedano et al. approached the nonlinearity of the thermal recycling problem by distributed numerical models of groundwater flow and heat transport combined with thermodynamic models of geothermal heat pumps [20]. Previati et al. presented a city-scale 3D FEM model to understand the hydrothermal regime of the urban aquifer disentangling the thermal contribution of natural and anthropogenic heat sources [21].

Several studies considering detailed situations and conditions were performed to solve the exchange flux and heat and/or mass transport in river-aquifer interface. Derx et al. and Nützmann et al. developed 2D and 3D riverine and riverbed model using SUTRA and simulated groundwater flow and heat transport processes that occurred between river and aquifer [22,23]. Munz et al. used 3D coupled groundwater flow and heat transport model including river and its both sides and quantified the natural water and heat flux across the river-groundwater interface [24].

The river-aquifer interaction is complicated process combined with geological, hydrogeological, thermal and climatic conditions, and complete solutions of these problems need sophisticated modeling methods. To correctly explain hydrogeological problems such as groundwater pumping in aquifer near water body, previous studies suggest that numerical model boundary defined as topographical river boundary is insufficient, the aquifer extending under water body must be included, and the exchange processes between surface water and aquifer must be described in the model.

The aim of this study is to establish a GWHP system in a dense urban area where has been considered difficult to install so far, and to investigate the sustainability of its operation. A groundwater flow and heat transport modelling method was studied to predict more accurately the groundwater temperature variation in a pumping well nearby the river. (1) A conceptual model is developed by depicting the detail features of the river-aquifer interface in the study area using Geomodeller and FEFLOW. (2) As water temperatures at the riverbed are changed with season and different depth, the accuracy of the model is improved by describing these temperature boundary conditions. Also other uncertain conditions are solved through calibration work. (3) The completed model is used to predict the change of groundwater temperature in the pumping well during the long-term operation to evaluate whether it affects the safe operation of the GWHP system.

2. Site Description

The study site is located on the right side of the Taedong River, flowing across the Pyongyang peneplain in middle-western Korean peninsula (**Figure 1**). The geomorphology of the study site is relatively flat with low hills. According to relevant climatic data, the annual precipitation is about 1000 mm/y, and the mean monthly temperatures range from −3.3 °C to 25.2 °C. In this site, the water level of the river is maintained 2.5–2.7 m above sea level (ASL) except on the occasion of heavy rainfall because the river stage is controlled by several locks in upstream and downstream. The average depth in the middle of the river is about 10 m. The study site is urban area, most of land surface is paved except some greens, so most of precipitation flows to the river through storm drains. Thus, the groundwater recharge in this area almost depends on the Taedong River. From the geological survey of the study site, the bedrock is fine sandstone of Songrimsan formation of Mesozoic age, and there are alluvial and flood sediment above bedrock. Quaternary deposits are the main aquifer, especially, gravel layer near river has good hydraulic characteristics. However, the thickness of aquifer reduces westward, the hydraulic conductivity is lower, too. Sandstone outcrop are exposed and formed small hill at about 1.2 km far away from the river. In the well location, the thickness of aquifer is about 24 m. The landfill, sandy clay and loamy layers are laid from the surface to depth of about 10 m, the sand and gravel layers are located at a depth between 10 m and 24 m. Sandstone which is considered as impermeable layer is overlain by the Quaternary deposits. Groundwater table is nearly equal to the river stage and tend to lower slightly as the distance from the river increases.

Figure 2 shows the hydrogeological cross section of transect AA′ in **Figure 1**.

The groundwater heat pump system was installed for geothermal cooling and heating of an office building in this area. The building is a 15-storey rectangular-style building with length of 130 m and width of 90 m, and its total floor space is 96,000 m^2, which has the offices and classrooms of 1497. The maximum heating load is 2790 kW, corresponding water flow rate is 280 m^3/h. To supply groundwater demand the pumping well was installed at the riverbank. The distance between riverbank and well is 75 m, the depth of well is 20 m and the diameter of well is 6 m.

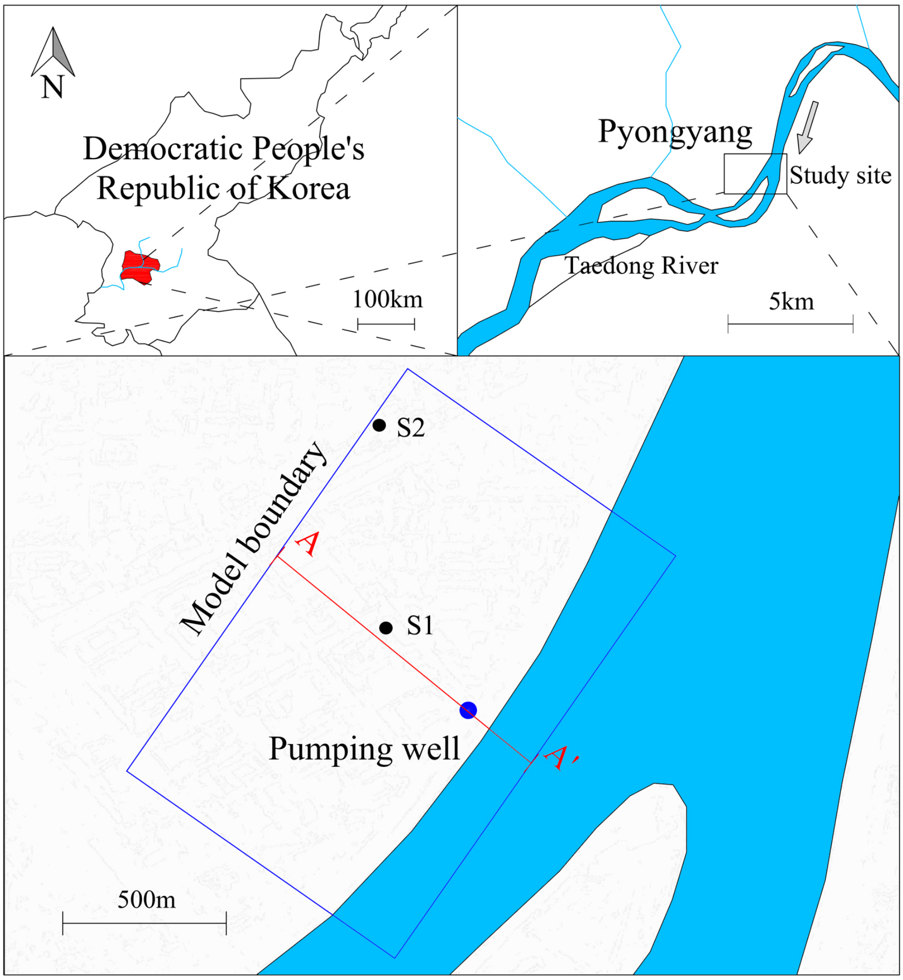

Figure 1. The location of study site.

Note: Blue rectangle: model boundary, blue dot: pumping well, black dots: survey points.

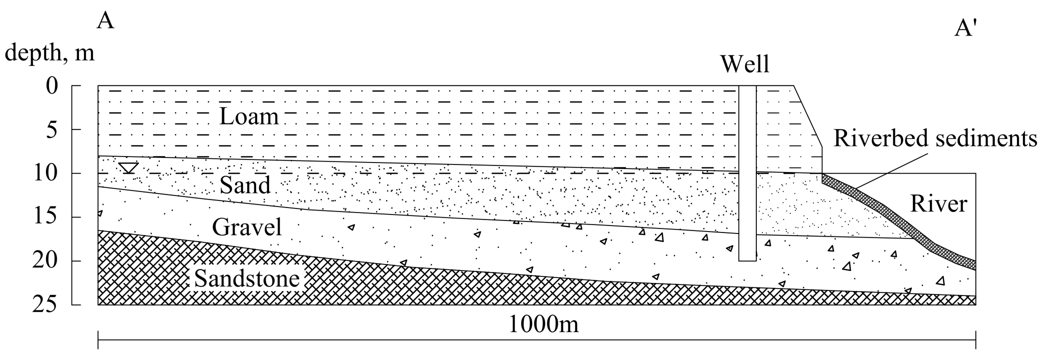

Figure 2. The hydrogeological cross section of study site (vertical zoom = 10).

The purpose of this well is to supply groundwater to GWHP system for heating and cooling of the building, the most important things are pumping rate and temperature. Also, it is important that drawdown is minimized and the extent of cone of depression is reduced to prevent subsidence for many buildings in this area. The supply of pumping water rate and decrease of drawdown were preceded in the designing step, pumping water temperature change during heating and cooling season was discussed under the condition that those issues were solved. So pumping well location was close to river, the maximum operation time in a day was prearranged about 12 h to hold pumping water temperature during heating and cooling season, especially above 10 °C in heating season. However, as a result of observation in operation of geothermal heating and cooling system, minimum water temperature was 12.3 °C in first heating season in spite of working more than 20 h, even 24 h in a frozen day. To evaluate the long-term behavior of geothermal cooling and heating systems and improve the operation strategy, it is necessary to develop a predictive model that more accurately describes the groundwater-surface water relationship in study region.

3. Modeling

In the common groundwater modeling softwares, 2D finite element mesh of model domain is firstly created and it is extended to 3D mesh. Therefore, it is difficult to use conventional method for the modeling of geological structure shown in **Figure 2**. Also, there are sensitive issues in the node and element selections for the definition of material properties of layers and boundary conditions even if mesh or grid is successfully generated.

In this paper, the meshing workflow function newly included in Geomodeller 4.0 was applied to easily develop the complicated model. It is very convenient to build the numerical model of complex shape of aquifer as geological information is mapped to FEFLOW.

3.1. Geological Model Setup

The 3D geological model of domain was developed using Geomodeller. The southeast boundary of model was defined as the middle of river, other boundaries were situated sufficiently far from the pumping well to avoid boundary effects. The model domain was determined with the size of 1500 × 1000 m, thickness of 17 m. The distance between pumping well and riverbank is 75 m, distance between riverbank and the middle of river is 175 m.

Generally, digital terrain model (DTM) is required for topographical data in Geomodeller. But groundwater flow and heat transport model is not typical geological model, therefore, the vertical part with no groundwater was not included to this model to reduce computational load. The topographic surface was defined as the elevation of riverbed at river part of the model, the virtual surface that is 2 m above groundwater level at land part. The reason that model contains 2 m thickness of strata above groundwater level is as follows. First, groundwater level is raised at the injecting well when pumping-injecting simulation is performed. Second, the border between river and land is drawn on topography of model to be convenient for selection of finite elements or nodes to build conceptual model. The available subsurface data helped to complete the geological model which was composed of loam, sand, gravel and sandstone as shown in **Figure 3**.

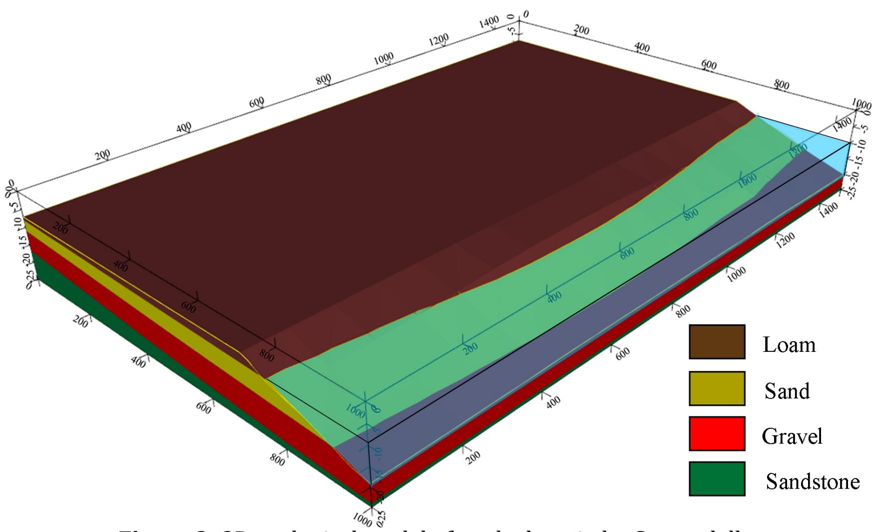

Figure 3. 3D geological model of study domain by Geomodeller.

Then, the finite element mesh was generated using meshing workflow 3 (MW3). It is convenient to select of elements or nodes of model for defining conditions and displaying simulation results because MW3 method converts given geological model into layered mesh which consists of layers and slices.

3.2. Numerical Model Setup

The finite element mesh generated by Geomodeller was imported in FEFLOW 7.0 and completed to the numerical model. The average mesh spacing in the model was 15–20 m, the mesh was refined to 3–5 m in the areas near the pumping and injecting wells. The mesh of domain had 40,794 nodes, 72,792 elements. **Figure 4** shows the pumping well and riverbed region in the mesh. Although there are several another wells along the river, no one is located in the model domain.

Initial and boundary conditions and material properties were assigned. The groundwater table was 10 m below land surface and undisturbed groundwater temperature was 14.1 °C. The groundwater table is slightly fluctuated depending on river stage. Below 10 m depth, the temperature of the subsurface is stable. It is considered to be almost unaffected by seasonal air temperature.

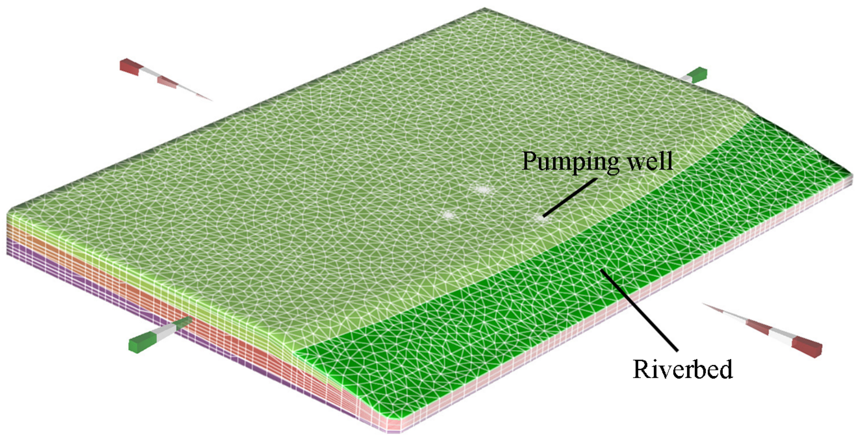

Figure 4. 3D finite element mesh of study domain by FEFLOW.

For assignment of boundary conditions, head boundary condition was assigned to riverbed region as shown in **Figure 4**. As mentioned above, the river stage in this area fluctuates in rainy season, however, it was eliminated and head boundary condition was set to the average level. Heat boundary condition was set to the temperature variation of river water in the same region. The temperature of river water changes with season and river depth. On the supposition that water temperature of the river bottom linearly changes from bank to the middle, heat boundary condition was defined by FEFLOW plug-in, which was developed using temperature data measured monthly at the surface and the bottom of river. The monthly temperatures of river water at surface and bottom are shown in **Figure 5**. Other lateral boundaries were set to no flow and thermal condition.

Pumping rate was fixed at a constant value of 4500 m^3/d in heating season, 4000 m^3/d in cooling season taking account of measured real-time flow rate and average operating time in a day.

Finally, material properties of formations were defined. The hydraulic properties of riverbed sediment and loamy layer above groundwater table was evaluated using infiltration test, those of sand and gravel layers were determined by pumping test in boreholes. Main aquifer consists of gravel in riverbank and riverbed, but, as the distance is farther from the river, the content of sand in aquifer is increased more and more, the quality of aquifer is worse. According to the pumping tests, the values of hydraulic conductivity of gravel aquifer are 81 m/d in pumping well, and 62 m/d and 29.8 m/d in the places of S1 and S2, respectively (**Figure 1**). So, the hydraulic conductivity was approximated linear decrease in the direction which was perpendicular to river. Based on the result of linear regression, the horizontal hydraulic conductivity was set to in the range of 30–

100 m/d. The porosities of layers were determined by analysis of soil sample collected during well installation. The thermal conductivity and volumetric heat capacity of groundwater were set to the default values in the FEFLOW, and those of solid materials were selected from literature using lithological features of layers [25]. The study site is the downstream of the Taedong River, the dredging is often performed because of the deposition of fine materials on the riverbed, so the distribution of riverbed sediment is heterogeneous. The clarification of its attitude was practically impossible, hence the riverbed sediment were simply modeled as the top mesh layer at riverbed region in FEFLOW with no modeling in Geomodeller. In calibration work, the validity of the hydraulic parameters was verified by the observed data of groundwater level. The dispersivity was assessed using the groundwater temperature data, and the validity of assumptions such as constant head in riverbed boundary and the neglect of precipitation were evaluated.

The list of the parameters used in the simulation is provided in **Table 1**.

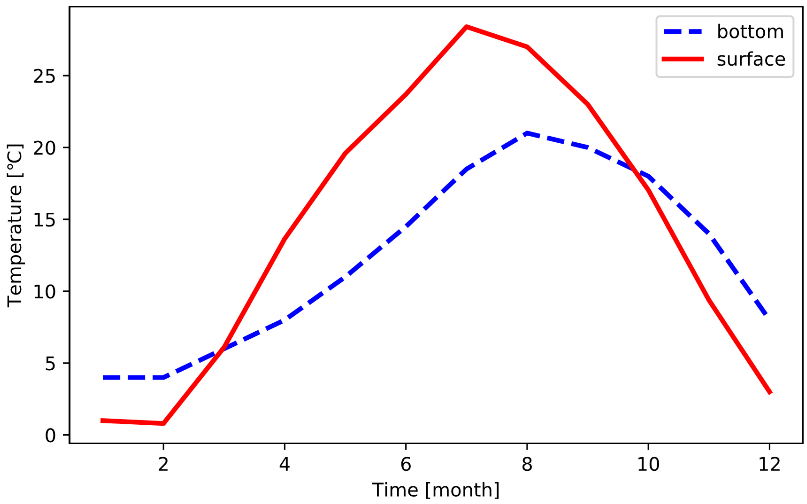

Figure 5. The water temperatures at the surface and bottom of the river.

Table 1. Thermal and hydrogeological parameters used in the simulation.

	Parameters	Riverbed Sediment	Loam	Sand	Gravel	Sandstone
Thermal parameters	Thermal conductivity (W/(m·°C))	1.8	2.4	2.5	2.9	2.3
	Volumetric heat capacity (MJ/(m^3·°C))	2	2.3	2.1	2.4	2.1
Hydrogeological parameters	Horizontal hydraulic conductivity (m/d)	1	3	10	30–100	0.001
	Vertical hydraulic conductivity (m/d)	1	1	3.3	10–33	0.001
	Specific storage (1/m)	0.0001	0.0001	0.0001	0.0001	0.0001
	Porosity (-)	0.4	0.3	0.3	0.25	0.05

The natural recharge by precipitation was neglected because most of land surface was paved, the sandstone bedrock was regarded almost impermeable. Also, vertical range of model was from 8 to 25 m depth, belonged to thermal constant zone, and geothermal heat flux was too small and ignored. After all, there was no hydrogeological and thermal boundary condition at upper and lower plane of model.

The flowchart of modeling is expressed as in **Figure 6.**

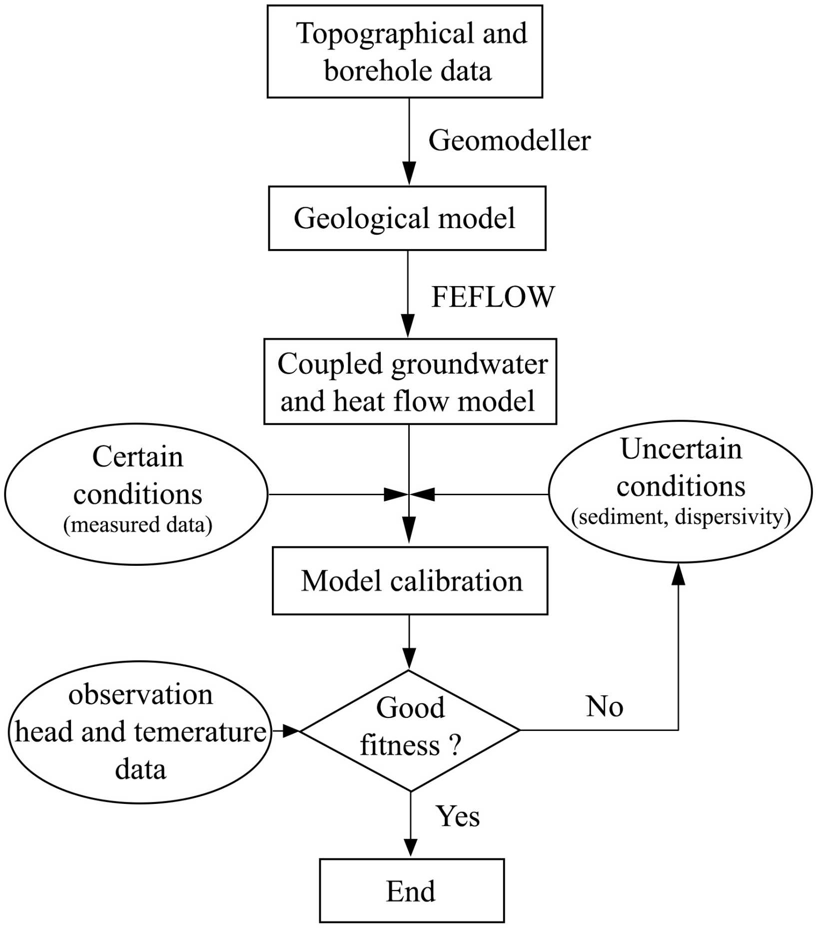

Figure 6. The flowchart of modeling.

4. Results

4.1. Model Calibration

The groundwater heat pump system was completed in October 2019, started operation from 9 November. Before formal operation, groundwater was pumped for about 20 days from July 2019 during well construction. The heating mode started in the situation that the temperature of aquifer was raised by infiltration of river water in summer. Thereafter, from the middle of June to early in September as cooling season, from the early in November to the early in April as heating season. This way, three and half years of cooling and heating cycles elapsed.

The perfect measured data during two years is applied to calibrate the numerical model. The water level and temperature data were measured by sensors that were installed within pumping well, displayed real-time, recorded hourly. The water level in the pumping well continuously varied because pumping was intermittent and the pumping rate was altered by frequency control for saving of groundwater as heating or cooling load changed.

As already mentioned, the water levels measured in pumping well varied, but the simulated result was unchanged at every season because daily average pumping rate was fixed as constant value in the model. So, the simulated result of water level was compared with the mean value of seasonal observed results. There were errors of 0.01 m in heating of 2019, 0.04 m in cooling of 2020, 0.08 m in heating of 2020, and 0.43 m in heating of 2021 (**Figure 7**). Despite of measured level data consisted of daily minimum values and daily mean pumping rate instead of real-time measured one were used in this simulation, the simulation results were in good agreement with the observations.

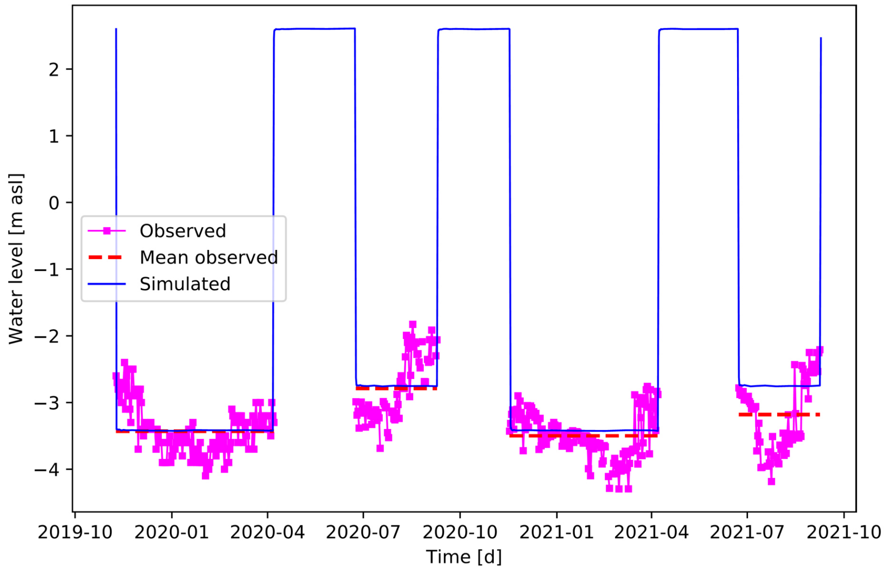

Figure 7. The observed and simulated result of water level in pumping well.

When the longitudinal dispersivity in the aquifer is ranged from 1 to 5, the comparison between measured and simulated results of temperature is shown in **Figure 8.** It is clear that the greater the dispersivity value, the greater the change of the pumping water temperature.

The comparison between the simulated and observed temperatures obtained under different longitudinal dispersivities is shown in **Table 2.**

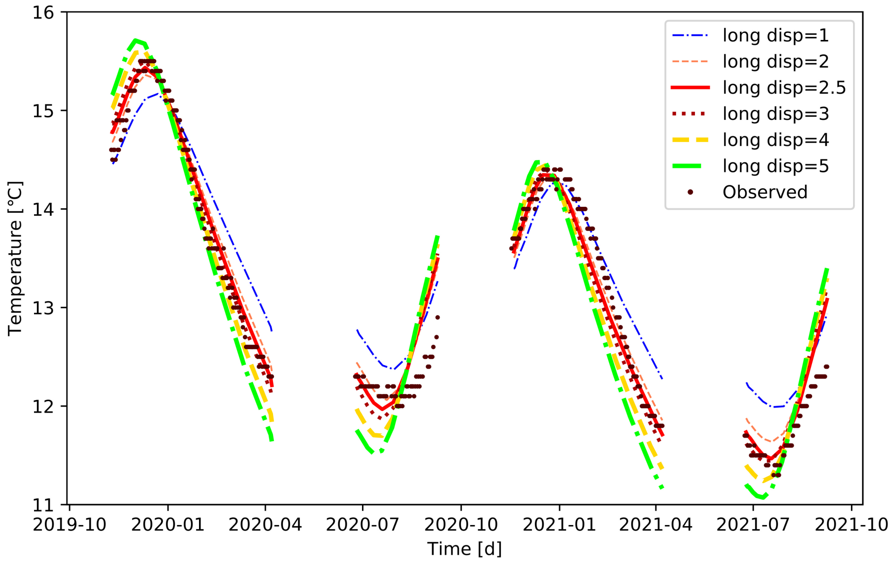

Figure 8. The simulated groundwater temperatures using various dispersivity values.

Table 2. The RMSE, coefficients of determination and correlation between the simulated and observed temperature of groundwater.

Longitudinal Dispersivity (m)	R^2	Pearson Coefficient	Spearman Coefficient	RMSE (°C)
1	0.902	0.932	0.99	0.381
2	0.969	0.975	0.989	0.22
2.5	0.971	0.973	0.986	0.211
3	0.949	0.95	0.985	0.276
4	0.911	0.911	0.969	0.375
5	0.839	0.840	0.959	0.5

As shown in **Figure 8** and **Table 2**, the good agreement was found when longitudinal dispersivity was set to 2.5 m and transverse dispersivity was 10 times smaller, 0.25 m. The results of the analysis of R^2 and RMSE were consistent very well, and the result of Pearson correlation was relatively good, too. The purpose of comparison in this study is not correlation but concordance, so the coefficient of determination was used instead of the Pearson or Spearman coefficient.

During the first heating and cooling seasons, temperature distributions in the gravel layer are shown monthly in **Figure 9**.

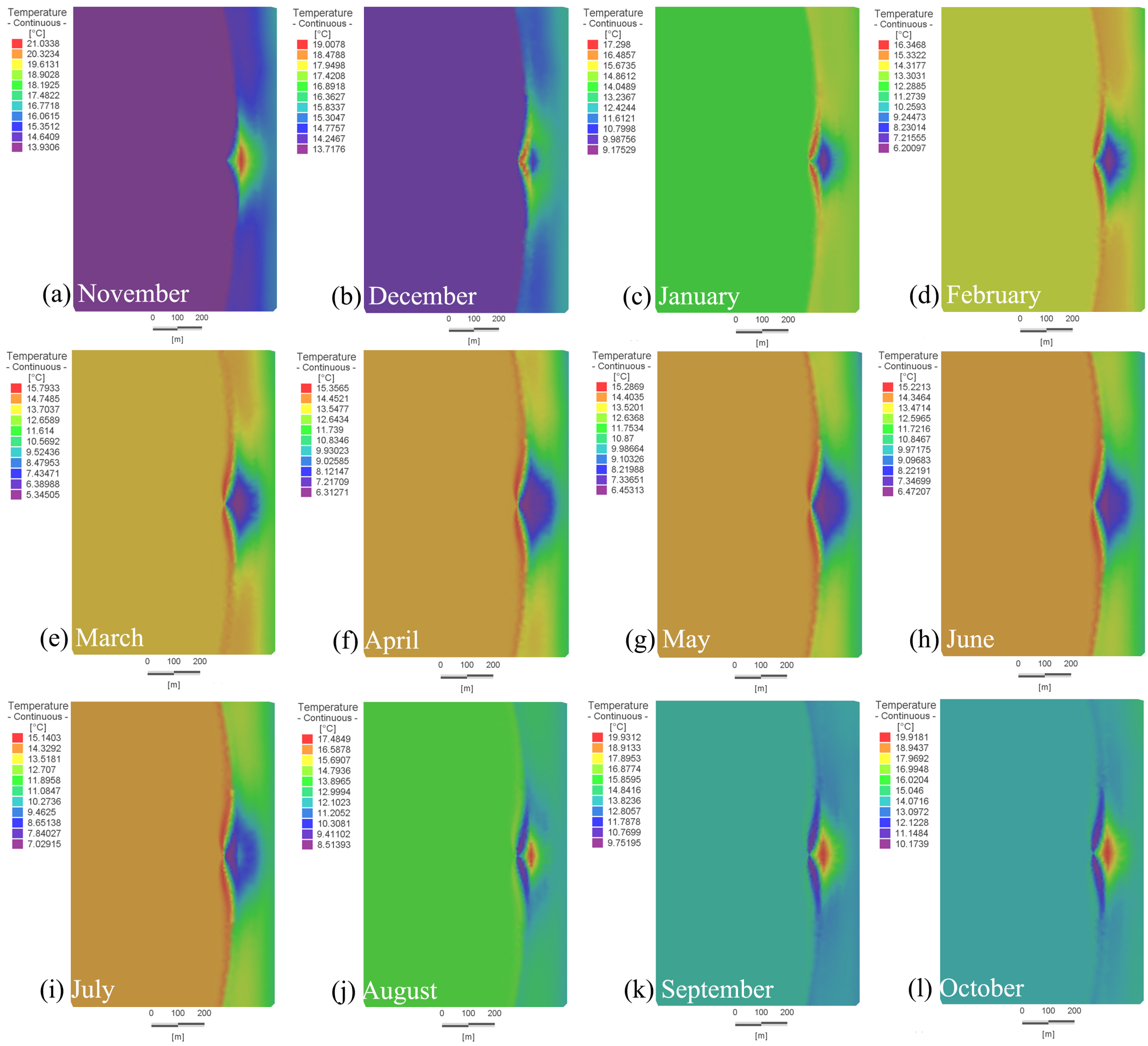

Figure 9. The monthly temperature distributions of aquifer during first heating and cooling seasons; the red and yellow color region in (**a**) means the aquifer was heated in summer. The brown and blue region in (**b**)–(**f**) shows aquifer was cooled in winter.

As can be seen in **Figure 9a**, the ground temperature at the beginning of the heating season is higher than normal due to the infiltration of surface water during well construction time in September 2019. Next, the low temperature region of riverine and riverbed was greater by means of the infiltration of cold surface water as heating season went by (**Figure 9b–f**). This region was almost maintained in rest time (**Figure 9g–h**) and gradually disappeared in cooling season (**Figure 9i–k**). After all, the aquifer was again heated in **Figure 9l**.

4.2. The Long Prediction of Groundwater Temperature

Up to now, the pumping water temperature is in the range that is appropriate for the safe operation of heat pump, however, groundwater temperature tends to decrease as time goes by. The results of the 15-year pumping groundwater temperature simulation using this calibrated model are shown in **Figure 10**. 15 years later, the minimum temperature in heating season is 10.97 °C and maximum in cooling season is 11.98 °C which is about 1.33 °C, 1.54 °C less than 2020, respectively.

Due to the climatic characteristics of the study area, the heating season is longer than cooling season, so the amount of infiltrated river water in winter is more than in summer. Hence, it is clear that the temperature decreases because the heat energy outflow from the aquifer is more than the inflow into the aquifer. To account for the gradual decline in temperature change over the years, annual heat losses in the aquifer is analyzed.

It is obvious that temperature decreases because outflow of heat energy from aquifer is more than inflow to aquifer.

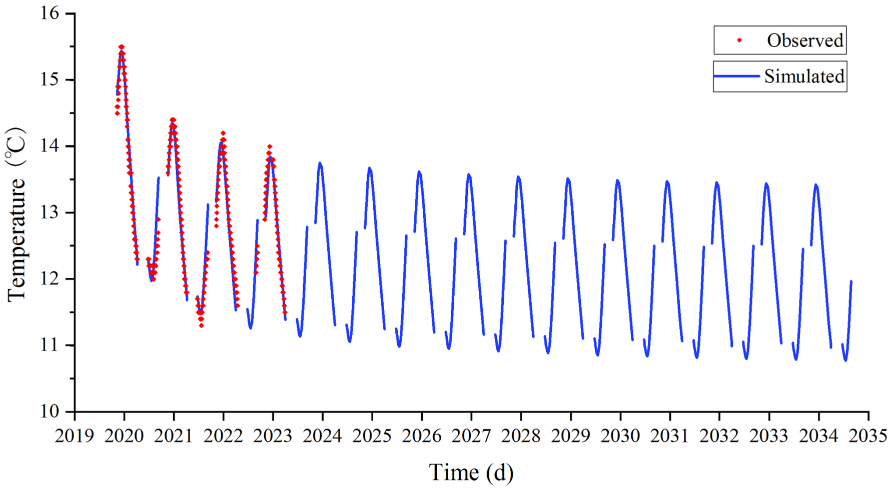

Figure 10. The groundwater temperature of the observed data in 3.5 years and predicted data during 15 years; convex curves mean heating season, concave curves mean cooling season and the spaces between two mean rest time.

Figure 11 shows the simulated heat loss of aquifer every year. Heat loss decreases from 5.3×10^{12} J in 2020 to 0.73×10^{12} J in 2034. The reason for the decrease in annual heat loss of the aquifer is that the energy gain due to the infiltrated river water in summer increases, but the energy loss due to the river water in winter decreases gradually, because of aquifer temperature decrease. If the aquifer temperature reaches at a certain value, the annual inflow and outflow of heat energy will be balanced.

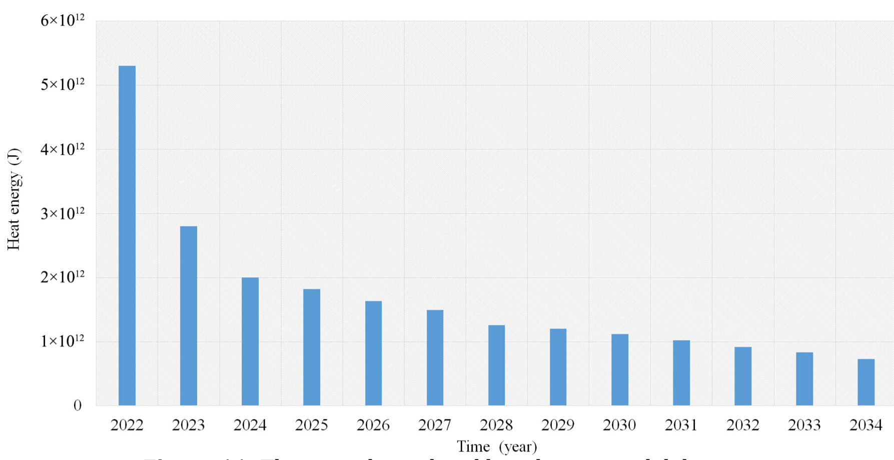

Figure 11. The annual simulated heat loss in model domain.

Despite the large difference in heating and cooling load, the results show that the groundwater temperature does not fall below a limited value and can maintain long-term operation of GWHP system.

5. Discussions

Firstly, the factors affecting groundwater temperature were discussed. To assess the validity of the assumptions neglecting rainfall and the variation of river stage, simulations were performed using the annual river stage and precipitation data (2019.11–2020.10). The river stage and precipitation during 1 year was shown in **Figure 12**. The river stage was set as the head boundary, and the precipitation was set considering the following conditions. The area where rainfall can infiltrate in the study area is about 2%. In the infiltrative zones, it is considered that the runoff was neglected and all rainfall was flowed into ground. So, 2% of the daily precipitation was set as the flow boundary condition on the top of the total model.

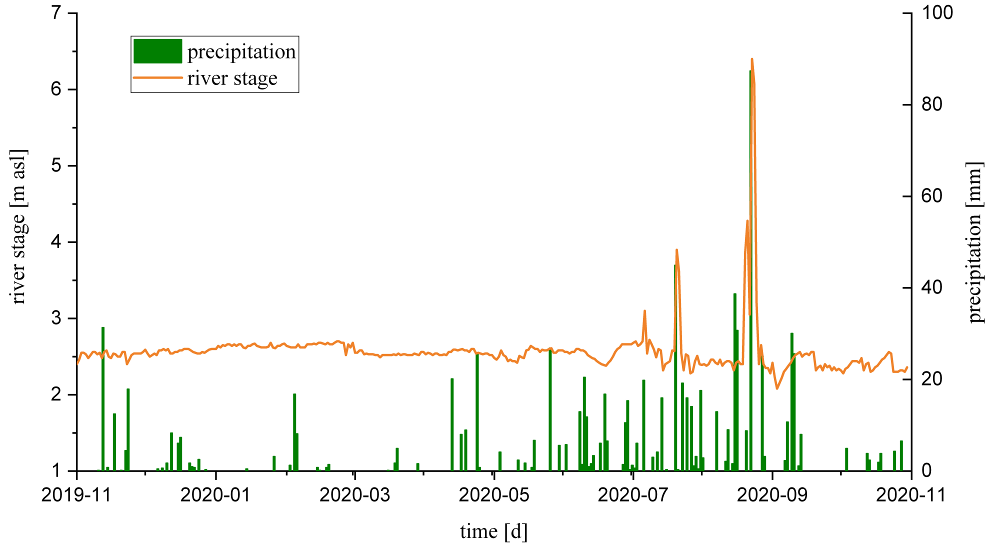

Figure 12. The precipitation and river stage variation from November 2019 to October 2020.

The initial simulation result was compared with new simulated results that added only the river stage condition and both the stage and precipitation conditions. The comparison results were shown in **Figure 13**. The temperatures of the heating season were almost identical, because the fluctuation amplitude of the river and rainfall is small in winter. But the temperatures of the cooling season had a slight difference, as shown in the magnified part of **Figure 13**. In the case of river level setting, the simulated result had temperature amplitudes of 0.03–0.08 °C during two river stage fluctuations. The reason can be explained as follows. If heavy rainfall is in river basin during short time, river stage suddenly rises and becomes normal a few days later. First, when the river-aquifer direction flow is greater, the surrounding cold groundwater body shown in **Figure 9i** flows further into pumping well, and the temperature is reduced. Next, when the river stage becomes normal again, the aquifer-river flow is temporarily dominant and this flow occurs the rise of temperature. The temperature amplitude is mainly related to the hydraulic conductivity of aquifer and the distance between well and river.

In the case of both level and precipitation conditions setting, the simulated result was shown to rise on average 0.034 °C overall as well as temperature amplitude due to river level fluctuations. The rising temperature means that the temperature of pumping groundwater is less affected by the river-aquifer flow. This is because the part of groundwater from precipitation increase, consequently, the river infiltration decrease. The difference occurred by the river stage and the rainfall conditions was insignificant, so that these conditions was neglected in the long-term simulation. But, if infiltration of precipitation is significantly great, it plays an important roles in the variation of temperature.

The effects of riverbed sediment thickness and surface water temperature were argued in more detail. To clarify the effect of uncertainty of riverbed sediment on groundwater temperature variation, the simulations conducted with hydraulic conductivity (K) of 0.5 and 2 m/d, respectively (**Figure 14**). The simulated values were in accordance with measured data (R^2 = 0.967, RMSE = 0.219 °C when K was 0.5 m, and R^2 = 0.97, RMSE = 0.21 °C when K was 2 m/d). These results indicated that the hydraulic conductivity of the sediment has a little effect on the temperature.

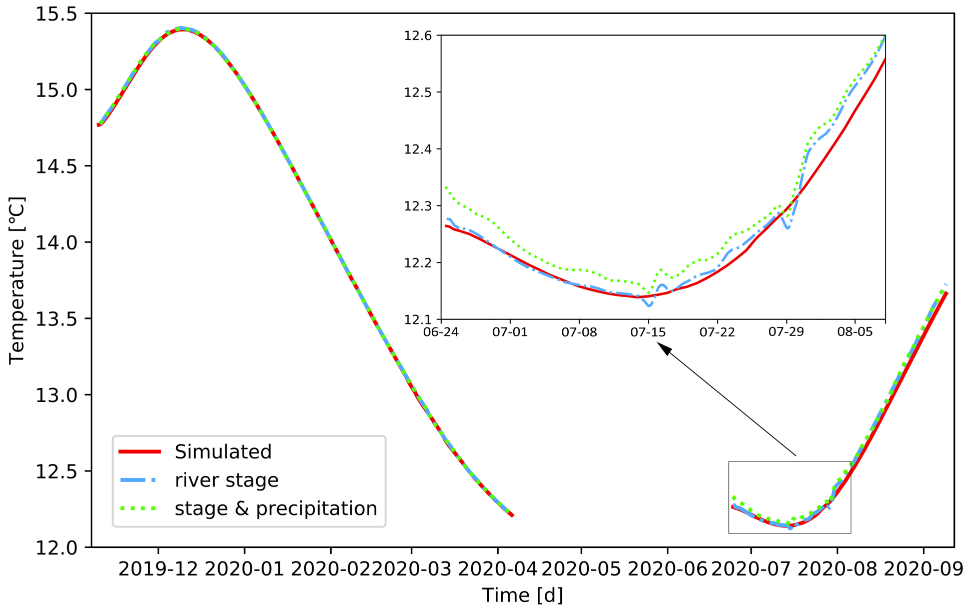

Figure 13. The Influence of river stage and precipitation on simulation results.

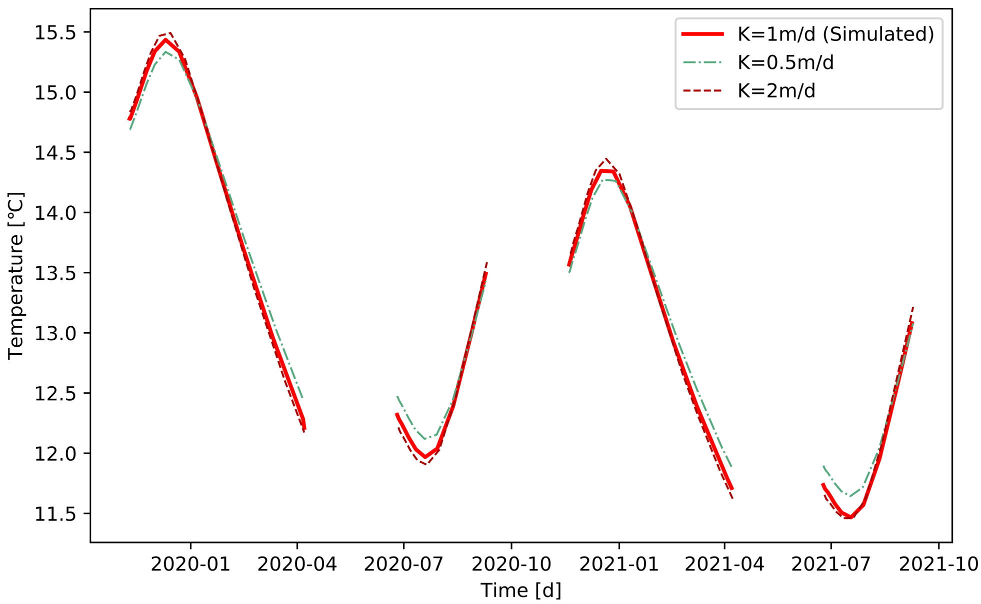

Figure 14. The prediction of groundwater temperature under different hydraulic conductivity of riverbed sediment.

The simulation and observation had discrepancy in case when measured temperatures in the surface or bottom of river were applied to the riverbed boundary, good simulation result was obtained only after river water temperature varying along the depth was defined. The results under different temerature condition at riverbed boundary are shown in **Figure 15.** The simulated results were slightly inconsistent with measured data (R^2 = 0.911, RMSE = 0.366 °C when the water temperature of the surface was set, and R^2 = 0.925, RMSE = 0.334 °C when the water temperature of the bottom was set). These results showed that it is importance the correct setting of temperature boundary conditions in predicting the groundwater temperature at riverine aquifer and wells.

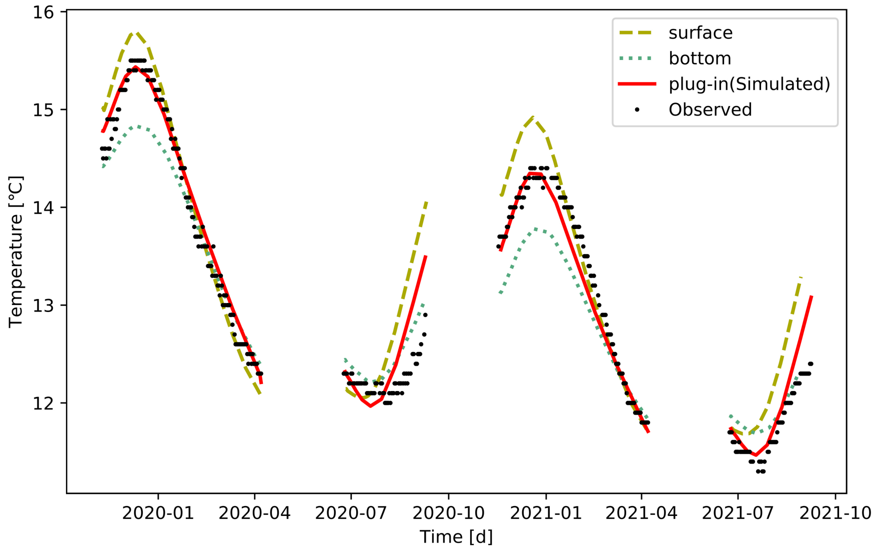

Figure 15. The prediction of groundwater temperature under different temperature boundary condition of surface water.

The good agreement between the simulated and observed pumping water temperatures was obtained with the coefficient of determination (R^2) of 0.948 and the RMSE of 0.239 °C. But, as shown in **Figure 15**, the results in heating seasons was similar, in cooling seasons, observed and simulated results were some difference. The observed temperature changes tended to be delayed than the simulated temperature and continued to increase after the end of the cooling season. In detail investigation of the observed temperature, water temperature was raised 0.1 °C in the period from 7 April to 24 June 2020, but raised 0.7 °C in the period from 6 September to 17 November 2020. Previously, it was thought that this phenomenon was due to river fluctuation, but the assumption was withdrawn by discussion in the preceding section. Further work can be needed to illustrate whether the reason is due to unknown hydrogeological and thermal conditions or simulation approach.

Secondly, the range of thermal affected zone (TAZ) were discussed. The groundwater level and temperature are reciprocal, and to reduce the drawdown that can cause environmental damage, the well have to be nearby the river, whereas to stabilize the groundwater temperature, the well must be far from the river. That is why the well construction of GWHP systems strongly requires detailed field studies. Between the pumping well and the river, a horizontal funnel-shaped TAZ is created. In this zone, heat is stored during cooling season, conversely, cool during heating season, so, the volume of TAZ determines the capacity of the GWHP system. The hydraulic conductivity is known the main factor, and the larger the hydraulic conductivity, the farther the well can be away from the river and the larger the TAZ extension. The shape of the river-aquifer interface is also important. In the study area, the gravel aquifer with a high hydraulic conductivity extends to the middle of the river, the horizontal area of TAZ was magnified from the well to the center of riverbed. The distance of TAZ in the direction parallel to the river was about 250 m on left and right of the well. Therefore, interval between wells for GWHP system in this area is suggested to be about 500 m. The depth of well is important, too. The TAZ included from the water table to the aquifer bottom due to the well screen installed at the deepest aquifer.

Finally, the subsidence by drawdown was briefly debated. The study area is urban and possible well location is limited, so the distance between the existing well and the building is only 27 m. Despite the short distance between the well and the building, no observable subsidence has occurred by means of good groundwater supply conditions.

6. Conclusions

In this study, to precisely simulate water level and temperature in pumping well close to the river, 3D hydrological and thermal model that included the situation of river-aquifer interface was developed. The numerical model was calibrated with the observed data of 2 years, and the changes of water level and temperature in the future were predicted using this model. The modeling method suggested in this study improved the accuracy of prediction by considering detail conditions such as the geometrical characteristics of river, the configuration of aquifers in riverbed, seasonal temperature change in bank and bottom of river in the simulation of infiltration through river-aquifer interface. The result indicated that the temperature of groundwater must be maintained as possible by appropriately adjusting heating and cooling load in correspondence with the local climate.

This study offers practical potential for applying GWHP systems even in limited region in urban areas. To prevent subsidence damage, the distance between the wells and buildings must be ensured, so that, if the pumping well approaches the river, the pumping rate for safe operation can be calculated using the proposed method. This will lead to more positive results than using conventional methods, and provide the realization possibility and cost reduction.

Like other clean energy technologies, GWHP systems should continue to evolve. As the implementation of geothermal cooling and heating systems is mainly done in urban areas, we will focus on the following issues in the future. The reason of the difference between predicted and observed temperature in the cooling seasons will be studied. The values of 0.5–0.7 °C are not small, it is especially necessary to clarify when cooling is the main purpose. The possibility to increase the heat extraction capacity will be investigated in the case that the pumping well is very close to the river. Besides, it is important to study the environmental issue such as the subsidence generation by scour and pore water pressure reduction due to groundwater pumping.

Author Contributions

Writing—original draft, methodology, investigation, visualization, I.J.K.; writing—review and edition, validation, T.G.C. Both authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare that they have no conflict of interest.

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