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rOGER: A method for determining the geothermal potential in urban areas

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ABSTRACT

Shallow geothermal energy is increasingly adopted for heating and cooling purposes because of the short payback time of initial installation investments. As a result, a relevant concentration of Ground Heat Exchangers is being experienced in urban areas. Planning issues thus arise to manage interferences and optimize the use of underground heat resources without depletion, harm to the environment nor efficiency losses on heat pumps or plant oversizing. This study provides a rational approach to optimise geothermal resources based on the use of Geographic Information Systems and transient 3D Thermo-Hydro numerical models. An optimised semi-analytical formula for the assessment of Borehole Heat Exchangers geothermal potential in hydrodynamic conditions is developed through a parametric numerical study. The long-term performances of BHE subjected to groundwater velocity in the range of 0 to 1 m/day were analysed with multiple aquifer thermal parameters. This analytical expression allows a fast and accurate assessment of the potential even in large areas without leading to excessively conservative evaluations. This may serve designers in the preliminary sizing of installations and city planners in the development of appropriate policies for the promotion and management of shallow geothermal resources. An example of the application to the central district of the city of Turin (Italy) is also shown.

1. Introduction

Shallow geothermal energy has gained more and more relevance in the renewable energy sector in the last decades. Amongst the shallow geothermal energy technologies, the Ground Heat Exchangers (GHE) are the most common one. GHEs are based on the circulation of a heat carrier fluid within pipes that are embedded in the ground at very low depths (horizontal heat exchangers) up to a few hundred meters depths (Borehole Heat Exchangers, BHE). The fluid is thus conveyed to a heat pump system that serves buildings and/or infrastructures to satisfy their heating and cooling loads.

Nowadays technological development ensures an extremely high efficiency of the ground-based heat pump systems, with Seasonal Performance Factors (SPF) values of up to 4 (Spitler and Gehlin, 2020). Furthermore, shallow geothermal is worldwide available and GHEs can be installed in most geological settings with extremely low environmental and visual impact. Despite these strengths, some factors still hamper the wider spreading of this technology including the high initial costs (Hwang et al., 2010) and the lack of confidence in the predictions about the amount of thermal energy that can be exchanged (Dehkordi and Schincariol, 2014). In most applications, the highest share of these costs is related to large and/or deep excavations. It is thus crucial to avoid oversizing the installation by properly determining the heat exchange rate of the Ground Heat Exchangers (GHE). In the case of BHE, the heat exchange capability, namely the geothermal potential, can be expressed as exchangeable thermal energy per element or exchangeable energy per unit length (Schiel et al. 2016; VDI 2010). The precision in the sizing of the installation is strictly related to the precision and reliability of the assessment of the so-called technical geothermal potential (Bayer et al. 2019).

The quantification of the geothermal potential is a complex operation. A variety of factors exert a relevant influence on the final result. These factors include ground properties, installation features, the presence of groundwater flows, the aquifer properties and the site temperature. Three main families of factors can be identified: site properties that depend on the hydro-geological and climatic conditions at a certain location, installation properties that account for the characteristics of the technology adopted and installation usage that depends on the user demands and on the way the installation is run. It should be noted that, especially in the case of the site properties, most of these factors are measured against high costs and their quantification is affected by large uncertainties. Because of the complexity of the quantification of the exchangeable heat, multiple approaches have been proposed in the literature, concerning both the regional scale and the city and district scale (Migliani et al. 2018; Heim et al. 2022; Sáez Blázquez et al. 2022;

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Nomenclature

α^*	thermal idrodispersive diffusivity
α_L	longitudinal thermal dispersivity
α_T	transverse thermal dispersivity
Λ_1	spherical part of the thermal conductivity tensor
λ_f	fluid phase thermal conductivity
λ_s	solid phase thermal conductivity
ρ_f	fluid phase mass density
ρ_s	solid matrix mass density
C_{gw}	correction factor for groundwater flow
COP	coefficient of performance
C_f	fluid phase specific heat capacity
C_s	solid matrix specific heat capacity
L	borehole length
n	porosity
Pe	peclet number
Q_{BHE}	borehole geothermal potential
Q_b	building seasonal thermal load
Q_i	local geothermal potential
R_b	borehole thermal resistance
SPF	seasonal performance factor
r_b	borehole radius
SR	satisfaction ratio
T_0	undisturbed ground temperature
T^*_0	corrected background temperature
T_{lim}	heat carrier fluid limit temperature
t_c	load cycle time
t_s	installation lifetime
t_y	period between two identical operative seasons
v_d	darcy velocity

Miocic et al. 2024; Previati and Crosta 2024).

Focusing on urban areas, the presence of groundwater flows contributes to the deformation and the migration of thermal plumes according to the water table setting (Alcaraz and Vives 2017; Alcaraz et al. 2016). Furthermore, the continuously growing use of subsurface resources in urban areas (Parriaux et al. 2004; Brandl 2016), including shallow geothermal energy exploitation, may lead to conflicting uses or overexploitation and depletion (Ferguson and Woodbury 2006; Quattrocchi et al. 2013; Vienken et al. 2015; García-Gil et al. 2020; Epting et al. 2020; Soltan Mohammadi et al. 2024). In this context, interactions amongst different geothermal users and with other subsurface uses are becoming more and more frequent and may result in strong alteration of the available technical geothermal potential (Fry 2009; Herbert et al. 2013; Lo Russo et al. 2014; Piga et al. 2017; Barla et al. 2018; Alvi et al. 2023). Thus, the need arises for urban and energy planning policies capable of handling this crucial development issue, especially in the light of land scarcity that characterizes large modern cities.

In the definition of geothermal potential, real thermal condition assessment is of crucial importance. These conditions are typically affected by high spatial and temporal variability due to the multiplicity of anthropogenic heat sources. The high complexity of the entities affecting the thermo-hydraulic regime of urban subsurface cannot be usually handled with simple analytical models. On the contrary, the availability of advanced numerical models that can account for several internal and external boundary conditions allows for accurate study of the thermo-hydraulic conditions of vast areas. Numerical studies furthermore enable the prediction of the future site conditions within an area based on scenario definition. This capability results in enhanced flexibility in the planning and management of geothermal resources especially in complex contexts.

This study aims to propose a rational approach to the planning of the use of geothermal resources that takes into account the spatial and temporal variations of the site conditions due to the dynamics of the aquifers and the interactions with other subsurface users. The method that is here presented is conceived as a 4-step procedure based on the combined use of Geographical Information Systems and numerical modelling of the thermo-hydraulic regime at the district and city scale. To fully benefit from the advantages of the prediction in highly transient conditions from numerical models, an enhanced version of the G.POT. (Casasso and Sethi 2016) formula is proposed to take into account advective and dispersive components of heat transfer also in case of heterogeneous conditions. It was proved that a correction factor should be applied to the formula when considering depth-weighted average values and a scalar indicator of the hydrodynamic thermal conductivity at the site. Such factor was numerically calibrated in a parametric study and is proved to depend on the ratio between hydrodynamic and hydrostatic components of the heat exchange. The expansion of the validity field of the closed-form solution allows for an accurate assessment of BHE geothermal potential at large scales in representative conditions of a typical urban area. This methodology can be useful to city managers and environmental authorities to assess optimal areas for the installation of new geothermal systems as well as manage actual interferences. An example of the application of the method to the central district of the city of Turin (Italy) is shown to highlight the geothermal potential in the area and the effectiveness of the method.

2. Geothermal potential assessment methods

The potential is often used as an indicator for the assessment of site suitability to host a geothermal installation and depends on site-specific characteristics.

The definition of the heat that can be exploited, namely the technical geothermal potential, is complex due to the high number of influencing factors that are affected by high uncertainty. Because of this, several approaches have been proposed in scientific and technical literature. These methods may be classified as qualitative and quantitative methods.

In the first class, the final result aims at the definition of the best areas where a geothermal installation can be implemented. To this end, traffic light maps are often adopted (Goetzl et al. 2020) to highlight the sites that meet minimum technical and legal requirements. These maps are also very effective in highlighting exclusion zones due to particular geological settings (e.g. karst) or interference with strategic resource assets (e.g. well fields for drink water extraction) or the best technology to adopt at a certain site.

The latter class of methods for geothermal potential assessment aims at the definition of the amount of energy that can be profitably exchanged with the subsoil. These methods depend on the specific technology that is examined (e.g. Open Loop, Horizontal Heat Exchangers, Borehole Heat Exchangers, etc.) and are frequently intended to give pre-dimensioning information for installers and stakeholders. Most attention was devoted to BHE potential assessments which are amongst the most common solutions adopted (Lund and Toth, 2021). However, these methods aim at managing the installations' deployment rather than at defining the overall potential over a territory.

Quantitative geothermal potential assessment methods are based either on empirical relationships (Ondreka et al., 2007; VDI 2010; Galgaro et al., 2015; Munoz et al., 2015; Schiel et al., 2016; Böttcher et al., 2019) or on numerical simulations rather than on analytical models (Miocic et al., 2024).

A strategy used in quantitative methods is to derive the values of heat exchange through experience and hence in an empirical way. To build these models it is necessary to collect a representative number of applications with specific features in known boundary conditions. Amongst these methods the most known is represented by the German standards (VDI, 2010) that are at the base of many feasibility studies for small plants in the scientific literature (e.g. Muñoz et al. (2015), Ondreka et al. (2007), Schiel et al. (2016)), worldwide recognized as engineering standards thanks to the relatively long history and the high profile of the author's panel (Reuss et al., 2006). VDI4640 are also widely adopted due to the easy use of specific heat extraction rates (expressed in W/m) that have been derived for several lithologies under predetermined operating time over the year (2400 h/y and 1800 h/y respectively) in heating mode only. Despite their easy use, the assessment of geothermal potential neglects different climatic conditions (impacting on the representativeness of the operating time) and the uncertainty is relatively high due to the categorization based solely on the lithology. Ground temperature is indeed neglected even if it is a key parameter in potential assessment.

Recent studies have also implemented artificial neural networks for the quantitative evaluation of geothermal potential or thermal properties. Such a kind of approach was used to build the thermal conductivity map of the territory of Cyprus (Kalogirou et al., 2015) where a limited number of boreholes with known lithology, rainfall, and temperature vs depth were used to train the neural network and consequently to assess the average thermal conductivity of the first 100 m subsoil. It should be noted that the method is widely exportable in its architecture to other contexts. Conversely, it is impossible to extract from an Artificial Intelligence algorithm the relationship that links input parameters to the output. Furthermore, the relationship that governs the black box is dependant on the training dataset and is thus specific to the area of study where, at a certain number of locations, all the input parameters have to be known as well as the investigated output, namely the geothermal potential. Another example is that from Zhang et al. (2023) who used a machine learning approach to assess geothermal resources in a study area.

Other quantitative methods that focus on the district and city scale are usually conceived on geometrical optimisation, often adopting GIS tools. Thus, the two main components in this kind of approach are the quantification of the single installation potential and the geometrical deployment of the installations. Area availability is indeed one of the most influential limiting factors in densely populated areas. A few studies have been carried out in recent years in this respect. Zhang et al. (2015) demonstrated that in the City of Westminster, U.K., up to 80 % of building heritage can meet the heating loads. Moreover, Schiel et al. (2016) demonstrated the influence of the urban pattern on the capability of shallow geothermal energy to fulfil energy needs at the district and city scale. Based on the consumption of buildings of typological settlements and specific heat extraction rates from VDI (2010), the GIS tool developed optimises the number of BHEs fitting each parcel of the study area. Similarly, also Miglani et al. (2018), applied an optimisation algorithm for BHE deployment as part of the definition of district-scale geothermal potential. Even if accounting for multiple BHE operations, via spatial and temporal superposition using the so-called g-function (Eskilson and Claesson, 1988), the technical potential was here determined neglecting the convection due to the formulation of Finite Line Source (Carslaw and Jaeger, 1959) which is at the base of the method. Indeed the superposition principle would not be applicable in case of groundwater fluxes due to non-linearity.

From the perspective of quantitative potential assessment on a large scale is indeed preferable to apply map algebra-based algorithms on GIS. These algorithms may be purely analytical or semi-analytical but rigorously expressed as closed formulas. It should be noted that empirical relations often require calibration of coefficients and parameters that has to be carried out with regard to the specific examined area. This aspect can represent a weak point in the straight repeatability of the assessment in different zones and requires advanced skills in the operators. On the contrary, formulas that are derived from analytical models rather than from numerical simulations gain general validity independently from the area of application (García Gil et al., 2015; Casasso and Sethi 2016). It should be mentioned that most of the currently adopted quantitative methods are based on heat-conduction-dominated models. This is the case of the analytical formulation adopted by García-Gil et al. (2015a) that relies on the Infinite Line Source model (Carslaw and Jaeger, 1959). This is also the case of methods based on the Finite Line Source or the Infinite Cylindrical Source models (Philippe et al., 2009; Erol and François 2018). This may lead to a conservative evaluation of the potential that neglects the hydrodynamic contributions to the heat exchange. This latter mechanism may indeed play a primary role in the case aquifer systems are present within the studied domain, which is often the case in urban areas, as the largest and oldest cities were indeed established in strategic locations where resources such as clean water and surface water bodies were available.

The fundamental contribution of fluid flux-related heat transport mechanism was included in the geothermal potential assessment approach developed by Alcaraz et al., 2016b, based on the Moving Infinite Line Source model. Nonetheless, the analytical solutions are not usually able to handle transient boundary conditions that are indeed typically represented by discontinuities and changes in heat extraction rates at various time scales as a result of the variation in heat loads in buildings. This issue was overcome in the semi-analytical approach G. POT. proposed by Casasso and Sethi (2016). It resulted in a numerically calibrated explicit formula for technical geothermal potential quantification of a Borehole Heat Exchanger. The method was indeed successfully tested and adopted in several European areas (Casasso et al., 2018; 2017; Casasso and Sethi, 2017). As the approach relies on the Infinite Line Source model, it is thus affected by the above-mentioned hypothesis of homogeneous subsurface conditions and conduction as the only heat transfer mechanism. This can lead to excessively conservative evaluations of the geothermal potential in areas where a significant groundwater flux is present.

To the aim of this work, the assessment of the potential over large urban areas is the main focus. In the following, the adaptation of a semi-analytical formula will be explained in the broader context of a method to deal with the specific issues of the urban areas in the quantification of the technical geothermal potential.

3. A new procedure for the optimisation of geothermal resources in urban areas

In this study, a method is proposed for the assessment and management of the shallow geothermal potential able to deal with the peculiar issues of the urban context. Indeed, geothermal potential depends on site-specific characteristics and hence may present relevant spatial variability. The highly variable and complex interaction in the subsoil at the district and city scale of active and passive users, structures and infrastructures requires flexible and powerful tools to investigate the thermal and hydraulic regime and to predict future scenarios. To this end, a numerical modelling approach was selected to accurately analyse the transient hydraulic and thermal behaviour. The attention was then focused on a procedure that helps decision-makers and stakeholders to optimise the use of shallow geothermal resources. Hence Geographic Information Systems were used due to their extreme suitability in potential assessment procedures as widely demonstrated in previous studies.

The method here described was named rOGER (acronym for Optimising GEothermal Resources in urban areas) and conceived in four main steps. It is based on the combined use of Geographic Information Systems, detailed numerical three-dimensional thermo-hydro transient models and an enhanced closed-form equation for potential quantification.

The best option to deal with spatially variable inputs and outputs is to use a georeferred database. The conceptual scheme of the method is shown in Fig. 1. It is hence clear that the GIS represent the backbone of

Fig. 1. Conceptual scheme of rOGER method for geothermal potential assessment.

the rOGER method, being used in all the different phases except for phase 2, which requires the usage of numerical modelling tools.

At first, the main relevant parameters are identified and appropriately organized as a spatial database on the GIS. Four main data categories were identified: hydrogeology, entities producing thermal and hydraulic impact, built environment and hydro-thermal regime. Accurate analysis was carried out to obtain an entity-relation model also with the intent of highlighting the elements that have to be later exchanged with the numerical model codes.

Secondly numerical model is set up and numerical analyses are run to finely reproduce the thermal and hydraulic regime of the studied domain.

Treatment of the numerical results with GIS constitutes the third step of the rOGER procedure. This step is devoted to the local geothermal potential assessment through manipulation and post-processing of the data in the hydro-thermal regime category. To this end, an enhanced formulation for BHE potential assessment in hydrodynamic conditions is adopted to fully take advantage of the numerical modelling capabilities.

The final step of the procedure assesses, at the scale of the district or of the city, the best locations and strategies for spatio-temporal optimisation in the use of shallow geothermal resources by aggregating site-scale geothermal potential and geo-processing these data with the energy demand.

3.1. Georeferred database

The geodatabase used in this method aims to quantitatively assess the technical geothermal potential from Borehole Heat Exchangers considering real (or realistic) thermal and hydraulic conditions. To meet this goal, the database structure and the included data have to fulfil minimum requirements as an appropriate scale of a planning tool which is the metric to decametric one. Hence spatial resolution of 1:5000 should not be exceeded by any of the raster data over the entire urban area. This general rule is expected to balance the need of accuracy with the computational effort for the application of the rOGER method to urban areas of up to 10,000 km^2. Although returns are scalar quantities spatially distributed, the database has to manage elevation data to handle heterogeneities in the vertical direction. Because of the significant difference in the dimensions of the vertical domain compared to the areal extension, the vertical resolution has to be smaller than the decametric scale up to the maximum depth of the BHE (about 150 m below the surface).

The boundaries of the study area also have to be defined from the perspective of significance from the thermo-hydraulic point of view and not only on an administrative basis.

The database needs interface capability to the numerical modelling codes that are used in stage 2 of the rOGER method both for data export and import. Although, this depends on the specific software package used for modelling, in most cases data exchange may be in the form of shapefile (.shp) and/or Drawing Interchange Format (.dxf).

The main datasets that are included in the database here adopted are grouped in four main families:

1. Hydrogeological data (stratigraphy, hydraulic and thermal properties related to the different subsoil classes, surface water bodies, groundwater bodies and pertaining monitoring networks);
2. Anthropogenic thermal impact due to deep underground structures (e.g. deep basements, underground car parks, etc.), underground linear infrastructures (e.g. urban road and rail tunnels, metro lines, district heating network, etc.), thermal and non-thermal users of the aquifer (e.g. water wells for industrial purposes, geothermal open loop systems, BHEs);
3. Building heritage and land use;
4. Thermo-hydro regime and derived geothermal potential.

In Fig. 2 the simplified conceptual model of the database and its interaction with the numerical model is shown. It should be noted that datasets are strictly related not only with matching fields but also by consequential processing of attribute tables. It should also be noted that under the class ‘Stratigraphy’, several data are grouped which are usually in the form of raster data. Their number depends on the specific area where the method is applied.

The building heritage constitutes the demand side of energy planning. By relating energy demand with the geothermal potential of the area beneath and around a building, the satisfaction ratio for energy supply both for the heating and cooling season can be calculated, leading to the definition of energy deficit or surplus.

For each of the layers identified in the ‘Stratigraphy’ class, values of groundwater velocity and temperature are defined. Hence within this feature class, a vertical profile of temperatures and the groundwater velocity can be obtained over the area at equally spaced points. This information can then be post-processed to calculate the proper attribute value of heating and cooling potential. These values represent the first and main result of the application of the method. Without the knowledge of the groundwater velocity field, conduction is the unique mechanism that can be taken into account.

Within the ‘Aquifer use’ class, open-loop shallow geothermal systems are included together with wells for water collection and industry discharging wells. Also, so-called passive users are taken into account, as they exchange heat fluxes with the subsurface because of being located underground. These are collected under the ‘BHE’, ‘Underground infrastructures’ and ‘Building’s basement’ classes.

The ‘Thermal and hydraulic regime’ class collects the results from the numerical modelling phase. Thus, this category of data includes a series of site-dependant quantities that might be mapped to represent the evolving thermal state of the aquifer in hydrodynamic conditions.

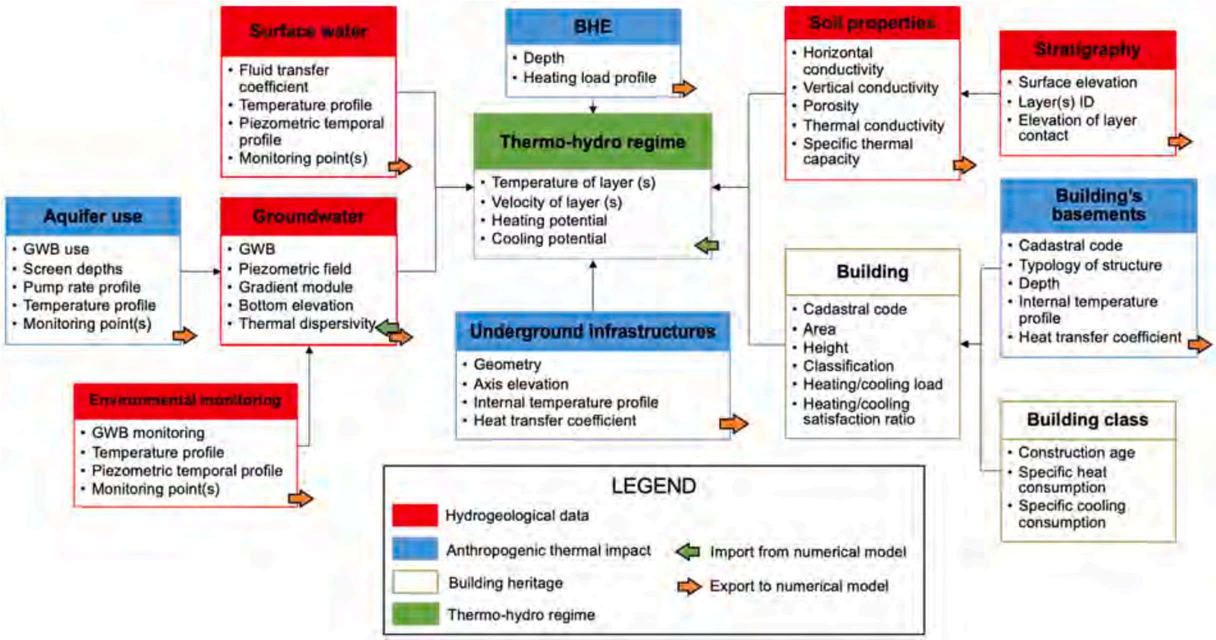

Fig. 2. Conceptual entity-relation model of the spatial database with data categorization and exchange fluxes with numerical codes.

3.2. Real thermal condition assessment

The aim of the second step within the procedure described in Fig. 1 is to provide a reliable temperature field to be later used for the calculation of the geothermal potential.

Only numerical models can properly capture the thermal and hydraulic regime within a domain where multiple external and internal transient boundary conditions are involved. Beyond the planimetric position, due to anthropogenic heat fluxes and the topographic boundary, the vertical dimension is of the utmost importance. Hence the need arises for tridimensional models.

It was demonstrated (García-Gil et al., 2015a) that neglecting the groundwater flow whenever it is present and the relative advective contribution to heat transfer is extremely conservative. In the perspective of optimization in shallow geothermal energy resources, the advection and dispersion hence represent an essential aspect to deal with also in the numerical solution by adopting the coupled mathematical formulation of hydraulic and thermal physics.

Starting from the area included in the GIS, the model domain has to reach at least the maximum BHE drilling depth with an additional minimum vertical tolerance in order to properly account for the vertical diffusion effect at the bottom of the heat exchanger. It should be noted that usually horizontal thermal diffusion is prominent, especially when a groundwater flow is present.

Several elements are taken into account in the model domain discretization. Surface water bodies, underground structures and infrastructures have to be fully included in the 3D geometry. This allows us to define the interface area where heat and fluid exchange take place. On these surfaces, proper transfer coefficients are defined in combination with the proper boundary condition. Water wells (including the Open Loop systems) and BHE are taken into account during the mesh generation process as well. Due to the relative dimensions of the cross-section with regard to the extension of the model, they can be modelled, simplistically, as linear vertical (or transverse) elements. To deal with the highly transient conditions that they induce in the subsurface during operation, a properly refined mesh is necessary around these points.

Assuming that model boundaries match the borders of groundwater bodies, the delineation of boundary conditions may be directly derived from GIS data. Regarding hydraulics on the lateral boundaries three conditions may occur:

- known hydraulic head: if groundwater-monitored data are available (e.g. presence of piezometers in the proximity to the GWB border);
- surface water body: rivers and lakes may feed or drain the shallow aquifer depending on the relative hydraulic head difference (these situations can coexist at different locations or can alternate depending on the level variations);
- impermeable outcrops, low-permeability layers or flow barriers: this situation occurs when bedrock layers emerge (usually associated with topographic discontinuities as hills) or when the hydraulic gradient field is known to be parallel to the boundary. In this case, the mass exchange can be neglected through the lateral boundary.

From the thermal point of view conditions to be imposed at the outer boundaries of the model are:

- known temperature (Dirichlet's boundary condition): along the surfaces where flow enters the model temperature has to be imposed. This is usually the case of data from environmental monitoring (e.g. piezometers, river water quality station) or from weather stations (surface air temperature);
- heat flow (Neumann's boundary condition). In this study, the geothermal heat flow is considered and hence this type of boundary condition is adopted for modelling.

With respect to material properties, influential factors are many. Thermal conductivity is the most influential for BHE (Casasso and Sethi, 2014; Han and Yu, 2016). Hydraulic conductivity is of primary importance to account for advective contributions. Thermal dispersivity is of extreme importance when dealing with groundwater fluxes. Nevertheless, the determination of its value is subject to large uncertainties and can be related to the scale of the problem (Sethi and Di Molfetta, 2007). Reported values in the literature range from 0,1 m to 20 m (Casasso and Sethi, 2015; Epting et al., 2013; Molina-Giraldo et al., 2011; Sethi and Di Molfetta, 2007) and are mainly derived from numerical evaluations rather than from dye tracer tests. A typical ratio between longitudinal and transverse thermal dispersivity of 1/10 is here adopted. These values may be used for preliminary analyses or in the case no direct measurements are available in the study area.

Nonetheless, material property values should be then preferentially chosen on the basis of on-site and laboratory tests. As it may be extremely expensive to carry out proper testing on vast areas because of the number of lithologies included in the subsurface volume under examination, numerical calibration can be performed whenever a sufficient amount of monitoring data is available at multiple locations to enhance the accuracy of the model results.

3.3. Site-specific geothermal potential

Besides the temperature field, numerical modelling results in a highly detailed description of the hydraulic regime. To take advantage of these results, a method that accounts for heat transport mechanisms related to groundwater fluxes has to be adopted. As previously mentioned, only a few methods are capable of dealing with advective contributions. Hence an enhancement of the G.POT method developed by Casasso and Sethi (2016) is proposed in the following to account for groundwater flux effects on heat transfer.

Amongst the approaches discussed, the G.POT has the advantage of a strong analytical and theoretical background that makes its explicit formulation not limited to a specific geological or geographical context.

A parametric numerical study was thus carried out for the sake of extending the field of validity of the above-mentioned formulation to hydrodynamic conditions which is described in detail in Baralis (2020).

The original G.POT formulation was modified so that the technical geothermal potential of a Borehole Heat Exchanger can be evaluated taking into account the advective and dispersive contributes as follows:

$$Q_{BHE}[W] = \frac{8\cdot\left(T_0^* - T_{lim}\right)\cdot\Lambda_1\cdot\left[C_{gw}(Pe)\right]^{-1}\cdot L\cdot\frac{t_c}{t_y}}{-0.619\cdot\frac{t_c}{t_y}\cdot\ln\left(\frac{r_b^2}{4\alpha^* t_s}\right) + \left(0.532\frac{t_c}{t_y} - 0.962\right)\cdot\ln\left(\frac{r_b^2}{4\alpha^* t_c}\right) - 0.455\frac{t_c}{t_y} - 1.619 + 4\pi\Lambda_1\cdot R_b}. \tag{1}$$

where T_0* is used instead of T_0 as the background temperature, being T_0* the actual temperature evaluated on the basis of the thermo-hydraulic numerical modelling. The complete list of symbols adopted is reported in the dedicated section. With respect to the original formulation, the extension to hydrodynamic conditions was handled with the use of Λ_1, namely the spherical part of the tensor of the thermal conductivities, instead of λ:

$$\Lambda_1 = \left[(1-n)\lambda_s + n\lambda_f\right] + \frac{\rho_f c v_D(\alpha_L + 2\alpha_T)}{3} \tag{2}$$

Moreover, α* stands for the thermal hydro-dispersive diffusivity of the soil:

$$\alpha^* = \frac{\Lambda_1}{(1-n)\rho_s c_s + n\rho_f c_f} \tag{3}$$

while C_{gw} (Pe) is a hydrodynamic correction factor that was numerically calibrated to not lead to overestimation of the geothermal potential:

$$C_{gw}(Pe) = 0.262\cdot\ln(Pe+1) + 1 \tag{4}$$

where Pe is the Peclet number. Slightly higher values of the correction factor may be adopted by changing the numerically calibrated factor up to 0.27 with respect to the first 20 % of year-round cycles during BHE project life, as a noticeable cumulative effect may happen especially in low to null groundwater velocity conditions.

It should be noted from Eqs. (2) to (4) that in hydrostatic conditions, the formula here presented degenerates in the original G.POT. formulation by Casasso and Sethi (2016). Being based on the ILS model, the application to vertically heterogeneous contexts is pursued by depth-weighted averaging of the parameters as T_0* which has been numerically demonstrated to be a viable solution in Baralis (2020). Depth-weighted averaging also includes the thermal dispersivity, thermal capacity, thermal conductivity, thermal diffusivity, and the Peclet number.

As the analytical formula was derived under constant background conditions, particular attention has to be paid while applying it to time-dependant numerical modelling results. In order to avoid overestimation of the geothermal potential, the extreme temperatures that are expected during the season while a BHE is in operation should be adopted. This is the case of this study, where time-dependant values from transient numerical models were employed.

The applicability of the above-mentioned formulation to hydrodynamic and heterogeneous contexts is of high theoretical and practical importance in the assessment of geothermal potential. Nonetheless, the thermal dispersivity values definition represents a major challenge in real applications due to its difficult measurement. It should be however mentioned that dispersivity values are commonly used in practice to assess the thermal impact of single installations or the evolution of thermal plumes from a variety of sources. This implies that this issue is commonly handled for purposes related to the design of the installation and hence does not represent an additional source of error in the planning. Furthermore, numerical calibration of dispersivity values can be performed in case monitored data are available. In worst cases, a quantification of related uncertainty can be carried out through numerical analysis.

In conclusion, by the adoption of Eq. (1) it is possible to fully take advantage of numerical modelling tools to assess the technical geothermal potential whenever a groundwater flow is present and existing users of the reservoir induce thermal alterations.

3.4. Assessment of the potential impact at the district and city scale

It was previously explained how the shallow geothermal potential can be assessed from numerical results using semi-analytical formulas. In order to assess the role at the city scale that the shallow geothermal energy can play, several results can be given. Temperature maps can be at first reconstructed by interpolation of the results from numerical modelling at several depths.

To the end of best locating new installations, a bunch of indicators may be used like the residual temperature shift, Integrated Relaxation Factor, Satisfaction ratio and the geothermal potential. The geothermal potential can be evaluated by Eq. (1) considering a variable depth value. This information can be resumed in a grid-based dataset that is thus included in map algebra computation. For the sake of consistency with the datasets included in the georeferred database, the grid is aligned with the North direction.

In order to quantitatively define the energy potential of an area, a summation of the single values on each cell of the grid has to be performed. Extreme relevance lies in the choice of the dimension of the raster grid cell. A 7 m by 7 m grid was selected balancing the avoidance of mutual interference amongst virtual BHEs which cannot be handled with Eq. (1) with the need for sufficient geometrical accuracy in an urban area subject to land scarcity issues. Although this value is commonly recognised in literature to minimize interferences (Miglani et al., 2018; Galgaro et al., 2015), in areas where groundwater flux is considerably high, the avoidance of interferences should be further investigated and the cell dimensions enlarged when appropriate. The here presented method does not take into account possible interference

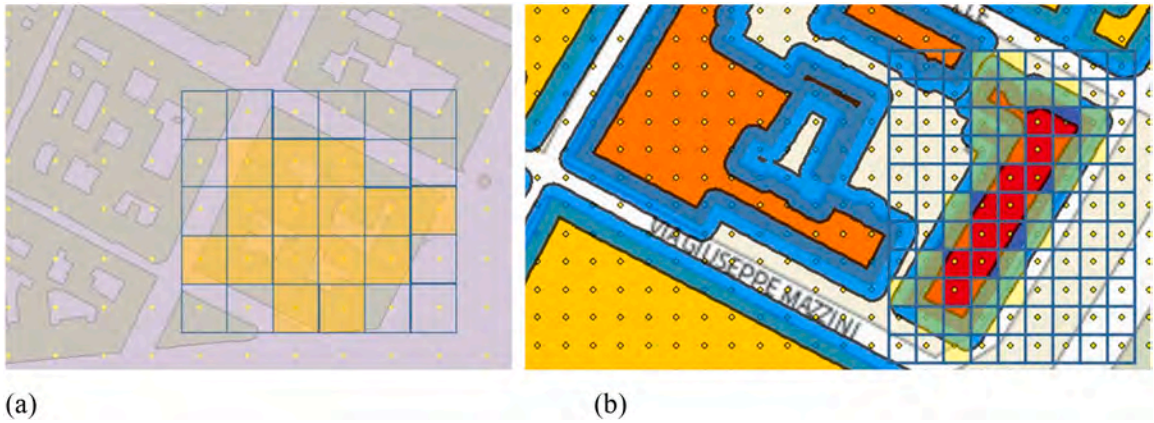

Fig. 3. Allocation of geothermal potential to the appropriate energy user. (a) Squares depicted highlight the cell margins. Highlighted yellow cells that have their centroid within the external perimeter of the buildings are considered as a first approximation scenario. (b) Squares highlight the cell margins with pertinent centroids. The blue area delineates the area considered for BHE installation. The cells highlighted are assumed to contribute to the energy supply of the building.

amongst neighbouring virtual BHEs.

The suitable area for the borehole heat exchanger has to be linked to the single entity that may profit from this energy, namely the target of geothermal energy. The definition of the energy available for the single target unit can be performed analogously to the geothermal potential assessment at the city scale. In particular summation of the value of the pertaining cells has to be addressed. In this scenario, the selection criterion on the installation area is of extreme impact on the quantification of energy availability as well as the definition of the cell dimension. Multiple scenarios can result depending on these choices. To a first approximation cells can be considered to contribute to the satisfaction of the building energy needs in the case their centroid is included within the external footprint perimeter of the construction (see Fig. 3a). A second approach can consider a buffer area around the building perimeter, as already adopted in the literature (Zhang et al., 2015). While the first approach allows to univocally relate a cell to one potential energy user only, the latter may account twice the cells whose centroid is included in the buffer area of multiple building footprints with different users. Furthermore, it should be mentioned that coincidence between the calculated geothermal potential and the city scale potential is not achieved. This is because open and green areas such as streets and urban parks are not taken into account to fulfil the demand. In this study, the cell dimension was set at a value of 7 m based on commonly accepted values. This distance might be further optimised in most cases based on thermal loads and site conditions (especially groundwater flow). Consistently, when using the second approach, the maximum buffer distance of 3.5 m was considered around the perimeter of built units (see Fig. 3b) including also public areas like streets, gardens and internal courts.

In the case of the buffer areas of adjacent buildings partially or completely overlapping, the zone width was locally reduced by taking into account the proximity of the buildings involved not to consider the cells' potential multiple times. This area manipulation was operated in GIS by geoprocessing operations as the creation of Thiessen polygons based on the building perimeter. Based on the above, the first approach might better account for the available energy potential on a cadastral plot and is better representative of possible utilization in the case of demolition and rebuilding. The latter approach, which is instead adopted in the application example of this study, might better represent the achievable energy utilization of existing buildings and thus the potential impact on the energy balance where built heritage has to be mostly preserved.

Once the definition of exchangeable energy has been performed, this is related through the GIS tools to the building or structure entity as an attribute and compared to the energy need of the built environment entity. This allows us to define an easy-to-use indicator of the relative importance of shallow geothermal. On the one hand, the energy need has to be determined by monitoring, energy balance model application or by classification. On the other hand, the energy that is exchanged with the subsurface has to be manipulated to define the deliverable energy to the user, considering a constant value of 4 for the coefficient of performance in heating mode and an Energy Efficiency Ratio of 4.0 for cooling operating mode (Santilano et al., 2016). Thus a satisfaction ratio *SR* can be defined as the energy need of a structure for heating or cooling divided by the geothermal deliverable energy:

$$SR = \frac{\sum_{N}^{1} Q_i \cdot \frac{COP}{COP-1}}{Q_b} \tag{5}$$

where the Qi is the single-cell geothermal potential of the cells whose centroid is included based on the above-mentioned criteria, while Qb is the seasonal thermal load of the building.

The cooling load satisfaction ratio can be accordingly derived by substitution of the COP with the Energy Efficiency Ratio (*EER*).

4. The application of the method to the central districts of the Turin metropolitan area

For the sake of demonstrating its applicability, the theoretical method described above was applied to the specific context of the central districts of the city of Turin (Italy). The city has been experiencing extreme interest in shallow geothermal energy (Lo Russo and Civita, 2009; Lo Russo et al., 2011; Barla et al., 2015). Thanks to the presence of a very productive shallow aquifer, an exponential growth in the number of open-loop systems was documented indeed (Barla et al., 2018).

The Turin metropolitan area lies on the narrow portion of the western Po plain, northwestern Italy, and extends over 130 km^2. The central districts of the city are located on a level area enclosed by the rivers Stura di Lanzo, Sangone and Po. This latter surface water body acts as the main discharge axis and separates the plain sector from a hilly area made up of Pleistocene marls and sandstones representing the low reliefs of Monferrato. The geological setting of the plain area is rather well-known thanks to numerous borehole drillings and the experience gained with multiple deep foundations and urban tunnel projects (Barla and Barla, 2005; 2012).

The major part of the city is located on the lowest portion of the Dora Riparia River alluvium fan. The altitude of the urban area is comprised between 270 m a.s.l. and 220 m a.s.l. (Bottino and Civita, 1986). Important heterogeneity has been documented as a result of the geological origin of the shallowest strata in the area which include coarse fluvio-glacial and fluvial deposits mainly constituted by pebbles, gravel and sand in a sandy-silty matrix in the upper 25–50 m of subsoil. Its heterogeneity is accentuated due to the highly variable degree of cementation. Cemented portions are distributed randomly and originate lenses with the characteristics of conglomerate rock (also known locally by the term Puddinga). The Villafranchiano formation, a succession of lacustrine and fluvial-lacustrine deposits represented by clays and silts locally including gravel lenses whose origin is the Upper Pliocene - Lower Pleistocene and ancient terrigenous succession of marine clayey and fossiliferous sand deposits originated in the Eocene - Middle Pliocene are found below. Cementation in the fluvial-glacial deposits is mainly related to calcareous deposition processes due to water mixing from different origins.

At first, to apply the rOGER method here presented, a study area of about 25.7 km^2 (Fig. 4) was defined and the pertaining GIS project was implemented. A depth of 100 m typical for borehole systems was investigated. A satisfactory detail was achieved as regards the shallower depths up to the base of the shallow aquifer.

The Digital Terrain Model (DTM) of the area and the bottom of the geological units were included in the database. The random distribution of the cementation degree of the shallowest geological unit cannot be described in a deterministic way both from the epistemic point of view (cemented levels are known just by borehole data and from underground open-face excavations) and from the computational effort. The intrinsic heterogeneity at the micro- and meso-scale has to be handled with an equivalent homogeneous approach. This heterogeneity was properly taken into account at the district macro scale by the definition of zones where the cementation degree statistically occurs between 0 and 25 %, 25–50 % and 50–75 % (de Rienzo and Oreste, 2011). In addition to stratigraphy, surface water bodies comprising the study area were included as a dedicated polygon feature shape file in the GIS model.

The creation and management of the georeferred database resulted in the collection of a wide variety of data from the environmental monitoring network of groundwater, aquifer thermal users and surface water bodies. A dedicated survey into public archives and specialized companies allowed us to identify BHE and open loop systems active in the area (a total of 12 open loop system installations were included). BHE users in the study area are not indexed in public archives and so the information is not easily obtainable. However, in the specific area studied, on the basis of the Authors' knowledge BHE installation is limited to a few occurrences, at the time of study, mainly due to the particularly favourable conditions for open loop systems. Also, passive aquifer users were considered, e.g. buildings basements, underground car parks and main underground infrastructures (the railway link urban tunnel and the metro line 1) were considered in the domain area. A second metro line is at the outline design stage at the date of writing and can represent an interesting opportunity for large-scale application of energy geostructures (Insana and Barla 2020; Barla et al., 2021; Barla and Insana, 2023).

Although the data collected are to some extent incomplete the application of the procedure allowed the set-up of numerical analyses able to capture the hydraulic and thermal regime of the area. Representativeness was obtained through numerical calibration and verified against measured data, as later explained.

A finite element numerical model was accurately set up by superimposing the variety of data from the georeferred database (Figs. 5 and 6), constituting the second step of the rOGER method. The commercial FEM code FEFLOW (Diersch, 2009) was adopted to cope with coupled TH transient conditions in three dimensions.

According to the characteristics of the different cemented layers of the fluvio-glacial and fluvial deposits, three different sets of hydraulic and thermal parameters, in line with previous work carried out in the metropolitan area of Turin (Barla et al., 2015), were adopted and are listed in Table 1. Underground anthropic structures (namely tunnels, car parks and building basements) and aquitard layers were considered with isotropic characteristics from the hydraulic point of view.

Transmissivity values adopted for passive users in this study were chosen from the literature and are reported in Table 2.

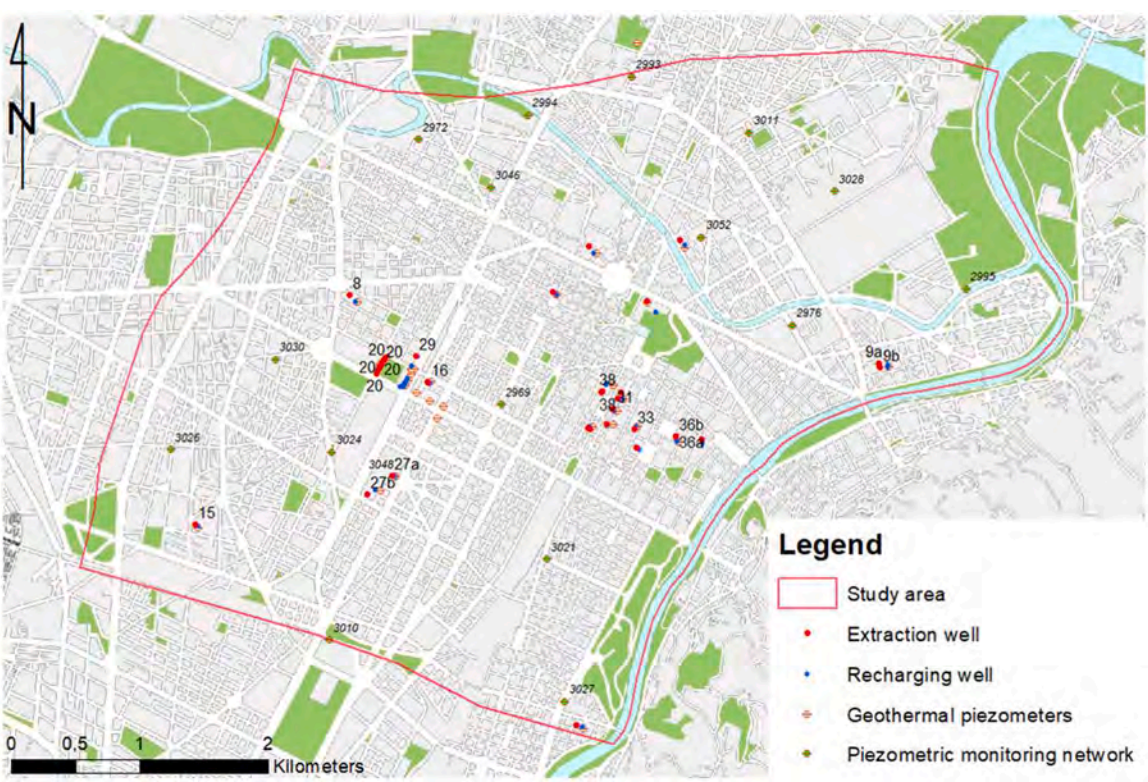

Fig. 4. Location of geothermal wells and relative monitoring points in the study area. Features not labelled refer to installations that are still not active. The piezometers of the metropolitan monitoring network are shown as well.

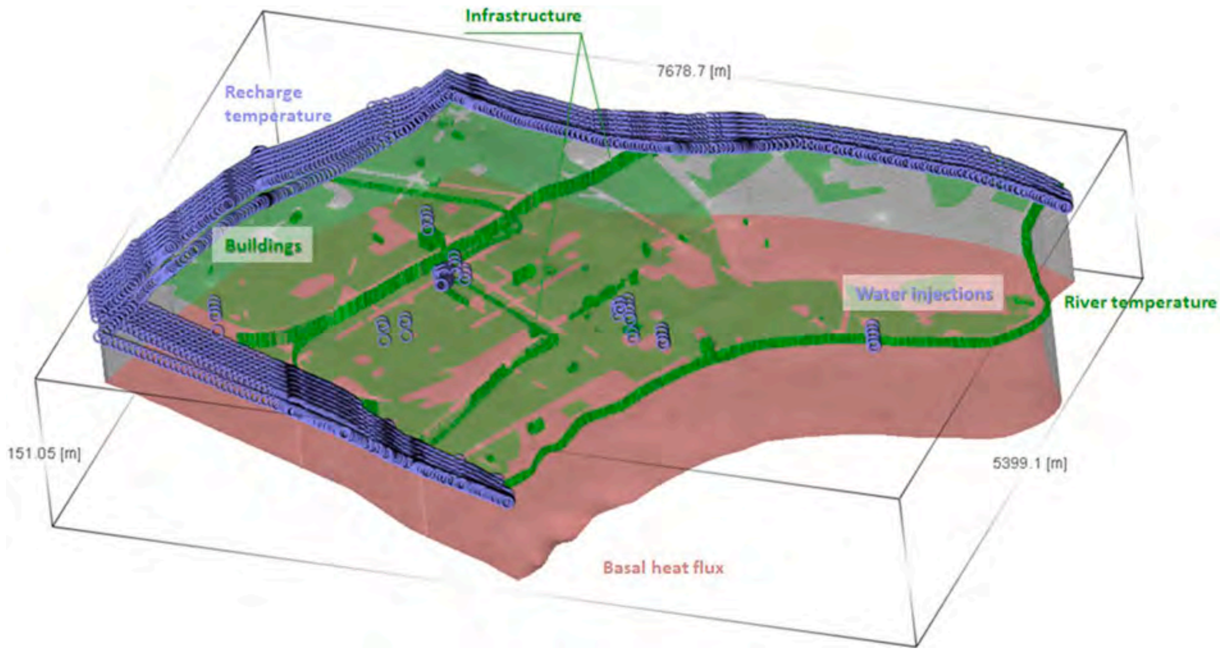

Fig. 5. Thermal boundary conditions. The labels indicate the typology of the thermal boundary conditions. The colours of the labels are associated with the relative boundary conditions.

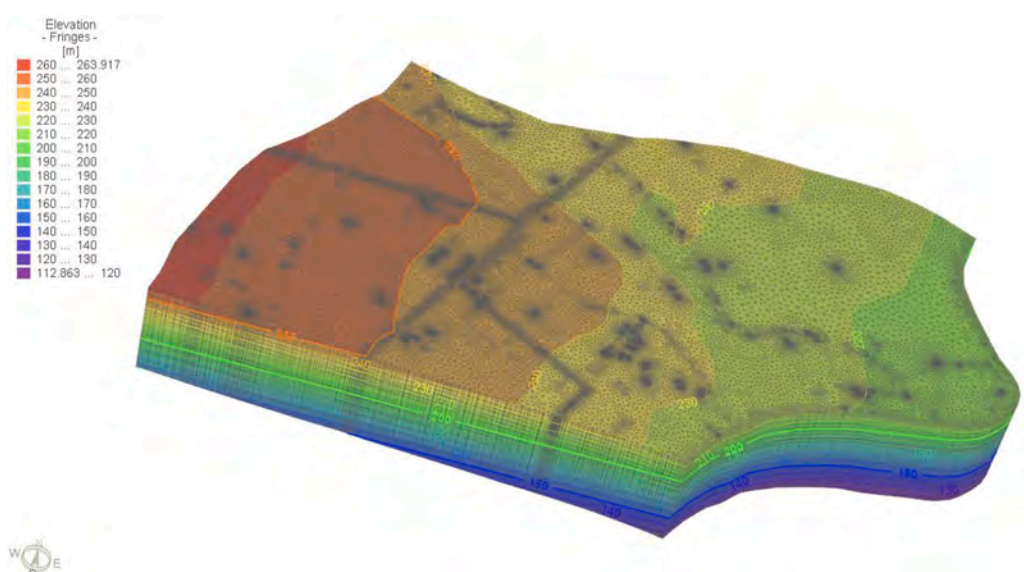

Fig. 6. 3D numerical TH model of Turin central districts. The colour ramp represents the nodes absolute elevation.

Table 1
Turin subsoil material properties adopted for TH numerical analysis. Thermal properties are referred to the solid phase only.

	Zones (degree of cementation)			Aquitard	Concrete
	0–25 %	25–50 %	50–75 %		
Hydraulic conductivity [10^{-3} m/s]	1.93	1.1	0.42	10^{-5}	10^{-13}
Anisotropy ratio	0.05	0.05	0.05	1	1
Porosity [%]	17.5	15	12.5	5	0
Thermal conductivity [W/mK]	2.7	3	3.3	1.7	1.5
Specific thermal capacity [MJ/m^{3}K]	1.8	1.7	1.7	2.3	2.19

Table 2
Thermal transfer parameters. Temperatures of urban tunnels and rivers are defined as range of the data history that is explained in the section devoted to boundary conditions.

	Transfer rate [W/m^{2}K]	Temperature [°C]
Buildings	0.3	15
Underground car parks	0.3	15
Urban tunnels	1.3	7.5 - 29.3
Rivers	0.015	5.0 - 26.6

Dirichlet's transient hydraulic boundary conditions were imposed at the north, west and south borders of the model. Although the main inflow boundary is known to come from the west border, as a precautionary measure the flow was not inhibited at the north and south borders that were chosen parallel to the main known groundwater local flow. Lateral inflows related to the natural slight direction variability of the groundwater field are thus allowed by appropriately fixing the piezometric level. The data histories were exactly imposed at the nearest location to the points of the metropolitan piezometric network. The values were linearly interpolated in all the other locations along the borders. A properly defined Neumann's boundary condition was imposed at the east border, based on the water gauge data measured along the river.

A constant heat flux was assigned at the bottom surface of the domain (see Fig. 5). The basal heat flux value of 0.06 W/m^2 was selected from mapped data at the national level (Consiglio Nazionale delle Ricerche, 2014). This value was assumed to be homogeneous over the domain. Furthermore, the temperature of the recharge water on the north, west and south borders of the saturated zone was assigned with a constant temperature of 14.2 °C. This value was assumed in line with the initial thermal condition and assuming that no thermal alteration is exerted outside of the domain. Although this assumption may result inaccurate at the north and south border, the limited groundwater flow exchange reduces the impact of this assumption. On the contrary, constant and undisturbed groundwater temperatures can be assumed at the west boundary as a result of the relatively high unsaturated thickness and of the setting of the aquifer recharge areas. This assumption is also in line with the monitored data in the area where undisturbed conditions are experienced.

Finally, the upper boundary is assumed adiabatic for simplicity. As a consequence, the model does not reproduce the realistic Y shape of the temperature profile with depth. Although this might seem an extreme simplification, the depth of the aquifer, virtually below the homoeothermic surface, combined with the strong groundwater flux, that flows mainly towards the river Po, i.e. the Western boundary of the model, exerts the main influence on the thermal regime in the area, particularly at the interested depths so that the assumption is not considered to alter the analyses results.

As regards the coupled temperature profiles, the two mentioned main urban tunnels were considered by including an approximation of the measured temperature. A constant temperature of 15 °C was supposed throughout the year in buildings' basements and underground car parks that were fully included in the model as volume entities. Heat exchange with these entities was taken into account by the transfer rate values listed in Table 2.

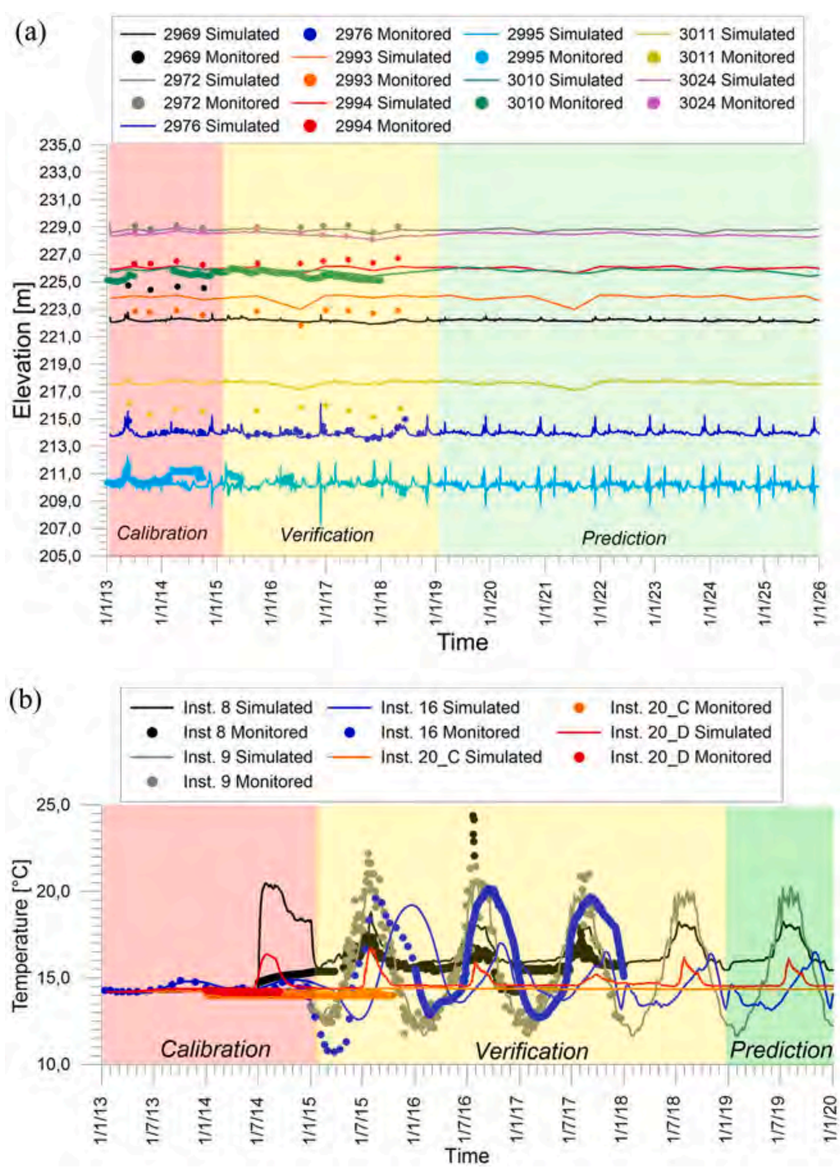

Fig. 7. Results of the numerical model: (a) water table at piezometric monitoring network points, (b) temperatures at geothermal installations piezometers.

The analyses investigated not only the past period when some monitored data were available but also a projection for future times. Past periods included both a calibration and a verification phase. In the first phase, measured data were employed for the calibration of the hydraulic parameters adopted in the model. On the contrary, the second phase allows the verification of the model results accuracy. These phases refer to the past times that constitute the history-matching part of the numerical analyses. In particular, the calibration phase was driven by adopting the PEST utilities (Doherty and Hunt, 2010) based on 23 monitored points where a total of 1676 measurements were available. Values reported in Table 1 represent the initial values for the calibration process of the hydraulic conductivity and fluid transfer coefficients, resulting in 42 parameters to be calibrated. While the pilot point method was adopted for the first class of values, a zone-based approach was adopted for the latter. The objective function resulted to be reduced to 15 % of the original value, while a Normalized Root Mean Square Error of 2.53 % and a correlation factor value of 0.997 were obtained at the end of the process. More details on the calibration process are available in Baralis (2020).

Analysis carried out allowed the prediction of a future scenario. A stable utilization level in the future was assumed to build the scenario in order to define the actual trend of shallow geothermal energy use.

History matching of numerical analysis resulted satisfactory in the major part of the points where real measures were compared. Furthermore, the regime of the water table well corresponds to expectations from previous studies (Civita and Pizzo, 2001). Also, the comparison of temperatures downstream to open loop systems is in most cases more than satisfactory. In some cases, almost perfect matching was achieved (Fig. 7). The good general agreement of thermal data seems to suggest that the numerical model can appropriately capture the thermal and hydraulic regime of the area.

Fig. 8 shows the background temperature to be used in Eq. (1) for the heating season, namely the lowest value during the period referred to the depth-weighted average. Together with the hydraulic dynamic distributions it was then post-processed within the GIS database to obtain indicators of actual level of utilization of geothermal resources.

Geothermal potential calculation was performed thanks to the enhanced version of the G.POT. formula. A standard BHE (double U-shaped pipes) of 100 m length was assumed for the calculation. The characteristic heating operative season of the area was adopted considering an 182-day period (e.g. 15 October to 15 April as by local regulation) on a lifetime of the installation of 50 years. The limit temperature at the inlet was conservatively assumed 0 °C. The resulting values of the geothermal potential are shown in Fig. 9 where high values of up to 26 MWh/y were obtained.

This work contributes to highlighting the best locations for new installations. A system of subsidies could be envisaged to stimulate the appropriate location of new installations considering them as a remedial measure to the current unbalanced situation. It results that the best location within the study area for new geothermal installation is at the confluence of the Dora Riparia and the Po River, where a single BHE can provide up to 2.97 kW.

The energy that can be provided to the user was calculated under the assumption of 95 % efficiency. For the sake of consistency, a COP of 4 was assumed to calculate the deliverable energy. Heat demand was assumed according to the IT.MidClim.AB.05.Gen building typology of the TABULA database (Corrado et al., 2012) that is expected to be representative of the built heritage in Turin. The specific heating load per unit volume of 30.16 kWh/m^{3}y was adopted in this study, considering an average height of 3 m per floor, a rate of 90 % of the building to be conditioned. The cooling demand was not taken into account in this study. This is also due to the fact that this operating mode is less employed in the area with the result that cooling demand is expected to be not sufficiently representative. As cooling demand will play a growing relevance in the frame of global warming also for the areas under study, further studies would be useful to address this aspect and the balance of cooling and heating loads to assess the long-term sustainability of shallow geothermal operations.

The results obtained are mapped in Fig. 10. It can be seen that about 62 % of the built area (representing about 57 % of the volume to be heated) can rely on geothermal energy for the satisfaction of the thermal heating load. Amongst the remaining 38 %, a share of 87.4 % can satisfy requirements for energy supply from renewable sources (that are imposed on new constructions and refurbished buildings by regulation). Energy needs are largely not met virtually only in the case of the tallest buildings in the metropolitan area. From the perspective of optimisation in the use of shallow geothermal resources, these highly demanding structures can be supported by neighbouring buildings that present an energy surplus. This would lead to smart communities and smart thermal grids. In this perspective, the refined assessment of the geothermal

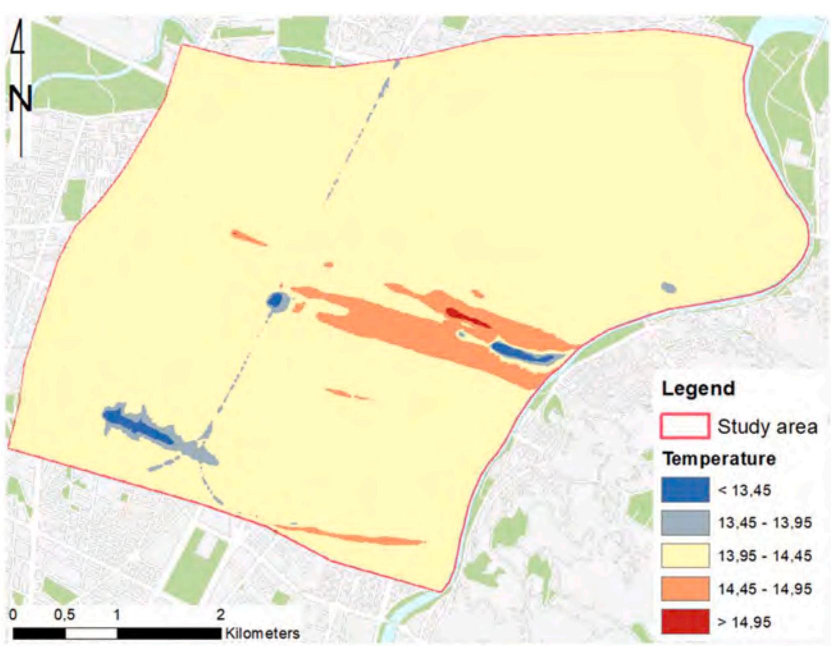

Fig. 8. Background temperature *T0** for the heating season in the study area.

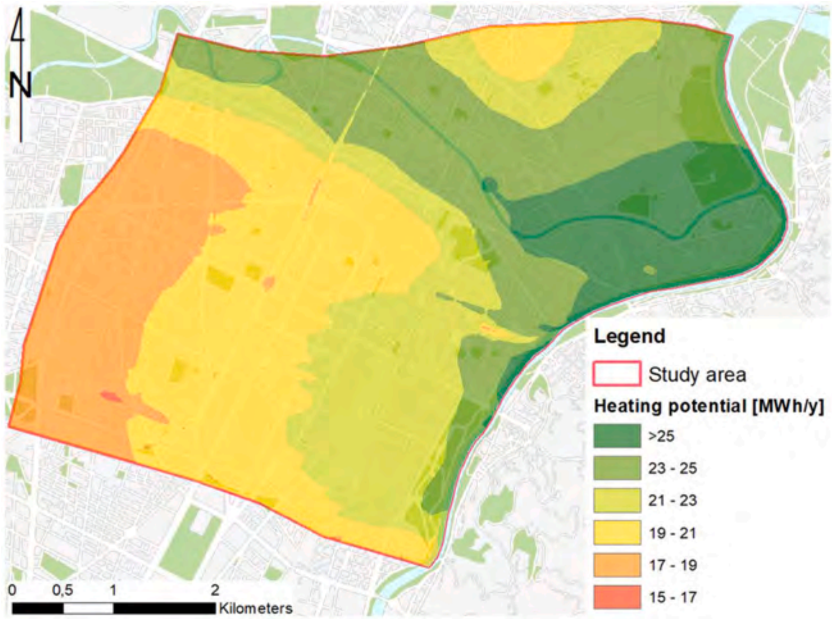

Fig. 9. Site-specific shallow geothermal potential in the study area accounting for groundwater fluxes and borehole heat exchangers of 100 m length.

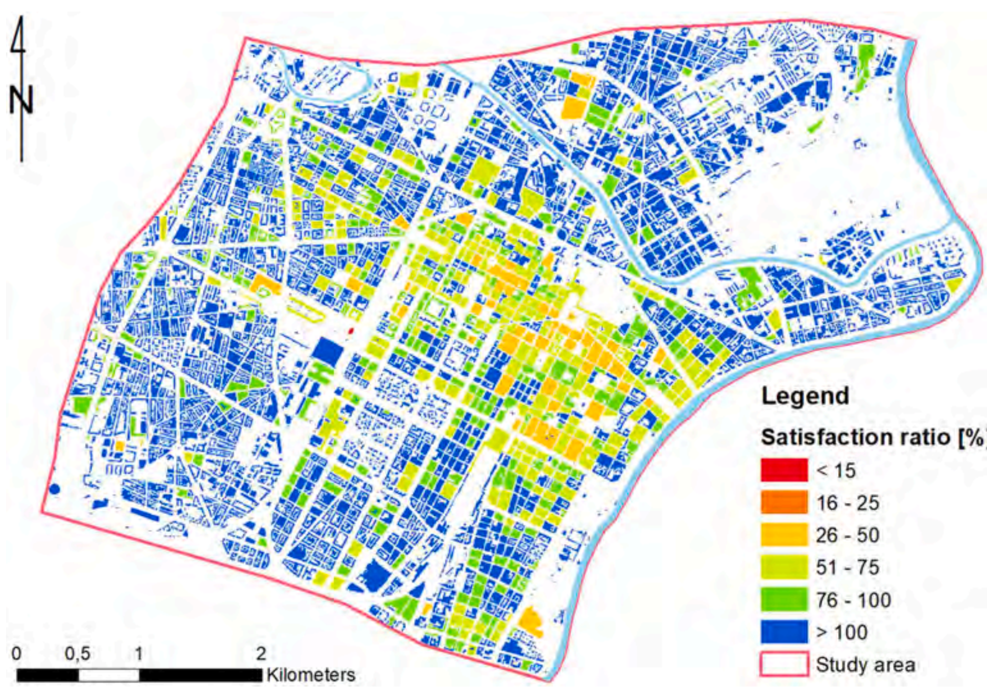

Fig. 10. Satisfaction ratio of the buildings' energy needs from geothermal energy accounting for BHE installed in a band of 7 m around the built perimeter of the built area.

potential would be useful to optimise the number of installations and the grid extension

The example of application described so far for the central area of the city of Turin could be carried out for other urban areas. Provided that a sufficient amount of data is available and collected at the site, the application of the rOGER method could provide city planners with a tool to assess optimal areas for the installation of new geothermal systems as well as manage actual interferences. The data needed and the budget to undertake such studies would generally be balanced and affordable for medium to large cities in Europe. In case the expertise required is not available at the municipality level this can be hired by an intermediary (researcher or consultant). Considering that conditions may vary frequently in a large urban setting, the model should be updated regularly, but there is no need to start the project from scratch every time, reducing the overall costs.

5. Conclusions

Shallow geothermal energy is a renewable, pervasively distributed and stable source of energy. In urban areas, anthropogenic heat fluxes and subsurface structures have the potential to significantly alter the potential natural state. To improve the use of shallow geothermal resources in this context, a novel geothermal potential assessment procedure was proposed to account for the real thermal state affected by anthropogenic groundwater and thermal usage elaborated through numerical analyses. The method can be useful to urban planners and environmental authorities to assess optimal areas for the installation of new geothermal systems as well as manage actual interferences. It was applied to a study area in Turin, Italy, to provide preliminary evidence of the capabilities of the tools developed.

The main conclusions derived so far can be summarised as the following:

- A new analytical method, derived from a modification of the original G.POT. Casasso and Sethi (2016), was introduced to assess the geothermal potential including the dispersive contribution. It is conceived in four main steps and based on the combined use of Geographic Information Systems and detailed numerical three-dimensional models able to account for coupled simulation of hydrodynamics and heat transport.
- The application to the central districts of the city of Turin showed how the method can be used to obtain geothermal potential maps to support rational planning and optimisation of shallow geothermal installations in urban areas.
- In the case of the Turin central districts, it is calculated that the heating demand of up to 57 % of the buildings volume in the area can be completely satisfied by shallow geothermal energy, demonstrating the great potential that can be achieved by exploiting this renewable and locally available energy source. It follows clearly that the massive and rational application of shallow geothermal energy technologies, such as open and closed loop systems as well as energy geostructures, can open new opportunities for developing cities to combat climate change effects and overcome sustainability challenges.

CRediT authorship contribution statement

Matteo Baralis: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Marco Barla:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Marco Barla reports financial support was provided by Politecnico di Torino, Department of Structural, Geotechnical and Building Engineering. Marco Barla reports a relationship with Politecnico di Torino, Department of Structural, Geotechnical and Building Engineering that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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