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Hydrolithology of the area between Tuscany, Latium and Umbria regions (Italy)

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Hydrogeological research lacks a standard methodology for supporting the management of groundwater resources in territory planning. The mapping of geological units in terms of their hydrogeological properties (such as permeability, effective infiltration, hydro-capacity) may provide a propaedeutical tool for calibration and validation of regional scale hydrogeological components (aquifer, aquiclude, aquitard). This work presents a hydrolithological map based on analysis of the 1:100,000 official cartography (provided by the Italian Geological Survey). The study area includes three distinct administrative regions (Tuscany, Latium and Umbria) and is a part of the central Apennines (Italy), an orogenic segment with distinctive tectono-stratigraphic sequences characterized by different degrees of permeability. A methodological approach is described that revises the geological information from the original cartography and builds a multicriteria database. The results are schematized in the attached map (at 1:100,000 scale) where the 'hydrolithological complex' (i.e. complex grouping lithologies with genetic and tectonic affinities and showing internal textural and compositional similarities that produce a comparable behaviour regarding groundwater flow and storage) is used as the key unit. Thematic maps illustrating permeability variation in the area and 'macro-complexes' are also included. The information is presented to outline the importance of revising, updating, and homogenizing geological cartography for providing direct multiscalar analysis suitable for territory planning.

Keywords: hydrolithological complex; GIS; territory planning; multiscalar analysis

1. Introduction

The characterization and evaluation of groundwater resources in wide areas is a necessary step to defining geo-environmental criteria necessary for decision-making in territory planning. Researchers continuously assess hydrogeological guidelines for developing and updating the source water management plans, and providing accurate and updated cartographic support (e.g. Brown, Lloyd, & Jacobson, 1990; Desiderio, Folchi Vici D'Arcevia, Nanni, & Rusi, 2012; Teixeira, Chaminé, Carvalho, Pérez-Alberti, & Rocha, 2013). Although the assessment of the hydrogeological scenario typically integrates a large spectrum of data sources, spanning engineering prospecting and monitoring to direct field surveys, it still lacks a standard

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methodology for the mapping of geological units in terms of their hydrogeological properties. In Italy, different hydrogeological approaches have been proposed for classifying geological units on the basis of their common hydrogeological features, such as permeability (Celico, De Vita, Monacelli, Scalise, & Tranfaglia, 2005), effective infiltration (Boni, Bono, & Capelli, 1986), and hydro-capacity (Capelli et al., 2012). Independently from the classification scheme, it is necessary to aggregate the geological units into appropriate complexes with hydrological affinities. The preparation of a hydrogeological map needs an adequate geological cartography illustrating the geometry and inherent lithological properties of the units outcropping in a study area. The better the geological information supplied, the better the hydrogeological interpretations. As a result, policies concerning regional groundwater extraction and preservation can then be based on critical geoscience information.

This work presents a hydrolithological map at a scale of 1:100,000 of a portion of central Italy pertaining to the inner sector of the orogenic chain of the Apennines (Figure 1a) and includes the administrative regions of Tuscany, Latium and Umbria (see the Main map). The selected area constitutes an appropriate case study for illustrating the complexities that result from regional geological mapping with a focus upon hydrogeology, because: (i) it belongs to an orogenic sector that experienced polyphase evolution (e.g. Bonini et al., 2014; Butler et al., 2004; Carmignani et al., 2001; Jolivet et al., 1998; Massoli et al., 2006; Pauselli et al., 2006); (ii) it includes three main paleogeographic domains (named Ligurian Domain, Tuscan Domain, Umbria-Marche Domain; e.g. Barchi, Minelli, & Pialli, 1998; Brogi & Fabbrini, 2009; Carmignani et al., 1994; Carmignani, Conti, Cornamusini, & Pirro, 2013; Elter, Grasso, Parlotto, & Vezzani, 2003; Ghisetti & Vezzani, 1997; Parotto & Praturlon, 1975) characterized by peculiar tectono-stratigraphic sequences (Figure 1b); (iii) the tectono-stratigraphy of each paleogeographic domain can be interpreted in terms of lithologies with different hydrogeological behaviours and

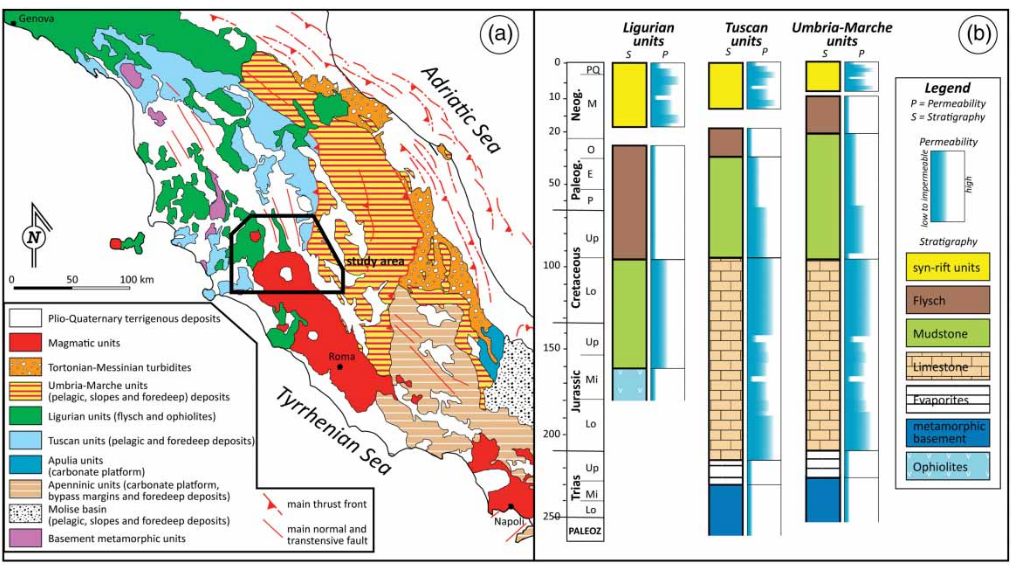

Figure 1. (a) Simplified geological map of the central Apennines showing the distribution of the main paleogeographic domains (modified and adapted from Bigi et al., 1990); (b) schematic relationship between palaeographic domains, lithological composition and permeability attitude. Note the width of boxes illustrating the permeability is expressed in chronostratigraphic terms and does not reflect the thickness of the lithological complexes. Stratigraphy of paleogeographic domains are obtained and adapted from Carmignani et al. (1994), Jolivet et al. (1998), Brogi and Fabbrini (2009), Mastrorillo and Petitta (2010).

hydrodynamics (e.g. Mastrorillo & Petitta, 2010; Nanni & Vivalda, 2005); (iv) the region contains distinctive major aquifers (the carbonate sequences and the volcanic deposits) that are partitioned into separate hydrodynamic compartments by sedimentary basins; and (v) the available geological cartography needs revision and homogenization. A geographical information system (GIS) has been used for acquiring, managing and visualizing the geological information. The GIS-based workflow enabled use of a database supporting multiscalar and multicriteria analysis. The paper emphasizes the methodological approach used for collecting cartographic materials, building a geological database and providing original cartography considering the 'hydrolithological complex' as the key unit at regional scale.

2. Existing geological maps

The size of the investigated area (about 9,000 km^2) and the importance of developing a multiscale synthetic hydrogeological model require two different cartographic scales:

– local model: 1:5,000–1:10,000;
– regional model: 1:50,000–1:100,000;

For the study area, available geological maps at large scale (e.g. at a scale of 1:10,000 or 1:5,000, or higher) are provided by the local administration (cadastre, municipality and province).

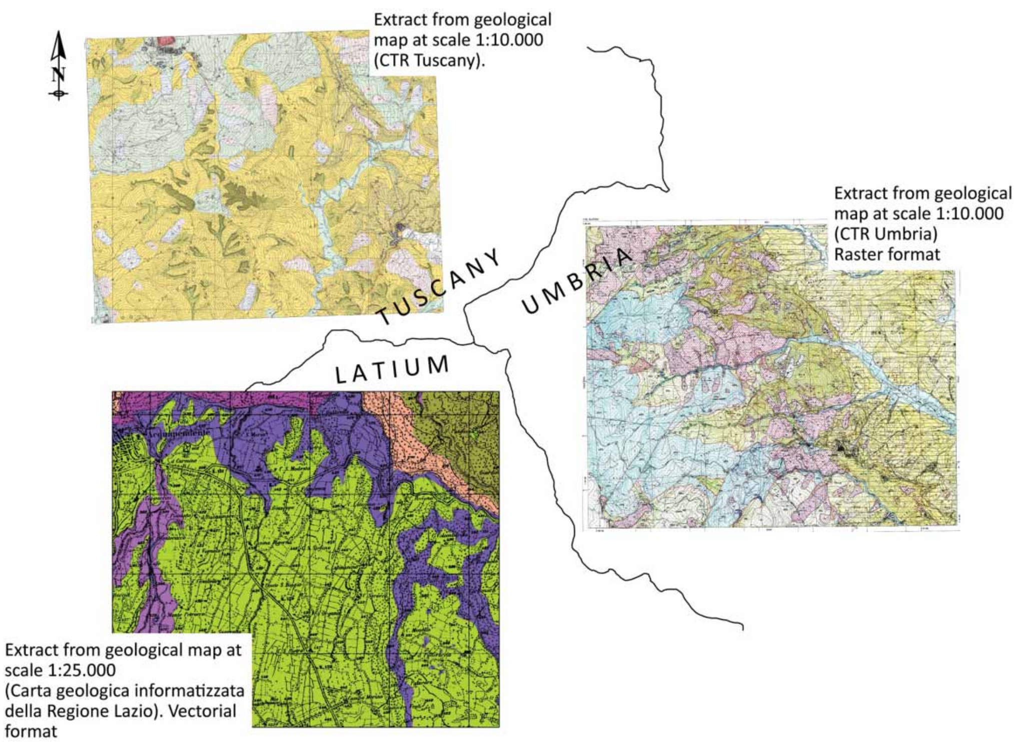

Figure 2. Examples of available geological cartography for three different administrative regions, showing heterogeneous mapping criteria. CTR: Regional technical cartography. The extracted frames are from: Regione Toscana (2006; http://www.regione.toscana.it), for Tuscany region; Regione Umbria (1999; http://www.territorio.regione.umbria.it/), for Umbria region; Cosentino and Pasquali (2012), for Latium.

Unfortunately, all these cartographic products are based on different and highly heterogeneous mapping criteria (i.e. lithological classification, hierarchical subdivision of units) that make their assembly unrealistic (Figure 2). The Italian Geological Survey is currently providing geological maps at a scale of 1:50,000 within the CARG project. The CARG (Geological CARtography) is a 'work-in-progress' project aimed at producing geological and geothematic sheets at a scale of 1:50,000 covering the entire Italian national area. However, the 1:50,000 map collection does not provide complete coverage of the study area. The official cartography at a scale of 1:100,000 provided by the Italian Geological Survey covers the whole Italian national territory with a total of 277 sheets and was chosen as the basis for the classification of hydrogeological formations. This cartography is available both in raster and vector formats. Six sheets (named n° 128, 129, 130, 135, 136, 137) cover the area considered in this work. Additional information about the cartographic design is reported in the Appendix.

3. Methodology

Figure 3 schematizes the adopted rationale used for (i) collating the geological information from existing paper maps at a scale of 1:100,000, (ii) developing the procedure for map digitization and (iii) compiling the final map for the hydrolithological complexes.

Each step of this approach is characterized by a specific procedure that includes creation of the database, data processing and the final map.

A series of preparatory steps has been done:

– collection of the official cartography (original products) both in paper and in vector formats;
– validation of the vector products by comparing with the original paper maps;
– re-organization and validation of shapefile attributes associated with the digital products;
– selection and standardization of criteria used for classifying the geological units in terms of lithological properties and hydrogeological behavior (hydrolithological complexes).

The major difficulty encountered in this process was due to the lack of a homogeneous cartographic legend for defining unequivocal geological units, due to different criteria used by the

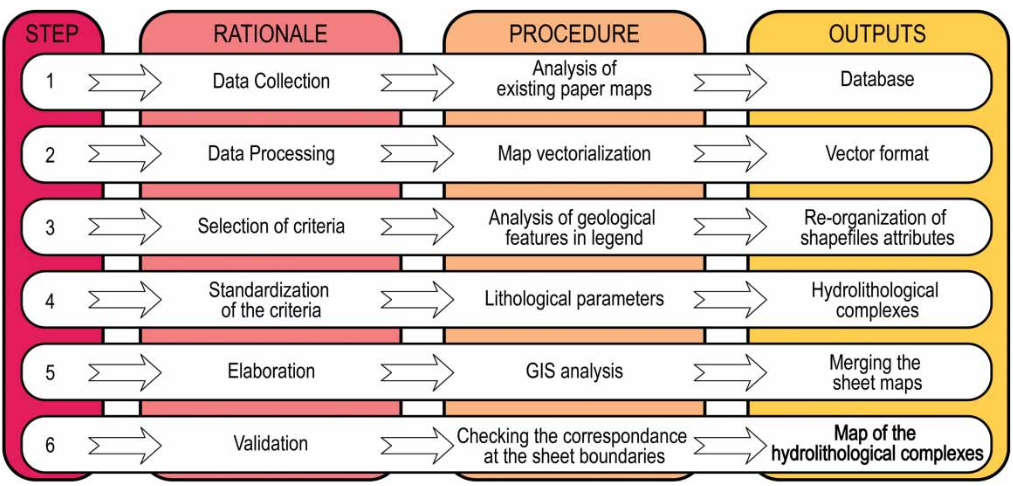

Figure 3. Flow chart illustrating the methodology adopted for hydrolithological complex mapping in the study area.

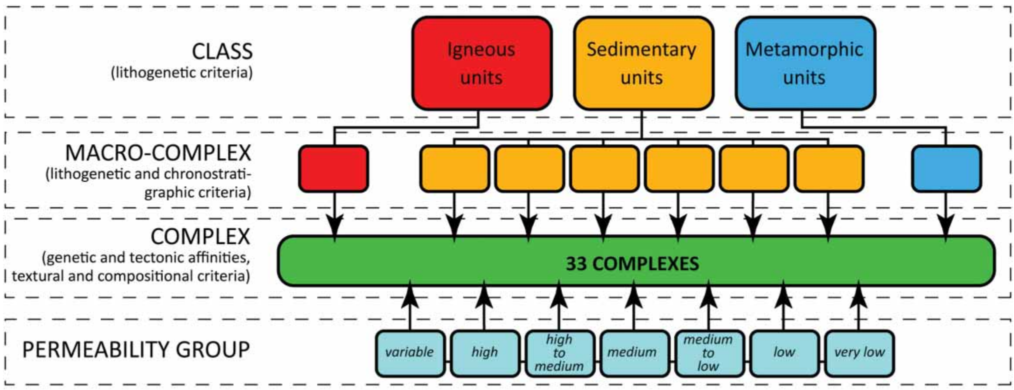

Figure 4. Hierarchical classification used for the redistribution of the geological units. The qualitative permeability attributed are also shown.

geological surveyors. This heterogeneity made it impossible to have available a uniform geological database for the entire Italian territory. The standardization of criteria has been based on the lithological features of the geological units obtained through a critical review of the cartographic legends. For each geological unit, information about chronostratigraphy, genetic environment, structural-stratigraphic setting, compositional and textural properties has been extrapolated. This process allowed us to homogenize the geological information and so produced a lithological classification with a hydrogeological focus.

4. Hydrolithological Complexes

The hydrolithological legend consists of the redistribution of the original geological units within a three-order hierarchical classification (Figure 4):

– class: identifying the main lithological groups on the basis of the lithogenetic criteria (sedimentary, magmatic and metamorphic classes);
– macro-complex: grouping geological units having lithogenetic and chronostratigraphic affinities;
– complex: grouping lithologies with genetic and tectonic affinities, showing internal textural and compositional similarities that produce similar behaviour regarding groundwater flow and storage.

A qualitative evaluation of the permeability (from very low to high rate) has been attributed to each complex. This produced 3 classes, 8 macro-complexes and 32 complexes, the latter distributed in 7 permeability groups. The hierarchical classification is presented in Table 1, where the details on the lithological and hydrological properties of each complex are reported.

5. GIS Analysis

A GIS has been used to implement a hierarchical and multiscalar cartographic database for representing the spatial distribution of the hydrolithological complexes at different scales. The following GIS operations were used to achieve the above classification:

Table 1. The hydrolithological complexes obtained for the study area.

Class	Macro-complex	Hydrolithological complex (abbr.)	Lithological description	Hydrological description
Sedimentary rocks	Continental Quaternary deposits	1	Alluvial and debris flow deposits, seldom cemented.	The complex contains unconfined aquifers, whose importance depends on the extremely variable permeability and irregular geometry of water bearing deposits.
				MEDIUM-HIGH PERMEABILITY
		2	Embankment of perennial streams, quarry dumps, landfills.	It does not take significant role at regional scale, but it assumes the hydrogeological features of the hosting complex.
				VARIABLE PERMEABILITY
		3	Lacustrine and palustrine deposits, loam soils with peat.	No significant groundwater flow. The sporadically occurrence of interbedded gravels and sand beds can cause limited local perched aquifer.
				LOW PERMEABILITY
		4	Actual and recent terrace deposits, colluvial and eluvial deposits, products of slope decomposition, intercalation of actual and recent lacustrine soils, silts, sands and gravels.	The lithological heterogeneity favours the formation of small perched aquifers. The alluvial deposits may contain large multistrata aquifers recharged by rives or contiguous aquifers.
				VARIABLE PERMEABILITY
		5	Ancient, recent and actual travertines, travertine concretions, calcareous silts, crusting travertines.	Wider travertine plateau can host important groundwater flowpath. Travertine lenses have high permeability and storage capacity, but generally contain modest aquifer due to their limited extension.
				MEDIUM-HIGH PERMEABILITY
		6	Compact clays and marls with sandy lenses, clayey silts with gravels.	Absence of a significant groundwater flow.
				VERY LOW PERMEABILITY

(*Continued*)

Table 1. Continued.

Class	Macro-complex	Hydrolithological complex (abbr.)	Lithological description	Hydrological description
		7	Sands, dominant siliceous pebbles, sands with lenses of clays, sands with lacustrine clays.	Absence of a significant groundwater flow.
				The lithological heterogeneity may promote the formation of small seasonal perched aquifers.
				LOW PERMEABILITY
		8	Gravels and sands with lacustrine clays, tufites with pumice layers, weakly cemented conglomerates, terraced conglomerates.	Absence of a significant groundwater flow. The conglomerate component, where more extensive, may favour the formation of small local aquifer.
				MEDIUM-LOW PERMEABILITY
	Marine and transitional Quaternary deposits	9	Fossiliferous clays and sands, grey clays interbedded with gravel layers, marine to brackish clays with brownish lignite.	Absence of a significant groundwater flow.
				VERY LOW PERMEABILITY
		10	Sands with poorly cemented conglomerates, sands and marls with volcanic material, sandy shelly limestones (bench).	Absence of a significant groundwater flow.
				The lithological heterogeneity may promote the formation of small seasonal perched aquifers.
				LOW PERMEABILITY
		11	Polygenic pebbles and coarse red sands.	Absence of a significant groundwater flow. The conglomerate component, where more extensive, may favour the formation of small local aquifer.
				MEDIUM-LOW PERMEABILITY
	Continental Neogene deposits	12	Sands, sandy red clays, blue-grey marls and clays, pebbly lenses with gypsum.	Absence of a significant groundwater flow.
				The lithological heterogeneity may promote the formation of small seasonal perched aquifers.
				LOW PERMEABILITY

	Marine Neogene deposits	13	Clays and sandy clays with blocks of Mesozoic limestone olistoliths, clays and sandy clays with olistoliths flysch, marls and grey clays with gypsum, fossiliferous clays.	Absence of a significant groundwater flow.
				VERY LOW PERMEABILITY
		14	Sandstone layers with interbedded clays, quartz-micaceous sandstones, clays and sands with lenses of conglomerates, seldom including blocks of Mesozoic limestone olistoliths.	Absence of a significant groundwater flow. The interbedded clays can support small seasonal perched aquifers
				MEDIUM-LOW PERMEABILITY
		15	Conglomerates with sandy cement, polygenic conglomerates alternating with marls, conglomerates with pebbles of basement units and Mesozoic covers.	It can host local important groundwater flow.
				MEDIUM PERMEABILITY
		16	Calcarenites and weakly massive sandy limestones including interbedded conglomerates, yellow sandstones and sandy mudstones containing abundant fossils.	Wider outcrops can host important groundwater flow.
				MEDIUM PERMEABILITY
	Flysch deposits	17	Mudstones, marls and marly limestone interbedded with grey marls, shales, marls with Cretaceous, Eocene and Oligo-Miocene microfaunas; limestones type ‘Palombino’, calcarenites and breccias with intercalations of ophiolites and molasses; locally include the marly limestones like ‘Pietraforte.’	Absence of a significant groundwater flow.
				VERY LOW PERMEABILITY

(*Continued*)

Table 1. Continued.

Class	Macro-complex	Hydrolithological complex (abbr.)	Lithological description	Hydrological description
		18	Quartz- and calcareous-sandstones alternating with silty marls containing Eocene and Miocene microfaunas; sandstones with calcareous cement like 'Pietraforte', including lenses of conglomerates.	Modest groundwater flow in sandstone lithologies, locally sustained by clayey lithologies.
				LOW PERMEABILITY
		19	Quartz-feldspathic-micaceous sandstones like 'Macigno' with calcareous breccias and shales containing Cretaceous and Eocene microfaunas.	It can host local important groundwater flow confined within the sandstone bodies.
				MEDIUM-LOW PERMEABILITY
	Mesozoic-Tertiary deposits	20	Grey-greenish marls and marly limestones showing red-purple colour towards the base.	The occurrence of frequent intercalations between marls and limestones determines small seasonal perched aquifers.
				LOW PERMEABILITY

		21	Reddish marly limestones and calcareous marls with red chert, pinkish limestones and marly limestones, white limestones and marly limestones with blackish or whitish chert nodules and bituminous layers; calcarenites, fine detrital limestones and calcareous marls.	It can be the site of significant groundwater flow in domains characterized by intensely fracturation and reduced occurrence of marls.
				MEDIUM-HIGH PERMEABILITY
		22	Yellowish marly limestones alternating with clay marls, grey-black calcareous marls with thin layered cherts; varicolours shales with fucoids; intercalations of whitish limestone debris.	Absence of significant groundwater flow. This complex defines the aquiclude between the hydrolithological complexes at the top and at the bottom.
				LOW PERMEABILITY
		23	Whitish to grey massive limestones and laminated limestones with nodules of chert in different colours.	The intense fracturation promotes an important groundwater flow within this complex, which feeds perennial regional aquifers.
				HIGH PERMEABILITY
		24	Laminated marly limestones with abundant chert and interbedded marly limestones with Haptic; siliceous shales, radiolarites, red and green marls; red marly limestones with typical nodular facies, marls with ammonites, bivalves and ostracods.	Absence of significant groundwater flow. Where unfaulted or unfractured, it defines the local aquiclude between the hydrolithological complexes at the top and at the bottom.
				MEDIUM-LOW PERMEABILITY

(*Continued*)

Table 1. Continued.

Class	Macro-complex	Hydrolithological complex (abbr.)	Lithological description	Hydrological description
		25	Marly limestones, massive grey-brown limestones with conchoidal fracture, well layered limestones containing grey chert in nodules or lenses; oolitic and pisolitic greyish limestones with corals and algae.	The intense fracturation promotes high infiltration that feeds massive aquifers hosted at bottom of the carbonate strata. The outcrops of this complex are the recharge area of the most important regional depth aquifers in carbonate environments.
				HIGH PERMEABILITY
		26	Limestones and dolostones, seldom with vacuolar appearance, containing gypsum.	It is characterized by significant groundwater flow, but of secondary importance compared to the circulation in the overlying complex. Regionally, it constitutes the basal aquitard of the complex 25.
				MEDIUM-LOW PERMEABILITY
		27	Whitish dolostones, whitish or dark grey dolomitic limestones, poorly stratified dark dolostones, evaporites.	The hydrogeological role of this complex is not yet fully known. The densely jointed dolomitic horizons are supposed to host a deep groundwater, whereas the evaporitic horizons may be regarded as aquicludes without significant groundwater flow. As a whole, this complex may be interpreted as an aquitard located at the base of the regional basal aquifer, in hydraulic continuity with the overlying complex.
				MEDIUM PERMEABILITY

Igneous rocks	Volcanic units	28	Scoria and welded lapilli beds, pumices, ballistic lava blocks; tephritic-leucititic and leucititic cinder cones, reddish layers and laminated lenses of scoria, laminated ash and lapilli tuffs variably compact.	It can be the site of an active groundwater flow with limited extension.
				MEDIUM-HIGH PERMEABILITY
		29	Rhyolitic and quartz-latitic lava domes with vitrophiric or ipocrystalline structure and phenocrysts of sanidine, plagioclase, biotite and pyroxene; leucitites, leucititic basalts, phonolites, trachybasalts, leucititic tephrites, olivintrachytes; reoignimbrites.	At local scale, it hosts a significant groundwater flow favoured by the occurrence of fracturing systems in more competent rock types.
				HIGH PERMEABILITY
		30	Massive and chaotic pyroclastic flow deposits; trachytic or leucititic-tephrytic ignimbrites showing cineritic matrix.	It is characterized by an extensive and articulated groundwater flow that feeds the most important regional aquifers in volcanic environments.
				PERMEABILITY MEDIA
		31	Alternations of: brownish tuffs, yellow tuffs with pumice, greyish volcanic silts and sands, granular tuffs, massive tuffs, travertine intercalations, paleosols, pyroclastic breccias, trachytic-phonolitic bedded tuffs related to the phreatic-magmatic eruptions, laminated lacustrine deposits.	Reduced groundwater flow. Locally, it can sustain perched aquifers and define local aquicludes in the flowpath.
				LOW PERMEABILITY
Metamorphic rocks	Basement units	32	Quartz-mica schists with interbedded graphitic shales; talc-shales with intercalations of whitish or yellow limestones; reddish quartz-sandstones with silty matrix, quartzschists; anagenites.	Absence of a significant groundwater flow.
				VERY LOW PERMEABILITY

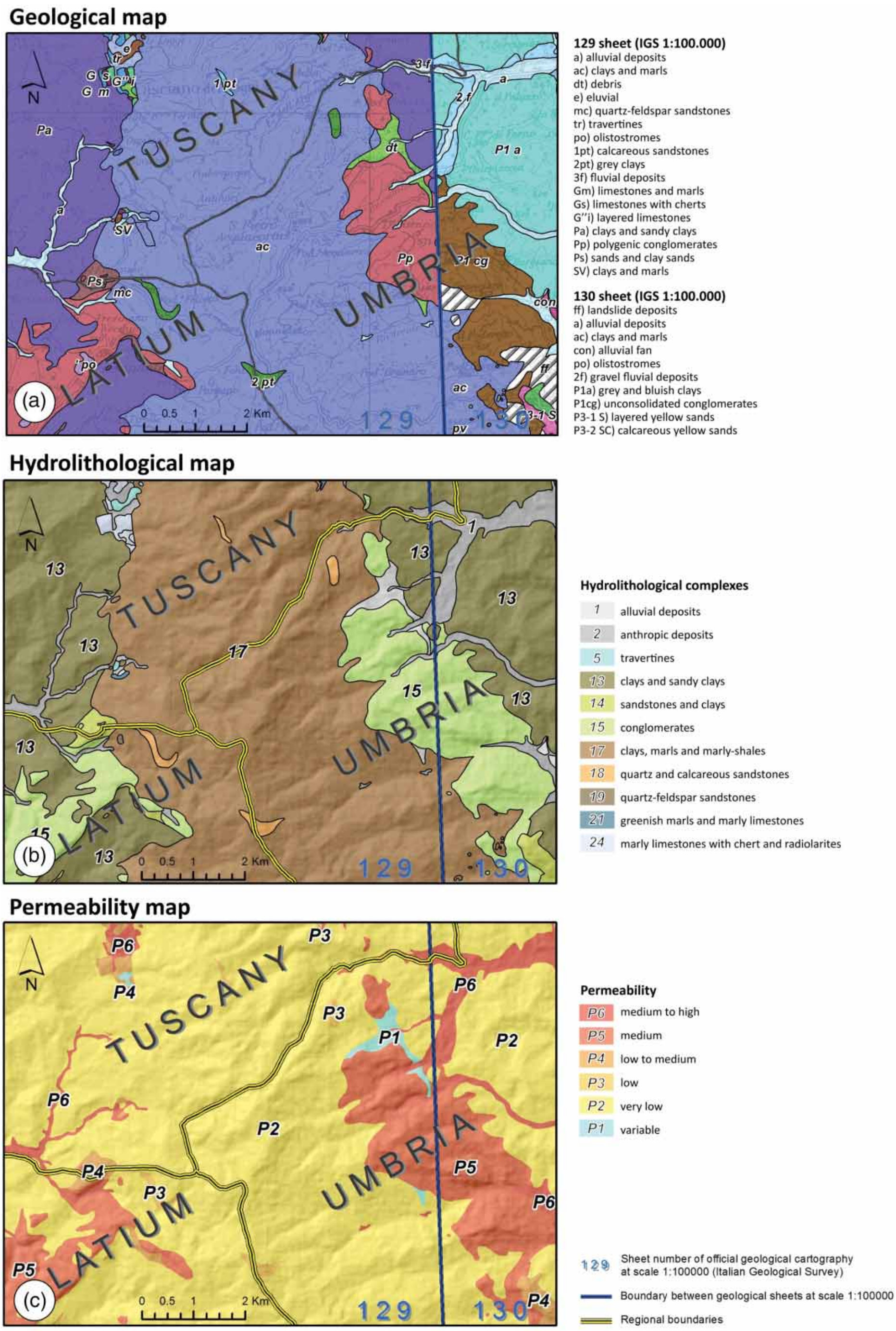

Figure 5. (a) An extract of the official geological cartography at a scale of 1:100,000 (Italian Geological Survey), including the administrative boundaries. Note the dissimilarity between legends of each sheet; (b) extract of the hydrolithological map of the study area and (c) the derivative permeability distribution map.

– for each shapefile (corresponding to a single geological sheet at scale 1:100,000), an unequivocal code was assigned to each record corresponding to the geological units;
– the original polygons (geological units) were aggregated into new polygons (complexes);
– new shapefiles were merged to a single uniform thematic layer;
– editing operations were used for modifying polygonal features at the boundaries between adjacent sheets, on the base of topological criteria.

The shapefile of the obtained hydrolithological map (see example in Figure 5) has an attribute table composed of both original and edited records. Starting from the original geological map (Figure 5a), the attributes allow us to visualize the map in terms of hydrolithological features (Figure 5b). The hydrolithological map constitutes the source map supporting production of thematic maps. The other subsequent maps can be derived by coupling base information provided by the hydrological maps with different themes, e.g., effective precipitation, piezometry, land cover. Figure 5c illustrates an example of thematic map obtained by assigning the hydrolithological complexes into different, qualitatively determined, groups of permeability.

6. Conclusions

The hydrolithological map presented in this study is based on the revision (production, interpretation and merging) of the original geological cartography at scale of 1:100,000 provided by the Italian Geological Survey. By reprocessing the geological information in a multicriteria database performed using a GIS, the map illustrates the spatial distribution of different hydrolithological complexes regulating the regional hydrogeological setting in this portion of the central Apennines.

Assessment of this GIS-based hydrolithological map provides the following considerations:

- The hydrolithological complex (grouping lithologies with genetic and tectonic affinity, and showing similar hydrological behaviour on the basis of their lithological properties) can represent the reference cartographic key for supporting hydrogeological study. The results from this study point out the importance of defining a standard method for grouping the geological units into appropriate complexes with hydrological affinities for the assessment of an official hydrolithological map.
- The approach used here outlines that hydrogeology requires the collation and revision of criteria used for geological cartography. Dissimilarities between legends of each 1:100,000 sheet (Italian Geological Survey) do not allow the organization of a uniform geological database for the entire Italian territory. Consequently, it is not possible to build a GIS-based geological map, but only thematic maps derived from the input, interpretation and merging of geological units. Despite various limitations in homogenizing the geological database in terms of hydrolithologies, the regional-scale approach constitutes a preliminary, but necessary, step for assessing the hydrogeological scenario.
- The hydrolithological map provides basic geo-environmental information directly supporting the regional-scale management of groundwater. Identification and validation of the main hydrogeological components (aquifer, aquiclude, aquitard), as well as the planning of groundwater exploration activities, can be extracted from the spatial distribution of the hydrolithological complexes. With regard to territory planning, it is worth noting that this GIS-based hydrolithological map is an example of digital product that can be easily upgraded, combined and integrated with further geo-environmental database (e.g. seismicity, distribution of anthropogenic activities, land use, etc.) in order to extract derivative products.

- In the case of local territory planning, it is necessary to produce hydrolithological maps derived from original geological cartography at scale higher than 1:10,000. The maps at larger scale are based on heterogeneous cartographic criteria provided by the individual local administrations. This heterogeneity does not provide a direct GIS multiscalar analysis for territory planning.

Software

ESRI ArcGIS 10.1 was used for production of the original shapefiles provided by the Italian Geological Survey and for map visualization. Further images shown in the map were produced using Adobe Illustrator CS and Coreldraw X3. Final editing of the map was performed using Photoshop CS4.

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Appendix

Topographic base map at 1:100,000 scale is provided by the Istituto Geografico Militare (IGM) and available by the Web Map Services (WMS) at the Italian National Geoportal (http://wms.pcn.minambiente.it/ogc?map=/ms_ogc/WMS_v1.3/raster/IGM_100000.map). Toponyms derived from the Web Features Services (WFS) of the Italian National Geoportal (http://wms.pcn.minambiente.it/ogc?map=/ms_ogc/wfs/Toponimi_2011.map). Regional boundaries are from the database provided by the Italian National Institute of Statistics (ISTAT) at http://www.istat.it/it/archivio/24580 (2011). The shaded relief map is derived from the digital elevation model with 30 m spatial resolution (SRTM) available at http://earthexplorer.usgs.gov.