Journal of Maps

ISSN: (Print) 1744-5647 (Online) Journal homepage: http://www.tandfonline.com/loi/tjom20

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To cite this article: De Vita Pantaleone, Allocca Vincenzo, Celico Fulvio, Fabbrocino Silvia, Mattia Cesaria, Monacelli Giuseppina, Musilli Ilaria, Piscopo Vincenzo, Scalise Anna Rosa, Summa Gianpietro, Tranfaglia Giuseppe & Celico Pietro (2018) Hydrogeology of continental southern Italy, Journal of Maps, 14:2, 230-241, DOI: 10.1080/17445647.2018.1454352

To link to this article: https://doi.org/10.1080/17445647.2018.1454352

JOURNAL OF MAPS, 2018
VOL. 14, NO. 2, 230–241
https://doi.org/10.1080/17445647.2018.1454352

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Science

Hydrogeology of continental southern Italy

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ABSTRACT

This paper summarizes the results of a study focused on the hydrogeological characterization and recognition of groundwater resources in continental southern Italy, developed under the European INTERREG IIC Programme. The study reconstructed up-to-date scientific knowledge regarding aquifers, groundwater circulation schemes and groundwater resources exploitation in the administrative regions of southern Italy included in the Objective I (Molise, Campania, Basilicata, Puglia and Calabria). In this paper, the methodological approaches applied to synthesize and homogenize bibliographic data collected from the hydrogeological literature and to set a regional hydrogeological mapping are described. Results presented are three hydrogeological maps, 1:300,000 scale, showing hydrogeological units and groundwater flow schemes that are relevant in the regional hydrogeological context, and a brief description of principal types of aquifer and groundwater resources of continental southern Italy.

ARTICLE HISTORY
Received 4 November 2017
Revised 12 March 2018
Accepted 15 March 2018

KEYWORDS
Southern Italy; hydrostratigraphic units; hydrogeological mapping; aquifers

1. Introduction

Under the INTERREG IIC Programme (European Commission, 1997), funded by the European Union and aimed at the drought prevention and analysis of the water cycle in the less developed regions (Objective 1 areas) of continental southern Italy (Molise, Campania, Basilicata, Puglia and Calabria), a study focused on the recognition and characterization of groundwater bodies was carried out. This study led to a preceding printed publication (Allocca et al., 2007) consisting of a hydrogeological map of southern Italy, 1:250,000 scale, and extended illustrative notes, both in Italian. Due to the limited number of printed copies and their distribution only at the national scale, in this paper, we propose a new digital edition of the hydrogeological map, 1:300,000 scale, a description of approaches used for hydrogeological mapping, and an outline of hydrogeological features of principal aquifers of continental southern Italy.

2. Database and methods for regional hydrogeological mapping

The study was based on the collection of all available published papers, as well as unpublished technical reports commissioned by government agencies and aqueduct companies, concerning different hydrogeological aspects of the Objective I regions. To homogenize bibliographical data, a relational database was designed based on 12 tables (Figure 1): (1) study identification; (2) administrative localization; (3) physiographic localization; (4) geological and hydrogeological characterization; (5) contents and results; (6) springs; (7) water table contour lines; (8) wells and piezometers; (9) rivers; (10) hydrogeochemical analyses; (11) precipitation data; (12) air temperature data. Tables were subdivided into 123 fields.

Considering the not univocal identification of springs, often due to the attribution of different names to the same one, a cross-checking among different sources of information was accomplished. Such control included also the geolocalization by the 1:25,000 topographic maps of the Italian geographic military service (I.G.M.I.). All major springs with a mean annual discharge equal or exceeding 0.050 m^3s^{-1} and those with lower values, but significant for comprehending groundwater circulation schemes, were mapped. The analysis of spring discharge data available in literature showed in many cases non-systematic measurements carried out in the 1930s and 1950s of the last century by the '*Ministero dei Lavori Pubblici*', a technical government agency, and

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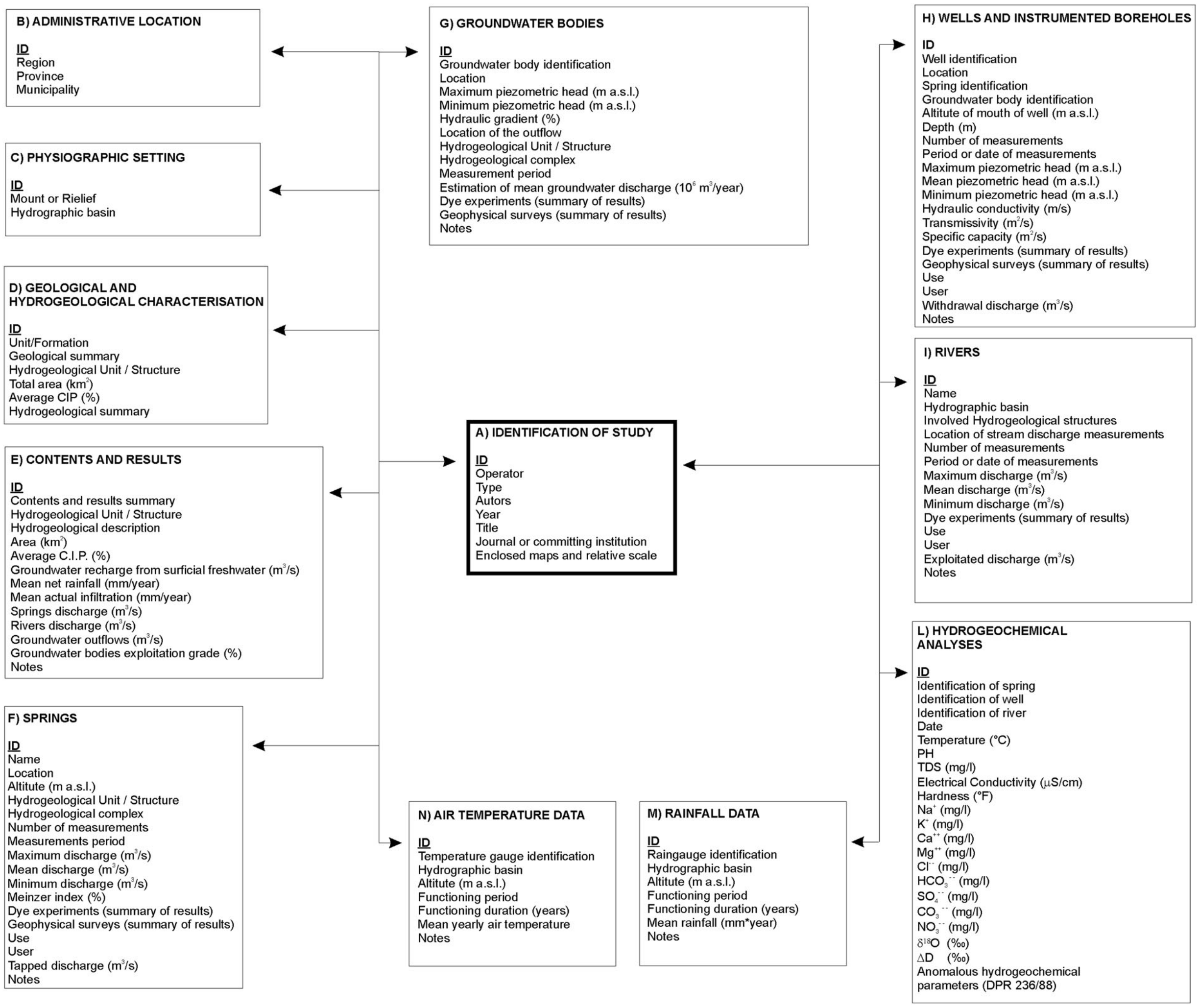

Figure 1. Thematic tables and links of the relational database in which bibliographic hydrogeological data have been filed.

published for the studied regions in the volumes '*Le sorgenti italiane*' (Italian springs) series (Ministero dei Lavori Pubblici, 1941, 1942, 1952a, 1952b). Finally, the groundwater exploitation was assessed by differentiating tapped and untapped springs and considering principal well pumping stations feeding aqueduct systems of regional and local relevance.

The recognition of groundwater bodies, meant as volumes of groundwater (Directive 2000/60/CE; European Parliament, 2000), is necessarily linked to the hydrogeological characterization of geological bodies that bear and convey groundwater by gravity (Meinzer, 1923), specifically to the institution of fundamental hydrostratigraphic units (Maxey, 1964). However, the geological and structural complexity of the Objective I regions of southern Italy makes the analysis and hydrogeological mapping challenging (UNESCO & WMO, 1977) as well. Different from other types of geological units (lithostratigraphic, biostratigraphic and chronostratigraphic), for which univocal criteria of nomenclature and formal classifications have been issued (ISSC, 1976), there is still a lack for of hydrostratigraphic units. Therefore, the definition of aquifer (Meinzer, 1923) and the US Geological Survey's (USGS) multi-rank nomenclature (Jorgensen & Rosenshein, 1987; Laney & Davidson, 1986; Owen, 1987), of aquifer system, aquifer and zone, were considered as fundamental references. Accordingly, the hydrogeological complex concept (Civita, 1975), defined as a set of lithotypes with a prevailing type of permeability, a permeability grade ranging in a limited interval and a proved spatial and structural unity, was considered applicable in this work. In fact, it is consistent with the meaning of hydrostratigraphic unit proposed by Maxey (1964) and with principles proposed by the UNESCO & WMO (1977) for hydrogeological mapping.

The identification of hydrogeological complexes was carried out by respecting the three fundamental criteria described below that allowed obtaining a homogeneous mapping, the highest detail possible and respect of geometrical relationships among lithostratigraphic and tectonic units (Main Map).

1) Reference to a common geo-structural regional scheme, suitable for the map scale. To such a purpose, the geological map of southern Italy (Bonardi, D'Argenio, & Perrone, 1988a), 1:250,000 scale, was

considered, which summarized both geological data and modern regional interpretations.

2) Identification of hydrogeological complexes (Civita, 1975) from lithostratigraphic and tectonic units forming the southern Apennine structure by considering their hydrogeological features, such as types of permeability (Freeze & Cherry, 1979) and permeability grade (Bureau of Reclamation, 1985; Civita, 1975), and respecting reciprocal geometrical relationships.
3) Recognition of hydrogeological units, formed by one or more hydrogeological complexes, which are significant at the regional scale for groundwater circulation patterns and exploitation (Celico, 1986).

This approach allowed the recognition of 9 hydrogeological domains (Figure 2) and 39 hydrogeological complexes, which were characterized by the permeability type and grade, as well as groundwater recharge coefficient (Figure 3). The latter was attributed by relying on results of hydrological budgets carried out on homogeneous hydrogeological units (Allocca, Manna, & De Vita, 2014; Boni, Bono, & Capelli, 1982; Celico, 1986). Geometries of outcropping areas were digitalized in a vector format and implemented in a Geographical Information System (GIS), georeferenced in the UTM projection and European Datum 1950. By linking map graphical objects to the relational database, derivative maps of permeability grade were also obtained (Figure 4).

3. Result and discussion of the regional hydrogeological characterization

Due to the rising needs of groundwater resources, hydrogeological studies in the continental part of southern Italy increased exponentially in the last decades forming a fundamental scientific heritage, which consists of 557 scientific papers and unpublished technical reports. The hydrogeological knowledge was mostly improved through studies carried out in the Special Projects 26 and 29 by the *Cassa per il Mezzogiorno* (1976, 1978), a government agency (1950–1992) aimed at the social and economic development of southern Italy in the post-Second World War period, as well as by university and research institutions.

The large territory including the Objective I regions is characterized by lithostratigraphic and tectonic units with highly variable and complex hydrogeological features (Main Map). These can be related to a palaeogeographic scheme formed by sedimentary domains of carbonate platforms and interposed oceanic basins that existed between the Triassic and early Cenozoic periods in the Paleo-Tethys Ocean (D'Argenio, 1988). These domains were deformed by the Miocene–Pliocene compressive tectonic phases and currently form tectonic units piled up in the Apennine fold-and-thrust belt (Casero et al., 1988; D'Argenio, Pescatore, & Scandone, 1975; Marsella, Bally, Cippitelli, D'argenio, & Pappone, 1995; Menardi Noguera & Rea, 2000; Mostardini & Merlini, 1986; Patacca & Scandone, 2001). Regarding the hydrogeological behaviour, the above-mentioned lithostratigraphic and tectonic units can be clustered into five principal groups of hydrogeological complexes. According to a decreasing relevance for feeding aqueduct systems, they can be identified as follows (Main Map): (a) Meso-Cenozoic carbonate platform complexes; (b) Plio-Quaternary alluvial and epiclastic complexes; (c) Plio-Quaternary volcanic complexes; (d) Palaeozoic crystalline complexes; (e) Meso-Cenozoic terrigenous complexes. For each group, an outline of the hydrogeological knowledge is described as follows.

3.1 Meso-Cenozoic carbonate platform complexes

The Mesozoic and Cenozoic carbonate series, belonging to carbonate platform palaeogeographic units, constitute mountain ranges that are among the highest of southern Italy and host the most important regional aquifers (Figure 2). They outcrop over about 10,500 km^2 (7200 km^2 in the Puglia region). The knowledge about the hydrogeological features of these aquifers greatly improved due to studies for the construction of the main tunnels and tapping works in southern Italy (Celico, 1978, 1983). The hydrogeological conceptual models proposed for these aquifers (Aquino, Petrella, Florio, Celico, & Celico, 2015; Celico, 1983; Celico, Celico, De Vita, & Piscopo, 2000; Celico, Petrella, & Celico, 2006; Celico et al., 2010; Fiorillo, 2011; Petrella, Aquino, Fiorillo, & Celico, 2015; Petrella, Capuano, Carcione, & Celico, 2009) identified strong similarities and differences with those of similar aquifers in other zones of the world (Drogue, 1992; Goldscheider & Drew, 2007; Jeannin, 1998; Kiraly, 1975, 2002; Klimchouk, 2000; Mangin, 1975; White, 1969, 2002).

The carbonate aquifers of the Molise, Campania, Basilicata and Northern Calabria regions supply the main drinkable water resources of southern Italy, having globally a mean water yield of about 4100×10^6 m^3 $year^{-1}$. Contrarily, the Apulian carbonate aquifers do not constitute sufficient supplies for the regional aqueduct systems due to the diffuse outflow of groundwater along the coastline, which implies difficult tapping. According to general hydrogeological features, the carbonate aquifers can be arranged into three subgroups (Allocca et al., 2007):

a) Limestone aquifers, generally characterized by a high permeability grade due to fracturing and karst, and represent the most important aquifers both for large extension and mean annual

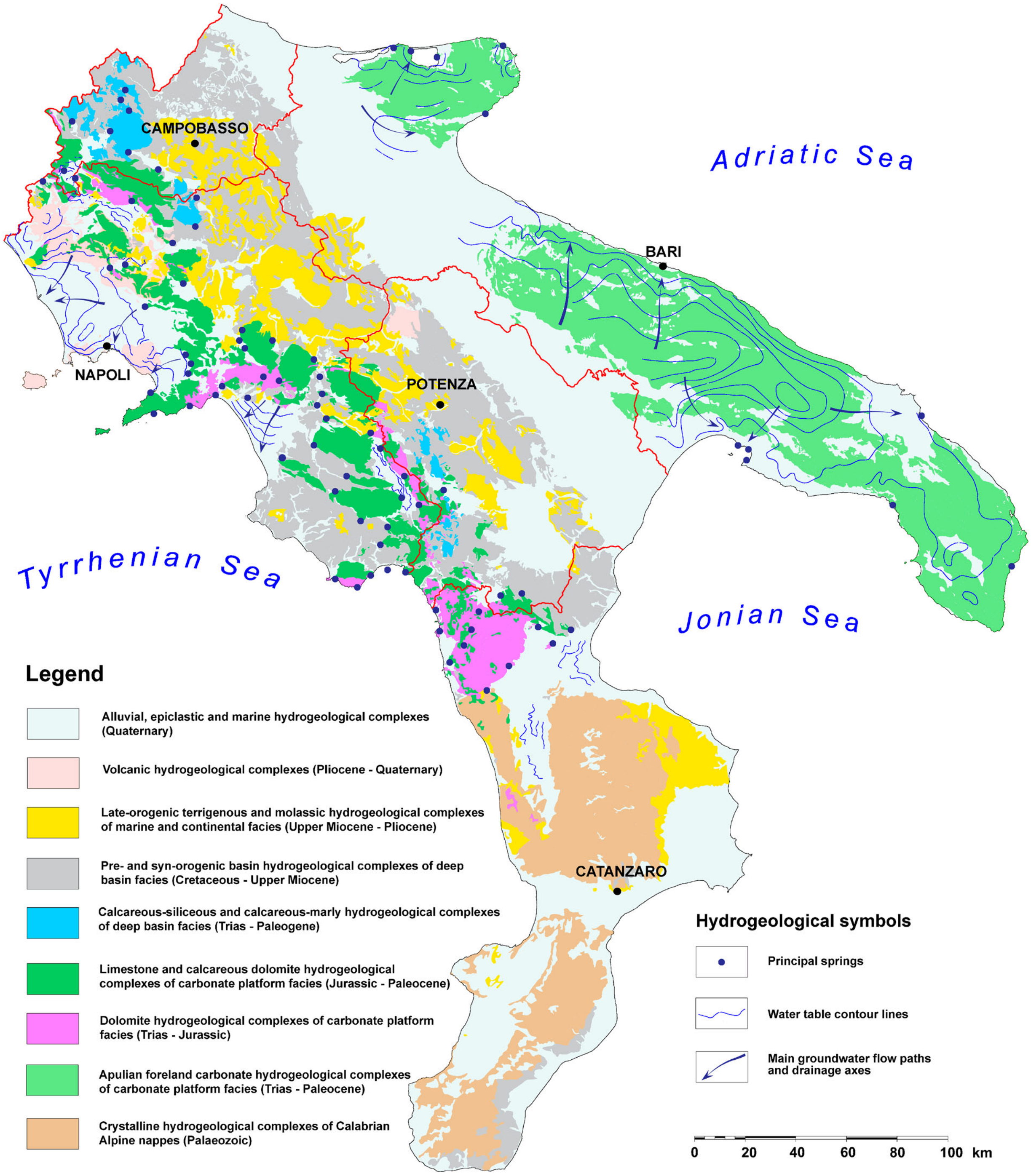

Figure 2. Hydrogeological scheme of continental southern Italy (redrawn from Allocca et al., 2007) showing groups of hydrogeological complexes clustered in nine principal domains.

groundwater yield, estimated at about 3700×10^6 m^3 year^{-1}. Hydrogeological units formed by these aquifers have a mean specific groundwater yield ranging from 0.016 to 0.035 m^3 s^{-1} km^{-2} (Figure 5).

b) Dolomitic aquifers are characterized in general by a medium permeability grade mainly due to fracturing and negligibly to karst. Their mean annual groundwater yield can be estimated at about 300×10^6 m^3 year^{-1}. Hydrogeological units formed by these aquifers show a mean specific groundwater yield ranging from 0.013 to 0.021 m^3 s^{-1} km^{-2} (Figure 5).

c) Carbonate aquifers, constituted by alternating limestone, limestone with chert, marl limestone and subordinately marls, are characterized by a permeability due chiefly to fracturing, and whose grade varies from medium to low, according to relative abundance of low-permeability lithotypes. Their mean annual groundwater yield can be estimated in about 100×10^6 m^3 year^{-1}. Hydrogeological units formed by these aquifers have a mean specific groundwater yield ranging from 0.009 to 0.015 m^3 s^{-1} km^{-2} (Figure 5).

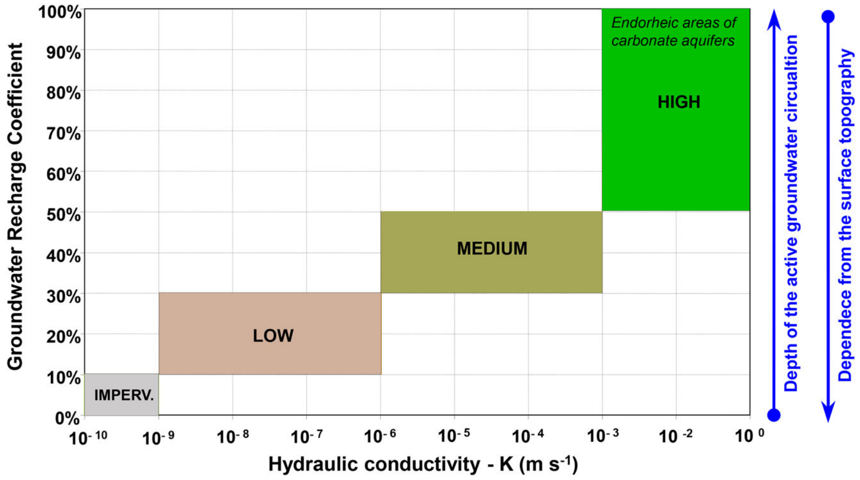

Figure 3. A conceptual model for the characterization of hydrostratigraphic units (Allocca et al., 2014; Bureau of Reclamation, 1985; Celico, 1986; Civita, 1975) based on relationships among permeability grade, hydraulic conductivity and groundwater recharge coefficient, determined as the ratio between groundwater recharge and effective precipitation. On the right side, conceptual relationships between depth of groundwater circulation and its dependence from surface topography are also shown.

The Miocene and Pliocene-Quaternary tectonic phases were accomplished by brittle mechanical behaviour and stresses which resulted in a pervasive fracturing of the carbonate aquifers which enhances karst processes, particularly in limestone aquifers. Therefore, the latter have a general high permeability grade especially in the surficial epikarst zone (Petrella, Capuano, & Celico, 2007, 2008). These characteristics coupled with extended endorheic morphologies lead to a high groundwater recharge rate, varying between 48% and 78% of the mean annual effective precipitation (Allocca et al., 2014, 2015) in dependence of the relative abundance of limestone and dolomite lithologies, as well as ash-fall pyroclastic covers (Celico et al., 2010; De Vita & Nappi, 2013; Fusco, Allocca, & De Vita, 2017; Fusco, De Vita, Napolitano, Allocca, & Manna, 2013). Groundwater flow directions are controlled by geometric relationships of the permeability boundaries with the adjoining low-permeability Meso-Cenozoic terrigenous complexes. Moreover, faults with low permeability, damage and core zones, or stratigraphic intervals in the carbonate serie, with marly or argillaceous composition, can divide the groundwater circulation allowing the compartmentalization of the aquifers in groundwater sub-basins. The latter can be reciprocally interconnected forming basin-in-series systems (Celico, 1983; Celico, Petrella, & Celico, 2006; Petrella et al., 2009). Main basal springs, with a mean annual discharge varying from 0.1 to 5.5 $m^3 s^{-1}$ and perennial regime, even if usually affected by high variability due to effects of karst conduits, are typically located at the lowest points along these permeability boundaries (Celico, 1983). The occurrence of high-altitude springs, characterized by discharge rates lower than the basal ones and often by ephemeral and high variable regimes, indicate a composite groundwater circulation that in some cases can be related to a perched groundwater flow circulating within the epikarst zone and in some others to the barrage effect of low-permeability fault zones that constrain the basal groundwater at higher altitudes (Petrella et al., 2009).

3.2 Plio-Quaternary alluvial and epiclastic hydrogeological complexes

The Pliocene-Quaternary porous aquifers are formed by clastic deposits of talus, alluvial, coastal and intramountain plains, outcropping over about 24,500 km^2. The high interest for these aquifers is linked to the intensive groundwater exploitation by wells, which is fostered by the limited depth of the groundwater table and numerous settlements with water-demanding activities, mainly for agricultural and industrial uses. Among the most extended alluvial-coastal aquifers are those corresponding to the Campanian, Sele, Ofanto, Bradano, Crati, Sant'Eufemia and Rosarno Plains, while many other alluvial aquifers occur in internal zones of the Apennine (Celico, 1983).

These aquifers are heterogeneous and anisotropic due to the spatially variable depositional mechanisms and energy controlling the grain sizes and the related permeability. Deposits only rarely present a low cementation grade, and their permeability is due to primary porosity. Depending on the occurrence of low-permeability levels interbedded within the aquifer deposits, at the local scale, the groundwater flow occurs in a multilayered aquifer system in which confined and unconfined aquifers can coexist (Allocca et al., 2018). Instead, at a large denominator scale, the behaviour of these composite groundwater bodies can be considered as unitary with a common circulation pattern (Celico, 1983). Besides the recharge from the effective rainfall, alluvial aquifers are fed directly by

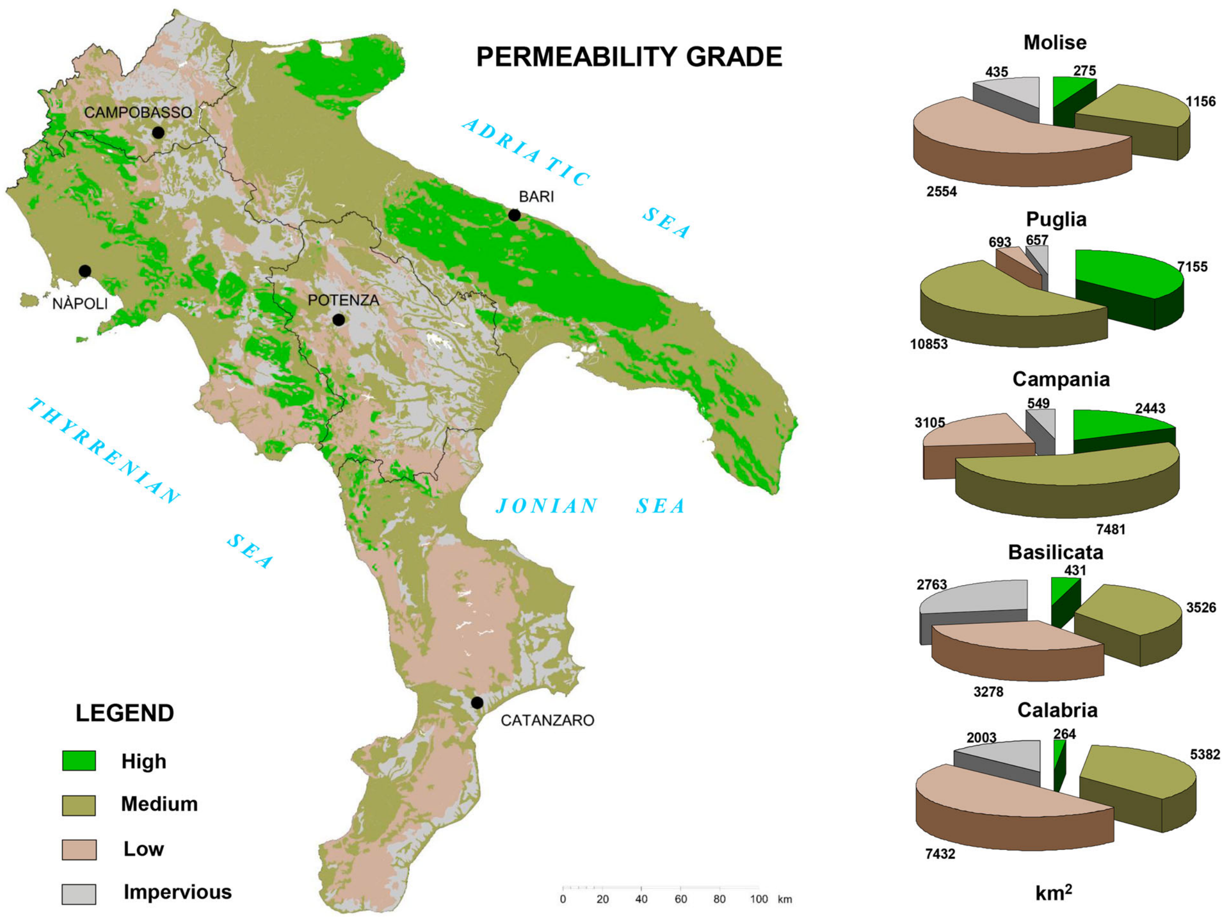

Figure 4. Permeability grade map of hydrogeological complexes and regional distribution of outcropping areas.

groundwater from the adjoining hydrogeological units, especially in the cases of carbonate and volcanic aquifers.

3.3 Plio-Quaternary volcanic hydrogeological complexes

The volcanic hydrogeological complexes of southern Italy are deposits of the eruptive centres that developed along the Tyrrhenian side beginning at the end of Pliocene (Roccamonfina, Phlegrean Fields and Somma-Vesuvius volcanoes), and in a position external to the Apennine chain (Vulture volcano). Aquifers formed by these complexes are relevant due to the high economic value of their groundwater, often characterized by valuable organoleptic properties like CO_2 concentration, among the others. The total outcropping area is about 920 km^2.

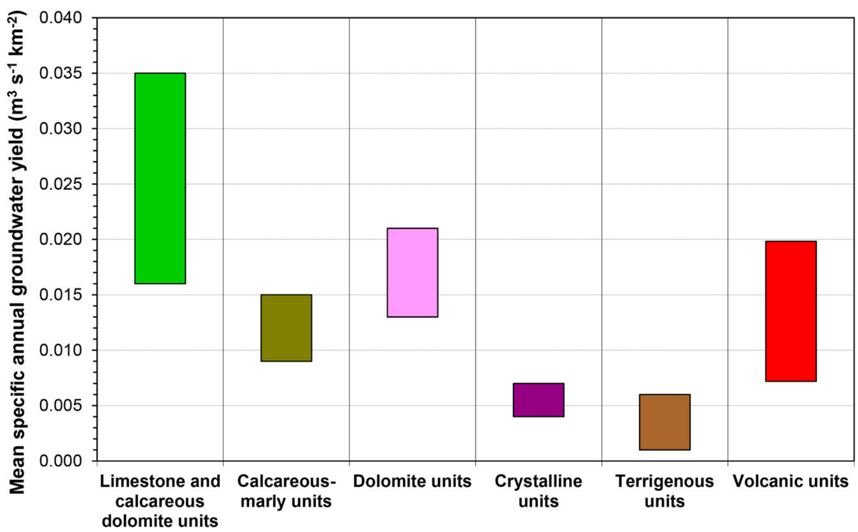

Figure 5. Mean specific annual groundwater yield of hydrogeological units studied by hydrological budget technique.

Hydrogeological features of these complexes depend on the variable hydraulic properties of volcanic soils, rocks, and the complex stratigraphic architecture (Custodio, 1978, 2007; Davis & De Wiest, 1966; Stearns, 1942). They form aquifers characterized by fracture permeability, as in hard volcanic rock masses or welded tuff, to porous permeability as in ash-fall pyroclastic deposits.

Owing to the alkali-potassic volcanism of southern Italy, with explosive and subordinately effusive styles of activity, pyroclastic deposits predominate on the lava hydrogeological complex. Pyroclastic deposits can be differentiated as ash-fall and ash-flow deposits, respectively forming aquifers with different hydrogeological properties. Ash-fall deposits are transported by ballistic mechanisms and prevailing winds as well, inducing a grain size sorting over different grain size classes. Thick pyroclastic ash-fall deposits fill plains in the surroundings of the Phlegrean Fields and Somma-Vesuvius volcanoes, where they are interfingered with alluvial deposits. In these zones, a unique global groundwater circulation exists, which is recharged also by groundwater circulation of the same volcanic structures (Celico, 1983; Celico, De Vita, Nikzad, Stanzione, & Vallario, 1991; Esposito & Piscopo, 1997).

In case the column, comprising pyroclasts and ash, collapses, a *nuée ardente* phenomenon occurs leading to the formation of ash-flow deposits. Lithification of the ash-flow deposits occurs by welding and/or recrystallization may occur in different grades and affect the hydrogeological properties of tuffs. The primary porosity of ash-flow pyroclastic deposits is inversely related to the lithification, which occurs by the partial occlusion of inter-clast pore spaces. The cooling fracturing represents an important part of the secondary porosity, which can exist in the lithified and brittle parts only. Depending on the slower cooling, higher lithification grade and hydraulic conductivity can be usually observed in the central part of the lithosome, due to fracturing favoured by brittle behaviour (Smyth & Sharp, 2006). In tuff aquifers of the Phlegrean Fields, hydraulic transmissivity values range from 1×10^{-3} to 1×10^{-5} m^2 s^{-1} (Celico et al., 1991; Celico, 2001). Owing to the high fracture grade of tuffs, these measurements are higher than those determined for similar aquifers in the USA (Winograd & Thordarson, 1975), ranging from 6×10^{-5} to 2×10^{-7} m^2 s^{-1}.

Volcanic rocks, derived by the cooling of lava flows, form aquifers whose hydraulic characteristics depend on the content of dissolved gasses and thickness of the deposit. The shallower part of lava flows is characterized by very high permeability due to the diffuse occurrence of breccias, open cooling cracks and outgassing pores. Instead, the central part is generally characterized by a relatively lower permeability, mainly related to cooling joint sets. Hydraulic conductivity ranges in these aquifers with a very wide interval, up to 11 magnitude orders, ranging from 10^{-8} to 10^{1} ms^{-1}. For volcanic rock aquifers of the Somma-Vesuvius and Roccamonfina volcanoes, values of hydraulic transmissivity ranging between 1×10^{-2} and 1×10^{-5} m^2 s^{-1} have been estimated (Celico, 1983).

Groundwater flow of principal volcanic structures (Roccamonfina, Phlegrean Fields, Somma-Vesuvius and Vulture) is unique at a global scale, being not divided in autonomous aquifers, with a radial pattern and recharge independent of adjoining aquifers (Baiocchi et al., 2017; Celico, 1983; Celico et al., 1991, 2001; Celico & Summa, 2004). Hydrogeological units formed by these aquifers show a mean specific groundwater yield ranging from 0.010 to 0.020 m^3 s^{-1} km^{-2} (Figure 5).

3.4 Palaeozoic crystalline hydrogeological complexes

Among aquifers that do not provide relevant supply for regional aqueduct systems in southern Italy are those formed by intrusive igneous and metamorphic hydrogeological complexes of the Calabrian-Peloritan Arc, which outcrop over about 5900 km^2.

These aquifers are formed by a composite hydrogeological system, which comprises three vertical zones (Acworth, 1987; Krásný, Sharp, & Troeger, 2014).

a) A surficial porous aquifer, formed by residual (saprolite) and transported (colluvium and talus) deposits of the weathering zone (regolith). The thickness of the weathering zone generally varies from a few meters to up to 100–150 m (Calcaterra & Parise, 2010), with a more enhanced deepening in correspondence of fault zones. The anomalous high thickness of the weathering zone is supposed to be developed under past environmental conditions such as tropical climate, peneplained landscape, tectonic inactivity and slight denudational processes (Guzzetta, 1974; Wyns, Quesnel, Simon-Coinçon, Guillocheau, & Lacquement, 2003).
b) Intermediate fractured aquifer are fractured rocks, some tens of meters thick, whose jointing mechanisms are controlled by tectonic stresses, unloading processes and stress state due to swelling of some minerals, particularly biotite (Lachassagne, Wyns, & Dewandel, 2011). In this zone, the permeability decreases with depth due to joint density reduction (Dewandel, Lachassagne, Wyns, Maréchal, & Krishnamurthy, 2006; Maréchal, Dewandel, & Subrahmanyam, 2004). Joints are mostly sub-horizontal in granite-type rocks and without a preferential orientation in metamorphic ones.
c) Deep zone with a rare fracture network, chiefly limited chiefly to fault zones, which behave as individual aquifers at the local scale and

interconnected groundwater bodies at the regional scale. The permeability of this zone is lower also due to the closing of joints caused by the higher lithostatic pressure.

Hydrogeological characteristics of the porous surficial aquifer depend on the weathering grade and grain size of residual deposits. It acts both as a temporary groundwater reservoir for effective infiltration and as a partially independent surficial aquifer. Owing to the heterogeneity of the surficial deposits, and particularly due to the occurrence of clay-rich horizons, ephemeral perched water tables can also occur in the surficial aquifer. In the intermediate fractured aquifer, a main groundwater flow occurs due to a favourable combination of aquifer thickness and hydraulic transmissivity. A higher fracturing grade occurs in the granite rock masses than the schistose rock mass, according to the different rheological behaviour. In fault zones, the rock mass is more intensely fractured, weathered and permeable. Groundwater circulation is generally unconfined and approximately parallel to the surface topography, therefore showing high piezometric gradients. Groundwater outflows occur mainly through linear springs along stream channels, leading to a valleyward increase of streamflow discharge during dry periods, and small springs scattered along slopes with discharges typically lower than 0.001 $m^3 s^{-1}$ and rarely greater than 0.050 $m^3 s^{-1}$. Only 150 springs among the 2662 surveyed in Calabria have a discharge which ranges between 0.010 and 0.050 $m^3 s^{-1}$.

In general, hydraulic conductivity tends to decrease from 10–15 m of depth (weathering zone) down to 50–60 m, passing from values of 1×10^{-2} to 1×10^{-4} ms^{-1} (Davis & De Wiest, 1996; Issar & Gilad, 1982; LeGrand, 1954; Summers, 1972). Calcaterra, Ietto, and Dattola (1993) estimated by Lugeon tests in Calabria values of hydraulic conductivity for the surficial part of the weathering profile ranging from 2.70×10^{-6} and 5.58×10^{-7} ms^{-1}, with a mean value of 1.35×10^{-6} ms^{-1}. Instead, mean values of hydraulic conductivity of about 1.20×10^{-4} ms^{-1} were found for the intermediate fractured zone, while values ranging from 1.97×10^{-3} to 9.16×10^{-4} ms^{-1} were found for the deeper zone. Studies carried out in different intrusive igneous and metamorphic aquifers of the world (e.g. Chilton & Foster, 1995; Foster, 2012; Maréchal et al., 2004; Taylor & Howard, 2000) have reported values of hydraulic transmissivity lower than 6×10^{-4} m^2s^{-1} for the weathering zone and fractured layer. Instead, estimations in the Serre massif of Calabria (Baiocchi, Dragoni, Lotti, & Piscopo, 2014; 2016), where both granite and schistose rocks outcrop, showed hydraulic transmissivity varying from 2.6×10^{-5} to 4.8×10^{-4} $m^2 s^{-1}$. The same authors estimated a mean specific groundwater yield in the Serre massif ranging from 0.004 to 0.007 $m^3s^{-1}km^{-2}$, with a principal groundwater flow occurring in the weathering and fissured zones (Figure 5).

3.5 Meso-Cenozoic terrigenous hydrogeological complexes

Other aquifers of minor hydrogeological relevance include the Meso-Cenozoic terrigenous sediments deposited in inner (foreland) and outer (foredeep and wedge top) marine basins (Bonardi et al., 1988b). Such lithostratigraphic units comprise mainly turbidite rocks from sandstone to calcarenite interbedded with mudrocks from shales to marls, constituting the minor mountains and hills of the southern Apennine. They form hydrogeological complexes with double permeability, due to chiefly fracturing and secondarily porosity. The permeability varies from medium grades to impervious, respectively, in cases where the relative abundance of the mudrock component is negligible or dominant. These hydrogeological complexes form units whose low-discharge springs can sustain only water needs of small rural settlements. The extension of these hydrological complexes covers about 9850 km^2.

In general, the permeability of the rock mass is relatively higher in the surficial zone due to the existence of a regolith mantle that allows the formation of a groundwater flow in the surficial zone. Such groundwater circulation occurs with an approximate correspondence between watershed and groundwater divides, with piezometric profiles roughly parallel to the topographic morphology. It feeds mainly springs classified as slope springs (Gargini, De Nardo, Piccinini, Segadelli, & Vincenzi, 2014), which are mostly located in the middle-lower part of slopes and characterized by discharge rates rarely exceeding few litres per second. A significant groundwater flow can exist in the un-weathered rock mass only in cases of a low-to-negligible relative abundance of the mudrock component and favourable structural settings, as indicated by some deep wells with fair yields. In such cases, faults zone can allow a groundwater drainage through adjoining watersheds resulting in the formation of trans-watershed springs (Gargini et al., 2014).

The arenaceous–conglomeratic complex, belonging to the Upper Miocene part of the series and formed by proximal turbidite series, comprising mainly sandstones and conglomerates (Castelvetere, Mount Sacro and Gorgoglione Formations) (Bonardi et al., 1988b; Pescatore, 1978), represents a special case in such a hydrogeological domain. In fact, due to the negligible occurrence of mudrock interbeddings, the rock mass reaches a medium grade of permeability; groundwater circulation is deep being independent from the external morphology, allowing the formation of springs with discharge rates of a few litres per second (Celico, De Vita, & Aloia, 1993).

Studies about the hydrogeological characterization of these aquifers are few and generally based on the analysis of the base flow during dry periods (Barnes, 1939; Dewandel, Lachassagne, Bakalowicz, Weng, & Al-Malki, 2003), recorded by discharge gauges located at the outlets of some sample catchments (Celico, De Innocentis, De Vita, & Vallario, 1992; Corbi, De Vita, & Vallario, 2000). From these studies, a groundwater recharge coefficient lower than 20% was estimated for the hydrogeological complexes formed by arenaceous–pelitic and calcarenite–pelitic series, while a value of about 30% for arenaceous–conglomeratic ones (Celico et al., 1993). These results are confirmed by other studies carried out on similar hydrogeological complexes of northern Apennine (Gargini et al., 2006, 2008, 2014). Hydrogeological units formed by these aquifers show a mean specific groundwater yield ranging from 0.0010 to 0.006 $m^3\ s^{-1}\ km^{-2}$ (Figure 5).

4. Conclusions

The homogenization and the implementation of bibliographic data in the Hydrogeological Map of continental southern Italy allowed the creation of a fundamental instrument for the interregional analysis and management of groundwater supply. It represents a possible example of the application of the Directive 2000/60/CE (European Parliament, 2000) establishing the recognition and characterization of groundwater bodies. Results of the hydrogeological regional mapping, and the setting up of the related GIS, can be considered a basic tool for management of quantity and quality of exploitable groundwater resources at the regional scale. In such a view, groundwater resources available for tapping could be considered in a programme that would balance exploitation and survival of fluvial ecosystems. This could be achieved, especially for hydrographic basins characterized by a high hydrogeological complexity, also considering the use of aquifers as regulation tanks (Celico et al., 2002) and effects of variability of groundwater recharge (De Vita, Allocca, Manna, & Fabbrocino, 2012).

Software

Cartographic data were elaborated by AutoCAD Map (Autodesk Inc.).

Disclosure statement

The I.S.P.R.A. (Istituto Superiore per la Protezione e la Ricerca Ambientale) released authorization (No. 0051076 of 19 December 2013) to publish a digital revised version of the 'Hydrogeological map of southern Italy' (Allocca et al., 2007) to *Journal of Maps*.

Funding

The research was funded by the European INTERREG IIC Programme, Section 'Territory regulation and contrast to the drought' (Decree n. 2231 of 31 July 1997 of the European Commission), concerning the Italian regions of the Objective I (Molise, Campania, Puglia, Basilicata and Calabria) and commissioned by the I.S.P.R.A. Governmental Agency (Istituto Superiore per la Protezione e la Ricerca Ambientale) to the University of Naples Federico II (Rep. No. 135 of 20 December 1999).

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