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Exploring the aquifers shaping Italy's sub-urban landscape

Rassegna degli assetti idrogeologici che caratterizzano il sottosuolo urbano italiano

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Riassunto

Questo articolo esamina le caratteristiche idrogeologiche e le sfide della gestione delle acque sotterranee urbane in dieci città italiane: Torino, Milano, Padova, Bologna, Roma, Pescara, Napoli, Bari, Catania e Cagliari. L'urbanizzazione ha posto una significativa pressione sui sistemi idrici sotterranei, evidenziando la necessità di una gestione sostenibile. Lo studio categorizza le città in base al loro assetto idrogeologico e agli usi delle acque sotterranee, identificando problemi chiave quali salinizzazione, contaminazione industriale e subsidenza del suolo. Il lavoro sottolinea l'importanza degli acquiferi urbani locali non solo per soddisfare l'approvvigionamento idrico sia per usi potabili che industriali, ma anche per garantire un sostegno ecologico, auspicando una gestione integrata delle acque urbane per aumentare la resilienza contro le potenziali future carenze idriche e gli impatti del cambiamento climatico.

Abstract

This review paper examines the hydrogeological characteristics and challenges of urban groundwater management in ten major Italian cities: Torino, Milano, Padova, Bologna, Roma, Pescara, Napoli, Bari, Catania, and Cagliari. Urbanisation has placed significant pressure on groundwater systems, highlighting the need for sustainable management. The study categorises the cities based on their hydrogeological settings and groundwater uses, identifying key issues such as salinisation, industrial contamination, and land subsidence. The findings emphasise the importance of urban local aquifers (ULAs) not only for meeting the demand for both drinking and industrial water but also for providing ecological support. The paper advocates for integrated urban water management and governance to enhance resilience against potential future water shortages and climate change impacts.

Introduction

Urbanisation poses significant challenges to the management and sustainability of groundwater resources. The importance of urban groundwater cannot be overstated, and there are many benefits derived from sustainable groundwater use in cities. These include: the economic value from diverse applications such as potable water supply, industrial processes, garden irrigation, and shallow geothermal energy; the ecological value in supporting groundwater-dependent ecosystems within urban areas; and the additional value inherent in groundwater storage, serving as both a buffer against urban storm flooding, future water scarcity, and fire hazards, as well as for "less noble" uses such as street washing and cooling (La Vigna et al. 2015). However, rapid urbanisation, coupled with anthropogenic activities, has placed unprecedented pressure on groundwater systems, leading to various challenges and uncertainties for the future. This is also true for the major Italian cities.

In this context, we introduce the term Urban Local Aquifer (ULA) to describe those aquifers (sometimes of local importance) existing beneath a city or a densely urbanised area. They are often overlooked, especially if of modest productivity, but they constitute an important city resource, frequently underpinning many ecosystem services and supplies for various uses.

In the varied geological and hydrogeological scenario of the Italian territory, urban settlements encounter different hydrogeological settings, which may either favour or hinder the use of ULAs for supply, and may also present obstacles to urban infrastructure or opportunities for sustainable urban development.

The aim of this review paper is to present this varied scenario of urban hydrogeology in Italy, considering the hydrogeological settings, uses, issues, and opportunities of ten major Italian cities. It is hoped that this review will highlight common features or issues and stimulate the exchange of best practices between them.

Review Method

This review was developed by considering the hydrogeological setting of the following ten major cities in Italy: Torino, Milano, Padova, Bologna, Roma, Pescara, Napoli, Bari, Catania, and Cagliari (Fig. 1). For each city, after a general description of the hydrogeological setting, the groundwater uses and issues are reported. The discussion presents the similarities and differences among them from the perspective of the sustainable use of local groundwater resources, highlighting the challenges faced by Italian cities in this regard. In this comparison, the Groundwater-City classification system proposed by La Vigna (2022) is used to identify city typologies.

General geological and hydrogeological setting of Italy

Italy boasts a geologically intricate landscape shaped by the convergence of tectonic plates, particularly the African and Eurasian plates, which resulted in the formation of the Apennine and Alpine mountain ranges (Compagnoni et al., 2011) (Fig. 1). The Apennines exhibit complex geological structures, characterised by diverse rock formations such as limestone, shale, and sandstone, indicative of intense tectonic activity (Barchi et al., 2001). In the southern part of the chain (Calabria Region and the north-eastern part of Sicilia), the domain is more crystalline, with similar formations existing on the island of Sardegna, where these types of rocks are dominant. In the Alps, the pressure formed great recumbent folds, or nappes, that rose out of what had been the Alpine Tethys and pushed northward, often breaking and sliding over one another to form gigantic thrust faults. Crystalline basement rocks, which are exposed in the higher central regions, form Mont Blanc, the Matterhorn, and high peaks in the Pennine Alps (Stampfli & Borel, 2004), while the southern and south-eastern Alpine margin exhibits sedimentary rocks such as the well-known Dolomites. Alternating with these important reliefs, and along the coastal areas, are various plains of varying thickness and areal extent; among these, the Po Plain (Pianura Padana) certainly occupies a significant place, both in terms of size and hydrogeological importance.

Notably, the active volcanoes in Italy, including Mount Vesuvius and the Phlegraean Fields near Napoli, as well as Mount Etna and the Aeolian Islands in Sicilia, represent manifestations of the extensive tectonics occurring along the Italian Peninsula (Santacroce et al., 2003). These volcanic structures have left a lasting impact on the geological makeup of the regions they dominate, shaping landscapes and contributing to the creation of fertile soils (Branca et al., 2023).

Hydrogeologically, Italy's geological features play a pivotal role in the distribution and availability of groundwater. The permeable limestone rocks in the central and southern Apennine mountains (Boni et al., 1986) serve as extensive karst aquifers, with some examples also found in the Alpine sectors (though with less storage and discharge), storing significant amounts of groundwater that contribute to the water supply of many cities and communities. Additionally, alluvial plains and coastal areas of Italy host aquifers, contributing to the diverse hydrogeological settings of the country and their various uses (Martinelli et al., 2018; Mastrocicco, 2021).

Even in those sectors (especially on the eastern side of the Apennines) where the rocks generally exhibit low permeability, the presence of local aquifers is evidenced by the abundance of low-discharge springs. These springs have historically supported local rural communities and small suburbs, sustaining human settlements across Italy (Petitta & Tallini, 2003).

To summarise, Italy's geological and hydrogeological characteristics showcase a complex interplay of sedimentation, tectonic, metamorphic processes, and volcanic activity, which has led to the development of various groundwater circulation patterns and influenced groundwater chemical characteristics. In this context, it is important to highlight that groundwater represents the largest water resource in Italy and satisfies 85% of the water demand (48% from wells and 37% from springs), significantly covering both agricultural and industrial needs (Ducci et al., 2017; ISTAT, 2019). According to the varied scenarios presented, and depending on their location, Italian cities exhibit distinctive characteristics as follows.

Hydrogeological setting of several Italian cities

Torino (Piemonte Region - Northern Italy)

General hydrogeological setting

Torino, located in the Piemonte Region in north-western Italy, lies on the banks of the Po River and is bordered by the crystalline rocks of the Alps to the north-west and the tertiary Piedmont Basin deposits of the Torino Hill to the south-east, contributing to its unique geological characteristics.

From a morphological perspective, the area is largely flat, with a topographical surface that gently slopes in a west-east direction, starting from the outermost edges of the Rivoli-Avigliana Amphitheatre.

A shallow unconfined aquifer is hosted in the glacial deposits of the Rivoli-Avigliana Amphitheatre (glacial deposits complex), and in the alluvial plain deposits (fluvial and fluvioglacial deposits complex), primarily composed of coarse gravel and sand, with occasional silty-clayey intercalations. Deeper confined and/or semi-confined aquifers are found within the 'Villafranchiano' complex (late Pliocene–early Pleistocene) and the Pliocene sandy marine sediments (De Luca et al., 2020).

Groundwater within the shallow aquifer flows predominantly eastward, towards the Po River, which acts as the main gaining element of the entire Torino Plain (Bortolami et al., 1976; De Luca & Ossella, 2014; Lasagna et al., 2016a). Piezometric levels range from a maximum elevation of 360 metres a.s.l. in the western sector to a minimum of 205 metres a.s.l. in the north-eastern sector, near the Po River. The depth of the water table varies between 50 metres in the Perialpine sector and 5 metres in the vicinity of Torino Hill and the surrounding areas adjacent to the main river systems (Debernardi et al., 2008; Forno et al., 2018). According to this hydrogeological description, Torino can be considered an Alluvial Groundwater City (AGC) (La Vigna, 2022) (Figs. 2 and 3).

Groundwater uses

The Piemonte Regional Law No. 22 of 30 April 1996, "Research, Use, and Protection of Groundwater", imposes significant restrictions on the exploration and use of groundwater. Under this legislation, while extracting water from the shallow unconfined aquifer is permitted for all purposes, extraction from confined and semi-confined

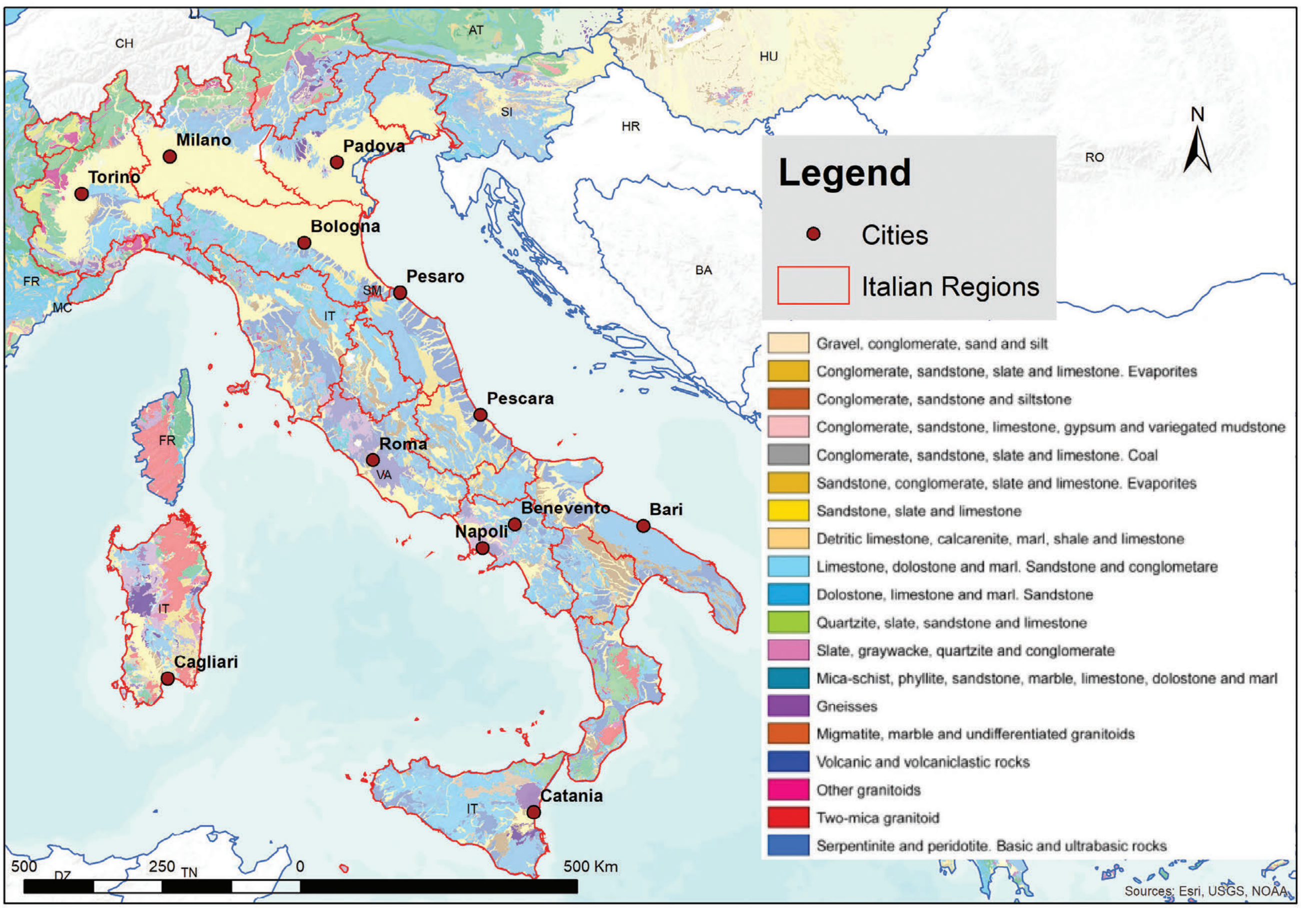

Fig. 1 - Cities presented in this paper on an excerpt of the EGDI 1:1 Million Pan-European Surface Geology (EGDI 2022).

Fig. 1 - Città presentate in questo articolo proiettate su uno stralcio della Carta geologica Pan-Europea di superficie (EGDI 2022).

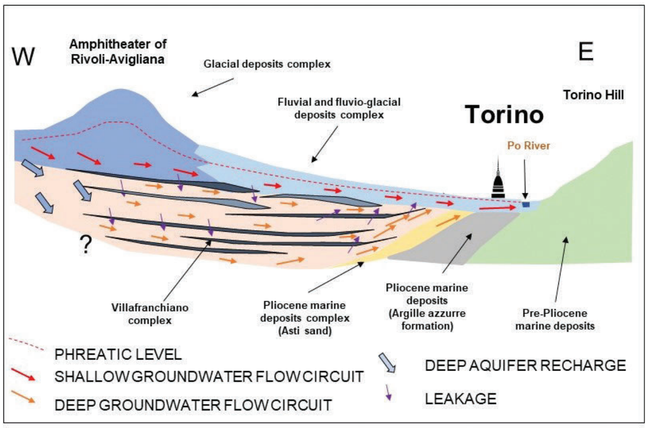

Fig. 2 - Conceptual hydrogeological model of the Torino area, showing deep aquifers, conditioned by the buried hilly structure, and a shallow aquifer, both flowing from the Alps towards east (modified from Forno et al. 2018).

Fig. 2 - Modello idrogeologico concettuale dell'area di Torino. Sono individuate due circolazioni principali entrambe con direzione prevalente dalla zona alpina verso Est; gli acquiferi profondi sono condizionati dalla struttura sepolta della zona collinare (modificato da Forno et al. 2018).

aquifers is only allowed for drinking water use. Consequently, groundwater for drinking water supply in the Torino area is entirely sourced from the confined Villafranchian aquifers. Many industries in Torino also depend on groundwater for their operations, including manufacturing processes, industrial cooling systems, and other industrial uses where water is essential. According to regional law, shallow aquifers are generally used for non-food industrial purposes, while water for food-related purposes, which require higher quality, is drawn from deep aquifers. Additionally, Torino's alluvial shallow aquifer is an important resource for harnessing low-enthalpy geothermal energy (Berta et alii, 2024; Gizzi et al., 2024). Finally, shallow groundwater is also used for irrigation in agricultural areas surrounding Torino, where farms extract groundwater to supplement surface water sources, particularly during periods of low rainfall or drought.

Groundwater issues

Significant anthropogenic pressure on the region, particularly over the past 50 years, has inevitably impacted groundwater resources, both qualitatively and quantitatively, necessitating the implementation of sustainable management practices (De Luca et al., 2019). The heavy exploitation of aquifers, particularly during the post-war economic boom, has resulted in the depletion of aquifers and the deterioration of their chemical-physical properties, especially within the shallow unconfined aquifer (Lasagna et al., 2014, 2019, 2020a).

Specific contamination problems include hexavalent chromium (Cr VI), chlorinated solvents, and nitrate pollution (Lasagna et al., 2015, 2016b; Martinelli et al., 2018; Lasagna & De Luca, 2019; Cocca et al., 2024). Furthermore, the impact of geothermal heat pump systems and borehole heat exchangers on groundwater in Torino's urban context is under investigation (Bucci et al., 2018; Taddia, 2018).

In addition, climate change is affecting groundwater both in alpine and plain environments, in terms of both quantity and quality (Bucci et al., 2017, 2019; Lasagna et al., 2020b; Bastiancich et al., 2022; Mancini et al., 2022; Egidio et al., 2022; Lasagna et al., 2024).

Milano (Lombardia Region – Northern Italy)

General hydrogeological setting

The city of Milano is located in the east-central part of the Lombardia Region, and its metropolitan area is one of the most densely populated regions in Europe, with 3.25 million people (2019) in an area of 1,575 km². From a hydrogeological perspective, the area is underlain by a vast regional aquifer, extending from the Adda to the Ticino River, and from the

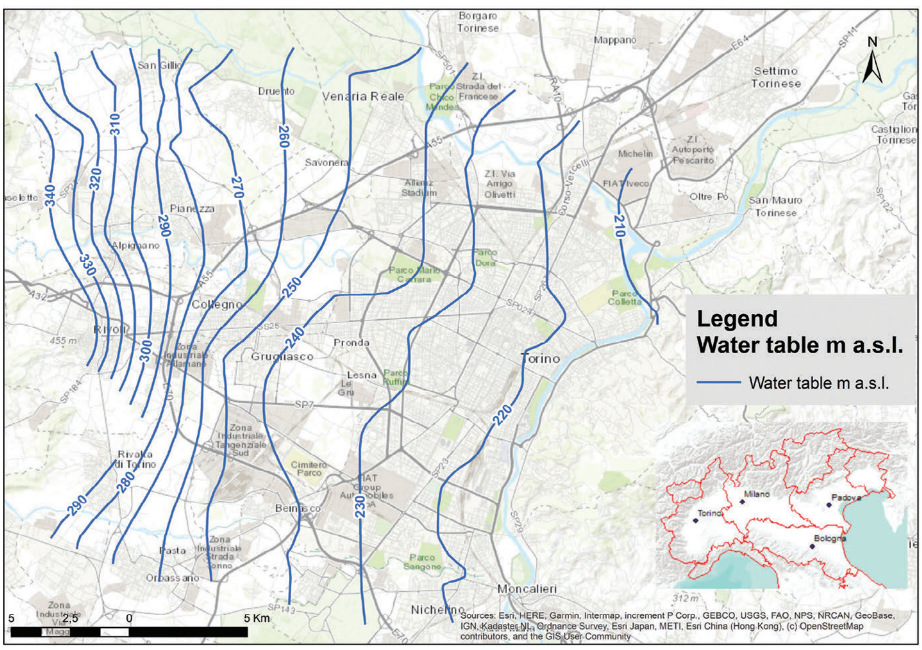

Fig. 3 - Water table map of the shallow unconfined aquifer (January 2000) (modified from De Luca & Ossella, 2014).

Fig. 3 - Carta piezometrica dell'acquifero superficiale freatico della Città di Torino. (Gennaio 2000) (modificato da De Luca & Ossella, 2014).

Prealps to the Po River, subdivided into eight groundwater bodies. In addition to the main rivers mentioned, the Milano plain is traversed by three smaller rivers (the Olona, Seveso, and Lambro) and five irrigation canals that feed a dense irrigation network. Stratigraphic data collected from various drilling studies have provided a well-known hydrogeological setting. The aquifer-bearing alluvial deposits are a sequence of Plio-Pleistocene sediments that filled the Po Plain, with a maximum thickness of around 500 metres (Bini, 1997; Perego et al., 2014). At the base of the sequence, sediments are predominantly clay and silt, while gravel and sand are dominant near the surface. Based on glacial depositional cycles, these deposits can be divided into four hydrogeological units (Fig. 4), referred to as Aquifer Groups A, B, C, and D (Regione Lombardia & Eni, 2002). These units, from the youngest (A) to the oldest (D), contain aquifers separated by clayey deposits, which act as aquitards. The shallower Aquifer Groups A and B are the most exploited: Aquifer Group A is primarily composed of gravels with sandy layers, forming the shallow unconfined aquifer (K from 10^{-4} m/s to 10^{-3} m/s), while Aquifer Group B consists of sands with silty-clayey lenses (K from 10^{-5} to 10^{-4} m/s) and can be divided into four sub-units (B1, B2, B3, and B4). Groundwater flow is generally oriented north-south and is influenced by the major rivers, Ticino and Adda (Fig. 5), which act mainly as gaining rivers (Alberti et al., 2016a). A 20 km-wide belt between the higher and lower plain is characterised by the presence of lowland springs (known as fontanili). Based on this hydrogeological setting, Milano can be classified as a typical Alluvial Groundwater City (AGC) (La Vigna, 2022).

Groundwater uses

In the Milano Metropolitan Area, groundwater is mainly extracted for drinking and industrial purposes through approximately 3,000 wells, making it one of the primary water resources for the region. In contrast, river water is mostly used for agricultural purposes and, in a few cases, for industrial use. Drinking water is extracted through wells managed by public water management companies (Metropolitana Milanese S.p.A. and Gruppo CAP). In 2022, the annual groundwater withdrawal in the metropolitan area amounted to 460 million m^3/year, of which 208 million m^3/year were extracted within the City of Milano. The actual volume of industrial groundwater use is harder to estimate, but in the same year, the total volume granted for extraction in the metropolitan area reached 205 million m^3/year. This amount was surpassed by geothermal use, which has grown significantly over the past 20 years, reaching 345 million m^3/year in 2022 (Sartirana et al., this volume; Sartirana et al., 2020, 2022).

Groundwater issues

Three main issues affect the groundwater in Milano: quality, quantity, and temperature regulation. Quality is the best-known and longest-standing issue. The industrial development experienced by the metropolitan area between the 1950s and 1980s created numerous contamination plumes of chlorinated hydrocarbons (CHCs), chromium, and hydrocarbons, which flow from the north into the city. Since the 1990s, public authorities have been addressing this problem (Colombo et al., 2019), identifying many sources of contamination and implementing remediation actions and/or hydraulic barrier interventions. Consequently, water quality is gradually improving, but the process is slow. In 2017, the Lombardia Region had to establish anthropogenic background values for perchloroethylene, trichloroethylene, and trichloromethane (D.D.U.O. No. 5590 of 16/05/2017; Azzellino et al., 2019; Alberti et al., 2019; Colombo et al., 2020).

Regarding quantity, Lombardia has long been considered a water-rich region due to its glaciers, lakes, numerous rivers, and large, thick aquifers. However, climate change has caused increasingly intense periods of drought, which in the 2000s, for the first time in Lombardia, led to conflicts of interest over water resource use. Groundwater levels have fluctuated significantly over time, with heavy exploitation leading to a minimum level around 1975 and a considerable rebound since the early

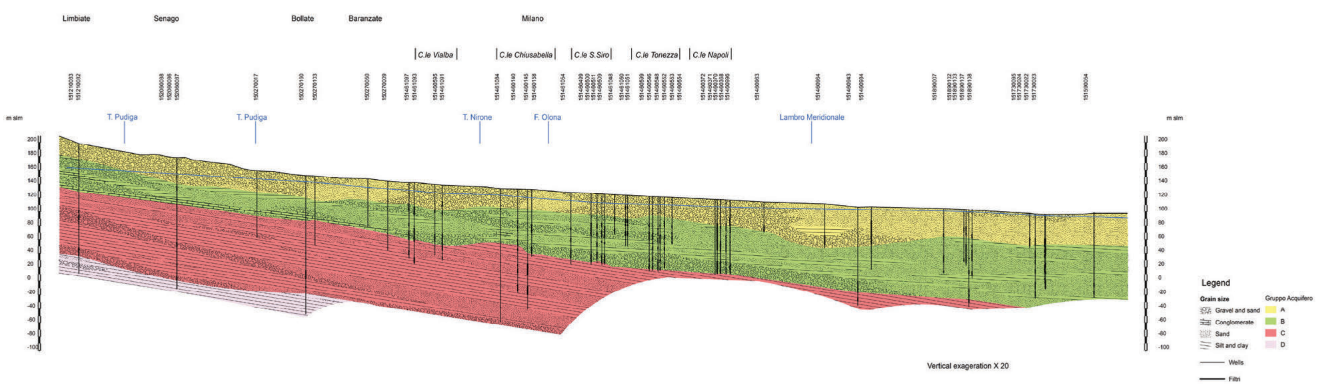

Fig. 4 - Hydrogeological cross-section N-S passing through Milano; yellow colour represents Aquifer Group A, green represents Aquifer Group B, red represents Aquifer Group C, and purple represents Aquifer Group D.

Fig. 4 - Sezione idrogeologica N-S passante attraverso Milano; il colore giallo rappresenta il Gruppo Acquifero A, il verde il Gruppo Acquifero B, il rosso il Gruppo Acquifero C e il viola il Gruppo Acquifero D.

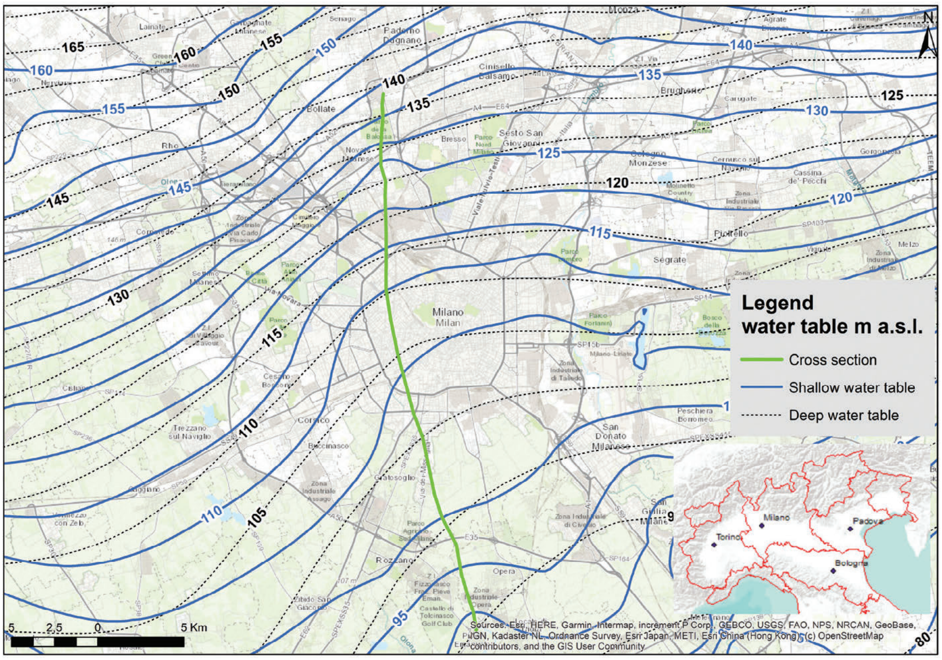

Fig. 5 - Water table of Group Aquifer A and B in 2014, with Milano city area at the centre of the figure (Lombardia Region, 2014).

Fig. 5 - Piezometria del Gruppo Acquifero A and B nel 2014 con l'area della Città di Milano nel centro della figura.(Regione Lombardia, 2014).

1990s, when levels rose due to industrial decommissioning (with a maximum rise of about 10–15 metres in the north). As a result, some underground infrastructure, including metro tunnels and car parks, have experienced flooding (Sartirana et al., this volume; Gattinoni & Scesi, 2017; Colombo et al., 2018). These factors have raised awareness among citizens and public authorities about the need for better management of surface and groundwater resources, which must take into account the impacts of climate change and the implementation of adaptation measures in the near future (Alberti, 2016b; Oberto et al., 2018; Colombo et al., 2024).

Finally, the need for cities to reduce their carbon footprint, along with the ongoing energy revolution, has led to a significant increase in the use of geothermal systems for heating and cooling buildings in the Milan Metropolitan Area. These systems are creating cold and hot thermal plumes that overlap, reducing system efficiency (Antelmi et al., 2021). For this reason, in densely urbanised areas like Milano, there is a growing need for stricter regulations on the design of new plants to ensure that geothermal resources are used sustainably, maintaining energy efficiency in the future.

Padova (Veneto Region – Northern Italy)

General hydrogeological setting

The city of Padova is located in the Veneto Region in the northeast of Italy, within an alluvial environment. Data from 120 shallow boreholes, drilled for remediation projects in potentially contaminated sites, have been analysed to understand the local hydrogeological setting. The findings indicate low permeability in the shallow lithologies.

These various lithologies were translated into "permeability degrees" for hydrogeological interpretation. Specifically, two cross-sections run across the entire territory of Padova, one in a roughly NW-SE direction (A-A') and the other in a NE-SW direction (B-B') (Figs. 6, 7 and 8).

Aside from the presence of anthropogenic deposits in the shallowest layers (such as backfill or archaeological deposits), the area is characterised by low-permeability deposits, primarily silty and silty-clayey layers. However, in the ENE area of Padova, some medium to high-permeability shallow horizons (sandy or sandy/gravelly, 5–6 m thick) have been identified (Figs. 7 and 8). These are mainly concentrated in areas where paleochannels are present (Mozzi et al., 2010, 2013, 2018; Ninfo & Mozzi, 2016).

Groundwater level measurements were taken from around 40 wells scattered throughout Padova's territory (Figs. 7 and 8). Based on this data, a water table map of the city has been drawn. The shallow water table is approximately 1 to 1.5 metres below ground level, with absolute elevations ranging from 6 metres (a.s.l.) in the southeast of Padova to about 15 metres (a.s.l.) moving northwest (Fig. 6). On a broader scale, the most notable characteristic is the groundwater flow direction, which runs from northwest to southeast, following the typical trend of the entire Venetian Plain in northeastern Italy. One particular feature of Padova's groundwater circulation is the noticeable drainage from the northwest, passing through the central part of the city and flowing towards the industrial zone on the east side, with a very low gradient (ranging from 0.15% to 0.03%). The calculated gradient varies from 1.3 to 1.5 per thousand where the isophreatic lines are closer together, while lower gradients of around 0.3 to 0.5 per thousand occur in areas where the isolines are slightly more spaced apart.

Based on this hydrogeological description, Padova can be classified as a typical Alluvial Groundwater City (AGC) (La Vigna, 2022).

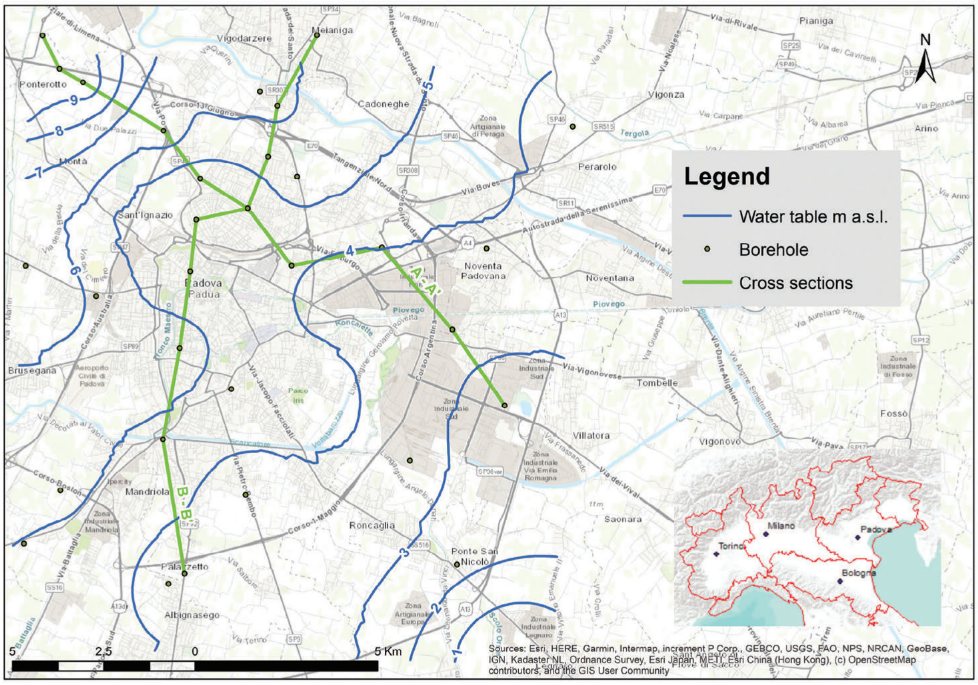

Fig. 6 - Water table map of Padova city (Fabbri & Zagati, 2021).

Fig. 6 - Piezometria della Città di Padova (Fabbri & Zagati, 2021).

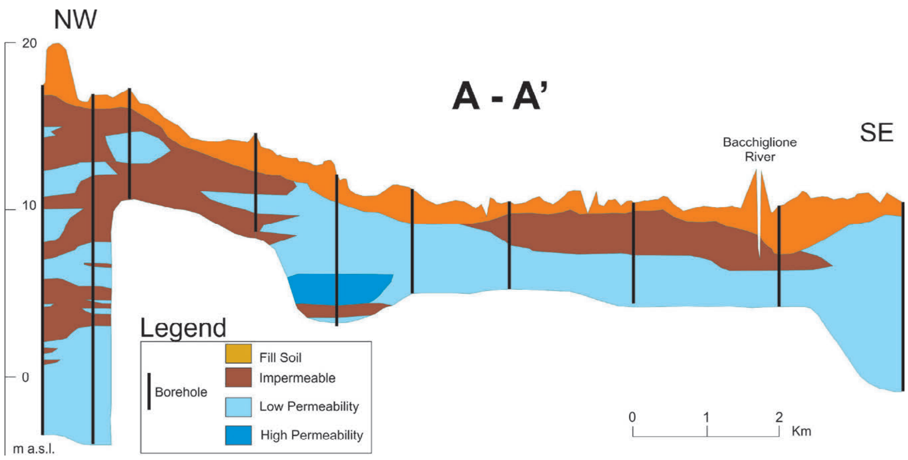

Fig. 7 - Hydrogeological cross section A-A' of Padova City (see Fig. 6).

Fig. 7 - Sezione idrogeologica A-A' della Città di Padova (vedi Fig. 6).

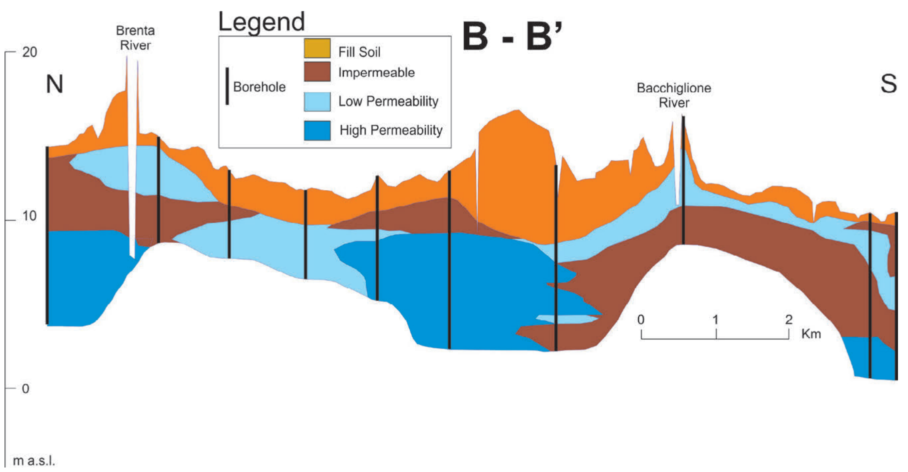

Fig. 8 - Hydrogeological cross section B-B' of Padova City (see Fig. 6).

Fig. 8 - Sezione idrogeologica B-B' della Città di Padova (vedi Fig. 6).

Groundwater uses

The groundwater from the phreatic aquifer is of very limited use due to its poor quality. The water supply for the city of Padova is entirely provided by well fields located in phreatic and confined porous aquifers about 40 km northwest of the city, in the province of Vicenza.

Groundwater issues

As mentioned earlier, the water table is very shallow. This shallow water table can pose problems for Padova's historic heritage. A notable example is the issue it presents for the crypt of the Scrovegni Chapel, one of the city's most famous monuments, frescoed by Giotto in 1303. The crypt serves as a barrier against soil moisture, protecting the frescoes from damage. However, during heavy rainfall, the rising groundwater level causes flooding of the pavement. To manage this flooding, a pumping system is eventually activated (Dalla Santa & Simonini, 2024).

From a quality perspective, the shallow aquifer contains high levels of iron, manganese, and arsenic, along with pollutants of anthropogenic origin, such as nitrates, halogenated organic compounds, and hydrocarbons.

Bologna (Emilia-Romagna Region, Northern Italy)

General hydrogeological setting

The main hydrogeological asset of the city of Bologna (392,000 inhabitants in 2023 in the municipality, around one million in the metropolitan area) is the vast alluvial fan of the Reno River (covering an area of around 400 km^2), located immediately west of the historic centre at the river's exit from the Northern Apennines into the higher sector of the Emilia-Romagna Plain, the southern portion of the broader Padano-Veneta Plain (Fig. 9). The fan consists of a continental alluvial Quaternary succession, reaching a thickness of over 300 metres (Fig. 10), and lying unconformably over Upper Pleistocene transitional and shallow marine deposits (Amorosi et al., 1996; Regione Emilia-Romagna & ENI AGIP, 1998; Giacomelli et al., 2023). The stacking of macroclastites (gravels and, to a lesser extent, sands) and fine-grained layers is organised according to tectonic and glacio-eustatic oscillations. In the proximal sector of the fan, gravels dominate, with amalgamated macroclastic bodies forming an unconfined aquifer connected to direct and lateral recharge. In the distal sector, a multilayer confined aquifer occurs, with an increased sandy fraction, an average M/P (Macroclastite/Pelite) ratio always less than 0.3, and vertical downward-directed leakance across the aquitard units (Fig. 10). To the east of the fan, the historic city sits atop an interfan sector dominated by overconsolidated fine-grained units. Further east lies a smaller alluvial fan formed by the Savena River, which provides a secondary contribution to the local groundwater supply (Fig. 9).

The total estimated groundwater stock in the macroclastic units of the Reno fan is around 8,000 Mm^3 (ARPAE, 2005). Reno fan aquifers are recharged both by effective infiltration in the proximal sector and by the Reno River itself across its gravelly bed through a focused recharge process. (Currently, the riverbed is disconnected from the water table, which has been lowered by pumping. This setting differs from the classical one found in humid climates, where a river loses water to a connected aquifer. Instead, it is more akin to a focused recharge typical of arid climates). Direct recharge of the Reno fan has been estimated at around 0.7–0.8 m^3/s (mean annual value for the period 1983–2006; Chahoud et al., 2013), while the contribution from the Reno River, estimated at around 1.1 m^3/s for the period 1983–1998 (ARPAE, 2005), is crucial for maintaining the hydrogeological balance of the system. According to this hydrogeological setting, Bologna can be considered a typical "Alluvial Groundwater City" (La Vigna, 2022).

Groundwater uses

Current groundwater withdrawals are used for public water supply, drawn from three well fields that tap into the permeable units from below 100 metres depth down to the base of the fan (around –300 metres relative to mean sea level). In 2020, total withdrawals amounted to 38 Mm^3, with an equivalent pumping rate of 1,200 L/s. This supply meets around 40% of the city's public water demand, with the remaining 60% provided by surface water from the Setta and Reno rivers in the mountainous sector of the metropolitan area. Industrial and domestic groundwater use, although more uncertain, is estimated to account for 25% of public water supply withdrawals, bringing the total extraction rate to around 1,500 L/s. The resulting drawdown has created a depression centred in the fan, inducing a centripetal groundwater flow (Fig. 9). Approximately 40 years ago, groundwater withdrawals were higher, with a total pumping rate of around 1,550 L/s for public water supply alone, alongside a more significant contribution from industrial abstractions (Zuccarini et al., 2024).

Groundwater issues

The main groundwater-related issues are diffuse urban contamination by chlorinated solvents and land subsidence due to inelastic deformation of aquitards caused by drawdown (Farina et al., 2014). Chlorinated hydrocarbons contaminated the shallow aquifer from historical point sources (such as metal degreasing factories and railway facilities), and were transported by downward leakance, induced by pumping, into the alluvial fan, resulting in cross-contamination reaching the deeper aquifer units. However, the regional centripetal flow, which draws groundwater from less contaminated areas surrounding the urban centre, helps dilute and attenuate the contaminant load.

Since the second half of the 20th century, Bologna has experienced significant anthropogenic subsidence, largely localised and linked to groundwater withdrawals (Zuccarini et al., 2024), with rates reaching 100–110 mm/year during the 1970s and 1980s. From the mid-1980s, these rates declined following the implementation of regulations on industrial and

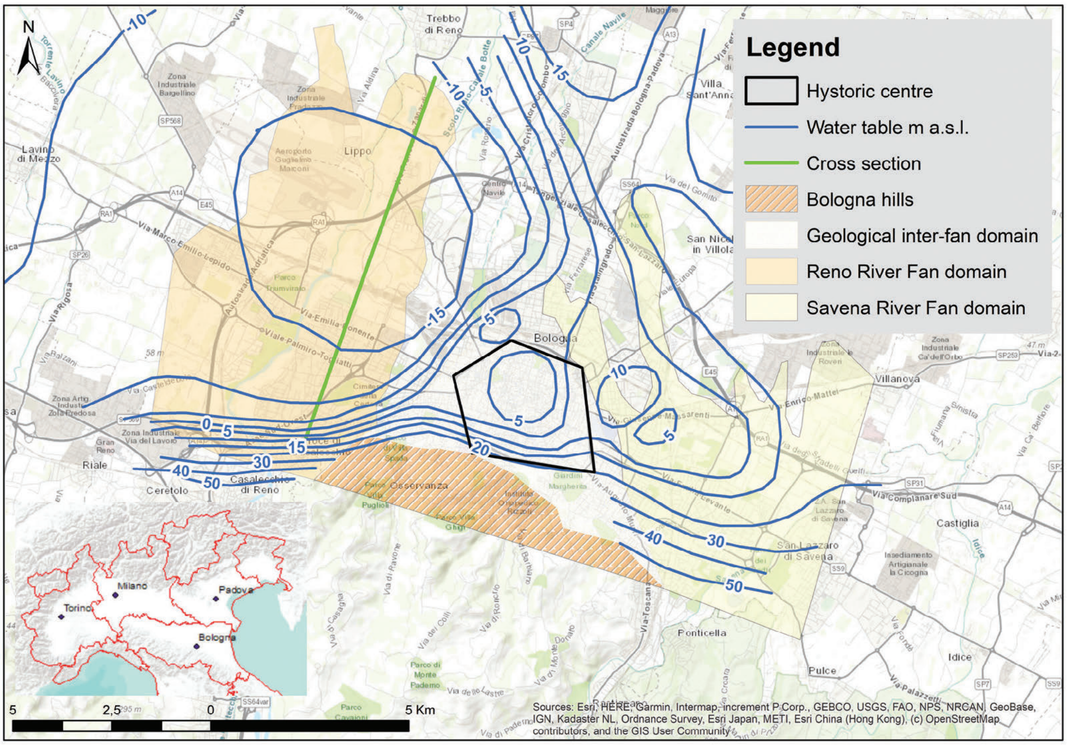

Fig. 9 - Broader urban area of Bologna with main geological and hydrogeological features. Water table (m a.s.l.) refer to groundwater hosted in intermediate and deeper sector of alluvial fan (Aquifer Groups B and C). Modified from: Zuccarini et al., 2024. Water table simplified from Comune di Bologna (2020).

Fig. 9 - Area urbana della Città di Bologna con le principali caratteristiche geologiche ed idrogeologiche. La piezometria (m s.l.m) si riferisce alle falde dei corpi acquiferi intermedi e profondi della conoide (Gruppi Acquiferi B e C). Modificato da Zuccarini et al., 2024. Piezometria semplificata da Comune di Bologna (2020).

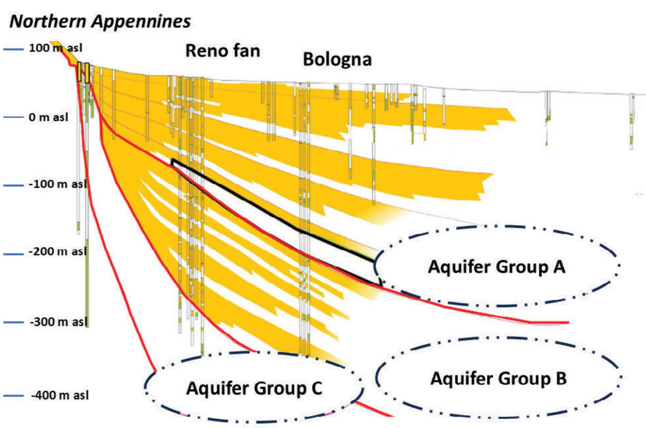

Fig. 10 - Longitudinal cross-section of Reno River alluvial fan (trace in Fig. 9) with the main hydrostratigraphic units (Aquifer Group). Aquifer Groups A and B are of alluvial origin; Aquifer Group C is of transitional origin. In orange the main macroclastic layers (dominant gravel) are put in evidence. Simplified from Regione Emilia-Romagna & ENI-AGIP (1998).

Fig. 10 - Sezione longitudinale della conoide del Fiume Reno (traccia in Fig. 9) con le unità idrogeologiche principali (gruppi acqiferi). I Gruppi Acquiferi A e B sono di origine alluvionale; il Gruppo Acquifero C è di transizione. In arancione sono riportati ed evidenziati i principali strati costituiti da materiale grossolano (ghiaia dominante). Semplificato da Regione Emilia-Romagna & ENI-AGIP (1998).

municipal well pumping and, since 2010, the introduction of alternative surface water resources. Ground displacement rates fell from 40–100 mm/year in the 1970s/1980s to around 5 mm/year (slightly above the natural threshold) by 2014–2016. However, since 2016, the rate of ground displacement has increased again, reaching around 20 mm/year. The current higher rates are found along the fan's fringe, where the M/P ratio is lower (indicating a higher proportion of compressible layers), and farther from the focused recharge effect of the Reno River, which locally enhances water table mounding and increases neutral pressure.

Roma (Lazio Region - Central Italy)

General hydrogeological setting

The hydrogeological framework and groundwater circulation pattern in Roma are influenced by the presence of a complex low-permeability substrate across the municipal area, by the geological structure, which leads to water exchange relationships between five different Hydrogeological Units, and by the presence of two perennial rivers (Mazza et al., 2015). The depressions and structural elevations of the basal aquiclude, along with the varying permeabilities that characterise some major hydrogeological complexes, define the boundaries between the primary aquifers and the main groundwater flow paths.

Within the territory of the city, several geological domains are encountered, giving rise to five Hydrogeological Units (HUs): Sabatini Mountains HU, Alban Hills HU, pre-volcanic continental deposits HU, recent and current alluvial deposits HU, and the Tiber River Delta HU (Fig. 11).

These HUs are underlain by a hydrogeological complex with very low permeability values, whose upper surface has been reconstructed based on hundreds of borehole data points and numerous scientific publications, and is documented in the Hydrogeological Map of Rome (1:50,000 scale) (La Vigna et al., 2016). This complex hydrogeological framework gives rise to various underground water flows beneath the city, sometimes overlapping, particularly along the slopes of the Alban Hills Volcano in the southeastern sector of the city. The main, mappable circulations at the city scale are essentially four: the regional aquifer that permeates almost all units, the shallow aquifer in the Alban Hills sector (sometimes also present in the Sabatini sector, North-Western sectors), supported by poorly permeable ignimbrite levels, the deep aquifer found in pre-volcanic sedimentary layers beneath the Alban volcanic rocks, and a confined aquifer within the basal gravels of the Tiber River alluvial deposits. The basal potentiometric level of the regional and shallow aquifers is regulated by the two main rivers, the Aniene and the Tiber, and by the sea along the Roman coastline southwest of the city (Fig. 12). According to La Vigna (2022), Roma can be classified primarily as a Volcanic Groundwater City (VGC) and, secondarily, as a Lagoon Delta Groundwater City (LDGC).

Groundwater uses

Roma has historically, since the Roman era, been supplied with water from karstic springs in the Apennine chain. Despite this, the city's local urban aquifers are currently used for non-potable purposes such as irrigation of public gardens, for commercial and industrial uses, and also for agriculture, given that Roma is the largest agricultural municipality in Europe (Curcio, 2023). The city's aquifers are monitored biannually through the Groundwater Monitoring Network of Rome (La Vigna et al., 2024; Roma et al., this volume).

Groundwater issues

Roma faces several groundwater-related challenges, including contamination, extraction activities, and urban groundwater flooding (Mastrorillo et al., 2016; La Vigna et al., 2019; Bonfà et al., 2017; La Vigna & Baiocchi, 2022). Contamination mainly arises from localised sources such as fuel distribution lines and accidental spills, with hydrocarbons being the most common pollutants. In addition, natural alterations in groundwater composition, such as elevated levels of certain substances due to volcanic origins, pose challenges for environmental management and remediation efforts.

Extraction activities, particularly open-pit mining, can impact groundwater levels and quality, disrupting natural flow patterns and causing potential contamination from surface water sources.

Urban groundwater flooding is another significant issue, with various processes contributing to inundation events. Groundwater flooding occurs primarily in reclaimed areas,

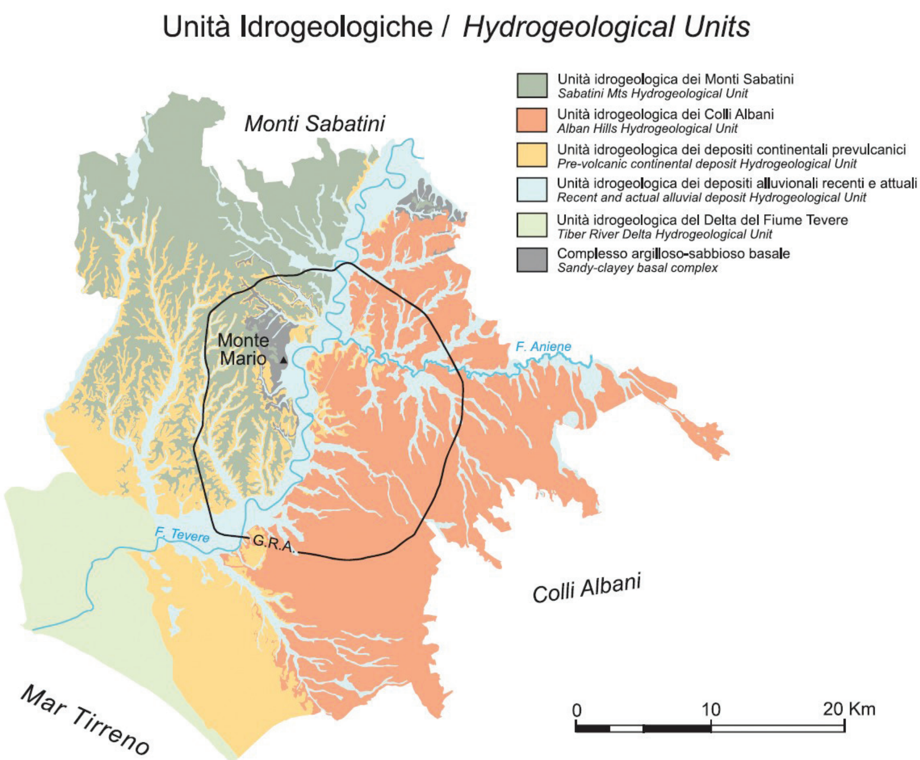

Fig. 11 - Hydrogeological Units of Roma (La Vigna et al. 2016).

Fig. 11 - Unità idrogeologiche dell'area di Roma (La Vigna et al. 2016).

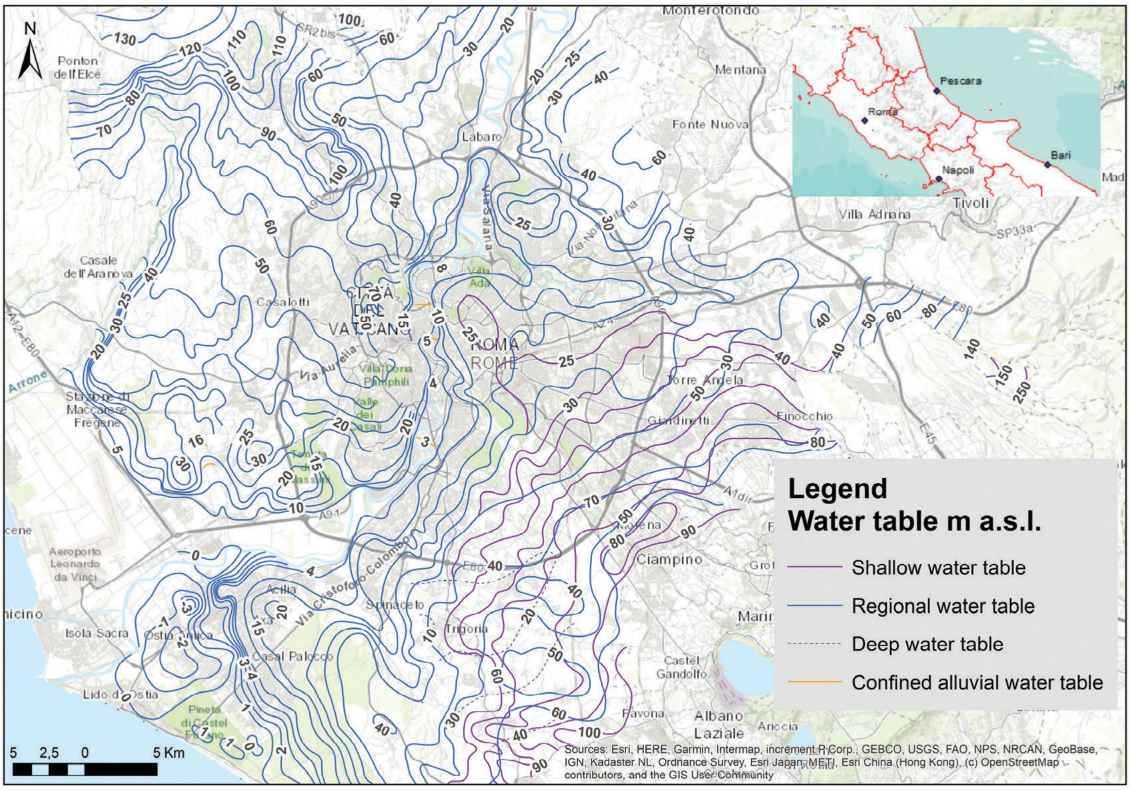

Fig. 12 - Piezometric pattern of the different aquifers of Roma (La Vigna et al. 2016).

Fig. 12 - Piezometrie sovrapposte dell'area di Roma (La Vigna et al. 2016).

exacerbated by the increase of impermeable surfaces and rising groundwater levels. Furthermore, inadequate stormwater drainage infrastructure and changing precipitation patterns have led to a rise in flash flooding in urban areas, necessitating improved flood management strategies (Lentini et al., 2022; Di Salvo et al., 2018).

Pescara (Abruzzo Region - Central Italy)

General hydrogeological sett

The urban area of Pescara extends seamlessly across the municipalities of Pescara, Montesilvano, Spoltore, San Giovanni Teatino, and Francavilla al Mare, covering a total urbanised area of approximately 135 km² with around 240,000 residents, whose drinking water needs are fully met by groundwater from the Apennine aquifers (Nanni & Rusi, 2003; Rusi et al., 2024).

Urbanisation affects three distinct morphological areas around the Pescara River and its mouth: the coastal delta, the alluvial plain, and the hilly area. From a hydrogeological perspective, the hilly area consists of clayey aquicludes, with water bodies of limited significance, used only for modest irrigation purposes.

The aquifer in the alluvial and coastal deposits (Desiderio & Rusi, 2000) comprises an alluvial series characterised by irregular alternations of sand, silt, and gravel, generally with a lenticular shape (Pleistocene-Holocene) (Fig. 13). At the edges and at higher elevations of the alluvial deposits, ancient terraced deposits outcrop, consisting of gravels with sand and silt. The "impermeable" substrate is made up of Plio-Pleistocene clayey deposits (Fig. 14).

Groundwater circulation occurs between lenses with varying degrees of permeability, extending irregularly and interdigitating with one another, forming overlapping aquifers that are hydraulically connected, creating a single multi-layer aquifer (Fig. 14). At the base of the alluvial deposits, in contact with the low-permeability substratum, there is a continuous gravel layer a few metres thick, hosting a semi-confined aquifer. The overall thickness of the aquifers varies from around 38 to 50 m, increasing towards the coast.

The deep confined aquifer is recharged in the upper part of the plain, while the multilayer aquifer is mainly recharged by rainfall and the river (Chiaudani et al., 2017). These recharge processes exhibit variable hydraulic relationships depending on the season, morphology, water usage, and human interference.

According to this hydrogeological description, Pescara can be classified predominantly as a Coastal Groundwater City (CGC), but also as an Alluvial Groundwater City (AGC) (La Vigna, 2022).

Groundwater uses

The semi-confined aquifer is exploited for industrial purposes on the western alluvial side of the urbanised area.

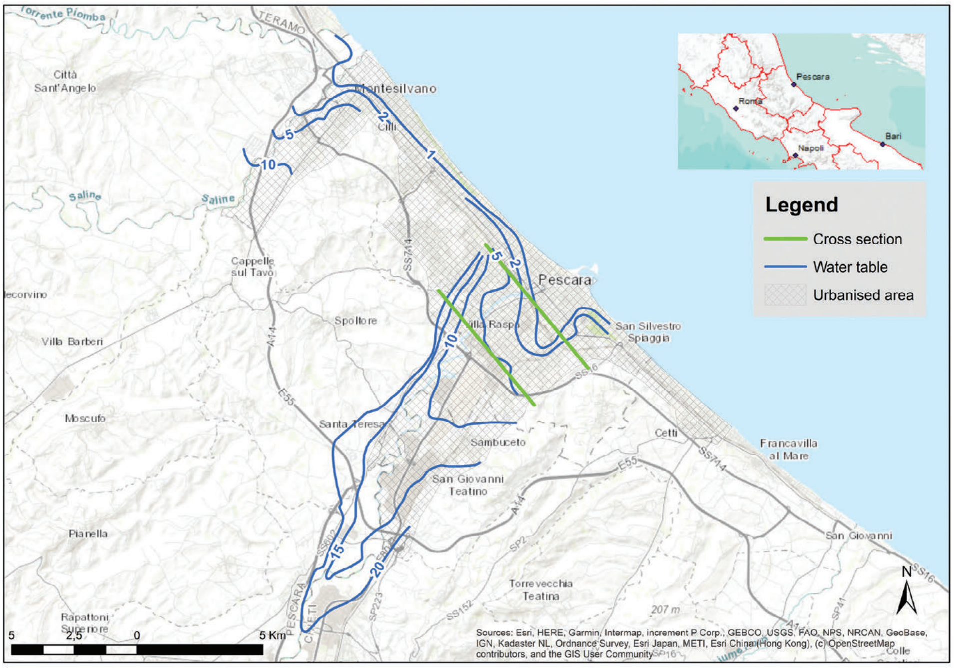

Fig. 13 - Water table of the city of Pescara (modified and updated from Desiderio et al., 2000,2007).

Fig. 13 - Piezometria della Città di Pescara (modificato e aggiornato da Desiderio et al., 2000,2007).

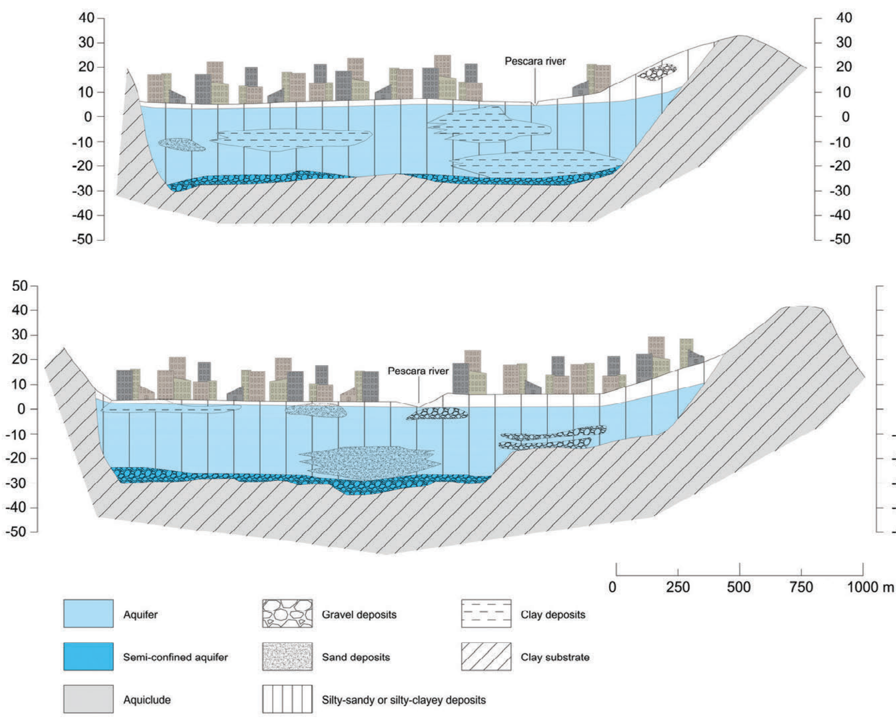

Fig. 14 - Schematic hydrogeological cross section of the urbanized area of Pescara, transversal to the river of the same name and parallel to the coastline. Above: structure in the western portion of the urbanized area about 3 km from the coastline. Below: structure about 1 km from the coastline.

Fig. 14 - Sezione idrogeologica schematica dell'area urbanizzata di Pescara, trasversale all'omonimo fiume e parallela alla linea di costa. Figura superiore: assetto della porzione orientale dell'area urbanizzata a circa 3 km dalla costa. Figura inferiore: assetto ad 1 km dalla costa.

Many wells contribute to significant withdrawals from this aquifer, with flow rates of a few dozen litres per second, generating depressions of a few metres in the piezometric surface. In the same area, wells in the multilayer aquifer extract small quantities of water (a few litres per second) for industrial and irrigation purposes.

The multilayer aquifer is also utilised in the coastal part of the city through wells for tourism and recreational purposes (particularly during the summer season), as well as for irrigation (a marginal and residual use).

Groundwater issues

Industrial exploitation causes slight and localised depressions in the semi-confined aquifer. In the coastal aquifer (Desiderio and Rusi, 2003), particularly in the area closest to the mouth of the Pescara River, the piezometric surface reveals a division in groundwater flows, with the creation of drainage axes running parallel to the Pescara River, influenced by pumping. A localised lowering of the piezometric surface below sea level has also been observed, with possible effects of seawater intrusion.

From a qualitative standpoint, the presence of former industrial areas in the port and urban zones near the river has led to contamination of the multilayer aquifer in sites that are currently undergoing remediation.

Napoli (Campania Region – Southern Italy)

General hydrogeological setting

The municipality of Napoli (117 km²) is located in the Campania region in the southern part of Italy. The city area (Fig. 15) spans three groundwater bodies (GWB): the volcanic Phlegraean Fields GWB (67%), the Eastern Plain of Napoli GWB (26%), and, in a small area, the volcanic Somma-Vesuvius GWB (7%).

Based on previous hydrogeological studies (Allocca et al., 2022; Corniello & Ducci, 2019; De Vita et al., 2018; Ducci & Sellerino, 2015), the urban area of Napoli can be divided into three distinct sectors from a hydrogeological and morphological point of view:

a. The hilly pyroclastic sector, which includes the Posillipo Hill to the west and the hills of Camaldoli, Capodimonte, and Vomero - Mt. Echia in the central part of the city. This sector is characterised (Fig. 16: section A) by welded pyroclastics (mainly tuffs deriving from the Phlegraean eruption of the Neapolitan Yellow Tuff, 14 kyr B.P.) and the presence of numerous volcano-tectonic lineations. The permeability is medium-low due to the fracture network, and groundwater flow is predominantly vertical.

b. The alluvial and marshy pyroclastic sector, comprising the plains of Agnano and Bagnoli in the western area, and the Sebeto River Valley in the eastern area (Fig. 16: section B). The aquifers in these plains are highly heterogeneous, being composed of Phlegraean and Vesuvian pyroclastics, reworked to varying degrees in an alluvial environment, interbedded with marine and marshy sediments. Groundwater flows in superimposed aquifers, interconnected through the interdigitation of deposits with various grain sizes and degrees of permeability.

c. The small coastal sector, between Posillipo Hill and Mt. Echia Hill (Fig. 15), where the aforementioned tuffs, covered by a few metres of loose deposits attributable to marine sediments, are interbedded with pyroclastics eroded from the surrounding hills.

Groundwater flow in this area is directed towards the sea. The alkalinity of groundwater increases from the east (Eastern Napoli – Sebeto River Valley), where the prevalent anion is HCO_3, to the west (plains of Agnano and Bagnoli), where it is of the Na-Cl type (Corniello & Ducci, 2019). Groundwater in Eastern Naples is also characterised by seawater intrusion and high levels of Fe and Mn, due to reducing conditions associated with the presence of peat layers. The proximity of the volcanic systems of the Phlegraean Fields and Vesuvius in the areas of Agnano, Bagnoli, and the Sebeto River Valley leads to elevated levels of fluoride and arsenic in the groundwater.

Close to the coastline of the Agnano and Bagnoli plains, numerous mineral waters, some with high temperatures (~50 °C), are present and were historically used for S.P.A.s. In the Mt. Echia area, in central Naples, there are two overlapping aquifers. A shallow aquifer flows through the weathered part of the tuff and shows no signs of seawater contamination; these waters are of the Na-HCO_3 type. The deeper groundwater is in coarse, loose pyroclastics beneath the tuff and feeds highly mineralised springs (Chiatamone springs), with high levels of TDS, CO_3, and occasionally H_2S; these waters also show no seawater contamination.

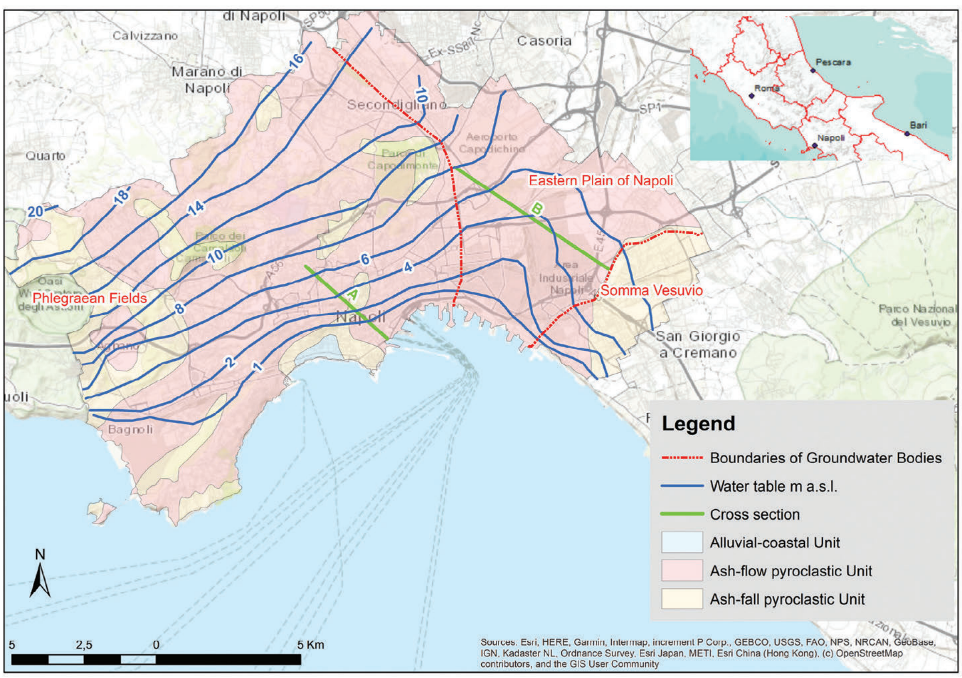

Fig. 15 - Hydrogeological Map of the City of Napoli (partially redraft and modified from De Vita et al., 2018).

Fig. 15 - Carta idrogeologica del Comune di Napoli (parzialmente ridisegnata e modificata da De Vita et al., 2018).

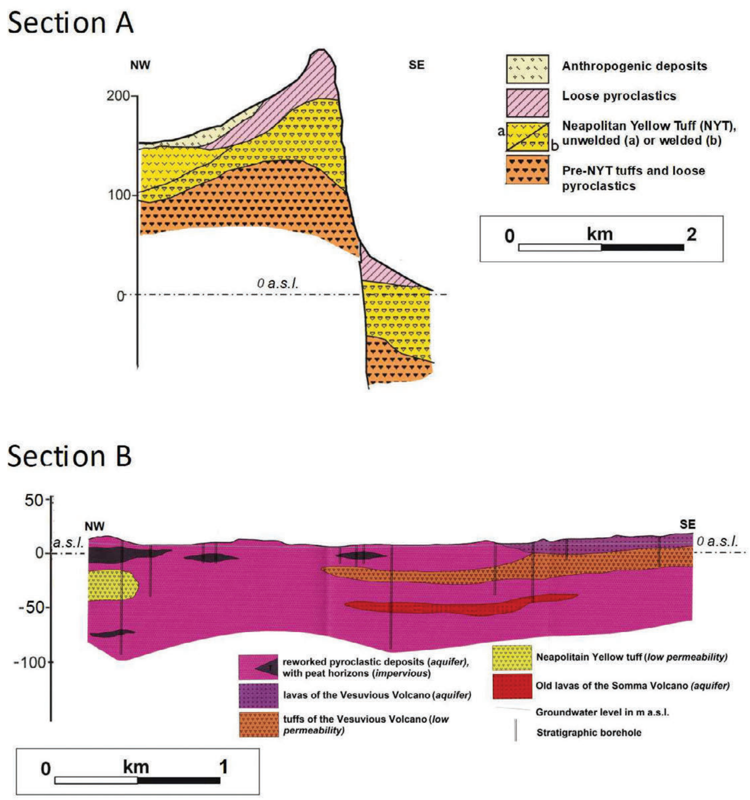

Fig. 16 - Hydrogeological Cross Sections (modified from Corniello & Ducci, 2019); traces are in Figure 15

Fig. 16 - Sezioni idrogeologiche (modificate da Corniello & Ducci, 2019); le tracce sono in Figura 15.

According to this hydrogeological description, Napoli can be predominantly considered a Volcanic Groundwater City (VGC), although some sectors can be classified as Coastal Groundwater Cities (CGC) (La Vigna, 2022).

Groundwater uses

In Napoli, local aquifers are scarcely used due to the unique hydrochemistry, which results in mineralised and gas-enriched springs. The city's primary water supply comes from the abundant karst springs of the Apennines, which are exploited for both their high availability and superior water quality. Approximately 25 years ago, knowledge of the hydrochemistry of the southern foot of Mt. Echia, where the mineralised and gas-enriched Chiatamone springs originate, spurred municipal projects aimed at enhancing this unique groundwater resource. In the past, this water was used with sodium bicarbonate to make lemon juice effervescent, and efforts were made to restore an old well built in 1846 in the Royal Palace of Napoli.

Groundwater issues

The fact that the ULAs in Napoli are not heavily exploited likely prevents significant saltwater intrusion in the coastal sector of the city. However, in the Bagnoli Plain area (located in the western sector, Fig. 15), freshwater overlies saline water, and under undisturbed conditions, the freshwater-saltwater interface reaches depths of 60-70 m below sea level, 600-800 m from the coastline (Corniello & Ducci, 2019). Additionally, the Bagnoli area is currently undergoing reclamation following steelworks activities conducted from 1910 to 1990. Groundwater contamination in this area is partly due to the natural contribution of volcanically related hydrothermal fluids and partly due to pollutants from industrial activities.

Since 2001, rising groundwater levels have been observed in the eastern part of the city (also undergoing reclamation as it once housed hydrocarbon tanks), leading to the flooding of building foundations and underground infrastructure (garages, subway tracks, etc.). This has been caused by a reduction in the extraction of water for industrial and drinking purposes in the central part of the Eastern Plain of Napoli GWB (Fig. 15) (Ducci & Sellerino, 2015).

Bari (Puglia Region – Southern Italy)

General hydrogeological setting

The city of Bari is located in the Puglia Region, with 317,000 inhabitants in the municipal area and 1,225,000 in the metropolitan area. The Calcarenite Formation (Gravina Calcarenites Formation, Pleistocene) outcrops widely within the city area (Fig. 17) and lies transgressively on the thick limestone-dolomite sequence of the Bari Limestone Formation (Lower–Upper Cretaceous) (Pieri et al., 2011; Polemio, 1994). It is composed of calcarenites, calcirudites, marly pelites, bioclastic deposits, sands, conglomerates, and gravels.

The Gravina Calcarenites Formation is generally less than 15 m thick, with a maximum thickness found in the morphological depressions of the limestone formation. Thin Holocene alluvial deposits (pebbles in a sandy-clayey or silty-clayey matrix) outcrop along the hydrographic network and cover the calcarenite rocks. The limestone formation is affected by karst and fracturing phenomena, extending even below sea level, and forms the large (approximately 250 km²) and deep (hundreds of metres) aquifer in this area (Fig. 17), which exhibits karst conditions (Polemio, 2010) and is affected by seawater intrusion (Polemio & Limoni, 2009).

The morphological features are typical of a karst plateau, which slopes towards the sea (from roughly 100 m a.s.l. in the southwest corner), descending through a series of terraces and slopes that are subparallel to the coast.

A zonation of the different groundwater flow conditions in the limestone aquifer has been carried out using data from many boreholes (Borri et al., 1996). In the inland part of the aquifer, groundwater flows under confined conditions, which gradually change to phreatic conditions towards the coastal sector. The top of the saturated and confined aquifer is found up to 180 m a.s.l. in the inner parts of the area (Fig. 17), with groundwater flowing from the southwest interior towards the coast due to a decreasing piezometric gradient (Fig. 17).

Hydraulic conductivity shows a wide range (from 4×10^{-6} to 6×10^{-3} m/s), due to the karst features and fractures, with an average value of 6.6×10^{-4} m/s (Masciopinto et al., 2017).

An old survey of basic qualitative parameters, conducted on wells from 11 sites within the city area, provides an important benchmark (Cotecchia et al., 1991), highlighting an inhomogeneous qualitative pattern due to the combination of natural conditions (e.g. seawater intrusion) and anthropogenic effects. Groundwater salinity ranges from fresh to saline (0.3 to 38.0 g/L). The very low salinity in some areas is likely due to leakage from aqueducts and/or the sewerage network (Cotecchia et al., 1991). Salinity close to seawater concentration was detected below the transition zone in the old town (Fig. 17) at depths greater than 40 m. Interestingly, a thick zone of flowing fresh groundwater can be observed close to the sea (areas 4–7). Salinity logs from farther inland (areas 8–11) do not show evidence of seawater intrusion, while in other wells (areas 2–7 and 12), at depths less than 50 metres, it is apparent. The higher piezometric head in the former case pushes the transition zone to greater depths than those reached by the boreholes (approx. 60 m).

Apart from peaks observed at very shallow depths near the coast, water temperatures above 18°C are generally due to low-enthalpy geothermal installations, the dominant effect of which is groundwater heating (Cotecchia et al., 1991). Natural and anthropogenic factors such as water network leakage, withdrawals, and heat exchange cause significant vertical variability in salinity and temperature. According to this hydrogeological setting, Bari can be considered both a "Karst Groundwater City" and a "Coastal Groundwater City" (La Vigna, 2022).

Groundwater uses

Two drinking water pumping sites, located along Bari's southwestern administrative border, operate within the study area, supplementing the public aqueduct system, which supplies the city with water from important karst springs located many kilometres away in the Apennine range. Outside the urban area, groundwater is widely used for agricultural purposes and other production processes. In the urban area, groundwater use is primarily for gardens and orchards, though increasing difficulties are encountered as the distance from the coast decreases due to groundwater salinisation.

Groundwater issues

The main issues involve the interference between the urban underground space and groundwater quality. The construction of new buildings or underground infrastructure

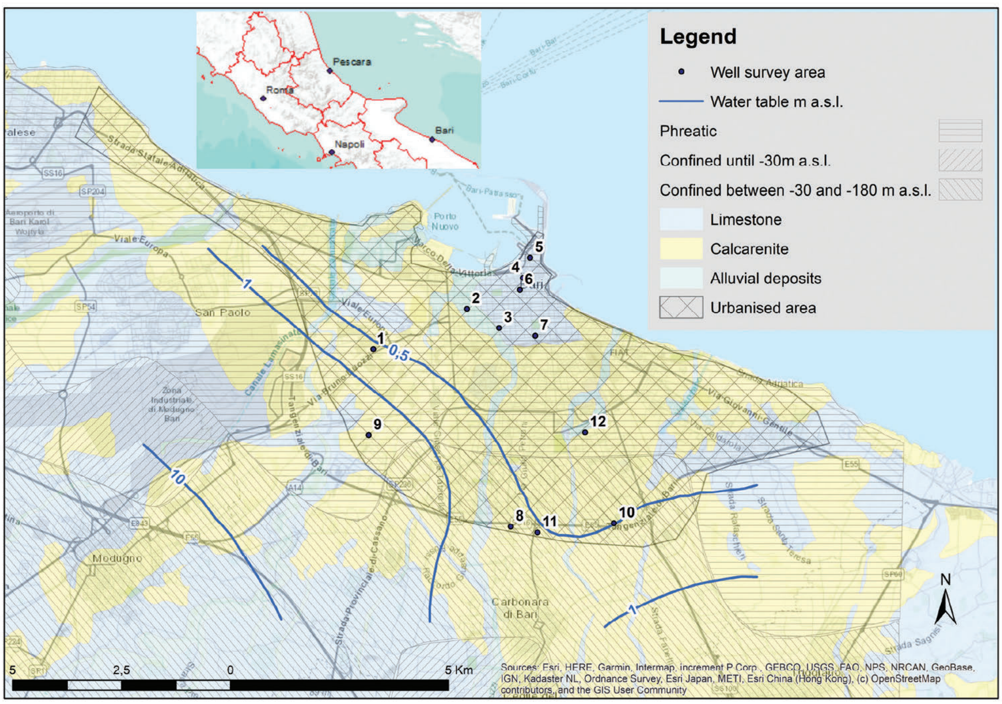

Fig. 17 - Schematic geological and hydrogeological map of the City of Bari (modified from Polemio & Limoni, 2009).

Fig. 17 - Carta geologica e idrogeologica schematica della Città di Bari (modificato da Polemio & Limoni, 2009) .

(e.g. car parks) below the phreatic surface can trigger or exacerbate problems for old buildings (late 18th or early 19th century) built without deep foundations, particularly outside the limestone outcrops and near the coast, where the water table is shallow. These problems relate to building stability or basement flooding. Although low groundwater quality trends, such as increased salinity or nitrate presence (Polemio & Limoni, 2006), are recognised within the urban area, they are not yet a significant issue outside the city, where major groundwater withdrawals take place.

Additionally, aside from the interference between the urban fabric and the local aquifer, the increasing use of groundwater for heat exchange in building cooling and heating requires the urgent implementation of regulations and the prescription of detailed hydrogeological studies. More broadly, a sustainable urban subsurface planning approach is necessary.

Catania (Sicilia Region – Insular Italy)

General hydrogeological setting

The city of Catania is located on the southeastern side of Mount Etna. The geology of the area before volcanic events consisted of a long sandy coastline and hills formed by Pleistocene clays and fluvio-lacustrine deposits of the middle-upper Pleistocene. The lava flows that form the geological substratum of the town flow from NW to SE: the oldest, called "Del Larmisi," dates back to approximately 4–5 kyr BCE (Monaco & Tortorici, 1999), while the most recent is from the 1669 eruption. These lava flows filled the ancient valleys and river incisions, covering the former topography. Records of the eruptions became reasonably complete from the early 15th century, with the 1669 eruption standing out as the largest event of the past 400 years. During this event, the widest and longest lava field was produced, destroying numerous settlements and parts of Catania (Pappalardo & Mineo, 2017).

The former Amenano River and Nicito Lake were the main hydrographical features since the foundation of Katane (the original Greek name for Catania) in 729 BCE, but the 1669 lava flow definitively covered them. The mouth of the Amenano River was located where Piazza Duomo is today, forming a small coastal lagoon separated from the open sea by a strip of sand. It is believed this was reclaimed, and the waters were channelled to feed some fountains at the base of the southern walls, including the Amenano Fountain. The coastline also changed due to the lava flows reaching the sea, which created a new shoreline. The Ursino Castle, once on the sandy coast south of the city, now sits 3 km inland due to the 1669 lava flow.

Numerous surveys conducted in the city have allowed the description of the stratigraphic succession, beginning with the pre-Etna formations of grey-blue Pleistocene clays and middle-upper Pleistocene sands and gravels. Subsequently, there are seven main lava flows in discordance. Debris closes the stratigraphic succession, with thicknesses varying up to about 7 metres. The lava flows consist of scoriaceous and massive portions. According to Pappalardo et al. (2017), due to the presence of irregular bubbles and vesicles, a widespread presence of microfractures has been identified using scanning electron microscopy. These cracks affect both the base paste and the phenocrysts. It is likely that the microcracks result from thermal contraction phenomena affecting large phenocrysts. These microcracks contribute to the rock's porosity and, therefore, its permeability.

Groundwater circulation beneath Catania consists of two porous aquifers, one in sedimentary soils and one in volcanic rock, with double porosity due to vacuoles and fissures/fractures (Ferrara & Pappalardo, 2004). The upper scoriaceous portion of the lava flows is characterised by primary porosity linked to degassing, while the massive microporous portion is fractured and fissured.

Groundwater flow primarily follows a northwest-southeast direction with a high hydraulic gradient, and the piezometric level ranges from 5 to 0 metres above sea level near the historic centre (Fig. 18). Permeability values for the volcanic aquifer from in-situ tests range between 1×10^{-7} and 1×10^{-3} m/s. According to this hydrogeological setting, Catania can be considered both a "Volcanic Groundwater City" and a "Coastal Groundwater City" (La Vigna, 2022).

Groundwater uses

Groundwater in Catania is used primarily for drinking water and, to a lesser extent, for irrigation.

Groundwater issues

The water supply for the metropolitan area of Catania is managed by both public and private companies, with drainage tunnels and wells distributed across an altitudinal range between the coastline and 600 metres above sea level. Until the 1960s, the city of Catania was relatively distinct from its neighbouring towns, but since the 1970s, rapid urbanisation occurred without proper planning or a sewage system. This expansion, coupled with the sprawl of small towns in the surrounding area, has resulted in continuous soil consumption (Ferrara & Pappalardo, 2008).

The drainage tunnels and wells built in the past are currently under significant anthropogenic pressure. Combined with the high permeability of volcanic rocks, this creates a high vulnerability for groundwater resources. Up to 1994, the flow rates withdrawn from the water supply systems were about 4 m^3/s, equivalent to an annual volume of about 126 Mm^3 (Ferrara & Pennisi, 1995). Widespread catchment drainage tunnels on Mount Etna allowed new and additional branches to be dug over the decades to intercept the water table, which continuously lowered. Although this currently ensures the water supply, it is not expected to remain sustainable in the coming years.

Cagliari (Sardegna Region – Insular Italy)

General hydrogeological setting

The city of Cagliari is situated on the southern coast of the island of Sardinia, on a promontory bordered by the Molentargius coastal lagoon to the east and the Santa Gilla

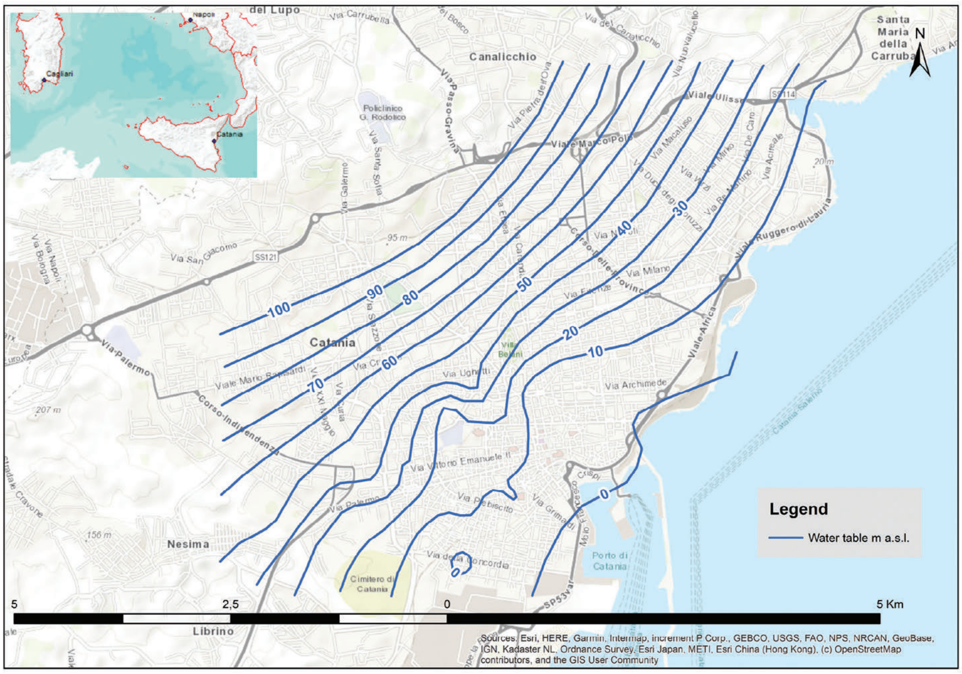

Fig. 18 - Water table map of the City of Catania (new original unpublished elaboration).

Fig. 18 - Piezometria della Città di Catania (nuova elaborazione inedita dei dati).

lagoon to the west. The climate is Mediterranean-maritime, with maximum rainfall typically occurring in November and minimum rainfall generally in July. There are significant fluctuations between monthly peaks and troughs, particularly over the last 6–8 years. Based on data from 2016–2022, the average annual rainfall in the area is approximately 450 mm (ARPAS, 2023), which is considerably lower than the regional average of around 746 mm per year during the same period (Braca et al., 2023). In such a semi-arid environment, dry and windy, and with an annual average temperature of about 18°C, evapotranspiration accounts for about 50% of precipitation. Due to the extensive impermeable surfaces in the heavily urbanised plain, and the steep, undeveloped slopes of the hills, natural recharge is expected to be lower than 40% of the potential net rainfall (Barrocu et al., 2010).

The hydrogeological structure of the urban area and its immediate hinterland is relatively straightforward. It includes an impermeable substrate composed of "Fangario Clays" and the primary aquifer known as the "Pirri Sandstones." These geological formations play a crucial role in controlling the movement and storage of groundwater in the region. Secondary aquifers consist of organogenic limestones (Pietra Forte), which are moderately permeable due to fracturing and karstification, along with Tyrrhenian deposits, coastal marine deposits, landfill materials, and quarry debris (Barrocu, 2009; Pala & Siriu, 1998). A low-permeability marly-sandy limestone, known as Pietra Cantone, underlies the organogenic limestones (Tramezzario and Pietra Forte) and contains various excavated cisterns of the municipal aqueduct due to its impermeable nature. These cisterns often collect water from the carbonate Pietra Forte aquifer, which also contains some springs with high-quality water (Fruttu & Girau, 1987; Cadinu et al., 2012; Cadinu, 2020).

The Pirri Sandstones are mostly incoherent, with more densely packed layers and weakly clayey lithological intercalations. These differences in cementation give rise to permeability variations, leading to locally multi-layered aquifers exhibiting distinctive characteristics (Pala & Siriu, 1998). The distribution of wells in the area reflects the variability of groundwater conditions across different regions within the urban area. The highest density of wells is in the San Benedetto neighbourhood, where the water table often reaches the ground surface. In this area, water wells provide up to 15,000 L/day, constituting the main supply for the largest city demand. Several hydrogeological surveys have been conducted from the 1990s to the last decade (Barrocu, 2009; Pala & Siriu, 1997; Staffa et al., 2008). Despite fluctuations observed in piezometric levels over different periods and years, the variations have been negligible. The depth to the water table ranges from a few centimetres above ground level along the coastline and in the San Benedetto neighbourhood to 20–30 metres below ground level in the area between Monte Claro and Su Planu. Piezometric head analysis reveals the primary groundwater divide, extending from San Michele Hill to Monte Urpinu, approximately NW–SE, passing through Monte Claro, Castello, and the San Benedetto neighbourhood. Perpendicular to this axis, the main groundwater flow directions extend towards the Molentargius lagoon to the east and the Santa Gilla lagoon to the west, with major drainage axes identified along these directions (Fig. 19). Transmissivity ranges between 0.6×10^{-3} m^2/s and 2.2×10^{-4} m^2/s (Pala & Siriu, 1998). According to this hydrogeological setting, Cagliari can be considered a "Coastal Groundwater City" (La Vigna, 2022).

Groundwater uses

The groundwater of Cagliari, once exploited for drinking purposes, is now affected by contamination from nitrogen compounds, namely ammonium, nitrites, and nitrates, most likely originating from leaks in the city sewer system, and by saltwater intrusion along the coast (Barrocu, 2009; Barrocu et al., 2010; Fruttu & Girau, 1987; Pala & Siriu, 1998; Staffa et al., 2008). Therefore, it is currently used primarily for irrigating city gardens and flowerbeds, car washes, and locally for heat pumps (Barrocu et al., 2010).

Groundwater issues

Several critical issues related to groundwater can be identified. The degradation in quality of this resource and the reduction in infiltration capacity due to soil sealing are undoubtedly major concerns, particularly considering that groundwater is a crucial resource in the context of climate change. The primary vulnerability of metropolitan areas lies in drought. However, according to Molinaro (2020), Cagliari remains entirely inactive in addressing climate change issues.

Moreover, urbanisation has significantly altered groundwater conditions, with notable effects on flow directions and hydrodynamic parameters. The eastern plain, once occupied by orchards and green areas, has been intensively urbanised and sealed. As a result, the aquifer, which once flowed freely near the ground surface, is now covered by buildings (Barrocu, 2009); consequently, groundwater has infiltrated several basements, and signs of rising water are visible in the foundation walls of many buildings, especially in the San Benedetto neighbourhood. Efforts to address rising water tables date back to the 1950s, with proposals for public drainage systems remaining unrealised. Therefore, the dewatering is managed through pumping from wells by private individuals (Pala & Siriu, 1998). The demolitions and constructions on the old rubble that occurred after World War II led to the formation of artificial aquifers with high and medium permeability inside the anthropogenic deposits. Leakage from water supply or sewer pipelines has, in some cases, caused significant structural damage to buildings.

Discussion

The non-exhaustive hydrogeological overview provided for several major Italian cities reflects the diverse and complex scenario outlined in the introduction, which applies broadly to the entire Italian territory. Although the selected cities do not evenly cover all regions of Italy (representing 10 cities across 20 regions), the sample can be regarded as representative of Italy's groundwater city typologies, as defined by La Vigna (2022). These typologies are illustrated in Figure 20, with (a) showing the primary classification and (b) the secondary.

The predominant typology within the sample is Alluvial Groundwater (GW) Cities, all located in the Po Plain in northern Italy. Given that most major northern cities are situated within this plain, this dominance is unsurprising.

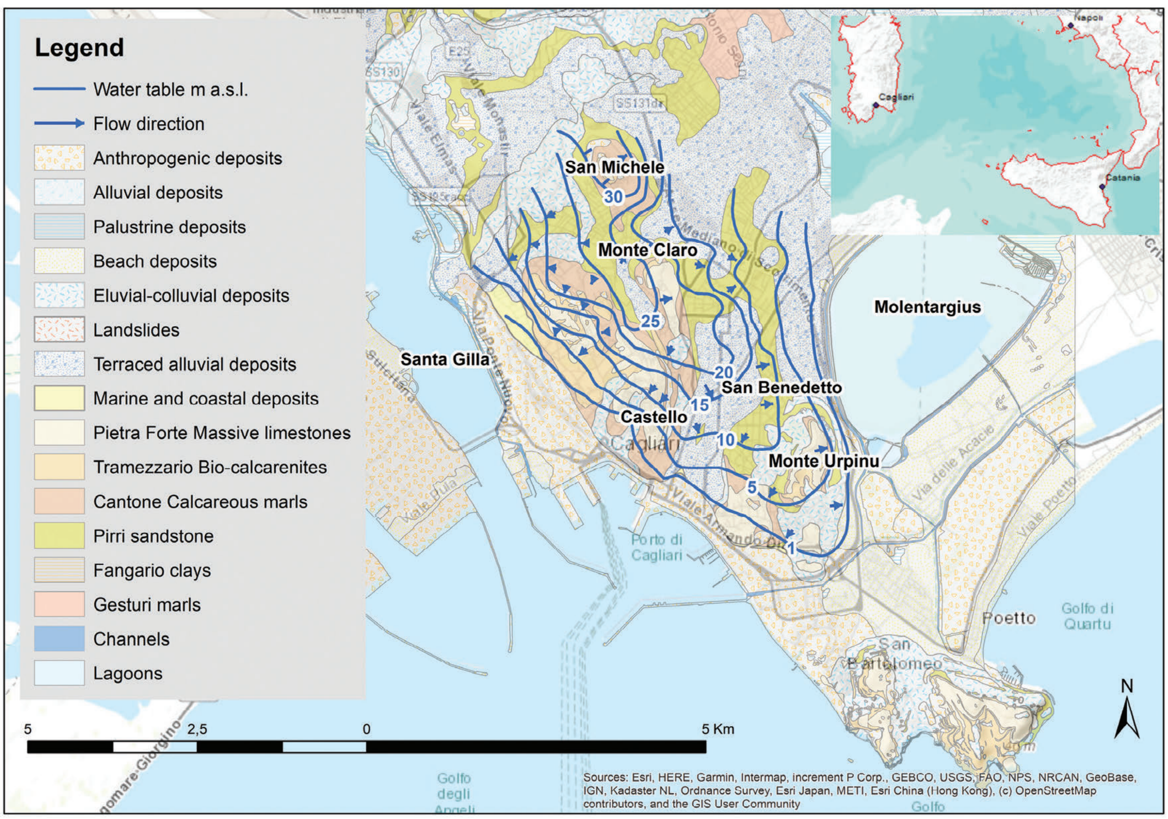

Fig. 19 - Hydrogeological map of the City of Cagliari (modified after Pala & Siriu,1998; Staffa et al., 2008).

Fig. 19 - Carta idrogeologica della Città di Cagliari (modificato dopo Pala & Siriu, 1998; Staffa et al., 2008).

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Although Pescara does not share the same geological context as the northern cities, it is classified under this typology as a secondary attribution. Coastal Groundwater Cities form the next category, comprising two cities primarily and three secondarily. Additionally, Roma is classified as a Lagoon Delta Groundwater City, which is considered part of the Coastal GW Cities group. The prevalence of Coastal and Lagoon Delta GW Cities (5+1 cities) corresponds with Italy's peninsular shape and its extensive coastal regions.

The third typology identified is Volcanic GW Cities, represented by Roma, Napoli and Catania, while the fourth is Karst GW Cities, exclusively attributed to Bari.

The use of groundwater across these cities varies significantly depending on local needs and conditions. For instance, in Bari and Cagliari, groundwater is employed for irrigating city gardens and agricultural purposes outside the urban area. In contrast, Catania relies heavily on groundwater from the slopes of Mount Etna for drinking water. Cities such as Milano and Bologna extract water from deep aquifers to meet their urban water supply needs. In Bologna, extensive groundwater extraction has led to accelerated land subsidence, which has caused infrastructure damage and increased the risk of flooding.

Torino presents a differentiated approach, where deep aquifers are preserved for drinking water, and shallow aquifers are allocated for other uses, such as agricultural irrigation and industrial activities, similar to the approach in Roma. Pescara demonstrates seasonal fluctuations in groundwater use driven by tourism and industrial activity, while Napoli and Padova exhibit limited local groundwater usage due to quality concerns. Each city faces unique groundwater challenges shaped by its geographical, geomorphological, geological, industrial, and urban characteristics. However, some commonalities emerge among cities of the same typology or size. For example, salinisation is a recurrent issue in coastal cities like Bari and Cagliari, where over-extraction and proximity to the sea lead to saltwater intrusion. This issue may be overlooked in urban contexts where water is sourced from outside the city, but salt intrusion can negatively impact local vegetation, especially when used for irrigation. Maintenance of flourishing green areas in cities is a very important action for climate change mitigation effects. Green areas mitigate the important urban heat island affecting the Italian cities in summer (Battista et al. 2023, Ellena et al. 2023), contributing to a significant drop in temperatures and greater liveability.

Industrial contamination significantly impacts groundwater quality, particularly in cities like Milano, Bologna, Pescara, Padova, and Torino, primarily affecting shallow aquifers. This concern also extends to Roma's industrial areas, though they are fewer in number. Contamination is a shared challenge for Alluvial Groundwater Cities, partly due to the low hydraulic conductivity of alluvial aquifers, which prolongs pollutant residence times. However, it may also be related to the higher concentration of industrial activity in alluvial plains. Additionally, cities like Padova and Napoli face naturally poor groundwater quality, with high mineralisation and adverse hydrochemical conditions further limiting its usability. Groundwater level fluctuations present another challenge in cities like Milano, Roma, and Padova. In Milano and Roma groundwater levels rise due to changes in extraction patterns or urban development, while in Padova this is related to the very shallow water table. The water table rising is a common issue in big cities also documented by several authors (Shanahan 2009, La Vigna 2022). At the beginning of city growing period, the affected water table is normally below the city area with a large cone of depression due to the local withdrawals; when the city expands the withdrawals move towards the peri-urban field and the water table in the central area starts to rise due to the local pumping stopping (in response to changes in the local water demand and/or changes in the local groundwater quality), but also due to the "urban" recharge coming from the losses of aqueducts and sewers.

Cagliari exemplifies the interaction between drought and soil sealing, where urbanisation exacerbates groundwater depletion. In highly urbanised areas, soil sealing prevents natural groundwater recharge, intensifying the effects of drought when local resources cannot be tapped to mitigate water shortages. This phenomenon is emblematic of the cascading challenges faced by cities in adapting to both natural and anthropogenic pressures.

In summary Urban Local Aquifers (ULAs) in Italy represent a significant yet often overlooked and dynamic resource. By this not exhaustive analysis the challenges and issues emerged more than sustainable uses and virtuous examples to be taken into consideration for the future city development. Among the many possible virtuous uses ULAs can strongly feed the urban green areas and local groundwater dependent ecosystems (GDEs) to mitigate heat island effects, can be used as a thermal storage for heat exchange low enthalpy systems, and can be used as natural tanks for harvesting stormwater during rainy season by the implementation of sustainable urban drainage systems (SUDS) and Green Infrastructures. Unfortunately, despite their importance, ULAs remain insufficiently recognised by local administrators and are not

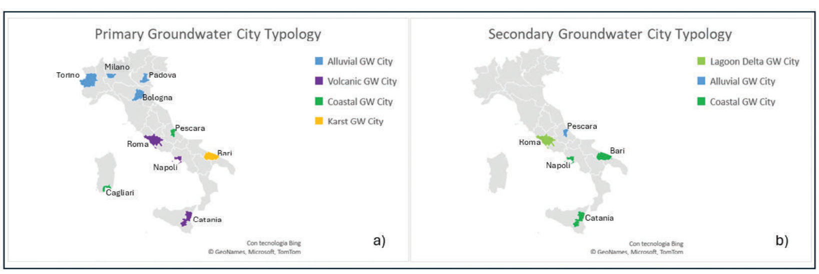

Fig. 20 - Italian Groundwater City Typologies (La Vigna 2022) for the selected cities (the colored areas are relative to the greater metropolitan areas): a) Primary typology attribution; b) Secondary typology attribution.

Fig. 20 - Tipologie di acquiferi urbani italiani (La Vigna 2022) per le città selezionate (le aree colorate corrispondono alle aree metropolitane): a) Tipologia primaria; b) Tipologia secondaria.

consistently monitored or managed. To fully harness the environmental benefits and resilience dividends that these aquifers offer to Italian cities, it is imperative to implement comprehensive and targeted policies. These policies should prioritise the systematic city-scale monitoring of both the quantity and quality of groundwater, alongside the development of adaptive management strategies designed to respond to evolving environmental conditions.

A key aspect of such strategies should be the promotion of natural recharge processes, facilitated through the implementation of green infrastructures and the reduction of soil sealing. These measures not only support the restoration of groundwater reserves but also contribute to broader urban sustainability goals, such as mitigating the effects of climate change and improving urban resilience.

Furthermore, it is crucial to increase awareness among both the public and local policymakers regarding the existence and importance of groundwater resources within urban environments. Educating city administrators about the role of ULAs in urban ecosystems is essential for fostering a shift in urban planning paradigms. In this context, the role of city-level governance is paramount, with local administrations expected to take a leading role in integrating groundwater management into urban development strategies.

To this end, groundwater resources must be incorporated into the strategic agendas of Italian mayors. Urban master plans should explicitly consider aquifers as critical components of the urban landscape, providing guidance and regulations for urban practitioners. By elevating the importance of ULAs within the framework of city planning, Italian cities can better safeguard their groundwater resources and enhance their resilience to environmental challenges.

Conclusions

This work highlights the diverse hydrogeological settings, groundwater uses, and associated issues across several major Italian cities. Understanding these variations is essential for developing effective and sustainable groundwater management strategies.

Urban local aquifers (ULAs) are becoming increasingly important in light of the growing impacts of global changes, and their sustainable management is crucial to addressing these challenges. Groundwater can emerge as a strategic resource when an integrated approach to urban water management and governance recognises the value of all available resources, moving away from reliance on extensive infrastructure and centralised water supply solutions (Grönwall & Oduro-Kwarteng, 2018). As noted by several authors, including Bricker et al. (2017) and La Vigna (2022), groundwater plays a significant role in enhancing urban resilience. Therefore, it should be considered a critical element in urban planning.

ULAs should be viewed not only for their economic value, derived from productive uses such as drinking water, industry, and garden irrigation, but also for their ecological value in supporting urban groundwater-dependent ecosystems. Moreover, they provide option value by serving as a reserve to mitigate future water shortages and offer potential as natural repositories for stormwater harvesting.

In Italian cities, the importance of ULAs in urban planning has often been underestimated, with a few notable exceptions. This is likely due to the long-standing practice of supplying cities with high-quality groundwater or surface water sourced from many kilometres beyond city boundaries or from deep aquifers. Over time, this has led to a diminished focus on local aquifers, resulting in increased vulnerability and a decline in both groundwater quantity and quality.

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Competing interest
The authors declare no competing interests.

Author contributions
Francesco La Vigna, coordination of co-authors, paper structure development, introduction, discussion and conclusions, Rome area section. All other authors contributed for the relative cities settings and the general review of the paper as follows: Luca Alberti, Milano; Stefania Da Pelo, Daniela Ducci, Napoli; Paolo Fabbri, Padova; Alessandro Gargini, Bologna; Manuela Lasagna, Torino; Giovanna Pappalardo, Catania; Maurizio Polemio, Bari; Sergio Rusi, Pescara.

Additional information
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