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USE OF A TEMPERATURE-MEASURING CHAIN FOR THE RECONSTRUCTION OF THE VERTICAL THERMAL DISTURBANCE INDUCED BY AN OPEN-LOOP GROUNDWATER HEAT PUMP SYSTEM

Martina GIZZI[(*)], Glenda TADDIA[(*)] & Stefano LO RUSSO[(*)]

[(*)]Politecnico di Torino - Department of Environment, Land and Infrastructure Engineering - C.so Duca degli Abruzzi 24, 10129 Torino (Italy)
Corresponding author: glenda.taddia@polito.it

EXTENDED ABSTRACT

I sistemi geotermici a bassa entalpia e ciclo aperto rappresentano attualmente uno dei sistemi di condizionamento più efficienti dal punto di vista energetico per le aree urbanizzate delle zone poste in fasce a clima temperato. A seconda della modalità di utilizzo (riscaldamento o raffreddamento), l'energia può essere estratta o immessa in corpi d'acqua o falde acquifere superficiali. Tra le problematiche di tipo ambientale associate a sistemi geotermici che sfruttano acquiferi superficiali vi è lo sviluppo di una zona termicamente alterata (TAZ) intorno ai punti di iniezione, quali i pozzi di re-immissione.

L'entità dell'impatto ambientale nel tempo è influenzata dalla quantità d'acqua immessa e dalle modalità di re-immissione. La compensazione dei disturbi termici avviene mediante meccanismi di trasporto conduttivo e convettivo legati al movimento della massa d'acqua all'interno dell'acquifero. Il processo di predisposizione di un adeguato sistema di monitoraggio è fondamentale per una corretta ricostruzione delle modalità di propagazione orizzontale e verticale della massa d'acqua termicamente alterata.

Nel tempo, la messa a punto e l'installazione di adeguati strumenti di monitoraggio nel piezometro di monitoraggio (S2) e in entrambi i pozzi di estrazione (P2) ed immissione (P4) dell'impianto geotermico (CF1) del Politecnico di Torino hanno consentito il costante monitoraggio dell'acquifero superficiale e la ricostruzione delle modalità di propagazione della plume termica al termine delle diverse stagioni di funzionamento dell'impianto.

Al fine di ricostruire con dettaglio la stratificazione termica verticale all'interno dell'acquifero superficiale durante i diversi periodi di maggiore scambio termico, nel mese di aprile 2019 è stata installata una catena per la misurazione della temperatura dell'acqua (tipo PT1004/Pt) nel piezometro di monitoraggio S2, caratterizzato da una profondità di 35 m. Lo strumento, caratterizzato da una lunghezza complessiva di 21 m, è composto da 12 diversi sensori, suddivisi in tre sotto-catene di misurazione della temperatura (T1-T2-T3). Esso è stato posizionato in maniera tale da consentire il monitoraggio dello spessore di acquifero superficiale compreso tra le profondità di 24 m e 38 m dal piano campagna.

I valori di temperatura dell'acqua (°C), registrati in modo continuo in corrispondenza dei diversi punti di monitoraggio, nel periodo compreso tra aprile 2019 e novembre 2019, sono stati inizialmente analizzati attraverso la costruzione di diagrammi di tipo boxplot. Successivamente, gli schemi grafici relativi ai valori misurati dai 12 diversi sensori in diversi istanti significativi di funzionamento dell'impianto, sono stati riportati in sezioni verticali.

Questo tipo di rappresentazione è risultata essere una efficace modalità di visualizzazione dei dati ai fini dell'analisi e del confronto delle risposte alla perturbazione termica dei livelli acquifero a cui si trovano i diversi sensori della catena termometrica. L'individuazione degli intervalli stratigrafici soggetti a maggiore o minore perturbazione termica prodotta dall'impianto geotermico a ciclo aperto del Politecnico di Torino, durante le diverse stagioni di funzionamento del sistema, ha rappresentato il principale risultato dello studio condotto.

Dalle elaborazioni grafiche ottenute è emerso come la maggiore entità in termini di variazione della temperatura tra sensori posti a diverse profondità si registri in periodi successivi allo spegnimento dell'impianto. Inoltre, sebbene la falda acquifera nei mesi estivi risulti essere continuamente interessata da fenomeni di perturbazione termica, non sembrano originarsi evidenti stratificazioni termiche verticali.

Conseguentemente, è stato possibile concludere che le caratteristiche costruttive del pozzo di immissione (P4) dell'impianto CF1 del Politecnico di Torino con 1) immissione verticale dell'acqua che avviene per gravità e 2) immissione dell'acqua nella falda acquifera attraverso una colonna di filtraggio con spessore 20 m, sono sufficienti a disperdere adeguatamente le perturbazioni termiche e favorire fenomeni di omogeneizzazione della quantità di acqua più calda immessa.

ABSTRACT

Open-loop groundwater heat pumps (GWHP) currently represent one of the most energy-efficient and environmentally friendly air-conditioning systems for densely urbanised areas. Depending on the use mode, energy can be extracted or injected into a shallow aquifer. Among the technical aspects associated with GWHPs that need to be constantly controlled, there is the development of a thermally affected zone (TAZ) around injection points. The environmental impact extent is strongly influenced by the water flow rates and the re-injection modalities. The process of setting up an adequate monitoring system is fundamental for the proper reconstruction of TAZ propagation modes, during each plant-operating season.

The work aims to analyse the potentialities of using a new sophisticated water temperature-measuring chain (type PT1004/Pt) as a monitoring tool for the identification of the vertical stratigraphic intervals of the Turin shallow aquifer that are more affected by the thermal disturbances produced by the Politecnico di Torino's open-loop GWHP system.

The installation of such a monitoring instrument, together with the information deriving from the application of the data analysis proposed, can contribute the most in understanding the adequacy of the constructional characteristics of an open-loop system re-injection well to properly disperse vertical thermal perturbations.

KEYWORDS: geothermal resources, groundwater heat pump systems, thermally affected zone, temperature-measuring chain

INTRODUCTION

Following the official GSE (2018) Italian national reporting, the share of geothermal heat production in the total thermal production by Renewable Energy Sources (RES) in 2017 was 1.3%. The vast majority of RES heat production was from solid waste (68%), followed by heat pumps (25.9%). Of the latter, only a very minor part was represented by Ground-Source Heat Pump systems (GSHPs), about 0.07% in the number of appliances and 0.62% in heat production (Manzella *et alii*, 2019).

Within the concept of GSHPs, the open-loop systems differ from the more common closed-loop technologies as they utilise groundwater as a source of thermal energy by employing a heat pump coupled with a heat distribution system in buildings. Despite their not widespread application at the national level, open-loop groundwater heat pumps (GWHPs) currently represent one of the most suitable technologies to be applied in the heating and cooling of buildings in densely urbanised areas. They were designed to take advantage of the heat available in the shallow subsurface aquifers by withdrawing water from a well, passing it through a heat exchanger, and discharging water into an injection well or nearby river (Sarbu & Sebarchievici, 2014; Taddia *et alii,* 2019).

In GWHPs, the heat pump system is connected with a shallow aquifer through a production well with a slotted screens column. A submersible pump is installed above the top of the well-screen to minimize the risk of air entering the aquifer, which potentially could allow air bubbles to clog the well-screen and the aquifer formation.

The performances of GWHPs strongly depend on the heating and cooling required thermal loads, heat pump design characteristics (e.g., compressor efficiency and heat exchanger configuration), control strategies and aquifer characteristics (e.g. groundwater temperature, thermal and hydraulic conductivity of geological formations). Depending on the use mode (heating or cooling), energy can be extracted or injected into a shallow aquifer.

Fouling and clogging are some of the major water quality problems that can be encountered in open-loop GWHPs (Gjengedal *et alii*, 2020). Besides, the ambient aquifer temperature turns out to be continuously disturbed as cold or warm plumes developed during the geothermal plant-operation periods. Water discharged into shallow aquifers has the potential to cause, even in the short term, significant environmental impacts associated with the groundwater thermal interference and the origin of a thermally affected zone (TAZ) in aquifers. TAZ plumes are considered a potential anthropogenic geothermal resource of pollution in urban areas; they might pose a risk to groundwater downgradient users, affecting the sustainability of the geothermal well-systems.

Over time, several studies have proposed qualitative and quantitative investigations of the subsurface environmental impacts associated with the variations in groundwater temperature within the TAZ, caused by the continuous increase in the implementation of open-loop GWHPs in densely urbanised cities (Yang *et alii.* 2011; Yu *et alii*, 2016; Lo Russo *et alii,* 2018). Comparison between analytical and simulation approaches have made also possible to properly understand and predict subsurface heat transport mechanisms at the end of different plant-functioning seasons (Molina-Giraldo *et alii*, 2011; Gizzi *et alii*, 2020). However, both analytical and numerical methods used to understand the dynamics of thermal interferences propagation modalities in shallow aquifers require to be validated, using continuous monitoring datasets coming from increasingly sophisticated monitoring systems and selecting adequate control points for defining the quality of the model developed. Thus, the processes of setting up and installation of adequate monitoring tools in available monitoring piezometers are fundamental for the proper reconstruction and comprehension of TAZ plumes considering both horizontal and vertical propagation modes.

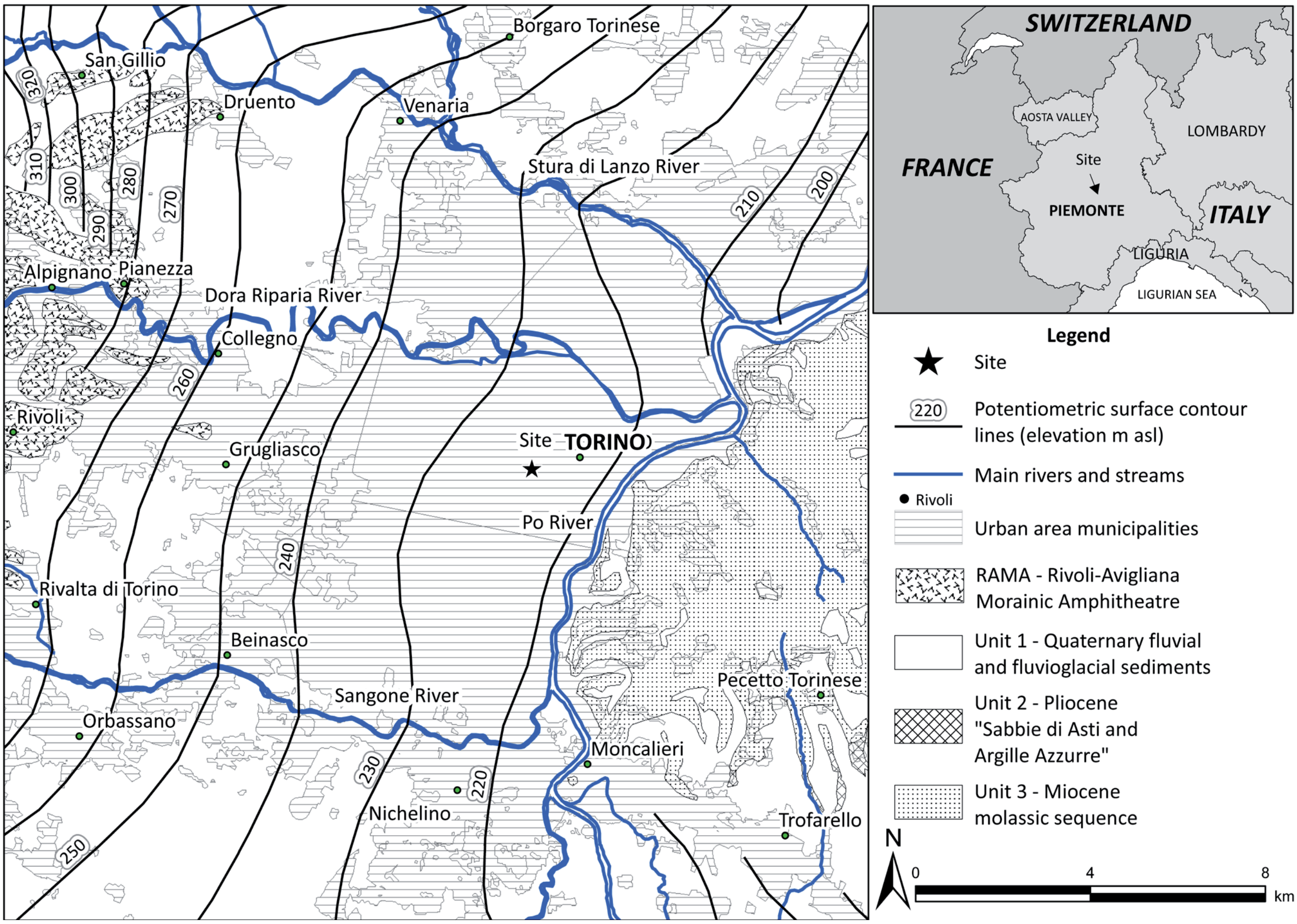


Fig. 1 - Hydrogeological map of the Turin area and the test site location (modified from Lo Russo et alii, 2018)

With the purpose to constantly monitor and properly reconstruct a possible thermal stratification induced by the open-loop GWHP plant serving the Politecnico di Torino (Turin, Northern Italy) in Turin shallow aquifer, during each period of heat exchange, a sophisticated water temperature-measuring chain (type PT1004/Pt) was installed in the 35m-deep piezometer (S2) of the analysed open-loop geothermal system.

The description of the benefits of using this new type of measurement tool for monitoring and the identification of specific stratigraphic intervals that could be influenced the most by aquifer thermal disturbance represents the main aim of the proposed study. The information deriving from the application of the water temperature-measuring chain data analysis proposed may contribute to the understanding the adequacy of construction characteristics of an open-loop system injection well, eventually allowing to hypothesize new well-doublet configuration-solutions to decrease thermal feedback risks.

MATERIAL AND METHODS

Geological and hydrogeological setting

Considering its geological and hydrogeological aspects, the Politecnico di Torino test site (Turin, Northern Italy) has been investigated in several previous works (Lo Russo *et alii*, 2014; Lo Russo *et alii*, 2018; Gizzi *et alii*, 2020). The Turin plain extends from the Rivoli-Avigliana Morainic Amphitheatre (RAMA) on its western extreme to the Torino Hill on its eastern border. Several rivers delimit the Turin urban area: the Stura di Lanzo River (northern boundary), the Sangone River (southern boundary), and the Po River (eastern boundary). The main surface water drainage network of the Turin plain (Stura di Lanzo, Sangone, Dora Riparia, and Po rivers) communicates hydraulically with an unconfined aquifer extending over the entire urban plain (Fig.1).

Regione Piemonte (2007) documented the hydrogeology of the plain area with a high degree of confidence. Information from drilled wells and downhole log tests has confirmed the presence of two different lithological units with distinct hydraulic

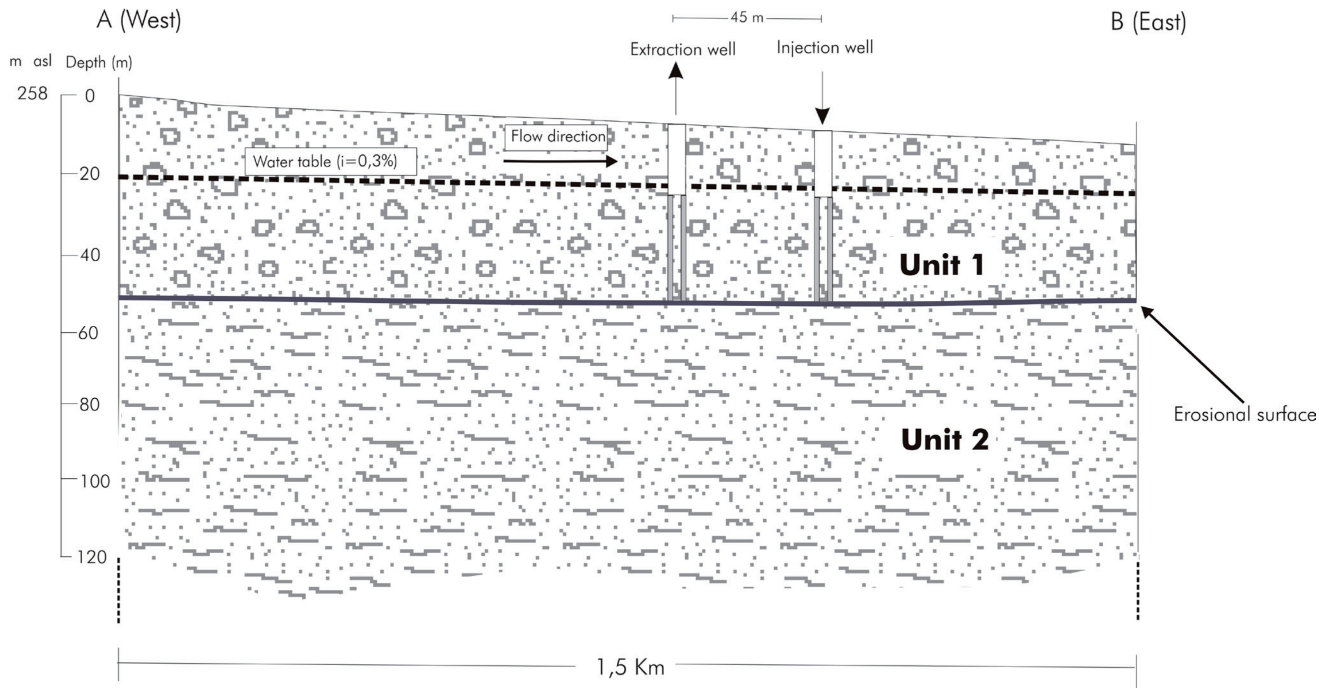


Fig. 2 - Schematic hydrogeological cross-section of the study area (modified from Lo Russo *et alii, 2018)*

properties, stratigraphic units 1 and 2: Stratigraphic unit 1 (Middle Pleistocene–Holocene) consists of a continental alluvial cover, primarily composed of coarse gravel and sandy sediments with local subordinate clay lens inclusions (≤1.5m thick). Stratigraphic unit 2 (early Pliocene–Middle Pleistocene) includes shallow marine environment deposits (Sabbie di Asti and Argille Azzurre) composed of fossiliferous sandy-clayey layers with subordinate fine gravelly and coarse sandy marine layers as well as quartz-micaceous sands (Bonsignore *et alii*, 1969; Regione Piemonte, 2005; Piana *et alii*, 2017). The outwash plain substrate consists of a Cenozoic terrigenous marine succession composed of conglomerates, sandstones, and marls (Piemont Tertiary Basin).

The saturated thickness of the unconfined aquifer at the site is approximately 24 m. Using a step drawdown test on the abstraction well (40m deep) of the Politecnico di Torino GWHP system, the unconfined aquifer hydraulic conductivity value (K1) of 2.5 × 10−3 ms−1 was evaluated. Based on the aquifer lithology determined by Lo Russo *et alii*., 2012 examining well-drilling logs, an effective porosity of 0.20 was estimated. Besides, for stratigraphic unit 1, a volumetric heat capacity value equal to 1.3 × 106 J·m-3K-1 was calculated as a composition-weighted mean based on the lithological records (Lo Russo *et alii*, 2014).

The shallow aquifer, generally exploited for geothermal purposes, is hosted in Unit 1. The potentiometric surface is 17 m below the ground level and displays an NNW–SSE gradient of 0.3% towards the Po river. The saturated thickness of the unconfined aquifer at the analysed site is approximately 30 m (Fig.2).

Politecnico di Torino open-loop Gwhp

The Politecnico di Torino open-loop GWHPs (CF1) is located in Turin, Piedmont region in NW Italy. The Politecnico di Torino CF1 system is composed of a 40m deep pumping well (P2), a 47m deep injection well (P4), and a 35m deep monitoring piezometer (S2), located downgradient of P4. Distances among the described components, measured along flux lines, are respectively: P2 – P4 = 77m, P4 – S2 = 35m, and P2 – S2 = 109m (Fig.3). The described well-doublet system works only during the spring and summer seasons, for cooling several of the central university buildings. All CF1 system components affect the Turin shallow unconfined aquifer. Water re-injection occurs via gravity disposal in P4 well at a depth of 10.9 m from the ground level. The warmer water is discharged into the well and through the well column of screens, which disperse water in the aquifer for a bridge slot-screens thickness of 27m. The P4 well annulus from the surface to 6 m depth was cemented with bentonite grout. Below 6 m to a depth of 47m, there is a filter pack consisting of calibrated gravel. Water is normally in natural motion and gradually transfers heat in the aquifer producing a thermal anomaly in its surroundings (TAZ).

The pumping and reinjection rates in P2 and P4, respectively, fluctuate hourly depending on demand during operation, with maximum flow rates of 50 ls−1. The GWHP system operates from 7 am to 6 pm on a Monday-to-Saturday weekly cycle from April through September in cooling mode. Piezometric level and temperature data are measured hourly by multiparameter probes installed both in the P2 and P4 wells and in the S2 piezometer.

THE WATER TEMPERATURE-MEASURING CHAIN

The constant monitoring of the thermal perturbation induced in the shallow aquifer by the open-loop GWHP plant serving the Politecnico di Torino during each functioning period turned out to be necessary to identify possible stratigraphic intervals that are affected by the thermal disturbances produced the Politecnico di Torino open-loop GWHP system. For this purpose, during the spring season of 2019, a water temperature-measuring chain (PT1004/Pt) was installed in the 35m-deep piezometer (S2) of the Politecnico of Torino open-loop GWHP plant (CF1) (Fig.4). The S2 piezometer is screened from 15 to 35m and it is located 35 m downgradient from the injection well (Fig.3). The undisturbed average groundwater temperature turns to be 15 °C in the saturated zone.

Fig. 3a - Politecnico CF1 plant GWHP system location (google Earth basemap)

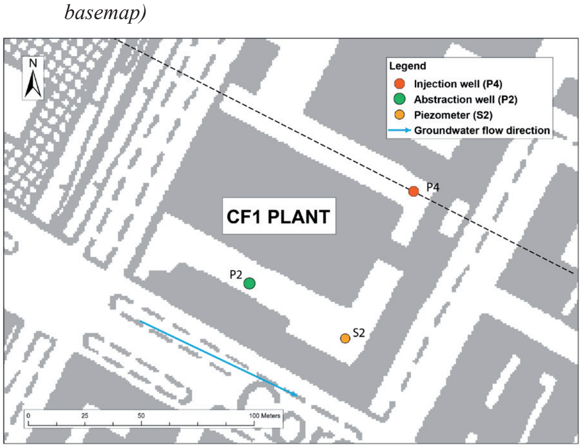


Fig. 3b - Politecnico CF1 plant GWHP System overview. P2 abstraction well. P4 - reinjection well. S2 - control piezometer. Dotted line indicates the direction of the cross-section line reported in Figure 1 (Modified fromGizzi et alii, 2020)

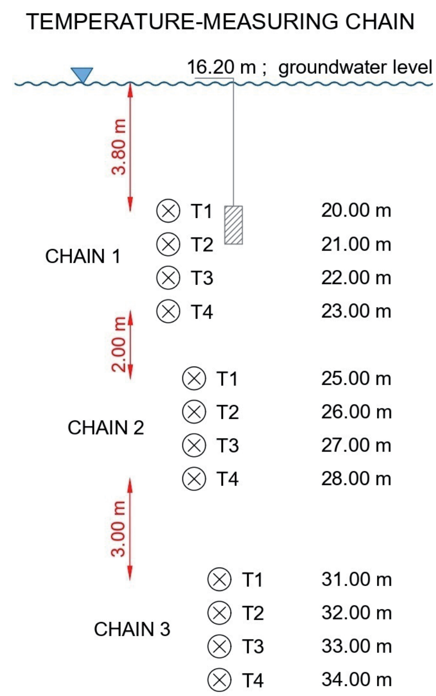


Fig. 4 - Simplified conceptual scheme of the water temperature measuring chain (PT1004/Pt) installed in S2-control piezometer of the Politecnico of Torino open-loop GWHPs

Fig. 5 - Water temperature measuring chain (PT1004/Pt) installed in S2-control piezometer of the Politecnico of Torino open-loop GWHPs

The installed water temperature-measuring chain (PT1004/Pt) has a total length of 21 m and is composed of 12 different temperature sensors, divided into three temperature-measuring sub-chains (T1; T2; T3). It was set in order to constantly monitor the aquifer thickness between the depths of 24 m and 38 m from the ground level. This instrument allowed refining the analysis of the monitored shallow aquifer, compared to what has previously been done by the single multiparameter probe, located at a depth of 20.5 m (Fig.5).

Starting from April 1, 2019, using the installed water temperature-measuring chain, hourly groundwater temperature values have been recorded at the different monitoring points where the 12 temperature sensors are located. Firstly, hourly temperature values recorded between April 1 and November 30, 2019 have been analysed by generating boxplot diagrams. Secondly, obtained boxplot diagrams, specific of the 12 different sensors and the different plant operation times have been plotted in vertical sections. This type of representation provides a useful way to visualise and compare the aquifer perturbation characteristics of the different water temperature-measuring chain sensors

RESULTS AND DISCUSSION

Considering the 2019 operating season, the Politecnico di Torino GWHP plant started its operation on May 25th and switch off on September 30th, 2019. Figures from 6 to 8 show different boxplot diagrams that have been developed considering recorded data during Spring (1/05/2019; 1/06/2019), Summer (15/06/2019; 15/07/2019; 1/09/2019; 15/09/2019), and Autumn seasons (15/10/2019; 15/11/2019). Specific dates were selected as representative of different functioning periods of the analysed geothermal plant. In detail, Figure 6 describes plant non-functioning dates (spring season) while figure 7 corresponds to plant-operating days (summer season). Considering the closing season of the specific geothermal plant (autumn season), figure 8 describes the behaviour of the shallow aquifer after the switching-off period.

For the different selected dates, plot diagram boxes reported in Fig.6, 7, 8 display a five-number summary of hourly datasets, showing different parameters such as the minimum, first quartile, median, third quartile, and maximum. A box from the lower quartile to the upper quartile is represented together with the vertical line of the median. The whiskers represent the two lines outside the box that extend to the highest and lowest observations.

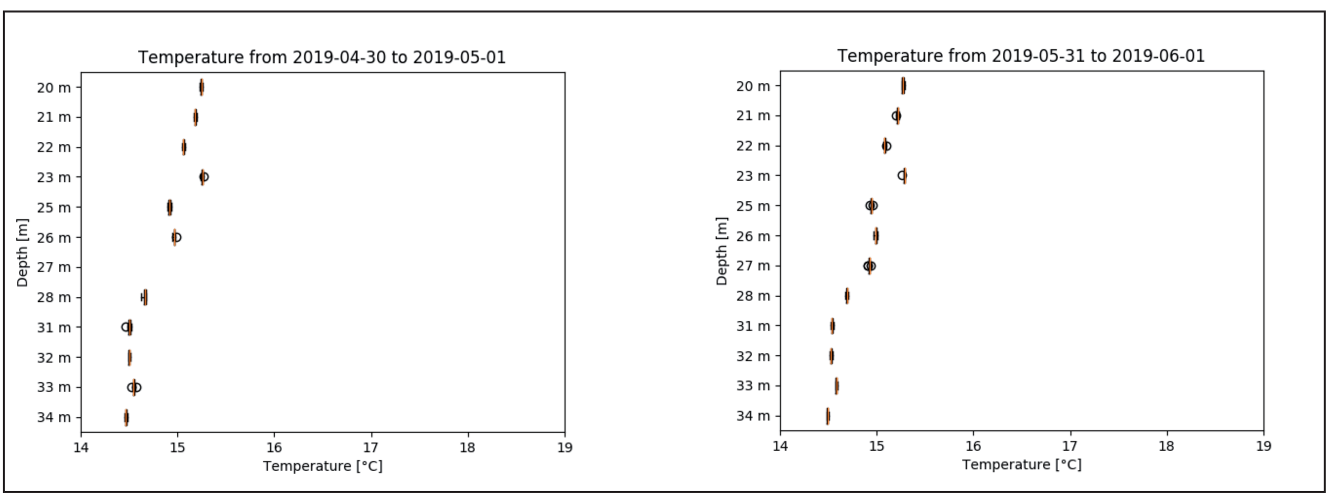
Daily boxplot representations allow seeing how the temperature fluctuates at different depth levels, establishing how the water temperatures change during the selected day.

Narrow boxplots for all the dates indicate weak daily temporal temperature changes. Observing boxplots reported in Fig.6 (1/05/2019; 1/06/2019 – spring season) it is possible to identify a weak vertical thermal stratification with temperature values recorded at greater depths (31-34m) less than those recorded by the sensors located more superficially (<15 °C).

Furthermore, boxplots reported in Fig.7 (15/06/2019, 15/07/2019, 1/09/2019 and 15/09/2019) describe shallow aquifer behaviour during different plant-operating days (summer season). The re-injection of hot water inside the re-injection well (P4) causes an increase in the groundwater temperature, which reaches up to 18 °C during the months between July and September. Although the aquifer turns to be continuously affected by a thermal perturbation in this period of the year, no obvious vertical thermal stratification seems to be originated: the differences in the medians of groundwater temperature values measured by the 12 different sensors at different depths are less than 0.5 °C.

Lastly, analysing daily boxplot representations in Fig.8 (15/10/2019, 15/11/2019), it is possible to describe a vertical thermal stratification with higher temperatures (17 °C) recorded in the upper part of the shallow aquifer. The higher variation entity in the measured temperature parameter between temperature sensors located at different depths is recorded in November. As reported in Fig.8b, the medians of the groundwater temperature values recorded by T1-sensor 1 and T3-sensor 1 are 16.6 °C and 15.1 °C, respectively.

The modest variations in temperature recorded in the various time-analysed date during the summer season (plant-operating



a b

Fig. 6 - Boxplot diagrams of different spring season plant-operation times: a. 01/05/2019; b. 01/06/2019. Data recorded by the water temperature measuring chain installed in piezometer (S2)

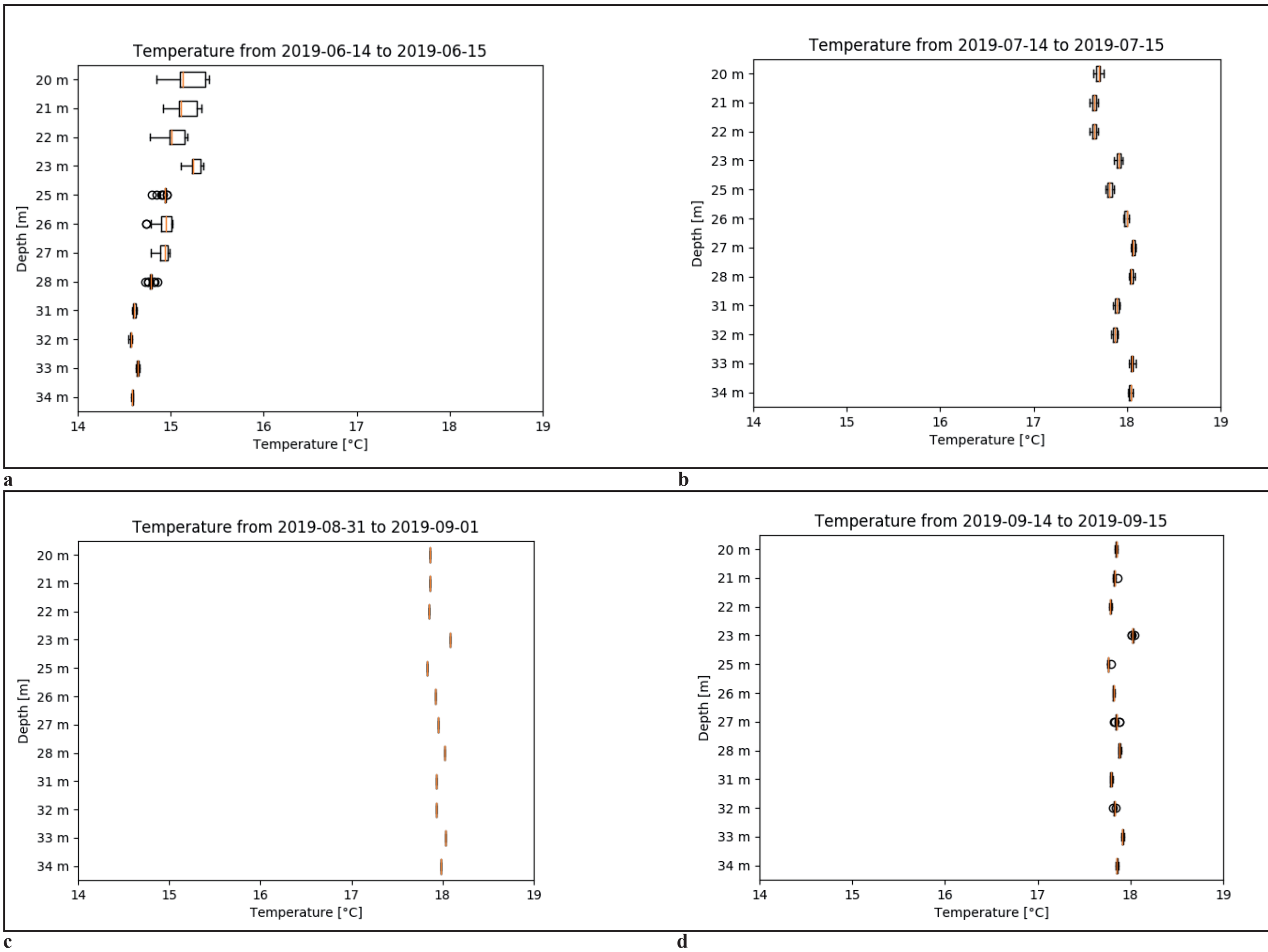


Fig. 7 - Boxplot diagrams of different summer season plant-operation times: a. 15/06/2019; b. 15/07/2019; c. 01/09/2019; d. 15/09/2019. Data recorded by the water temperature measuring chain installed in piezometer (S2)

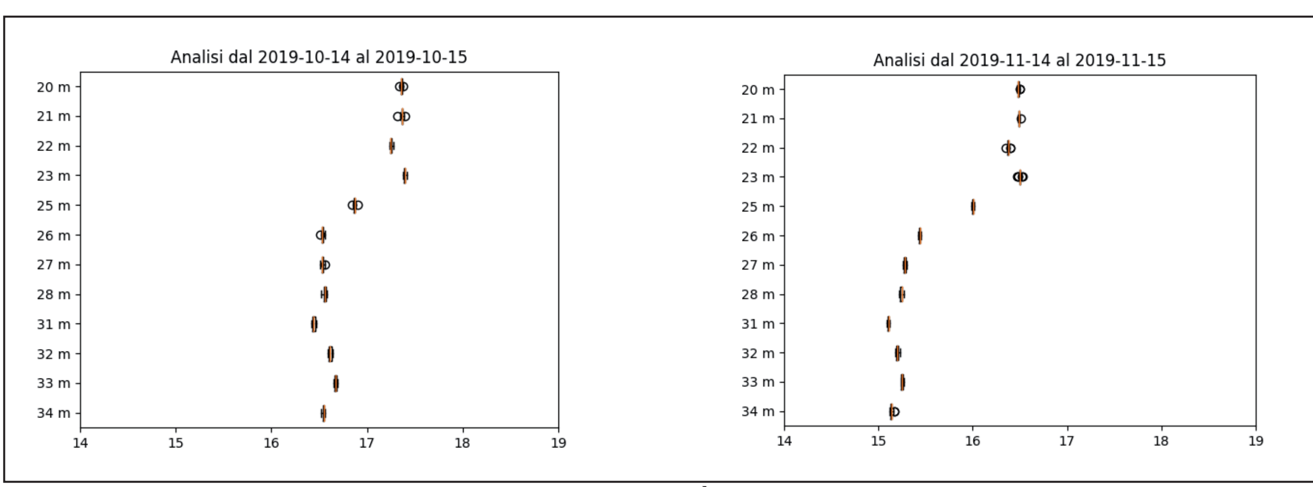


Fig. 8 - Boxplot diagrams of different autumn season plant-operation times: a. 15/10/2019; b. 15/11/2019. Data recorded by the water temperature measuring chain installed in piezometer (S2)

periods) can be associated with mixing and homogenization phenomena of the water re-injected into the P4 column well. Otherwise, during the spring and autumn seasons, it is possible to identify a weak vertical stratification of the temperature, with slightly higher temperature values recorded in the superficial levels of the aquifer.

CONCLUSIONS

The environmental impact caused by an open-loop GWHP system such as the Politecnico di Torino geothermal plant, which discharges water into shallow aquifers for cooling and heating buildings can be notable, compromising the cooling schemes and causing efficiency issues in nearby plants located in urban areas. Over time, the processes of setting up and installation of adequate monitoring tools in the Politecnico di Torino open-loop GWHP monitoring piezometer (S2) allowed the monitoring of the TAZ plumes over different plant functioning seasons, understanding the heat transport mechanisms and horizontal propagation modes.

In addition, the installation of a new monitoring tool represented by a water temperature-measuring chain (type PT1004/Pt) in April 2019 inside the 35m-deep piezometer (S2) has permitted the identification of the vertical stratigraphic aquifer intervals subject to greater or lesser thermal perturbation, during the 2019-operating season.

From the graphic elaborations obtained after the hourly temperature data processing, has indeed emerged how the higher variation entity of the sensor's temperature located at different depths is recorded in the geothermal plant switch-off period. Moreover, although the aquifer in the summer months turns to be continuously affected by thermal perturbations, no evident vertical thermal stratification seems to be originated.

The constructional characteristics of the re-injection well (P4), including 1) the water re-injection that occurs via gravity and 2) the warmer water that is discharged into the aquifer through a 20m well column of screens turned out to be sufficient to properly disperse thermal perturbations, favouring homogenization phenomena along the vertical section.

The choice to install such a water temperature-measuring chain, together with the information deriving from the application of the data analysis proposed in this work can contribute to the understanding the adequacy of construction characteristics of an open-loop system injection well. Moreover, in case of implementation in numerical simulation models, the use of the hourly temperature data available at different depths could not only allow their validity but also facilitate the understanding of the areal extent of the impact that such temperature variations could have on down-gradient located users.

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