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Groundwater vulnerability of principal aquifers of the Campania region (southern Italy)

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ABSTRACT
The assessment of groundwater vulnerability is an important aspect of territorial planning aimed at the management and protection of groundwater quality. This topic is particularly relevant for the Campania region (southern Italy) due to the abundance of groundwater resources and the strong dependence on them of current economic, social and environmental settings. The region is characterized by complex geological, structural and hydrogeological frameworks which make challenging and innovative the assessment of groundwater vulnerability with SINTACS, a parametric method officially recognized by the Italian environmental agencies. In order to apply results obtained to current regional regulations, groundwater vulnerability was estimated for the 80 principal aquifers, hosting respective groundwater bodies, as recognized by the application of the Directive 2000/60/EC. Among principal results, the alluvial and limestone (karst) aquifers, which are the most productive of the region, show the highest groundwater vulnerability, even with spatially variable conditions depending on local hydrogeological features.

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Directive 2000/60/EC; groundwater vulnerability; parametric method; SINTACS; regional-scale analysis

1 . Introduction

The Campania region (southern Italy) is characterized by a geological and structural setting representing the main features of the southern Apennines (Vitale & Ciarcia, 2018 and references therein). This results in a complex hydrogeological framework comprising the most relevant aquifers of southern Italy, such as karst, alluvial, volcanic and terrigenous ones, as well as flysch and basin series aquitards and aquicludes (De Vita et al., 2018). As a consequence, a high availability of groundwater resources does occur in this region, depending also on the relevant amount of mean annual precipitation. These hydrogeological features have contributed to a relevant social and economic development of the region after the World War II, as well as to an intensive land use, developed especially in the high-urbanized plain and coastal areas (Forino et al., 2015; Romano et al., 2017), and, therefore, to an increasing groundwater demand.

In recent years, the strong urbanization of the plain areas, particularly of the city of Naples and its surroundings, has caused worrying cases of environmental degradation involving soils, surface water and groundwater. A progressive degradation of the groundwater quality due to pollution from agriculture and urban sources, has been noticed affecting especially shallow alluvial aquifers (Ducci et al., 2019; Fusco et al., 2020). Moreover, due to urban waste mismanagement, the environmental pollution has reached very high levels in some sectors of the Metropolitan City of Naples. As a consequence, mass media overemphasized its effects on inducing the public awareness to perceive the contamination as extended to the whole region. In such a framework, with the aim to assess and safeguard the quality of agricultural and zootechnical products of the whole region, the regional government funded the *Campania Trasparente* (Transparent Campania) Project (www.campaniatrasparente.it). The project was focused on studying the environmental state of the three principal environmental matrixes: soil, water and air. Within the water environmental matrix, a section of studies was dedicated to the assessment of groundwater vulnerability. Results obtained by these studies were considered fulfilling requirements of the Water Framework Directive (2000/60/EC; European Parliament, 2000) and Groundwater Directive (2006/118/EC; European Parliament, 2006) as well as the related Italian laws (Dlgs 152/2006 and 30/2009) concerning the protection of groundwater resources.

In this research, the assessment of groundwater vulnerability was focused on the 80 Principal Aquifers (PAs) of the Campania region, hosting respective relevant Groundwater Bodies (GBs), namely distinct

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volumes of groundwater within an aquifer or aquifers, as officially recognized in the Water Management Plan issued by the Southern Apennine District Basin Authority (http://www.ildistrettoidrograficodellappenninomeridionale.it/dam_083.htm) under the application of the Directive 2000/60/EC. In such a view, groundwater vulnerability was assessed for the PAs, which were considered equivalent to the GBs hosted.

The SINTACS method (Civita & De Maio, 2000), which is recognized by the Agenzia Nazionale per la Protezione dell'Ambiente – ANPA (National Agency for the Environmental Protection) (De Maio et al., 2001), was applied for the estimation of groundwater vulnerability.

2. Hydrogeological setting of the Campania region

The Campania region covers about 13,595 km^2 including composite geological (Figure 1) and geomorphological frameworks. It embraces a wide sector of the southern Apennines chain, whose structure was originated during the Miocene by compressive tectonic phases involving the subduction of oceanic crust of the African plate (Carminati et al., 2012; Cosentino et al., 2010). During this crustal shortening, series of palaeo-geographical units varying from shallow-water carbonate platform to terrigenous ocean basin environments, which developed in the Tethys palaeo-ocean during the Meso-Cenozoic period, were detached, tectonically deformed in fold-and-thrust sheets, carried north-eastwardly and overthrust the Apulian carbonate platform foreland (Patacca & Scandone, 2007). During the Miocene tectonic phases, the tectonic pile was unconformably covered by turbidite wedgetop basin series (e.g. Ascione et al., 2012). Subsequently, during the Quaternary post-orogenic extensional tectonic phases, the western side of the Apennine chain was faulted forming semigraben structures in which a back-arc volcanic activity began (Milia &

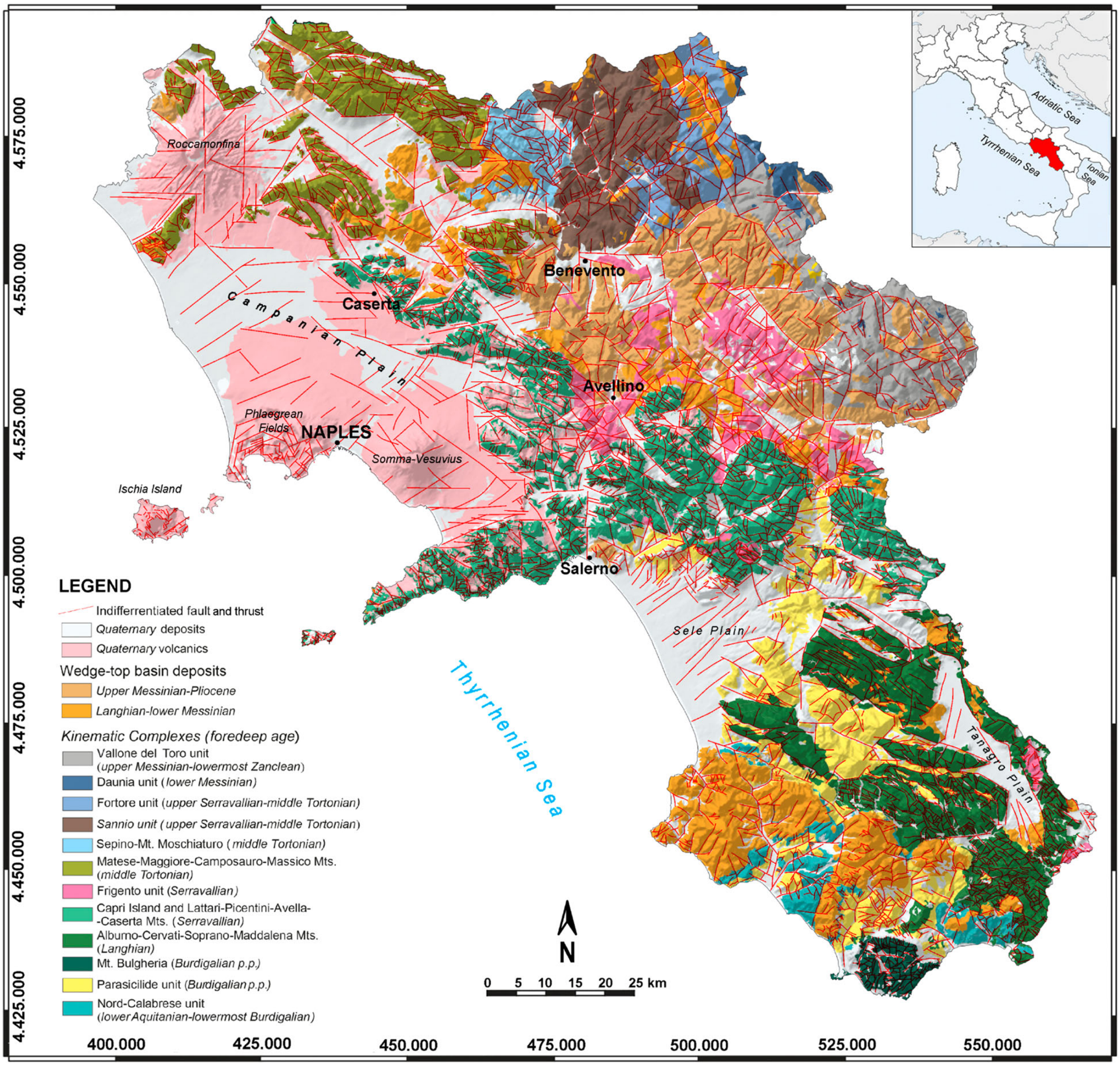

Figure 1. Kinematic complexes of the Campania region (modified from Vitale & Ciarcia, 2018).

Torrente, 2014; Milia et al., 2017) with the Roccamonfina volcano (700 k-year), Ischia Island (150 k-year), Phlegraean Fields (60 k-year) and Somma-Vesuvius volcano (25 k-year). During the Quaternary, these structurally lowered zones, as well as other intermontane depressions, were filled by alluvial and volcanic deposits forming the actual Campanian, Sele River and Tanagro River principal alluvial plains (Figure 1).

The lithological and structural complexity of the region controls the variability of hydrogeological settings, identifying several hydrostratigraphic units (De Vita et al., 2018; Maxey, 1964), which can be classified in four principal genetic groups: carbonate, alluvial, volcanic and terrigenous. The first includes Mesozoic limestone and subordinately dolomite aquifers, forming the most prominent mountain ranges and the primary sources of drinking water of the region (De Vita et al., 2018). These aquifers are generally characterized by pervasive fracturing and karst phenomena that increase the global permeability, thus allowing high groundwater recharge and mean annual yield. Moreover, the mountain ranges forming carbonate aquifers are generally characterized by large plateaus and endorheic zones on the top favoring further infiltration and groundwater recharge (Allocca et al., 2014; Allocca et al., 2015). Another hydrogeological peculiarity is given by the covering of ash-fall pyroclastic soils erupted by the Somma-Vesuvius and Phlegrean Field volcanoes (De Vita & Nappi, 2013; Fusco et al., 2017, 2013) which controls the development of the epikarst zone (Celico et al., 2010). Geological and structural factors control groundwater circulation outflowing from both perennial low-altitude springs, with mean annual discharge varying from 0.1 to 5.5 m^3 s^{-1} (total discharge of about 70 m^3 s^{-1} for the whole region), and ephemeral high-altitude springs, with discharge values generally lower than 0.1 m^3 s^{-1} (Celico, 1983; De Vita et al., 2018), respectively dependent on basal and perched groundwater circulations. The hydrogeological behavior of these aquifers is consistent with conceptual models proposed in the literature for karst aquifers (Bonacci, 1993; Celico, 1978, 1983; Drogue, 1992; Goldscheider & Drew, 2007; Jeannin, 1998; Kiraly 1975, 2003; Klimchouk 2000; Mangin, 1975; White, 1969, 2002). Among the most important controls on the basal groundwater circulation is the tectonic juxtaposition of these aquifers with low-permeability hydrostratigraphic units belonging to terrigenous pre-orogenic (Cretaceous-Paleogene) and syn-orogenic (Miocene) basin and turbidite series (Celico, 1983). Other minor stratigraphic or tectonic factors, such as faults with low-permeability damage and core zones or marly and argillaceous intervals in the carbonate series, allow the compartmentation of the basal groundwater circulation (Celico, 1983; Celico et al., 2006). Due to the Apennine thrust structure, carbonate aquifers are in general reciprocally isolated (Ravbar et al., 2011), but, in some cases, receiving groundwater exchanges from the adjoining alluvial aquifers. For coastal carbonate aquifers, groundwater circulation outlets from submarine springs. A minor groundwater circulation also occurs in the surficial zone, being controlled by epikarst development (Allocca et al., 2018a; Celico et al., 2010) or other local structural or stratigraphic factors, feeding high-altitude springs with highly variable regimes and low discharges, generally lower than 0.01 m^3 s^{-1}.

Alluvial aquifers represent the second groundwater resource of the region forming aquifer systems at the regional scale with a general medium to high permeability grade. The groundwater recharge occurs by direct infiltration and by the groundwater exchange from the adjoining carbonate aquifers. These aquifers can be distinguished in costal alluvial and internal alluvial. The high water-demand for agricultural and industrial practices, which are very diffused in these areas has led to a high anthropogenic pressure on these aquifers (Allocca et al., 2018b, 2016; Coda et al., 2019a, 2019b). Generally, the water table is shallow and the intensive cultivation practices make them extremely exposed to pollution (Fusco et al., 2020).

The volcanic structures of Roccamonfina, Somma-Vesuvius, Phlaegrean Fields and Ischia Island (Figure 1) represent other important aquifers and groundwater resources of the region. Notwithstanding their limited extension and annual groundwater yield, these aquifers have an important economic value for their valuable thermal and mineral waters (Celico et al., 1992, 1998, 1999).

A minor type of aquifers is represented by terrigenous Miocene-Pliocene turbidite, molasse and clastic series as well as Cretaceous-Paleogene basin series outcropping mainly in the interior areas. These series, especially of the first type, can form significant aquifers at the local scale in arenaceous-conglomeratic stratigraphic intervals (Casciello et al., 1995; Celico et al., 1993).

The climate type (Geiger, 1954) varies from the Mediterranean type (Csa) in the coastal sector to the Mediterranean mild climate (CSb) in the interior areas. Higher orographic precipitations, with maximum values up to 1700–2000 mm, occur along the Apennine ridge, crossing the interior part of the region, while the mean annual value for the region is around 1100 mm. The annual precipitation is strongly affected by complex cyclical decadal variability due to the North Atlantic Oscillation (De Vita et al., 2012; Manna et al., 2013), which controls the interannual variability of groundwater recharge.

3. Approaches for the assessment of groundwater vulnerability

The assessment of groundwater vulnerability is a crucial aspect of territorial planning aimed at the safeguard of groundwater resources (Directive, 2006/118/EC) because expressing the potential impact of pollutants, depending on hydrogeological conditions and processes occurring in the unsaturated and saturated zones (Goku & Dassargues, 2000). Groundwater vulnerability is generally distinct in intrinsic and specific (NRC, 1993). The intrinsic groundwater vulnerability is defined as 'the specific susceptibility of aquifer systems, in their various parts and in the various geometric and hydrodynamic settings, to ingest and diffuse fluid and/or hydro-vehiculated contaminants, whose impact on groundwater quality is dependent on space and time' (Civita, 1994). Instead, the specific vulnerability is related to a definite contaminant or group of contaminants, thus it is based on considering specific hydraulic and geochemical processes of attenuation (Goku & Dassargues, 2000).

In the last decades, many approaches were developed to assess groundwater vulnerability, which can be grouped into three fundamental categories, depending on the scale of territorial analysis and quality of data (Civita, 2010): Hydrogeological Complexes and Settings (HCS) methods, Parametric System (PS) methods and Numerical Models (NM). The first category is based on the assessment of groundwater vulnerability by the qualitative analysis of hydrogeological factors (Albinet & Margat, 1970). The second category is focused on the semi-quantitative assessment of factors controlling groundwater vulnerability and is divided into three sub-groups: Matrix Systems (MS), Rating Systems (RS) and Point Count System Models (PCSM). The MS methods are based on a few parameters that are opportunely calibrated and applied to local case studies, such as the method selected for the Flemish Region of Belgium (Goossens & Van Damme, 1987), which is based on soil thickness and texture, water table depth and aquifer hydrogeological features. The RS methods are based on the assignment of index values to the parameters considered and define a vulnerability index as the sum of index values selected for each parameter. Among this type of methods, the best known is GOD (Foster, 1987), which considers three parameters (groundwater confinement, overall lithology of aquifers and water table depth). The PCSM methods advance the preceding ones by introducing multiplying weights for each parameter. Among these methods, the most known is DRASTIC (Aller et al., 1987) which considers seven parameters and the respective indexing with scores ranging from 1 to 10, depending on specific criteria indicated in tables and graphs: (1) Depth to water table; (2) net Recharge; (3) Aquifer media; (4) Soil media; (5) Topography; (6) Impact of vadose zone; (7) hydraulic Conductivity. Two lines of multiplying weights identify different scenarios of groundwater vulnerability: one for normal conditions and the other for conditions of intensive agricultural activity. Several variations to this method were experimented for adapting it to specific pollutants as agricultural nitrate fertilizers (i.e. Kazakis & Voudouris, 2015). Among PCSM methods, derived from DRASTIC, is SINTACS (Civita, 1994, 2010; Civita & De Maio, 2000), which is based on the same seven parameters (the different acronym is due to the Italian name of parameters), but with different index values. Moreover, this method considers five lines of multiplying weights related to the following scenarios: (a) normal impact; (b) relevant anthropic impact; (c) drainage; (d) karst; (e) fissured rocks. The final result is the SINTACS index ($I_{SINTACS}$), given by the sum of products between index values assigned to each parameter and respective multiplying weights, leading to six groundwater vulnerability classes.

Finally, the numerical models are quantitative being based on simulation of the physical, chemical and biological processes controlling transport of a pollutant (e.g. Fusco et al., 2020).

4. Data and methods

The groundwater vulnerability of the Campania region was estimated by analyzing geological, hydrogeological, geomorphological, pedological, piezometric, climatic and land use data. All data were structured in a raster GIS environment with a spatial resolution of 200×200 meters. The large quantity and quality of available data allowed the application of the SINTACS method (Civita & De Maio, 2000) whose use has been validated for the Mediterranean areas (e.g. Al-Shatnawi et al., 2016). The parameters and sources of data considered as well as elaborations carried out for their estimation are described following.

4.1. Assessment of SINTACS parameters

4.1.1. Depth to water table (the S-parameter)

This parameter accounts for the travel length, and time, of pollutants through the unsaturated zone, therefore it is conceptually conceived as directly controlling the attenuation of their concentration. Due to the large extension and complex hydrogeological settings of the Campania region, a regional map of piezometric levels and the inherent depth to water table map were not available. Therefore, the assessment of piezometric levels was carried out for the whole region by different data and approaches. Firstly, data of piezometric contours, generally available for major alluvial plains and volcanic aquifers only (De Vita et al., 2018), were considered (Main Map). Instead, for carbonate aquifers, which are chiefly characterized by a general lack of piezometric measurements due to the high depth to water table, piezometric levels were reconstructed by considering: altitude of basal springs, typical values of piezometric gradient (5‰) and delimitations of groundwater basins, known by the hydrogeological literature (Celico, 1983). Following, the depth to water table was reconstructed for these aquifers by the difference between piezometric level and the Digital Elevation Model (DEM). The highest value found is 1,640 m.

Finally, for the other turbidite and basin series, forming small aquifers and aquitards, due to the unavailability of water table depth, this parameter was assumed as constant and equal in average to 4 m as commonly observed for such hydrostratigraphic units (De Vita et al., 2015).

4.1.2. Net recharge or infiltration (the I-parameter)

This parameter represents the amount of rainfall (P) exceeding evapotranspiration (ETR) and runoff (R), which infiltrates and recharges groundwater (Healy, 2010). Therefore, it constitutes both the main vehicle for pollutants toward the saturated zone as well as a diluent which can diminish their concentrations. To estimate the mean annual groundwater recharge for the Campania region, a distributed regional model of the mean annual effective precipitation (P − ETR) was considered (Allocca et al., 2014). The maximum value obtained for the studied area is 2,221.8 mm year^{-1}. Net recharge was estimated considering also the mean annual groundwater recharge coefficient (AGRC) (Allocca et al., 2014; De Vita et al., 2018).

4.1.3. Impact of vadose zone (the N-parameter)

This parameter accounts for the attenuation of pollutants during the transport through the unsaturated zone. It is meant to be dependent on the lithology, and, subsequently, permeability, of the vadose zone. Therefore, it was estimated by the regional hydrogeological map (De Vita et al., 2018) considering lithology of the unsaturated zone of aquifers.

4.1.4. Soil media (the T-parameter)

This parameter depends on the grain size and controls the reactive processes occurring in the soil and leading to the reduction of pollutant concentration. It was estimated by the regional map of soil features, 1:250,000 scale, available for the Campania region (Di Gennaro et al., 2002).

4.1.5. Hydrogeological characteristic of the Aquifer (the A-parameter)

This parameter, which corresponds to the type of aquifer, is intended to be dependent on permeability and mechanisms of saturated flow (e.g. porous, fractures or karst) because expressing the capability to transport of a pollutant through the saturated zone. It was obtained by the regional hydrogeological map (De Vita et al., 2018).

4.1.6. Aquifer's hydraulic Conductivity (the C-parameter)

This parameter indicates the capacity of the saturated zone to convey groundwater (and pollutants) through a unitary draining section and under an ordinary piezometric gradient. Therefore, it was conceived as indicating proportionally the proneness to pollution. Starting from the aquifer type (De Vita et al., 2018), this parameter was estimated as the mean of values chosen from ranges known in the literature (Civita & De Maio, 2000; Freeze & Cherry, 1979).

Table 1. Multiplying weights (w_i) considered by the SINTACS method for the five hydrogeological scenarios (Civita & De Maio, 2000).

Parameter	Multiplying weights (w_i)				
	Normal	Severe	Seepage	Karst	Fissured
S	5	5	4	2	3
I	4	5	4	5	3
N	5	4	4	1	3
T	3	5	2	3	4
A	3	3	5	5	4
C	3	2	5	5	5
S	3	2	2	5	4

4.1.7. Slope (the S-parameter)

This parameter expresses the slope gradient and accounts inversely for the predisposition to infiltration and groundwater recharge. It was estimated by the Digital Elevation Model (200×200 m). The highest value found is 54.7°.

For the attribution of multiplying weights, all five scenarios (natural, relevant impact, drainage, karst and fissured rocks) were considered (Table 1) in respective raster maps. Weights for the normal and relevant impact scenarios were obtained by the regional map of agricultural land use, known as CUAS map (www.sit.regione.campania.it). Weights for drainage scenario were obtained by the intersection of the irrigation areas, identified by the CUAS map, and areas with water table depth less than 2 m. Weights for karst (limestone aquifers) and fissured rocks (dolomite and volcanic rock aquifers) were assigned on the basis of regional hydrogeological map of southern Italy (De Vita et al., 2018).

4.2. Estimation of SINTACS index

The assessment of the seven parameters (P_i) and the five lines of multiplying weights (w_i) allowed the calculation of the SINTACS index ($I_{SINTACS}$) expressing groundwater vulnerability as shown in the Main Map:

$$I_{\mathrm{SINTACS}} = S \times w_i + I \times w_i + N \times w_i + T \times w_i + A \times w_i + C \times w_i + S \times w_i \quad (1)$$

Parameters, multiplying weights and the $I_{SINTACS}$ were calculated for outcropping areas of 80 PAs of the Campania region, hosting respectively significant GBs, as represented in the Main Map.

In order to cope with the uncertainty related to the attribution of index values to parameters more affected by subjectivity (Impact of vadose zone, Soil media and Hydrogeological characteristic of the Aquifer), because not guided by specific criteria indicated by the method itself, a sensitivity analysis was carried out. This analysis allowed to estimate the minimum and maximum values of $I_{SINTACS}$ obtainable and compare them with the most probable ones, which were assigned on a reasonable judgment. By this approach, the validation of index values attributed to these parameters was accomplished.

5. Results and discussion

Values of $I_{SINTACS}$, estimated for all PAs, range globally between 58 and 247 and are distributed across all six groundwater vulnerability classes, from the very low to the very elevated. In order to characterize groundwater vulnerability for all PAs, a descriptive statistic of $I_{SINTACS}$ was carried out by showing respective minimum, mean and maximum values (Figures 2–4). Results obtained for single PAs were aggregated

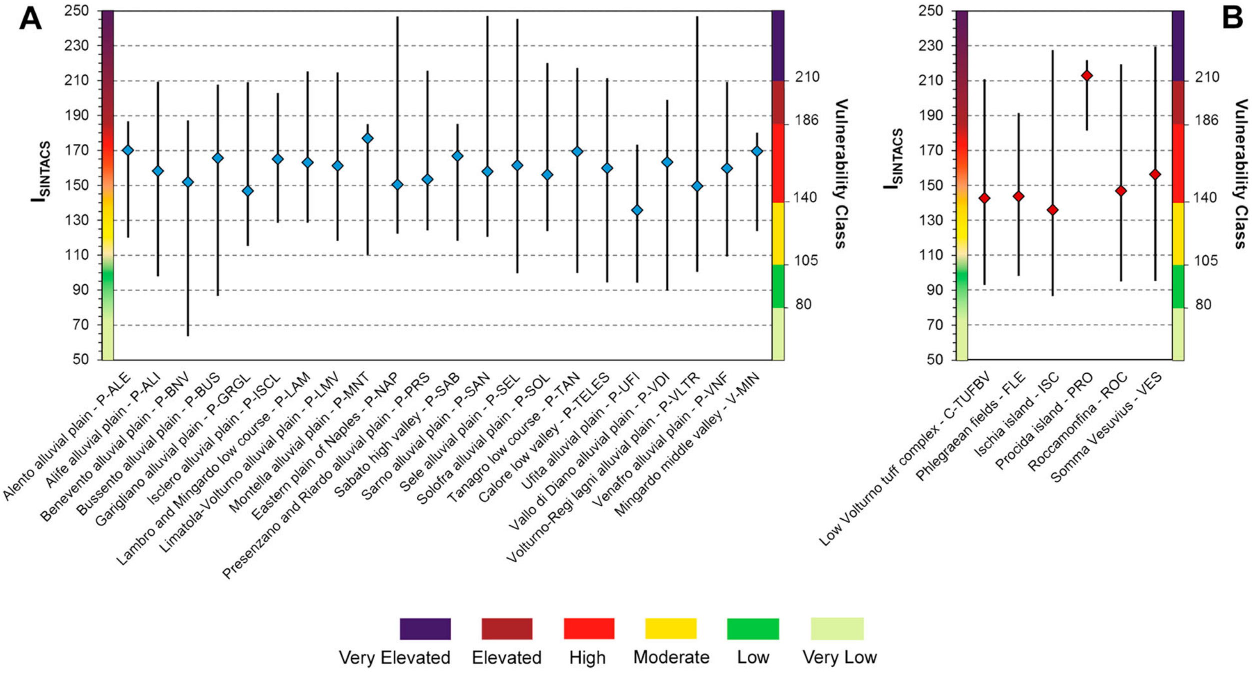

Figure 2. Range of $I_{SINTACS}$ for PAs belonging to Quaternary alluvial (A) and volcanic (B) hydrogeological domains.

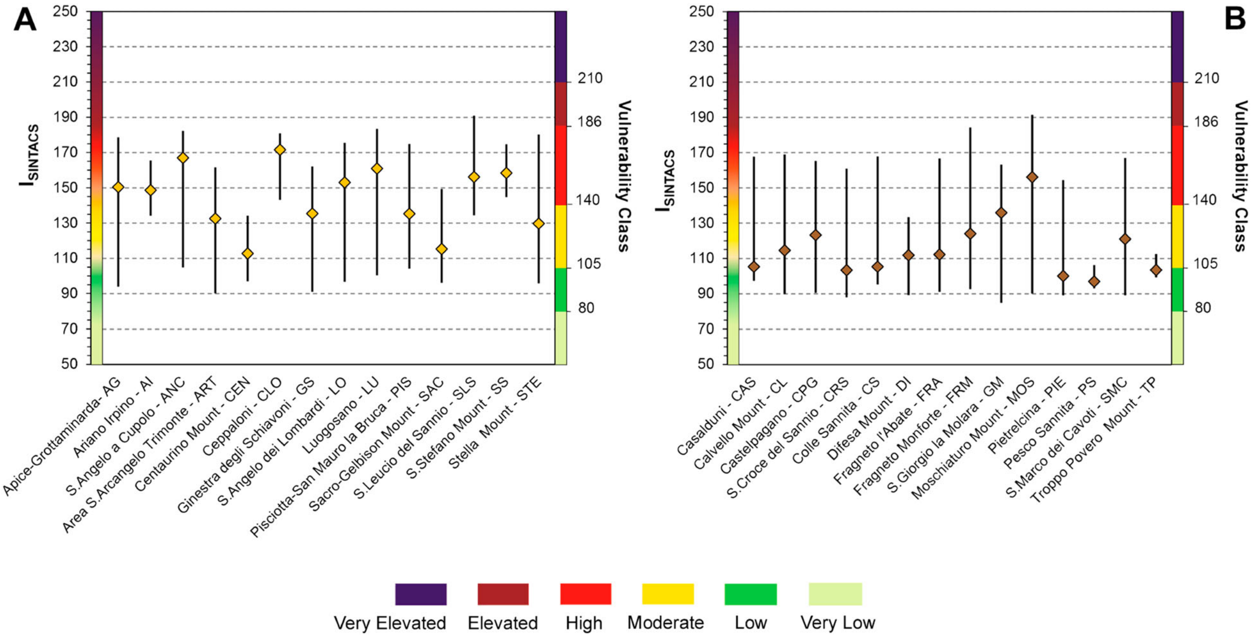

Figure 3. Range of $I_{SINTACS}$ for PAs belonging to Miocene-Pliocene turbidite, molasse and clastic (A) and Cretaceous-Paleogene basin series hydrogeological domains (B).

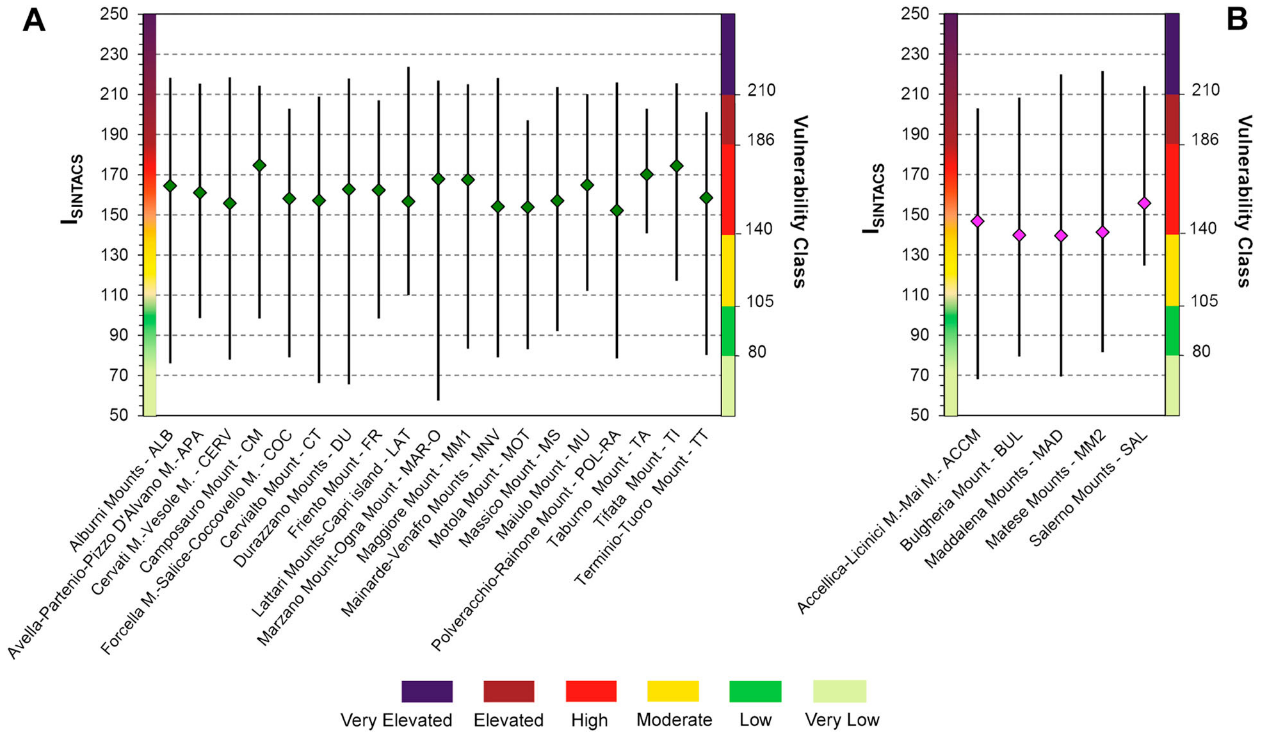

Figure 4. Range of $I_{SINTACS}$ for PAs belonging to Mesozoic limestone (A) and Mesozoic dolomite (B) hydrogeological domains.

according to the six types of hydrogeological domains to which they belong: (1) Quaternary alluvial (Figure 2(a)); (2) Quaternary volcanic (Figure 2(b)); (3) Miocene-Pliocene turbidite, molasse and clastic (Figure 3(a)); (4) Cretaceous-Paleogene basin series (Figure 3(b)); (5) Mesozoic limestone (Figure 4(a)); (6) Mesozoic dolomite (Figure 4(b)). Values of $I_{SINTACS}$ were furtherly aggregated and analysed statistically in order to compare differences among principal hydrogeological domains (Figure 5), also considering areal extension of vulnerability classes (Figure 6).

In detail, the 22 alluvial PAs resulted with mean values of $I_{SINTACS}$ ranging from 140 to 173, thus belonging to the high class of groundwater vulnerability (Figure 2(a)). Mean values of $I_{SINTACS}$ for the 6 volcanic PAs (Figure 2(b)) are comprised, for most cases, between 136 and 156, thus belonging to groundwater vulnerability classes crossing from the moderate to the high, with the only exception of the Procida's PA, which is comprised in the highest vulnerability class. For the 14 Miocene-Pliocene turbidite, molasse and clastic PAs, mean values of $I_{SINTACS}$ range between 113 and 172, thus being significantly scattered across the moderate and high classes of groundwater vulnerability. The 14 PAs belonging to Cretaceous-Paleogene basin series hydrostratigraphic units have a mean value of $I_{SINTACS}$ varying from 97 to 156, thus are classifiable across the low and moderate classes (Figure 3(b)). The 19 karst PAs, belonging to Mesozoic limestone hydrostratigraphic units (Figure 4(a)), show mean values for $I_{SINTACS}$ ranging from 152 to 175 and therefore are included in the high class. The 5 Mesozoic dolomite PAs (Figure 4(b)) show a mean value for $I_{SINTACS}$ varying from 141 and 156 being comprised in the moderate and high class.

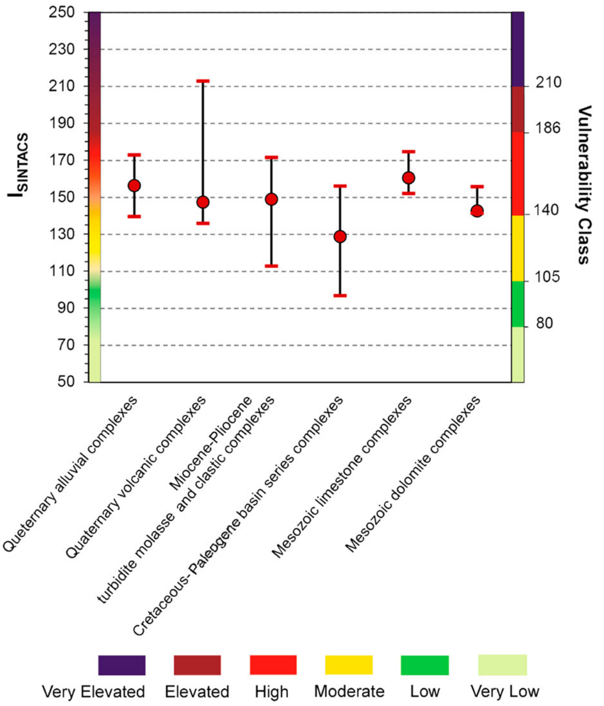

Figure 5. Range of $I_{SINTACS}$ for PAs of the six hydrogeological domains. Mean values are weighted by the outcropping areas of PAs.

By further analysis of mean values of $I_{SINTACS}$ weighted by the outcropping areas of PAs (Figure 5), alluvial and limestone PAs result the most vulnerable, with a value higher than 160, a limited variability and the inclusion in the high class of vulnerability. This

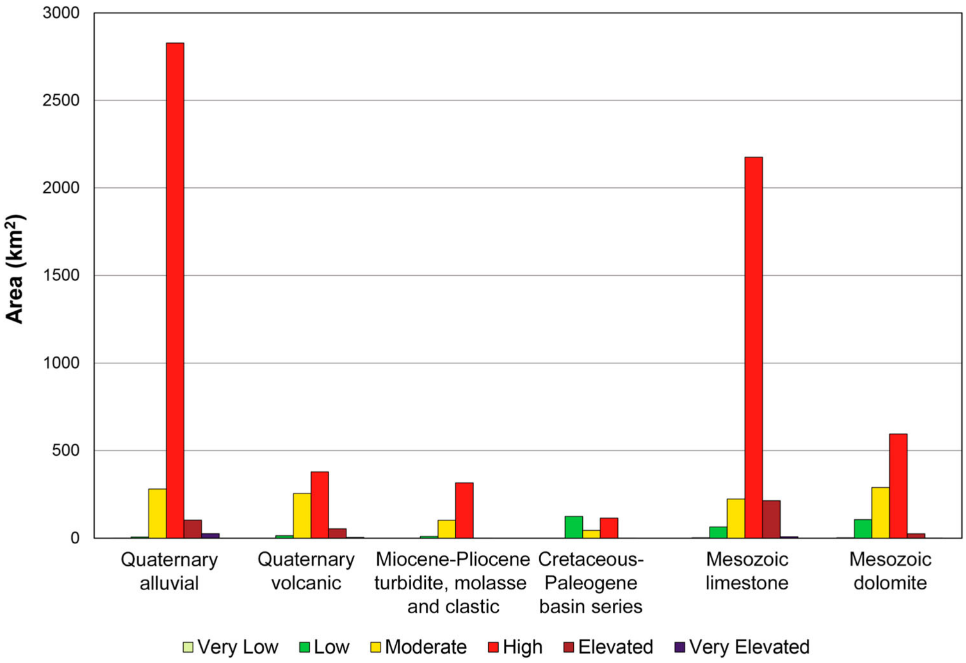

Figure 6. Extension of SINTACS groundwater vulnerability classes for principal hydrogeological domains.

condition appears to be due, among the other factors, respectively to the generally limited depth to water table (the S-parameter) of alluvial aquifers and high permeability of limestone aquifers (the A and C parameters), determined by fracturing and karst. Volcanic PAs show a value of about 150 and a great variability due to, among the other parameters, different conditions of hydraulic conductivity (the A and C parameters) and water table depth (the S-parameter). The Miocene-Pliocene turbidite, molasse and clastic PAs indicate a value of 149, but with a relevant variability across the moderate and high vulnerability classes. The Mesozoic dolomite PAs show a value of 143, with a very limited variability scattering across the border between the moderate and the high classes of groundwater vulnerability. The lower values of groundwater vulnerability, in comparison to the Mesozoic limestone PAs, is chiefly due to the lower permeability of the aquifer and the negligible karst phenomena. Finally, the Cretaceous-Paleogene basin series PAs show a value of 129 with a limited variability and comprised across the low and moderate groundwater vulnerability classes. In this case, even considering the general shallow water table depth (the S-

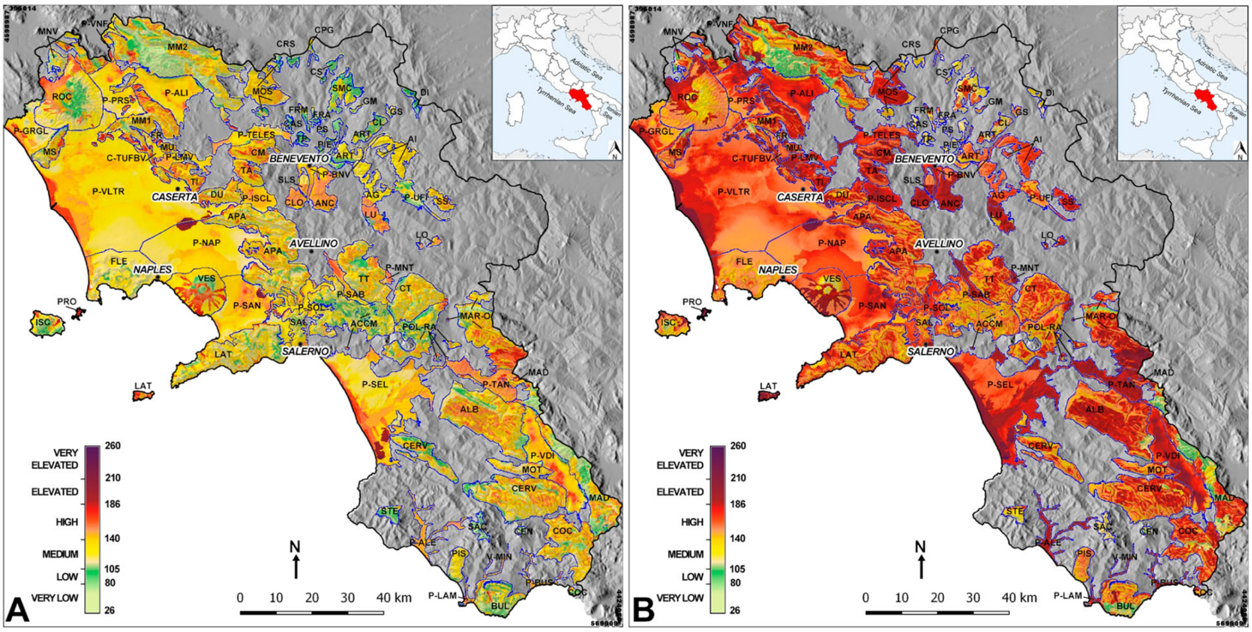

Figure 7. Map of minimum $I_{SINTACS}$ (left) and maximum $I_{SINTACS}$ (right) of the PAs of the Campania region obtained by a sensitivity analysis applied to Impact of vadose zone, Soil media and Hydrogeological characteristic of the Aquifer parameters.

parameter), the lowest value of groundwater vulnerability is related to the low permeability of the unsaturated and saturated zones due to the argillaceous component.

Results of the sensitivity analysis, based on the assignment of a range of possible values to those parameters mostly affected by subjectivity, give interesting hints. Specifically, the overall range of variability between the minimum $I_{SINTACS}$, comprised between 54 and 232, and the maximum $I_{SINTACS}$, varying from 76 to 247, are not relevantly different from that obtained by considering the most reasonable values chosen for the above-mentioned parameters. Specifically, the $I_{SINTACS}$ shows a variability due to the sensitivity analysis limited to ± 15 in average as a result. In addition, the comparison between the minimum and maximum $I_{SINTACS}$ obtained for PAs of the Campania region reveals that the most probable value of groundwater vulnerability is much closer to maximum than the minimum (Figure 7).

For the other areas of the Campania region, not corresponding to PAs, $I_{SINTACS}$ was generally assessed ranging from 85 to 120 (from very low to moderate classes). This is due to the low permeability of terrains characterized by flysch and argillaceous rocks, not hosting significant GBs.

Due to the lack of extensive studies on groundwater quality over the whole territory of the Campania region, a validation of the groundwater vulnerability estimated is possible for principal alluvial aquifers only, in which a high level of nitrates, related to agricultural activities and urban settlements, was assessed (Ducci et al., 2019), thus confirming the high vulnerability of these aquifers.

6. Conclusions

The prevention of groundwater pollution is a fundamental issue to be tackled for the Campania region due to the intense exploitation of groundwater for drinking, agricultural and industrial uses. For this reason, groundwater vulnerability of principal aquifers, hosting respective significant groundwater bodies, was estimated by the parametric and weight method SINTACS (Civita & De Maio, 2000; De Maio et al., 2001), which was applied for the first time at a regional scale. In particular, for each principal aquifer, identified in the Water Management Plan (Directive 2000/60/EC), groundwater vulnerability was assessed with a spatial resolution of 200×200 m and results obtained were analysed statistically.

The adopted methodology and results obtained can be conceived as significant for the implementation of a known method to the assessment of groundwater vulnerability at the regional scale and, particularly, in a complex regional hydrogeological setting, such as that of the Campania region. Beyond the specific outcomes regarding the assessment of groundwater vulnerability of the principal aquifers, which show a general high groundwater vulnerability of most important aquifers, such as karst and alluvial ones, results obtained by this study can be considered applicable to any type of territorial planning aimed at the protection and mitigation of risk to pollution of groundwater resources.

Software

The cartographic analyses were carried out by the QGIS – GRASS open source software (www.grass.osgeo.org; www.qgis.org), while the map was composed by AutoCAD Map (Autodesk Inc.).

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Disclosure statement

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

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References

Al-Shatnawi, A. M., El-Bashir, M. S., Khalaf, R. M. B., & Gazzaz, N. M. (2016). Vulnerability mapping of groundwater aquifer using SINTACS in Wadi Al-Waleh Catchment, Jordan. *Arabian Journal of Geosciences*, *9*(1), 67. https://doi.org/10.1007/s12517-015-2080-4

Albinet, M., & Margat, J. (1970). Cartographie de la vulnérabilité à la pollution des nappes d’eau souterraine. [Mapping of vulnerability to pollution of groundwater]. *Bull. BRGM*, 2^{éme} série, section III, 4, 13–22, Orléans.

Aller, L., Bennet, T., Lehr, J. H., Petty, R. J., & Hachet, G. (1987). *DRASTIC: A standardised system for evaluating groundwater pollution potential using hydrogeologic settings (EPA 600/2-87)*. Environmental Research Laboratory, Office of Research and Development, US Environmental Protection Agency Report, Tucson, 622.

Allocca, V., Celico, F., Celico, P., De Vita, P., Fabbrocino, S., Mattia, S., Monacelli, G., Musilli, I., Piscopo, V., Scalise, A. R., Summa, G. M., & Tranfaglia, G. (2007). Illustrative notes of the hydrogeological map of southern Italy. *Istituto Poligrafico e Zecca Dello Stato*, 211. ISBN 88-448-0215-5.

Allocca, V., Coda, S., De Vita, P., Di Rienzo, B., Ferrara, L., Giarra, A., Mangoni, O., Stellato, L., Trifuoggi, M., & Arienzo, M. (2018a). Hydrogeological and hydrogeochemical study of a volcanic-sedimentary coastal aquifer in the archaeological site of Cumae (Phlegraean Fields, southern Italy). *Journal of Geochemical Exploration*, *185*, 105–115. https://doi.org/10.1016/j.gexplo.2017.11.004

Allocca, V., Coda, S., De Vita, P., Iorio, A., & Viola, R. (2016). Rising groundwater levels and impacts in urban and semirural areas around Naples (southern Italy). Rendiconti Online Della Società Geologica Italiana, *41*, 14–17. https://doi.org/10.3301/ROL.2016.81

Allocca, V., De Vita, P., Manna, F., & Nimmo, J. R. (2015). Groundwater recharge assessment at local and episodic scale in a soil mantled perched karst aquifer in southern Italy. *Journal of Hydrology*, *529*, 843–853. https://doi.org/10.1016/j.jhydrol.2015.08.032

Allocca, V., Manna, F., & De Vita, P. (2014). Estimating annual groundwater recharge coefficient for karst aquifers of the southern Apennines (Italy). *Hydrology and Earth System Sciences*, *18*(2), 803–817. https://doi.org/10.5194/hess-18-803-2014

Allocca, V., Marzano, E., Tramontano, M., & Celico, F. (2018b). Environmental impact of cattle grazing on a karst aquifer in the southern Apennines (Italy): quantification through the grey water footprint. *Ecological Indicators*, *93*, 830–837. https://doi.org/10.1016/j.ecolind.2018.05.075

Ascione, A., Ciarcia, S., Di Donato, V., Mazzoli, S., & Vitale, S. (2012). The Pliocene-quaternary wedge-top basins of southern Italy: An expression of propagating lateral slab tear beneath the Apennines. *Basin Research*, *24*(4), 456–474. https://doi.org/10.1111/j.1365-2117.2011.00534.x

Bonacci, O. (1993). Karst springs hydrographs as indicators of karst aquifers. *Hydrological Sciences Journal*, *38*(1), 51–62. https://doi.org/10.1080/02626669309492639

Carminati, E., Lustrino, M., & Doglioni, C. (2012). Geodynamic evolution of the central and western Mediterranean: Tectonics vs. Igneous petrology constraints. *Tectonophysics*, *579*, 173–192. https://doi.org/10.1016/j.tecto.2012.01.026

Casciello, C., De Vita, P., Stanzione, D., & Vallario, A. (1995). Hydrogeology and hydrogeochemistry of the Mount della Stella (Cilento–campania meridionale). *Quaderni di Geologia Applicata*, *2*, 327–334.

Celico, F., Naclerio, G., Bucci, A., Nerone, V., Capuano, P., Carcione, M., Allocca, V., & Celico, P. (2010). Influence of pyroclastic soil on epikarst formation: A test study in southern Italy. *Terra Nova*, *22*(2), 110–115. https://doi.org/10.1111/j.1365-3121.2009.00923.x

Celico, F., Petrella, P., & Celico, P. (2006). Hydrogeological behavior of some fault zones in a carbonate aquifer of southern Italy: An experimentally based model. *Terra Nova*, *18*(5), 308–313. https://doi.org/10.1111/j.1365-3121.2006.00694.x

Celico, P. (1978). . Schema idrogeologico dell'Appennino carbonatico centro-meridionale. [Hydrogeological scheme of the central-southern carbonate Appennine]. *Memorie e Note Istituto di Geologia Applicata di Napoli*, *14*, 1–97.

Celico, P. (1983). Idrogeologia dei massicci carbonatici, delle piane quaternarie e delle aree vulcaniche dell'Italia centro-meridionale (Marche e Lazio meridionali, Abruzzo, Molise e Campania). [Hydrogeology of carbonate massifs, quaternary plains and volcanic areas of centra-southern Italy (Marche and southern Lazio, Abruzzo, Molise and Campania)]. *Quaderni CASMEZ*, *4*(2), 225.

Celico, P., Dall'Aglio, M., Ghiara, M. R., Stanzione, D., Brondi, M., & Prosperi, M. (1992). Geochemical monitoring of the thermal fluids in the Phlegraean Fields from 1970 to 1990. *Bollettino Della Societa Geologica Italiana*, *111*, 409–422.

Celico, P., De Vita, P., & Aloia, A. (1993). Caratterizzazione idrogeologica della formazione di Monte Sacro (Cilento-Campania meridionale). [Hydrogeological characterization of the Monte Sacro formation (Cilento-southern Campania)]. *Geologia Applicata e Idrologia*, *28*, 243–251.

Celico, P., Stanzione, D., Esposito, L., Formica, F., Piscopo, V., & De Rosa, B. (1999). La complessità idrogeologica di un'area vulcanica attiva: L'isola d'Ischia (Napoli-Campania). *Bollettino Della Societa Geologica Italiana*, *118*, 485–504.

Celico, P., Stanzione, D., Esposito, L., Ghiara, M. R., Piscopo, V., Caliro, S., & La Gioia, P. (1998). Caratterizzazione idrogeologica e idrogeochimica dell'area vesuviana. *Bollettino Della Societa Geologica Italiana*, *117*, 3–20.

Civita, M. (1994). *Aquifer vulnerability maps to pollution*. Pitagora Editor.

Civita, M. (2010). The combined approach when assessing and mapping groundwater vulnerability to contamination. *Journal of Water Resource and Protection*, *02* ((01|1)), 14–28. https://doi.org/10.4236/jwarp.2010.21003

Civita, M., & De Maio, M. (2000). *SINTACS r5 a new parametric system for the assessment and automatic mapping of groundwater vulnerability to contamination*, 226. Pitagora Editor.

Coda, S., Confuorto, P., De Vita, P., Di Martire, D., & Allocca, V. (2019b). Uplift Evidences related to the Recession of groundwater Abstraction in a pyroclastic-alluvial aquifer of southern Italy. *Geosciences*, *9*(5), 215–215. https://doi.org/10.3390/geosciences9050215

Coda, S., Tessitore, S., Di Martire, S., Calcaterra, D., De Vita, P., & Allocca, V. (2019a). Coupled ground uplift and groundwater rebound in the metropolitan city of Naples (southern Italy). *Journal of Hydrology*, *569*, 470–482. https://doi.org/10.1016/j.jhydrol.2018.11.074

Cosentino, D., Cipollari, P., Marsili, P., & Scrocca, D. (2010). Geology of the central Apennines: A regional review. *Journal of the Virtual Explorer*, *36*(11), 1–37. https://doi.org/10.3809/jvirtex.2010.00223

De Maio, M., Civita, M., Farina, M., & Zavatti, A. (2001). Linee-guida per la redazione e l'uso delle carte della vulnerabilità degli acquiferi all'inquinamento. [Guidelines for editing and use of aquifer vulnerability maps to pollution]. *Agenzia Nazionale per la Protezione Dell'Ambiente (ANPA).–Roma*, 4.

De Vita, P., Allocca, V., Celico, F., Fabbrocino, S., Mattia, C., Monacelli, G., Musilli, I., Piscopo, V., Scalise, A. R., Summa, G., Tranfaglia, G., & Celico, P. (2018). Hydrogeology of continental southern Italy. *Journal of Maps*, *14*(2), 230–241. https://doi.org/10.1080/17445647.2018.1454352

De Vita, P., Allocca, V., Di Clemente, E., Fusco, F., Manna, F., Mastrogiovanni, G., Napolitano, E., et al. (2015). The Instability of Colluvial Mantle in turbidite flysch series of the Cilento region (Campania–southern Italy): the November 26, 2010, Ostigliano Translational Slide. In G. Lollino (Ed.), *Engineering Geology for Society and territory*, (Vol. 2, pp. 1045–1048). Springer.

De Vita, P., Allocca, V., Manna, F., & Fabbrocino, S. (2012). Coupled decadal variability of the north Atlantic

Oscillation, regional rainfall and karst spring discharges in the Campania region (southern Italy). *Hydrology and Earth System Sciences Discussions*, *8*(5), 11233. https://doi.org/10.5194/hessd-8-11233-2011

De Vita, P., & Nappi, M. (2013). Regional distribution of ash-fall pyroclastic soils for landslide susceptibility assessment. In C. Margottini, P. Canuti, & K. Sassa (Eds.), *Landslide Science and Practice* (pp. 103–109). Springer.

Di Gennaro, A., Aronne, G., De Mascellis, R., Vingiani, S., Sarnataro, M., Abalsamo, P., Cona, F., Vitelli, L., & Arpaia, G. (2002). I sistemi di terre della Campania. Monografia e carta, 1:250.000, con legenda. [The land systems of Campania. Monograph and map, 1:250.000, with legend].

Drogue, C. (1992). Hydrodynamics of karstic aquifers: Experimental sites in the Mediterranean karst, southern France. *International Contributions to Hydrogeology*, *13*, 133–149.

Ducci, D., Della Morte, R., Mottola, A., Onorati, G., & Pugliano, G. (2019). Nitrate trends in groundwater of the Campania region (southern Italy). *Environmental Science and Pollution Research*, *26*(3), 2120–2131. https://doi.org/10.1007/s11356-017-0978-y

European Parliament. (2000). Directive 2000/60/EC of the European Parliament and the Council of 23 October 2000. Establishing a framework for Community action in the field of water policy. *Official Journal of the European Communities*, L327, 22.12.2000.

European Parliament Union. (2006). Directive 2006/118/EC of the European Parliament and of the Council of 12 December 2006 on the protection of groundwater against pollution and deterioration. *Official Journal of the European Union*, 372, 19–31.

Forino, G., Ciccarelli, S., Bonamici, S., Perini, L., & Salvati, L. (2015). Developmental policies, long-term land-use changes and the way towards soil degradation: Evidence from southern Italy. *Scottish Geographical Journal*, *131*(2), 123–140. https://doi.org/10.1080/14702541.2015.1047895

Foster, S. S. D. (1987). *Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy. Vulnerability of soil and groundwater to pollutants*, 69–86. Netherlands Organization for Applied Scientific Research.

Freeze, R. A., & Cherry, J. A. (1979). *Groundwater*. Prentice Hall. P. 604.

Fusco, F., Allocca, V., Coda, S., Cusano, D., Tufano, R., & De Vita, P. (2020). Quantitative assessment of specific vulnerability to nitrate pollution of shallow alluvial aquifers by Process-based and Empirical approaches. *Water*, *12*(1), 269. https://doi.org/10.3390/w12010269

Fusco, F., Allocca, V., & De Vita, P. (2017). Hydro-geomorphological modelling of ash-fall pyroclastic soils for debris flow initiation and groundwater recharge in Campania (southern Italy). *Catena*, *158*, 235–249. https://doi.org/10.1016/j.catena.2017.07.010

Fusco, F., De Vita, P., Napolitano, E., Allocca, V., & Manna, F. (2013). Monitoring the soil suction regime of landslide-prone ash-fall pyroclastic deposits covering slopes in the Sarno area (Campania - southern Italy). *Rendiconti Online Società Geologica Italiana*, *24*, 146–148. Springer.

Geiger, R. (1954). Klassifikation der klimate nach. In W. Köppen (Ed.), *Landolt-Börnstein–Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik* (Vol. 3, pp. 603–607).

Goku, R. C., & Dassargues, A. (2000). Current trends and future challenges in groundwater vulnerability assessment using overlay and index methods. *Environmental Geology*, *39*(6), 549–559. https://doi.org/10.1007/s002540050466

Goldscheider, N., & Drew, D. (2007). *Methods in karst hydrogeology*, pp. 1–264. Taylor & Francis. ISBN 9780367388980.

Goossens, M., & Van Damme, M. (1987). *Vulnerability mapping in Flanders, Belgium*. In W. van Duijvenbooden, G.H. van Waegeningh (Eds.), *Vulnerability of soil and groundwater to pollutants international conference* (Vol. 38, pp. 355–360). Proceedings and information 38, TNO Committee on Hydrological Research, The Hague.

Healy, R. W. (2010). *Estimating groundwater recharge. Cambridge University Press*, 256.

Jeannin, P.-Y. (1998). Structure et comportement hydraulique des aquifères karstiques. [Structure and hydraulic behavior of karst aquifers]. [Doctoral thesis, University of Neuchâtel]. http://hydrologie.org/THE/JEANNIN.pdf

Kazakis, N., & Voudouris, K. S. (2015). Groundwater vulnerability and pollution risk assessment of porous aquifers to nitrate: Modifying the DRASTIC method using quantitative parameters. *Journal of Hydrology*, *525*, 13–25. https://doi.org/10.1016/j.jhydrol.2015.03.035

Kiraly, L. (1975). Rapport sur l'état actuel des connaissances dans le domaine des caractères physiques des roches karstiques. [Report on the current state of knowledge in the field of physical characteristics of karst rocks]. *Hydrogeology of karstic terrains (Hydrogéologie des terrains karstiques) International Union of geological sciences, Series B*, (3), 53–67.

Kiraly, L. (2003). Karstification and groundwater flow. *Speleogenesis and Evolution of Karst Aquifers*, *1*(3), 155–192.

Klimchouk, A. B. (2000). The formation of epikarst and its role in vadose Speleogenesis. In A. B. Klimchouk, D. C. Ford, A. N. Palmer, & W. Dreybrodt (Eds.), *Speleogenesis. Evolution of karst aquifers* (pp. 91–99). National Speleological Society, Inc.

Mangin, A. (1975). Contribution à l'étude hydrodynamique des aquifers karstiques. *Ann. Spéléol., Première Partie*, *29*, 283–332.; Deuxième partie, 29, 495–601; Troisième partie, 30, 21–124.

Manna, F., Allocca, V., Fusco, F., Napolitano, E., & De Vita, P. (2013). Effect of the north Atlantic Oscillation on groundwater recharge processes in karst aquifers of the Cilento Geopark. *Rendiconti Online Società Geologica Italiana*, *28*, 106–109. ISSN 2035-8008.

Maxey, G. B. (1964). Hydrostratigraphic units. *Journal of Hydrology*, *2*(2), 124–129. https://doi.org/10.1016/0022-1694(64)90023-X

Milia, A., & Torrente, M. M. (2014). Early-stage rifting of the southern Tyrrhenian region: The Calabria–sardinia breakup. *Journal of Geodynamics*, *81*, 17–29. https://doi.org/10.1016/j.jog.2014.06.001

Milia, A., Valente, A., Cavuoto, G., & Torrente, M. (2017). Miocene progressive forearc extension in the Central Mediterranean. *Tectonophysics*, *710-711*, 232–248. https://doi.org/10.1016/j.tecto.2016.10.002

NRC -– National Research Council. (1993). *Ground water vulnerability assessment: Predicting relative contamination potential under conditions of uncertainty*. National Academies Press.

Patacca, E., & Scandone, P. (2007). Geology of the southern Apennines. *Bollettino Della Società Geologica Italiana*, *7*, 75–119.

Ravbar, N., Engelhardt, I., & Goldscheider, N. (2011). Anomalous behavior of specific electrical conductivity at a karst spring induced by variable catchment boundaries: The case of the Podstenjsek spring, Slovenia. *Hydrological Processes*, *25*(13), 2130–2140. https://doi.org/10.1002/hyp.7966

Romano, B., Zullo, F., Fiorini, L., Marucci, A., & Ciabò, S. (2017). Land transformation of Italy due to half a century of urbanization. *Land Use Policy*, *67*, 387–400. https://doi.org/10.1016/j.landusepol.2017.06.006

Vitale, S., & Ciarcia, S. (2018). Tectono-stratigraphic setting of the Campania region (southern Italy). *Journal of Maps*, *14*(2), 9–21. https://doi.org/10.1080/17445647.2018.142

White, W. B. (1969). Conceptual models for carbonate aquifer. *Ground Water*, *7*(3), 15–21. https://doi.org/10.1111/j.1745-6584.1969.tb01279.x

White, W. B. (2002). Karst hydrology: Recent developments and open questions. *Engineering Geology*, *65* (2-3), 85–105. https://doi.org/10.1016/S0013-7952(01)00116-8

GROUNDWATER VULNERABILITY OF PRINCIPAL AQUIFERS (DIRECTIVE 2000/60/EC) OF THE CAMPANIA REGION (SOUTHERN ITALY)

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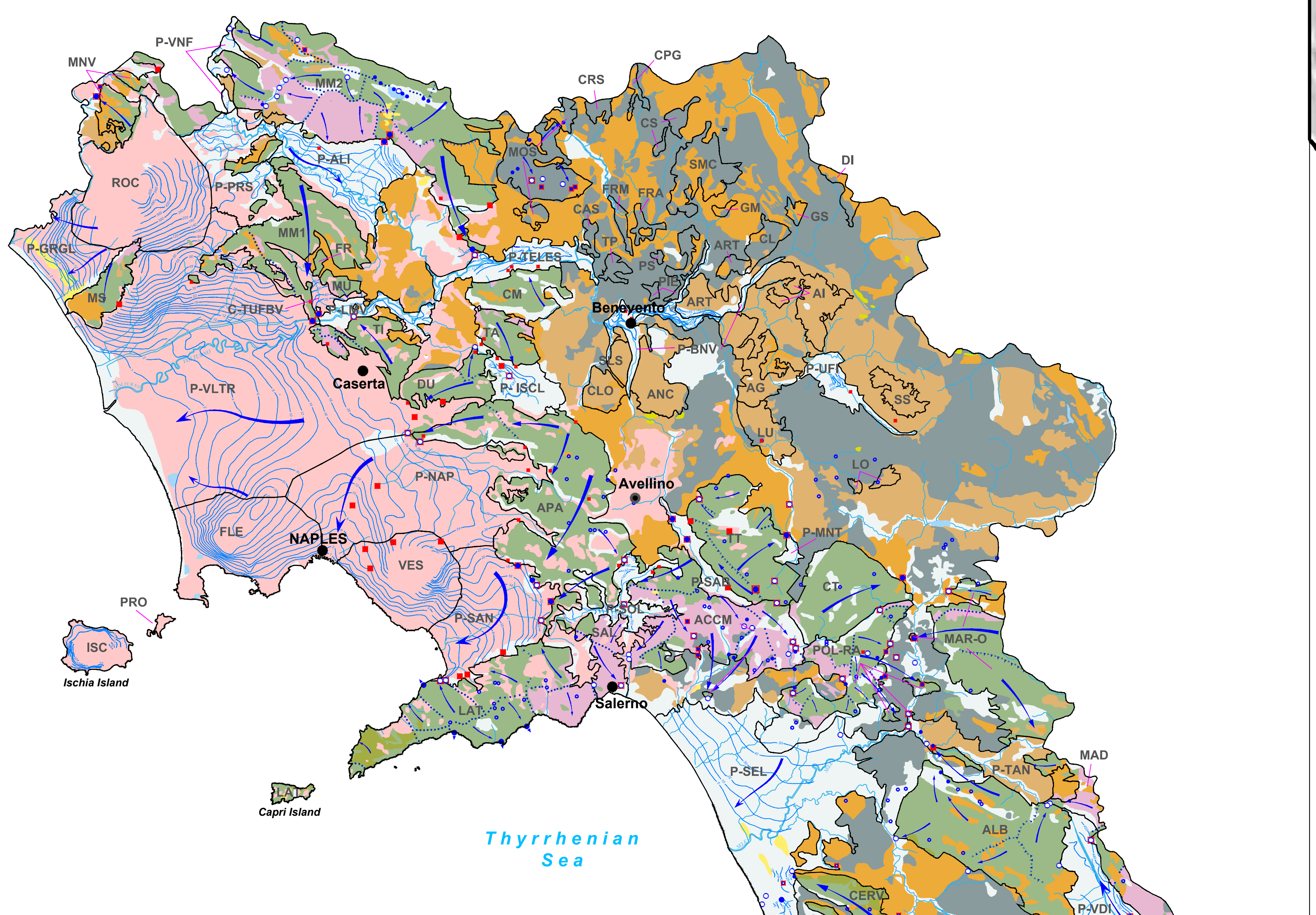
Hydrogeology and principal aquifers (Directive 2000/60/EC) of the Campania region



Principal aquifers and groundwater bodies (Directive 2000/60/EC)

Quaternary alluvial aquifers

- P-ALE - Alento alluvial plain
- P-ALI - Alife alluvial plain
- P-BNV - Benevento alluvial plain
- P-BUS - Bussento alluvial plain
- P-GRGL - Garigliano alluvial plain
- P-ISCL - Isclero alluvial plain
- P-LAM - Lambro and Mingardo low course
- P-LMV - Limatola-Volturno alluvial plain
- P-MNT - Montella alluvial plain
- P-NAP - Eastern plain of Napoli
- P-PRS - Presenzano and Riardo alluvial plain
- P-SAB - Sabato high valley
- P-SAN - Sarno alluvial plain
- P-SEL - Sele alluvial plain
- P-SOL - Solofrana alluvial plain
- P-TAN - Tanagro low course
- P-TELES - Calore low valley
- P-UFI - Ufita alluvial plain
- P-VDI - Vallo di Diano alluvial plain
- P-VLTR - Volturno-Regi lagni alluvial plain
- P-VNF - Venafro alluvial plain
- V-MIN - Mingardo middle valley

Quaternary volcanic aquifers

- C-TUFBV - Low Volturno tuff complex
- FLE - Phlegraean fields
- ISC - Ischia island
- PRO - Procida island
- ROC - Roccamonfina
- VES - Somma-Vesuvius

Miocene-Pliocene turbidite, molasse and clastic aquifers

- AG - M. Apice-Grottaminarda
- AI - Ariano Irpino
- ANC - S. Angelo a Cupolo
- ART - Area S. Arcangelo Trimonte
- CEN - Centaurino Mount
- CLO - Ceppaloni
- GS - Ginestra degli Schiavoni
- LO - S. Angelo dei Lombardi
- LU - Luogosano
- PIS - Pisciotta-San Mauro la Bruca
- SAC - Monte Sacro-Gelbison
- SLS - S.Leucio del Sannio
- SS - S.Stefano Mount
- STE - Stella Mount

Cretaceous-Paleogene basin series aquifers

- CAS - Casalduni
- CL - Calvello Mount
- CPG - Castelpagano
- CRS - S.Croce del Sannio
- CS - Colle Sannita
- DI - Difesa Mount
- FRA - Fragneto l'Abate
- FRM - Fragneto Monforte
- GM - S. Giorgio la Molara
- MOS - Moschiaturo Mount
- PIE - Pietrelcina
- PS - Pesco Sannita
- SMC - S.Marco dei Cavoti
- TP - Troppo Povero Mount

Mesozoic limestone aquifers

- ALB - Alburni Mounts
- APA - Avella-Partenio-Pizzo D'Alvano Mounts
- CERV - Cervati M.-Vesole M.
- CM - Camposauro Mount
- COC - Forcella M.-Salice-Coccovello M.
- CT - Cervialto Mount
- DU - Durazzano Mounts
- FR - Friento Mount
- LAT - Lattari Mounts-Capri island
- MAR-O - Marzano Mount-Ogna Mount
- MM1 - Maggiore Mount
- MNV - Mainarde-Venafro Mounts
- MOT - Motola Mount
- MS - Massico Mount
- MU - Maiulo Mount
- POL-RA - Polveracchio-Rainone Mount
- TA - Taburno Mount
- TI - Tifata Mount
- TT - Terminio-Tuoro Mount

Mesozoic dolomite aquifers

- ACCM - Accellica-Licinici M.-Mai
- BUL - Bulgheria Mount
- MAD - Maddalena Mounts
- MM2 - Matese Mounts
- SAL - Salerno Mounts

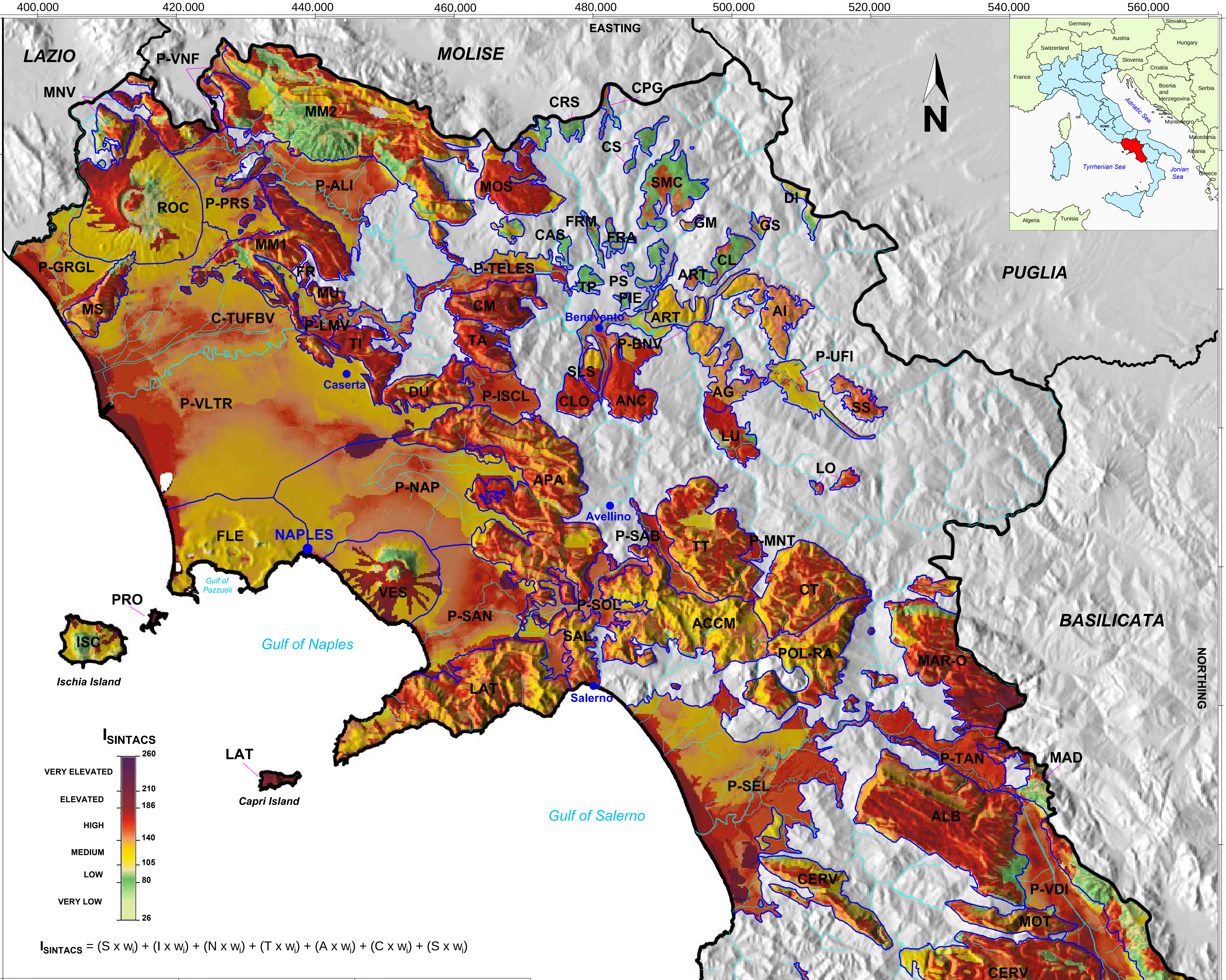
HYDROGEOLOGICAL DOMAINS	HYDROSTRATIGRAPHIC UNITS
Quaternary alluvial	Quaternary complexes
Quaternary volcanic	Quaternary volcanic complexes
Miocene-Pliocene turbidite, molasse and clastic	Pliocene-Quaternary clastic complexes Pliocene molasse series complexes Miocene turbidite series complexes
Cretaceous-Paleogene basin series	Cretaceous-Cenozoic basin series complexes
Mesozoic limestone	Paleogene carbonatic series complexes Mesozoic carbonate platform series complexes
Mesozoic dolomite	Mesozoic dolomite platform series complexes
	Natural and artificial continental freshwater bodies (> 3 milions m^3)

SPRINGS

UNTAPPED		TAPPED
●	$Q_{average} < 0.10$ m^3/s	▣
○	0.10 m^3/s $< Q_{average} < 1.00$ m^3/s	▣
●	1.00 m^3/s $< Q_{average} < 5.00$ m^3/s	▣
	$Q_{average} > 5.00$ m^3/s	▣
○	Springs with unknown discarge ($Q<0.10$ m^3 s^{-1})	▣
●	Submarine springs	▣
■	Well fields	

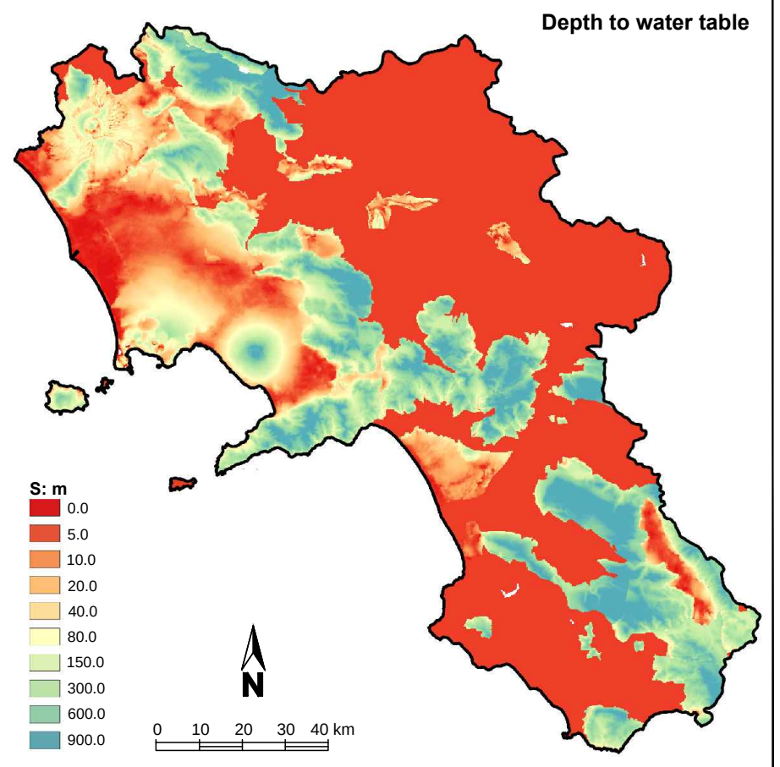
SYMBOLOGY

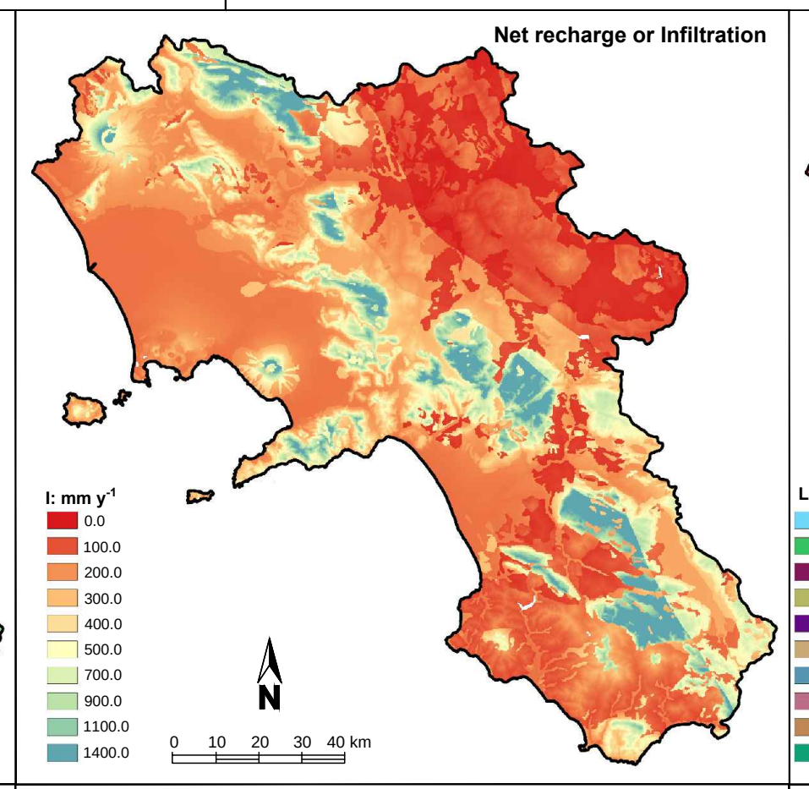
- Probable limits of springs and groundwater recharge areas, within the hydrogeological structures, with hydraulic interchanges
- Probable limits of springs and groundwater recharge areas, within the hydrogeological structures, with negligible hydraulic interchanges
- Main groundwater flow paths within the more relevant hydrogeological structures at regional scale
- Groundwater head contour lines (m s.l.m.)
- Main preferential drainage axes within the more relevant hydrogeological structures at the regional scale, identified from the piezometric surveys
- Regional boundaries

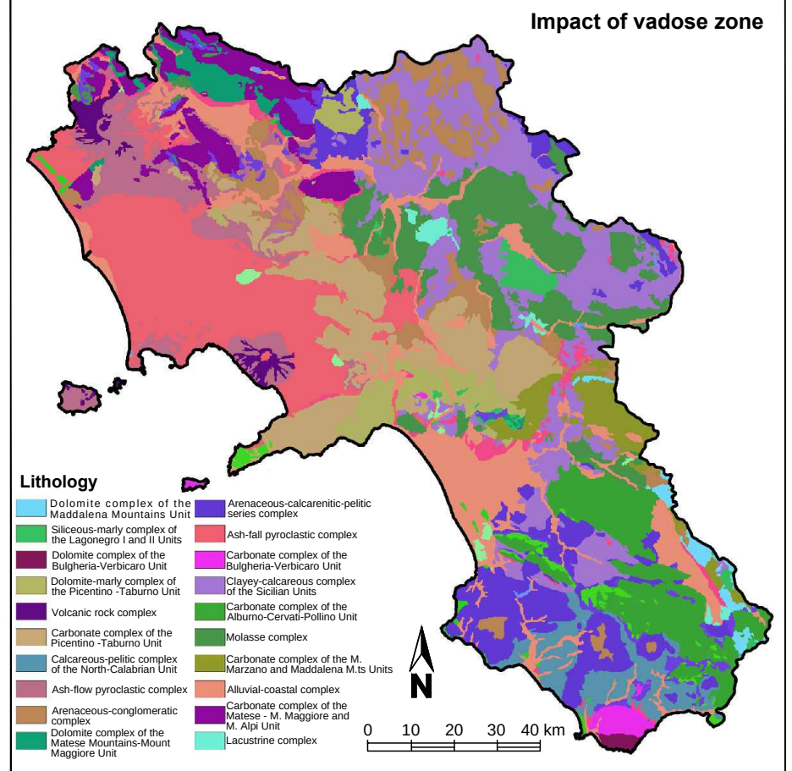


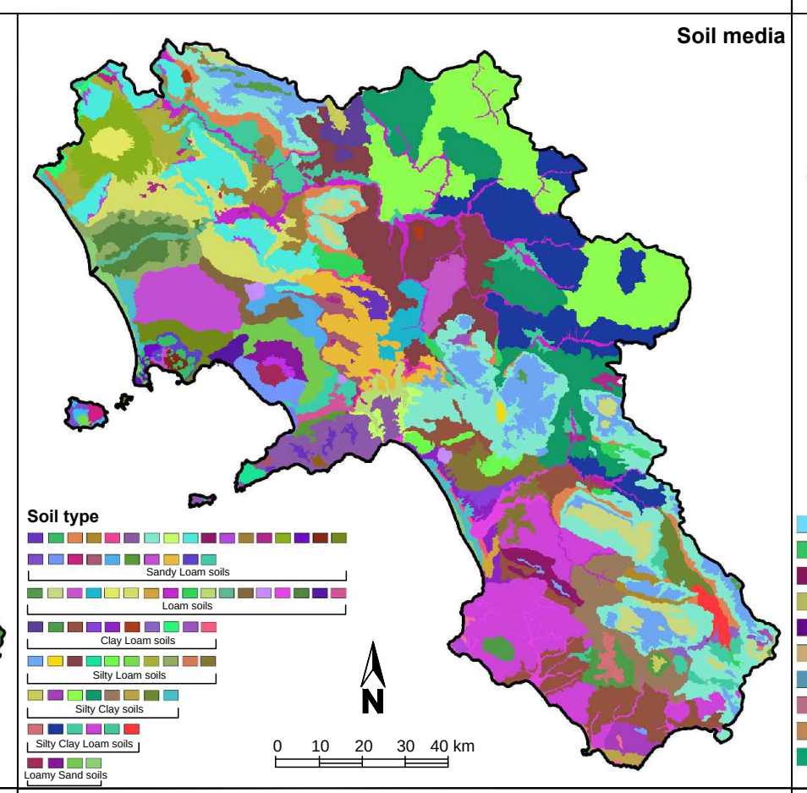
$$I_{SINTACS} = (S \times w_i) + (I \times w_i) + (N \times w_i) + (T \times w_i) + (A \times w_i) + (C \times w_i) + (S \times w_i)$$

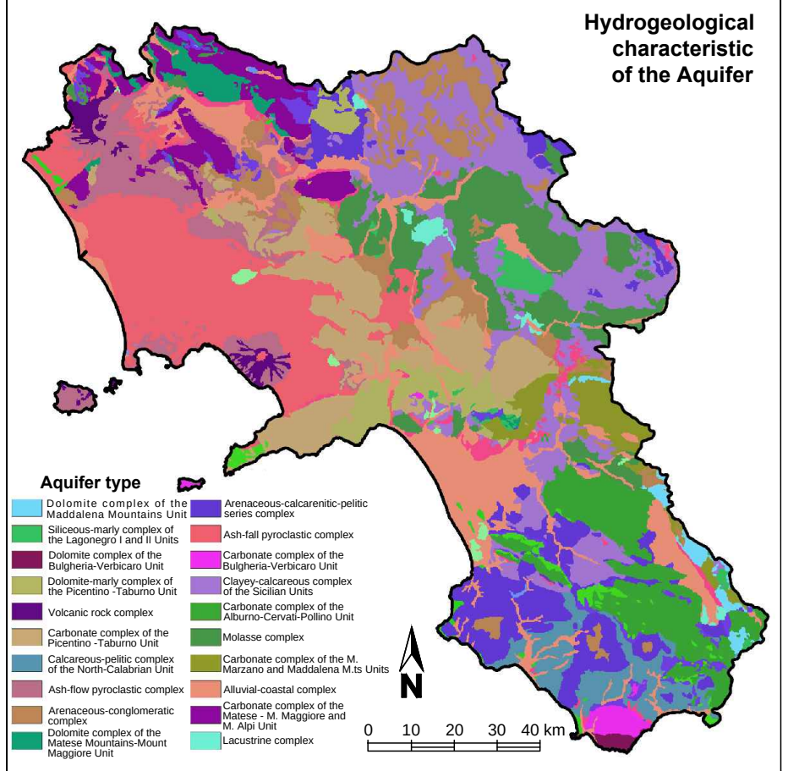
Scale 1:250.000

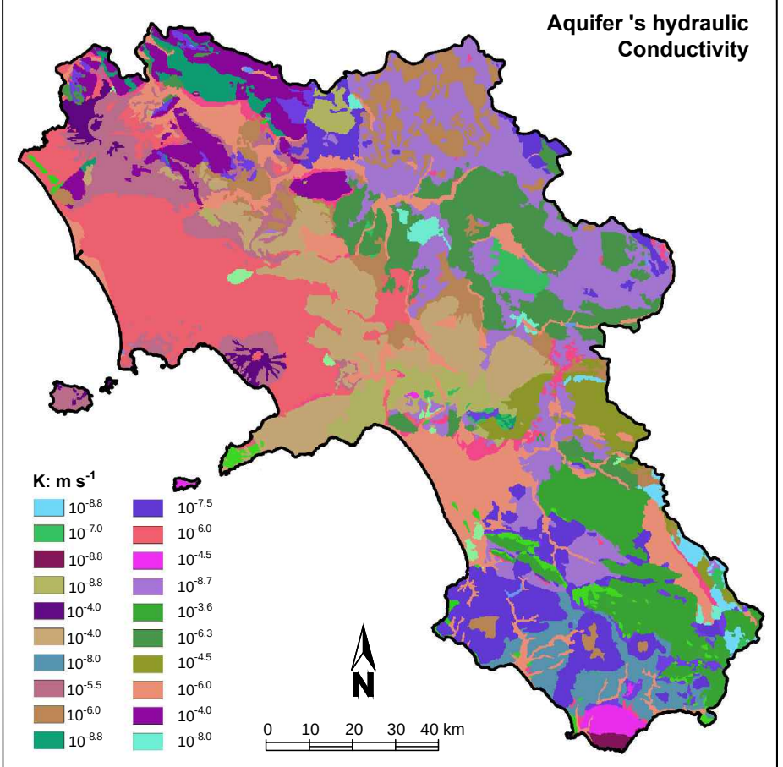

Depth to water table

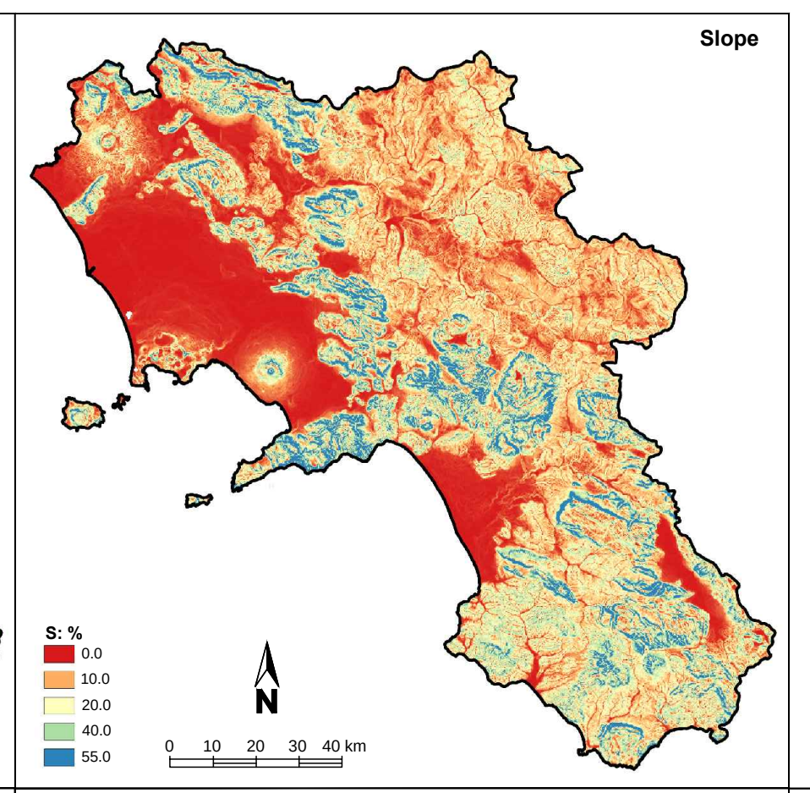

Net recharge or Infiltration

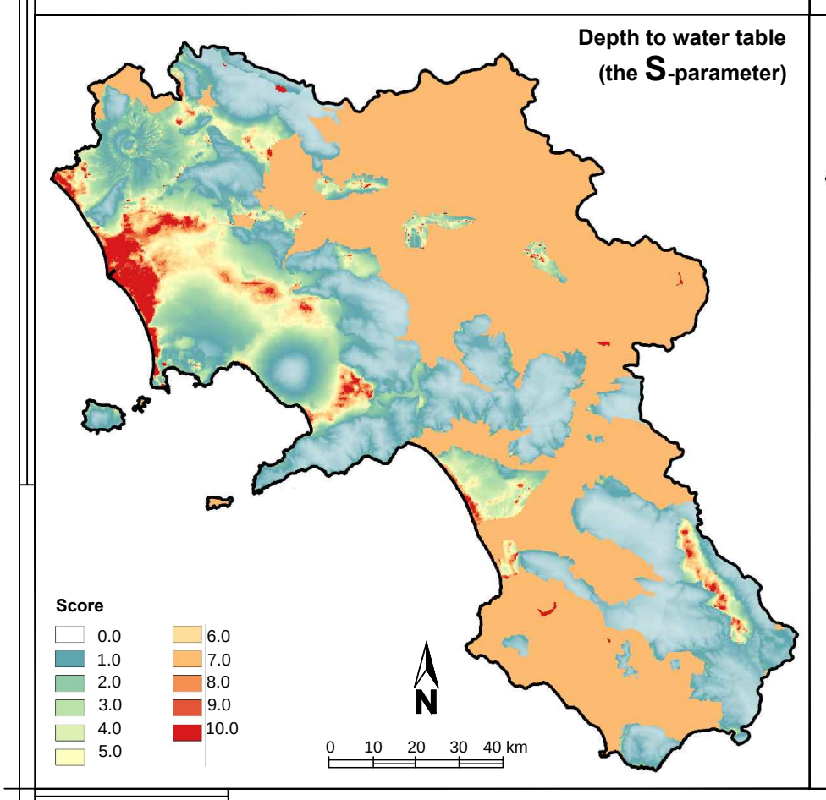

Impact of vadose zone

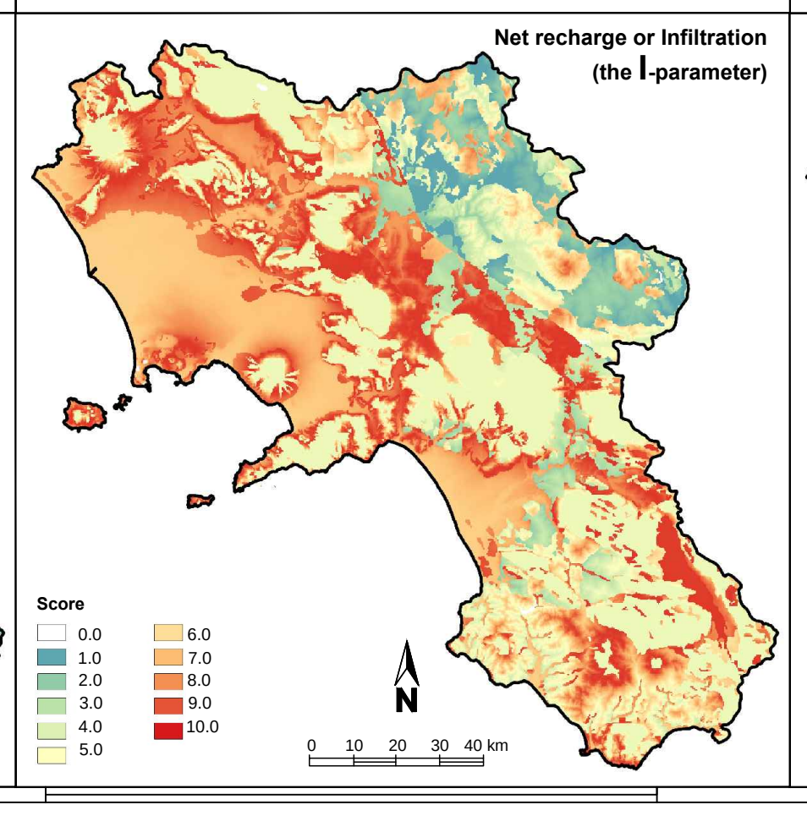

Soil media

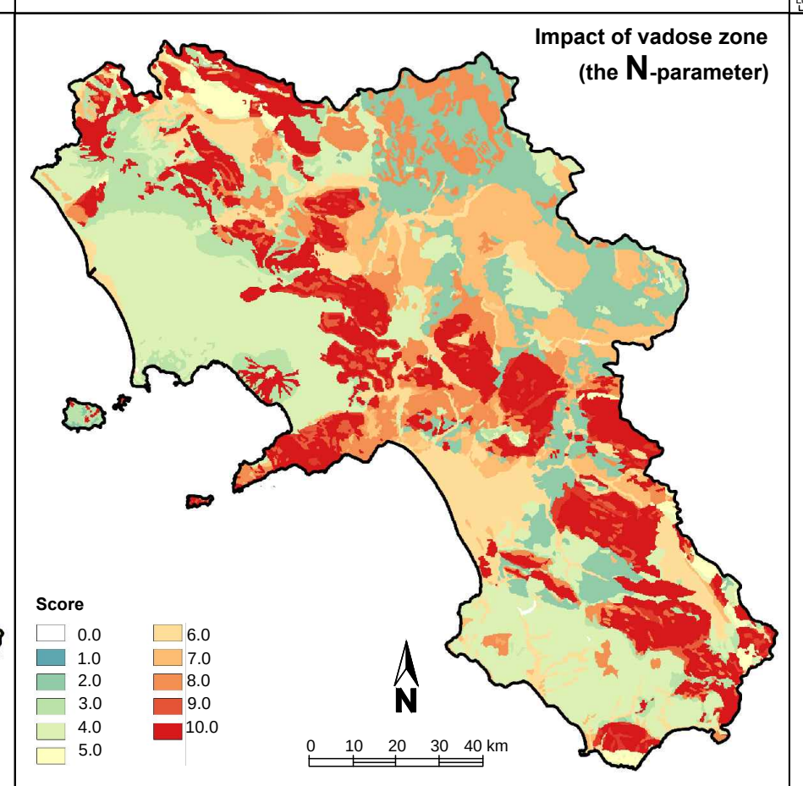

Hydrogeological characteristic of the Aquifer

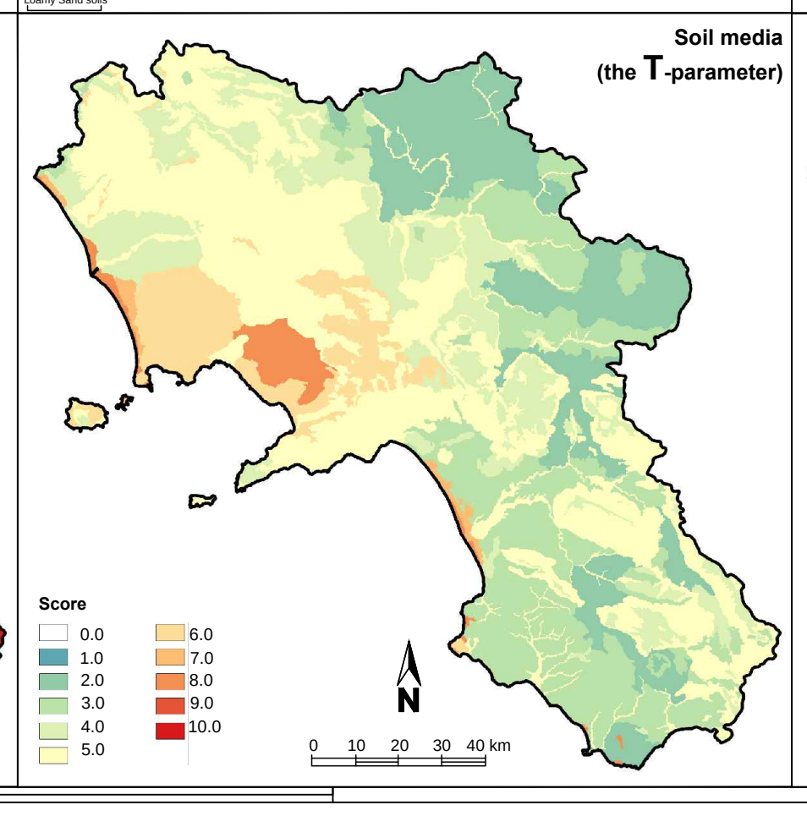

Aquifer 's hydraulic Conductivity

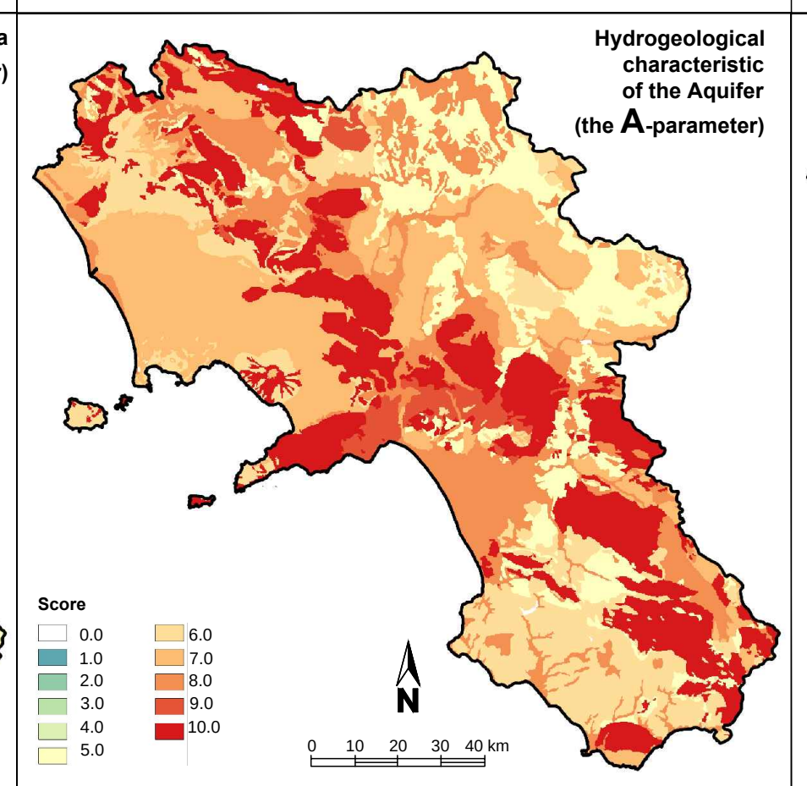

Slope

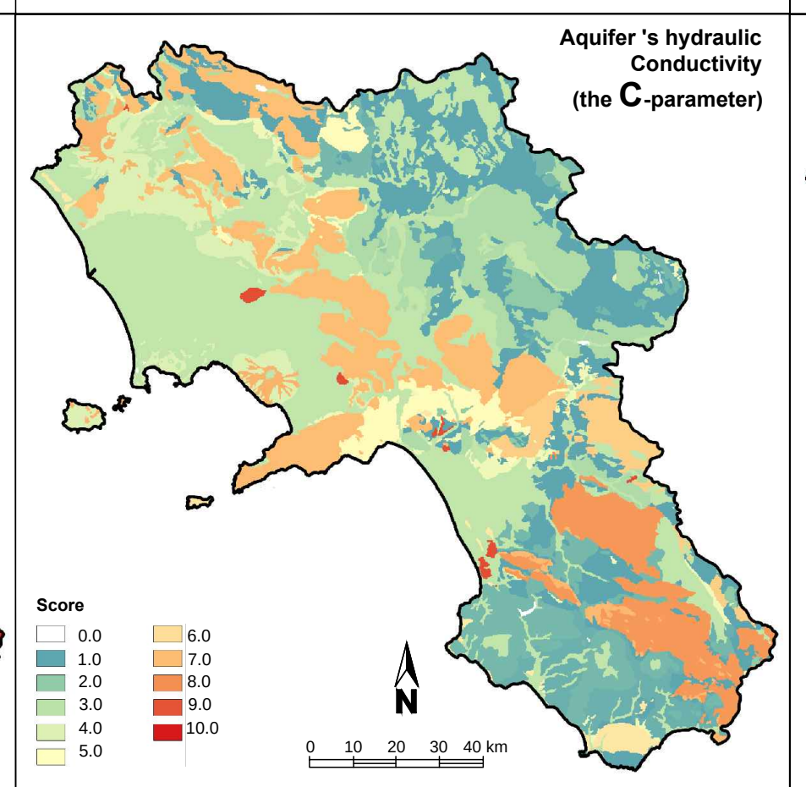

Depth to water table (the **S**-parameter)

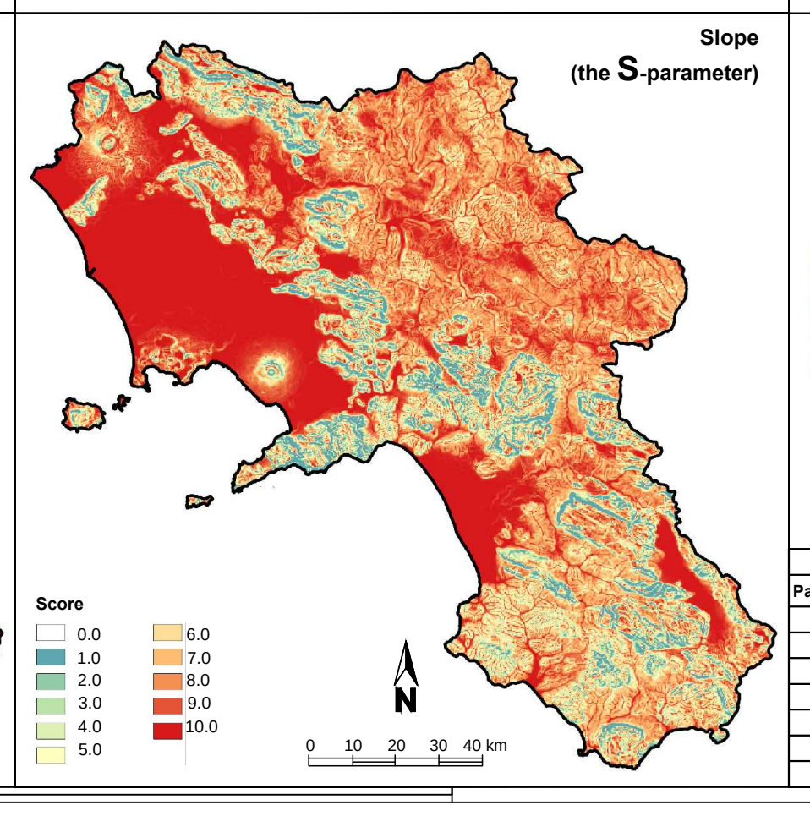

Net recharge or Infiltration (the **I**-parameter)

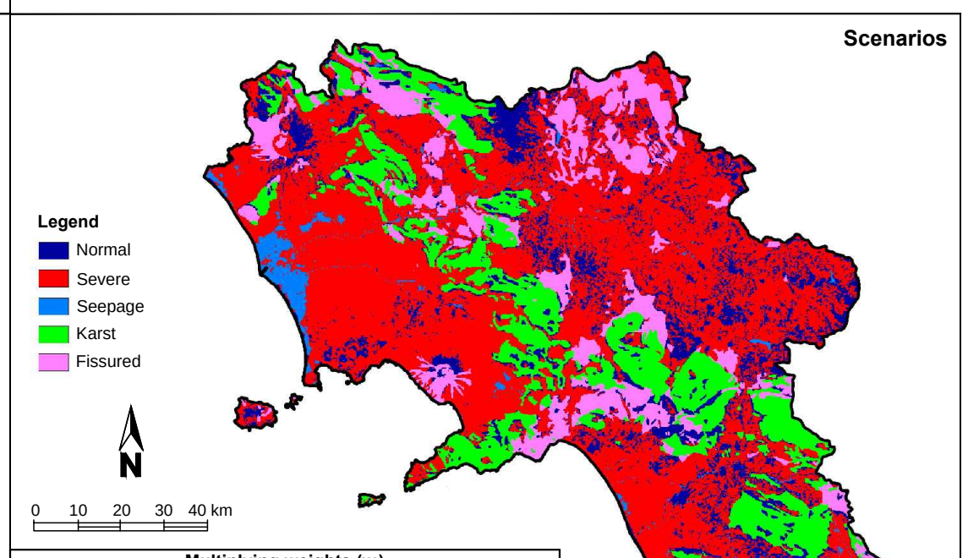

Impact of vadose zone (the **N**-parameter)


Soil media (the **T**-parameter)


Hydrogeological characteristic of the Aquifer (the **A**-parameter)


Aquifer 's hydraulic Conductivity (the **C**-parameter)


Slope (the **S**-parameter)


Scenarios

Multiplying weights (w_i)					
Parameter	Normal	Severe	Seepage	Karst	Fissured
S	5	5	4	2	3
I	4	5	4	5	3
N	5	4	4	1	3
T	3	5	2	3	4
A	3	3	5	5	4
C	3	2	5	5	5
S	3	2	2	5	4

Projection: Universal Transverse Mercator (UTM), 33 zone
Datum: World Geodetic System 1984