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UNDERGROUND EXPLOITATION IN URBAN AREAS BY GEOTHERMAL HEAT PUMP SYSTEMS: THE EXAMPLE OF TURIN POLITECNICO TEST SITE (NW ITALY)

Glenda Taddia

Dipartimento di Ingegneria dell'Ambiente, del Territorio e delle Infrastrutture, Politecnico di Torino, Italy
Corresponding author: G. Taddia <glenda.taddia@polito.it>

ABSTRACT: The Turin urban district (NW Italy), is a flat area, at about 248 m asl, mainly developed on the outwash plain constituted by several outwash coalescing fans connected to the Pleistocene expansion phases of the Susa glacier. Its geological context is well known with three main stratigraphical units described, i.e. Unit 1: Miocene molassic sequence; Unit 2: Pliocene Sabbie di Asti, Argille Azzurre Formation and Villafranchian deposits; Unit 3: Quaternary deposits (outwash sediments). Once these geological features were taken into consideration we focused on the issues related to the impact of geothermal heat pump systems to groundwater in the Turin urban context where a significant number of installations of medium and large sized groundwater heat pumps is present. Local environmental features may influence the development of low-enthalpy geothermal systems and the choice of the most suitable type of system to install. In the case of open loop heat pumps, water re-injected in the aquifer after its use is characterized by a different temperature with respect to the undisturbed aquifer. This thermal disturbance propagates through the groundwater and may affect the temperature of water withdrawals operated by downstream installations. The analyses of Politecnico Turin's Open loop systems have confirmed that the main factors controlling the Thermal Affected Zone (TAZ - thermal plume) are those related to the advective component of heat flow. The piezometric surface was obtained by means of a well and piezometer survey, during hydrogeological investigations. The Turin Politecnico test site attests the relevance of the geological and hydrogeological characterization of the subsoil in the design the GWHP systems in urban areas.

Keywords: GWHP systems, sensitivity analysis, hydrogeological parameters, Turin, Italy

1. INTRODUCTION

Geothermal heat pumps represent an interesting technology expected to contribute significantly to the reduction of primary energy use for heating and cooling. Additional benefits of this technology, which also meets the European Union targets, are the possibilities of integration with discontinuous energy resources, in particular wind, combining heat and power.

The replacement of conventional heating systems such as boilers, with general heat pump systems allows the de-localization of emissions of micropollutants from urban centers to the sites in which thermal power stations are operating. For example the District heating is a system for distributing heat generated in a centralized location for residential and commercial heating requirements such as space heating and water heating (Verda & Ciano 2005; Poma et al. 2010). This also enhances the emissions monitoring and control. Furthermore, the use of distributed production systems based on the use of renewable sources reduces also CO_2 emissions (Baccino et al., 2010; Lo Russo et al., 2011).

In this general context, the discharge of water, at different temperatures compared to baseline (warmer in summer and colder in winter), poses a number of problems in relation to the potential functionality of many existing situations of use of the groundwater (drinking water wells, agricultural plants, industrial plants, etc.). In addition, there may be cases of interference between systems, especially in the more densely urbanized areas.

In this paper, some fundamental aspects related to the development of open-loop heat pumps have been explored in a typical urban contest (Turin city, NW Italy). In particular, appropriate hydrogeological investigations and simulation modelling were performed for the characterization of the main hydrogeological parameters of the subsoil at the considered site. The results of the work have allowed to define several fundamental aspects in order to optimize the design choices of Groundwater Heat Pump (GWHP) systems and the importance of geological and hydrogeological surveys. After a general description of the low enthalpy geothermal heat pumps technologies, the analysis and comparison of the current hydrogeology problems in urban area are described, considering the impact of groundwater heat pump system in an urban contest. The conceptual model for the groundwater flow system, the schematization of the aquifer boundaries and the estimation of basic hydrogeological parameters are among the main issues which should be investigated in the development of open-loop heat pumps plants. In particular, some characteristics of urban elements require particular attention if compared to less anthropized areas.

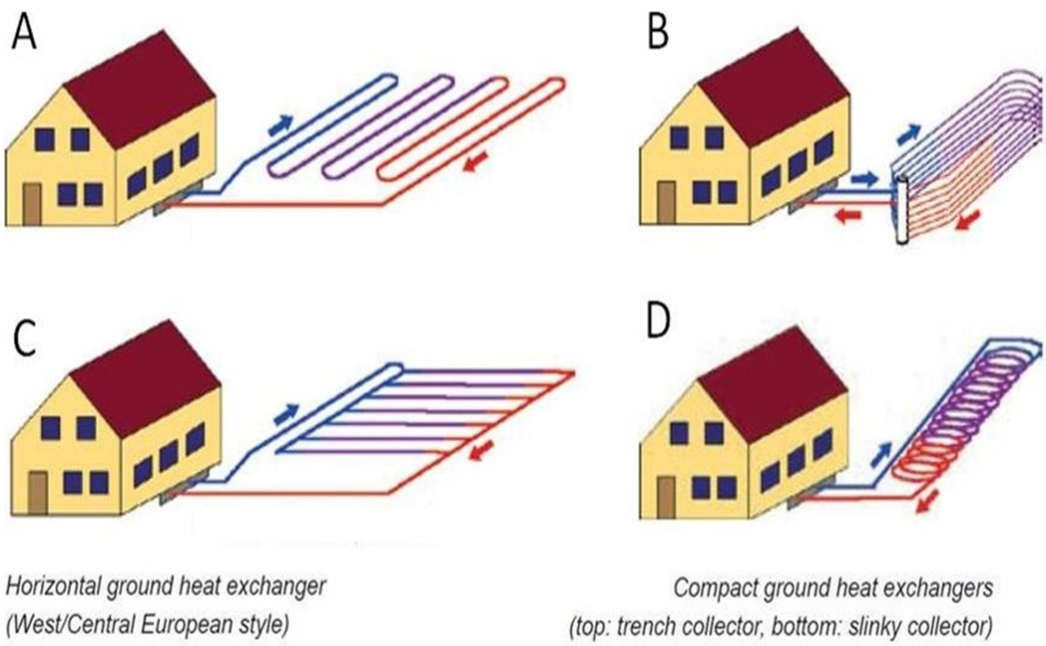

Fig. 1 - Closed-loop horizontally system, with ground source heat pump (GSHP). Various type of configuration are represented: A) connection in series, B) trench connection, C) connection in parallel and D) spiral slinky connection (Rafferty, 2000; Lund, 2007).

2. MATERIALS AND METHODS

2.1 Low enthalpy geothermal systems

The discharge of water at different temperatures compared to baseline (warmer in summer and colder in winter) poses a number of problems in relation to the potential functionality of many existing situations of groundwater use.

The successful implementation of very low enthalpy geothermal plants for heating and cooling buildings in several sectors of city has highlighted one such technology.

Two basic geothermal heat pump systems exist: an earth-coupled (closed-loop) type (GSHP) and a groundwater (open-loop) type (GWHP) (Rafferty, 2000; Lund, 2007). In the first type heat exchangers are located underground:

- horizontally-type, in various kind of configuration: connection in series (Fig. 1A), trench connection (Fig. 1B), connection in parallel (Fig. 1C) and spiral slinky connection (Fig. 1D);
- vertically (Fig. 2), downhole heat exchanger (DHE);
- obliquely, a heat carrying medium is circulated within the exchanger, transferring the heat from or to the ground via a heat pump and the connection are obliquely respect the surface.

The GSHP (horizontally configuration) is usually the most cost-effective configuration when adequate yard space is available and trenches are easy to dig, especially while a building is under construction. DHEs are widely used when there is a need to install sufficient heat exchange capacity under a confined surface area, such as when the soil is rocky close to the surface or where minimum disruption of the landscape is necessary.

Open-loop groundwater heat pumps (Fig. 3) typically withdraw groundwater to provide heat (PDEP, 1996). In winter, the GWHP extracts heat from the water to provide space heating. With reversible heat pumps, the heat-transfer process can be reversed in the summer and the groundwater absorbs heat from the living or working space and cools the air (DOE, 1999; Banks, 2012). GWHPs are suited to regions with extended shallow aquifers, from which it is relatively easy and not very expensive to extract groundwater (Drijver & Willemsen, 2001).

Three different configurations of open-loop systems exist as summarized in Fig.4.

Direct open-loop heat pumps (Fig. 4A), where the water is passed directly through the heat exchangers of the heat pump, are largely used for residential and very small commercial applications (Rafferty, 2001). This system is most suitably applied where low-salinity groundwater is available, because the direct use of high-salinity waters can cause scaling, i.e. the deposition of mineral scales in pipes, valves and/or heat exchangers (PDEP, 1996). Standing Column Well systems (SCWs) (Fig. 4B) are used in locations where groundwater wells do not produce sufficient water for a conventional open-loop system and where water quality is also good chemical characteristic. In SCW systems, groundwater is recirculated from one end of the column well (static water level) to the heat pump, and back to the other end (bottom) of the deep bore.

In other words, if consider the figure 4B where we recirculate a carrier fluid (groundwater) down the well bore (extraction and injection well) and up a rising main we obtain that a certain proportion of that flow to waste (following passage through the heat pump). This will have the effect of lowering heads within the borehole

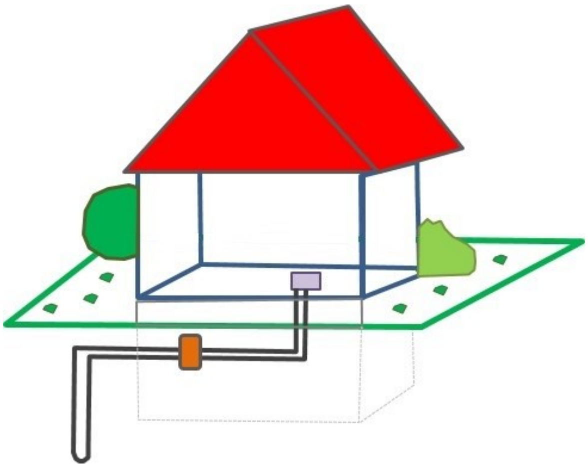

Fig. 2 - Closed-loop vertical system with downhole heat exchanger (DHE).

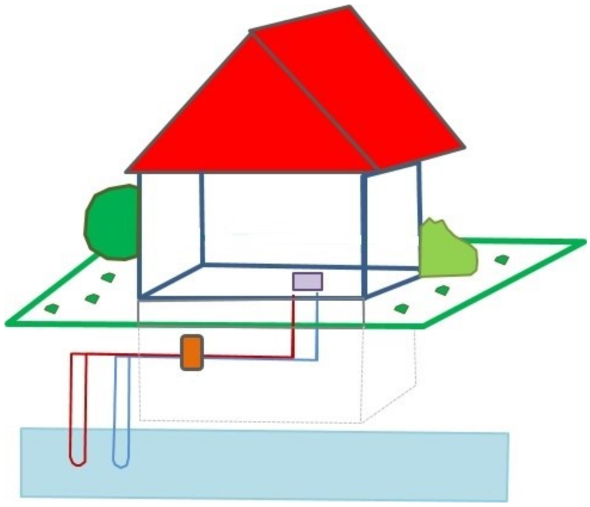

Fig. 3 - Open-loop system, with groundwater heath pump GWHP.

and inducing the influx of a corresponding amount of new groundwater to the borehole. This groundwater will also transfer a new 'load' of heat to the system by advection (Banks, 2012).

Usually, only one well is required for conventional buildings; larger projects may have several wells in parallel. SCW systems can be thought of as a cross between closed-loop earth-coupled systems and open-loop groundwater source systems.

The indirect open-loop systems (Fig. 4C) generally involve a heat exchanger between the building loop and the groundwater, which eliminates exposure of any building components to groundwater (Rafferty, 2001). The most important consideration in GWHP design is to

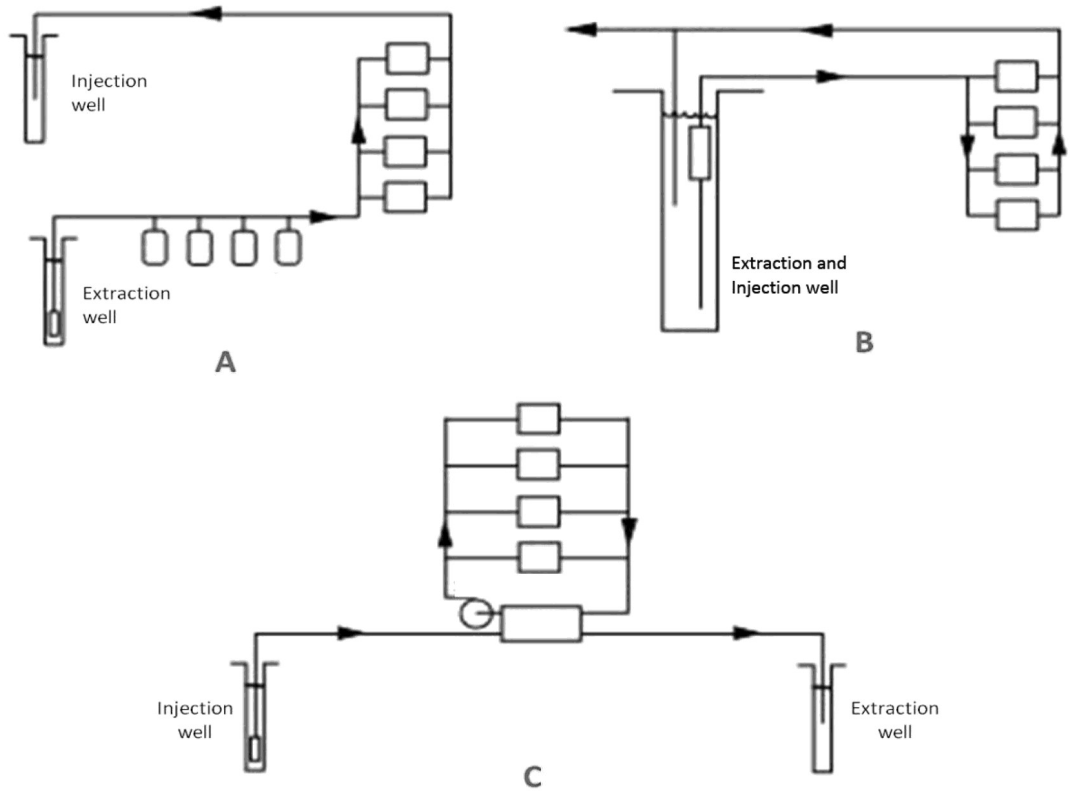

Fig. 4 - Several types of Open-Loop Systems: A) Direct open loop heat pumps; B) Standing Column Systems (SCW); C) Indirect Open Loop Systems (Rafferty, 2001).

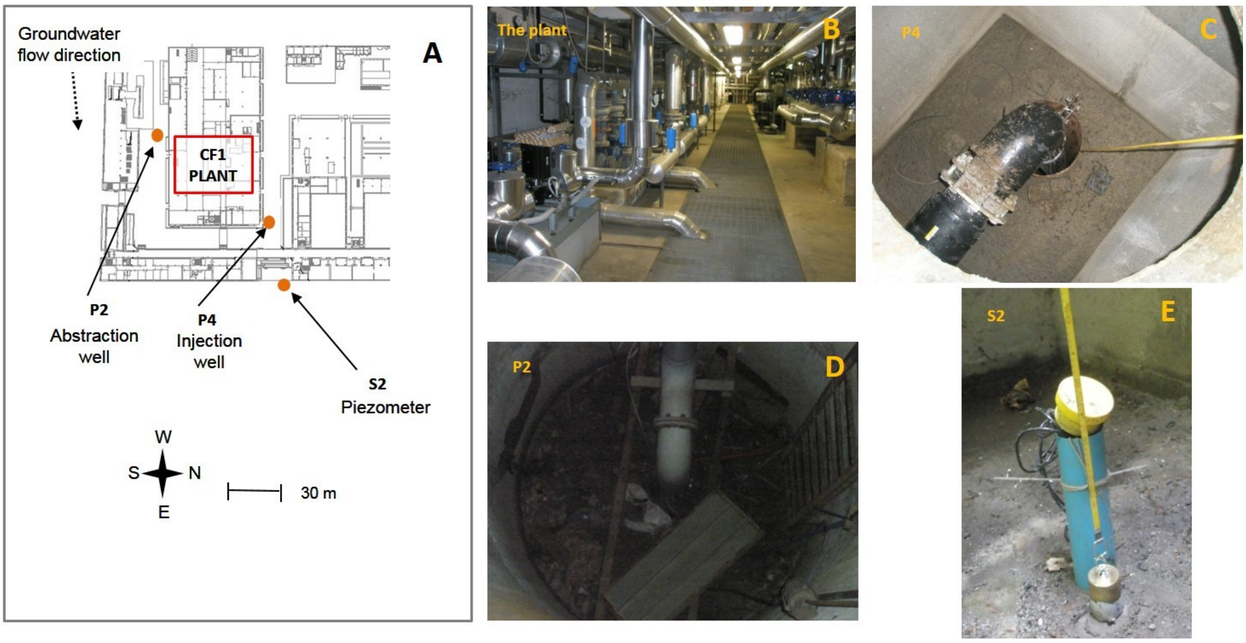

Fig. 5 - Open Loop System (GWHP) installed in the "Politecnico di Torino" for cooling some of the university buildings. Schematic map with location wells and piezometer (A), the heat pump plant (B), P4 is the injection well (C), P2 is the extraction well (D) and S2 is the piezometer located towards respect the wells (E).

obtain a plentiful amount of groundwater with a very stable temperature. Generally, a highly productive, shallow (within 30 m of surface) aquifer would favor successful and efficient functioning of the GWHP.

2.2 Site application: Politecnico of Turin

The site is located in center of the city of Turin (Piemonte Region) where in the last fifteen years territorial changes have produced effects on the intensive urban transformation processes. The latter, mainly represented by the progressive re-organization of the metropolitan transport network (including the construction of a railway link and the first line of the subway system) and by lots of urban regeneration projects, transformed abandoned industrial (polluted) sites in restored new houses and services areas (commercial, cultural and, partly, productive) (Lo Russo & Taddia, 2009; 2010). The dynamic consequences of these intense and rapid transformations affected significantly the environmental conditions of the urban groundwater system.

The first experimental results derived by a groundwater monitoring around an injection well of an open-loop GWHP has been discussed. This system has been installed in the Politecnico of Turin (Fig. 5) for cooling some of the university buildings, such as offices and laboratories. Two 47 m-deep wells, one used for groundwater extraction (P2) and the other for injection (P4), and a piezometer (S2) in placed 35 m downgradient respect to the P4, having the same technical characteristics (Fig. 6) are present at the site. The wells have a steel casing diameter of 355 mm. The bridgeslot screens are located below 19 m down to 47 m. The annulus from the surface to 6 m depth is cemented with bentonite grout. the filter pack is represented by calibrated gravel below 6 m down to 47 m depth (Fig. 6).

The plant was performed during the cooling period (summer) to assess the warm TAZ development around the injection well. Through multiparameter probes (OTT ecoLog800) (Fig. 7) installed in the pumping and injection wells and also inside the piezometer, it is possible to check the water level, temperature and conductivity in groundwater and then the movement of the warm plume over time during the operating period of the heat pump. The multi-temporal thermal logs in S2 highlighted the plume thermal stratification in the aquifer and confirm the hypothesis about the prevailing advective transport component for heat flow.

The potential impact of the heat pump groundwater has been assessed according to the features of the site, users, wells and the machine installed through an approach based on numerical simulations. The main software that it was utilized is FEFLOW®.

FEFLOW® (Finite Element subsurface FLOW system) is a program for simulating groundwater flow, mass transfer and heat transfer in porous and fractured means (Diersch 2010). The numerical models were validated by comparison with experimental data from significant open loop heat pumps systems installed in Politecnico of Turin.

The geological and hydrogeological site characteristics in the modeling can be great help to determine the geometry and operating mode.

2.3 Geological and hydrogeological context

The Turin urban area is situated in the north-Western Po plain, surrounded by Alps. On the outwash plain of several outwash coalescent outwash fans associated to the Pleistocene expansion phases of the Susa Glacier. The Turin Plain is bounded by the Rivoli-Avigliana Morainic Amphitheatre on the west side and

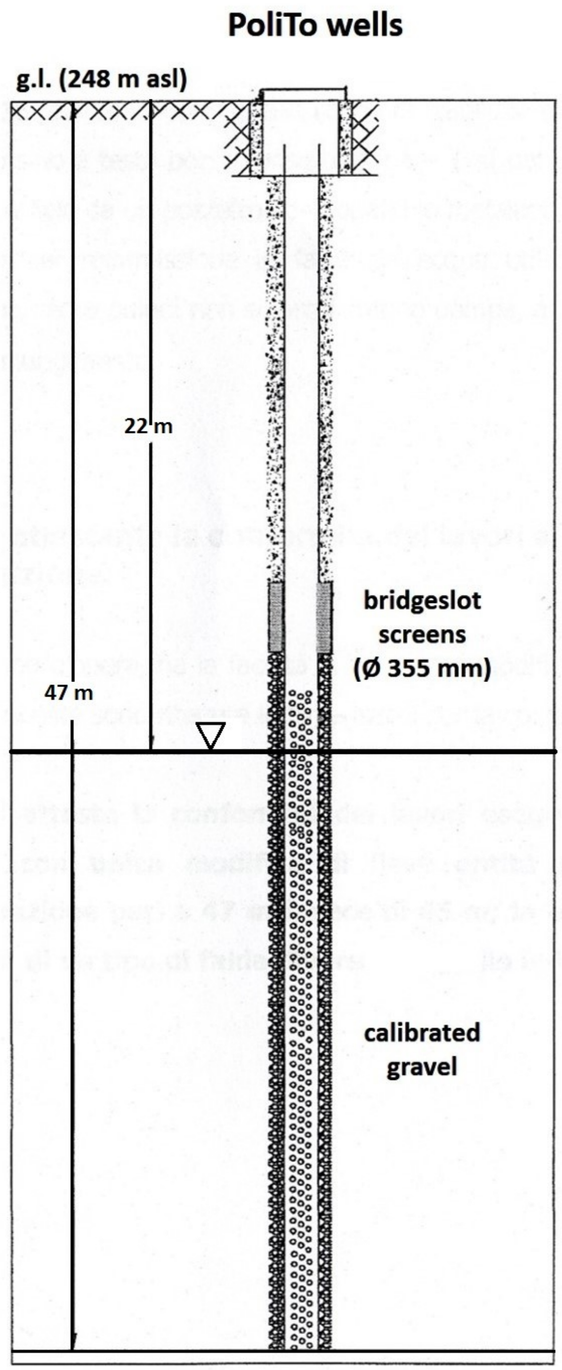

Fig. 6 - Technical scheme of the Politecnico wells, utilized for Open Loop System (GWHP).

Turin Hill on the east.

The geological setting of this area is quite well known by numerous wells (Regione Piemonte, 2007) and detailed geological studies (Boano et al., 2004; Forno & Lucchesi, 2005; Forno et al., 2018).

The geological setting of the plain urban area is characterized by a strong geographical anisotropy.

Fig. 7 - The OTT Multiparametric probe, a compact system for monitoring water level, temperature and conductivity.

Comprehensive geological and hydrogeological studies (Civita et al., 2004; Regione Piemonte, 2005) including the "historical" information, trying to produce integrated geo-referred database and maps, permitted the definition of the subsurface geological setting and the interpretation of the groundwater system. A broad analysis of this database has led to a new explanation of the subsurface stratigraphic relationships among the different (hydro) geological bodies. Three main (hydro) stratigraphic units have been distinguished based on depositional age, structural setting, lithological composition and hydrogeological properties. Their characteristics and relative relationships are described below (Fig. 8).

The oldest unit (Unit 1-Miocene) is constituted by conglomerates, sandstones and marls typical of the terrigenous sequence belonging to the Piemonte Tertiary Basin. The upper part is locally characterized by the presence of evaporites belonging to the Messinian Gessoso-solfifera Formation. Unit 1 is stratigraphically overlapped by the subsequent Unit 2 (Pliocene) or truncated by the main erosional Quaternary surface and therefore directly in contact with the upper outwash deposits (Unit 3 - Quaternary). Despite the limited deep geological evidence the stratigraphic correlations within Unit 1 confirms the presence of the westward buried extension of the asymmetric anticline verging to the NW, with a SW-NE axis characterizing the Turin Hill sector.

Unit 2 is characterized by a different sedimentation environment with a lateral heteropic transitional relationship. The Unit 2 consists of shallow marine deposits, traditionally defined as Sabbie di Asti and/or Argille Azzurre Formation, mainly composed of fossiliferous sandy and clayey layers with subordinate barren fine gravely and coarse-grained sandy marine layers or by quartz-micaceous sands. In the other part of the Torino area (not in the site area) Villafranchian deposits are present. They consist of fine-grained sediments (sand, silt and clay with inter-bedded gravel) which were organized into several sedimentary bodies (Forno et al., 2015). Typical litho-facies are blue-grayish clayey sands and silts and yellowish to grayish sands and silts, usually with a rhythmic or pseudo-varved structure. At a local level it is possible to recognize fan-delta deposits formed by gravel layers in a sandy matrix and, less commonly, boulders in a sandy-silty-clayey matrix. The top of Unit 2 was erod-

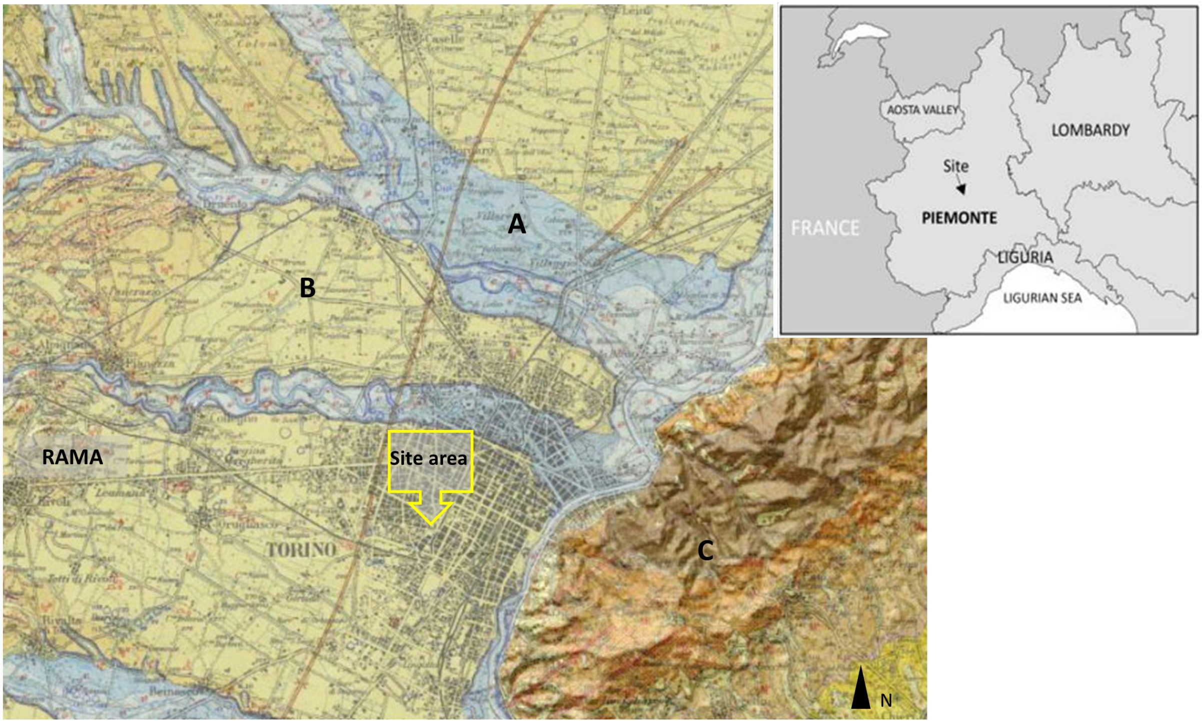

Fig. 8 - Geological sketch map, with the main geological Units that represent the Turin area. (Geological Map of Italy, scale 1:100000, layout 56, not in scale) where **A**: Unit 3, fluvial deposits; **B**: Unit 3, Fluvioglacial deposits; **C**: Unit 1 and Unit 2, Tertiary Succession; **RAMA**: Rivoli-Avigliana Morainic Amphitheatre.

ed away and covered by the outwash alluvial deposits characterizing Unit 3 (Fig. 9). Outcrops of Unit 2 are to be found on the southern side of Turin Hill. On the opposite, Unit 2 is fully buried under Unit 3 in the Turin city area and it can be recognized only by analyzing logs data. In detailed the hydrogeological regional setting is strongly influenced by the presence of the Rivoli-Avigliana Morainic Amphitheatre (RAMA) on the West side and the Turin Hill sector on the East (Ivy-Ochs et al., 2018). The buried lithotypes of Unit 1 below Units 3 and 2 (Figs. 8 and 9) represent the bottom impermeable layer for the unconfined eastward groundwater regional down-flowing mainly developed in the Quaternary deposits (Unit 3). As a matter of fact, Unit 3 represents an important unconfined high productive aquifer hydraulically connected to the main surface water drainage network (Sangone, Dora Riparia, Stura di Lanzo and Po rivers). The permeability can reach high values (K1 =

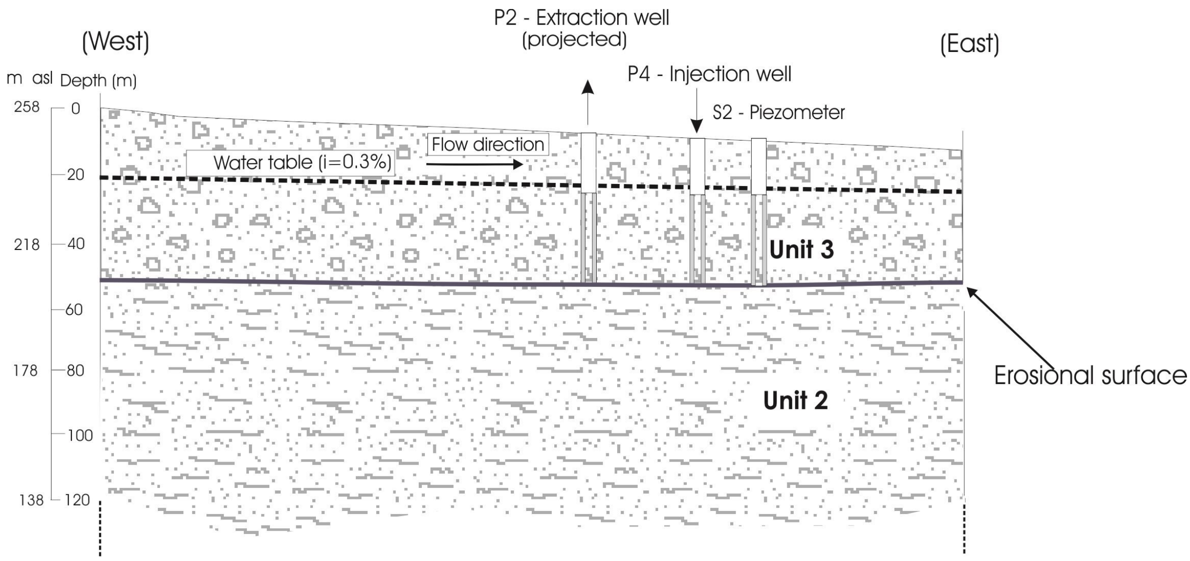

Fig. 9 - Cross-section of the Open Loop System (GWHP) installed in the “Politecnico di Torino” for cooling some of the university buildings.

1×10−3 ¸ 1×10−4 m sec-1) depending on the local sediment granulometry. This aquifer is quite vulnerable to pollution because of its shallowness and the absence of significant natural barriers (clay levels) in the sedimentary body (Unit 3 in Fig. 9). The potentiometric surface shows generally a W-to-E gradient ranging from 0.6-1.2% (mean 0.9%) (Civita et al., 2004; Regione Piemonte, 2005). The shallower underground of Site area is characterized by two main stratigraphic Units (Units 3 and 2) with hydraulic properties and the gradient is about 0.3% (Fig. 9).

Symbols	Parameter	Value
Kxx; Kyy	Horizontal hydraulic conductivity [m/s]	0.00027
Kzz	Vertical hydraulic conductivity [m/s]	0.000054
ε	Storativity	0.106
n	Porosity	0.2
$\rho^f c^f$	Vol. heat cap. fluid [10^6 J/m³K]	4.2
$\rho^s c^s$	Vol. heat cap. solid [10^6 J/m³K]	2.52
λ^f	Heat conduc. fluid [J/msK]	0.65
λ^s	Heat conduc. solid [J/msK]	3
α_L	Longit. dispersivity [m]	5
α_T	Transv. dispersivity [m]	0.5

Tab. 1 - Thermal and hydrodynamic parameters used as input data in FEFLOW modelling.

3. RESULTS

3.1. The importance of hydrogeological parameters in the numerical modeling

Proper installation and effective maintenance of GWHP plants requires an appropriate characterization of subsurface heat transport processes such as conduction and convection. During the process, the aquifer temperature is disturbed and cold or warm plumes develop. These disturbances are reduced by lateral conductive heat transport and convection due to moving water (Hecht-Mendez et al., 2010). The use of the well doublets for groundwater-sourced heating or cooling typically results in a thermal plume of cool or warm reinjected groundwater. Such a plume may be regarded either as a potential anthropogenic geothermal resource or as pollution, depending on downstream aquifer usage. A thermal plume may pose an external risk to downstream users and environmental receptors or an internal risk to the sustainability of the well doublet, due to the phenomenon of thermal feedback.

During the preliminary design of GWHP systems the aquifers are usually investigated to determine the parameters affecting heat flow. These investigations involve hydrogeological measurements both in situ and in the laboratory and are often costly and difficult to perform. Physical properties of the aquifer such as the porosity and density of the aquifer framework may be obtained through field and laboratory geotechnical testing. Hydrogeological parameters such as hydraulic conductivity and the storativity are usually obtained from pumping test results. Hydrothermal parameters such as the specific heat capacities and thermal conductivities of the groundwater and the aquifer framework may be calculated from laboratory tests and heated water injection data (Zhou & Zhou, 2009).

The first issue that was conducted was a sensitivity analysis (Lo Russo et al., 2012) to test in the site the influence of several parameters on the development of TAZ.

The TAZ is defined as the area included by the isotherm 16° C (i.e. 1°C difference with the undisturbed underground temperature). The subsoil parameters tested using the sensitivity analysis were related to the unconfined aquifer under exploitation and include the hydraulic conductivity (horizontal Kxx; Kyy and vertical Kzz), the porosity n, the storativity ε, the natural hydraulic gradient dh/dl, the volumetric heat capacity of fluid (water) $\rho^f c^f$ and solid (aquifer matrix) $\rho^s c^s$, the heat conductivity of the fluid λ^f and solid λ^s and the longitudinal α_L and transversal α_T thermal dispersivity (Tab. 1). The simulation results reported in Fig. 10 refer to the parameters under sensitivity analysis. The horizontal Kxx; Kyy and vertical Kzz hydraulic conductivity, the hydraulic gradient dh/dl as well as the porosity n, the longitudinal α_L and transverse α_T thermo-dispersivity condition the size of the TAZ in an appreciable way. Finally the effects on the variations of the values of storativity ε and the heat conductivity of fluid λ^f and solid λ^s appear to be almost negligible.

The results highlight that the parameters most affecting the TAZ development are connected to the advective component of the heat flow in the aquifer.

Another important element which resulted in validate numerical models was the comparison between experimental data and real data from plants with significant heat pumps open-loop of the Politecnico of Turin.

The time variability of the building's energy demand can affect both the groundwater withdrawal and injection flow rates Q = Qout= Qin and the temperature difference between the injection and extraction wells ΔT = (Tin− Tout). Pumps may be equipped with inverters so the water mass flow rate can be reduced when heating/cooling requirements decrease, maintaining high system efficiency during periods of partial load. Generally, inverter technology induces variability in both the flow (Q) and temperature differential (ΔT).

Correct assessment of the TAZ around the injection well and good correspondence between the simulation results and measured data require an effective numerical model that takes into account the time transient variability of Q and ΔT. However, there is generally a lack of accurate input data concerning the dynamic variability of Q and ΔT parameters over time, particularly during preliminary GWHP plant design phases. In practical engineering, the effects of time variability on the TAZ calculations are often disregarded, and the subsurface numerical simulation of the TAZ is developed using Q

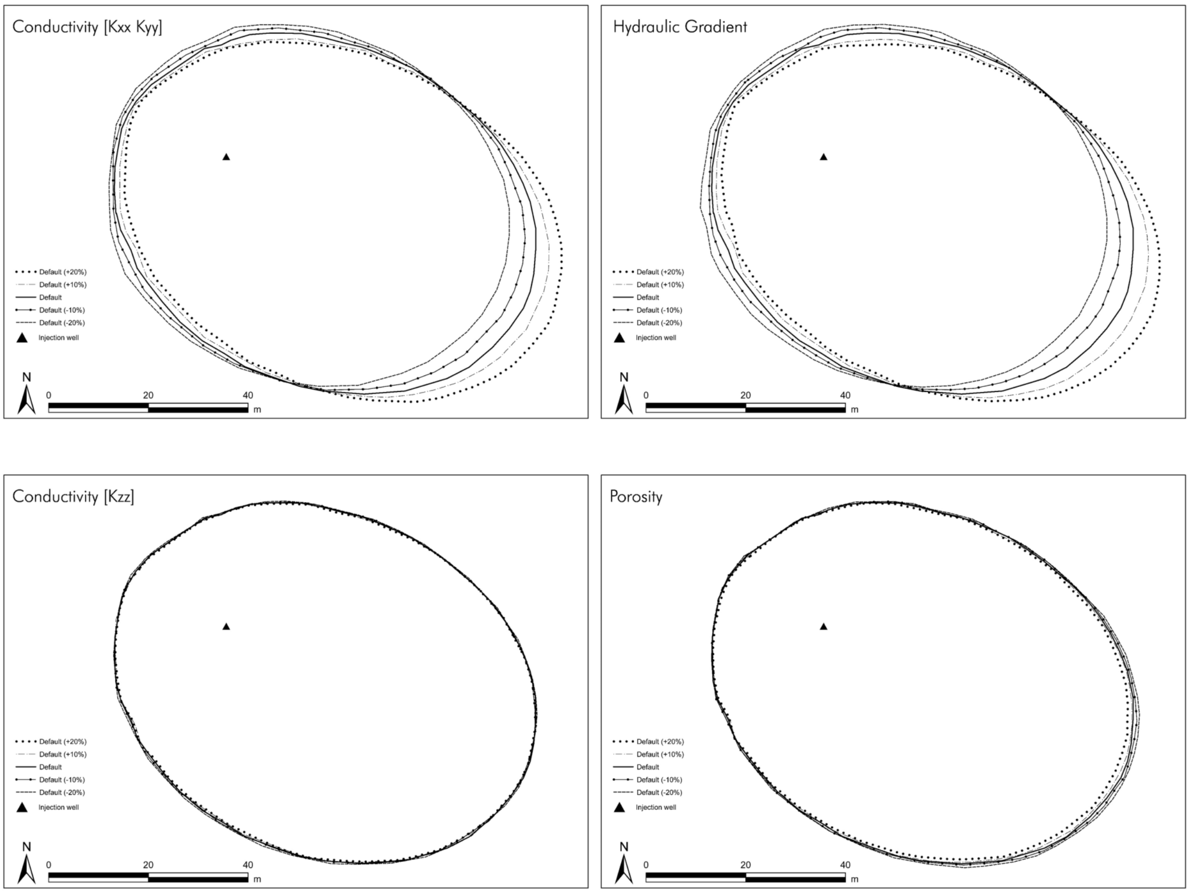

Fig. 10 - Location of 16.0°C isotherms after 60 days of injecting warmer water for various values of Horizontal and vertical conductivity, hydraulic gradient and porosity.

and ΔT values that are held constant over an extended time interval (usually a month or an entire season). These time-averaged values of Q and ΔT are usually derived from simulations of building energy needs and are calculated based on the principle of energy equivalence. From a practical stand point, the use of time-averaged flow rates and temperatures reduces the computational load, but the simplification may also negatively impact the quality of the temperature predictions. During the study, the flow and energy transport simulations were executed using hourly data. Using this hourly data set and taking into account the energy conservation principle, we calculated daily, monthly, and seasonal energy equivalent values for Q and ΔT and performed additional subsurface simulations using the averaged data. The results were analyzed using linear regression analysis and statistical testing in order to verify their ability to correctly predict TAZ development. The simulations were performed during the cooling period to assess the development of a warm TAZ around the injection well (P4). Appropriate FEFLOW® time-varying functions (TVFs) for Q and ΔT were defined based on monitoring data extracted from the heat pump control system. All parameters were measured on an hourly basis. To assess the TAZ, four computational modeling scenarios were defined and tested. The first (T1) took into account the hourly variable data for Q and ΔT. The TVFs for Q and ΔT were derived directly from the monitoring data. The second scenario (T2) used daily averages calculated from the hourly data. The third (T3) used monthly equivalents, and the last (T4) scenario employed a seasonal equivalent value for Q and ΔT. The equivalent volumetric flow rates and temperature differences used in scenarios T2–T4 were obtained by averaging the quantities in a balanced manner and the time interval was selected period (day in T2, month in T3 and season in T4), Δt is the simulation time interval (1h).

The reliability of the simulations was obtained by comparing simulated temperatures with the piezometer measurements (S2) plotted in Fig. 11. T1, T2, and T3 exhibited the same trend as the measured data, while the fourth (T4) was quite different from the observed groundwater temperature profile (Lo Russo et al., 2014).

In conclusion, in order to obtain a good match between simulated and current groundwater temperatures during modeling of the TAZ produced by a GWHP plant, it is necessary to model the injection using realistically variable flow rates and injection temperature data. The use of average hourly, daily or monthly injection flow rate and temperature data produced good quality simulation results. In contrast, the use of seasonal average values did not produce good estimates of the TAZ. This

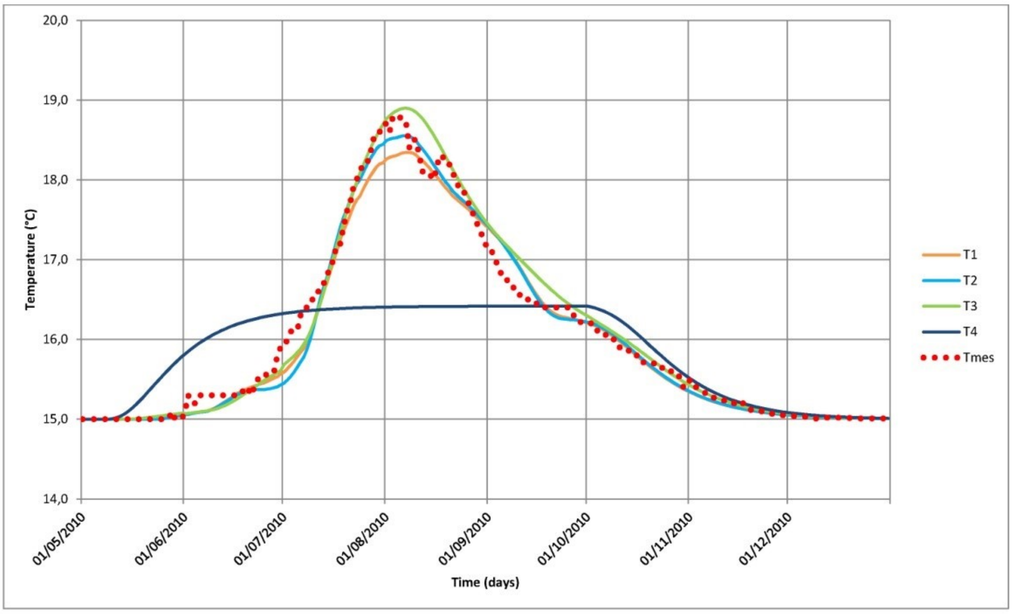

Fig. 11 - Temperatures in piezometer S2. The dotted line corresponds to the measured data

element is particularly important in the design of plants in which it is necessary to assess the extent and dynamics of the underground thermal perturbation to avoid interference with nearby plants or wells used for other purposes.

4. CONCLUSIONS

In conclusion, the territory of the city of Turin is well suited to the analysis of issues related to the impact of heat pumps to groundwater. In this area, many installations of medium and large size groundwater heat pump have been performed and this number is still increasing.

In the case of open loop heat pumps, water reinjected in the aquifer after its use is characterized by a different temperature than the undisturbed aquifer. This thermal disturbance propagates through the groundwater and may affect the temperature of water withdrawals operated by downstream installations. Heat pump efficiency depends on the inlet temperature of water, thus there may be unforeseen changes in performances that often leads to primary energy requirements larger than the initial expectations.

The unconfined aquifer that extends over the entire urban plain, including the location of the investigated site, is hydraulically connected to the main surface water drainage network in the area (i.e. the Dora Riparia and Sangone rivers). For this reason, the developed research has shown the existing potential of the low enthalpy geothermal heat pump system, both regionally and locally because in Turin area there is a lots of quantity water resource.

In this context it is possible to support that the prediction modeling is necessary both to assess the effects on the environment around the plant and to optimize the design choices. The modeling can be very helpful to determine the geometry and operating mode.

The analyses of Politecnico Turin's Open loop systems have confirmed that the main factors affecting the development of the Thermal Affected Zone (TAZ - thermal plume) are those related to the advective component of heat flow. In fact, the sensitivity analysis of the main parameters that most influence the development of the thermal plume has been shown that it should be pay attention to the geological and hydrogeological subsurface characterization. The reconstruction of the piezometric surface obtained by means of a well and piezometer survey, also appears to be essential in a correct program of geological and hydrogeological investigations. The determination of the TAZ around the injection points is a fundamental aspect in the project phase of groundwater open-loop geothermal systems development. In fact, it is important to know in the earlier phase of the project if the exploited aquifer is suitable for the system to be implemented and if the TAZ is interfering with other previously existing wells or subsurface infrastructures and land uses.

Then the input data are fundamental to affecting the quality of the simulation. For this reason, the geological and hydrogeological surveys are very important to reconstruct the geothermal heat pump design choices. However, even taking into account all the limitations of the open-loop heat pumps technology, we believe that these systems represent one of the most promising potential clean energy sources especially in the urban areas under transformation in order to reach the important goal of greenhouse-gas emission reduction of the future Smart livable Cities.

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