Department of Environment, Land and Infrastructure Engineering

Master of Science in Petroleum and Mining Engineering

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Master's Thesis in Petroleum Engineering

Evaluation and mapping of shallow geothermal potential in urbanized areas of Turin

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ABSTRACT

Geothermal energy is considered as a promising renewable resource, which has valuable advantages for both energy sustainability and environmental conservation. When the internal heat of the Earth is harnessed, a stable, low-emission alternative to conventional fossil fuels is provided by geothermal systems. This research focuses on the low-enthalpy geothermal potential of the Turin aquifer and optimization of groundwater heat pump (GWHP) operations in a way that the sustainable management of aquifer resources are ensured.

This study uses advanced Geographic Information System (GIS) techniques to spatially manage the hydraulic parameters of the aquifer such as hydraulic conductivity, hydraulic head, and aquifer base. Also, a QGIS plugin called Smart-Map is used to enhance the spatial accuracy of these parameters. This plugin takes advantage of the Kriging interpolation method, in which high-resolution spatial datasets are generated that are essential for precise modeling and analysis.

The study applies three distinct methodologies to calculate the maximum sustainable flow rate from the aquifer: Thiem's approach, Cooper and Jacob's approach, and Darcy's approach. In Thiem's method the parameters are directly substituted into a logarithmic equation to evaluate the flow rate. On the contrary, in the Cooper and Jacob's method a quadratic equation should be solved, that requires the discriminant calculation and the identification of a physically meaningful root. Finally, in the Darcy's approach the flow rate is estimated by calculating the total groundwater flux passing through a given cross-sectional area, based on Darcy's law, which assumes that all water moving through the area can be abstracted, often leading to overestimated values.

Besides the calculations of flow rate, in this research the potential energy transfer between pumped groundwater and external bodies is estimated. The temperature difference between the groundwater and the external environment determines the energy transfer. These calculations highlight the significant role of water's physical properties in determining the potential energy transfer in geothermal systems.

The importance of accurate parameter interpolation and selecting appropriate calculation methods in the management of geothermal resource is highlighted in this research. The findings will lead to a sustainable use of groundwater resources, which promotes utilizing effective geothermal energy and minimizing environmental impacts.

ACKNOWLEDGEMENTS

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1. INTRODUCTION

The European Union has set ambitious and optimistic goals to decarbonize the energy industry and mitigate climate change. These goals include reaching a minimum of 32% share of renewable energy by 2030 and reducing greenhouse gas emissions to 80–95% below 1990 levels by 2050. It is believed that low enthalpy shallow geothermal energy can effectively replace common carbon-based heating and cooling techniques (such fossil fuel burners and air-coupled heat pumps) (Lund and Boyd 2016). Shallow geothermal systems still require energy to extract heat from the soil, but they do it with a lot less electricity and greenhouse gas emissions than conventional heating and cooling systems (Blum, Campillo et al. 2010). It has been demonstrated that the use of geothermal energy in typical residential and commercial buildings in Europe can reduce greenhouse gas emissions by 31% to 88% when compared to conventional heating systems like oil and gas fired boilers and air-coupled heat pumps (depending on the source of the supplied electricity and the efficiency of the installation) (Saner, Juraske et al. 2010).

Italy has already achieved its national target in 2014, with 38.6% of the electricity and 18% of the heat production provided by Renewable Energy Sources (RES) (Energetici 2015), one of the best performances among EU Member States. Efforts should now concentrate on heat generation, where the most regularly used renewable energy sources are ligneous biomass (68.9%) and heat pumps (25.8%), in order to better integrate with Roadmap 2050. Given the detrimental impact biomass heating has on air quality, it seems unlikely that this trend will continue (Herich, Gianini et al. 2014, Pietrogrande, Bacco et al. 2015). Conversely, heat pumps produce no emissions on-site and, depending on the energy mix used to produce electricity, can reduce greenhouse gas emissions from fossil fuel burners by up to 90% (Blum, Campillo et al. 2010, Saner, Juraske et al. 2010). In Italy, about 60% of the total production of electricity is covered by fossil fuels, with an emission factor of 326.8 g CO_2/kWh (Caputo and Sarti 2015) . The consequent reduction of CO_2 production is of about 50% compared to a methane boiler (Casasso and Sethi 2017) .

Furthermore, despite their high initial investment costs, low enthalpy geothermal systems have shown to be the most economical cooling alternative for a variety of structures (Self, Reddy et al. 2013).

Over the next ten to fifteen years, there will likely be a significant increase in the use of GSHPs, which has been steadily rising in recent years (Italiana 2011, Antics, Bertani et al. 2013). It is commonly known that the high installation costs are a barrier to more heat pump installations overall and especially for geothermal heat pumps. The high cost of power for home use is another significant obstacle in Italy. As a result, heat pumps generate a smaller savings margin over fossil fuel-fueled boilers as compared to other nations. In order to address the issue of increased installation costs, a substantial tax refund of 65% has been introduced for energy retrofit projects on existing buildings, which includes GSHPs (ENEA 2011). The fact that most EU nations still know very little about shallow geothermal energy technology and potential is a last issue. In order to spread awareness about GSHPs, several EU-funded projects have been carried out recently, including training sessions, workshops, and case studies (Giambastiani, Tinti et al. 2014, Somogyi, Sebestyén et al. 2017). These initiatives increased the various stakeholders' understanding of the potential uses for shallow geothermal energy (Casasso and Sethi 2017). However, as it depends on site-specific factors and the technology used, the suitability of various territories for GSHPs needs to be investigated on a modest scale (Casasso and Sethi 2014). Geothermal potential, which is defined differently but generally refers to the ground's or aquifer's ability to supply heating and/or cooling, is a widely used indicator (Lo Russo and Civita 2010, Gemelli, Mancini et al. 2011, Busoni, Destro et al. 2012, Di Sipio, Galgaro et al. 2014, Galgaro, Di Sipio et al. 2015, Casasso and Sethi 2016).

Integrating geothermal energy use in both urban modern notions of subsurface space management requires an understanding of the geothermal potential (Bayer, Attard et al. 2019).

This thesis's main goal is to evaluate and quantify the shallow geothermal potential in Turin's urbanized area, with a particular emphasis on figuring out the groundwater's sustainable flow rates in the area. In order to have sustainable and efficient energy, geothermal energy systems have to be installed successfully, and this evaluation is critical to that process.

By combining and evaluating the important hydrogeological factors, such as hydraulic conductivity, hydraulic head, and aquifer base, the study tries to give a detailed understanding of Turin's geothermal resources by using advanced spatial analysis tools. This requires the evaluation of the potential of the shallow geothermal systems as well as considering the limitations to be insured that their applications is beneficial and realistic for the energy plan of the region.

In the research several techniques are contrasted and confirmed for the estimation of groundwater flow rates. The study also seeks to develop the field of geothermal energy by providing insights into the most reliable ways for geothermal potential evaluation.

By assessing the geothermal measurements, the main goal is the promotion of sustainable energy approaches and also looking for more efficient and ecologically friendly energy options.

2. GSHP TECHNOLOGY

Usually concentrated on the upper hundreds of meters, shallow geothermal ground and groundwater utilization is implemented as both closed-loop and open-loop systems (Huang 2012, Stauffer, Bayer et al. 2013, Rees 2016) (Fig 1). These geothermal applications mostly use subsurface energy extraction to power heat pumps and supply buildings' heating systems (Bayer, Attard et al. 2019).

Low enthalpy shallow geothermal systems can be subdivided into two main categories: (Previati and Crosta 2021)

- **Ground-coupled heat pumps (GCHP–Closed-Loop):** The heat transfer fluid moves in a loop buried in the earth that it is not in direct touch with. The piping material is where heat transfer with the ground happens (Previati and Crosta 2021). Systems consisting of a ground source heat pump (GSHP) and horizontal ground heat exchangers (GHE) (Fig. 1a) are typically installed in the framework of individual homes and are quite shallow (< 5 m depth). The vertical borehole heat exchangers (BHEs, Fig. 1b) on GSHPs allow access to depths ranging from several hundred meters to tens of meters. These are the most widely used technological variations, which can be applied to one or many BHEs. Vertical heat exchangers integrated into foundation piles, known as energy piles (Fig. 1c), are only encountered in newly constructed buildings. Aquifer thermal energy storage systems (ATES) function wells, whereas borehole thermal energy storage systems (BTES) are closed-loop applications of several BHE fields (Fig. 1e, f) (Bayer, Attard et al. 2019).

- **Groundwater heat pumps (GWHP–Open-Loop):** By going through the heat exchanger directly, the heat is transferred with the groundwater. The water is returned to the aquifer or surface water bodies following the heat exchange (Fig. 1d, f) (Previati and Crosta 2021). The majority of installations in shallow aquifers are based on a well-doublet design, which consists of an extraction well that extracts groundwater and an injection well that re-injects warmed or cooled water at a different temperature into the same aquifer at the same rate. Usually, the wells are not deeper than 50 meters (Banks 2012, Stauffer, Bayer et al. 2013). The slow heat transmission in porous medium limits natural replenishment, which is necessary for an installation that constantly draws energy from the ground. In addition, heat advection brought on by groundwater flow can both spread and quicken the replenishment of thermal anomalies created in the earth. A hybrid system that uses shallow geothermal energy for both heating and cooling is the best one.

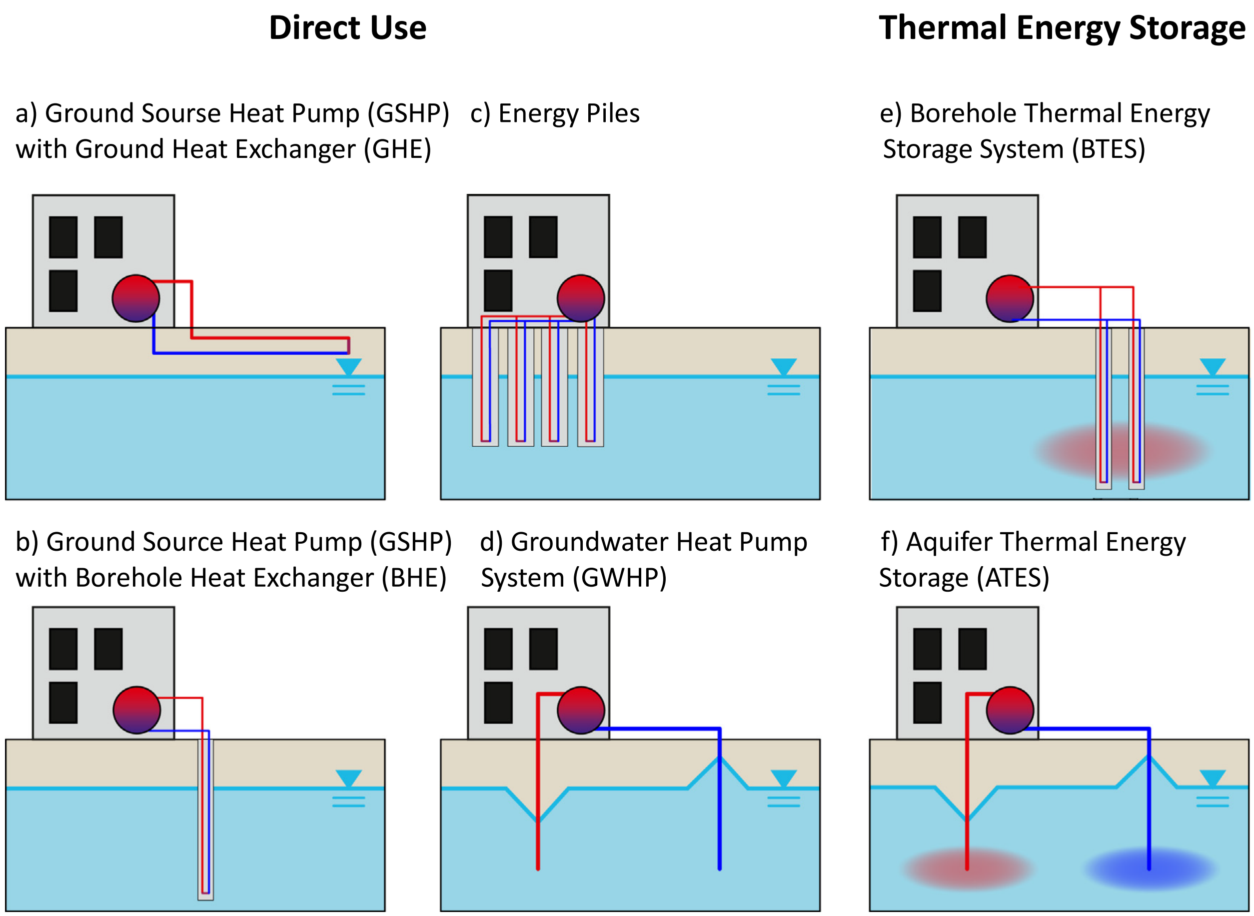


Fig. 1. Technological variants of shallow geothermal use in urban aquifers (Bayer, Attard et al. 2019)

3. CASE STUDY

Turin is the capital of piedmont region and is, located in northern part of Italy. With a total area of roughly 169.191 km² (Fig 2), this region hosts 843,514 people (mean population density: 4,985.57 people/km²). The Po Plain, which underlies the city of Turin, has a notable geothermal potential due to its advantageous hydrogeological circumstances (Gizzi, Berta et al. 2024). The increasing need for sustainable energy solutions is met by the fact that these systems can be deployed for the heating and cooling usage. Turin's geothermal exploration is well-positioned to take advantage of these circumstances for the advancement of energy efficiency and environmental sustainability.

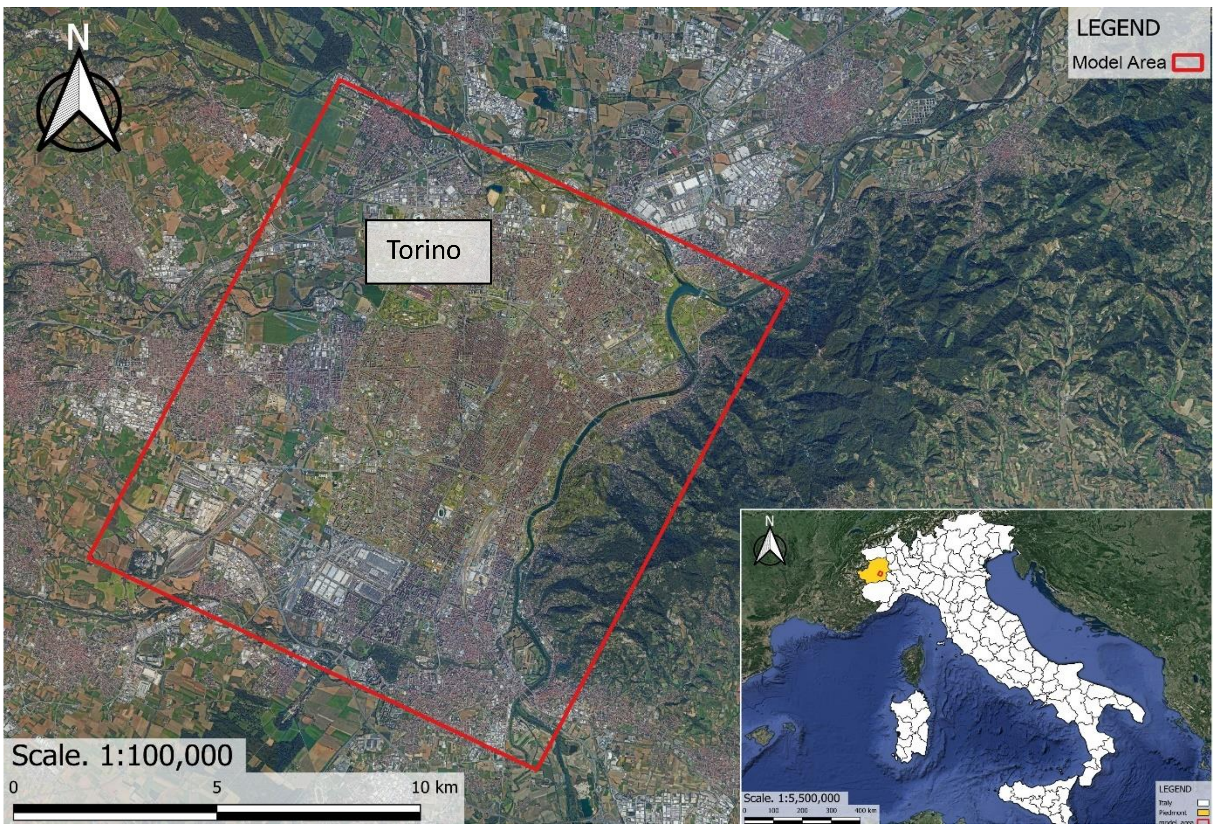


Fig. 2. Area of case study

3.1. CLIMATE

The study area experiences a climate that is shaped by both its orographic characteristics and its location within Italy's continental climate zone. The region experiences distinct seasonal temperature variations, which directly impact interior heating and cooling demands throughout the year.

In the Piedmont region's plains, where Turin is located, the average annual temperature range is approximately between 10°C to 12.5°C. Winters are cold, in which the temperature is close to freezing. In this situation a prolonged heating period is created, which typically starts from October to March. On the opposite, in the summer the temperature reaches over 25°C, necessitating cooling systems in residential and commercial buildings, particularly from May through mid-September.

This seasonal temperature variation defines the heating and cooling cycles for building interiors. During winter, the low temperatures across the Piedmont plains require significant energy for heating, while the warmer summer months drive cooling needs. Overall, the Piedmont region's climate results in one of Italy's higher heating demands, emphasizing the importance of energy-efficient systems for sustainable temperature control.

The Piedmont region's plains are experiencing an increase in temperature of 0.8 degrees Celsius each century, according to a review of historical climate data. The average yearly temperature rose between 1870 and 2010 and between 1971 and 2010 from 12.5 to 13.7 degrees. Moreover, due to the urban heat island phenomenon, temperatures in the Turin region were higher in the city than in the nearby rural areas over the majority of the 20th century (Bucci, Barbero et al. 2017).

More heat is absorbed and re-emitted by man-made structures like highways, buildings, and other infrastructure than by naturally occurring environments like woods and bodies of water. Urban areas create "islands" of greater temperatures compared to surrounding areas because of the high concentration of these structures and the scarcity of greenery. "Heat islands" are the term used to describe these hot spots. Heat Islands have impact on the quality of groundwater, which are the physical, biological, and chemical effects and energy planners and drinking water suppliers have attention on potential and sustainability of shallow geothermal systems (Blum, Menberg et al. 2021) .Due to the effects of heat islands, in the city center the temperature of the groundwater (T_{GW}) is higher and closer to the highest reinjection thresholds (T_{lim}) of 21 degrees, which is for the cooling mode. Thus, the difference of T_{GW} and T_{lim} is lower, and the cooling thermal potential will have a decrease (Previati, Epting et al. 2022).

3.2. GEOLOGY AND HYDROGEOLOGY

Turin Province area consists of three major sectors (with the total area of 6,830 km2): the hilly area, the alpine region, and the plain known as Turin Po Plain. There are four rivers, namely the Po river to the east, the Sangone river to the south, the Dora Riparia river to the west, and the Stura di Lanzo river to the north, that surround the city and stream into the Po River and flow northeastward along the western edge of Turin hill (Lo Russo and Glenda 2009). These waterways significantly influence the city hydrological landscape.

A mixture of sedimentary deposits and alluvial plains characterizes the Turin's geological context, due to the Alpine elevation, that surrounds the city. Quaternary formations are the main focus of the investigation (Fig 3) (Berta and Taddia 2024). The lowlands, which make up the majority, are bounded to the west and east by hills and mountains, respectively.

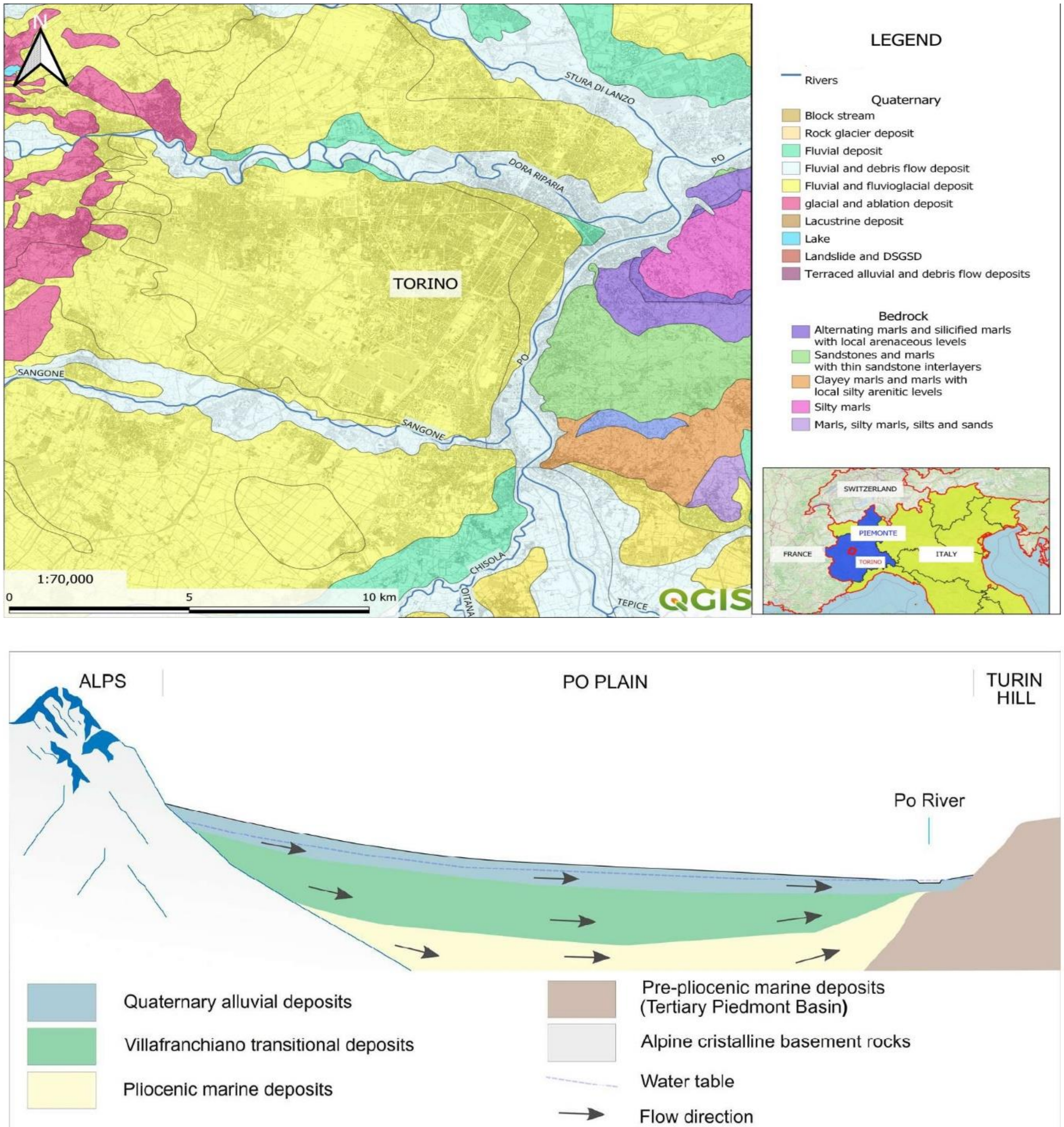


Fig. 3. Geological map of Torino urban area made from ARPA Piemonte geodatabase (De Luca, Lasagna et al. 2020, Berta and Taddia 2024)

Based on the detailed geological analysis that the average thickness of coarse detrital fluvioglacial deposits in the region is about 70 meters. In addition, lacustrine and deltaic formations from the Pliocene–Pleistocene transition are responsible for deposits with finer, more compact features and thicknesses up to 200 m. Furthermore, marine tertiary formations are visible, with thicknesses in the hundreds of meters (Berta and Taddia 2024).

In the subsurface of the Turin Po Plain, four superposed geological and hydrogeological complexes have been identified, varying in terms of the pore sizes and permeability of sediments: (De Luca, Destefanis et al., 2014):

• The highly cemented sediments of the deep pre-Pliocene complex (Eocene-Miocene) are mostly composed of marl, sand, and clay, with gravel occurring only in some areas. Significant aquifers are absent from these layers with unusually low permeability;

• The Pliocene marine complex (Lower-Middle Pliocene) has a fine sandy texture (Sabbie di Asti) or a clayey-silty texture (Argille di Lugagnano). An example of an aquitard is the Argille di Lugagnano, which has poor permeability. The Sabbie di Asti are locally significant aquifers with a fluctuating permeability;

• A multilayer aquifer is formed by the transitional Villafranchian complex (Middle Pliocene-Lower Pleistocene), that consists of alternating clayey silt, sand, and minute gravel. In the mentioned aquifer, the gravelly and sandy permeable layers form significant semi-confined aquifers.

• Coarse gravel and sand with minor clayey silt form the surficial fluvial complex (Middle-Upper Pleistocene and Holocene), which show a generally high permeability; The water table in this complex, being a significant shallow aquifer is strictly linked to the surficial hydrographic network; The sediments of the Po Plain create a continuous, highly permeable porous substrate supporting multiple groundwater systems. Traditionally, the hydrogeology of the area is described in terms of one shallow unconfined aquifer and several deeper confined aquifers (De Luca, Destefanis et al., 2014). The shallow unconfined aquifer, located within the Late Pleistocene and Holocene units of the surficial fluvial complex, is primarily recharged by the infiltration of rainfall and river water in the high plain sections. The water table ranges in depth from 1 to 50 m, with minimums in the high plain areas, and it generally follows the topographical surface trend. Hydraulic conductivity varies between 1.19×10^{-4} m/s and 4.76×10^{-3} m/s, making this aquifer a significant opportunity for the development of shallow geothermal systems.

The deep confined aquifers are found beneath the continental units, within the sandy intercalations of the transitional Villafranchian and Pliocene marine complexes. These aquifers consist of multiple layers where groundwater circulates primarily in the sandier strata. Recharge occurs in high plain sectors where these units outcrop or where low-permeability intercalations are discontinuous. Shallow and deep groundwater systems are divided vertically by low-permeability early Pleistocene sediments.

Groundwater flow in the Turin Po Plain is significantly influenced by the region's hydrographic network. Groundwater generally flows southeast toward the Po River, the primary regional discharge axis. The low plain sectors act as discharge zones, while the high plain areas are recharge zones. The hydraulic gradient varies across the plain. The hydraulic gradient in the Turin Po Plain's southern sector ranges from 0.1% in the Low Plain to 3% at places like the Alps' edge. A sudden drop in the hydraulic gradient (from 0.6–0.7 to <0.3%) was noted in the plain's central sector. The hydraulic gradient generally decreases in the Turin area south of Stura di Lanzo R. as it moves from the peak of the Dora Riparia River fan towards the Po River. Hydraulic gradient values are highest directly on the High Plain, reaching 1.1%; the hydraulic gradient is approximately 0.4–0.5% close to the Po River. The hydraulic gradient drops north of the Stura di Lanzo River from the High Plain (which is likewise higher than 4.4%) to the Po River, reaching minimal values under 0.5% near the Dora Baltea River confluence.

The piezometric surface closely follows the Po River's course as it moves towards the base level, with an average hydraulic gradient of 0.35% and average runoff directions alternating between northwest-southeast and west-northwest-east-southeast (Berta and Taddia, 2024). In the southeast portion of the Turin Po Plain, particularly the Poirino Plateaux, groundwater flows most frequently towards the Po River. In specifics, groundwater flows toward a small creek (Banna S.) from both the north and the south, which is the most significant draining component locally (De Luca, Destefanis et al. 2014).

The Po River's draining movement significantly impacts groundwater in the Turin Po Plain. In the central region, other rivers such as the Chisola Stream, the Stura di Lanzo River, and the Orco Stream also contribute to groundwater drainage. Groundwater flows with a substantially undisturbed direction at depths of 10–15 meters below the riverbed. The Dora Riparia River generally shows no association with groundwater throughout most of the plain, except near its confluence with the Po River, where it replenishes the groundwater level.

In the urban city of Turin, the water table depth ranges between about 15m to 25 below ground level. Therefore, the aquifer thickness ranges from 15m to 30m (Gizzi, Berta et al. 2024). The unconfined aquifer's average hydraulic conductivity equals to approximately 2.5×10^{-3} m/s and the analysis of well-drilling logs and the aquifer's lithology suggest the effective porosity to be 0.20 (Russo, Gnavi et al. 2014). Due to these features, the shallow unconfined aquifer is considered as an important resource for potential geothermal energy applications within the urban context.

The hydrogeological conceptual model of the Piedmont Plain (Fig. 6), as described by (De Luca, Lasagna et al. 2020), arranges the geological complexes in a stratigraphic sequence from top to bottom. The Alluvial Deposits Complex (Lower Pleistocene-Holocene) lies at the surface and contains the shallow unconfined aquifer within Quaternary alluvial deposits. Beneath this, the Transitional Villafranchian Complex (Late Pliocene–Early Pleistocene) consists of fluvial-lacustrine sediments forming deeper multilayer aquifers. At the base of the model is the Marine Complex (Pliocene), contributing to the deeper hydrogeological structure but lacking significant aquifers due to low permeability.

4. STANDARDS AND REGULATIONS

Because a thermally impacted zone (TAZ) will arise if thermally altered water is reinjected into the exploited aquifer, there may be substantial short-term environmental effects. As a result, especially in highly developed areas, it is frequently required to investigate alternate discharge strategies, such as using surface rivers (Beretta, Coppola et al. 2014, Lo Russo, Taddia et al. 2015). In light of their thermal influence on groundwater resources, it is imperative to guarantee the medium- and long-term sustainable growth of groundwater heat pumps (GWHPs). Thus, the two main objectives of new planning standards and laws must be met: 1) encourage the quick growth of open-loop GWHPs; and 2) protect aquifers over the long run by taking the subsurface's hydrogeological features into account during the authorization and decision-making processes (Berta, Gizzi et al. 2024).

4.1. RENEWABLE ENERGY SOURCES: ITALIAN DEVELOPMENT FRAMEWORK

By 2030, Italy has the intention to obtain 30% of its gross final energy consumption from renewable sources. It is expected that the renewable energy sources cover 33.9% of the consumption of heating sector's energy, up from the current 20%. However, there is a challenge in the accurate measurement of the geothermal heat pump systems distribution, because there is no national inventory and standardized regulations, which leads to fragmented and inconsistent data.

Legislative Decree No. 22 of February 11, 2010 [1], reorganized Italy's regulations on geothermal resource exploration and extraction, defining small-scale geothermal applications as systems with less than 2 MW of thermal power and wells up to 400 meters deep. The first significant step in formalizing and regulating closed-loop geothermal systems was denoted by the decree issued on September 30, 2022 [2]. Moreover, ministerial decree introduced the Thermal Energy Account in 2012, which offers incentives for heating systems upgrading, including those using geothermal energy. Tradable proof of energy savings from efficient cogeneration and renewable energy projects are provided by white certificates (Berta, Gizzi et al. 2024).

Annex 3 of Legislative Decree No. 28 of 2011 [3], implementing the RED Directive, requires new

[1] Gazzetta Ufficiale

[2] Gazzetta Ufficiale

[3] dlgs_03_03_2011_28.pdf (mase.gov.it)

buildings and major renovations to integrate renewable energy sources (RES). Since 2018, renewable energy resources must provide at least 50% of a building's thermal energy for hot water, heating, and cooling. A €500 million fund was established by decree-Law No. 34 of April 30, 2019 [4], to support the projects of municipalities in energy efficiency and sustainable development. The Italian National Recovery and Resilience Plan [5] also prioritizes RES, with goals to meet 2030 targets and improve energy efficiency, including streamlined authorization processes for renewable energy projects.

4.2. GWHPs: THE PIEDMONT REGION STANDARDS AND REGULATIONS

In the Piedmont Region, authorization is required for wastewater discharges. The Article 124 of Legislative Decree No. 152/06 obliges an open-loop system to obtain prior authorization and must respect the water and subsoil protection regulations. The discharge endpoint could be an aquifer or a natural or artificial watercourse. In order to prevent and control the pollution, the standards for the groundwater pollution monitoring at the regional level is established by the Water Protection Plan – PTA [6]. Controlling point and diffuse pollution, which is done by following a clear set of behaviors, the Provincial Territorial Coordination Plan – PTC2 [7] leads to achieve the qualitative and quantitative levels for surface water and groundwater at the provincial level. The sustainable use and water resources preservation at the local level is encouraged by the Metropolitan General Territorial Plan, or PTGM [8] as a heritage and universal right of all living things, as well as an important public good for the environment, social and economic advancement, and the environment. Furthermore, according to paragraph 2 of the Article 29, these authorizations are granted following an investigation that verifies the following: (a) the hydro-chemical and geometric properties of the water body receptor; (b) the morphological changes made to the piezometric surface; (c) alterations in the aquifer's chemistry caused by the evaluation of effects on the thermal and hydro-chemical status; and (d) the impact of any additional geothermal plants that insist on using the groundwater body in the investigation area.

[4] Gazzetta Ufficiale
[5] Ministero dell'Economia e delle Finanze - Ministry of Economy and Finance (mef.gov.it)
[6] Piano di Tutela delle Acque – Aggiornamento 2021 | Regione Piemonte
[7] PTC2 - Piano vigente - Città Metropolitana di Torino... (cittametropolitana.torino.it)
[8] PIANO TERRITORIALE GENERALE METROPOLITANO e relativa VAS - Città Metropolitana di Torino... (cittametropolitana.torino.it)

The Single Environmental Authorization (AUA) was established by Presidential Decree No. 59 on March 13, 2013 [9] in an effort to simplify regulations for small and medium-sized businesses and any facilities that are not included by the Integrated Environmental Authorization (AIA): it combines the environmental authorizations that the industry is needed to have, which the business should have already acquired individually, into one document. Moreover, it is important to confirm that there is no interference between the extraction and discharge wells and that there is no coincidence with nearby facilities. Installing temperature, volume, flow rate, and recording instruments on the intake and discharge of water is required to obtain authorization for plant discharge. It is necessary to compile and submit an annual report that details the monitoring results using graphs and/or tables that illustrate trends over time and the updated thermal plume based on the observed data.

[9] § 5.4.168 - D.P.R. 13 marzo 2013, n. 59. Regolamento recante la disciplina dell'autorizzazione unica ambientale e la semplificazione di adempimenti amministrativi in materia ambientale [...] (edizionieuropee.it)

5. METHODOLOGY

This research mainly focusses on determination of the maximum sustainable flow rate that can be extracted from the Turin aquifer and assessing the groundwater geothermal potential at the same time in the urbanized area of Turin. Advanced Geographic Information System (GIS) techniques is employed in this study, that uses QGIS software, which will be described in the next section, as a basic tool for spatial analysis. The research utilizes the features of QGIS for handling and processing the spatial data, that is related to important hydrogeological parameters, such as hydraulic head, aquifer base, and hydraulic conductivity. These parameters are vital in understanding the aquifer dynamics and are interpolated with a Gaussian process. The prior covariances (Kriging) govern this process, which is a statistical method that enhances the spatial predictions accuracy.

The Smart-Map plugin within QGIS is used in order to facilitate this interpolation. This plugin is integral to the process and allows for the input and manipulation of spatial data layers.

End users face difficulties in the application of machine learning (ML) algorithms because they have lots of variations. In order to solve this problem, the Smart-Map plugin is developed, which uses modern artificial intelligence (AI) tools. The interpolated maps are generated by implementing Ordinary Kriging (OK) and the Support Vector Machine (SVM) algorithm. The SVM model uses Vector and raster layers, which are available at the time of interpolation as covariates. The covariates in the SVM model are selected according to the spatial correlation and is measured by Moran's Index. Five models of isotropic theoretical semivariograms are fit by this plugin: linear, linear with sill, exponential, spherical, and Gaussian. This semivariogram model is selected through a cross-validation method (Pereira, Valente et al. 2022).

Two key statistical indicators help to select the most suitable model: Root Mean Square Error (RMSE) and Pearson correlation coefficient (R^2). The optimal model is chosen for the interpolation process, which minimizes RMSE and maximizes R^2. This step ensures that the spatial representation of the hydrogeological parameters is as accurate as possible, providing a solid foundation for further analysis.

Besides generation of the interpolation maps, Smart-Map has other functionalities such as: performing cluster analyses using the fuzzy k-means method, that yields to Management Zones (MZ) maps (Pereira, Valente et al. 2022).

Following the interpolation, the "Raster Calculator" tool within QGIS was utilized to compute the required parameters for evaluating the flow rates. This tool enables the combination and manipulation of raster data to derive new spatial datasets that are essential for the subsequent analysis.

The application of different approaches is possible by using the calculated parameters, that are involved in estimation of the maximum extractable flow rate from the Turin aquifer.
These approaches will be discussed in detail in the following sections of the methodology, which will provide a comprehensive understanding of the procedures. After reviewing different papers and evaluating various techniques, the Thiem's, Cooper and Jacob's, and Darcy's approaches has been selected as the most suitable methods.

5.1. QGIS

QGIS (Quantum Geographic Information System) is an open-source software, that is used for spatial analysis, especially in hydrogeology and geothermal energy studies. This software is flexible and has a user-friendly interface. Also, it is compatible with external algorithms like SAGA and GRASS that leads to the improvement of its analytical capabilities (Duarte et al. 2021). In hydrogeology, QGIS has been used for mapping the vulnerability of groundwater, while in geothermal energy it helps identifying the areas with high-potential for exploration (Duarte et al. 2019; Elbarbary et al. 2022). In this thesis, QGIS enables the mapping and groundwater data analysis, which supports sustainable resource management.

5.2. KRIGING

Kriging is a Gaussian process modeling technique and is typically applied for spatial interpolation and prediction uncertainty quantification. This modeling is valuable across fields like machine learning and geosciences and is known for its flexibility. Kriging supports detailed spatial analyses that integrate trends observed in datasets. In hydrogeology, kriging is utilized for groundwater level estimation and mapping hydrogeological parameters, which offers improved accuracy rather than traditional methods (Rawling 2022; Pardo-Igúzquiza et al. 2023). In geothermal studies, kriging facilitates pollutant distribution and environmental factors assessment and enables more precise spatial assessments, which is essential in management of sustainable resource (Zhang et al. 2023).

5.3. THIEM'S APPROACH

In 1906 Günther Thiem introduced an analytical solution, which plays a key role in hydrogeology for describing radial flow to a pumped well in the steady-state condition (Henry, Neville et al. 2023). Thiem's analytical solution, based on equations of groundwater flow and Darcy's law principles, is an important concept in hydrogeology and helps the research and practical applications in managing the sustainable groundwater resources. Furthermore, Thiem's analytical solution has importance in other applications, like the examination of the tide-induced fluctuations in groundwater levels in coastal aquifer systems with a submarine outlet-capping (Liu, Chen et al. 2012). Another application of this solution is in investigating the groundwater flow in leaky confined aquifer systems near open tidal water (Tang and Jiao 2001).

Thiem's equation is as following:

$s(r) = \frac{Q}{2\pi T} . \ln(\frac{R}{r})$, where:

- s is the drawdown at the radial distance r (it is the difference of water levels between two wells after the steady conditions have reached),
- T is the homogenous transmissivity of the aquifer,
- R is the radius of influence,
- r is the well radius,
- Q is the constant pumped water flux (García-Gil, Vázquez-Suñe et al. 2015)

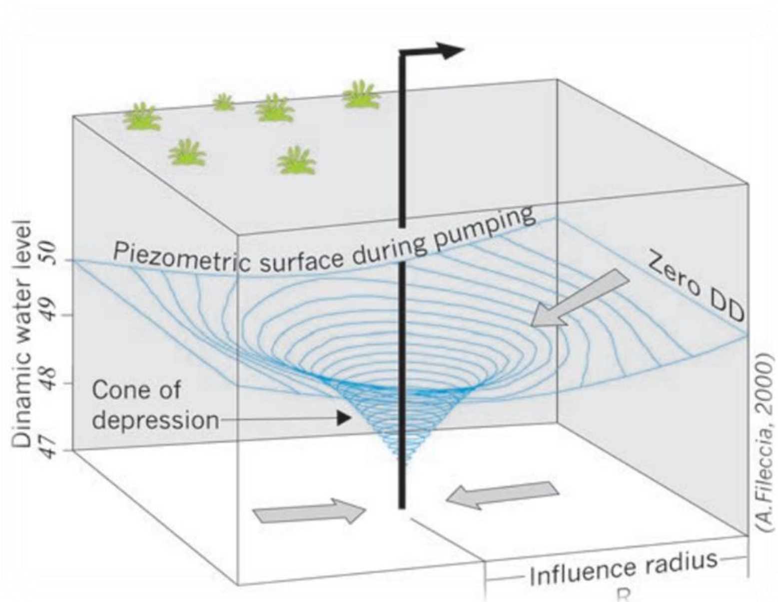


Fig. 4. Section showing depression cone in an aquifer for development of Thiem's approach (Fileccia 2016)

5.4. COOPER AND JACOB'S APPROACH

This approach (equation) determines the aquifer parameters such as hydraulic conductivity, specific capacity, transmissivity, and storativity. In the studies of aquifer, this equation is utilized to analyze the behavior of the groundwater flow. In the situation, where transient expressions are needed for analyzing the borehole, this equation is used (Bennecke 1996). To have an accurate estimation for the characteristics of an aquifer, this equation is applied along with hydraulic head measurements and pump-out test data (Bahrami, Ardejani et al. 2016). Furthermore, in the Cooper and Jacob's method, which is a simplified model of the Theis solution, specific aquifer conditions are assumed for its application, like a confined, isotropic, and homogeneous aquifer with infinite extent (Twining, Maimer et al. 2021). Researchers modify and adapt this equation in different studies to meet specific research needs. For example, improved straight-line fitting methods have been proposed to analyze the recovery data of pumping test based on the Cooper and Jacob's equation (Zheng, Guo et al. 2005). Moreover, this equation develops an iterative method to enhance the reliability of aquifer transmissivity estimations (Richard, Chesnaux et al. 2015).

The equation of Cooper and Jacob is as following :

$s_w(Q) = \frac{Q}{4\pi T} . \log (2.25\frac{Tt_{pump}}{Sr_w^2}) + CQ^2$, where:

- s_w is the drawdown,
- T is the transmissivity of the aquifer,
- t_{pump} is the pumping time,
- r_w is the well radius,
- C is the coefficient of the quadratic term of the Rorabaugh equation,
- Q represents the flow rate of the well.

In 1947, a model was introduced by Jacob, where well loss is proportional to the square of the discharge rate: CQ^2 (Jacob 1947). In this mathematical representation C is the coefficient of the non-linear well-loss, and CQ^2 stands for the non-linear component known as "well loss."

Rorabaugh (Rorabaugh 1953) refined later the Jacob's model, in which a more general expression was introduced by replacing the fixed exponent of 2 with a variable exponent "p", greater than 2. The value of "p" typically is between 2.4 and 2.8, with an average value of 2.5, as Rorabaugh reported. In the model of Rorabaugh, the coefficient of well-loss (C) and the exponent "p" correlate with each other. By applying an extensive dataset, the relationship between these parameters has been analyzed in detail. A strong correlation between these parameters is shown using the semi-logarithmic plot of p values versus C values (Fig 5). This analysis is a challenge for assuming a constant p in Jacob's model.

The relationship between the parameters is expressed by the equation:

$p = 0.2315 . \ln C + 0.5838$, where C is measured in s^2/m^5.

In the study the amount of "p" is considered to be equal to 2 and the amount of C is 1900 s^2/m^5.

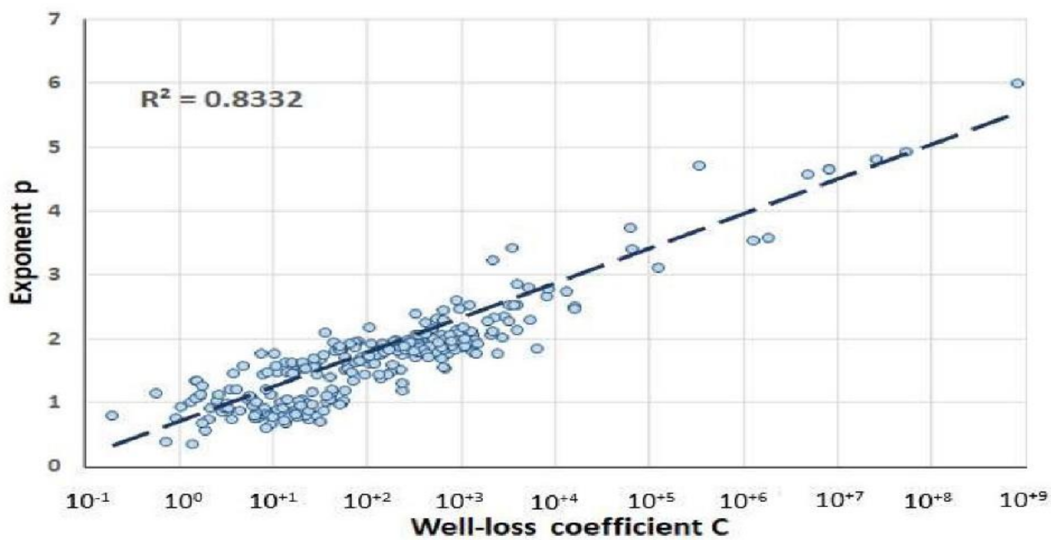


Fig. 5. Plot of the exponent p values vs. Well-loss coefficient C values (Kurtulus et al., 2019)

5.5. DARCY'S APPROACH

Henry Darcy developed a law in 19th century, which is a fundamental principle in fluid mechanics and is used for the description of fluid flow through porous media. Darcy's law explains that the volumetric flow rate of a fluid relates to the permeability of the medium and the negative pressure gradient.

The equation is as the following :

$$Q = -k \cdot A \cdot \frac{\Delta P}{L}$$

Where,

- Q is the volumetric flow rate (given in m^3/s),
- k is the permeability of the material,
- A represents the area of the cross-section that the fluid flows through,
- ΔP is the pressure difference,
- L is the length, in which the pressure drops

This law respects some assumptions such as: laminar flow conditions and is used mainly in the situations where there is low flow velocity and the fluid is incompressible (Dejam, Hassanzadeh et al. 2017)

In hydrogeology, Darcy's law is utilized for modeling the groundwater flow through aquifers. For instance, for estimation of the aquifers hydraulic conductivity this law is utilized, which is crucial for resource planning and management of the groundwater. The application of Darcy's law in modeling the hydrology of the hillslope is shown in a study by Rosso et al. In this study, Darcy's law describes the seepage flow and its impact on slope stability (Rosso, Rulli et al. 2006). Through this application, the movement of water through the layers of soil and rock is understandable. This movement influences both the recharge of the groundwater and surface water interactions.

Modeling of the intrusion of saltwater in coastal aquifers is another example in hydrogeology. In Yao's study, Darcy's law is used for simulation of the saline water movement into freshwater aquifers (Yao and Zhang 2023). Through this simulation, hydraulic gradients and permeability is understandable, which is vital in freshwater resources management in coastal regions. This application is mostly used in the areas, where the level of salinity is increased due to the extraction of groundwater and consequently the quality of water is affected.

In geothermal studies, Darcy's law is used to understand the heated fluids flow through geological formations. For example, in a study conducted by Ahmed and Ali, to analyze the hydromagnetic flow in heated porous channels a modified Darcy-Forchheimer law was applied, which is related to geothermal energy extraction processes optimization (Ahmed and Ali 2019). To enhance the geothermal systems efficiency and predicting their performance under various operational conditions, modeling the fluid flow accurately in geothermal reservoirs is an essential matter. Moreover, other alternative models have been developed due to the Darcy's law limitations in high-velocity flow conditions. The Darcy-Brinkman formulation is an example, in which the viscous effect in porous media is included and is beneficial in geothermal applications, where the fluid behavior is strongly affected by temperature gradients. A better understanding of fluid dynamics in complex geothermal systems is possible by this adjustment (Golfier, Lasseux et al. 2015).

Darcy’s law is also defined as :

$$Q = \frac{K \,.\, b \,.\, L \,.\, hydraulic\ gradient}{porosity}$$

Where,

- Q denotes the volume flow rate (given in m³/s),

- K is the hydraulic conductivity (m/s), which accounts for the permeability of the medium and the fluid properties (such as viscosity and density),

- b is the aquifer thickness (m),

- L is the horizontal length of the flow path (m),

- Hydraulic gradient is the change in hydraulic head per unit length, $\frac{\Delta h}{\mathrm{L}}$

- Porosity (n) is the fraction of the porous medium's volume that is void space and can transmit fluid.

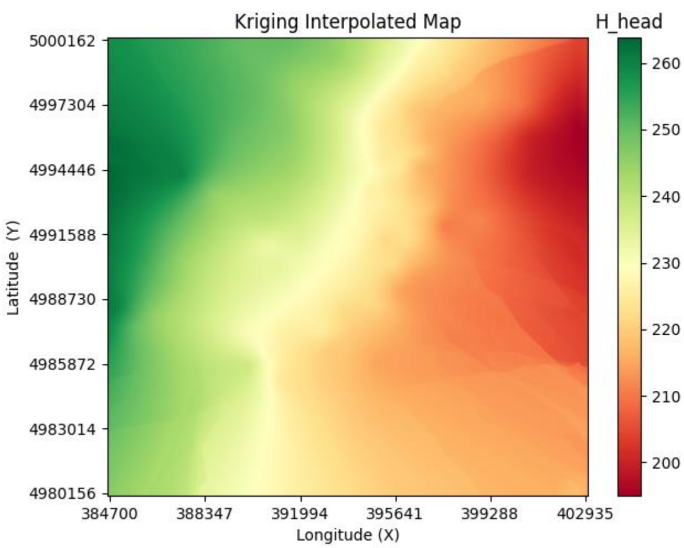
This formula is also applied in hydrogeology in order to determine the extent of water, moving through an aquifer or groundwater system. This equation is useful for estimation of the sustainable groundwater amount, pumped from a well or aquifer without depleting the resource. In this study, where heat is extracted or injected by the groundwater, the formula can be beneficial in determination of the water amount, which flows through the system and can also calculate the potential energy transfer, which is key for the geothermal potential assessment of the site.

6. RESULTS AND DISCUSSION

Three different approaches, namely Thiem, Cooper and Jacob, and Darcy were employed for the flow rate determination. In each of these approaches, a specific equation with its own set of variables is utilized. Although there are differences between the equations, some variables are common to methods. The drawdown, which is has a constant value of 0.5 meters, well radius, that is equal to 0.25 meters, and transmissivity, which is calculated as the product of hydraulic conductivity and the thickness of the aquifer, are the common parameters across approaches.

The interpolation of log K values result in the hydraulic conductivity, where K represents the hydraulic conductivity. Due to the small values of K, that show poor correlation when interpolating, for obtaining more reliable estimates the logarithmic values of K are used. As discussed in the Methodology section, this interpolation is done by the Smart-Map plugin, which enhances the spatial accuracy in the log-transformed hydraulic conductivity data.

In addition to hydraulic conductivity, the datasets for hydraulic head and aquifer base are also interpolated (Fig 6), allowing for a more precise calculation of aquifer thickness.



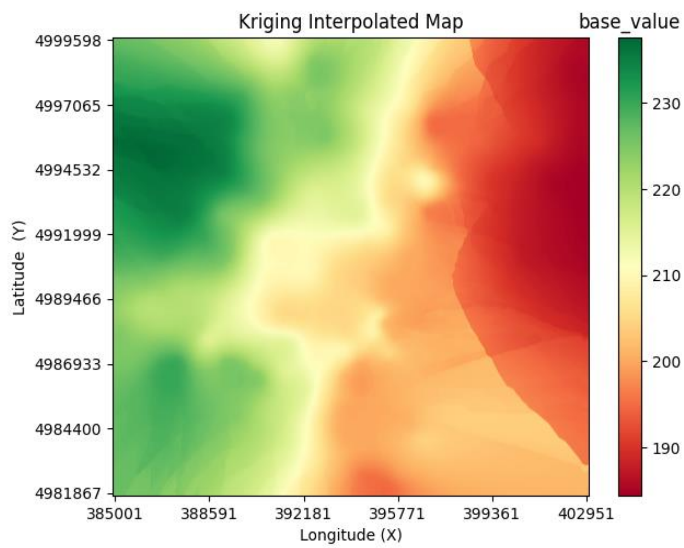


Fig. 6. Hydraulic head interpolated map

Aquifer base interpolated map

The best fit for the parameters of Hydraulic Head, Aquifer Base, and Hydraulic Conductivity are gaussian, linear, and spherical model, respectively (Fig 7-9).

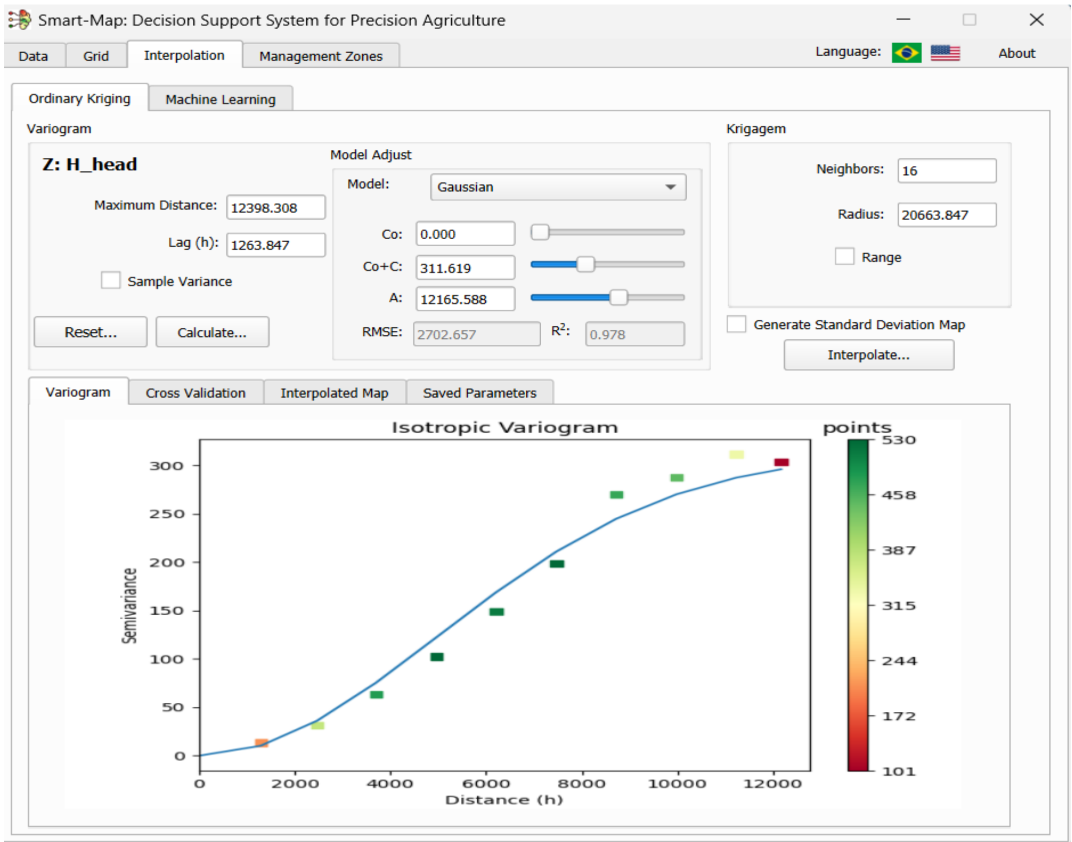


Fig. 7. Best fit for hydraulic head: Gaussian model

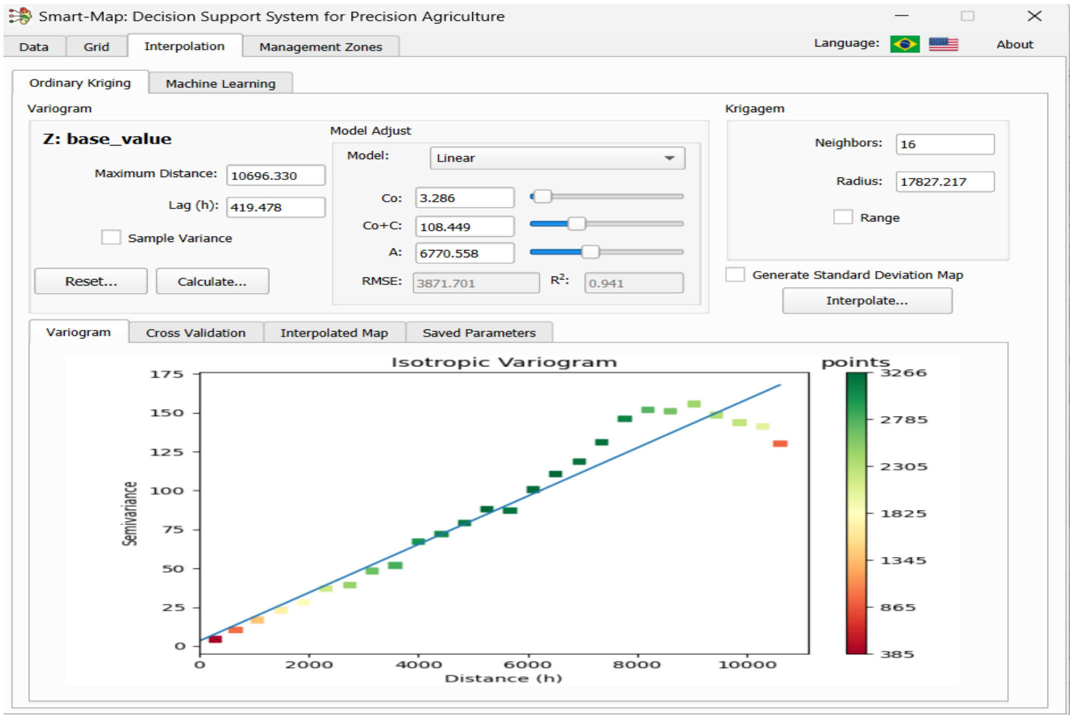


Fig. 8. Best fit for aquifer base: Linear model

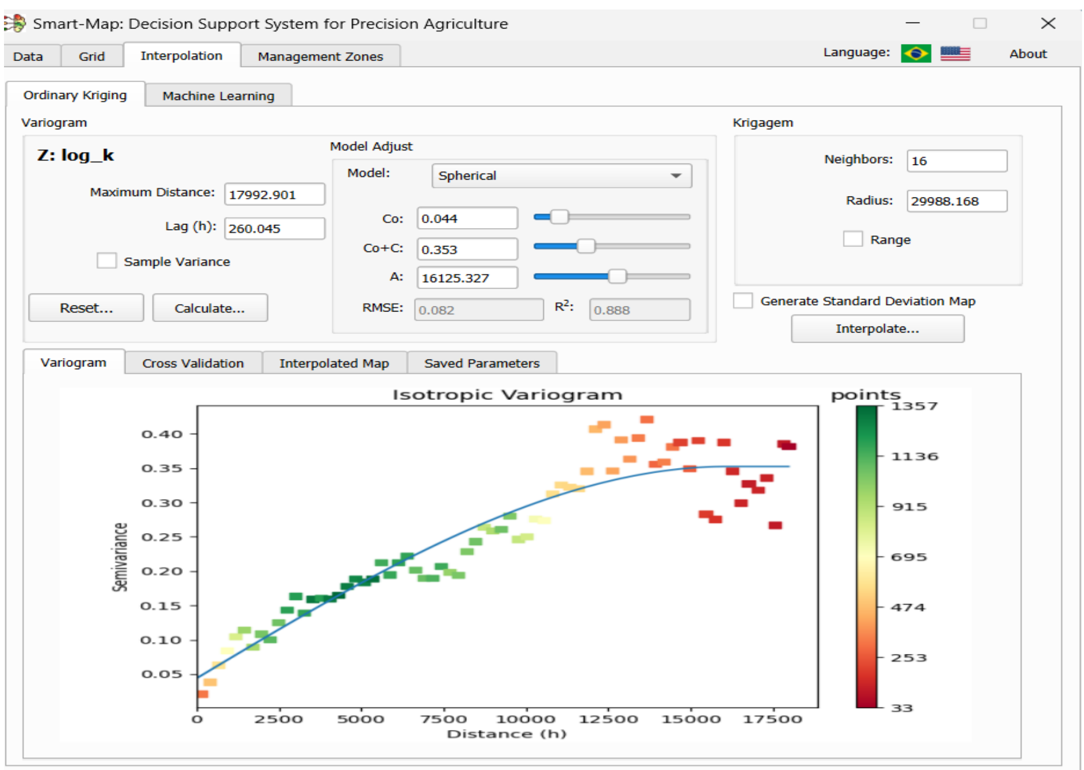


Fig. 9. Best fit for hydraulic conductivity: Spherical model

The thickness is determined by calculating the difference between the interpolated values of the hydraulic head and the aquifer base (Fig 10). All these calculations, including the interpolation and subsequent derivation of transmissivity, were carried out using the Raster Calculator tool in QGIS.

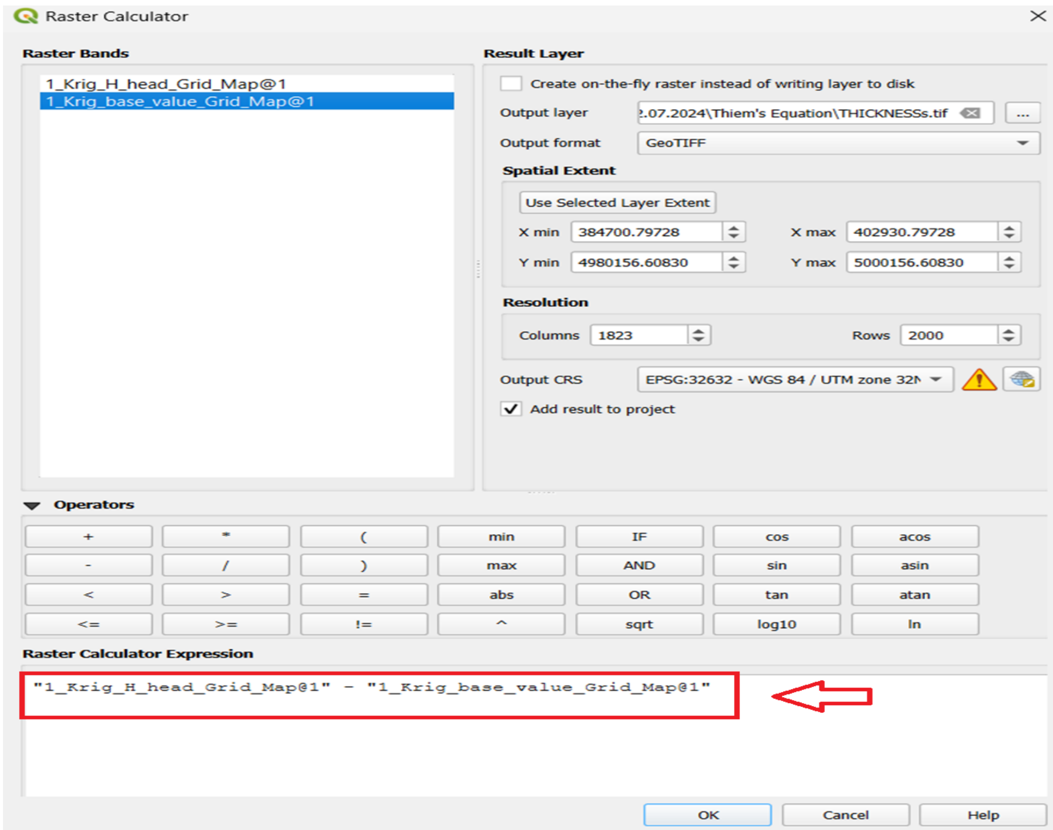


Fig. 10. Calculation of thickness using raster calculator

6.1. THIEM'S APPROACH

For Thiem's approach, the equation utilized is: s(r) = $\frac{Q}{2\pi T}$. ln ($\frac{R}{r}$). For the flow rate calculation, the equation is modified into Q = $\frac{s(r)\ .\ 2\pi T}{\ln(\frac{R}{r})}$. For solving the equation some parameters are needed. S(r), the drawdown, is fixed at 0.5 meters. Transmissivity (T) is the result of the multiplication of hydraulic conductivity and aquifer thickness, calculated using the Raster calculator. The range of the transmissivity values for the study area is between 9.76×10^{-4} to 11.29×10^{-2} m²/s, which reflects the variability in the properties of the aquifer.

The radius of influence, R, has the constant value of 50 meters, representing the distance over which the drawdown effect extends. Also "r" represents the radial distance from the well and is equal to 0.25 meters.

These values are substituted into the equation and the calculations within the raster calculator in QGIS are applied (Fig 11). Then a spatially distributed raster file is generated, which shows the flow rate across the model area. The flow rate will result in the range between 0.579 and 66.95 lit/sec, representing the variability that occurs in extraction of groundwater in the region of study (Fig 12).

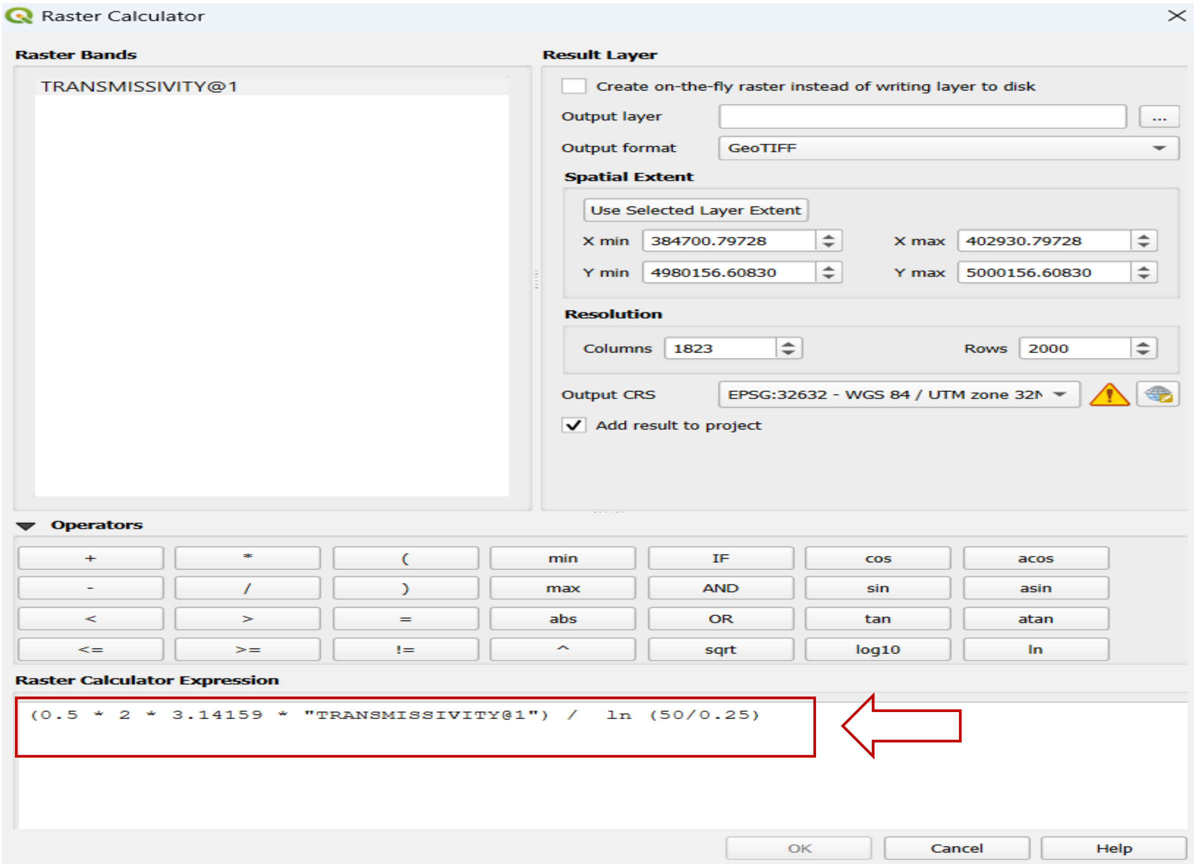


Fig. 11. Calculation of flow rate in Thiem's approach

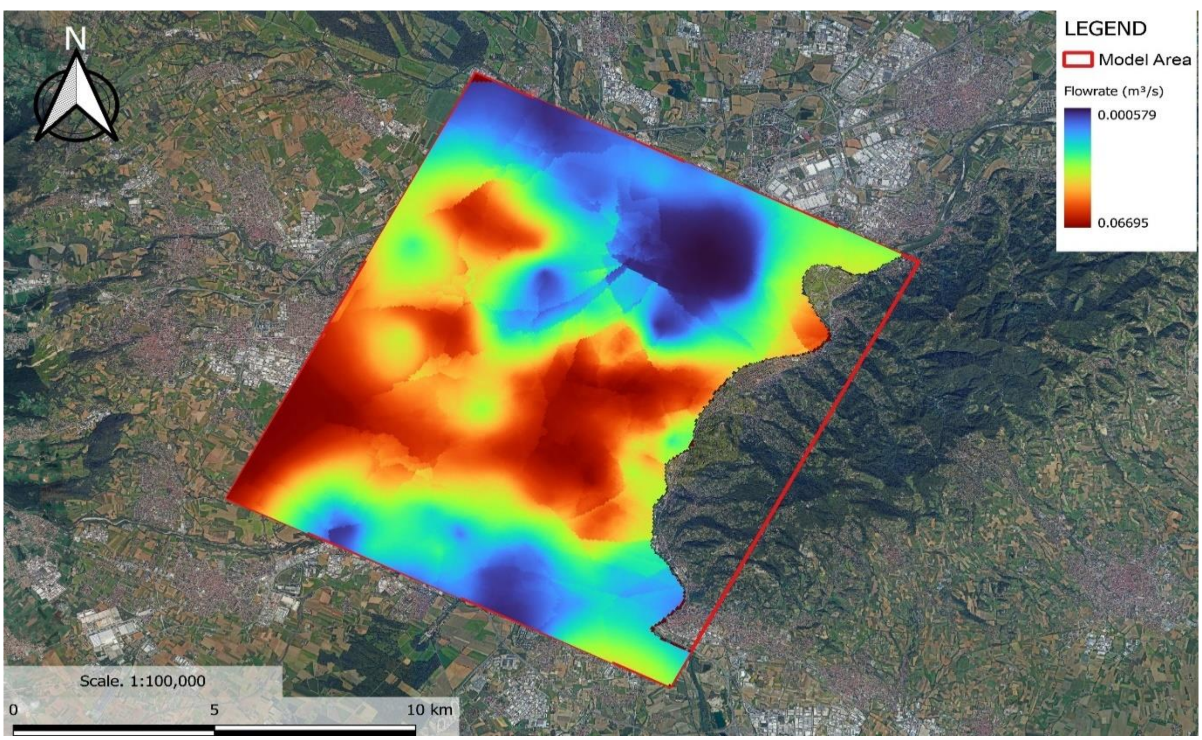


Fig. 12. Flow rate ranging from 0.579 to 66.95 lit/sec

6.2. COOPER AND JACOB'S APPROACH

The method is determined by the equation:

$$S_W(Q) = \frac{Q}{4\pi T} . \log\left(2.25\frac{Tt_{pump}}{Sr_w^2}\right) + CQ^2$$

The flow rate (Q) is determined by rearrangement of the equation into the standard quadratic form:

$$CQ^2 + \left(\frac{\log\left(2.25\frac{Tt_{pump}}{Sr_w^2}\right)}{4\pi T}\right). Q - S_W(Q) = 0$$

In the equation above, C represents the coefficient of the quadratic term and has the constant value of 1900 s^2/m^5. The transmissivity (T) has a range with values between 9.76×10^{-4} m^2/s and 11.29×10^{-2} m^2/s. The pumping duration (t_{pump}) is constant and equals to 200 days, equivalent to 17.28×10^6 seconds. The storage coefficient (S) ranges between 0.1 to 0.3 for unconfined aquifers, is set to 0.2 in this situation. The well radius (rw) is 0.25 meters, and the drawdown (S_w) is set to 0.5 meters, similar to the amounts, used in Thiem's method.

The discriminant method, which is a fundamental approach in algebra is applied to solve the quadratic equation in order to obtain Q. The discriminant, shown as delta, is calculated with the following formula: $\Delta = b^2 - 4ac$. For a general quadratic equation with the form of $ax^2 + bx + c = 0$, the nature of the roots is determined by the discriminant. The formula $Q = \frac{-b \pm \sqrt{\Delta}}{2a}$ determines the root. In the Cooper and Jacob's equation, a is replaced by C (1900 s^2/m^5), b by the term $\left(\frac{\log\left(2.25\frac{Tt_{pump}}{Sr_w^2}\right)}{4\pi T}\right)$, and c by - S_w, equal to -0.5.

The given values are then substituted into the discriminant equation and then a range for Δ is obtained, which varies from 3836.273 to 283196.968 s^2/m^4. Because the discriminant is positive, the quadratic equation will have two unique real roots. However, it has to be taken into consideration, that the positive root is only meaningful for this scenario and a negative flow rate does not correspond to any practical reality.

Thus, the positive root, being the flow rate (Q), is calculated with the help of the raster calculator and varies between 0.943 and 14.714 lit/sec. This flow rate calculation is beneficial in the management and assessment of groundwater resources (Fig 13).

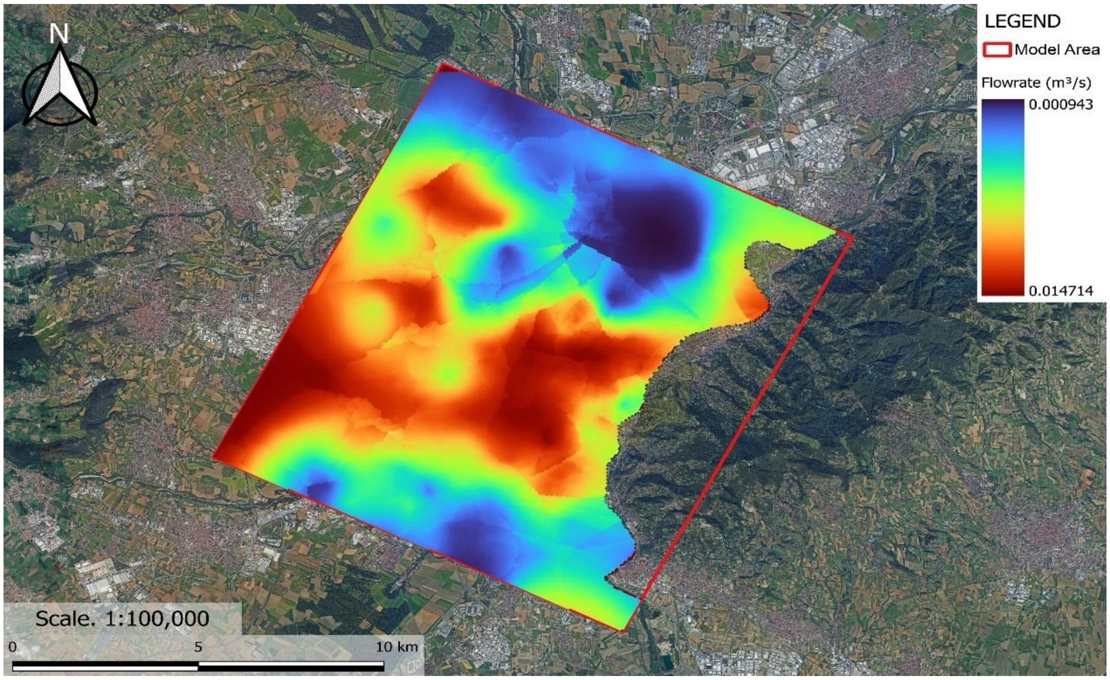


Fig. 13. Flow rate ranging from 0.943 to 14.714 lit/sec

6.3. DARCY'S APPROACH

This approach is a practical method for calculating the groundwater flow rate within a porous medium.

$$Q = \frac{K \cdot A \cdot \frac{dh}{dl}}{ne}$$

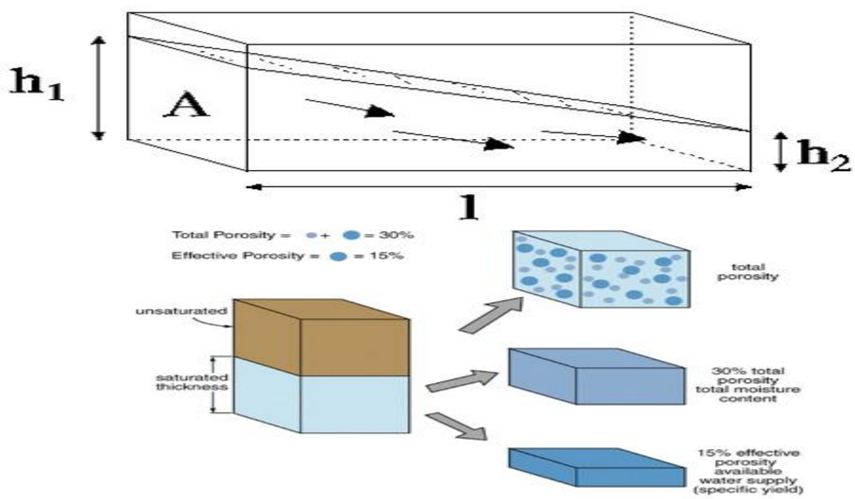


Fig. 14. Schema for explaining Darcy's law [10]

In the equation above, K is the hydraulic conductivity, calculated by the interpolation of log K values in the study area. A is the cell area, which is the product of the aquifer thickness (b) and the cell length (L), set at 50 meters. The hydraulic gradient ($\frac{dh}{dl}$), which is the hydraulic head difference between two points per unit distance in flow direction, is calculated by evaluating the upper part slope of the aquifer. This calculation has been done with the aim of the "slope" tool from the processing toolbox in QGIS. In this step the unit of the slope is in degrees. The slope unit is then converted to radians with the formula:

$$\tan(\frac{slope(in\ degrees)\ .\ \pi}{180})$$

[10] Groundwater Storage and Flow

Finally in the Darcy's equation, the denominator represents effective porosity (ne), that is assumed to be equal to 0.2.

The aforementioned parameter values are then substituted into the equation and with the aim of the raster calculator, the resulting flow rate ranges between 0.084 and 1130.361 lit/s (Fig 15). This range illustrates the variability of groundwater flow within the study area, as influenced by the spatial differences in hydraulic conductivity, aquifer thickness, and the hydraulic gradient. This range offers valuable insights for assessing the geothermal energy potential of the aquifer, facilitating the design and optimization of groundwater heat pump systems for sustainable use.

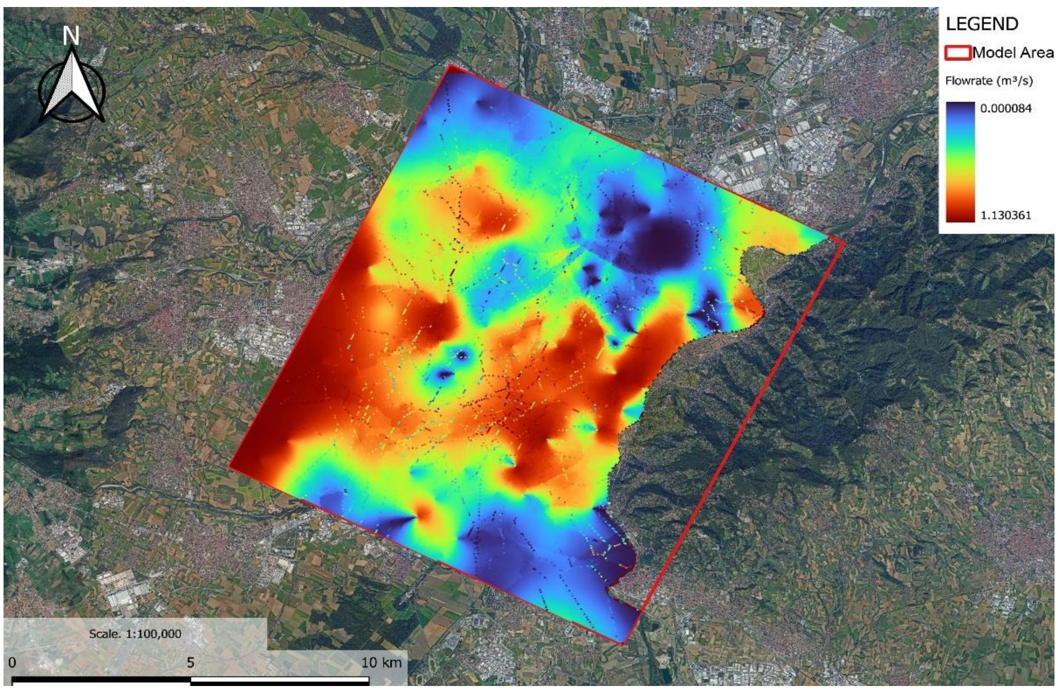


Fig. 15. Flow rate ranging from 0.084 to 1130.361 lit/sec

6.4. CALCULATION OF POTENTIAL ENERGY TRANSFER

When the subsurface water is pumped from an aquifer, its temperature is different from an external body, like the atmosphere or surrounding structures. Between the pumped groundwater and the external body, the potential energy can be transferred per unit time and is determined through the following equation:

$$P = Q \cdot c_w \cdot \rho_w \cdot \Delta T$$

Where,

- P denotes the power, the rate of energy transfer, in Joule per second (J/s) or watts (W)
- Q is the flow rate of the groundwater (m^3/s)
- c_w is the water specific heat capacity, which has a constant value of 4186 J/kg°C
- ρ_w is the water density, equal to 998 kg/m³
- ΔT represents the temperature difference, in degrees Celsius (°C)

The temperature difference (ΔT) is defined as the difference between the average temperature of the subsurface water and the external environment temperature.

The regulatory standards in the city of Turin define the maximum permissible injection temperature for water as 22°C, while the average temperature of the ambient is around 15°C. Thus, the temperature difference, ΔT, is 7°C.

The flow rate values, calculated in Thiem's approach are then substituted into the potential equation and the result ranges from 16.922 kW to 1957.836 kW (Fig 16). This range provides insight into the energy that can be harnessed or dissipated during groundwater pumping operations using the Thiem method.

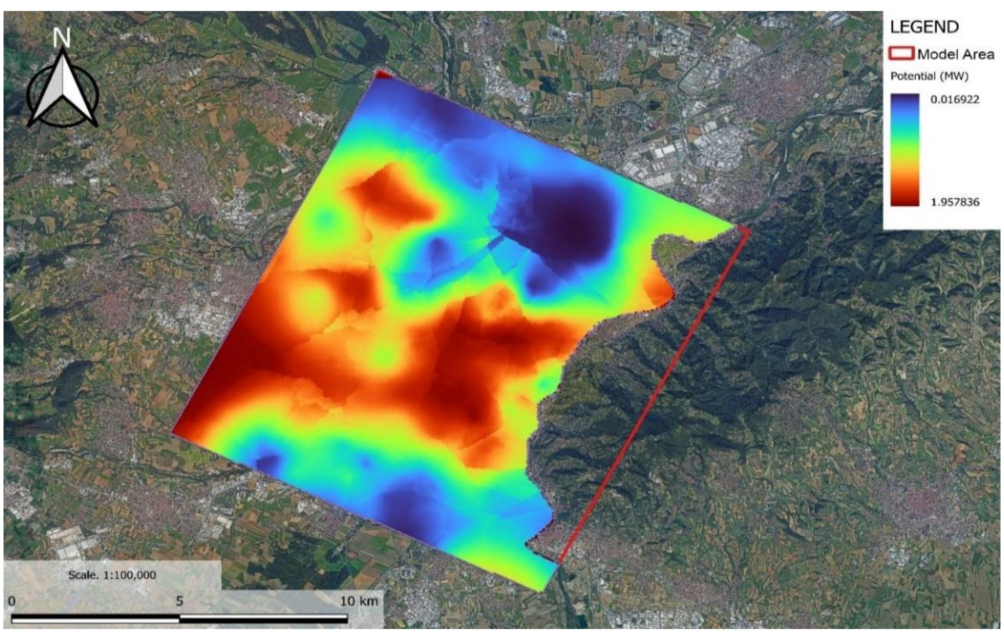


Fig. 16. Potential ranging from 16.922 kW to 1957.836 kW

Similarly, using the values of flow rate, obtained by Cooper and Jacob's approach, the potential energy transfer ranges from 27.624 kW to 431.162 kW, offering a broader range of potential energy exchange due to the different flow rates calculated by this method (Fig 17).

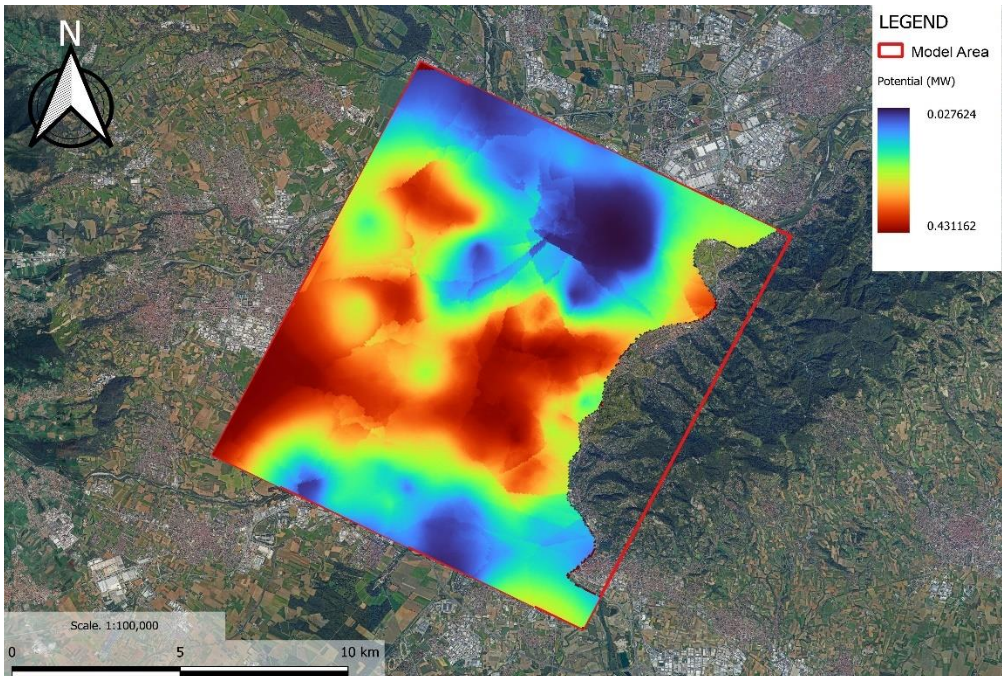


Fig. 17. Potential ranging from 27.624 kW to 431.162 kW

Finally, in Darcy's approach, the potential energy transfer varies between 2.45 kW and 33055.5 kW (Fig 18). The large range has been resulted due to the significant variability in flow rates, as influenced by the spatial heterogeneity of the aquifer properties and hydraulic gradient.

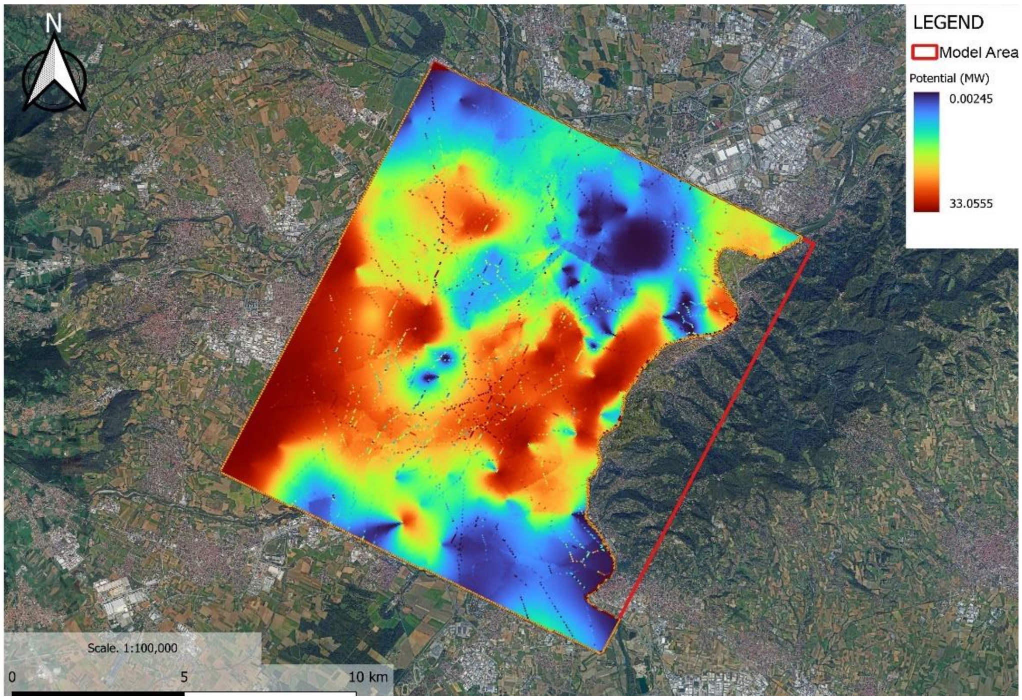


Fig. 18. Potential ranging from 2.45 kW and 33055.5 kW

These calculations provide valuable information for understanding the scale of energy that is transferred between groundwater and external bodies, such as heating or cooling systems. It is also evident, how different flow rates impact the energy exchange, emphasizing the groundwater importance as a thermal resource, especially in cities such as Turin, where regulations in temperature govern the management of groundwater and utilization of energy systems.

6.5. STATISTICAL ANALYSIS FOR HYDRAULIC CONDUCTIVITY AND POTENTIAL ENERGY TRANSFER

The hydraulic conductivity values in the urban area of Turin are analyzed statistically for a better understanding in their distribution and implications for groundwater flow rate and geothermal potential.

The statistical analysis shows the hydraulic conductivity heterogeneity across the region. The areas with higher hydraulic conductivity are advantageous for geothermal applications, because these regions flow the fluid better and transfer the heat more easily.

The analysis is based on the histogram of hydraulic conductivity values (in m/s) (Fig 19), that describes a clear bimodal distribution, which suggests the existing heterogeneous geological formations.

The hydraulic conductivity values vary between 1.079×10^{-4} m/s to 4.925×10^{-3} m/s and represents a broad variation across the area. Most of the data are in the lower range, that the highest frequency ranges between 6.25×10^{-4} m/s and 7.96×10^{-4} m/s. This means that a large section of the area contains low permeability.

The mean hydraulic conductivity is calculated as approximately 1.573×10^{-3} m/s, which tends closer to the middle range of the data and a large portion of the data is lower than the mean value.

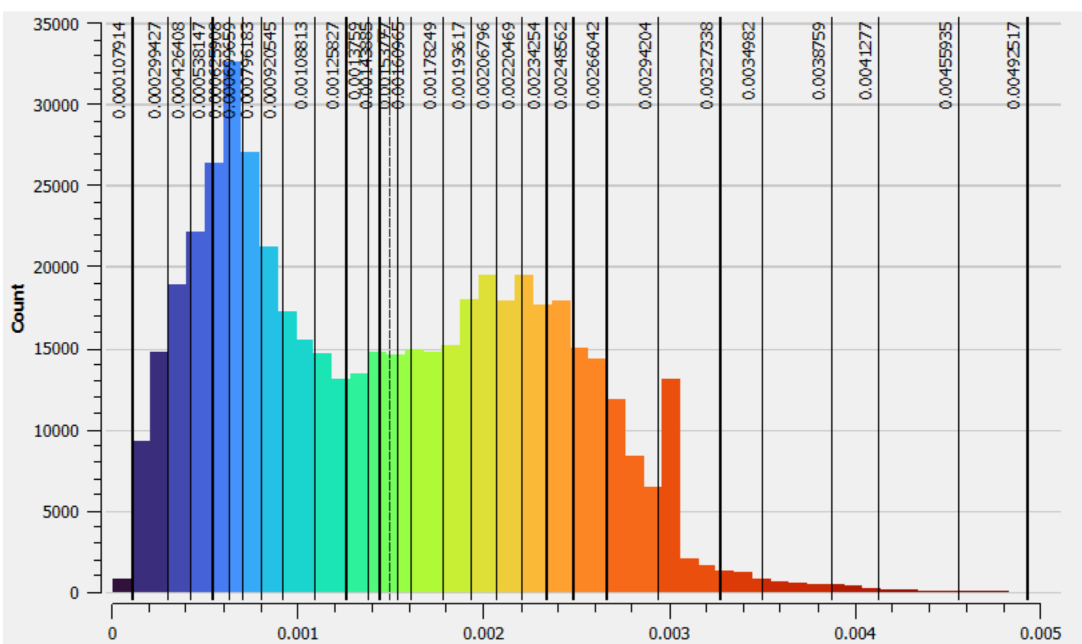


Fig. 19. Histogram of Hydraulic Conductivity in Turin area

In addition to hydraulic conductivity, potential energy transfer values (in megawatts) were analyzed to assess the geothermal energy extraction potential in the same area (Fig 20). The potential energy transfer values, based on the flow rate calculated by Thiem's approach, range from approximately 15.5 kW to 1567.2 kW, with a mean value of 468.62 kW.

It is transparent in the histogram of energy transfer, that most areas have relatively low energy transfer potential. The highest frequency is observed between 126.67 kW and 215.86 kW, with the largest concentration of data around 175 kW, suggesting that the majority of the study area experiences low to moderate potential energy transfer.

The distribution also shows a smaller section of regions with notably higher energy transfer potential, in which the values extend up to 1567.2 kW. These areas exhibit more ideal situations for geothermal applications, such as enhanced thermal gradients and higher flow rates, that leads to the better energy extraction capacity.

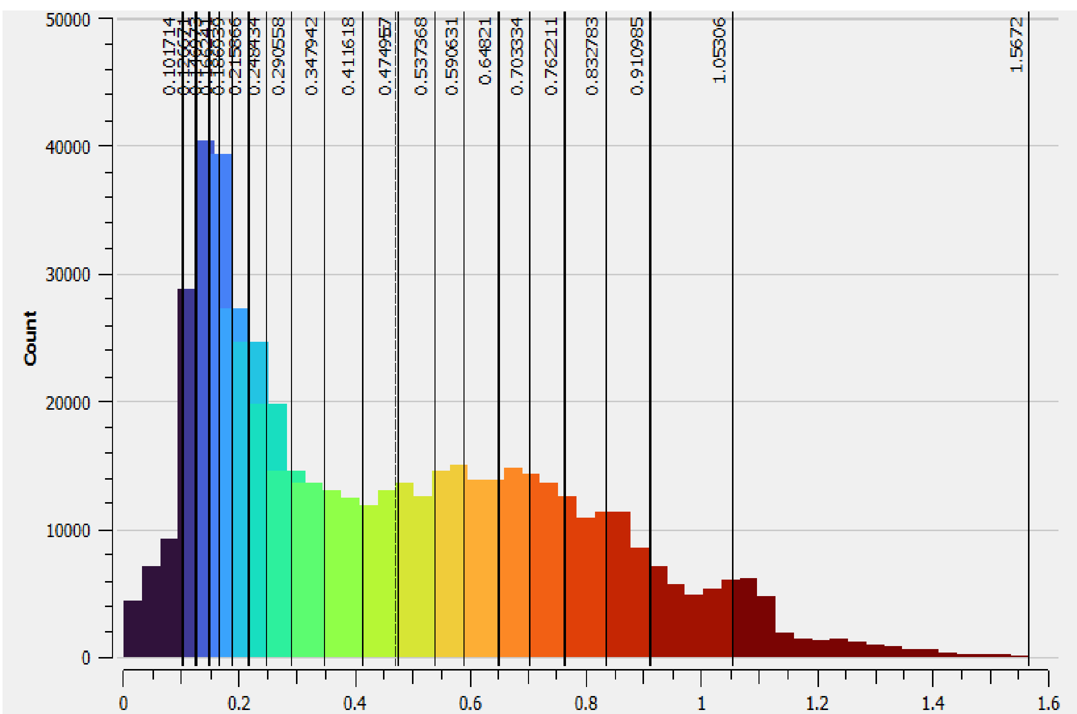


Fig. 20. Histogram of Potential Energy Transfer in Turin area

6.6. COMPARISON OF FLOW RATE ESTIMATION APPROACHES AND THEIR IMPACT ON POTENTIAL

A comparison of the three distinct approaches employed to estimate groundwater flow rate and geothermal potential—Thiem's approach, Cooper and Jacob's approach, and Darcy's approach is presented here. Each method provides unique insights based on its underlying assumptions, yielding different ranges of flow rates and potential energy transfer values. The comparison highlights the strengths and limitations of each approach in the context of geothermal energy extraction.

Thiem's approach, relying on steady-state assumptions, produces results that are closely aligned with observed real-world measurements. It estimates flow rates and potential energy transfer with moderate accuracy, making it suitable for practical applications in urbanized environments like Turin. Cooper and Jacob's approach, on the other hand, is more appropriate for transient, confined aquifers but tends to underestimate flow rates due to the assumption of homogeneity within the aquifer. Finally, Darcy's approach, while comprehensive, assumes that all water passing through the cross-sectional area can be abstracted, leading to significant overestimations of flow rate and energy potential.

The open-loop geothermal well near the "Politecnico di Torino", has a drawdown equal to 0.5 meters with a corresponding flow rate of 50 lit/sec, based on the data from the drawdown test. By comparing this observed actual flow rate with the estimation amounts near the university entrance area calculated by the three approaches, it is apparent that Thiem's approach offers the most reliable results (Fig 21). The flow rate calculated by Thiem's approach is consistent with the actual measurements, that confirms the method's accuracy not only for flow rate but also for potential energy transfer estimation.

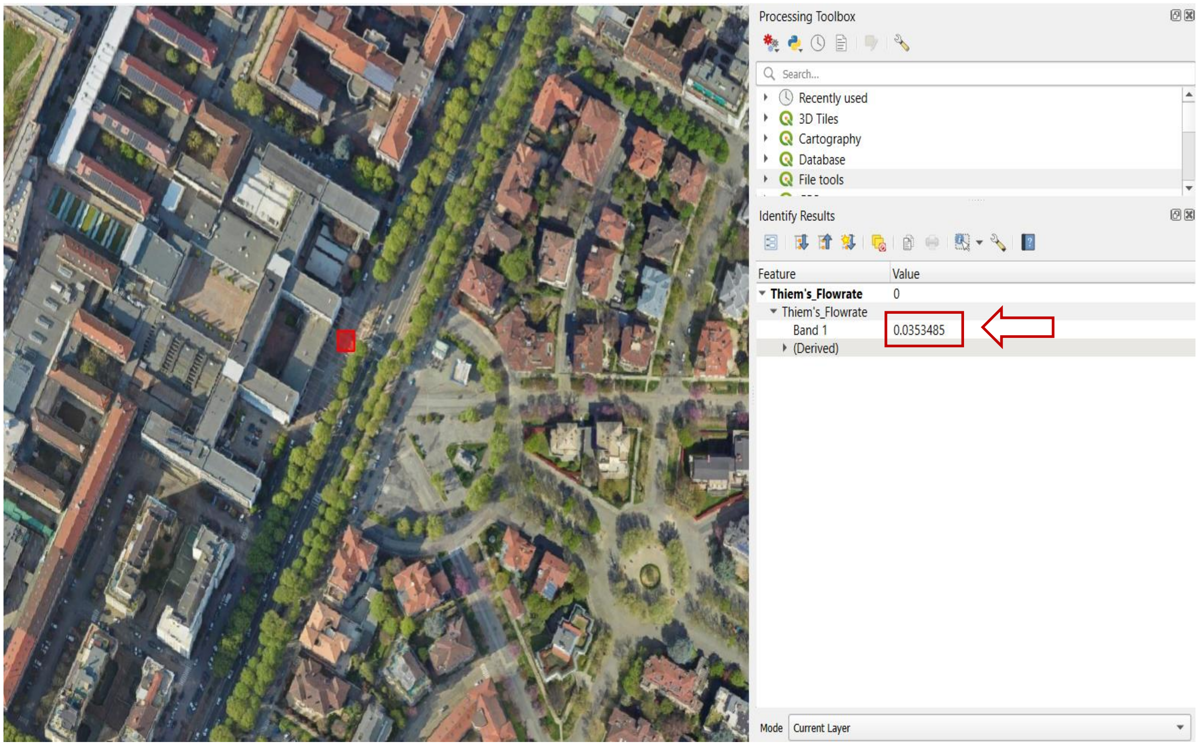


Fig. 21. Flow rate amount (35.348 lit/sec) in Thiem's approach near Politecnico entrance

The table below summarizes the key findings from each approach, detailing the range of flow rates, potential energy transfer, and specific advantages or limitations:

Parameter	Cooper and Jacob's	Thiem's	Darcy's
Flow rate range (lit/sec)	0.943 – 14.714	0.579 - 66.95	0.084 – 1130.361
Average flow rate (lit/sec)	9.8	16.1	29.8
Flow rate value near Polito entrance (lit/sec)	13.575	35.348	57.873
Potential Energy Transfer (kW)	27.62 – 431.1	16.9 – 1957.8	2.4 – 33055.5
Potential value near Polito entrance (kW)	398.079	1038.158	1727.454
Estimation Accuracy	Lower (due to assumptions)	Moderate (closer to real flow)	High (tends to overestimate)
Limitations	Assumes confined, homogenous aquifer	Assumes steady-state flow	Overestimates total abstraction
Advantages	Useful for transient flow analysis	Consistent with real measurements	Comprehensive; includes aquifer properties
Potential Applications	Small-scale heating systems	District heating networks	Large-scale industrial applications

Table. 1. Table for comparing different approaches

The geothermal potential calculated in the aforementioned approaches show different amounts and can be therefore used in different applications:

Cooper and Jacob's approach suggests applications suitable for localized heating systems such as small-scale residential heating, and heating for greenhouses.
The geothermal potential range in Thiem's approach aligns with urban-scale applications like district heating systems. The results from this approach are used for mid-sized energy requirements.
With a wide potential range, Darcy's approach shows applicability for large-scale industrial uses or centralized energy production. However, due to the overestimation amounts in this approach, the values must be selected carefully before being applied for such high-demand applications.

Apart from the indicated applications, the limitations of the approaches should be taken into consideration:

In the Cooper and Jacob's method, the aquifer is assumed confined and homogeneous, which does not fully represent real conditions in heterogeneous or semi-confined aquifers. As a result, it underestimates the geothermal potential and limits its accuracy and application in complex aquifer systems.
While Thiem's method provides results, that are more correlated to real-world observations, it assumes steady-state flow conditions, neglecting the transient effects, which could impact long-term predictions of geothermal potential and resource sustainability.
Darcy's method overestimates the flow rate and geothermal potential due to its assumption that all water passing through the surface is abstracted. Without validation, its predictions are less applicable for precise energy planning.

7. CONCLUSIONS

This thesis set out to evaluate the geothermal potential of the Turin aquifer and optimize the operation of groundwater heat pump (GWHP) systems by comparing three well-established methods for estimating flow rates: Thiem’s, Cooper and Jacob’s, and Darcy’s approaches. Additionally, the study aimed to quantify the potential energy transfer between pumped groundwater and external bodies, providing insights into the viability of geothermal energy utilization in an urban setting.

Parameters common to all methods include aquifer thickness, defined as the difference between the hydraulic head and the aquifer base, and transmissivity, calculated as the product of hydraulic conductivity and thickness. While Thiem’s method provides a direct calculation of flow rate, the Cooper and Jacob method involves a more complex process due to its quadratic nature.

Upon comparing the results obtained from all methods with actual flow rate measurements obtained from drawdown tests at the entrance of Politecnico, it was observed that Thiem’s method yielded results more consistent with the collected data. It suggests that this method may offer a more reliable estimate of the aquifer’s flow rate under the given conditions.

The results showed that Thiem’s approach, which produced flow rates ranging from 0.444 to 51.352 lit/sec, aligned more closely with observed data compared to Cooper and Jacob’s and Darcy’s methods. The observed variation in results reflects the sensitivity of all methods to transmissivity and other aquifer parameters, emphasizing the importance of accurate spatial modeling of aquifer properties. Thiem’s approach proved more consistent, making it a more reliable method for flow rate estimation in complex urban aquifers with heterogeneous transmissivity.

The potential energy transfer calculations further demonstrated the geothermal potential of the Turin aquifer. Using Thiem’s flow rate estimates, the energy transfer ranged from 16.9 kW to 1957.8 kW, while Cooper and Jacob’s approach provided a range of 27.624 kW to 431.162 kW. Moreover, in Darcy's approach, energy transfer ranged between 2.45 kW to 33055.5 kW. As it is evident, different approaches show different results, representing the differences in flow rate calculations. The outcomes represent the groundwater capacity in the Turin aquifer that can be a significant thermal resource, which offers potential applications in heating and cooling systems.

While this study has provided valuable insights, it is important to acknowledge several limitations. Thiem’s and Jacob’s methods used to estimate flow rates are based on certain simplifying assumptions, such as a constant drawdown and homogenous aquifer properties, which may not fully capture the complexities of the subsurface environment.

While this research provides a solid foundation for understanding the geothermal potential of the Turin aquifer, further work is necessary to improve the precision and applicability of the results. The methods applied—though effective—might not fully capture the detailed variations of aquifer characteristics across the study area. Incorporating techniques in refined spatial modeling, additional field measurements, and advanced hydrological models, representing dynamic factors such as seasonal changes and longer-term aquifer fluctuations should be considered in future research. These considerations will enhance the estimation of the flow rate and the assessment of the geothermal potential would be more accurate, which contributes to a more sustainable groundwater resources usage in energy systems.

In conclusion, this thesis aids to understand the management of sustainable aquifer and extraction of geothermal energy. By comparing the different methods in estimating the flow rate and energy transfer potential, the study explains about the efficient GWHP operations development in urban areas such as Turin, which leads to the groundwater resources integration into renewable energy strategies that refers to the challenges in environmental and energy sections.

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