EVALUATION OF THE EFFECTS INDUCED ON GROUNDWATER'S THERMAL STATE AFTER RE-INJECTION OF ALTERED TEMPERATURE WATER: THE CASE STUDY OF HEAT TRANSPORT SIMULATION IN THE SHALLOW AQUIFER OF TURIN CITY (NW ITALY)

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Introduction. A case study of heat transport modeling in the shallow aquifer of the Turin City (NW Italy) with finite-difference computer code is here reported. A detailed geological characterization of the subsoil and the estimation of hydrogeological and thermal features of the shallow aquifer are essential tools in support of heat transport simulations for the design of open-loop system. This modeling has the purpose of evaluate the thermal plume propagation connected to the re-injection of altered thermal water in the aquifer with temperature higher or lower than the average annual value.

This research focuses on the following problems: a) to study the effects induced by the discharge of water in the shallow aquifer at temperature higher than the annual average value and the consequent rise of temperature induced downstream of the same. In this case, the thermal modeling of the shallow aquifer allows to estimate the alteration on the thermal groundwater state in order to predict phenomena of "*groundwater's thermal pollution*" with associated environmental problems; b) to study the effects related to the injection in the aquifer of water at lower temperature than the annual average value. The discharge of water at lower temperature causes a decrease of the water calorific power with a consequent loss of efficiency of the geothermal plant.

From the practical point of view, the methodology here proposed can be applied in the preliminary stages of a geothermal system design, where it is convenient to assess the optimal distance between extraction and injection wells in order to avoid "*thermal feedback phenomena*" and, more generally, assessing the environmental impact related to the extension of the thermal anomaly in the subsurface.

Morphological and geological setting of the Turin city. The Turin city is located in a narrow strip of the north western Po Plain, between the Alps and Turin Hill (Fig. 1A). In particular, it is placed in a marginal position, at the edge with the Turin Hill, where the current course of the Po River is located that separates a plain sector from a hill one.

The plain area (altitude ranging from 200 – 350 m a.s.l.) shows a weak inclination towards east and NE (about 1‰).

In detail, the morphology is slightly articulated by the presence of small embankments and depressions connected with ancient trends of Po River, characterized by small areal extension, height of few meters and mostly discontinuous areal development (Forno and Lucchesi, 2012). Nevertheless, the morphology of the plain is affected by a generalized anthropic reshaping that causes the modification of numerous natural forms and the creation of new anthropic forms.

The plain does not have the typical structure of a subsiding plain, instead, it presents a sector with important recent uplift, connected to the Padane Thrust Front (TFP), that influences the geometry of the sedimentary bodies and created important variations of the hydrographic network during the Pleistocene up to the recent settling of the Po River to the north of the hill (Forno, 1982; Forno and Lucchesi, 2012).

The shallow subsoil of Turin consists of Pleistocene fluvial and outwash sediments linked to Alpine watercourses forming wide fans, cut by the erosional scarps linked to the present course of the Po River and partly filled by its Holocene fluvial sediments. The distribution area of the deposits linked to Po River is restricted to the narrow band at the edge of the river bed. Overall, the fluvial and outwash deposits show a shallow thickness, comprised between 10 m, on the edge with the Turin Hills, up to 80 m towards the Alpine chain. These sediments are organized

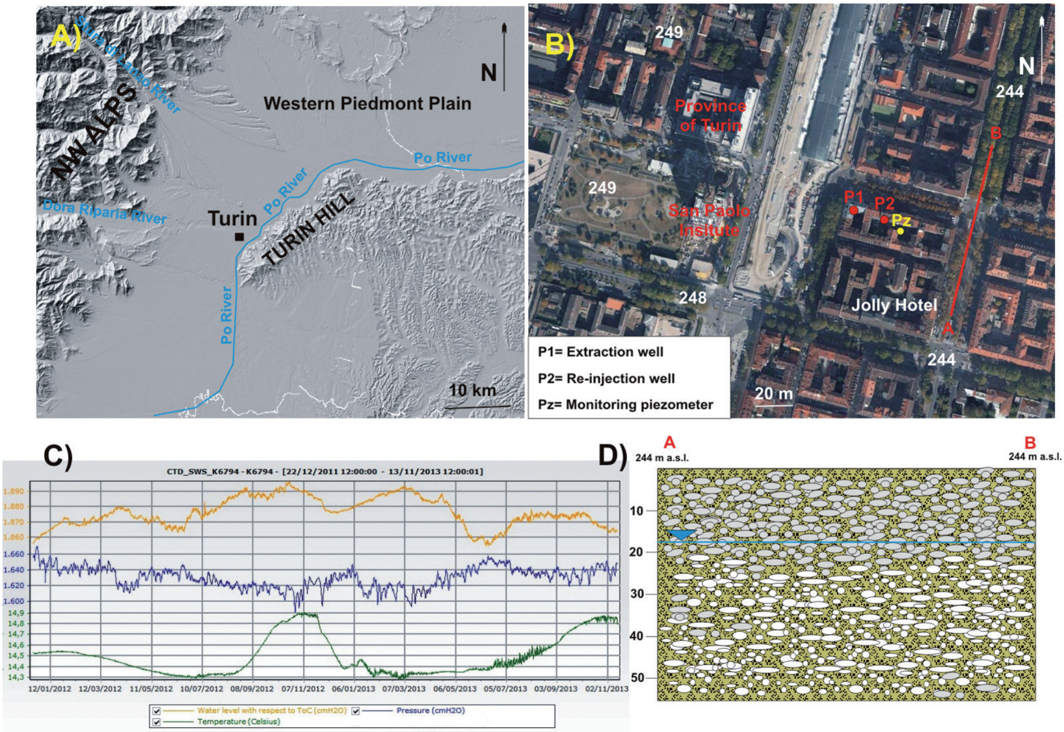

Fig. 1 – Sketch of north-western Piedmont Region (A); satellite view of the study area (B); monitoring parameters: static level and temperature of the aquifer (C); simplified stratigraphic cross section of the subsoil (D).

in different sedimentary bodies separated by erosional surfaces with areal range development, representing the main elements of the succession (Bonsignore *et al*., 1969; Dela Pierre *et al*., 2007). This sedimentary succession rests on the “villafranchian succession”, comprising deltaic deposits (Lower Complex) and fluvial deposits (Upper Complex), referred to Piacenzian and Calabrian respectively, separated by an unconformity (Cascina Viarengo Surface) (Carraro Ed., 1996; Forno *et al*., 2015), and deep marine clay deposits (Lugagnano Clay) with littoral sandy deposits (Asti Sand) referred to Zanclean (Festa *et al*., 2009).

Hydrogeological setting of the Turin city. This study focuses on the shallow aquifer hosted within the fluvial deposits. The shallow aquifer is mainly supplied by direct rainfall and rivers at the outlet of the valleys in the plain. This aquifer has a thickness generally ranging between 20 and 50 m; in spite of the variable thickness of the aquifer, it has a high productivity and has a regional importance. The water table generally follows the topographic surface. The bottom of the shallow aquifer is generally well marked by a textural variability of the deposits. The local presence of thick and relatively continuous layers of silt or clay-rich deposits allows a clear separation between the shallow aquifer and deep aquifers, hosted mainly in marine and permeable horizons of the villafranchian succession (Canavese *et al*., 2004; Bove *et al*., 2005; De Luca and Ossella, 2012; Irace *et al*., 2009).

Technical characteristics of the geothermal open-loop system. The project, object of this research, corresponds to an open-loop system constituted by two wells (P1 and P2 in Fig. 1B), extraction well and re-injection well, for heating-cooling and hot water health. The wells are placed at a distance of 20 m. Both wells were drilled up to 45 m depth from ground level and together intercept a shallow aquifer. The reintroduction of thermal water therefore, occurs in the same aquifer from which it was extracted for the operation of the open-loop system.

The wells have been realized in rotation with reverse circulation of fluid. The wells, with a diameter ∅ = 800 mm, are 45 m deep. The blank casing and the bridge screens, butt welded, have diameters ∅ = 406 mm.

Extraction well has bridge Johnson screens placed between 16.00 - 40.00 m from ground level; while the injection well has bridge Johnson screens placed between 10.00 - 40.00 m from ground level. The gravel packing (siliceous gravel) was put between 10.00 – 40.00 m from ground level.

A monitoring piezometer (Pz in Fig. 1B), with diameter ∅ = 127 mm and depth of 30 m, was realized downstream from the well of restitution at a distance of 12 m. The piezometer was equipped with a multiparametric probe ("Schlumberger water service"), placed at a depth of 25 m from ground level, with the aim of monitoring the variability of water table and the temperature of the water. Measurements collected concern the following parameters: static level and temperature of water (Fig. 1C).

Geological and geotechnical features of the subsoil. By the stratigraphy drawn up during the drilling of the wells and the piezometer, the subsurface can be so exemplified:

- 0.00-21.00 m: gravel and pebbles with very dense sandy-silty matrix, interbedded by cemented gray layers (conglomerate);
- 21.00-45.00 m: gravel with moderately compacted brown silty sand and subordinates pebbles.

In Fig. 1D is shown a simplified stratigraphic cross section of the subsoil.

The granular soil is characterized by a high angle of friction (expressed in terms of effective stress), and then by a high shear strength resistance. These geotechnical features are indicative of a load-bearing capacity of the soil where the high value cannot be reduced in any way as a result of any changes of the water table.

Hydrogeological and thermodynamic features of the aquifer. The hydraulic and hydrogeological features of the aquifer are essential tools for the simulations of thermal motion.

The aquifer is unconfined and the natural movement of the groundwater is towards NW-SE. The *static level of the water table* l_s is equal to 18.50 m from ground level (value measured in November 2011).

The *hydraulic gradient i* is equal to 0.00476; the *horizontal hydraulic conductivity* $k_{x,y}$ is equal to $4.3 \cdot 10^{-3}$ m/s; the *vertical hydraulic conductivity* k_z has been assumed equal to $1/10\ k_{x,y}$ m/s; the *radius of influence R* estimated and adopted in the simulations is 100 m.

The *specific storage* S_s has been assumed equal to 0.0001 (1/m) and the *specific yield* S_y has been assumed equal to 0.2.

The hydrogeological characteristics of the aquifer were deducted by performing a *pumping test* (step-drawdown test). The pumping test was carried out in 4 steps, with the duration of 45 minutes each. The test allowed to obtain the *critical discharge* Q_c = 42 l/s according to the Dupuit equation. In particular, for a discharge of Q = 12 l/s corresponds a lowering of 0.17 m; for Q = 20 l/s corresponds a lowering of 0.30 m, for Q = 30 l/s corresponds a lowering of 0.50 m and, finally, for Q = 55 l/s corresponds a lowering of 1.60 m.

The *transmissivity T* = $2.38 \cdot 10^{-2}$ m^2/s was calculated using the equation $T = 0.183 \cdot Q_c/s$, where *s* is the lowering of the groundwater during the time interval considered. The *permeability K* = $9.31 \cdot 10^{-4}$ m/s of the aquifer was obtained by dividing the transmissivity for the thickness of the aquifer.

The *specific discharge* was calculated with the expression $q_s = Q/s$, where s is the lowering of the water in the well and Q is the discharge. For Q =20 l/s and s = 30 cm, we obtained q_s = 60 l/s·m.

The *specific lowering* s* = s/Q is equal to 15 m/m^3/s for a discharge of Q = 20 l/s and a lowering of water s = 30 cm. In conclusion, at the maximum discharge operating of 12 l/s, the loss of linear load imposed by the hydrodynamic parameters of the aquifer (consequent to the laminar flow of the same) is to be considered negligible.

As SEAWAT simulates the temperature as a solute dissolved in the aquifer, is necessary to estimate the hydro-dispersive parameters: the *effective porosity* n_e has been assumed equal to 0.20, *horizontal dispersivity* α_L has been assumed equal to 10 (m), the ratio between *horizontal and vertical dispersivity* (α_l) and α_v was set equal to 0.1, while the ratio between the *vertical dispersivity* (α_v) and α_L was set equal to 0.01 for each simulation.

The thermodynamic parameters required for the calculation are: the *dry bluk density* ϱ_b, the *molecular diffusion coefficient* K_d, assimilable to the *heat diffusion coefficient,* and then the *thermal diffusivity* α. Based on the literature, for the shallow aquifer under consideration, were assumed the following parameters: ϱ_b was set equal to 2000 kg/m^3, K_d was set equal to 10^{-7} l/mg and α was set equal to 0.20 m^2/die.

Sensitivity analysis of the thermodynamic parameters carried in similar contexts (Piccinini *et al.*, 2012) have shown that as the heat transfer is a process mainly advective-diffusive, the progressive increase of two orders of magnitude of α not induce significant changes in temperature, instead an increase of n_e over 60% leads to a decrease of 0.5°C for the temperature while, a variation of K_d of an order of magnitude changes the velocity of rebalances of the system at the end of the activity. In conclusion, the most significant parameters for dimensioning the distance between the extraction and re-injection wells are K_d and n_e, while, α may be considered negligible.

Materials and methods. *Thermal characteristics of the aquifer.* Through the introduction of a sensor installed inside the piezometer, at 25 meters of depth from ground level, the temperature data of the aquifer have been recorded. Starting from December 2011, temperature data are collected periodically, three times a day every eight hours (4:00,12:00 and 20:00) (Fig. 1C). The monitoring is still ongoing.

The analysis of data temperature collected during the monitoring period December 2011-December 2014, shows that the temperature ranges around a mean value of 14.6 °C. The recorded temperature are contained within the value 0.60 °C.

This average temperature value is in agreement with recent studies on temperature distribution in the subsoil finalized to check the "homoeothermic surface" with its relative temperature value, within the Quaternary fluvial deposits hosting a shallow aquifer. The study conducted in Turin city and its hinterland (Barbero *et al.*, 2015) and in the surrounding plain sector (Barbero *et al.*, 2014) show an average temperature value of <T> = (14.56 ±0.40) °C and <T> = 14.00 ±0.60°C respectively.

SEAWAT code. Simulations of flow and heat transport have been performed in order to evaluate the environmental thermal impact within the aquifer product by the re-injection of water used for heat exchange cycle.

The simulations were performed using SEAWAT, a three-dimensional finite-difference computer code developed by the US Geological Survey for the modeling of the flow of variable density in saturated porous media. This code combines the capabilities of two existing codes: MODFLOW and MT3DMS, useful for the simulation of water flow of variable density and solute transport multi-species and heat respectively. SEAWAT (Version 4) is able to simulate the transport of heat and consider the variations in the density of the fluid as a function of the concentration of solute and temperature (Thorne *et al.*, 2006).

For the purpose of geothermal modeling, it's necessary to determine both hydraulic and thermal parameters of the aquifer. The values of hydraulic conductivity and storage were obtained by pumping tests, described in the preceding paragraph instead, other parameters of difficult experimental testing as conductivity, heat capacity, effective porosity and dispersivity were taken from literature.

The hydrogeological and thermal parameters, have been implemented in SEAWAT for the realization, in the short and in long period, of some scenarios regarding the expansion of thermal bubble.

From the practical point of view, the results of the simulations in the short period can be used to optimize the distance between the extraction and re-injection wells during the preliminary stage of design, while in the long period are useful to assess the interference of the geothermal plant in question with other geothermal wells located in the area (i.e. Jolly Hotel and Province of Turin Institute) and other wells in the phase of realization (San Paolo Institute) in order to avoid thermal anomalies. Error design can in fact lead to "*thermal feedback phenomena*": this phenomenon occurs when the distance between the wells (extraction and injection wells) is relative short; in this case, a recall of the thermal plume by the well of extraction it is observed, with a consequent pumping of groundwater with temperatures close to those discharged, compromising the efficiency the geothermal plant (Cultrera, 2012; Piccinini *et al.*, 2012; Galgaro and Cultrera, 2013). Another phenomenon, known in literature, and partially related to the previous one, is "*thermal breakthrough*" (Banks, 2009; Piccinini *et al.*, 2012; Galgaro and Cultrera, 2013): it consists in the slow diffusion of the thermal plume upstream.

Governing equation. Heat transport and solute transport contain many similarities (Anderson, 2005). Their mathematical representation is similar when the terms describing heat transport are formulated in equivalent solute expressions. SEAWAT leverages these similarities by using MT3DMS to simulate heat transport.

The heat transport equation, manipulated by Thorne *et al.* (2006), highlights the similarity with the solute transport. In Eq. 1 tensors and vectors shown in bold.

$$\left(1+\frac{(1-\theta)}{\theta}\frac{\rho_s}{\rho}\frac{c_{Psolid}}{c_{Pfluid}}\right)\frac{\partial(\theta T)}{\partial t}=\nabla\cdot\left[\theta\left(\frac{k_{Tbulk}}{\theta\rho c_{Pfluid}}+\boldsymbol{\alpha}\frac{\boldsymbol{q}}{\theta}\right)\cdot\nabla T\right]-\nabla\cdot(\boldsymbol{q}T)-q'_sT_s \quad (1)$$

where: q (m/s) is specific discharge; α (m) is the dispersivity tensor; θ (-) is the volumetric water content; q'_s (s^{-1}) is a source or sink of fluid with density ϱ_s; ϱ_s (kg/m^3) is the density of the solid (mass of the solid divided by the volume of the solid); ϱ (kg/m^3) is the density of the fluid; c_{Psolid} (J/kg·°C) is the specific heat capacity of the solid; c_{Pfluid} (J/kg·°C) is the specific heat capacity of the fluid; k_{Tbulk} (W/m·°C) is the bulk thermal conductivity of the aquifer material; T (°C) is the temperature of the fluid; T_s (°C) is the source temperature; t is time (s). ϱ_b, ϱ_s, and θ are related by: $\varrho_b = \varrho_s (1-\theta)$.

Variations in temperature inside a saturated porous medium may give rise to vertical convective motions, which determine the upward movement of the water masses hottest and lighter and the downward movement of the masses more cold and heavy. These motions, can influence the water flow of the system.

The form of the equation of density-dependent flow is solved by SEAWAT Eq. 2 (Langevin *et al.*, 2007; Langevin *et al.*, 2010) and allows to consider the variations of density and viscosity as a function of temperature.

$$\nabla\cdot\left[\rho\frac{\mu_0}{\mu}K_0\left(\nabla h_0+\frac{\rho-\rho_0}{\rho_0}\nabla z\right)\right]=\rho S_{S,0}\frac{\partial h_0}{\partial t}+\theta\frac{\partial\rho}{\partial t}-\rho'_S q'_S \quad (2)$$

where: μ (kg/m·s) is the fluid dynamic viscosity; μ_0 (kg/m·s) is the reference fluid dynamic viscosity (reference fluid is generally freshwater at temperature T = 25 °C); K_0 (m/s) is the hydraulic conductivity tensor of material saturated with the reference fluid; h_0 (m) is the hydraulic head (m) measured in terms of the reference fluid of a specified concentration and temperature; z (m) is the cartesian coordinate; $S_{s,0}$ (1/m) is the specific storage, defined as the volume of water released from storage per unit volume per unit decline of h_0; q'_s (1/s) is a source or sink of fluid with density ϱ_s.

Computational domain. The flow model was initially implemented with MODFLOW, along with SEAWAT code for the simulation of the heat transport. The domain of the model was discretized by a 1000 x 1000 m uniform grid mesh, with square cells of 10 m^2. In the area of distribution of the wells, the cell sizes have been reduced until obtaining cells of 1 m^2.

The subsurface was simplified into three layers:

1st layer: unsaturated zone located between the ground surface and the water table;

2nd layer: shallow aquifer;

3rd layer: impermeable soil beneath the aquifer.

Boundary conditions. Boundary conditions are used to define the water exchanges, mass or heat occurring at the interface between the volume modeled and the outside.

The hydraulic (piezometric) gradient was set through boundary conditions of type 1 (Dirichlet): this condition allows to assign the hydraulic load (m) to cells/nodes of the domain (command "*Constant and General Head in MODFLOW*").

The extraction and reinjection wells were simulated with conditions of 2nd type (Neumann) through which it's possible to assign a hydraulic flow (m/s) to cells/nodes of the domain (command "*Well in MODFLOW*").

As regards the thermal features of the model, the thermal regime of the aquifer has been reproduced with a condition of constant temperature (command "*Constant concentration* in SEAWAT"). This condition was set to upstream to the direction of groundwater flow. The constant value assigned at the temperature is equal to the undisturbed average temperature of the aquifer.

The model no examines phenomena of recharge of the aquifer and loss through evapotranspiration.

Results. After defining the hydrogeological conceptual model and heat transfer model of the area, several simulations were carried out with the aim to evaluate the effects on the thermal state of groundwater related to the propagation of thermal bubble.

As a reference value of undisturbed temperature we assumed the annual average recorded in the piezometer by multiparametric probe and equal to 14°C.

Two scenarios were simulated: the first concerns the thermal effects related to the use of extraction and re-injection wells (P1 and P2 in Fig. 1B); the second scenario considers the effects caused by the operation of the wells of Province of Turin Institute and the wells of the San Paolo Institute placed upstream of one's considered in the first scenario.

First scenario. It was hypothesized a cycle of operation so structured: In winter (October to March): Q_{peak} = 10 l/s; extraction temperature water: 14°C; discharge temperature water: 10°C; ΔT= 4°C.

In summer (April to September): Q_{peak} =10 l/s; extraction temperature water: 14°C; discharge temperature water: 9°C; ΔT= 5°C.

The two cycles are spaced from one month for stopping of the system.

In Fig. 2 it is shown the extension of the thermal bubble respectively at the end of the first summer cycle (Fig. 2A), after one year (Fig. 2B) and after two years (Fig. 2C) of operation of the plant.

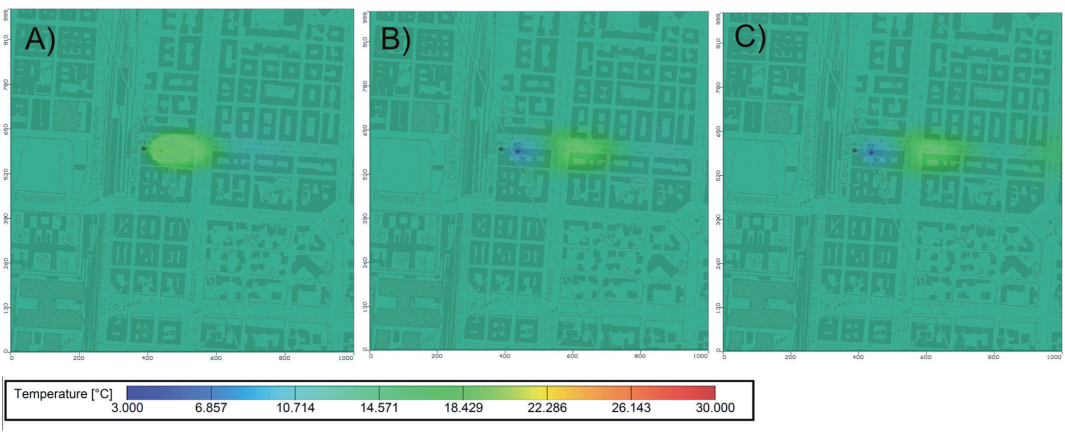

Fig. 2 – Simulations of thermal bubble extension at the end of the first summer cycle (A), after one year (B) and after two years (C) of operation of the plant.

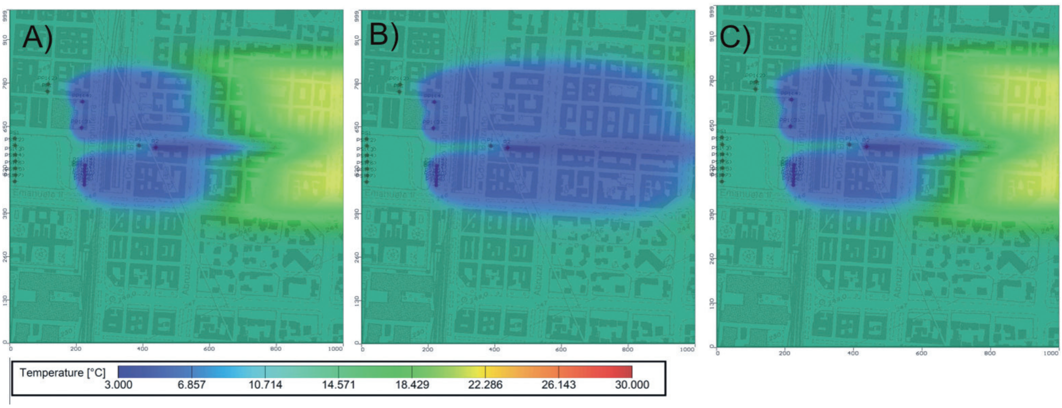

Fig. 3 – Simulations of thermal bubble extension after one year (A), after 16 months (B) and after two years (C) of operation of the plant.

The simulations show that the thermal impact a few hundred meters downstream of the discharge is practically negligible. The extension of the thermal plume upstream (i.e. "*thermal breakthrough*"), it is clearly more limited for hydraulic reasons. Finally, it is observed that the distance between the extraction and re-injection wells is sufficient to prevent the temperature increase of the groundwater in correspondence of the extraction well: this means absence of the phenomenon of "*thermal feedback*".

Second scenario. It was hypothesized a cycle of operation so structured: In winter (October to March): Q_{peak} = 15 l/s; extraction temperature water: 8°C; discharge temperature water: 3°C; ΔT= 5°C.

In summer (April to September): Q_{peak}= 15 l/s; extraction temperature water: 22°C; discharge temperature water: 27°C; ΔT= 5°C.

The two cycles are spaced from one month for stopping of the system.

This hypothesis, highly conservative, assumes that the thermal plume, produced by the wells of Province of Turin Institute and San Paolo Institute, located upstream, are able to determine, in correspondence of the extraction well, a temperature of groundwater during the winter cycle equal to 8°C and during the summer cycle equal to 22°C.

The simulations (Fig. 3) show the extension of the thermal after one year (Fig. 3A), after 16 months (Fig. 3B) and after two years (Fig. 3C) of operation of the plant.

The thermal situation created by the operations San Paolo Institute and Province of Turin Institute wells, does not significantly change the operation of the wells P1 and P2. The simulations show a thermal bubble with increase or decrease of temperature in the aquifer of reduced size.

Conclusions. The study highlights the utility of using finite-difference computer codes in support of water flow and heat transport simulations. The modeling of groundwater flow with MODFLOW and heat transport with SEAWAT code, allow to evaluate the propagation of thermal bubble and therefore the correct design of the geothermal plant (e.g optimize the distance of extraction and re-injection wells) for estimating the effects on the thermal state of groundwater. Therefore, long period simulations are useful to evaluate the environmental effects inducted by the extension of the thermal plume.

The monitoring of groundwater temperature and other parameters (static level and electric conductivity of the aquifer), still ongoing, allows the future validation of the model as well as the protection of groundwater resources from groundwater's thermal pollution.

In conclusion, scenarios above proposed have shown a remarkable aptitude of the aquifer in the mitigation of thermal anomalies, as evidenced by the temperature values recorded in the monitoring piezometer and compatible with the average annual value of the temperature in the subsurface.

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