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GROUNDWATER HEAT PUMPS DIFFUSION IN THE TURIN CITY URBAN AREA: MODELLING FOR THE THERMALLY AFFECTED ZONE ANALYSIS OF AN OPEN-LOOP GEOTHERMAL SYSTEM

Martina GIZZI[(*)], Alessandro BERTA[(*,**)], Federico VAGNON[(*)] & Glenda TADDIA[(*)]

[(*)]Politecnico di Torino - Department of Environment, Land and Infrastructure Engineering (DIATI) - Torino, Italy
[(**)]Politecnico di Torino - Department of Energy (DENERG) - Torino, Italy
Corresponding author: alessandro.berta@polito.it

EXTENDED ABSTRACT

Nelle aree urbane caratterizzate da condizioni geologiche e idrogeologiche favorevoli, le pompe di calore ad acqua di falda a ciclo aperto risultano essere una tra le soluzioni più efficienti in termini di riduzione delle emissioni associate a sistemi di riscaldamento e raffreddamento. Nel caso della Città di Torino, l'acquifero superficiale di natura alluvionale costituisce una risorsa preziosa per lo sfruttamento dell'energia geotermica a bassa entalpia ad esso associata. Tuttavia, l'adozione di pompe di calore ad acqua di falda a ciclo aperto non può prescindere da una corretta conoscenza dell'assetto geologico e idrogeologico locale. Sebbene tali sistemi vantino un notevole potenziale in termini di efficienza energetica, il loro impatto ambientale può rappresentare un fattore limitante, specialmente alla scala di quartiere. Gli impatti sul regime di flusso indisturbato delle acque sotterranee e sul campo di temperatura, derivanti dalle specifiche modalità di funzionamento degli impianti geotermici, possono essere valutati utilizzando software di modellazione numerica esistenti.

Ad oggi, all'interno dell'area urbana della Città di Torino, risultano essere presenti 44 sistemi geotermici del tipo a ciclo aperto. Informazioni riguardo le modalità di funzionamento di tali impianti, in termici di portata immessa in acquifero da sistemi di pozzi di immissione, possono essere ottenute esaminando la documentazione specifica che autorizza lo scarico di volumi di acqua in acquifero (autorizzazione ambientale unica – AUA). Per la Regione Piemonte, le autorità locali responsabili del processo di autorizzazione richiedono un'analisi, mediante l'esecuzione di modelli di simulazione numerica, dell'evoluzione della perturbazione termica generata in acquifero a seguito e nel corso di diverse stagioni di funzionamento dell'impianto. In questo lavoro di ricerca è proposto un tentativo di ricostruzione dell'impatto sull'acquifero superficiale sfruttato causato dai 44 sistemi geotermici a ciclo aperto esistenti nell'area urbana di Torino. A tal fine è stato elaborato un modello numerico alla scala urbana attraverso l'utilizzo del modello di flusso a differenze finite (MODFLOW 6) sviluppato dallo U.S. Geological Survey. Il modello di trasporto MT3DMS è stato quindi utilizzato per simulare il trasporto di calore generato in acquifero. Due diversi scenari di simulazione della durata di tre anni, considerando portate di funzionamento degli impianti medie e massime sono stati elaborati e descritti. Il valore di portata massima per ogni impianto è stato determinato in base alle informazioni fornite nei documenti autorizzativi. Al contrario, il valore di portata media di funzionamento è stato impostato pari ad un quarto della portata massima precedentemente definita. Valori di temperature di re-immissione delle acque in acquifero sono state fissare pari a 8°C e 21°C, rispettivamente per le stagioni invernali (6 mesi) ed estive (6 mesi).

Dall'analisi dei risultati ottenuti è stato possibile descrivere gli effetti sull'acquifero, in termini di abbassamenti/innalzamenti generati e di variazioni della temperatura indisturbata dell'acquifero (15°C). I risultati ottenuti sono stati descritti considerando il dettaglio dell'areale del complesso universitario del Politecnico di Torino. Alla scala di quartiere considerata, per entrambi gli scenari di funzionamento considerati, l'acquifero ha mostrato una risposta positiva sia in termini di disturbi idraulici che termici. Per lo scenario a portata media, la massima alterazione termica registrata a seguito di una stagione di funzionamento invernale dell'impianto è rappresentata dall'isoterma di 8°C. Per lo scenario a portata massima, la perturbazione termica derivante dalla terza stagione di funzionamento estiva è definita da un'isoterma di variazione di temperatura di tre gradi (18 °C). Le alterazioni termiche più elevate associate alle ultime due stagioni invernali di funzionamento dell'impianto sono rappresentate rispettivamente dalle isoterme di 13 °C e 9 °C. A causa delle variazioni nella temperatura naturale delle acque sotterranee associate allo scenario a portata massima, l'installazione di un nuovo sistema geotermico lungo la direzione di flusso delle acque sotterranee potrebbe subire effetti avversi dovuti a interferenze termiche causate dall'esistente impianto a monte. La progettazione accurata di nuovi impianti geotermici risulta quindi cruciale, specialmente in contesti caratterizzati da complessi sistemi di estrazione e immissione e da elevate portate di pompaggio.

Modelli di simulazione numerica come quello proposto rappresentano uno strumento fondamentale, non solo per determinare l'alterazione causata dall'estrazione e/o dall'immissione di energia termica, ma soprattutto per identificare strategie adeguate relative a nuovi prelievi d'acqua, alla pianificazione del paesaggio urbano o alle conseguenze di nuove situazioni di sviluppo pianificazione energetica.

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ABSTRACT

In urban areas with favourable geological and hydrogeological conditions, Groundwater Heat Pumps (GWHPs) offer an efficient solution for reducing emissions in heating and cooling systems. Turin City's alluvial shallow aquifer serves as a valuable resource for harnessing low-enthalpy geothermal energy. However, a site assessment to evaluate the consequences of the technical solutions when promoting GWHPs is essential. Despite their proven potential in terms of energy efficiency, the environmental impact is a factor that can limit their development. This study reconstructs the impact of 44 open-loop geothermal systems in Turin's area: an urban-scale numerical model was set up, and two simulation scenarios have been performed. The impacts simulated around the university buildings of the Politecnico di Torino are described. Findings from the average flow rate scenario demonstrated the absence of relevant hydraulic and thermal disturbances. The aquifer shows a positive response over three years, even in the maximum flow rate (Qmax) scenario with cooling/heating operating seasons for six months/year. However, due to changes in natural groundwater temperature connected to the Qmax scenario, downstream systems could experience adverse effects due to thermal interference. Precision in designing the construction of a new geothermal structure is crucial, particularly in areas with complex extraction systems.

Keywords: *renewable energy, hydrogeology, numerical modelling, groundwater heat pump system, Italy*

INTRODUCTION

In urban and metropolitan areas with favourable geological and hydrogeological conditions and accessible resources, groundwater heat pump systems (GWHPs) have become a prevalent and practical solution for reducing emissions in heating and cooling systems. A GWHP is a form of a ground-source heat pump (GSHP) that harnesses the low-temperature groundwater stored in shallow aquifers to fulfil buildings energy needs. It offers great efficiency, significant energy savings, and limited pollution (Taddia *et alii*, 2019, Gizzi *et alii*, 2023, Li *et alii*, 2023).

In the Turin alluvial plain, the shallow aquifer serves as a crucial water resource that can support significant exploitation of associated geothermal energy. Although the implementation of GWHPs remains limited at the urban scale, the positive role the above-mentioned technology can play in achieving the energy systems thermal efficiency is evident. As reported by Berta *et alii*, 2024 , by June 2023, 44 geothermal plants have been built in the Turin city area. Presently, there exists an insufficiency of detailed information concerning geothermal wells. However, information about the position of the discharge wells and the maximum flow rate can be obtained by scrutinising the single environmental authorisation (AUA) on the Metropolitan City of Turin website (Metropolitan City of Turin, 2023). Similarly, specifics about the extraction wells, including the position of the wells and, in some cases, the mean flow rate, can be obtained from data sourced from the ARPA Piedmont website.

Despite their proven potential in terms of energy efficiency, the environmental impact of GWHPs is a factor that can limit their development. Thermal interferences among different users could be a concern, especially in historic urban areas where well proximity is dictated by building closeness and the potential for multiple group plants nearby. The thermal impact on aquifers from GWHPs is inevitable, yet it can be examined and supervised using tools that facilitate urban-scale planning. Besides, as a GWHP system runs, the thermal breakthrough is a crucial feature of system design that can result in a progressive shift in pumping water temperature and negatively impact the plant performance (Gizzi *et alii*, 2020).

For the Piedmont Region, local authorities in charge of the authorization process for a GWHP allow a maximum temperature difference in the well-doublets of 7°C. The thermal plume evolution during both the initial design phase and after several seasons of plant operation, by performing numerical simulation models, is also required by competent offices. Groundwater and thermal models serve as anticipatory instruments for identifying suitable strategies related to water withdrawal, the interplay between surface water and groundwater, urban landscape planning, or the consequences of new energy plan developmental (Kumar & Kumar, 2014).

The primary goal of this study was to evaluate the impact on the groundwater flow and temperature resulting from the existing geothermal plants, considering thermal exploitation modalities and pumping well-schemes in the Turin urban area. An urban-scale numerical model was set up and proposed as a preliminary tool for professionals and local authorities to allow the analysis of thermal perturbations potentially generated in the shallow aquifer. Three-year simulation scenarios were performed, considering different pumping capacities of plants (maximum and average monthly flow rate) to satisfy the energy demand of buildings. The preliminary results obtained by the numerical modelling can be analysed for each geothermal plant with a case-by-case approach: a description of the impacts simulated at the neighbourhood scale recorded around the university buildings of the Politecnico di Torino is proposed. The different contributions of the Politecnico di Torino GWHPs, in terms of impact on groundwater, was also highlighted.

MATERIALS AND METHODS

The Study Area: Geological And Hydrogeological Setting

The Turin plain stretches between the Rivoli-Avigliana Morainic Amphitheatre in the west and Torino Hill in the east. Various rivers define the boundaries of the Turin urban area: the Stura di Lanzo River marks the northern border, the Sangone River delineates the southern one, and the Po River forms the eastern edge. Information obtained from drilled wells and downhole log tests has revealed the existence of two separate lithological units characterized by different hydraulic properties (named in the following as Stratigraphic Units 1 and Stratigraphic Units 2) (Fig. 1A). 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 (≤ 1.5 m thick). Stratigraphic Unit 2 (Early Pliocene–Middle Pleistocene) includes shallow marine environment deposits (Sabbie di Asti and Argille di Lugagnano) composed of fossiliferous sandy-clayey layers with subordinate fine gravelly and coarse sandy marine layers as well as quartz-micaceous sands (Bonsignore & Bertolami, 1969). The outwash plain substrate (Unit 3) consists of a Cenozoic terrigenous marine succession composed of conglomerates, sandstones, and marls (Piemonte Tertiary Basin). An assessment of the average thickness of coarse detrital fluvioglacial deposits suggests a value of approximately 70 meters (Fig. 1B). Furthermore, deposits characterized by finer and more compact sediments, with thicknesses extending up to 200 meters, can be attributed to lacustrine and deltaic formations from the Pliocene-Pleistocene transition. Additionally, discernible marine tertiary formations, with thicknesses in the order of hundreds of meters, are present (Forno & Gianotti, 2021).

From a hydrogeological perspective, the main surface water drainage network of the Turin plain (Stura di Lanzo, Sangone, Dora Riparia, Po rivers) communicates hydraulically with an unconfined aquifer, hosted in the Stratigraphic Units 1 and extended over the entire urban plain (NNW–SSE gradient of 0.3% towards the Po river). The water table in the city is found at a depth ranging from about 15 to 25 m below the surface (Fig. 2). Thus, the thickness of the aquifer ranges between 15 and 30 m. Following the information reported by (Lo Russo *et alii*, 2014), a mean

A

B

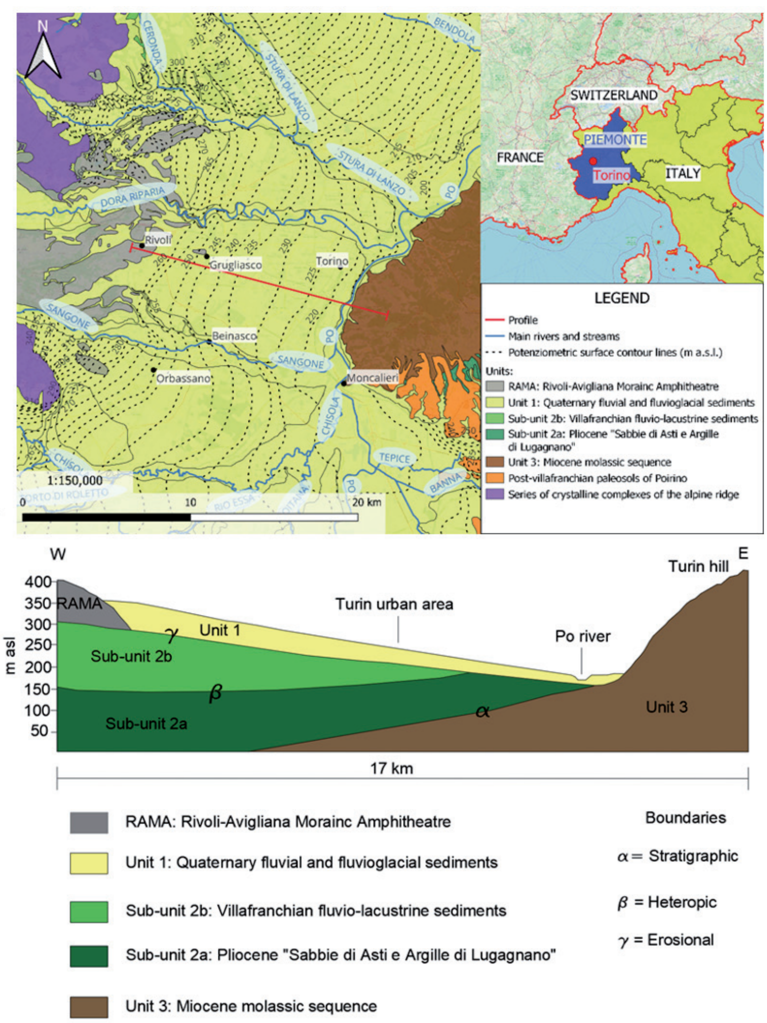

Fig. 1 - A) Hydrogeological map of the Turin plain area (Berta et alii, 2024); B) Cross-section and stratigraphic relationships (Berta et alii, 2024)

hydraulic conductivity value of 2.5×10^{-3} ms^{-1} was estimated for the unconfined aquifer. Based on the aquifer lithology determined by examining well-drilling logs, an effective porosity of 0.20 was estimated. In addition, for stratigraphic Unit 1, a volumetric heat capacity value of 1.3×106 $Jm^{-3}K^{-1}$ was calculated as a composition-weighted mean based on the lithological records.

HYDROGEOLOGICAL DATA COLLECTION AND CHARACTERISATION

The spatial distribution of the geological and hydrogeological variables is essential in the preliminary phases of a numerical model definition: continuous variables need to be correctly mapped for the entire study area by using a point-information interpolation approach (Previati & Crosta, 2021) . Three distinct sources of hydrogeological data for the Turin area are available for professionals: the Geoportale Piemonte, provided by the regional authority, the Geoportale Arpa Piemonte of the Regional Environmental Agency (ARPA) and the open-access portal aperTo, provided by the City of Turin (Fig. 2). While data on the piezometric level, aquifer thickness, and depth are accessible through vector file archives, defining the spatial distribution of hydraulic conductivity of the shallow aquifer in Unit 1 has required a methodological approach to ensure accurate characterization. In addition to the available accessible step drawdown test results (Regione Piemonte, 2007), stratigraphic sections from the Arpa Piemonte database were considered for defining hydraulic conductivity (K) values at the model scale. From the lithological description of geological layers, encountered in each specific borehole, the hydraulic conductivity parameter was categorised into three different classes, as outlined in Table 1.

Stratigraphic Class	Unit Description	K value (m/s)
1	Gravel with pebbles	3.10^{-3}
2	Gravel with sand	2.60^{-3}
3	Sand with gravel in a silty matrix	1.50^{-3}

Tab. 1 - Assigned hydraulic conductivity (K) values

MODEL SETUP

Fluid flow and heat transport mechanisms in the unconfined aquifer were modelled by using the modular finite-difference groundwater flow model (MODFLOW 6) developed by the U.S. Geological Survey (USGS) (McDonald & Harbaugh, 1988). The governing three-dimensional flow equation used by MODFLOW (Harbaugh *et alii*, 2000) combines Darcy's Law and the principle of conservation of mass via Equation (1):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)-\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+q_s=S\frac{\partial h}{\partial t} \quad (1)$$

where K_{xx}, K_{yy} and K_{zz} are the values of hydraulic conductivity along the x, y, and z coordinate axes oriented parallel to the major axes of

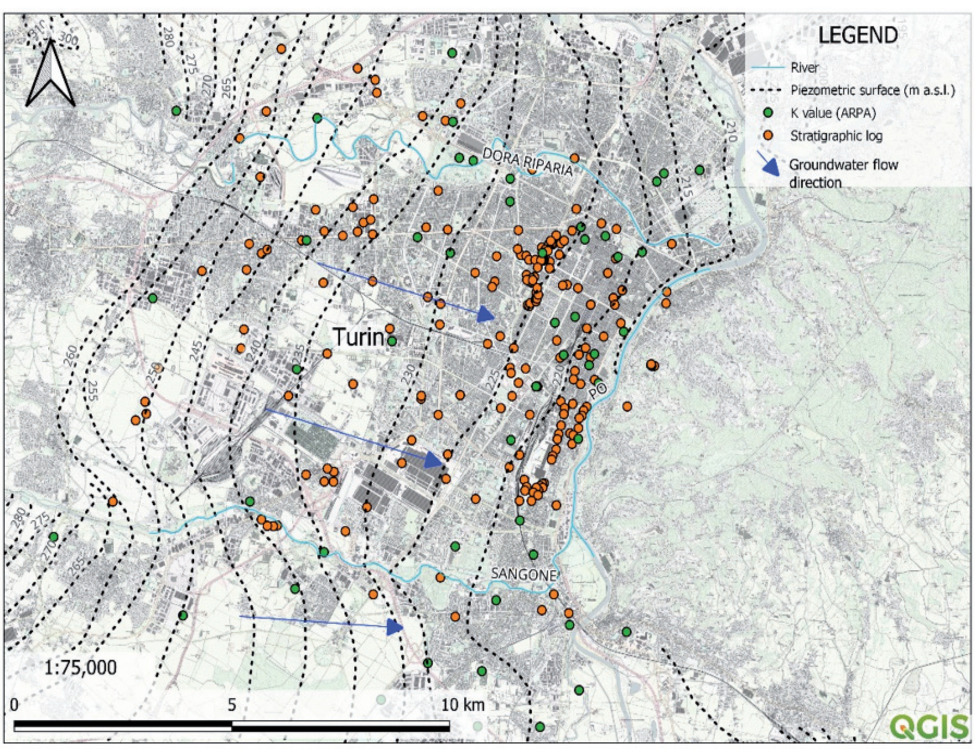

Fig. 2 - Available geological and hydrogeological information and data for the Turin plain area

hydraulic conductivity [*L/T*], h is the hydraulic head [*L*], *qs* is the volumetric flux of groundwater sources and sinks per unit volume [*1/T*] with positive values indicating flow into the groundwater system, *S* is the specific storage [*1/L*], and t [*T*] is the time.

MODFLOW solves a volume-averaged form of Equation (1). The groundwater flow equation is solved using the finite-difference approximation. The flow region is subdivided into blocks in which the medium properties are assumed to be uniform. Flowrate and cumulative-volume balances from each type of inflow and outflow are computed for each time step. The multi-species transport model MT3DMS is applied to simulate heat transport in shallow confined aquifers (Bedekar *et alii*, 2016). ModelMuse (version 5.1.1.0) was used as a graphical user interface and modelling environment (Winston, 2019).

Starting from the assigned hydrodynamic and thermal parameters for Unit 1 and Unit 2, a two-unit conceptual model simulation was performed, wherein hydro-stratigraphic Unit 1 contains the exploited unconfined alluvial aquifer. The plan-view grid dimensions in the model were set at 11×11 km (121 km^2). The model area was intentionally designed to be larger than the Turin city urban area under investigation to minimize the impact of assumed boundary conditions on model outcomes. Boundary conditions were fixed as follows: the recharge area limits of the deep aquifer at the western border, Dora Riparia, Sangone and Po River at the North, South and East border, respectively. General Heads Boundary (GHB) were set on the western and eastern boundaries following available onsite potentiometric surface measurements. An average natural groundwater temperature of 15°C was set throughout the shallow aquifer, as reported in Gizzi *et alii*, 2021, reflecting the undisturbed average groundwater temperature of the saturated zone. The river package is used to simulate the interference with rivers, while the well package is used for existing geothermal wells. Information on the operation of 44 geothermal plants, available from the single environmental authorization (AUA) (Metropolitan City of Turin, 2023), was considered, and 154 wells were modelled through the following three-years scenarios: 1) maximum flow rate (Qmax) scenario with cooling/heating operating seasons mode for 6 months/year; 2) average monthly flow rate (Qmean) scenario with cooling/heating operating seasons mode for 6 months/year. The Qmax value for each plant was determined based on the information provided in the AUA documents. It depends on the size of the plant, with the value ranging between 1 l/s flow rate for very small plants and 100 l/s flow rate for large plants. Conversely, the Qmean value considered was set at one-fourth of the Qmax. Reinjection temperatures of 8 °C and 21°C were considered for the winter (6 months) and summer (6 months) plant-functioning seasons, respectively. Moreover, abstracted and reinjected discharges were considered to be equal over the plant operational period. Due to the lack of infiltration data and the predominantly impermeable surface characteristics of the model area, covered mostly by buildings and roads, rainfall infiltration rate was considered negligible. Additionally, based on continuous monitoring of groundwater level, the unperturbed groundwater flow was assumed to be stable throughout the year.

RESULTS AND DISCUSSION

The disturbances on the groundwater flow and temperature fields resulting from the operating modes of the analysed 44 GWHP plants were modelled using the previous-described two-unit hydrogeological model of the Turin plain. The results from the two simulation scenarios, involving different pumping capacities (maximum and average monthly flow rate) can be individually analysed for each geothermal plant, adopting a case-by-case approach for identifying preliminary strategies related to water withdrawal and urban landscape planning. Below, a description of the impacts recorded around the university complex of the Politecnico di Torino is provided.

The buildings connected to the existing Politecnico di Torino GWHP plants host university offices and laboratories. The open-loop geothermal plants at Politecnico di Torino include three 35-m deep control piezometers downstream of the injection wells (S2, S3, S4), as well as five abstraction and three injection wells with similar technical characteristics. All components of these geothermal systems affect the Turin shallow unconfined aquifer. Both scenarios showed changes in the piezometric levels and the extent of the thermally affected zone at the end of the three-year operation period. The findings from Qmean scenario reveal that the aquifer exhibits a positive response to both hydraulic and thermal disruptions during a three-year analysis period (Fig. 3) since there are no significant alterations in the groundwater flow field detected around the Politecnico di Torino complex. However, noticeable thermal variations are linked to the modelled operational season the Politecnico di Torino plants, specifically during the last winter and summer of the third year of plant operation. Upon examining the generated scenario, the thermal plume resulting from the third summer plant operation season is characterised by a one-degree temperature change compared to the average undisturbed groundwater temperature (15°C). The highest recorded thermal alteration associated with winter plant operation season is represented by the 8°C isotherm. The described Qmean scenario turns out to realistically define the existing conditions: taking into account the temporal aspect, particularly during a specific season of synchronized operation, newly constructed plants located in the Politecnico di Torino downstream direction can be favourably impacted by this disturbance. This setup can capitalize on the undisturbed temperature of the aquifer, which remains at 16ºC.

The same positive response was observed for the Qmax scenario (Fig. 4). The maximum alteration in the groundwater flow level detected around the Politecnico di Torino University complex is 0.2 m. Visible changes in the undisturbed groundwater temperature

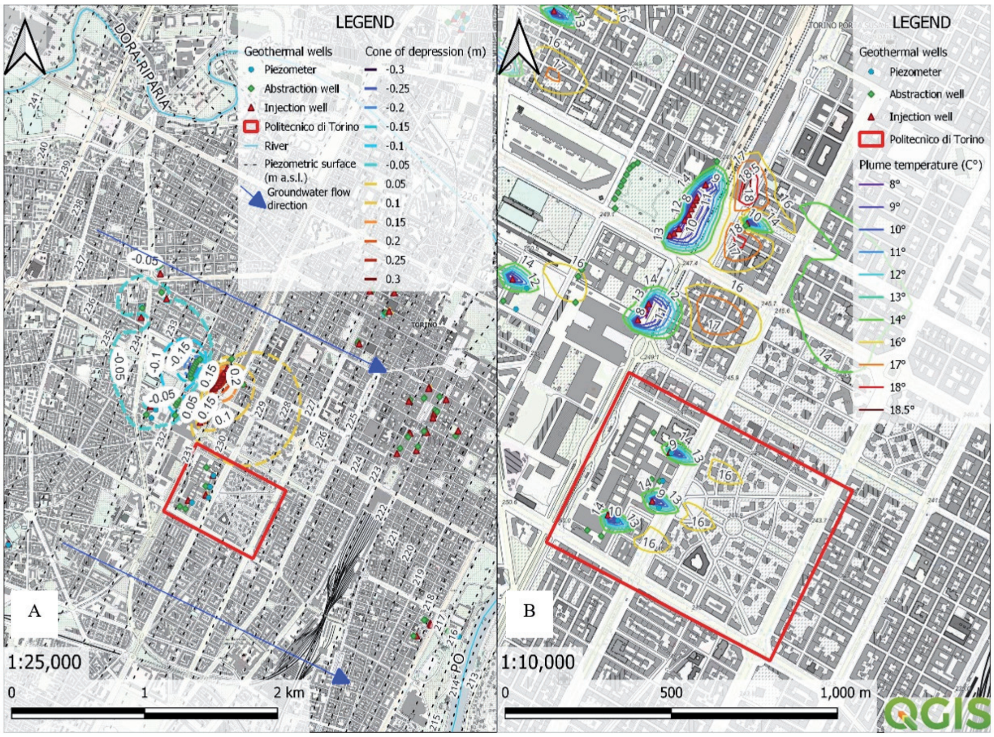

Fig. 3 - Average flow rate (Qmean) scenario's results with cooling/heating operating seasons mode for 6 months/year: A) groundwater flow field disturbances B) temperature field disturbances

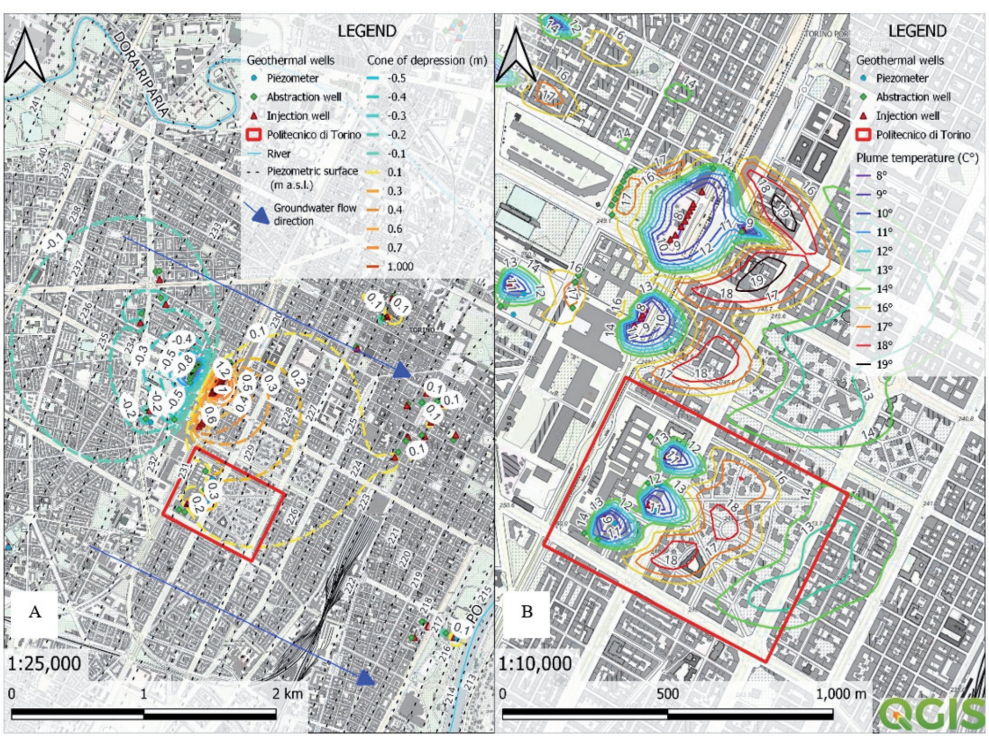

Fig. 4 - Maximum flow rate (Qmax) scenario's results with cooling/heating operating seasons mode for 6 months/year: A) groundwater flow field disturbances B) temperature field disturbances

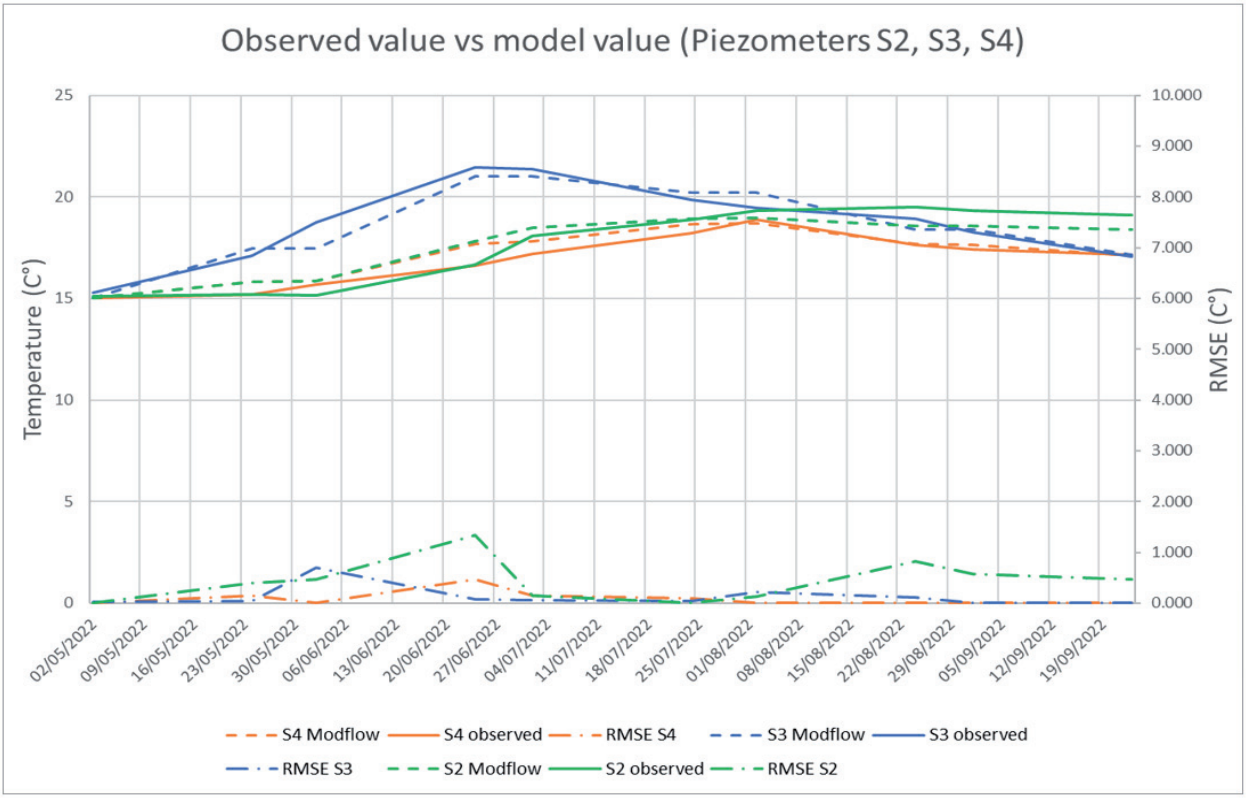

Fig. 5 - Comparison between Observed and Simulated values and RMSE calculated values for the three piezometers considered, located downstream the geothermal plants at Politecnico di Torino

(15°C) are connected to the operational seasons modelled in the last two years. Upon analysing the generated scenario, the thermal plume arising from the third summer plant operation season is defined by a three-degree temperature variation isotherm (18°C).

The highest recorded temperature alterations associated with the last two winter plant operation seasons are represented by the 13°C and 9 °C isotherms, respectively. Although this scenario exaggerates the influence on the undisturbed state of the aquifer, a downstream geothermal system will experience adverse effects due to thermal interference from the upstream one. Properly designing the construction of a new plant is crucial, and this involves accurately characterizing the hydrogeological system at the neighbourhood scale (*i.e.*, water drainage network, groundwater flow direction, groundwater hydrogeological gradient, aquifer hydraulic conductivity value). Therefore, determining the appropriate distance between plants becomes essential.

The reported and described results appear to be valid: this is confirmed by the findings from the validation process conducted on Qmean scenario results. Hourly recorded data from Politecnico di Torino plants' control piezometers S2, S3, S4 were considered for this purpose. To test the performance of the urban-scale model, a comparative analysis was conducted between the observed and recorded groundwater temperature data and the model-simulated one. Daily averages were calculated from hourly measurement data from S2, S3, S4; these values were thus compared with the daily average values for selected plant operation days. Root Mean Square Error (RMSE) turned out to be less than 1°C, as shown in Figure 5. June had the highest error rate due to the intermittent operational status of Politecnico di Torino's facilities caused by ambient temperature fluctuations. Therefore, the modeling framework that relies on average flow rates and temperatures is insufficient in capturing these variations. During July and August, when there are continuous operational activities, the average error rate decreases to less than 0.5 degrees Celsius. This validates the model's ability to capture spatiotemporal thermal dynamics within the Politecnico di Torino.

CONCLUSIONS

GWHPs represent a key technology for promoting widespread adoption at different scales, particularly in urbanized areas of the temperate zones such as Turin, where shallow aquifers serve as valuable sources of renewable energy. At present, urban planning tools need to address two primary goals: facilitating the rapid widespread adoption of open-loop groundwater heat pump systems

(GWHPs) and ensuring the effective, long-term safeguarding of groundwater resources. Achieving these goals requires integrating an understanding of the geological and hydrogeological system into the decision-making process, with continuous monitoring of the enduring effects of GWHPs on the shallow aquifer through advanced methods and existing numerical modeling tools.

An attempt to investigate the impact on the shallow aquifer beneath the Turin city area caused by the 44 existing open-loop geothermal systems was proposed, and an urban-scale numerical model was set up for this purpose. Utilizing available, open-source data and flow rate values determined for each plant based on information from single AUA documents, fluid flow and heat transport mechanisms in the unconfined aquifer were modelled by using the modular finite-difference groundwater flow model (MODFLOW 6). The multi-species transport model MT3DMS is applied to simulate heat transport in shallow confined aquifers.

Findings from the Qmean scenario demonstrated the absence of relevant hydraulic and thermal disturbances around the Politecnico di Torino University complex. At the neighbourhood scale considered, the shallow aquifer exhibited a positive response to both hydraulic and thermal disruptions over three years, even in a scenario considering the maximum flow rate (Qmax) with cooling/heating operating seasons for six months per year. Thus, the modeling results confirmed that the hydrogeological characteristics of the site could provide the required volume of groundwater and associated energy with a limited impact on the environment. However, in the Qmax scenario, changes in the undisturbed groundwater temperature (15°C) could lead to adverse effects on downstream geothermal systems due to thermal interference from the upstream one. Properly designing the construction of a new geothermal structure is crucial, especially in areas with complex extraction/reinjections well systems and high pumping flow rates, where determining the appropriate distance between plants is fundamental.

Numerical models at the urban scale, combined with scenario considerations for existing operational plants, serve as valuable tools in early stage urban planning. While the Qmax scenario may overstate the impact of existing plants on groundwater, it offers insights into defining the feasibility of the new plant with a cautious perspective. The Qmean scenario provides a realistic vision of the impact caused by network of existing plants. Unlike other Italian urban and metropolitan contexts where the aquifer resource appears to be over-exploited, it can be asserted that the Turin area has available opportunities for additional resource exploitation.

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