Vertical thermal aquifer stratification related to an open-loop ground-water heat pump system: numerical modeling results and experimental evidences

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1. Introduction

Open-loop groundwater heat pumps (GWHP) are considered one of the most energy efficient and environmentally friendly air-conditioning systems for temperate climate zones. One of the fundamental aspects in the realization of an open loop low-enthalpy geothermal system is the capacity to forecast the effects of thermal alteration produced in the ground, induced by the geothermal system itself.

The impact on the groundwater temperature in the surrounding area of the re-injection well (Thermal Affected Zone - TAZ) is directly linked to the aquifer properties. Physical processes affecting heat transport within an aquifer include advection (or convection) and hydrodynamic thermodispersion (diffusion and mechanical dispersion). If the groundwater flows, the advective components tend to dominate the heat transfer process within the aquifer and the diffusion can be considered negligible.

The transient dynamic of groundwater discharge and temperature variations should be considered to assess the subsurface environmental effects of the plant.

The experimental groundwater heat pump system used in this study is installed at the "Politecnico di Torino" (NW Italy, Piedmont Region). This plant is constantly monitored by multiparameter probes measuring the dynamic of groundwater temperature.

A finite element subsurface flow and transport simulator (Feflow; Diersch, 2005) was used to investigate the vertical thermal aquifer alteration. Numerical modelling is useful for delineating temperature anomalies.

The simulations were performed during the cooling period (May-October 2010) to assess the warm TAZ development around the injection well.

2. Material and Methods

The test site (Politecnico di Torino) is located in the urban area of Turin (NW Italy, Piedmont Region; geographical coordinates 45°03'45''N, 7°39'43''E, elevation 248 m a.s.l.). This plant provides summer cooling needs for the university buildings and is composed by a pumping well, a downgradient injection well and a piezometer that monitors the aquifer. Downhole log data in the study area indicate the presence of two lithologic zones with distinct hydraulic properties (Lo Russo et al., 2010):

Unit 1 - (Middle Pleistocene-Holocene; from the surface to 47 m depth). Continental alluvial cover composed mainly of coarse gravel and sandy sediments derived from alluvial fans aggraded by the Alpine rivers downstreaming towards the east.

Unit 2 - (Early Pliocene-Middle Pleistocene; from 47 m depth). Originally deposited in a shallow marine environment (Sabbie di Asti and/or Argille di Lugagnano), composed of fossiliferous sandy–clayey layers with subordinate fine gravely and coarse sandy marine layers or by quartz-micaceous sands with no fossil evidences. The top of the Unit 2 has been eroded away and covered by the alluvial deposits of Unit 1.

Two multi-temporal thermal logs have been conducted in the piezometer during the geothermal plant functioning phase (August 2010) and after the plant closure (October 2010), in order to verify the thermal stratification in the aquifer.

The subsurface environmental effects of the GWHP system, were evaluated using the finite-element Feflow® package developed by Diersch (2005). A conceptual model with two units was simulated using physical properties appropriate to the hydrogeology of the formations. The initial groundwater temperature for Units 1 and 2 was set at 15.0 °C as experimentally determined. The horizontal hydraulic conductivity (K_{xx}, K_{yy}) was derived from the step-drawdown pumping test results. The vertical hydraulic conductivity (K_{zz}) and the storativity were determined by means of a constant-rate pumping test. The porosity and the volumetric heat capacity for water and rocks was set by examining the logs recorded during the wells drilling in Unit 1. The remaining parameters for Unit 1 and all the other ones characterizing Unit 2 were set equal to the Feflow default values (Tab. 1).

The model was assumed to be closed to fluid flow at its top and bottom; rainfall infiltration was not included in the calculations due to a lack of measured infiltration data. Instead, the recharge to the system was simulated by fixing groundwater levels at all the outer boundaries of the model (Dirichlet conditions). These levels were determined by calibrating the model initially against the steady-state groundwater heads obtained from a potentiometric surface map (Civita et al., 2004). The numerical simulations of the heat transport in the aquifer were solved with transient conditions and were performed by considering only the heat transfer within the saturated aquifer, without any heat dispersion above or below the saturated zone due to the lack of detailed information regarding the unsaturated zone. Appropriate Feflow time-varying functions for discharge and temperatures have been implemented for injection well and only discharge function for pumping well. These functions were derived from groundwater monitoring. The simulations were performed during the cooling period (summer - May to October 2010) to assess the warm TAZ development around the injection well (Fig. 1).

3. Results

The multi-temporal thermal logs have highlighted the thermal stratification in the aquifer and the progressive restoring of the initial temperature vertical homogeneity occurred only several weeks after the plant closure.

Simulated temperature values were compared with experimental ones derived from groundwater monitoring in the surrounding area of the injection well and from two multi-temporal thermal logs conducted in the piezometer.

In general, good agreement is obtained between the experimental aquifer temperatures measured every meter and the simulated values.

Model results were validated through two statistical methods: Root Mean Square Error (RMSE) and Method of Efficiencies (EF). Such analysis have demonstrated the reliability and the good accuracy of the model implemented in Feflow.

4. Conclusions

The aim of this study was to model trends in temperatures around a real GWHP system and to verify the vertical thermal aquifer stratification. The good agreement of the experimental aquifer temperatures with the model results demonstrates the accuracy and the practical applicability of Feflow code.

Furthermore, the results obtained highlight the importance of the hydrodynamic parameters correlated with groundwater flow; the thermal stratification in the aquifer can be explained by the prevailing advection phenomena.

The modeling effort has focused exclusively on cooling mode; future work will include heating applications.

References

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PARAMETERS	VALUE
UNIT 1	
Conductivity Kxx [m/s]	0.0025
Conductivity Kyy [m/s]	0.0025
Conductivity Kzz [m/s]	0.0005
Storativity	0.106
Porosity	0.2
Volumetric heat capacity of the fluid [10^6J/m^{3}K]	4.18
Volumetric heat capacity of the solid [10^6J/m^{3}K]	1.3
Heat conductivity of the fluid [J/msK]	0.65
Heat conductivity of the solid [J/msK]	3
Longitudinal dispersivity [m]	5
Transverse dispersivity [m]	0.5
UNIT 2	
Conductivity Kxx [m/s]	0.00027
Conductivity Kyy [m/s]	0.00027
Conductivity Kzz [m/s]	0.000054
Storativity	0.106
Porosity	0.2
Volumetric heat capacity of the fluid [10^6J/m^{3}K]	4.2
Volumetric heat capacity of the solid [10^6J/m^{3}K]	2.52
Heat conductivity of the fluid [J/msK]	0.65
Heat conductivity of the solid [J/msK]	3
Longitudinal dispersivity [m]	5
Transverse dispersivity [m]	0.5

Tab.1 - Thermal parameters used for Feflow modeling.

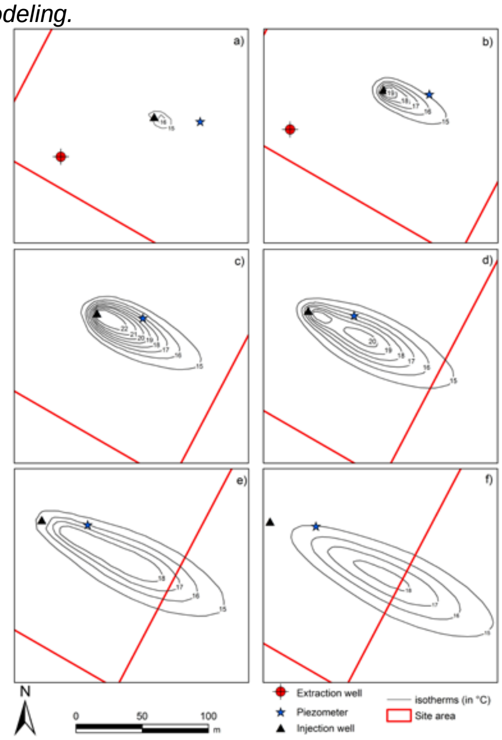

Fig. 1 - Study area. Temperatures [°C] in the Unit 1 unconfined aquifer during the cooling period - May-October 2010. Isotherms: (a) May, (b) June, (c) July, (d) August, (e) September, (f) October.