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Groundwater of Italy: hydrogeological mapping at 1:500,000 scale

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ABSTRACT
This paper presents the Hydrogeological Map of Italy at a scale of 1:500,000 (CI500K). The map is organized into four sheets, accompanied by supplementary notes and tables, and complemented by an online version providing an updated and harmonized national overview of groundwater systems in Italy. The CI500K synthesizes the country's hydrogeological framework, describing groundwater distribution, recharge conditions, and use. It builds on recent regional cartographic studies and integrated datasets, adopting a unified methodology for defining hydrogeological complexes, relative permeability classes, and aquifer productivity. Developed through extensive GIS processing, including a WebGIS platform to promote a participatory work with technicians and researchers of different institutions, the map includes key thematic layers such as perennial freshwater tapped springs, thermal and coastal springs, piezometric contours, and major groundwater flowpaths. This cartographic product provides key information for sustainable water management and climate adaptation strategies consistent with European water policies.

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Key policy highlights

- The map legend includes correspondence with historical hydrogeological classifications and the national legal framework (Legislative Decree 30/2009), enhancing its utility for regulatory and planning purposes.
- Aquifer productivity was assessed by comparison with the information available for groundwater bodies under the Water Framework Directive (WFD, European Parliament and Council, 2000) and then locally refined based on expert knowledge and other factors, such as the presence of wells or springs.
- The map database design supports scheduled updates and the integration of new evidence, including monitoring wells, spring-discharge series, and hydrochemical datasets, thereby preserving relevance over time for designing informed sustainable water management policies.
- The map allows for European interoperability by aligning with INSPIRE Directive (European Parliament and Council, 2007) and the European Environmental Agency standards, facilitating comparative assessments and cross-border analyses.

1. Introduction

Groundwater represents the largest reservoir of unfrozen freshwater on Earth and plays a pivotal role in sustaining water supply, food security, and environmental resilience (Gleeson et al., 2016; 2020). Globally, it provides nearly half of all drinking water, supports about 40% of irrigated agriculture, and sustains rivers baseflow and dependent ecosystems (de Graaf et al., 2019; Siebert et al., 2010). Italy relies heavily on groundwater due to its environmental and hydrological characteristics: more than 84% of potable water demand is supplied by aquifers (ISTAT, 2024), making it the strategic backbone of national water security. Its natural buffer capacity renders it less sensitive to short-term hydrological variability than surface water (Taylor et al., 2013). As a result, it represents a crucial stabilizing factor under climate change, which is increasing the frequency of

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hazardous events such as droughts, floods, and heat extremes (Kuang et al., 2024; Scanlon et al., 2023). Until the present study, the latest national hydrogeological map of Italy was that of Fried et al. (1982), which still constitutes the legal reference framework for groundwater management (referenced in Legislative Decree 30/2009).

Capturing the complexity of groundwater systems through state-of-the-art standardized hydrogeological mapping has therefore become essential (Richts et al., 2011). Hydrogeological maps not only delineate aquifers and recharge systems but also provide fundamental tools for land-use planning, drought preparedness, hazard assessment, and sustainable resource management (UNESCO, 2022). Responding to this need, the Hydrogeological Map of Italy at 1:500,000 scale (CII500K) provides an integrated, GIS-based reference built from diverse geological and hydrogeological sources. This national layer provides a reference framework for groundwater assessment and policy across Italy and is designed for iterative updates as new monitoring and geochemical information becomes available.

This initiative aligns with previous international mapping efforts such as the International Hydrogeological Map of Europe at 1:1,500,000 (IHME1500) (Duscher et al., 2015), which offers a continent-wide, harmonized overview of groundwater conditions, the Hydrogeological Map of France at 1:500,000 (BRGM, 2015); the Hydrogeological Map of Switzerland at 1:500,000 (Schürch et al., 2007); and the UK digital hydrogeology map at 1:625,000 (BGS, 2020). Moreover, at the Italian regional scale, representative examples include the maps of Latium (1:100,000; Capelli et al., 2012), Campania (1:200,000; Budetta et al., 1994), Umbria (1:100,000; Boscherini et al., 2005) and Piedmont (1:300,000; De Luca et al., 2020) accessible through interactive portals and GIS services that provide scalable access from regional syntheses to local detail. These maps are routinely used to support regulatory decisions, protection zoning, vulnerability assessment, and basin planning.

Within this context, the overall aim of the CII500K project is to update and harmonize the national hydrogeological framework of Italy through the revision of the 1982 reference map (Fried et al., 1982). This revision seeks to provide a synoptic national-scale representation of aquifer types and permeability distributions, thereby supporting the identification of major recharge zones. The map is also intended to support sustainable water resource management, environmental planning, and policy implementation, particularly in identifying vulnerable areas and prioritizing protection strategies (Martinelli et al., 2018; Mastrocicco, 2021). The specific objectives are:

- To reinterpret reservoir rocks as hydrogeological complexes, establishing a consistent and nationally coherent classification scheme.
- To integrate and consolidate more than 40 years of regional and local hydrogeological studies through a participatory and collaborative approach.
- To assess groundwater availability by evaluating aquifer productivity, piezometric trends, and spring discharge.
- To promote the transition toward dynamic cartography by developing a WebGIS-based, interactive, and continuously updatable platform.

2. Methods in map design

The Hydrogeological Map of Italy (CII500K) was constructed through a rigorous process of cartographic generalization and standardization, based on existing regional hydrogeological maps and geological datasets. All information was processed using GIS platforms and harmonized according to standardized criteria for permeability classes, hydrogeological complexes, and aquifer productivity.

Hydrogeological complexes were defined by grouping geological formations of the last edition of the Geological Map of Italy (Compagnoni et al., 2011) based on their relative permeability and importance to groundwater circulation. Relative permeability was classified into four classes according to the Italian guidelines for official hydrogeological maps (ISPRA, 2018; Roma & Vitale, 2008): high, medium, low, very low. This classification primarily follows lithological criteria, with a necessary degree of simplification due to the map scale. A total of 19 hydrogeological complexes were identified. Lithological hatching was not used and each complex is represented solely by a solid color. The color scheme was designed as follows:

- high permeability classes were represented using shades of red;
- medium permeability classes (the majority of the map) were represented using yellow to brown tones;
- low permeability classes were assigned green tones;
- very low permeability classes were shown in shades of gray.

Aquifer productivity levels were assigned to polygons previously classified as hydrogeological complexes using a multi-phase methodological approach (Figure 1). The general productivity levels, based on aquifer typology and qualitative assessment of the potential water withdrawal, have been assigned according to the European Hydrogeological Map legend (Duscher et al., 2015). Initially, a correlation

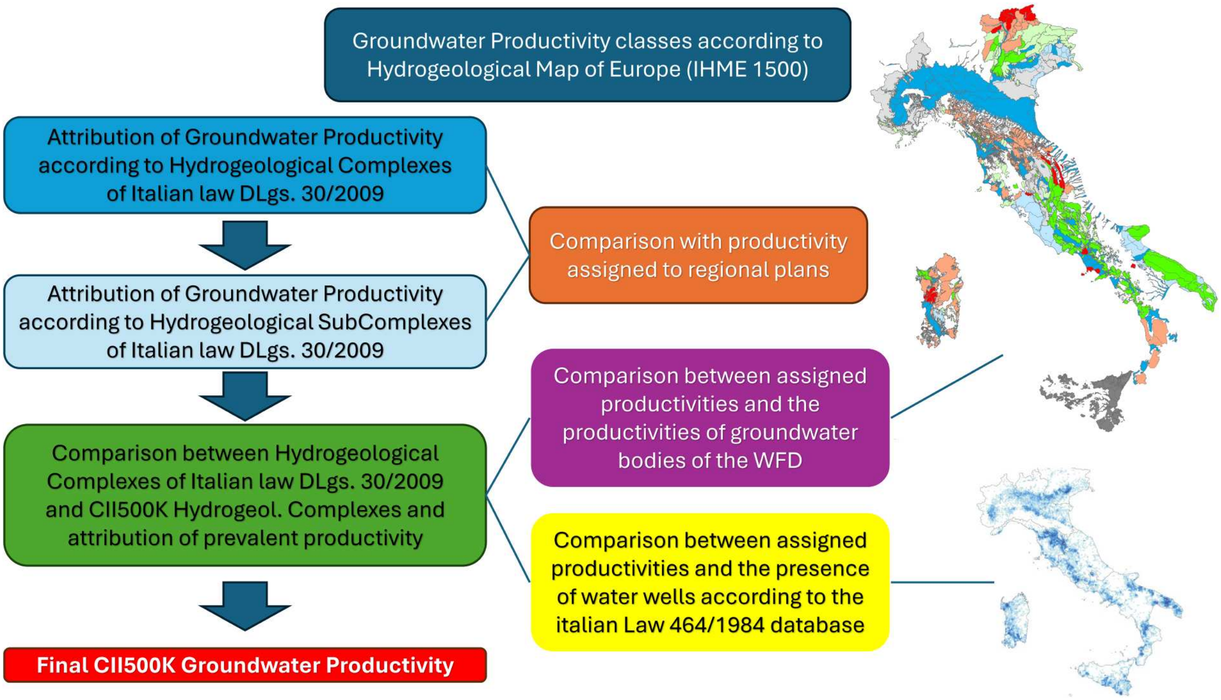

Figure 1. Multi-phase methodological approach for the Groundwater Productivity definition in the CII500K.

was established with the complexes defined in the map by Fried et al. (1982), to which productivity values had already been assigned in previous studies (ADB PO, 2010). This correlation enabled a preliminary classification of productivity classes. In the second phase, these preliminary assignments were further assessed by comparison with the information available for groundwater bodies under the Water Framework Directive (WFD, European Parliament and Council, 2000). Subsequently, the higher level of detail of the new map allows identifying more complexes than the 1982 map, by locally refining the preliminary classifications using expert knowledge and other information, such as the presence of wells or springs.

Aquifer productivity was categorized according to six classes, within which the main groundwater flow types are also defined:

- HPP – high productivity of porous aquifers;
- MPP – moderate productivity of porous aquifers;
- HPF – high productivity of fractured and karst aquifers;
- MPF – moderate productivity of fractured and karst aquifers;
- LPL – low productivity of aquitards or aquifers of local importance;
- NGW – predominantly non-productive zones and aquicludes.

Using individual polygons as areal units to assign productivity allows for the representation of variations in groundwater productivity within the same hydrogeological complex, including in the vertical dimension. A notable example is that of the alluvial bodies of the Po-Venetian Plain: although some outcropping complexes in the area display low permeability characteristics, the multi-aquifer system of the broad plain allows for the assignment of high productivity, as confirmed by both the WFD groundwater body data and the presence of a substantial number of wells.

To depict the degree of productivity on the map, an overlay symbol system was used on top of the hydrogeological complexes. A dotted pattern represents porous aquifers: widely spaced dots for high productivity and closely spaced dots for medium productivity. Solid lines indicate fractured and karst aquifers: vertical lines for high productivity and diagonal lines for medium productivity. Horizontal solid lines are used for low productivity units. No overlay symbol was applied to non-productive areas (aquicludes), thereby preserving the original color of the corresponding hydrogeological complex.

In addition to areal units, the map includes linear and point features such as main springs (classified as thermal, tapped – cold, or coastal), and groundwater flow lines. The map shows only tapped cold springs with a discharge greater than 10 L/s. This representation was chosen due to the current lack of a systematic national springs database and is based on data from the National Institute of Statistics survey (ISTAT, 2024). Consequently, several important untapped springs (linear or diffuse types) may not be represented. Piezometric contour lines, representing regional groundwater flow trends, were collected from existing regional hydrogeological maps and from data acquired during the participatory phase of the map design.

Other layers of the map are related to urbanized areas, taken from the topographic base map, and River Basin District Authorities administrative areas. Topographic and geological references are aligned with the Italian Military Geographic Institute base maps and use the WGS84/UTM 33N coordinate system.

3. Hydrogeological insights about the sketched area

Italy's hydrogeological framework reflects a highly articulated geological history shaped by the convergence of the African and Eurasian tectonic plates, which led to the formation of the Alpine and Apennine mountain chains (Compagnoni et al., 2011). This geodynamic evolution has produced a complex mosaic of rock types and structural settings, with significant hydrogeological implications.

The Apennines are characterized by an assemblage of carbonate, terrigenous, and volcanic formations, often deformed by thrusting and folding (Barchi et al., 2001). In the southernmost sectors, such as Calabria and north-eastern Sicilia, crystalline rocks become prevalent, with similar lithologies also dominating the island of Sardegna. Moreover, in the south-eastern part of the peninsula, the Apulian-Gargano region is characterized by important carbonate aquifers. In the Alps, large-scale nappes formed by compressive tectonics (Stampfli & Borel, 2004) include both crystalline basement rocks (predominantly north of the Periadriatic lineament) and extensive outcrops of sedimentary units (particularly along the chain southern and south-eastern margins).

At the base of these mountainous systems, extensive plains of glacio-fluvio-lacustrine and marine origin stretch along the coasts and intermontane depressions. Among these, the Po Plain (Pianura Padana) stands out as the most significant lowland area, both in terms of areal extent and hydrogeological importance.

Italy also includes several active and quiescent volcanic systems, such as Mt. Vesuvius and the Phlegraean Fields in Campania, Mt. Etna and the Aeolian Islands in Sicily, and Mt. Amiata, Sabatini Mts. and Colli Albani in Tuscany and Latium volcanic areas, which represent surface expressions of regional extensional ongoing tectonic processes along the peninsula (Santacroce et al., 2003). These volcanic regions contribute not only to regional geodiversity but also host highly productive aquifers, particularly in Latium and Campania (Branca et al., 2023).

From a hydrogeological standpoint, this complex setting results in a wide array of aquifer types, recharge mechanisms, and groundwater flow patterns. Four main macro-areas can be identified based on hydrogeological behavior:

- The Alpine sector, where fractured and karstic aquifers are mainly developed in carbonate and crystalline rocks.
- The Apennine chain, with groundwater flowing through a combination of carbonate, flysch, and volcanic units, often forming multilayered or confined systems.
- The coastal and alluvial plains, which host aquifers in porous fluvial, marine, and deltaic deposits, typically more vulnerable to overexploitation and saltwater intrusion than fractured aquifers.
- The main islands of Sardinia and Sicily, characterized by heterogeneous hydrogeological settings: Sardinia features predominantly crystalline basement rocks (granite and metamorphic complexes) with localized volcanic and sedimentary aquifers, while Sicily displays a combination of carbonate platforms, volcanic formations (Mt. Etna), and Neogene sedimentary basins, with significant karstic systems and coastal alluvial aquifers subject to salinization in areas of intensive exploitation.

Karst aquifers in the central and southern Apennines play a key role in water supply, thanks to the high permeability of carbonate rocks (Boni et al., 1986). Similar, though less extensive, systems are found in the Southern Alps. Even areas where the bedrock shows low permeability – especially on the eastern side of the Apennines – may support local aquifers, as evidenced by numerous low-discharge springs that have historically sustained rural settlements and communities (Petitta & Tallini, 2003).

Groundwater flow patterns are influenced by both natural and anthropogenic factors, including lithostratigraphy, tectonic structures, recharge conditions, and land use. Piezometric data often reveal flow directions converging toward rivers, lakes, or coastal zones, with regional hydraulic gradients shaped by topography and structural controls.

4. Results

The final products include four cartographic sheets covering the entire country, accompanied by detailed explanatory notes and online supplementary tables (Beretta et al., 2025). The map provides a consistent and up-to-date characterization of hydrogeological complexes, aquifer productivity, piezometric trends, and spring distribution for the whole Italian territory.

The printed cartographic layout includes a main map with a classification of hydrogeological complexes into four permeability classes (High, Medium, Low, Very Low) and an overlaid symbol system representing six productivity classes derived from aquifer type (porous, fractured-karst, low- or no-flow). Additional thematic elements include captured and bibliographically known major springs (including high-discharge, thermal, and coastal springs), main underground flow paths, piezometric contour lines, zones of spring resurgence (*fontanili*) in the Po Plain, and urbanized areas (Farina & De Angelis, 2024; La Vigna et al., 2024; Roma et al., 2024; Sartirana et al., 2024). Groundwater well densities (based on the national database under Law 464/1984) are also represented in the margin diagrams, supporting interpretation of groundwater exploitation pressures.

Another section of margin diagrams represents the climate analysis (precipitation and evapotranspiration data) conducted for the historical time period (1981-2010), current conditions, and future climate variation (2036-2065) under two IPCC scenarios: RCP4.5 (strong mitigation) and RCP8.5 (high emissions). This analysis leverages convection-permitting climate simulations at ~2.2 km resolution over Italy (Raffa et al., 2023), derived via dynamical downscaling with a non-hydrostatic regional climate model. The very high spatial and temporal resolution enables a realistic representation of precipitation structure and extremes, as well as land – atmosphere feedback relevant to evapotranspiration. Using these data, precipitation and (potential) evapotranspiration indicators have been computed across different time windows to quantify spatial patterns, trends, and scenario-dependent changes, thereby providing hydrogeological meaningful inputs.

The map legend also includes correlations with historical hydrogeological classifications (Fried et al., 1982) and the national legal framework (Legislative Decree 30/2009), enhancing its utility for regulatory and planning purposes.

To support its usability and ensure continuity of updates, the CII500K has been fully integrated into a WebGIS platform, available through the ISPRA-SINA online geoportal. The interactive viewer (https://sinacloud.isprambiente.it/portal/apps/sites/#/idrogeologia/pages/cartaidrogeologica500k) enables users to navigate the hydrogeological information layers dynamically, consult metadata, extract digital data, and download associated thematic tables (e.g. spring attributes, flow paths, thermal spring databases).

Moreover, in the online viewer of the CII500K an innovative solution has been adopted in terms of accessibility for the over 350 million people in the world with color vision deficiency. When recognizing the impact that color can have in maps, it is important to understand the types of colorblindness that people can experience and give them the opportunity to read the map notwithstanding their vision deficiency with alternative color ramps (Oliver, 2025; Stampfli & Borel, 2004; Wong, 2023). Therefore, the online version of the CII500K has a tool that can easily swipe from the original color shape of the map to the equivalent colorblind version for type of colorblindness protanopia (Figure 2).

4.1. National areal patterns of hydrogeological characteristics

Figure 3 summarizes the areal distribution of hydrogeological characteristics across Italy, offering an integrated view of the relative extent of hydrogeological complexes, permeability classes, and groundwater productivity classes. This representation highlights how the diverse lithological domains influence its hydrogeological functioning and how these domains translate into distinct permeability and productivity patterns at the national scale.

Regarding hydrogeological complexes, the national distribution is highly diversified across the 19 mapped classes. No single complex dominates the landscape; rather, the territory is divided among several major lithological units. The most extensive are the *Arenaceous-conglomeratic-calcarenitic complex* (14.2%), the *Flysch and marly complex* (13.7%), and the *Prevailing sand complex (alluvial and transitional)* (12.6%). Other important contributions derive from the *Carbonate complex* (9.4%), intrusive and metamorphic assemblages such as the *Intrusive and gneiss complex* (7.2%), and various gravel, pelitic, volcanic, and calcareous – marly complexes.

The distribution of permeability classes provides a synthetic view of how these lithologies influence groundwater circulation. Nationally, medium-permeability formations dominate (48.6%), corresponding mostly to widespread sandstones and mixed clastic units. Low-permeability units account for 23.2% and include pelitic, metamorphic, and some volcanic complexes. High-permeability classes are typical of upper plain sectors (characterized by prevailing gravelly and sandy deposits), highly fractured carbonates and porous volcanic units, covering 16.9% of the territory. Very low-permeability units (e.g. clays, marls, and massive metamorphic rocks) represent 10.6% of Italy. Water bodies occupy only 0.6% of the national surface.

Finally, the productivity classes highlight the hydrogeological potential of the Italian aquifer systems. High-productivity porous aquifers represent 20.4% of the national area, corresponding mainly to major alluvial plains. Other high-productivity aquifers are associated to fractured and karst lithologies (mostly associated with carbonate massifs) and account for 14.2%. Moderately productive porous aquifers cover 13.6%. Moderately productive fractured and karst systems extend over 18.1%. Low-productivity aquitards or aquifers of local importance

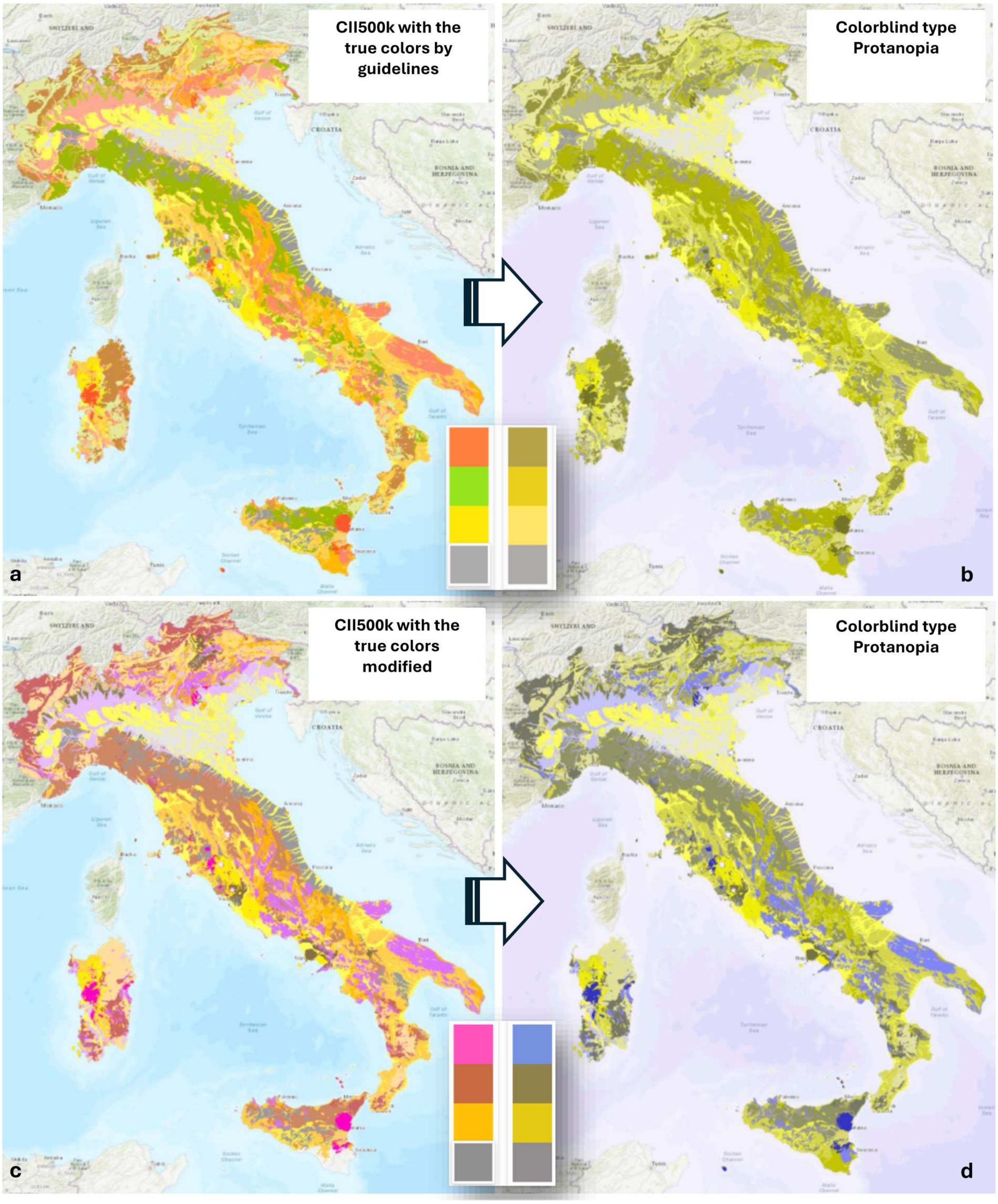

Figure 2. Definition of the CII500K color palette to ensure accessibility for users with color vision deficiencies – type of colorblindness protanopia. (a) The true color palette of CII500K according to guidelines (ISPRA, 2018); (b) how a person with protanopia perceives the CII500K with difficulty in distinguishing red and green colors; (c) true colors changed in the WebGIS platform to improve the form of red-green colorblindness; (d) how a person with protanopia perceives the CII500K with the new color palette.

constitute 19.3%, and predominantly non-productive zones and aquicludes occupy 14.4%.

Overall, these patterns reflect Italy's structurally and lithologically complex setting, which encompasses orogenic, volcanic, and alluvial domains. This diversity gives rise to a highly heterogeneous hydrogeological system. High-productivity aquifers and efficient recharge zones coexist with broad sectors where groundwater infiltration and availability are strongly constrained by low-permeability lithologies.

4.2. Basin-authority areal patterns of hydrogeological characteristics

Figure 4 illustrates how the hydrogeological structure of Italy varies across the eight District Basin Authorities, which are administrative entities responsible

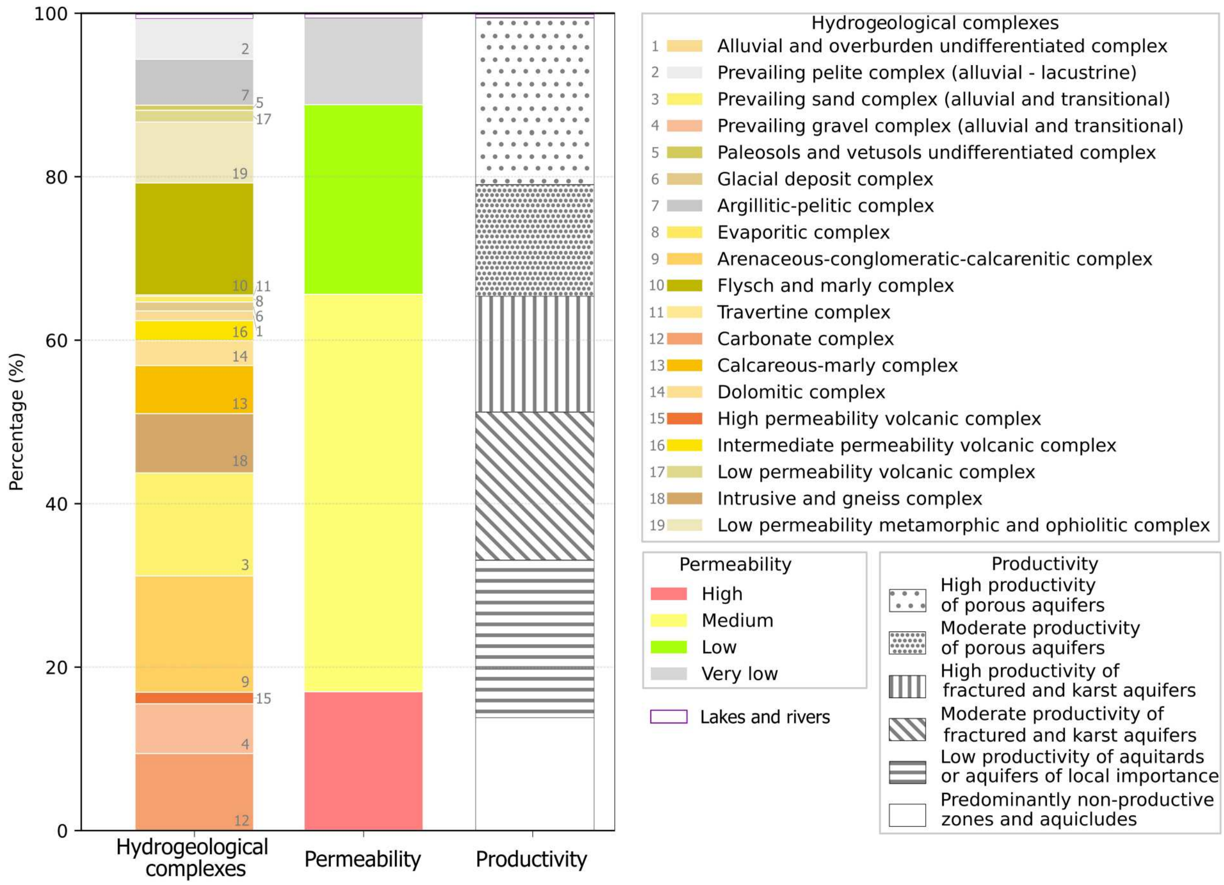

Figure 3. Areal percentage distribution of hydrogeological complexes, permeability, and productivity classes across the Italian territory. The histogram summarizes the relative extent of the 19 hydrogeological complexes, grouped according to their lithological and hydrogeological characteristics, and their classification into four permeability classes (high, medium, low, very low) and six groundwater productivity classes (from high-productivity porous aquifers to predominantly non-productive aquicludes). Percentages refer to the areal coverage of each class at the national scale.

for the planning and integrated management of water resources and hydrogeological risk within a river basin or a group of basins. By comparing the areal proportions of hydrogeological complexes, permeability, and groundwater productivity, the panels highlight strong regional contrasts driven by local geological settings and the distribution of sedimentary, volcanic, and metamorphic formations. Overall, the patterns (Figure 4) demonstrate that each district is characterized by a distinct combination of aquifer types and lithological domains, with implications for groundwater availability, recharge potential, and hydrogeological planning by the District Authorities.

The hydrogeological complex distribution shows marked differences among districts (Figure 4a). The Eastern Alps district is dominated by carbonate formations, flysch, and intrusive – gneissic complexes, reflecting its predominantly alpine geology. In contrast, the Po River district presents a strong prevalence of alluvial and transitional sand and gravel complexes, consistent with the Po Plain alluvial environment. The Northern and Central Apennines districts are characterized by a mosaic of flysch, arenaceous, pelitic, and calcareous – marly complexes, mirroring the structural complexity of the northern and central Apennines. Further south, the Southern Apennines district shows an increased presence of carbonate and volcanic complexes, linked to the southern Apennines and Campanian volcanic provinces. Island districts show distinct patterns: Sardinia district exhibits widespread intrusive and metamorphic complexes, whereas Sicily district displays significant contributions from volcanic complexes, evaporites, and alluvial units.

Permeability patterns closely follow the underlying lithological distribution (Figure 4(b)). Most districts are dominated by medium-permeability formations, especially the Apennines' districts, where sandstones, marls, and mixed clastic units are widespread. High-permeability areas are most extensive in the Po River district – due to major alluvial plains – and in the Southern Apennines and Sicily, where highly fractured carbonates and volcanic terrains occur. Low-permeability domains, typical of pelitic, metamorphic, or massive volcanic units, are more prominent in Sardinia and in the Central Apennines. Very-low permeability units, mainly clays, marls, and other aquicludes, occur significantly in Sardinia and portions of Sicily.

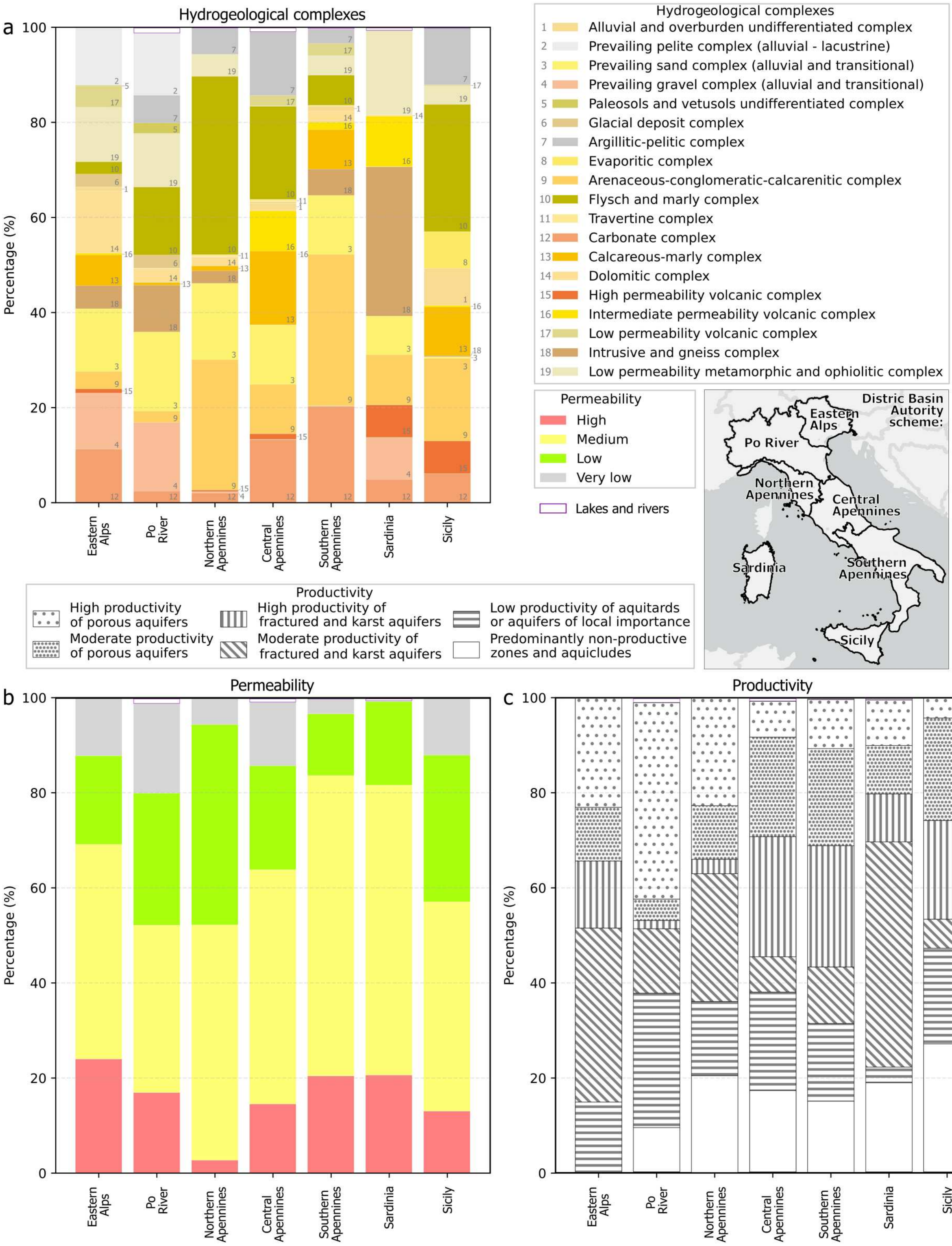

Figure 4. Areal percentage distribution of hydrogeological characteristics across the Italian District Basin Authorities. (a) Relative extent of the hydrogeological complexes within each district. (b) Distribution of the four permeability classes (high, medium, low, very low). (c) Distribution of the six groundwater productivity classes, ranging from highly productive aquifers to predominantly non-productive zones.

Groundwater productivity also varies strongly across districts, mirroring differences in both lithology and permeability (Figure 4(c)). The Po River district stands out as the most productive, with large proportions of high- and moderate-productivity porous aquifers related to the Po Plain alluvial system. The Southern Apennines and Sicily districts show high percentages of productive fractured and karst aquifers, associated with extensive carbonate massifs and volcanic terrains. Conversely, Sardinia is dominated by low-productivity and non-productive zones, consistent with the predominance of metamorphic and intrusive rocks. The Northern and Central Apennines districts display a mixed pattern, with moderate-productivity fractured systems interspersed with less productive pelitic – marly complexes. These differences underscore how the geological framework of each district determines the distribution of high-yield aquifers and areas with limited groundwater potential.

5. Conclusions

The Hydrogeological Map of Italy at 1:500,000 (CII500K) marks a major milestone in Italy's hydrogeological synthesis and meaningfully contributes to Europe's capacity to manage groundwater under increasing environmental and socio-economic stress. By compiling and harmonizing regional datasets into a coherent, user-oriented GIS framework, it strengthens both the scientific evidence base and the administrative capacities for groundwater management and planning.

A defining feature of the project is its participatory architecture. An open WebGIS enabled the hydrogeological community (regional surveys, universities, and independent experts) to review, comment on, and iteratively improve draft products. This collaborative workflow promotes transparency and reproducibility, broadens acceptance across disciplines and institutions, and helps aligning methods and symbologies across jurisdictions. In addition, the digital environment ensures wide accessibility and helps supporting informed decision-making for groundwater management, monitoring, and protection on both national and local scales.

The map is intentionally not static. Its database design supports scheduled updates and the integration of new evidence, including monitoring wells, spring-discharge series, and hydrochemical and isotopic datasets, thereby preserving relevance over time. Functionally, the CII500K serves as a national synthesis and as a starting point for basin- and site-specific investigations, providing boundary conditions and cross-scale constraints for numerical models and applied studies in agricultural planning, climate-change adaptation, and natural-hazard reduction. The general hydrogeological framework of the CII500K will serve as the basis for the national thematic hydrogeological mapping at a 1:50,000 scale (CARG project) and for the update of the related guidelines, to facilitate the homogeneity of national official cartography. Beyond its national value, the CII500K allows for European interoperability by aligning with INSPIRE Directive (European Parliament and Council, 2007) and the European Environmental Agency standards, facilitating comparative assessments and cross-border analyses.

Future developments should include the incorporation of 3D representations of aquifer systems (e.g. Stevenazzi et al., 2023), enhanced integration of time-series data (e.g. piezometric trends), and strong linkages with existing national climatic and hydrological models (e.g. BIGBANG; Braca et al., 2021, 2024). Additionally, expanding chemical–physical datasets (including stable isotopes) will be essential for comprehensively characterizing groundwater quality, recharge zones, and groundwater age. The CII500K thus represents a fundamental tool not only for addressing current challenges, but also for guiding sustainable groundwater management in the decades to come.

Software

All data processing was carried out using GIS software (ESRI ArcGIS) and database management systems compatible with geospatial standards. Vector graphic tools (e.g. Adobe Illustrator), supplemented with cartographic publishing plugins (e.g. MAPublisher), were used to produce the final graphic output and printing layout. The integration of geological, hydrogeological, and topographic layers was achieved by using national geological geodatabases (e.g. CARG, Italian Geological Mapping Project) and shapefiles derived from previous regional hydrogeological maps.

Open Scholarship

This article has earned the Center for Open Science badge for Open Data. The data are openly accessible at Data available at https://sgi3.isprambiente.it/download/CII-500K/Geopackage_CII_500k_v1.zip

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Author contributions

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No potential conflict of interest was reported by the author(s).

Data availability statement

The map data are accessible through the link https://catalogosgi.isprambiente.it/geoportal2/catalog/search/resource/details.page?uuid=%7BA1F834DF-2B74-42CE-8B69-B5044663A542%7D (metadata only in Italian language), available both in standard format through WMS services and in vector open format through a geopackage. Furthermore, a thematic visualizer showing the layers included in the map by means of a webGIS system can be found at the following link https://sinacloud.isprambiente.it/portal/apps/webappviewer/index.html?id=efd789fe79a9491fb70d9ab83f3f0cb4.

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References

Autorità di Bacino Distrettuale del Fiume Po. (2010). Descrizione generale delle caratteristiche del distretto idrografico, a norma dell'articolo 5 dell'Allegato II (Report art. r). Piano di Gestione Acque 2010.

Barchi, M., Landuzzi, A., Minelli, G., & Pialli, G. (2001). Outer Northern Apennines. In G. B. Vai & I. P. Martini (Eds.), *Anatomy of an orogen: The Apennines and adjacent Mediterranean basin* (pp. 215–254). Kluwer Publishers.

Beretta, G. P., La Vigna, F., Camera, C. A. S., Gafà, R. M., Citrini, A., Martarelli, L., Monti, G. M., Roma, M., Silvi, A., Vitale, V., Fiori, C., Masetti, M., Pascarella, F., Proietti, R., Lo Faro, S., Congi, M. P., Gerardi, M., Tersigni, S., Baldoni, T., … Giugliano, G. (2025). Carta Idrogeologica d'Italia alla scala 1:500.000–4 Fogli, Note integrative e tabelle online – Hydrogeological Map of Italy 1:500.000 scale. 4 Sheets, Supplementary Notes and online tables. ISPRA – Dipartimento per il Servizio Geologico d'Italia – Geological Survey of Italy. Roma.

BGS. (2020). BGS datasets, Hydrogeology, 625 K digital hydrogeological map of the UK. https://www.bgs.ac.uk/datasets/hydrogeology-625k/ (last accessed on 07/03/2026)

Boni, C. F., Bono, P., & Capelli, G. (1986). Schema Idrogeologico dell'Italia Centrale – A) Carta idrogeologica (scala 1:500.000); B) Carta idrologica (scala 1:500.000); C) Carta dei bilanci idrogeologici e delle risorse idriche sotterranee (scala 1:1.000.000). Hydrogeological scheme of Central Italy – A) Hydrogeological map (scale 1:500.000); B) Hydrological map (scale 1:500.000); C) Map of hydrogeological balances and groundwater resources (scale 1:1.000.000). *Memorie della Società Geologica Italiana*, *35*(2), 991–101.

Boscherini, A., Checcucci, R., Natale, G., & Natali, N. (2005). Carta idrogeologica della Regione Umbria a scala 1:100.000. *Giornale di Geologia Applicata*, *2*, 399–404.

Braca, G., Bussettini, M., Lastoria, B., Mariani, S., & Piva, F. (2021). Il Bilancio Idrologico Gis BAsed a scala Nazionale su Griglia regolare – BIGBANG: metodologia e stime. Rapporto sulla disponibilità naturale della risorsa idrica. Rapporti n. 339/21, ISPRA, Roma.

Braca, G., Mariani, S., Lastoria, B., Tropeano, R., Casaioli, M., Piva, F., Marchetti, G., & Bussettini, M. (2024). Bilancio idrologico nazionale: stime BIGBANG e indicatori sulla risorsa idrica. Aggiornamento al 2023. Rapporti n. 401/2024, ISPRA, Roma.

Branca, S., Cinquegrani, A., Cioni, R., Conte, A. M., Conticelli, S., De Astis, G., de Vita, S., Di Vito, M. A., Donato, P., Forni, F., Francalanci, L., Gaeta, M., Giaccio, B., Giordano, G., Giuffrida, M., Isaia, R., Lucchi, F., Marra, F., Massaro, S., … Viccaro, M. (2023). The Italian quaternary volcanism. *Alpine and Mediterranean Quaternary*, *36*(2), 221–284. https://doi.org/10.26382/AMQ.2023.09

BRGM. (2015). Carte hydrogéologique de la France à 1:1 000 000.

Budetta, P., Celico, P. B., Corniello, A., Riso, R. D., Ducci, D., & Nicotera, P. (1994). Carta idrogeologica della Campania 1/200.000 e relativa memoria illustrativa. – STAMPA.

Capelli, G., Mastrorillo, L., Mazza, R., Petitta, M., Baldoni, T., Cascone, D., Di Salvo, C., La Vigna, F., Taviani, S., & Teoli, P. (2012). Carta Idrogeologica del Territorio della Regione Lazio scala 1: 100.000 (4 fogli), Regione Lazio, S. EL. CA. Firenze.

Compagnoni, B., Galluzzo, F., Bonomo, R., Capotorti, F., D'Ambrogi, C., Di Stefano, R., Graziano, R., Martarelli, L., Pampaloni, M. L., Pantaloni, M., Ricci, V., Tacchia, D., Masella, G., Pannuti, V., Ventura, R., & Vitale, V. (2011). Carta geologica alla scala 1:1.000.000 con Note illustrative. *The geological map of Italy*, *1:1.000.000*), scale. Servizio Geologico d'Italia/Dipartimento Difesa del Suolo-ISPRA. SELCA, Firenze (Italia).

de Graaf, I. E. M., Gleeson, T., (Rens) van Beek, L. P. H., Sutanudjaja, E. H., & Bierkens, M. F. P. (2019). Environmental flow limits to global groundwater pumping. *Nature*, *574*(7776), 90–94.

De Luca, D. A., Lasagna, M., & Debernardi, L. (2020). Hydrogeology of the western Po plain (Piedmont, NW Italy). *Journal of Maps*, *16*(2), 265–273. https://doi.org/10.1080/17445647.2020.1738280

Duscher, K., Günther, A., Richts, A., Clos, P., Phillip, U., & Struckmeier, W. (2015). The GIS layers of the International Hydrogeological Map of Europe 1:1,500,000 in a vector format. *Hydrogeology Journal*, *23*(8), 1867–1875. https://doi.org/10.1007/s10040-015-1296-4

European Parliament and Council. (2000). Directive 2000/60/EC establishing a framework for Community action in the field of water policy. *Official Journal of the European Communities*, *L 327*, 1–73.

European Parliament and Council. (2007). Directive 2007/2/EC establishing an Infrastructure for Spatial Information in the European Community (INSPIRE). *Official Journal of the European Union*, *L 108*, 1–14.

Farina, D., & De Angelis, S. (2024). Groundwater in the city of Pesaro (Marche, Italy): Anthropic impact and interference with the urban environment. *Acque Sotterranee - Italian Journal of Groundwater*, *13*(3), 123–132. https://doi.org/10.7343/as-2024-773

Fried, J. J., Mouton, J., & Mangano, F. (1982). "Studio sulle risorse in acque sotterranee dell'Italia" – Commissione delle Comunità Europee vol. 6 dell'Atlante delle risorse idriche sotterranee della Comunità Europea – "Tema 1 – Acquiferi".

Gleeson, T., Befus, K., Jasechko, S., Luijendijk, E., & Bayani Cardenas, M. (2016). The global volume and distribution of modern groundwater. *Nature Geoscience*, *9*(2), 161–167. https://doi.org/10.1038/ngeo2590

Gleeson, T., Wang-Erlandsson, L., Porkka, M., Zipper, S. C., Jaramillo, F., Gerten, D., Fetzer, I., Cornell, S. E., Piemontese, L., Gordon, L. J., Rockström, J., Oki, T., Sivapalan, M., Wada, Y., Brauman, K. A., Flörke, M., Bierkens, M. F. P., Lehner, B., Keys, P., … Famiglietti, J. S. (2020). Illuminating water cycle modifications and Earth system resilience in the Anthropocene. *Water Resources Research*, *56*(4), e2019WR024957. https://doi.org/10.1029/2019WR024957

ISPRA – Istituto Superiore per la Protezione e la Ricerca Ambientale – Servizio Geologico d'Italia. (2018). Carta Idrogeologica d'Italia – 1:50.000. Nuove linee guida al rilevamento e alla rappresentazione della Carta Idrogeologica d'Italia. "Hydrogeological Map of Italy – 1:50.000 scale. New guidelines to survey and mapping for the Hydrogeological Map of Italy". Quaderni ISPRA-Servizio Geologico d'Italia, serie III, vol.14, Rome, Italy.

ISTAT. (2024). *Annuario Statistico Italiano*. Istituto Nazionale di Statistica.

Kuang, X., Liu, J., Scanlo, B. R., Jiao, J. J., Jasechko, S., Lancia, M., Biskaborn, B. K., Wada, Y., Li, H., Zeng, Z., Guo, Z., Yao, Y., Gleeson, T., Nicot, J., Luo, X., Zou, Y., & Zheng, C. (2024). The changing nature of groundwater in the global water cycle. *Science*, *383*(6686), eadf0630.

La Vigna, F., Alberti, L., Da Pelo, S., Ducci, D., Fabbri, P., Gargini, A., Lasagna, M., Pappalardo, G., Polemio, M., and Rusi, S. (2024). Exploring the aquifers shaping Italy's sub-urban landscape. *Acque Sotterranee - Italian Journal of Groundwater*. *13*(3), 43–66. https://doi.org/10.7343/as-2024-806

Martinelli, G., Dadomo, A., De Luca, D. A., Mazzola, M., Lasagna, M., Pennisi, M., Pilla, G., Sacchi, E., & Saccon, P. (2018). Nitrate sources, accumulation and reduction in groundwater from Northern Italy: insights provided by a nitrate and boron isotopic database. *Applied Geochemistry*, *91*, 23–35. https://doi.org/10.1016/j.apgeochem.2018.01.011

Mastrocicco, M. (2021). Studies on water resources salinization along the Italian coast: 30 years of work. *Acque Sotterranee – Italian Journal of Groundwater*, *10*(4), 7–13. https://doi.org/10.7343/as-2021-537

Oliver, S. (2025). Designing Maps for Colorblind Readability, ARC GIS Blog, https://www.esri.com/arcgis-blog/products/arcgis-pro/mapping/designing-maps-for-colorblind-readability

Petitta, M., & Tallini, M. (2003). Groundwater Resources and Human Impacts in a Quaternary Intramontane Basin (L'Aquila Plain, Central Italy). *Water International*, *28*(1), 57–69. https://doi.org/10.1080/02508060308691665

Raffa, M., Adinolfi, M., Reder, A., Marras, G.F., Mancini, M., Scipione, G., Santini, M., & Mercogliano, P. (2023). Very High Resolution Projections over Italy under different CMIP5 IPCC scenarios. *Scientific Data*, *10*(1), 238. https://doi.org/10.1038/s41597-023-02144-9

Richts, A., Struckmeier, W. F., & Zaepke, M. (2011). WHYMAP and the groundwater resources map of the world 1: 25,000,000. In J. Jones (Ed.), *In Sustaining groundwater resources: a critical element in the global water crisis* (pp. 159–173). Springer Netherlands.

Roma, M., Bonfà, I., Congi, M. P., Gafà, R. M., Martarelli, L., Monti, G. M., Papiccio, C., Silvi, A., Vitale, V., & La Vigna, F. (2024). Guardians of the aquifers: enhancing Rome's groundwater monitoring network. *Acque Sotterranee - Italian Journal of Groundwater*, *13*(3), 135–143. https://doi.org/10.7343/as-2024-812

Roma, M., & Vitale, V. (2008). Strumenti e metodologie informatiche per l'idrogeologia: dai dati alla rappresentazione cartografica – Information tools and methodologies applied to hydrogeology: from data supply to cartographic representation. In A. R. Scalise, & L. Martarelli (Eds.), *Studi sperimentali finalizzati alla cartografia idrogeologica – Field surveys for the implementation of the hydrogeological cartography* (Vol. 81, pp. 47–58). Memorie Descrittive della Carta Geologica d'Italia.

Santacroce, R., Cristofolini, R., Volpe, L. L., Orsi, G., & Rosi, M. (2003). Italian active volcanoes. *Episodes*, *26*(3), 227–234. https://doi.org/10.18814/epiiugs/2003/v26i3/013

Sartirana, D., Zanotti, C., Rotiroti, M., Caschetto, M., Redaelli, A., Bruno, S., Fumagalli, L., De Amicis, M., & Bonomi, T. (2024). Urban water management in Milan metropolitan area, a review. *Acque Sotterranee - Italian Journal of Groundwater*, *13*(3), 103–122. https://doi.org/10.7343/as-2024-763

Scanlon, B. R., Fakhreddine, S., Rateb, A., de Graaf, I., Famiglietti, J., Gleeson, T., Grafton, R. Q., Jobbagy, E., Kebede, S., Kolusu, S. R., Konikow, L. F., Long, D., Mekonnen, M., Schmied, H. M., Mukherjee, A., MacDonald, A., Reedy, R. C., Shamsudduha, M., Simmons, C. T., … Zheng, C. (2023). Global water resources and the role of groundwater in a resilient water future. *Nature Reviews Earth & Environment*, *4*(2), 87–101. https://doi.org/10.1038/s43017-022-00378-6

Schürch, M., Kozel, R., & Jemelin, L. (2007). Hydrogeological mapping in Switzerland. *Hydrogeology Journal*, *15*(4), 799–808. https://doi.org/10.1007/s10040-006-0136-y

Siebert, S., Burke, J., Faures, J. M., Frenken, K., Hoogeveen, J., Döll, P., & Portmann, F. T. (2010). Groundwater use for irrigation – a global inventory. *Hydrology and Earth System Sciences*, *14*(10), 1863–1880. https://doi.org/10.5194/hess-14-1863-2010

Stampfli, G. M., & Borel, G. D. (2004). The TRANSMED Transects in Space and Time: Constraints on the Paleotectonic Evolution of the Mediterranean Domain. In Cavazza, W., Roure, F., Stoelzle, M., and Stein, L. (2021). Rainbow color map distorts and misleads research in hydrology – guidance for better visualizations and science communication. *Hydrology and Earth System Sciences*, *25*(8), 4549–4565.

Stevenazzi, S., Zuffetti, C., Camera, C. A. S., Lucchelli, A., Beretta, G. P., Bersezio, R., & Masetti, M. (2023). Hydrogeological characteristics and water availability in the mountainous aquifer systems of Italian Central Alps: A regional scale approach. *Journal of Environmental Management*, *340*, 117958. https://doi.org/10.1016/j.jenvman.2023.117958

Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J. S., Edmunds, M., Konikow, L., Green, T. R., Chen, J., Taniguchi, M., Bierkens, M. F. P., MacDonald, A., Fan, Y., Maxwell, R. M., Yechieli, Y., … Treidel, H. (2013). Ground water and climate change. *Nature Climate Change*, *3*(4), 322–329. https://doi.org/10.1038/nclimate1744

UNESCO. (2022). *The United Nations World Water Development Report 2022, Groundwater: Making the invisible visible*. 225 pp.

Wong, B. (2023). Author Correction: Points of view: Color blindness. *Nature Methods*, *20*(8), 1266. https://doi.org/10.1038/s41592-023-01974-0