Exploring Urban Sustainability: The Role of Geology and Hydrogeology in Numerical Aquifer Modelling for Open-Loop Geothermal Energy Development, the Case of Torino (Italy)

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Exploring Urban Sustainability: The Role of Geology and Hydrogeology in Numerical Aquifer Modelling for Open-Loop Geothermal Energy Development, the Case of Torino (Italy)

Alessandro Berta [1,2,*] and Glenda Taddia [1]

[1] Department of Environment, Land and Infrastructure Engineering (DIATI), Politecnico di Torino, C.so Duca degli Abruzzi 24, 10129 Torino, Italy; glenda.taddia@polito.it
[2] Department of Energy (DENERG), Politecnico di Torino, C.so Duca degli Abruzzi 24, 10129 Torino, Italy
* Correspondence: alessandro.berta@polito.it; Tel.: +39-0110907698

Abstract: This research examines the integration of geological and hydrogeological data in numerical aquifer model simulations, with a particular focus on the urban area of Torino, Italy. The role of groundwater resources in urban sustainability is analysed. The objective is to integrate open-loop geothermal plants into the district heating network of IREN S.p.A. Two case studies are examined: the Torino Nord area and the Moncalieri area, both of which host district heating plants. The work entails the collection and analysis of data from a variety of sources, including geognostic surveys and permeability tests, in order to construct a three-dimensional numerical model of the surface aquifer. Models were built using the public MODFLOW 6 (model of groundwater flow) code and calibrated using PESTHP (High Performance of Model Independent Parameter Estimation and Uncertainty Analysis). Results indicate the potential of urban aquifers as renewable energy sources and the necessity of comprehensive geological and hydrogeological assessments for optimal ground water heat pump (GWHP) system installation. This paper emphasises the significance of sustainable water management in the context of climate change and urbanisation challenges.

Keywords: groundwater resources; open-loop geothermal energy; climate change; Torino urban area; sustainable water management; geological and hydrogeological characteristics; district heating; MODFLOW 6; model calibration; PESTHP

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1. Introduction

Water is a crucial resource, intrinsically linked to society and culture development, food and energy security, well-being, environmental sustainability, and poverty reduction.

However, several factors, including urbanisation, population growth, land use and soil consumption, and industrial and agricultural development, endanger water resource sustainability in terms of availability, quality, management, and demand. Groundwater resources represent about 97% of liquid freshwater resources on Earth [1] and play a key role in water supply and proper preservation of ecosystems. Groundwater resources are of utmost importance for their mitigation effects during dry periods, and their reduction can impact the whole hydrological cycle. Groundwater is a fundamental natural resource that acts as a reservoir from which good-quality water can be collected for drinking purposes, requiring few purifying treatments compared to surface water [2].

The process of urbanisation has a significant impact on the hydrological cycle at the local level, with groundwater playing a particularly important role in highly urbanised areas. Despite this, groundwater is often overlooked in urban planning. To ensure the long-term preservation and protection of groundwater, it is crucial to address the heavy pollution that groundwater is susceptible to.

The Piemonte Plain is located in the westernmost part of the Po Plain, representing a hydrogeological system of European relevance [3].

Torino city is located in the north-western region of Italy, in Piedmont, on the Po plain, south of the Western Alps. With a total population of 857,910 inhabitants (inh) (Figure 1A) in Torino city at the end of 2019 [4], it stands as the fourth largest city in Italy, covering an area of 130 km^2 with a population density of less than 6600 inh km^2. The Metropolitan City of Torino comprises 315 municipalities covering an area of 6821 km^2 with a population of approximately 2,208,370 residents (Figure 1B). The economic and demographic analysis of Torino's history sheds light on the various processes of urban development. It also highlights the recent negative trend resulting from the closure of various companies.

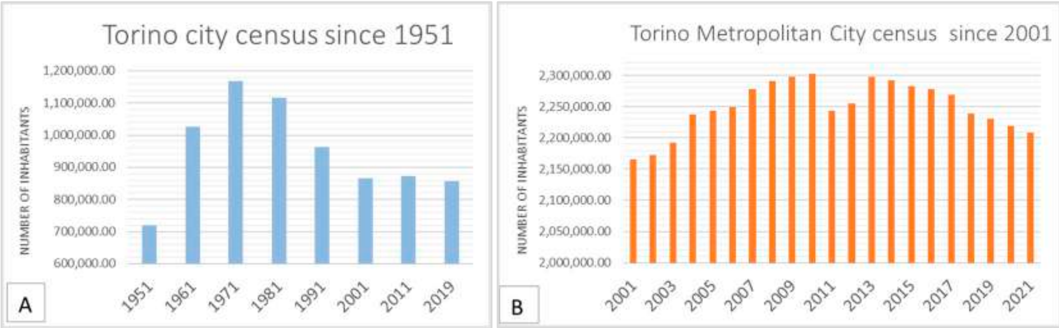

Figure 1. (**A**) Number of inhabitants in Torino city since 1951, data from ISTAT; (**B**) Number of inhabitants in Torino Metropolitan City since 2001, data from ISTAT.

Torino is one of ten Italian cities selected to take part in the EU's "100 Climate-Neutral and Smart Cities by 2030" mission, which aims to achieve ambitious targets for rapidly reducing emissions while testing innovative approaches with citizens and stakeholders. A resilient city consists of several energy sources, infrastructure that is highly efficient, reduced resource demand for the purpose of decarbonizing, and sustaining the urban system [5]. Sustainable mobility, energy efficiency, and green urban planning will be the focus of the actions taken. In this context, to achieve the goal of zero CO_2 emissions by 2030, which is 20 years ahead of the rest of Europe, investment in renewable energy systems is essential. In order to achieve these goals at the community level, it is essential to stimulate investment in effective sustainable technologies, such as GWHPs, with larger companies acting as the primary stakeholders capable of making a real difference. Therefore, it is essential to conduct a geological and hydrogeological examination at both urban and site-specific levels to facilitate the optimal installation of GWHP plants and evaluate their potential environmental impacts.

In urbanised areas, aquifers are becoming a renewable energy source for large cities. Water management is a significant area of concern in Europe, and The United Nations World Water Development Report 2022 suggests that adequate protection is the most sustainable and cost-effective approach for managing groundwater quality to prevent contamination. Vulnerability mapping, developing groundwater protection zones, and land use planning are effective for achieving this objective. The joint management of surface water and underground resources requires particular attention. The use of this technology requires a thorough knowledge of the study area in terms of geology, hydrogeology, population, and urbanisation.

This study analyses the geological and hydrogeological conditions in certain areas of Torino by simulating a calibrated numerical flow model. The model is essential for a subsequent design study of open-loop low enthalpy geothermal plants, which will integrate this renewable technology into the IREN S.p.A. district heating network. Normally, the term plant refers to medium-high-enthalpy geothermal plants for electricity generation or direct energy use without the use of heat pumps. In this case, however, the term has been chosen because, at the end of the various integration processes, the geothermal system is fully integrated into the grid and constitutes a single plant.

The geological and hydrogeological analysis focused on two case studies in the urban area of Torino:

- Case study 1: Torino Nord area;
- Case study 2: Moncalieri area.

Both case studies currently host a district heating plant of the IREN S.p.A. Company, section IREN Energia Torino Italy, Italy.

District heating systems encompass a complex interplay of heat generation units, transmission and distribution networks, substations, and end-use consumers. This technology is gaining widespread recognition in global urban landscapes due to its commendable energy-saving attributes and consequential reduction in CO_2 emissions. The existing district heating network of IREN corresponds to the third generation, relying on average temperatures around 100 °C [6]. The transition to the fourth generation necessitates a reduction in temperatures to 50 °C, while the fifth generation exclusively harnesses geothermal resources with peak temperatures below 30 °C [7]. Currently, low-enthalpy geothermal energy is composed of two distinct technologies: the closed-loop and the open-loop. It is important to note that these technologies operate at different depths, temperatures, and pressures, which impact their effectiveness and applicability in various contexts. The closed-loop configuration entails circulating a heat transfer fluid through an interconnected piping network. This fluid is specifically intended for a closed system in order to efficiently absorb heat from a low-temperature geothermal source. Subsequently, the fluid is heated and undergoes a controlled transfer of thermal energy to a secondary fluid within a dedicated heat exchanger. This perpetual closed-loop circulation characterises a dynamic process that enables continuous heat exchange between the geothermal source and the secondary fluid.

On the other hand, in an open-loop geothermal system, water is extracted from a shallow aquifer and subjected to heat exchange before being returned to the same aquifer at a different temperature. The energy efficiency and sustainability of these systems are essential, and they should be encouraged for widespread deployment at various scales [8]. Regarding the classification of groundwater in Italy, Legislative Decree No 152 of 3 April 2006 defines groundwater as located beneath the surface of the ground, in the saturation zone, and in direct contact with the soil and subsoil. This includes both shallow and deep groundwater, while the permeable rock formations that contain it are referred to as "aquifers". Article 2 (3) of Regional Law 22/1996, as amended by Regional Law 6/2003, defines a shallow aquifer as the aquifer nearest to the ground surface that receives direct feeding from surface infiltration waters and is in direct connection to the hydrographic network. The characteristics of the shallow aquifer include its general unconfined type, although it may experience localized confinement, direct accessibility by infiltration waters from the ground surface, and its direct connection with rivers. Article 2 (4) of Regional Law 22/1996, amended by Regional Law 6/2003, defines deep aquifers as those located beneath shallow aquifers, with low outflow velocities, longer turnover times, and distinct hydrochemical qualities compared to those in the shallow portions. The protection of the deep aquifer is crucial, and it should not be utilised for energy purposes [9]. Therefore, an examination of the surface geology and hydrogeology will be conducted to efficiently plan for potential open-loop geothermal power plants in the two research areas.

Closed-loop geothermal facilities present various advantages, notably a diminished environmental footprint in comparison to traditional geothermal systems. However, their implementation necessitates boreholes of greater depth than those required for open-loop systems and is contingent upon an anomalous geothermal gradient [10]. In geological and hydrogeological contexts such as the Torino plain, characterised by an average geothermal gradient of 30 °C per kilometre, closed-loop plants mandate substantially deeper drilling to attain temperatures conducive to district heating when juxtaposed with their open-loop counterparts. This depth requirement results in diminished efficiency for closed-loop systems. Therefore, a deliberate choice was made to avoid examining closed-loop facilities and focus on promoting the most comprehensive geological and hydrogeological evaluation feasible for leveraging Torino's surface aquifer in open-loop applications. Open-loop groundwater heat pumps (GWHPs), currently recognized as particularly apt shallow geothermal technologies for urbanised areas, have the potential to substantially augment the share of renewable energy sources within the thermal sector [11]. Additionally, shallow geothermal energy can be effectively harnessed in third-generation district heating systems, employing high-temperature and high-performance heat pumps to provide heating for older buildings [12].

2. Materials and Methods

To create a hydrogeological model of the shallow aquifer, it is essential to have a thorough understanding of geology and hydrogeology. This comprehension is crucial not only for the initial feasibility analysis but also for constructing a forecast model required for subsequent authorization phases by the authorities. It is important to utilise all available data sources to establish and maintain a comprehensive geodatabase. This enabled a comprehensive examination of the geological and hydrogeological context. A multifaceted approach was adopted, and the data obtained from these sources was meticulously analysed. The study area was examined thoroughly by integrating diverse datasets from regional and municipal portals. In the case of Torino City, open data that can be accessed, including shapefiles and rasters, are obtained from three separate repositories: The Geoportale Piemonte, facilitated by regional authorities [13] the Geoportale Arpa Piemonte, provided by the Regional Environmental Agency [14], and aperTo, offered by the City of Torino [15], are three platforms that share similar functionalities [16]. Data retrieval primarily involves keyword searches within the respective websites. The open web GIS portals host four principal types of data. Users can download zip files containing shapefiles, PDF documentation, and CSV files for direct manipulation and graphical representation of raw datasets. After acquiring the data, they can be integrated into the GIS software (e.g., QGIS 3.34.8 in its long term release - LTR) for a comprehensive examination of the dataset's content and characteristics. In addition, detailed records from geognostic boreholes proved to be invaluable in understanding the subsurface geology. Specifically, data from 11 geognostic boreholes drilled in 2006 in the Torino Nord area (Case Study 1, Figure 2) for IREN S.p.A. and 2 boreholes drilled in 2022 in the Moncalieri area (Case Study 2, Figure 3) were thoroughly studied and analysed. The boreholes were crucial in determining the geological composition of the study area and reconstructing the subsurface. Furthermore, the Piemonte Geoportal provided several borehole logs from the Regional Environmental Protection Agency (ARPA), which were used to improve the understanding of the subsurface environment. These logs provide detailed information on borehole depths, lithology, and stratigraphy, enabling a comprehensive reconstruction of the subsoil. For this particular case study, which focuses on the municipality of Torino, data sourced from the Piedmont Region are relevant. The first step is to filter out extraneous data that are not related to our area of interest. Subsequently, managing the dataset involves cross-referencing and validating against multiple sources wherever possible. Two distinct datasets are available for piezometric surface data in Torino. The first dataset is an interpolated dataset derived from a piezometric campaign conducted by ARPA Piemonte in June–July 2002, covering the entire Piedmont plain. This dataset, available as a downloadable shapefile, illustrates the piezometric trends. The second dataset consists of data from piezometric campaigns conducted by ARPA from 2012 onwards, with semi-annual updates specifically for the Torino area. The dataset consists of point data, where each point represents a piezometer and is linked to measurements taken over the years. To process these data, it is necessary to isolate measurements from a particular month campaign and average them across different years. This step is crucial in reducing seasonal variations in piezometric surfaces and minimising associated errors during subsequent analyses.

The Geographical Information System (GIS) required for model development was established using QGIS version 3.34.4. QGIS is an open-source desktop GIS software that provides functionalities for pre- and post-processing of data for MODFLOW I/O. It enables the management of various information layers, such as tables, vector, and raster layers. To maintain consistency with the source data, the Coordinate Reference System (CRS) WGS 84/UTM zone 32N, identified by the EPSG code 32632, was adopted.

Geographical information pertinent to this study was acquired from various sources, including:

- Annual Reference Cartographic Base 2023 raster b/w 1:10,000 (Year: 2023);
- Digital Terrain Model (DTM 5) derived from ICE 2009–2011 aerial survey, boasting 0.30 m accuracy and 5 m resolution in raster format;
- Surface water table piezometry data at a scale of 1:100,000 in shapefile format, acquired during the June–July 2002 period;
- Surface aquifer base at a scale of 1:50,000, updated to 5 April 2022.

The developed model is a three-dimensional finite difference numerical model. However, it is referred to as a semi-analytical model as it assumes homogeneity in the distribution of some hydrogeological parameters. The model was constructed using the US Geological Survey's MODFLOW 6 public domain code [17,18], which is an international standard for three-dimensional finite difference modelling of groundwater flow. The model construction process was carried out using version 5.2 of the open-source software Model Muse [19]. This software has a graphical interface that can handle MODFLOW 6 version 6.4.4, as well as other MODFLOW-compatible software packages, such as the PESTHP code for model calibration [20]. The two models (representing the two case studies) exhibit a similar and comparable structure, comprising two layers representing the different aquifer systems (described in Section 2.1), two General Head Boundaries (GHB) corresponding to the upstream and downstream boundary conditions of the model, and the simulation of the watercourses using the River package (described in the Sections 2.2 and 2.3).

The calibration of a numerical hydrogeological model can be conducted under various conditions, including steady-state, transient, or a combination of both. In the two cases under consideration, the calibration was executed using the Pilot Points (PP) technique in a steady-state regime, utilising average piezometric level data collected from wells and piezometers of ARPA Piemonte in May. The entire procedure was managed via the PESTHP inverse modelling code, a tool designed for the estimation of parameters and the analysis of uncertainties in complex numerical environmental models. The method employed involves an iterative procedure to optimize the parameters. This allows for the reiteration of the process steps, which include the resolution of the flow equation, the verification of the correlation between calculated and observed piezometry, and the modification of the parameters to enhance the correlation. This process is repeated until the difference between the calculated and measured loads reaches a minimum that is deemed acceptable. In this case, a minimum acceptable error of 0.01 m was set. The optimization of the parameters results in the minimisation of the objective function Φ, defined as the weighted sum of the squares of the differences between the experimental observations h' and the simulated loads h:

$$\Phi = \sum_{i=1}^{m} [w_i (h'_i - h_i)]^2$$

The weight attributed to an observation, denoted by the symbol (w_i), is inversely proportional to its variability or uncertainty. This ensures that more emphasis is placed on the most reliable observations. In the two cases under consideration, each observation point has the same weight, as all measurements were checked by ARPA.

The parameters involved in the calibration process can be assigned not only according to the classic uniform value zones but also through spatial distributions (interpolations) defined at some points, known as Pilot Points (PP) [21]. This method applies the principles of geostatistics to transition from the points where the parameter value is associated to the spatial distribution over the entire considered area (model domain). The surfaces are generated from the PP through the process of Kriging, which estimates the unknown values through a weighted average of the measured points, with the relative weights depending on the size of the search radius. In this case, the unknown parameter (hydraulic conductivity) varies spatially in a gradual manner based on geostatistical schemes (variograms) that take into account the heterogeneity of the model. Pilot Points play a pivotal role in the calibration process, enabling a more realistic representation of the spatial variability of parameters within the model. Rather than assigning a uniform value to a large area, the parameter values can gradually vary across the model domain based on the values assigned. Consequently, during the iterative calibration process, the values at the PP are adjusted to minimise the difference between the simulated and observed data. This implies that the PP directly influences the optimisation of the model parameters. By capturing the spatial variability of parameters and allowing for their optimisation, this technique can significantly improve the accuracy of the model predictions. This leads to a more reliable and robust hydrogeological model. The weights assigned to the observations at each PP are inversely proportional to their variability or uncertainty. This means that more reliable observations have a greater influence on the calibration process, thereby reducing the overall uncertainty of the model.

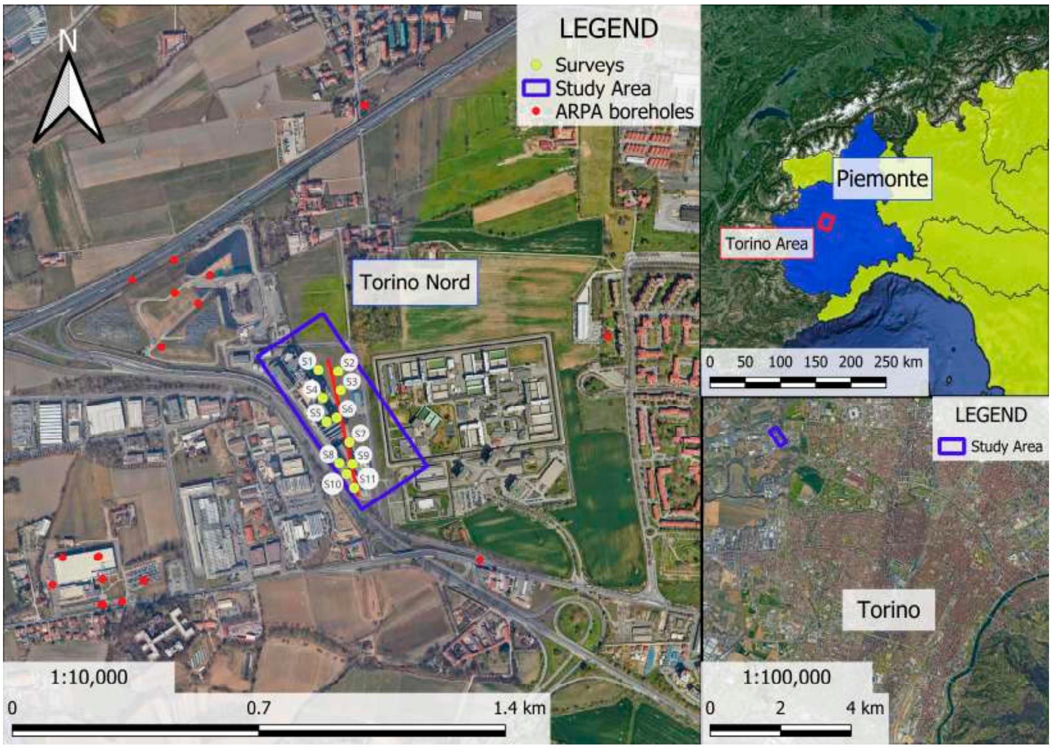

Figure 2. Location of the Torino Nord study area and boreholes.

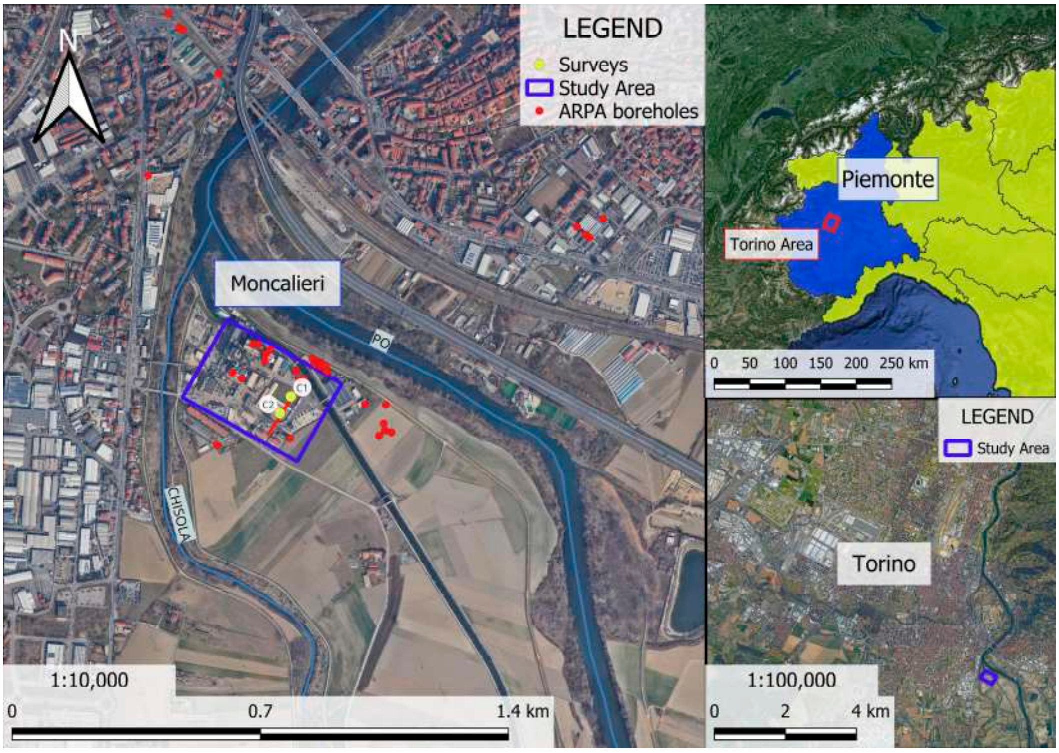

Figure 3. Location of the Moncalieri study area and boreholes.

2.1. General Geological and Hydrogeological Setting

The urban area of Torino encompasses the plain extending from the Rivoli-Avigliana Moraine System (RAMAs Susa Glacier) in the west to Turin Hill in the east. This region is delineated by natural features, including the Stura di Lanzo river to the north, the Dora Riparia river in the central region, and the Sangone river to the south (Figure 4). These rivers collectively discharge into the Po River, which flows northeastward along the western boundary of Turin Hill [22].

Drawing upon comprehensively documented general information pertaining to the Turin plain, from its hills to the final Alpine foothills, a tentative assessment of the average thickness of coarse detrital fluvioglacial deposits in the area suggests a magnitude of approximately 70 m. Furthermore, deposits characterised by finer and more compact attributes, with thicknesses extending up to 200 m, can be attributed to lacustrine and deltaic formations from the Pliocene–Pleistocene transition. Additionally, marine tertiary formations, with thicknesses in the order of hundreds of meters, are discernible. The subsurface composition of Torino manifests as a marine–deltaic complex concomitant with proglacial fluvial sediments associated with the RAMA. A suite of entrenched fluvial terraces is also evident, correlating with various late glacial and post-glacial watercourses [23].

This study is primarily concerned with Quaternary formations (Figure 4), which are described briefly from the most recent terms:

- Recent and current river floods are relatively weak and are confined to the active river beds, consisting of clean gravels and sands with occasional finer lenses. They are situated on less permeable interglacial conglomerate beds;
- Medium to recent river floods are mostly scarce on current riverbeds and occur along the Po and other primary watercourses. They predominantly consist of sandy-gravel deposits and are limited to a few metres thick;
- Ancient river floods appear as discontinuous patches slightly terraced relative to the present riverbed and often fill in the “fossilized meanders” of the paleo-river. These outcrops gradually yield to the recent and ongoing river floods;

- Gravelly sandy-clay fluvioglacial deposits, a terrace system with reddish-yellow palaeosols, is located approximately ten metres above the Middle-Recent Alluvium of the Po River. It presents itself as a strong alternating sequence of partially altered gravels and sands, reaching tens of metres in depth, intermixed with finer sandy and silty layers that are generally less cohesive.

The morphology of the terraces' boundaries is marked by deep incisions, particularly along the Dora Riparia River's riverbed. The sample appears as a dense, well-cemented gravel. The matrix consists of a limited amount of silt and clay, with abundant pebbles that are more than a tenth of a metre in size. The proportion of sand is minor, while gravel is dominating.

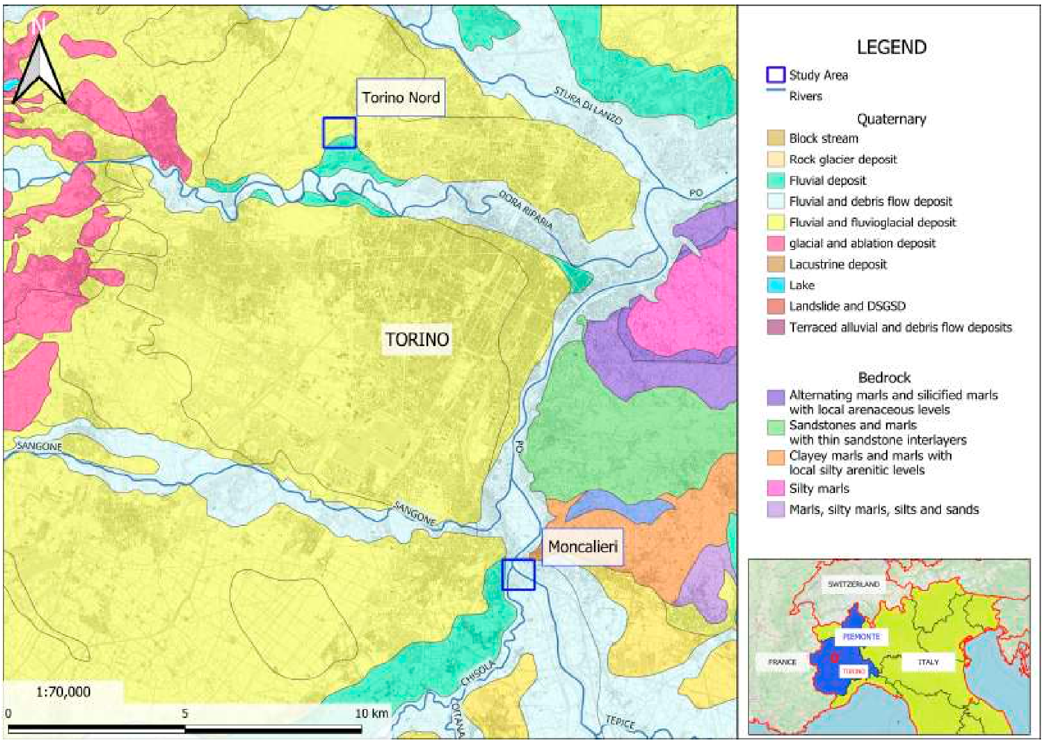

Figure 4. Geological map of Torino urban area made from ARPA Piemonte geodatabase.

The geological formations that outcrop in Piemonte can be classified into three primary categories depending on their permeability: rocks permeable through porosity, fracturing, and karst (which include limestones and chalks). Based on their hydrogeological characteristics, the formations can then be further divided into hydrogeological complexes (Figure 5). The subsoil's hydrogeological structure seems to be influenced by the RAMA to the west and the Turin Hill Miocene anticline to the east. The piezometric surface gradually flows towards the nearby base level, which follows the path of the Po River. The average runoff direction fluctuates between NW-SE and WNW-ESE, with an average hydraulic gradient of 0.35%.

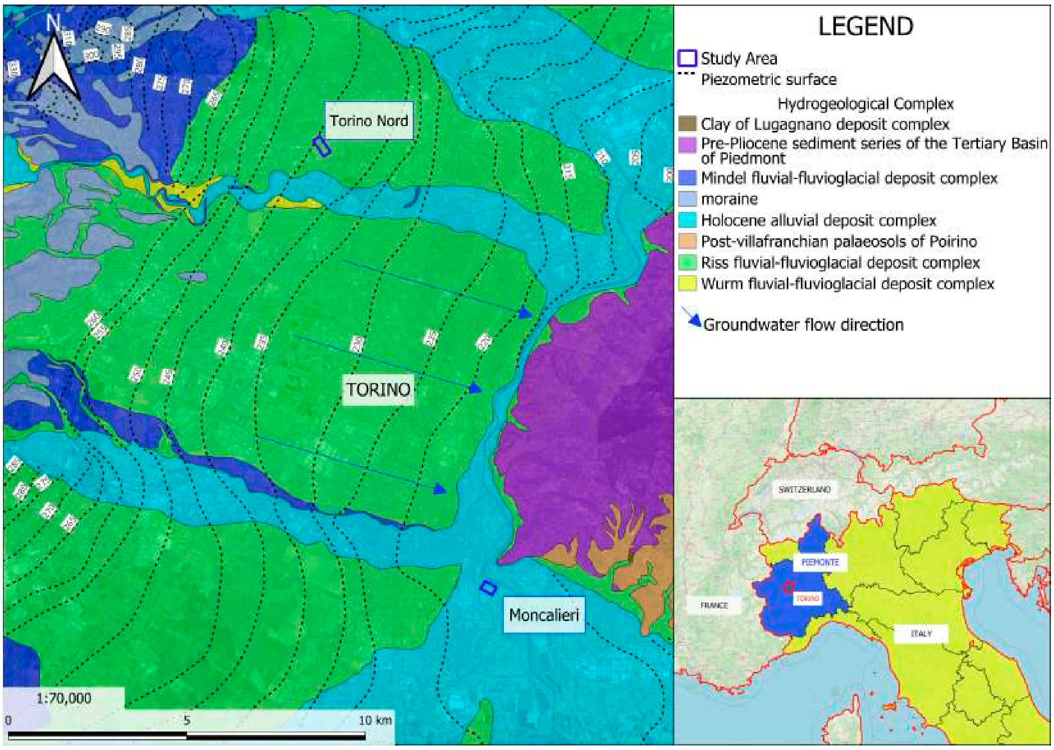

Figure 5. Hydrogeological map of Torino urban area made from ARPA Piedmont geodatabase. The dashed line represents the piezometric surface of the Torino area and the related hydraulic head in m a.s.l..

The hydrogeological conceptual model of the Piedmont plain (Figure 6) comprises superimposed complexes represented with the Alluvial deposits complex at the top (lower Pleistocene–Holocene), followed by the 'Villafranchiano' transitional complex (late Pliocene–early Pleistocene) and Marine complex (Pliocene) at the base [3]. The shallow unconfined aquifer is hosted in the Quaternary alluvial deposits complex and is represented by Layer A of the numerical model. Deeper aquifers are present in the underlying fluvial–lacustrine 'Villafranchiano' complex, represented by Layer B in the numerical model. These aquifers serve as key sources of drinking water in the Piedmont plain, due to their productivity and the superior groundwater quality compared to the shallow aquifer [24]. However, they cannot be used for energy purposes.

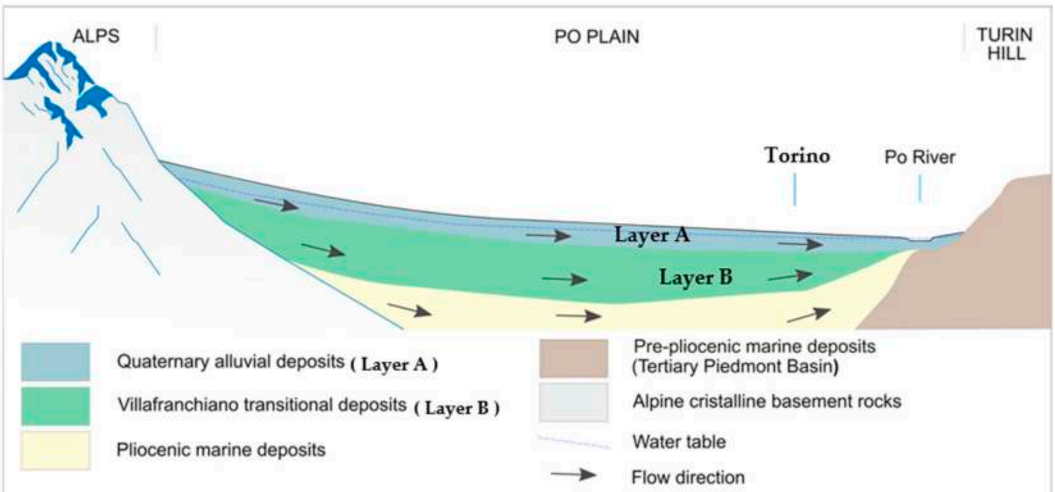

Figure 6. Cross section (W-E orientation), modified from [3].

2.2. Case Study 1: Torino Nord Area

In order to gain detailed knowledge of the subsurface, 11 rotary geognostic boreholes drilled to depths of 15–30 m were analysed, totalling 220 m of drilling. In addition, 62 in-hole SPTs (Standard Penetration Test) and permeability tests were carried out in 3 boreholes. Surface soil and groundwater samples were also collected, and open standpipe piezometers were installed in three of the boreholes to allow periodic measurement of the piezometric level. The formations exposed on the surface in the study area are all associated with the last glaciations and are therefore of recent continental origin. The underlying materials are also composed of recent continental sediments originating from fluvioglacial and fluvial sources, extending down to depths of tens of metres. In the borehole stratigraphies, soils composed of sand and gravel are found at depths of up to 30 m from the current surface (Figure 7).

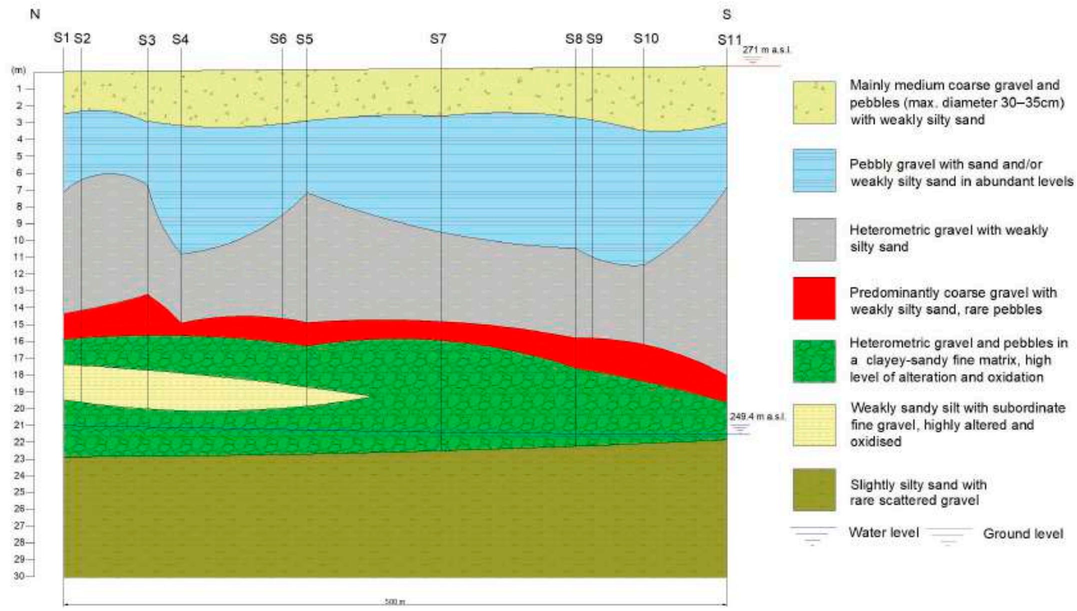

Figure 7. Interpretative geological cross-section derived from the 11 boreholes conducted by IREN S.p.A. Company.

The research site is situated on a level terrain, shielded from erosive remodelling phenomena directly or indirectly associated with the riverbed, which lies at a considerably lower altitude and a safe distance. The elevation difference between the analysed area, positioned at approximately 271 m above sea level (m a.s.l.), and the base of the river incision is approximately 12–15 m. The Dora Riparia river traverses this region through a well-defined and incised riverbed within a predominantly horizontal context. The study area is located on the Mindelian-Rissian fluvioglacial terrace, extending from the mouth of the Susa Valley to the Po River. This terrace is divided into north and south sectors due to the erosion of fluvioglacial sediments by the Dora Riparia River, resulting in the deposition of a layer of recent alluvial deposits several meters thick.

From a hydrogeological perspective, the shallow aquifer in this case study area is approximately 25 m thick (Figure 7) and is composed of pebbles, gravel, and permeable sands resulting from fluvioglacial processes. Additionally, discontinuous and localized cemented strata, a few decimetres thick, are present. The surface aquifer underwent successful hydrodynamic characterisation through transient groundwater tests conducted over several years. This characterisation revealed a water table with delayed drainage, with average values for transmissivity ($5.87 \cdot 10^{-2}$ m^2/s), effective porosity (0.15), and hydraulic conductivity ($3.0 \cdot 10^{-3}$ m/s). In the study area, the water table level varies from 250 m a.s.l. (extreme north) to 249.4 m a.s.l. (extreme south), and the average groundwater depth (Figure 8) ranges between 20 and 25 m.

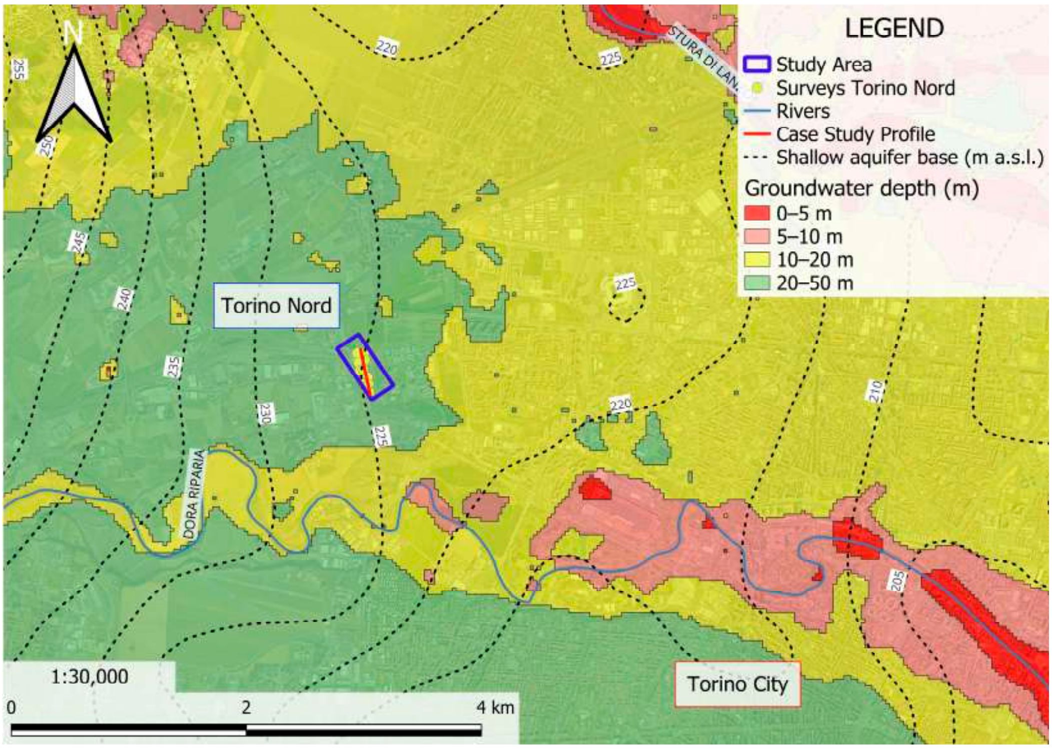

Figure 8. Groundwater depth map of Torino and base of the shallow aquifer made from ARPA Piemonte geodatabase.

The numerical flow model of the area was constructed using information obtained from site-specific surveys and data accessible on geoportals. The model domain covers an area of approximately 10.4 km^2, with a uniform grid of 25 × 25 m, comprising a total of 16,660 cells. The available stratigraphic data have been analysed to define and adopt a vertical discretization within the calculation domain. This discretization provides two layers to represent the first two aquifer groups. These layers are distinguishable but not hydraulically independent.

The upper limit of the modelled volume, which is the surface of layer A, was constructed by assigning the height of the top of each cell in the first layer with the corresponding value from the 5 × 5 m Digital Terrain Model of the Piedmont Region (ICE 2009–2010 aerial survey). The elevations taken from the interpretation of the data reported on the geoportal of the Region of Piedmont for the base of the aquifer of Turin (D.G.R. n. 34-11524 of 3/06/2009, updated to April 2022) were used to reconstruct the bottom of layer A, which represents the base of the shallow aquifer. Instead, Layer B represents a portion of the deeper aquifer. The dataset for the height of the stratigraphic contact was interpolated using the geostatistical ordinary kriging technique within the PLPROC (Parameter List PROCessor) [25] software package of PEST. The river Dora Riparia is also represented within the model, as a result of the RIV package, which is available on MODFLOW 6. In the case of a head in a cell connected to a river that drops below the riverbed, water will enter the groundwater system from the river at a constant rate. Conversely, if the head is above the riverbed, water will either leave or enter the groundwater system, depending on whether the head is above or below the head in the river. The conductance term will be multiplied by the difference between the head in the cell and the head in the river to determine the flux [26]. The river's geometry was simulated using a shapefile created on QGIS, and the conductance was set using the formula "((Kz · ObjectSectionIntersectLength) · DrainWidth)/DrainSedimentThickness". Where Kz is the vertical hydraulic conductivity (considered 1/10 of Kx); then, 'ObjectSectionIntersectLength' is the length of intersection between a cell or element and a two-dimensional projection of a section of the object (river) that is returned via MODFLOW automatically. The 'DrainWidth' is the width of the boundary condition and 'DrainSedimentThickness' is the thickness of the sediment in the boundary condition perpendicular to the flow between the boundary and the cell (vertical thickness of the sediment). Two distinct General Head Boundaries (GHB) were incorporated into the model, respectively situated upstream of the flow to represent inflow and downstream of the model to represent outflow. The General Head Boundary package is employed to simulate head-dependent flux boundaries. In the GHB, the flux is consistently proportional to the difference in head; there is a linear relationship between the flux into (or out of) groundwater and the head in the cell [27]. The value used for the boundary conditions was evaluated on the piezometric surface data available on the ARPA Piemonte website.

The calibration was configured with 310 Pilot Points (PPs) relative to the hydraulic conductivities of Layer A and Layer B (shallow aquifer and deeper aquifer, respectively). The distribution of PPs is concentrated at locations where high precision was required, predominantly in proximity to the case study area. The initial hydraulic conductivity, also known as prior information, of layer A ranged from a minimum of $1.6 \cdot 10^{-4}$ m/s to a maximum of $3.4 \cdot 10^{-3}$ m/s. This was determined through a comprehensive analysis of ARPA data, derived from well tests conducted in the Torino area, and a stratigraphic examination of borehole points available on the Piedmont Geoportal. Furthermore, additional site-specific data from IREN S.p.A. were also incorporated into this study. Utilising these data points, a hydraulic conductivity map was generated using kriging interpolation from the PLPROC package (Figure 9). It is important to note that while the initial information is crucial, it does not impose any restrictions on the calibration process. For the purpose of this model, 16 observation points within the model were employed, thereby ensuring a robust and accurate simulation of the aquifer.

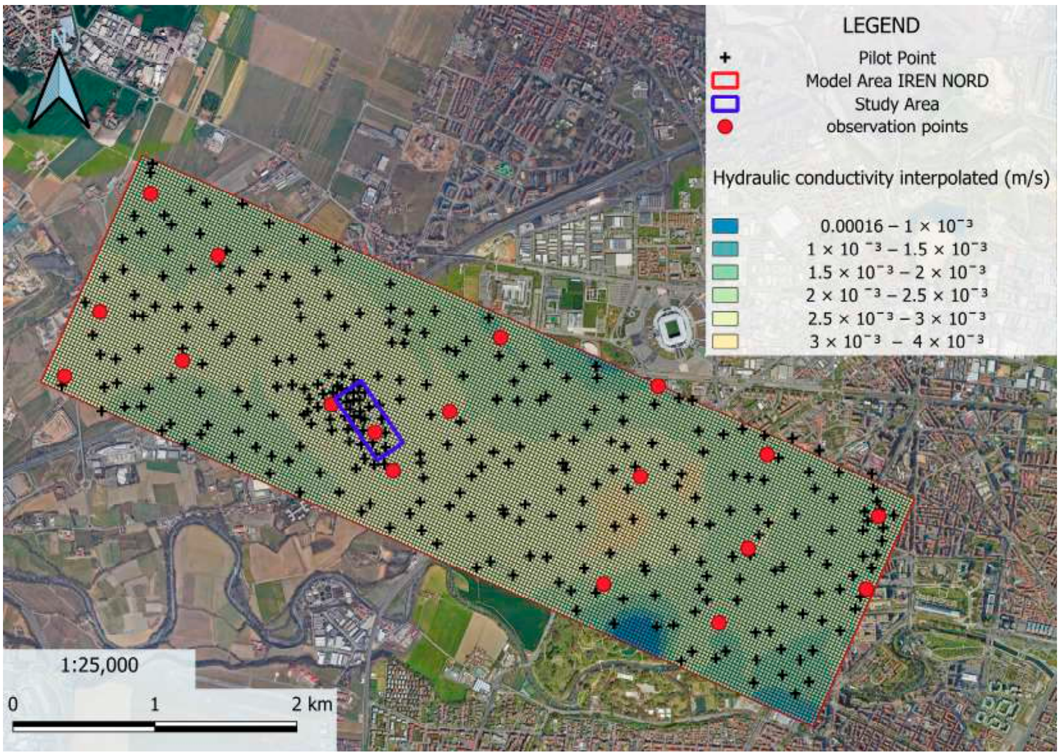

Figure 9. Hydraulic conductivity map, generated by kriging. The red circles represent the observation points, while the crosses represent the pilot points used.

2.3. Case Study 2: Moncalieri Area

To obtain a comprehensive understanding of the subsoil, two geognostic surveys (C1 and C2) at a depth of 30 m from ground level were analysed, with undisturbed sampling. The surveys also involved 5 dynamic penetrometric tests, surface geophysical surveys, MASW (Multi-channel Analysis of Surface Waves)-type seismic tests, deep down-hole geophysical surveys, and geotechnical analysis laboratory granulometric tests for the classification of the samples taken in the surveys. Drilling was carried out in October 2022 using a rotary technique with continuous coring. The groundwater level measured after drilling has a static depth of 5.20 m from the ground level and is fully consistent with the groundwater flow pattern indicated by the regional hydrogeological survey. The geological–stratigraphic model can be summarised as follows (Figure 10): backfill soil is present up to a maximum depth of 2.5 m from ground level. The heterometric alluvial series consists of lentiform layers of gravel with pebbles and sand and extends to a depth of approximately 21 m. Subsequently, there is continuous and homogeneous, grey-coloured marly siltstone, which is consistent with the sub-lithoid and exists from a depth of approximately 21 m to the bottom of the borehole (Figure 11).

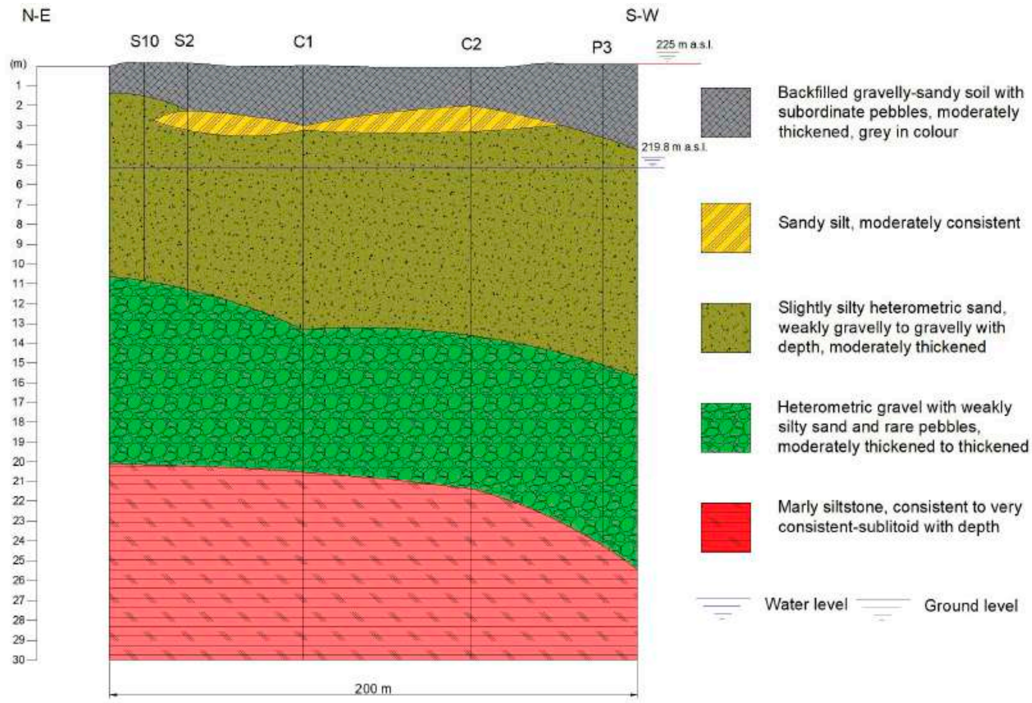

Figure 10. Interpretative geological cross-section derived from the 2 boreholes (C1 and C2) conducted by IREN Company S.p.A. and 3 ARPA boreholes (S10, S2, and P3).

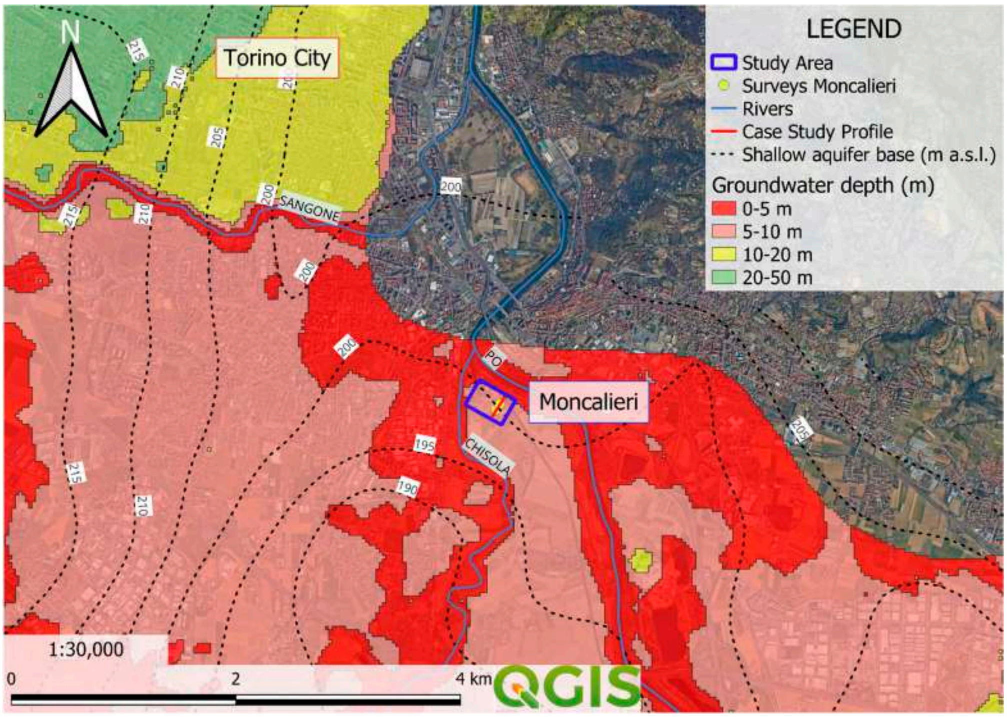

Figure 11. Groundwater depth map of Torino and base of the shallow aquifer made from ARPA Piemonte geodatabase.

In this case study, the shallow aquifer measures roughly 20 metres thick (Figure 11). The base of the shallow aquifer consists of marly siltstone, beginning at an altitude of 200 metres a.s.l.

The numerical flow model of the area was constructed using information obtained from site-specific surveys and data accessible on geoportals. The model domain covers an area of approximately 1.13 km^2, with a uniform grid of 10 × 10 m, comprising a total of 22,796 cells. The same settings of case study one were employed for the development of the model, with the objective of adapting it to the specific characteristics of the area. Rivers Chisola and Po are also represented within the model, as a result of the RIV package. The calibration was configured with 200 Pilot Points (PPs) relative to the hydraulic conductivities of Layer A and Layer B. The distribution of PPs is concentrated at locations where high precision was required, predominantly in proximity to the case study area. The initial hydraulic conductivity, also known as prior information, of layer A ranged from a minimum of 7.1×10^{-4} m/s to a maximum of 1.5×10^{-3} m/s. This was determined through a comprehensive analysis of ARPA data, derived from well tests conducted in the Moncalieri area, and a stratigraphic examination of borehole points available on the Piedmont Geoportal. Furthermore, additional site-specific data from IREN S.p.A. were also incorporated into this study. Utilising these data points, a hydraulic conductivity map was generated using kriging interpolation from the PLPROC package (Figure 12). For this model, four observation points within the model were employed, two provided by ARPA and two by IREN S.p.A.

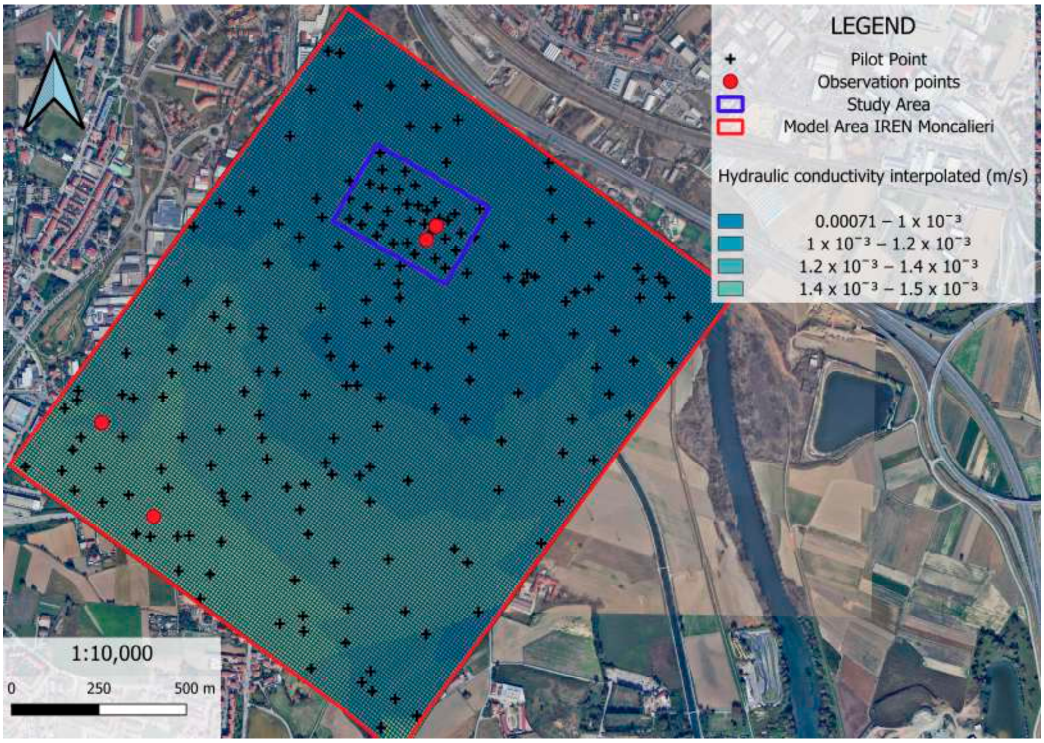

Figure 12. Hydraulic conductivity map, generated by kriging. The red circles represent the observation points, while the crosses represent the pilot points used.

3. Results

In the first case study, a steady-state model was constructed in order to accurately represent the shallow aquifer in its natural state [28]. Several packages within the MODFLOW 6 suite were employed (GHB, RIV, OBS) in order to generate a three-dimensional numerical simulation of the model area. Following this, a calibration process was undertaken. The use of PESTHP enabled the parallelisation of the calculation processes, which, in this case study, comprised more than 30 optimisation operations. In each optimisation operation (610 equations solved) the weights were adjusted in accordance with the regularisation target objective function. Figure 13 shows the plot of simulated versus observed data from the calibration process with an RMSWR of less than 0.0238 (0.15 m average error).

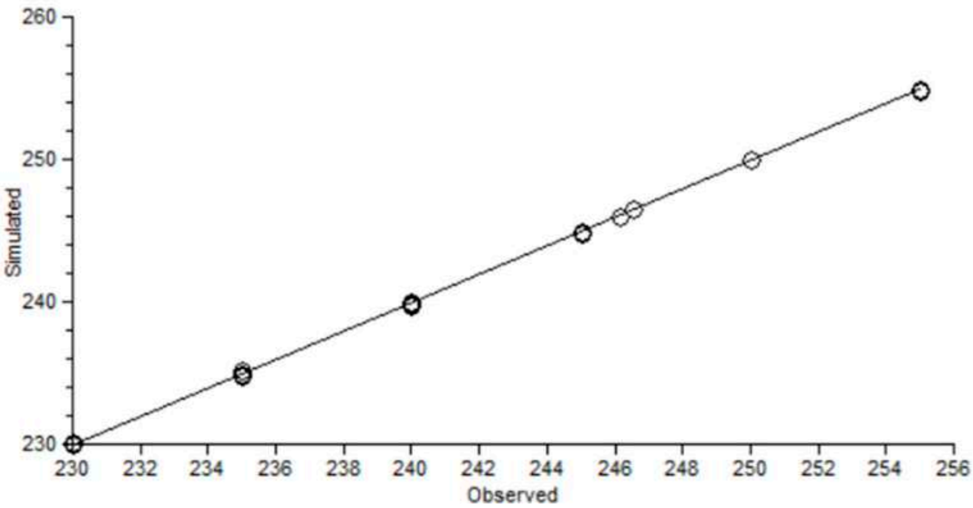

Figure 13. Graph of the simulated vs. the observed points after the model calibration process.

Figure 14 illustrates the change in hydraulic conductivity following calibration and its deviation from the prior information. Additionally, the range of values is distinct, with a minimum of 5.9×10^{-5} and a maximum of 1×10^{-2} (Figure 14).

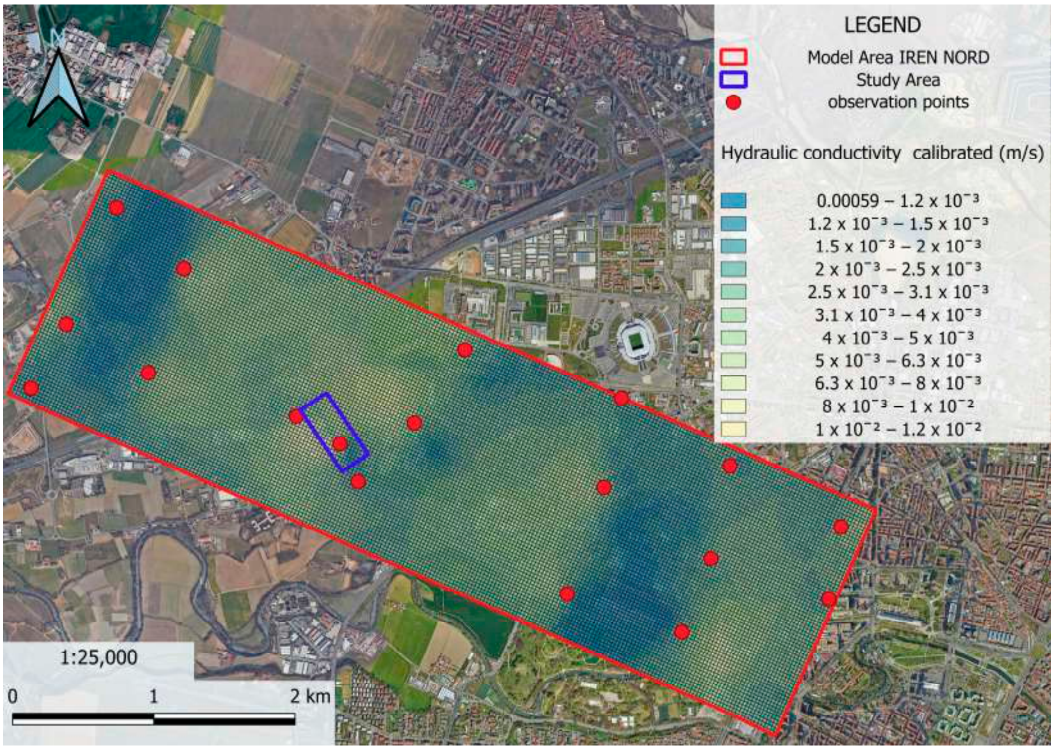

Figure 14. Hydraulic conductivity distribution of MODFLOW 6 after PESTHP calibration process.

In Figure 15, a comparison is made between the piezometry simulated with the MODFLOW 6 software following calibration and the interpolated piezometry provided by ARPA in 2002. The result is a slight difference, which is mainly due to the interpolation process and the data available. The purpose of calibration is to analyse the uncertainties resulting from the great variability of the geomaterials. The resulting outcome demonstrably enhances the representation of reality in comparison to more simplistic numerical models that solely consider a single value of hydraulic conductivity.

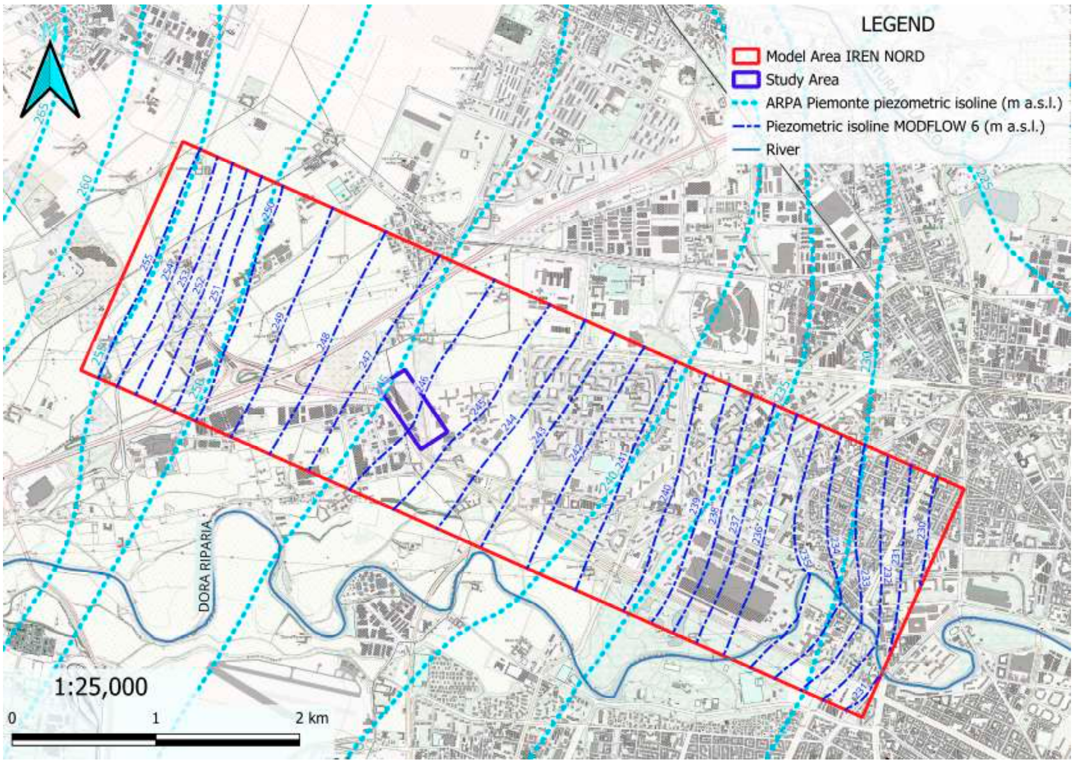

Figure 15. Comparison between the piezometry simulated through MODFLOW 6 and the calibration process, as well as the piezometry available on the Piedmont Geoportal.

Also, for the second case study, a steady-state model was constructed using MODFLOW 6. The use of PESTHP enabled the parallelisation of the calculation processes, which, in this case study, comprised more than 20 optimisation operations. In each optimisation operation (400 equations solved), the weights were adjusted following the regularisation target objective function. Figure 16 shows the plot of simulated versus observed data from the calibration process with an RMSWR of less than 0.04656 (0.21 m average error).

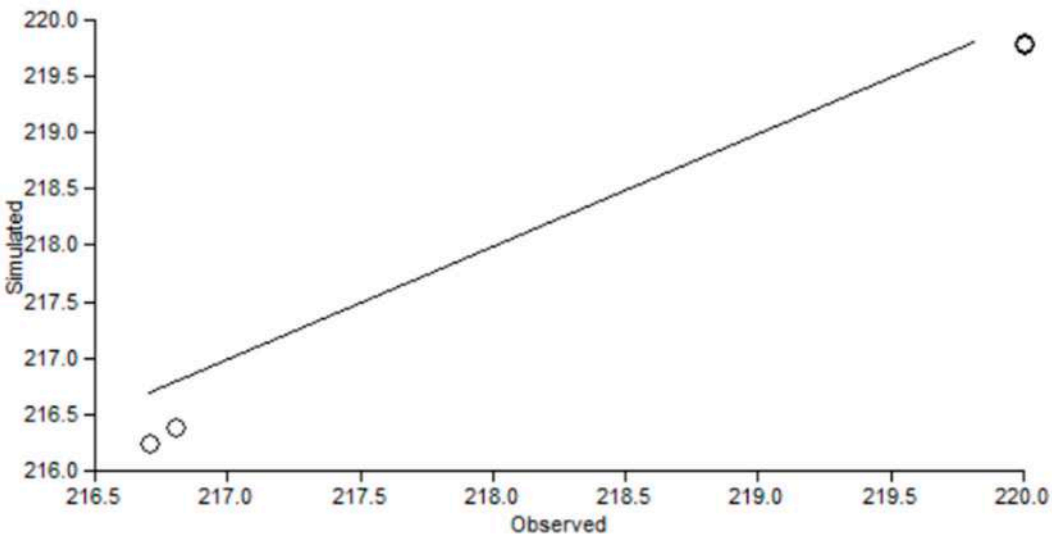

Figure 16. Graph of the simulated vs the observed points after the model calibration process.

Figure 17 illustrates the change in hydraulic conductivity following calibration and its deviation from the prior information. Additionally, the range of values is distinct, with a minimum of 8.3×10^{-5} and a maximum of 4.5×10^{-3} (Figure 17).

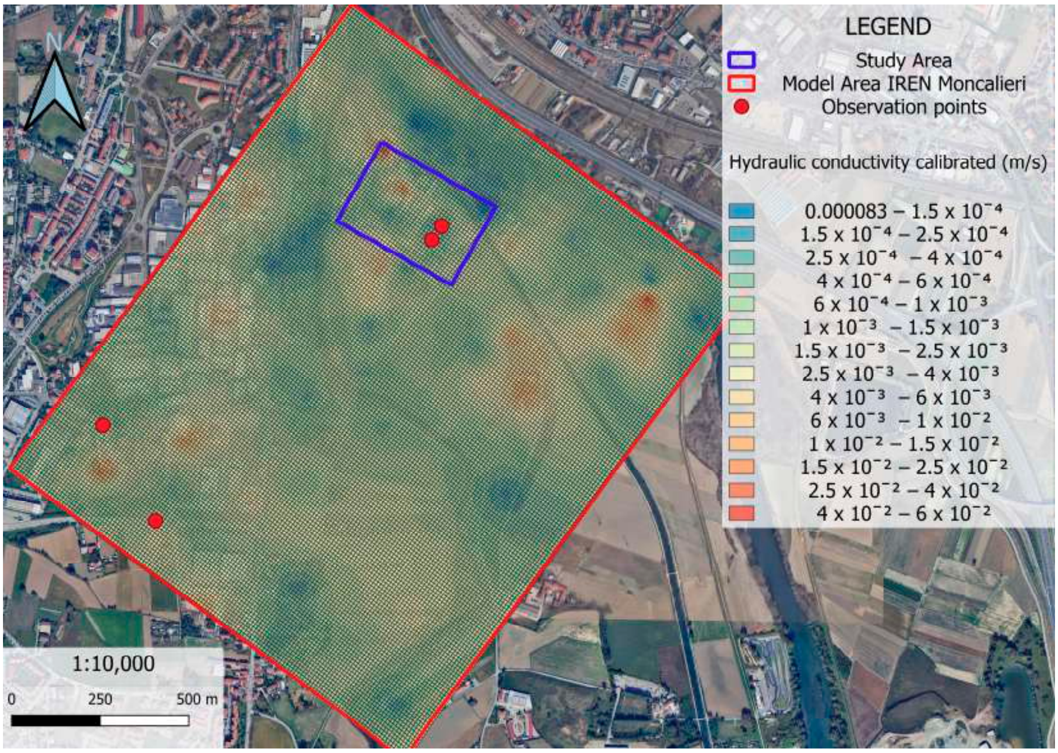

Figure 17. Hydraulic conductivity distribution of MODFLOW 6 after PESTHP calibration process.

In Figure 18, a comparison is made between the piezometry simulated with the MODFLOW 6 software following calibration and the interpolated piezometry provided by ARPA in 2002. In this case, the available data are less comprehensive than in case study one, and there are no piezometric isolines within the area.

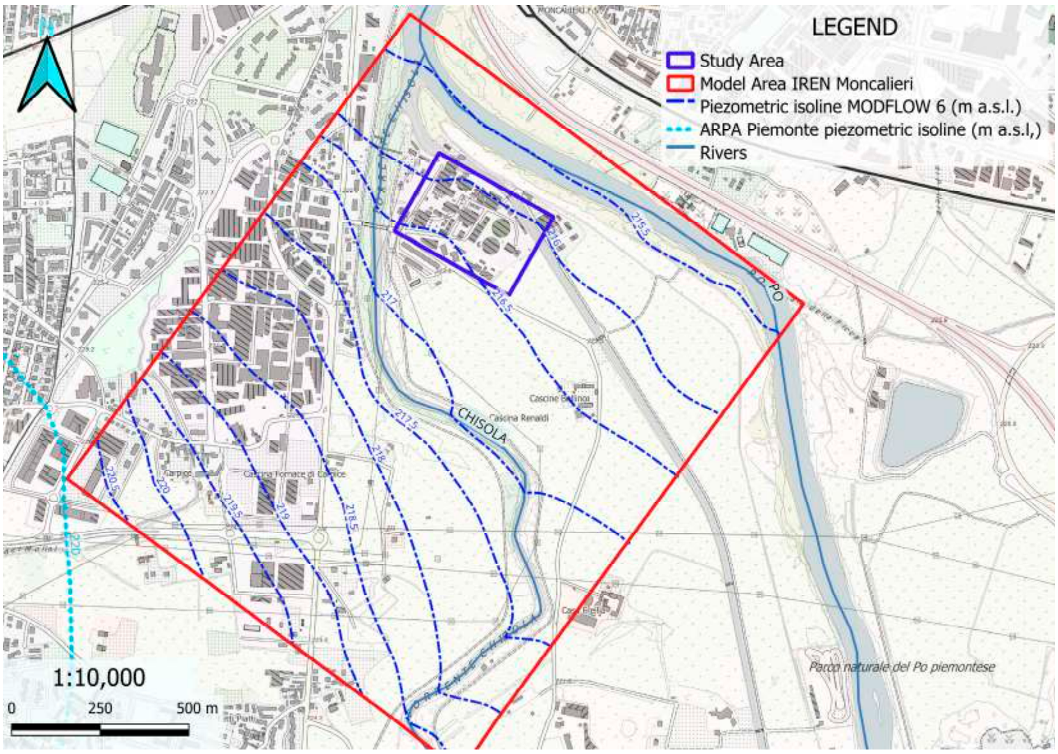

Figure 18. Comparison between the piezometry simulated through MODFLOW 6 and the calibration process, as well as the piezometry available on the Piedmont Geoportal.

4. Discussion

The imperative task of assessing the repercussions of climate change on groundwater resources not only stands as a priority in water management but also represents a compelling scientific challenge. The multifaceted influences on groundwater systems in urbanised areas, characterised by a convergence of natural and anthropogenic factors, underscore the complexity of the issue. The distinct characteristics of urban loadings, marked by multifactorial attributes, varying effects on recharge and discharge, irregular temporal and spatial patterns, and concentration within limited areas, emphasize the intricate interplay shaping hydrogeological conditions. It is evident that the rates and degrees of change in these conditions are intrinsically linked to the joint action of anthropogenic influences and the inherent characteristics of geological, hydrogeological, and hydrological conditions [16,29]. In order to be able to simulate anthropic influences such as the installation of geothermal plants in the area, it is necessary to start from a solid base with a model that can best represent the undisturbed natural environment [30].

The two case studies represent two marginal portions of the urban context of Torino, yet they exhibit some differences. These differences are evident in the modelling analysis that was carried out for both cases. Indeed, the two model areas exhibit significant differences due to their distinct hydrogeological contexts. It is of paramount importance to select an appropriate model size for numerical simulations of aquifers, as the boundary conditions may otherwise affect the area of interest. In the first case study, the decision was made to utilise a larger-scale model with a smaller cell size, to avoid overburdening and lengthening the calculations. In the second case, given that the area of interest is mainly affected by the interference of the two main watercourses, the Po and Chisola rivers, and having much less data available, a smaller area but smaller cell size was chosen to increase accuracy.

The phase of identifying, analysing, and selecting the data to be included in a numerical simulation model is of fundamental importance for the generation of a consistent result. Furthermore, the process of calibration and uncertainty analysis serves to enhance the model, thereby approximating reality. This is evidenced by a comparison of the distribution maps of hydraulic conductivity values before and after the process (Figures 9, 12, 14, and 17). The objective function is of paramount importance in model calibration, as it quantifies the discrepancy between model predictions and observed data. Calibration is the process of minimising this discrepancy by adjusting model parameters, with the objective function guiding the optimisation process to help PESTHP identify the optimal parameter values. During calibration, PESTHP evaluates the model across different parameter combinations (e.g., hydraulic head and hydraulic conductivity). For each set of parameters, the model output is computed and compared to observed data (e.g., groundwater levels). In the first case study, an average error of 15 cm between simulated and observed values was deemed acceptable. In the second case study, an average error of approximately 21 cm was considered acceptable. This difference is primarily due to the varying number of observations in each case. Increased precision in the second case study would result in significantly longer computation times, with no guarantee of enhanced physical accuracy in the final output. These models serve as the foundation for the future design of open-loop systems and the simulation of interference in terms of water and heat flow. In addition to geological and hydrogeological considerations, it is vital to ascertain whether there are already operational open-loop facilities in the vicinity that may pose a potential risk to, or be influenced by, any new facilities. For this reason, the current distribution of open-loop facilities in Turin is presented in Figure 19.

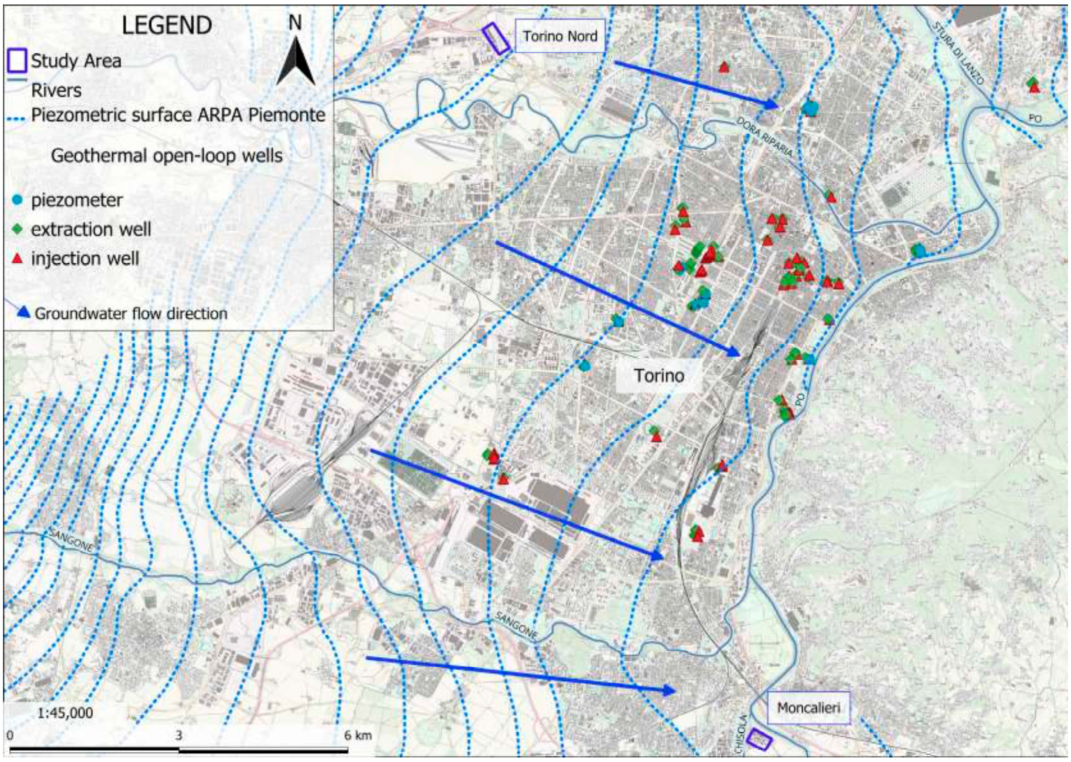

Figure 19. Spatial distribution of geothermal wells and flow direction of shallow aquifer in Torino.

As depicted in Figure 18, the Torino Nord study area is situated more than 4 km away from the closest existing geothermal plant. This considerable distance, tailored to the characteristics of the Turin shallow aquifer, provides a suitable context for the establishment of a new geothermal open-loop plant without causing interference with other extant facilities. In the second case study, positioned in proximity to the River Po and River Chisola, the potential for geothermal water discharge into these rivers adds a layer of intrigue. This approach not only mitigates the issue of thermal plume generation, which could perturb the normal temperature of the shallow aquifer, but also aligns with the regulatory framework outlined in Article 29 of the Plan Regulations of the PTA of Piemonte Region and is consistent with the stipulations in Article 104 of Legislative Decree No. 152/2006. This regulatory compliance underscores the strategic alignment of the proposed geothermal water discharge method with established environmental and legislative standards, further substantiating its feasibility and sustainability.

From a geological point of view, the Torino Nord area is situated on alternate gravel and sand deposits that correspond to the Mindelian-Rissian fluvioglacial terrace. Based on the detailed analysis carried out by the IREN company, the lithology results indicate that at a depth of up to 30 m, there is a good mix of granules, which includes gravel, pebbles, gravel sand, and silt in subordination. The clay content is consistently low, with only localised and minor portions exhibiting a higher sandy fraction than gravel. The occurrence of silty, silty-sandy, or silty-clayey textures is rare and limited to thin layers. From a hydrogeological perspective, these features typically lead to good continuity and a greater emphasis on horizontal movement of the water table rather than vertical percolation into the ground. Additionally, the water table depth averages around 22 m with an aquifer thickness of approximately 25 m. The Moncalieri area is situated on sand and gravel alternations that correspond to Holocene fluvial deposits. Based on the in-depth analysis carried out by IREN, the lithological results indicate that the upper 10 m of the site are composed of sand with gravelly silt, followed by gravel with a silty-clayey sand texture down to a depth of 20 m, and finally marly silt which, from a hydrogeological point of view, forms the base of the shallow aquifer. The average depth of the water table is approximately 5 m, with an aquifer average thickness of 15–20 m.

In the context of planning geothermal systems, both case studies exhibit favourable attributes for the following reasons:

- Geological and lithological properties align with the requisites of geothermal plant installations;
- Economically viable flow rates are attainable;
- Hydrogeological properties, encompassing conductivity, porosity, and flow speed, demonstrate favourable conditions (considering the numerical simulation);
- The likelihood of thermal feedback with neighbouring systems is minimal (due to the distance).

These characteristics collectively contribute to the suitability of the selected case studies for the implementation of geothermal systems, ensuring compatibility with geological and hydrogeological considerations while minimising potential interference with neighbouring systems.

5. Conclusions

The IREN Company district heating network presently comprises over 726 km of double tube, supplying over 2500 GWh/year energy to the networks and servicing around 500,000 residents. The potential for geothermal resource integration in the IREN Company district heating network, which presently relies heavily on cogeneration plants with a negligible proportion of renewable energy, underscores the importance of this sustainable energy source.

Both case studies have favourable initial hydrogeological features for the development of open-loop geothermal technologies. However, to ensure the responsible deployment of large geothermal plants, comprehensive numerical simulations are indispensable. Precise determination of the thermal impact on the aquifer and mitigation of potential interference with existing systems demand rigorous assessments. In particular, this applies to case study one, which is located upstream from other plants and has the potential to cause disruption with the current geothermal plants. In the second case study, the lack of data and the influence of rivers can present a challenge if not addressed in an appropriate manner and with due consideration of the uncertainties inherent in the methodological approach of model calibration. The collaboration with industrial partners, in particular IREN S.p.A., is of great importance to the success of this research. It demonstrates the value of industry–academic partnerships in driving forward innovative energy solutions. This synergy facilitates the practical application of theoretical models, ensuring that research outcomes are both scientifically rigorous and practically viable.

For future research, the numerical models presented in this work will be employed to analyse in detail the influence of future open-loop plants and the environmental impact on the surface aquifer, in terms of piezometric variation and thermal interference. Continued research, investment, and collaboration are essential for the full realisation of the potential of geothermal technology. The continued utilisation of numerical modelling will be of paramount importance in this endeavour, as it will provide the necessary tools to optimise system design, predict performance, and ensure sustainability. These endeavours will facilitate a significant contribution of geothermal energy to Italy's transition to renewable energy, which will in turn promote environmental sustainability and economic resilience.

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Data Availability Statement: The data utilized, with the exception of IREN surveys, is accessible via the following website: https://geoportale.igr.piemonte.it/cms/; https://geoportale.arpa.piemonte.it/app/public/; http://aperto.comune.torino.it/.

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Conflicts of Interest: The authors declare no conflicts of interest.

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