PAPER

Modeling the effects of the variability of temperature-related dynamic viscosity on the thermal-affected zone of groundwater heat-pump systems

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Abstract

Thermal perturbation in the subsurface produced in an open-loop groundwater heat pump (GWHP) plant is a complex transport phenomenon affected by several factors, including the exploited aquifer's hydrogeological and thermal characteristics, well construction features, and the temporal dynamics of the plant's groundwater abstraction and reinjection system. Hydraulic conductivity has a major influence on heat transport because plume propagation, which occurs primarily through advection, tends to degrade following conductive heat transport and convection within moving water. Hydraulic conductivity is, in turn, influenced by water reinjection because the dynamic viscosity of groundwater varies with temperature. This paper reports on a computational analysis conducted using FEFLOW software to quantify how the thermal-affected zone (TAZ) is influenced by the variation in dynamic viscosity due to reinjected groundwater in a well-doublet scheme. The modeling results demonstrate non-negligible groundwater dynamic-viscosity variation that affects thermal plume propagation in the aquifer. This influence on TAZ calculation was enhanced for aquifers with high intrinsic permeability and/or substantial temperature differences between abstracted and post-heat-pump-reinjected groundwater.

Keywords Groundwater heat pump · Thermal affected zone · Dynamic viscosity · Groundwater viscosity · Thermal conditions

Introduction

A large portion of energy use in buildings is related to heating and cooling. Ground-source heat pump systems represent an important potential technology for mitigating greenhouse gas emissions related to space heating and cooling. They are environmentally friendly and energy efficient technologies that exploit the relatively constant temperature of the ground, or a medium thermally coupled to the ground, versus outside air temperature. In particular, groundwater heat pumps (GWHPs) utilize the natural thermostability of groundwater. GWHP systems abstract groundwater from one or more wells, pass it through a heat exchanger, and discharge water back into the aquifer or nearby surface water. Depending on the use mode,

energy can be extracted (heating) or injected (cooling). Such reinjection disturbs the natural aquifer temperature, producing a thermal plume of colder or warmer reinjected groundwater, known as the thermal affected zone (TAZ). As reported by Diao et al. (2004), advection (or convection), mechanical dispersion, and diffusion are the main physical processes that affect heat transfer within an aquifer. Convection, called forced convection when the flow field is caused by external forces, is the energy transport mechanism mediated by fluid motion within the medium (Carslaw and Jager 1959). Diffusion occurs by conductive transport in a solid or liquid and can be described by a linear expression relating heat flux to the temperature gradient. Under most conditions of natural groundwater flow, diffusion can be neglected. Lo Russo and Taddia (2010) illustrated the prevalence of a heat advective transport component of the dispersion phenomenon, by analyzing the groundwater monitoring results of the surrounding area of an injection well.

The thermal impact of reinjection of colder or warmer groundwater into an aquifer, with respect to both groundwater heat pump systems (Andrews 1978; Lippmann and Tsang

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1980; Sauty 1981) and aquifer thermal energy storage (Molson et al. 1992), has been studied for a long time. The utilization of groundwater for cooling or heating purposes for a site-specific investigation involves, typically, a quantitative assessment of the available hydraulic capacity of the aquifer, the optimal number, location and operation mode of pumping/recharging wells, and the likely resulting temperature distribution in the groundwater downstream of the site (Liang et al. 2011). It is important to know, even before constructing a GWHP system, whether the TAZ will interfere with downgradient pre-existing plants, wells, or subsurface infrastructure or with the plant itself (thermal feedback). This determination depends fundamentally on the TAZ extent around the planned injection point.

As pointed out by Bear (1972), an aquifer is a composite medium in which heat dispersion is affected by both fluid- and solid-phase properties. Different researchers have studied the different hydrodynamic parameters that can affect the extent of the TAZ. Gringarten and Sauty (1975) proposed a mathematical model for investigating the transient temperature evolution of a pumped aquifer with uniform regional flow during the reinjection of heat-depleted water into aquifers. The results are presented in terms of dimensionless parameters helpful for the design of GWHP systems in order to prevent the heat-depleted-water breakthrough before a specified time and to maintain the temperature variations at the production wells after breakthrough within reasonable limits. Warner and Algan (1984) reported a predictive study in the USA which showed, by computer modeling, the thermal impact of nine different residential groundwater heat pump systems on the associated aquifer, in the case where a well-doublet system is used (i.e. where water is pumped from and reinjected into the same aquifer through separate adjacent wells). They introduced the important role of aquifer parameters (porosity, thickness, density, volumetric solid and fluid heat capacity, dispersivity) and well properties (well design and spacing) which affect the distribution of thermal changes. Lo Russo et al. (2012) realized numerical simulations of a GWHP system located in Politecnico di Torino (NW Italy) and a sensitivity analysis of the subsurface parameters, and analyzed how they influenced the TAZ development. They determined that the hydrodynamic parameters related to the advective heat flow component more significantly affect the TAZ development. These hydrodynamic subsurface parameters are then of major importance to reliable modeling of the TAZ, and on-site investigations should be concentrated on determining these parameters (hydraulic conductivity and gradient, porosity, etc.). Park et al. (2015) analyzed also in detail the importance of thermal dispersivity in designing groundwater heat pump (GWHP) systems.

In this paper, attention has been drawn to the effects of temperature-related dynamic-viscosity variability on the modeling of the thermal-affected zone of a groundwater heat pump system. Temperature influences several physical parameters characterizing an aquifer, including the density and viscosity of the water, as well as the thermal conductivity and heat capacity of the porous medium.

Hydraulic conductivity varies with temperature due to temperature-related variation in the dynamic viscosity of water. Consequently, temperature can affect heat transport values through hydraulic conductivity variation (Hecht-Mendez et al. 2010). Typically, computations of heat transport in an aquifer neglect variation of the dynamic viscosity of groundwater, assuming a constant viscosity. In order to check whether this modeling approach is suitable, in the present study, different temperature-value scenarios for reinjected groundwater in an existing well-doublet system have been simulated. The test system is located in the urban plain area of the city of Turin, Italy, and provides cooling needs for some buildings in Politecnico di Torino University. Using the FEFLOW® 6.2 software package developed by Diersch (2010), a comparison between the TAZ calculations of a model with a constant dynamic viscosity of groundwater and a model with a variable value related directly to reinjected groundwater temperature, have been realized. The two model setups were compared under three different prescribed injection temperature values and three different hydraulic conductivity values across the simulation domain, in order to understand when it is proper to assume a constant viscosity value.
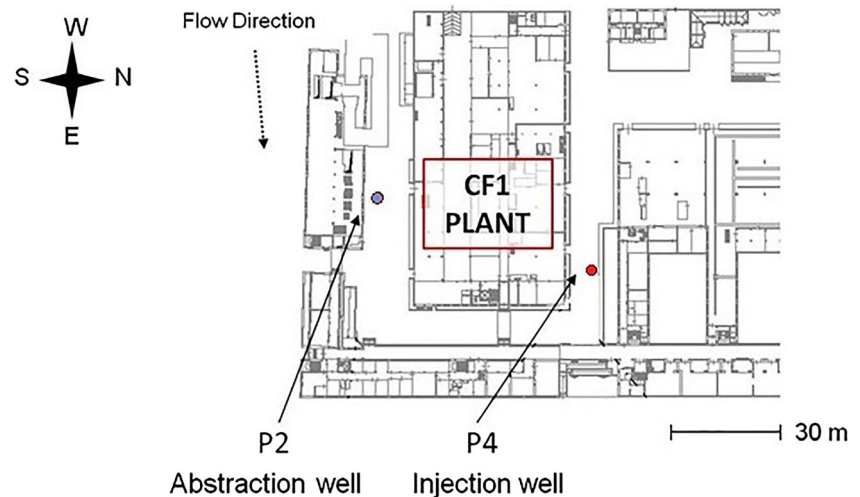
Methods

Test site

The test site at Politecnico di Torino is located in northwest Italy in the urban area of Turin (geographical coordinates: 45° 03′ 45″ N, 7° 39′ 43″ E, elevation 250 m a.s.l.). It has a well-doublet system (see Fig. 1) that works during the spring and summer to cool some university buildings. The system is comprised of a 40-m-deep abstraction well (P2) situated 77 m immediately up hydraulic gradient from a 47-m-deep reinjection well (P4). The two wells have similar technical characteristics: a steel casing (diameter 35.5 cm), bridge slot screens from 19 m to the hole bottom, and a cemented annulus from the surface to a depth of 6 m. This system draws exclusively upon a surficial alluvial aquifer. The Politecnico di Torino test site is well known in terms of geological and hydrogeological characteristics as it has already been studied in mentioned previous works (Lo Russo and Taddia 2010; Lo Russo et al. 2012).

Geologic characteristics of the site

The site is in central Turin, an urban area situated mainly on the outwash plain of several glacio-fluvial coalescing fans

Fig. 1 GWHP-system plan illustration at the Politecnico CF1 plant. P2 is the abstraction well and P4 is the injection well

The potentiometric surface in the area is, on average, 20 m below ground level. The conceptual model is represented in Fig. 3. A hydraulic conductivity of $K_1 = 3.15 \times 10^{-3}$ m s^{-1} was obtained from a step-drawdown test performed in well P2 in October 2015. Based on the lithology of the aquifer determined by examining the logs recorded during well drilling, the effective porosity was estimated to be 0.20.

connected to the Pleistocene-Holocene expansion phases of the Susa glacier. The plain is bounded by the Rivoli-Avigliana Morainic Amphitheater on the west side and Torino Hill on the east (see Fig. 2). The geological setting of this area is known with a high degree of confidence owing to information developed from numerous drilled wells (Regione Piemonte 2007) and downhole log tests. It is characterized by two lithologic zones, corresponding to stratigraphic Units 1 and 2 with distinct hydraulic properties.

Unit 1 (middle Pleistocene–Holocene) is a continental alluvial cover composed primarily of coarse gravel and sandy sediments with limited-area local subordinate clay lenses that are up to 1–1.5 m thick. These sediments are related to aggradation of alluvial fans by east-flowing alpine rivers. Unit 1 overlies unit 2, with its base dipping gently (0.5%) toward the northeast.

Unit 2 (early Pliocene–middle Pleistocene) is composed primarily of fossiliferous sandy-clayey layers with subordinate fine gravelly and coarse sandy marine layers (Argille di Lugagnano) or quartz-micaceous sands (Sabbie di Asti). The sedimentation profile is related to a shallow marine environment. Unit 2 has been eroded and covered by the alluvial deposits of unit 1 (Baccino et al. 2010).

Aquifer characteristics

The tapped aquifer is unconfined, extending over the entire urban plain. It consists of the alluvial sediments of unit 1 and is hydraulically connected to the main surface-water drainage network of rivers, including the Stura di Lanzo, which flows NW–SE, the Sangone and Dora Riparia, which flow nearly W–E, and the Po, which flows along the western border of Torino Hill. The water table displays a NNW–SSE gradient of 0.29% toward the Po River.

Under the investigation site, the bottom of unit 1 is at a depth of approximately 50 m (Lo Russo and Civita 2010).

Test-site model

A two-unit conceptual model simulation was run with scenarios involving different physical property assumptions, wherein unit 1 represents the exploited unconfined alluvial aquifer (Fig. 4). A complete list of hydrodynamic and thermal parameters assigned to units 1 and 2 in the simulations is provided in Table 1.

The plan-view dimensions of the model grid are 4,048 m W–E by 3,608 m N—S. This model area is larger than that of the site under investigation to ensure that the model limits were sufficiently remote to reduce any impact of the assumed boundary conditions on model outcomes. The average mesh spacing in the more refining central area varies between 4 and 7.5 m to facilitate thermal plume estimation. Additional refining was performed around the injection point to a mesh spacing of 0.08 m. The grid spacing was defined after a suitable trial test.

Surface infiltration was not included in the calculations and the model was assumed to be closed to fluid flow at the bottom. Constant heads (Dirichlet conditions) are simulated on the western (230 m a.s.l.) and eastern boundaries (220 m a.s.l.) in accordance with onsite potentiometric surface measurements (Fig. 4).

The regional potentiometric surface is well known thanks to some studies undertaken by Regione Piemonte (2007); furthermore in the Politecnico test site the groundwater levels and temperature are measured in the extraction and injection wells and in a control piezometer using installed monitoring probes. These measurements are also taken in other wells/piezometers located near the study area.
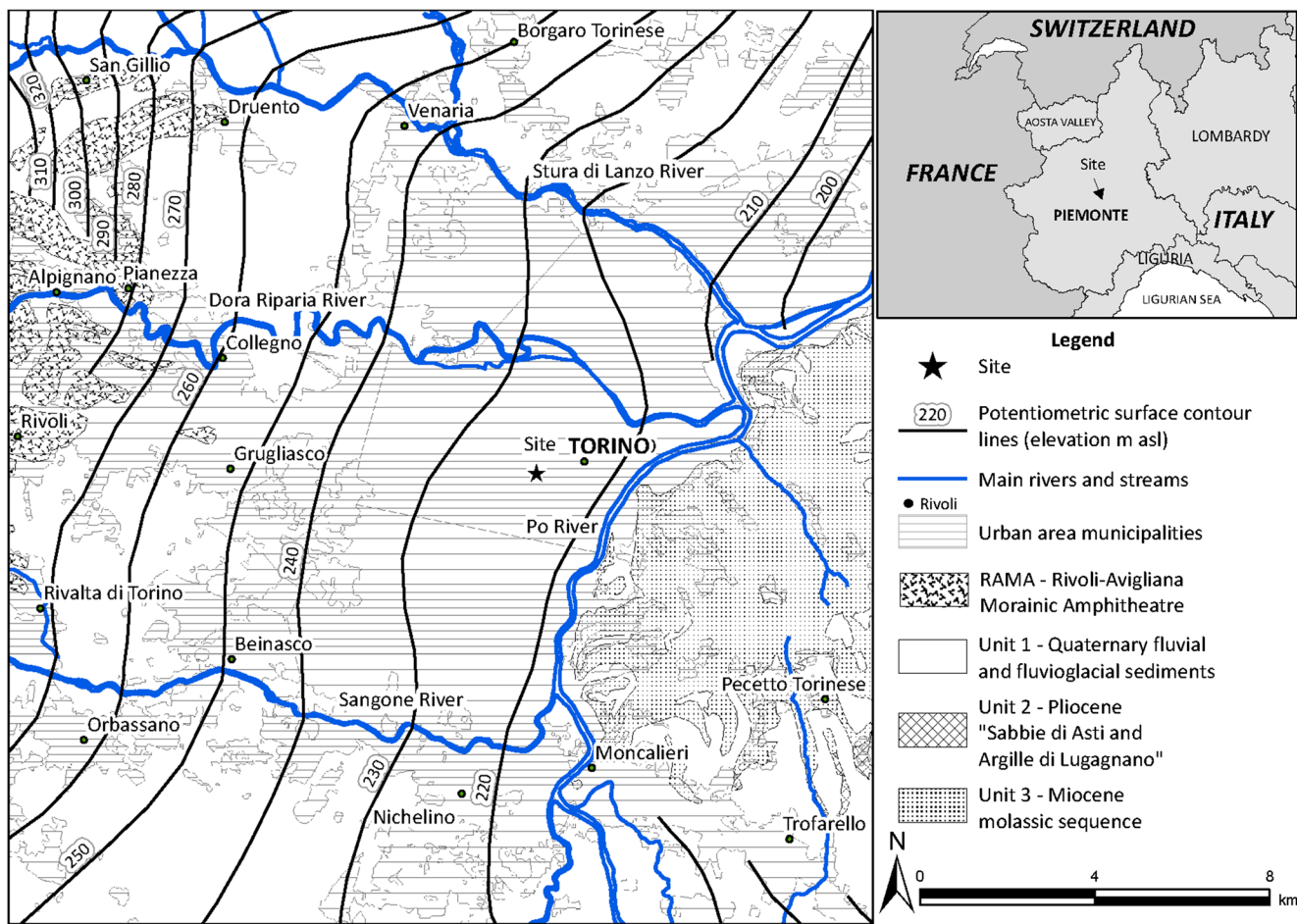
Fig. 2 Hydrogeologic map of the Turin area and site location (Lo Russo et al. 2012)

The average natural groundwater temperature was set to 15.0 °C throughout the aquifer because two thermal logs performed in the extraction and injection wells before pumping showed negligible vertical temperature deviation from the average. These experimental data are compliant with those reported by Bucci et al. (2017). Undisturbed groundwater temperature for unit 2 is the same as that of unit 1.
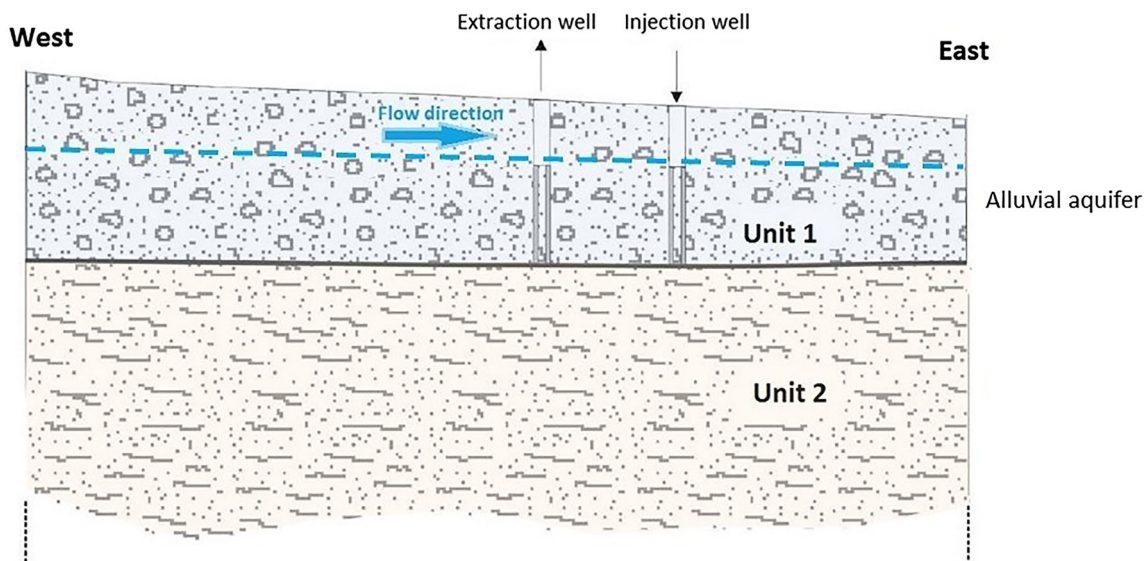

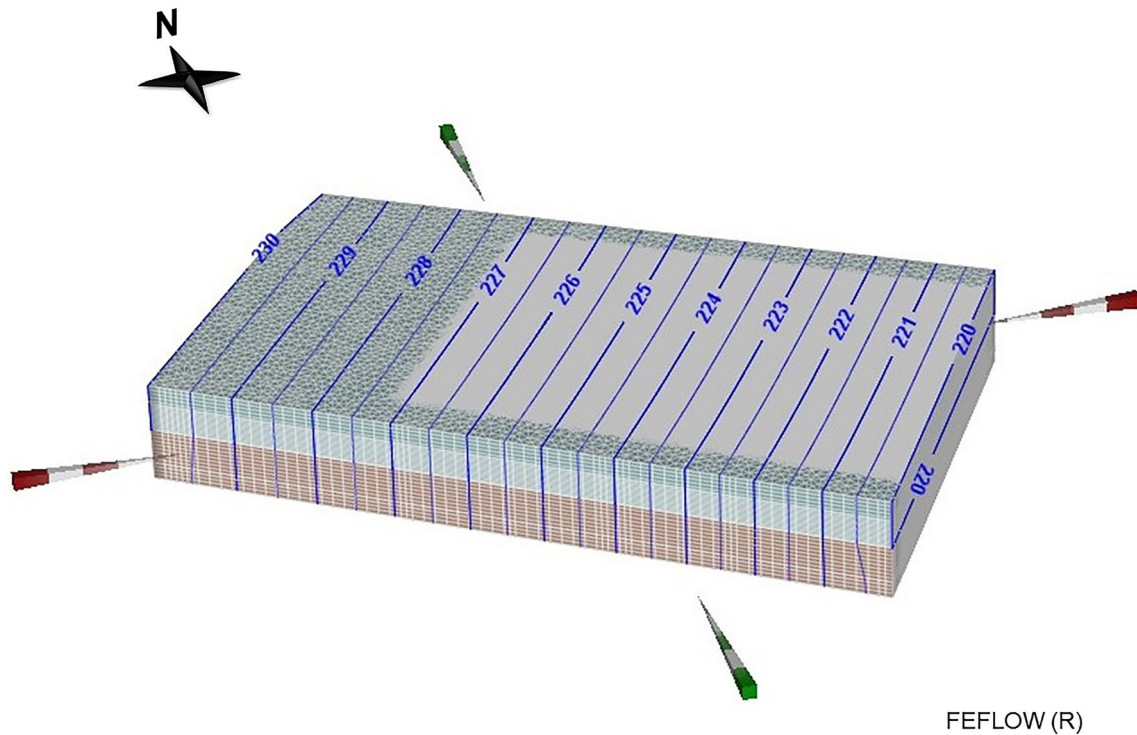**Fig. 3** Conceptual hydrogeological cross-section

Fig. 4 FEFLOW three-dimensional model. The units are color-coded: unit 1 in light blue and unit 2 in orange. Blue lines indicate the hydraulic level

Heat transport was simulated with transient flow conditions. The injection rate was set to a constant value of 5 L/s. Despite the fact that this simplification does not strictly represent the real functioning conditions of the plant, which in fact operates at variable load depending on the building cooling demand, it was assumed that the use of a constant withdrawal rate does not affect the reliability of the assessment of the effects of temperature on the variable dynamic viscosity.

Table 1 Thermal and hydrodynamic parameters used as input data in FEFLOW modeling

Parameter	Symbol	Unit of measure	Test-site value
Unit 1			
Horizontal hydraulic conductivity	$K_{xx1} - K_{yy1}$	$[\text{m s}^{-1}]$	0.00315
Vertical hydraulic conductivity	K_{zz1}	$[\text{m s}^{-1}]$	0.00001
Effective porosity	n_1	$[-]$	0.2
Volumetric heat capacity of the fluid	$q^{f}c_1{}^{f}$	$[10^6 \text{ J m}^{-3} \text{ K}^{-1}]$	4.18
Volumetric heat capacity of the solid	$q^{s}c_1{}^{s}$	$[10^6 \text{ J m}^{-3} \text{ K}^{-1}]$	1.3
Heat conductivity of the fluid	$\lambda_1{}^{f}$	$[\text{J m}^{-1} \text{ s}^{-1} \text{ K}^{-1}]$	0.65
Heat conductivity of the solid	$\lambda_1{}^{s}$	$[\text{J m}^{-1} \text{ s}^{-1} \text{ K}^{-1}]$	3
Longitudinal dispersivity	α_{L1}	$[\text{m}]$	5
Transverse dispersivity	α_{T1}	$[\text{m}]$	0.5
Unit 2			
Horizontal hydraulic conductivity	$K_{xx2} - K_{yy2}$	$[\text{m s}^{-1}]$	0.00001
Vertical hydraulic conductivity	K_{zz2}	$[\text{m s}^{-1}]$	0.000001
Effective porosity	n_2	$[-]$	0.1
Volumetric heat capacity of the fluid	$q^{f}c_2{}^{f}$	$[10^6 \text{ J m}^{-3} \text{ K}^{-1}]$	4.2
Volumetric heat capacity of the solid	$q^{s}c_2{}^{s}$	$[10^6 \text{ J m}^{-3} \text{ K}^{-1}]$	2.52
Heat conductivity of the fluid	$\lambda_2{}^{f}$	$[\text{J m}^{-1} \text{ s}^{-1} \text{ K}^{-1}]$	0.65
Heat conductivity of the solid	$\varLambda_2{}^{s}$	$[\text{J m}^{-1} \text{ s}^{-1} \text{ K}^{-1}]$	3
Longitudinal dispersivity	α_{L2}	$[\text{m}]$	5
Transverse dispersivity	α_{T2}	$[\text{m}]$	0.5

The simulation time covers 365 days (1 year) starting from the 1st of May. After 15 days, the plant starts and runs for 123 days (May 15th–September 15th) under a constant cooling load without deactivation of the heat pump. After the 15th of September, the plant switches off and the simulation runs until the next May 1st.

Simulation scenarios

As described by Rühaak et al. (2010), computation of heat transport within a porous medium requires the solution of a set of balance equations. Firstly, the following mass conservation equation of a fluid in a saturated porous medium has been employed (Diersch 2005):

$$S_0 \cdot \frac{\partial h}{\partial t} = \nabla \cdot [\mathbf{K}(\nabla h + \chi \mathbf{e})] + Q \qquad (1)$$

where S_0 is the specific storage attributable to the fluid and medium compressibility (m^{-1}), h is the hydraulic head (m), t is time (s), $\chi = \rho - (\rho_o / \rho_o)$ is the buoyancy coefficient (−), and $\mathbf{e}$ (which equals −g/|g|) is the gravitational unit vector (−). Q corresponds to the bulk sources and sinks of flow (s^{-1}).

The hydraulic conductivity tensor ($m\,s^{-1}$), abbreviated as $\mathbf{K}$, was defined in accordance with Eq. (2)

$$\mathbf{K} = \frac{\mathbf{k}\rho_f g}{\mu_f} \qquad (2)$$

where $\mathbf{k}$ is the permeability tensor (m^2), ρ_f is the fluid density ($kg\,m^{-3}$), g is the gravitational force present ($m\,s^{-2}$), and μ_f is the dynamic fluid viscosity ($kg\,m^{-1}\,s^{-1}$).

The Darcy velocity $\mathbf{q}$ ($m\,s^{-1}$) is given by Eq. (3).

$$\mathbf{q} = -\mathbf{K}(\nabla h + \chi \mathbf{e}) \qquad (3)$$

Heat transport, including both conductive and advective components, is represented by

$$(\rho c)_g \frac{\partial T}{\partial t} = \nabla \left[\lambda \nabla T - (\rho c)_f \mathbf{q} T \right] + H \qquad (4)$$

where T is the temperature (K), λ is the thermal conductivity ($W\,m^{-1}\,K^{-1}$), $(\rho c)_g$ is the bulk volumetric heat capacity ($J\,m^{-3}\,K^{-1}$), $(\rho c)_f$ is the fluid volumetric heat capacity, and H refers to internal energy sources and sinks ($W\,m^{-3}$).

In open-loop systems, reinjected groundwater temperature is time-variable depending upon heat-pump functioning conditions and the building's cooling and heating requirements. Usually, these transient conditions are simulated with time-varying functions in heat transport modeling equations, while the dynamic viscosity of groundwater is set at a constant value. Here, this scenario of conditions (FEFLOW program default) is used as a reference setting (scenario SC2) for comparison with TAZ calculations determined when dynamic viscosity varies with reinjected groundwater temperature

(scenario SC1). If viscosity dependencies are incorporated in the calculation, all conductivity values refer to a predefined reference temperature. Internal conductivities are then recalculated for the actual temperature in each element at a given time (FEFLOW 6.2 Help).

Sensitivity analysis

The hydraulic conductivity (K_{xy}) of unit 1 varies according to simulation conditions (see Table 2). All other parameters characterizing units 1 and 2 are assumed to be constant during the modeling.

For both scenarios (SC1 and SC2), nine different cases have been considered using combinations of three conductivity classes and three different injection temperatures values. For each conductivity class, three injection temperatures were considered. The temperatures were set to explore the real potential functioning conditions of the heat pump. These parameters are provided in Table 2 according to the simulation case. The isotherms obtained in SC1 versus SC2 for each case (K_{xy}–T_{INJ}) have been analyzed and compared, as reported in Table 2.

Simulation results were compared with respect to the TAZ that had developed at the end of the reinjection period (September 15th). The TAZ area was graphically defined as the maximum plant extent of the 16 °C isotherm in the thermal plume. The total surface area enclosed by that isotherm was computed. The length of the TAZ area along the groundwater flow direction (X) was also measured (Fig. 5).

Results

The simulated TAZs are compared in Fig. 6. The percentage change in the plan area and the difference between the maximum distances along the flow direction (ΔX) are summarized in Table 3. The data demonstrate that the size of the TAZ is sensitive to variations in dynamic viscosity in relation to groundwater temperature: both the TAZ area variation and, more prominently, ΔX for equal initial K_{xy} values tend to increase with warming of the reinjected water. Furthermore, this TAZ size variation is more pronounced at higher values of initial K_{xy}: the maximum TAZ area variation in SC1 is always typical of the highest input conductivity value ($K_{xy} = 1 \times 10 - 2$ m/s). Considering ΔX values, in cases 1, 2 and 3 ($K_{xy} = 1 \times 10 - 4$ m/s and $T_{INJ} = 20$–30 °C) and cases 4 and 5 ($K_{xy} = 1 \times 10 - 3$ m/s and $T_{INJ} = 20$–25 °C), TAZ area variation related to variation in dynamic viscosity with groundwater temperature can be considered negligible. In general, TAZ variation becomes more evident moving downgradient with respect to the injection well.

Table 2 Values of initial horizontal conductivity (K_{xx}), vertical conductivity (K_{yy}), and groundwater injection temperature (T) utilized for each simulation case

| Simulation case	$\Delta T + 5$ °C	$\Delta T + 10$ °C	$\Delta T + 15$ °C
K_{min}	Case 1 $K_{xx1} = K_{yy1} = 1 \times 10^{-4}$ m s^{-1} $T_{INJ} = 20$ °C	Case 2 $K_{xx1} = K_{yy1} = 1 \times 10^{-4}$ m s^{-1} $T_{INJ} = 25$ °C	Case 3 $K_{xx1} = K_{yy1} = 1 \times 10^{-4}$ m s^{-1} $T_{INJ} = 30$ °C
K_{med}	Case 4 $K_{xx1} = K_{yy1} = 1 \times 10^{-3}$ m s^{-1} $T_{INJ} = 20$ °C	Case 5 $K_{xx1} = K_{yy1} = 1 \times 10^{-3}$ m s^{-1} $T_{INJ} = 25$ °C	Case 6 $K_{xx1} = K_{yy1} = 1 \times 10^{-3}$ m s^{-1} $T_{INJ} = 30$ °C
K_{max}	Case 7 $K_{xx1} = K_{yy1} = 1 \times 10^{-2}$ m s^{-1} $T_{INJ} = 20$ °C	Case 8 $K_{xx1} = K_{yy1} = 1 \times 10^{-2}$ m s^{-1} $T_{INJ} = 25$ °C	Case 9 $K_{xx1} = K_{yy1} = 1 \times 10^{-2}$ m s^{-1} $T_{INJ} = 30$ °C

Conclusions

Numerical modeling is a fundamental tool for predicting environmental effects in the design stage of open-loop geothermal-heat-pump plants prior to construction as well as for assessing the effects of warmer (or colder) water injection and its possible interference with existing wells, subsurface infrastructure, or land use. As extensively explored in the literature, many different subsurface hydrodynamic parameters involved in the thermal plume simulations can significantly affect the numerical assessment of such phenomena.

The present study examines how the variation of the dynamic viscosity of groundwater affects thermal plume propagation computations at a real field well-doublet test site located in the alluvial Po plain of the city of Turin (NW Italy). The comparative analysis of scenarios, which were designed to detect through a suitable sensitivity analysis whether variation in dynamic viscosity effects on TAZ computing can be considered negligible,

Fig. 5 Geometric representation of the TAZ plan view. The X axis is measured along the groundwater flow direction. The Y axis is the normal axis passing over the injection well
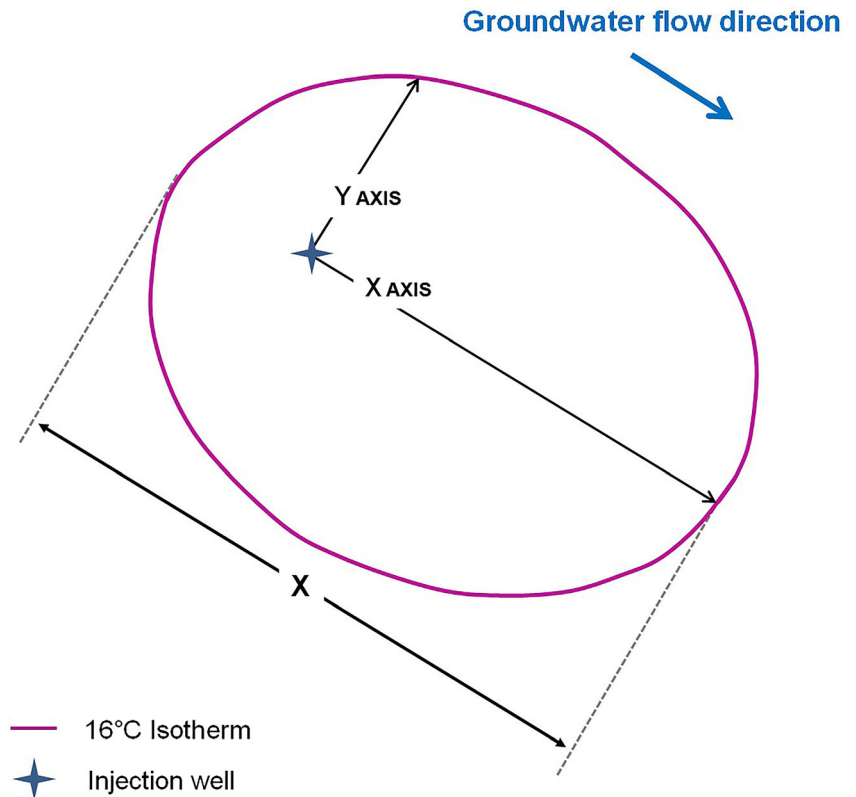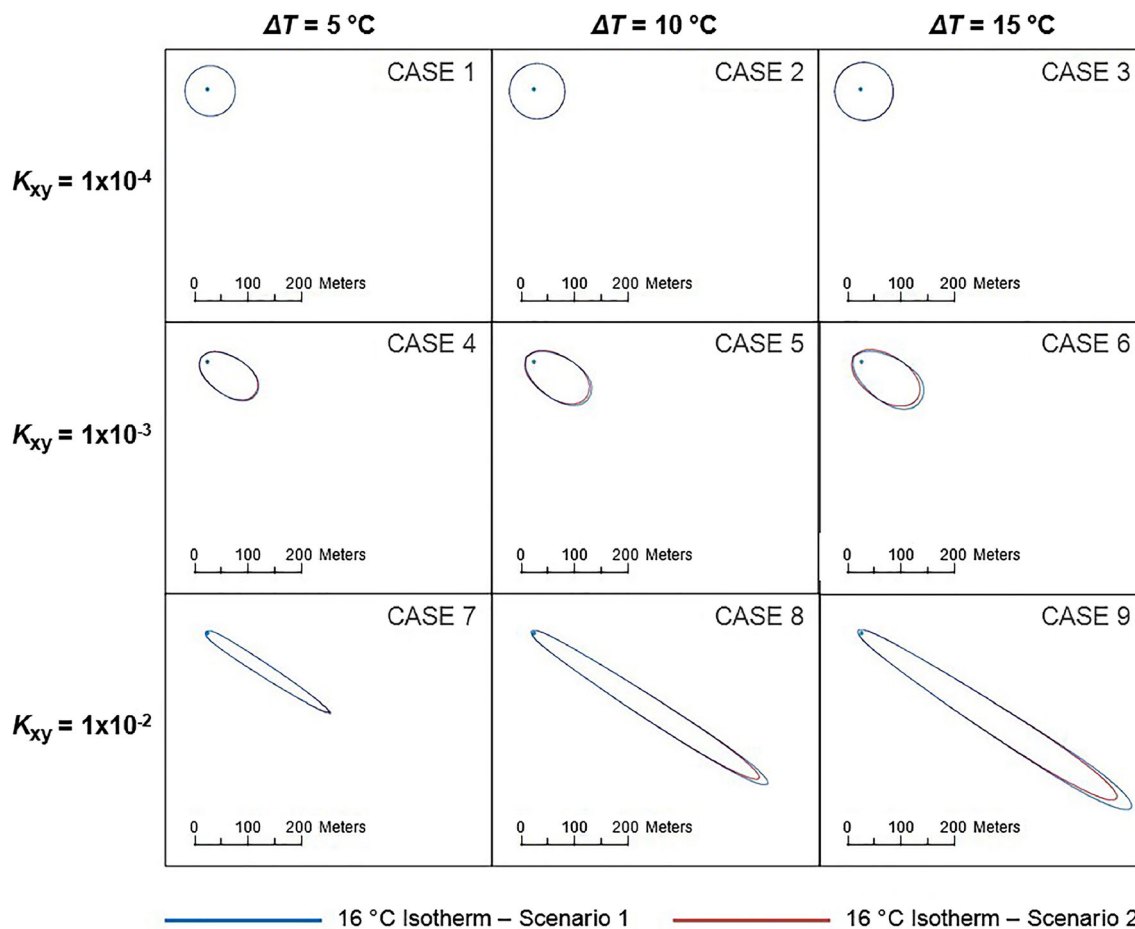
Fig. 6 Comparison between 16 °C isotherm of scenario 1 (variable dynamic viscosity: blue line) and scenario 2 (constant dynamic viscosity: red line) for each $(K - T_{INJ})$ case studied. The plan view refers to the maximum extent of this isotherm in the thermal plume at the end of a 123-day reinjection period

indicated that variation in dynamic viscosity with groundwater temperature has a significant influence on the geometry and extension of the TAZ, especially in the presence of high aquifer hydraulic conductivity and/or relatively warm injected water. Therefore, at least in these modeling contexts, dynamic viscosity variance should be taken into account to enable accurate assessment of subsurface thermal perturbation.

Table 3 Geometric parameters of the TAZ calculated for each case study and comparison between SC1 and SC2

Parameter	K value	SC 1 variable dynamic viscosity			SC 2 constant dynamic viscosity			Comparison between SC1 and SC2		
		$\Delta T = +$ 5 °C	$\Delta T = +$ 10 °C	$\Delta T = +$ 15 °C	$\Delta T = +$ 5 °C	$\Delta T = +$ 10 °C	$\Delta T = +$ 15 °C	$\Delta T = + 5$ °C	$\Delta T = + 10$ °C	$\Delta T = + 15$ °C
Area [m²]	K_{xy} 1×10^{-4}	6,962.25	8,479.67	9,280.52	6,961.11	8,447.95	9,264.16	$\Delta TAZ^a = -0.02\%$	$\Delta TAZ = -0.4\%$	$\Delta TAZ = -0.2\%$
	K_{xy} 1×10^{-3}	6,895.90	8,501.98	9,696.49	6,872.01	8,478.98	9,449.19	$\Delta TAZ = -0.3\%$	$\Delta TAZ = -0.3\%$	$\Delta TAZ = -2.6\%$
	K_{xy} 1×10^{-2}	5,662.53	18,286.86	27,796.96	5,543.00	17,150.89	25,114.42	$\Delta TAZ = -2.1\%$	$\Delta TAZ = -6.2\%$	$\Delta TAZ = -9.7\%$
X	K_{xy} 1×10^{-4}	94.48	104.41	109.25	94.46	104.23	109.22	$\Delta X = 0.02$	$\Delta X = 0.18$	$\Delta X = 0.03$
	K_{xy} 1×10^{-3}	123.33	138.29	149.58	121.68	135.76	143.97	$\Delta X = 1.65$	$\Delta X = 2.53$	$\Delta X = 5.61$
	K_{xy} 1×10^{-2}	279.24	525.51	610.97	276.75	505.86	578.10	$\Delta X = 2.49$	$\Delta X = 19.66$	$\Delta X = 32.87$

[a] ΔTAZ is equal to TAZ_{SC2} variation with respect to TAZ_{SC1} [%]

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