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Assessing temperature of riverbank filtrate water for geothermal energy utilization

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ABSTRACT

Utilization of riverbank filtrate water for heating and cooling of buildings can reduce installation costs considerably by using the existing operating facilities for water purification and supply. Changwon city, Korea, has been using riverbank filtrate water for the indoor air-conditioning at its Daesan water treatment plant since 2006. In this method, the most important factor for determining the efficiency of heating and cooling is the temperature of the filtrate water. Numerical simulation of the temperature profile of riverbank filtrate water in the Daesan plant using HydroGeoSphere shows that the primary factor in determining filtrate water temperature is the pumping rate. This is because of the proportion of the river-originated water which increases with pumping rate. It also shows that maintaining the facility operation at the current pumping rate for the next 30 years will not cause any significant change in the water temperature. However, following the new city plan to install an additional 37 wells with a 6 times greater pumping rate than the current system might cause about 2 °C decrease in filtrate water temperature 10 years after the extension. This temperature drop will result in a significant change from the original design in heating and cooling performance.

1. Introduction

The growing trend in energy demands and rising oil prices threaten the national economy and environment, which has led to various attempts of finding new and renewable energy sources as an alternative to the expensive oil demand. Geothermal energy is one of the sustainable energy sources and its importance has become recognized in recent years. Geothermal energy is usually used for the heating and cooling of buildings. It has been proven to be cost-effective and eco-friendly in many of the ways in which it is utilized. Riverbank filtrate water can also be used as sources of energy for heating and cooling.

Riverbank filtration (RBF) is an artificial aquifer recharge method for the fresh water supply. By the construction of several production wells in the riverbank, surface water flows downward into pumping wells through riverbed and bank materials. During this process, water would be filtrated by aquifer materials, attenuating its chemical and biological pollutants [1]. Although the extracted water is the mixture of filtrated river-originated water and groundwater, it largely comes through RBF. So this extracted water is often called ‘riverbank filtrate water’. Riverbank filtrate water has the property of being cooler than surface water in summer and warmer in winter, exhibiting a stable water temperature profile [2]. This temperature characteristic enables us to use the riverbank filtrate water for cooling in summer and for heating in winter. So the estimation of the riverbank filtrate water temperature is essential for effective heating and cooling using RBF. The temperature of riverbank filtrate water can be determined by coupling groundwater flow with heat transfer. Moisture content and soil thermal conductivity should be simultaneously considered to calculate temperature in an unsaturated subsurface domain [3]. Su et al. (2004) showed that simulated temperature profiles in an alluvial aquifer were very sensitive to changes in the hydraulic conductivity of the domain and the inclusion of an unsaturated zone is expected to be important when precipitation events are considered [4]. Fluctuations in the temperature of riverbank filtrate water were balanced out due to age-stratification of the filtrated river water [5]. But Sheets et al. (2002) observed the temperature of extracted water varying with its location and pumping rate [6]. All of these studies demonstrate that basic hydrogeological information should be combined to calculate the possible temperature range of riverbank filtrate water.

The RBF facility of Daesan water treatment plant (WTP), located in Changwon city, South Korea, has been operating to supply the

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Nomenclature

$\mathbf{q}$	groundwater flux tensor ($m\,s^{-1}$)
Q	volumetric fluid flux source/sink per unit volume ($m^3\,m^{-3}\,s^{-1}$)
t	time (s)
θ	volumetric ratio of the material (–)
S	degree of saturation (–)
$\mathbf{K}$	hydraulic conductivity tensor ($m\,s^{-1}$)
k_r	relative permeability (–)
Ψ	pressure head (m)
z	elevation head (m)
l_p	pore connectivity (–)
α	Van Genuchten parameter (m^{-1})
β	Van Genuchten parameter (–)
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
T	temperature (K)
C	heat capacity ($J\,m^{-3}\,K^{-1}$)
ϕ	porosity (–)
γ	steepest slope of air–surface water temperature function (–)
μ	air temperature at the inflection point of air–surface water temperature function (K)

Subscript

sw	saturated water
r	residual water
e	effective
b	bulk
s	solid
w	water
a	air
sfw	surface water
min	minimum
max	maximum

municipal water of Changwon city at the maximum pumping capacity of 10,000 m^3/day since it was constructed in 2002. Most of the pumped water has been used for domestic water demands while around 50 m^3/day has been used to heat and cool the facility buildings since 2006. In order to prospect RBF utilization for the heating and cooling application, it is required to predict the range of the temperature of riverbank filtrate water under various conditions at its beginning phase. The objective of this study is to predict the temperature range of riverbank filtrate water at the Daesan RBF site by means of numerical modeling. This must be done in order to assess the efficiency and applicability of geothermal energy utilization through the RBF facility under various conditions. The change of saturation ratio and river stage caused by rainfall events is considered and the resulting variation of thermal capacity and thermal conductivity will be reflected on.

2. Study site

The study site, Daesan, is located in north-eastern end of Changwon city (Fig. 1). The land use of this area is dominated by rural agricultural practices.

Palyongsan tuff and Jusan andesite of the Cretaceous Yucheon Group occupies the basement of the study area from a depth of 60–80 m below the surface. Unconsolidated Quaternary alluvium is unconformally overlain on this low permeability rock. This unconsolidated layer is mainly composed of sand and pebbles with high permeability, which is a characteristic of a flood plain depositional environment [7]. Analysis of a core sample from this area has revealed the detailed composition of the strata, which consists of a sand layer, a sandy gravel layer and a weathered zone in descending order.

Daesan RBF facility consists of 7 pumping wells along the Nakdong riverside area at about 45–110 m distance from the river. The Nakdong River, located at the north side of the site, plays an important role of being the source of the water supply for the south-eastern area of South Korea including Changwon city [8]. It is under strict control of the Korea Water Resources Corporation and the Nakdong River Flood Control Center. The river stage is governed mainly by the dams of the upper reaches of the river. Among them, Namgang dam and Hapcheon dam control the overall river stage in the study area. The altitude of the riverbed is −0.1 m and the annual average river depth for the year between 2003 and 2006 is about 1.4 m. The river stage is nearly constant at 1.0 m for 8 months from October to June and shows high flow during the wet season from July to September. The vertical distribution of geological stratification at the 7 pumping wells and 7 observation wells is obtained from the core sample data and the pumping tests obtained from the 7 pumping wells in the study area were carried out to obtain transmissivity and storativity by Kim et al. (2004). They also have calculated the hydraulic conductivity of each layer from grain size analysis and concluded that the main aquifer in this region is a fine gravel layer [9].

The Annual average temperature in this site is about 13.4 °C and the annual precipitation was 1685.3 mm for the year 2003. More than a half of the annual precipitation is concentrated during the 2–3 months of the summer period. Hamm et al. (2005) calculated the recharge rate of the study area at 19.68 % while the average recharge rate of Korea is 18% [10].

3. Basic equations for groundwater flow and subsurface heat transfer

The governing equation for three-dimensional groundwater flow in a variably saturated porous medium is written by Richard's partial differential equation:

$$-\nabla\cdot\mathbf{q}\pm Q = \frac{\partial}{\partial t}(\theta_{sw}S_w) \tag{1}$$

And $\mathbf{q}$ is given by:

$$\mathbf{q} = -\mathbf{K}\cdot k_r\nabla(\Psi+z) \tag{2}$$

To describe S_w, the following saturation–pressure relation is used.

$$\begin{aligned} S_w &= S_r+(1-S_r)\left[1+|\alpha\Psi|^{\beta}\right]^{-\nu} \quad \text{for } \Psi<0 \\ S_w &= 1 \quad \text{for } \Psi\geq 0 \end{aligned} \tag{3}$$

And k_r is given by

$$k_r = S_e^{l_p}\left[1-\left(1-S_e^{1/\nu}\right)^{\nu}\right]^2 \tag{4}$$

where, $S_e=(S_w-S_r)/(1-S_r)$ and $\nu=1-1/\beta$.

Heat transfer in a saturated zone has two components: conduction via solid and liquid and convection via liquid. All of the pores are assumed to be filled with water, thus porosity is equal to