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A comparison of methods for assessing groundwater vulnerability in karst aquifers: the case study of Terminio Mt. aquifer (Southern Italy)

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Abstract

The assessment of groundwater vulnerability to pollution is becoming even more important all over the world due to the increase of impacts of human activities on groundwater resources and the related risks to the human health, economics, and the environment. Owing to the variability of methods known for estimating groundwater vulnerability, basically depending on hydrogeological parameters considered and the scale of analysis, the comparison of results of different methods appears straightforward for identifying the best approach in a given hydrogeological condition and reference scale. In such a view, this work attempts to assess the groundwater vulnerability of the Terminio Mt. karst aquifer, by applying four different groundwater vulnerability methods, index-based, and comparing results in order to identify the best performing one in karst environments. The study aquifer, located in the Picentini Mts Regional Park (Campania region, southern Italy) represents a strategic drinking water resource since Roman times and hosts massive groundwater resources which outflow mainly from tapped basal and subordinately perched springs.

The peculiar characters of the study karst aquifer, which favour direct infiltration and groundwater recharge processes, as well as the occurrence of industrial, agricultural and grazing activities, make it very vulnerable to groundwater pollution, thus requiring a proper and careful territorial management.

Beside the most frequently and generally used methods for assessing groundwater vulnerability, such as the DRASTIC and SINTACS, also DAC and COP methods specifically designed for karst aquifers were applied and mutually compared. Results of SINTACS, DRASTIC and DAC methods show groundwater vulnerability maps of the Terminio Mt. karst aquifer as chiefly characterized by two classes of intrinsic groundwater vulnerability, varying between the medium and high degrees. Furthermore, high and extremely high values of groundwater vulnerability were found in areas controlled by the shallow depth of the water-table. Instead, the COP method resulted as the most effective in identifying the endorheic areas and the related karst morphologies as very high groundwater vulnerability zones, therefore the most suitable in capturing specific hydrogeological features of karst areas that control groundwater pollution and vulnerability.

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Results obtained will support decision tools aimed at the land use planning and protection of karst aquifers from pollution in karst areas.

Keywords Intrinsic groundwater vulnerability, Parametric method, Karst aquifer, Southern Italy

1 Introduction

Groundwater represents a valuable source of freshwater for drinking, irrigation, and industrial uses as well as sustaining ecosystems in many countries across the globe. It is considered an important resource due to its relatively lower susceptibility to pollution in comparison to surface water [1].

However, the sustainability of this resource is being threatened by the overexploitation and land use mismanagement favoring the increase of potential pollutant human activities [2–4]. Notably the widespread occurrence of organic contaminants such as polycyclic aromatic hydrocarbons (PAHs), released into the environment mainly from anthropogenic sources, impact on groundwater resources, therefore on the human health and environment [5]. Specifically, in an aquatic environment, PAHs are readily adsorbed by particulate matter, consequently remaining in higher concentrations in surface sediments [6] and in surface water [7], which can percolate and reach groundwater, therefore contaminating it.

Since the groundwater contamination has increasingly become a severe environmental issue, several directives and policies [8–10] were issued to protect groundwater quality by the reduction of pollution and minimization of the release of hazardous chemicals and materials. Therefore, the prevention of groundwater pollution is essential for effective groundwater resource management, especially of the most relevant and productive aquifers.

In the Mediterranean area, karst aquifers are the most productive and strategic due to the high permeability which favor the high groundwater recharge and circulation. These aquifers feed about 25% of the world's population [11] contributing to the freshwater supply of the most part of Mediterranean countries, therefore constituting a fundamental resource for the economic development and well-being. In the southern Italy, and especially in the Campania region, a high availability of groundwater resources does occur in karst aquifers because of their hydrogeological structural setting, which favor a basal groundwater circulation due to the hydrogeological confinement with adjoining low-permeability terrigenous series.

The high productivity of karst aquifers of southern Italy is mainly related to high permeability of karst rocks, the relevant amount of mean annual precipitation and the occurrence (up to 1500 $mm \cdot yr^{-1}$) of large summit endorheic and flat areas that favor infiltration and recharge processes [12]. However, the existence of the "pyroclastic soil-epikarst-carbonate bedrock" system, peculiar of the Campania karst massifs surrounding the volcanic centres (Roccamonfina, Phlegraean Fields and Somma-Vesuvius), is a factor influencing the transport of microbial contaminants [13] and groundwater recharge by acting as a temporary water storage tank that controls the infiltration processes [14].

Because of their hydrogeological and hydraulic features, groundwater resources of karst aquifers are highly vulnerable to pollution [15–17]. Therefore, the protection of karst aquifers and the related groundwater resources must be considered as a very high priority, according to the European regulations [8–10], especially if considering the future increase in groundwater demand, land use and anthropic activities potentially pollutant for groundwater resources.

Groundwater vulnerability mapping is the common method for assessing spatially the relative susceptibility of an aquifer to contamination. In addition, comparing the results of different vulnerability techniques constitute an important research challenge in order to analyse their reliability [18], as well as a reference for the protection zoning and proper land-use planning. As a principal limitation is the quality and quantity of available data needed for the application of methods for estimating and mapping groundwater vulnerability. Moreover, several studies have already shown that whenever different methods are tested in the same area, using the same database, the resulting maps were sometimes different. Therefore, the reliability of methods used for estimating and mapping groundwater vulnerability maps is difficult to determine a-priori because it depends on the structure of the methods itself as well as by quality and quantity of data.

Some of the most frequently used methods for estimating groundwater vulnerability are DRASTIC [19], GOD [20], Aquifer Vulnerability Index (AVI) [21] and SINTACS [22] which is recognized as the official method by the Italian National Agency for the Environmental Protection [23]. However, these methods do not provide specific tools for karst groundwater vulnerability assessment. For example, these methods do not consider the occurrence of allogenic recharge and infiltration into karst swallow holes. The first method accounting for the specific properties of karst aquifers was EPIK [24]. Later, COST Action 620 proposed a "European approach to vulnerability and risk mapping for the protection of karst aquifers" [25]. Several methods aimed at the groundwater vulnerability mapping were developed within this framework such as the COP method [26]. This method was developed for the assessment of intrinsic vulnerability of karst aquifers in the framework of the European COST Action 620 (COST is the acronym for COoperation in Science and Technology) which considered "Vulnerability and Risk Mapping for the Protection of Carbonate (Karst) Aquifers" and ran between 1997 and 2003. This Action contributed to the development of the EU Water Framework Directive 2000/60/EC for river basin management [8] and the Directive 2003/0210/EC [9] for protection of groundwater from pollution.

In such a framework, the assessment of the groundwater vulnerability of the Terminio Mt. karst aquifer is considered, because it represents a strategic groundwater resource of southern Italy for drinking use. The aquifer currently supplies three regional aqueduct systems (AQP S.p.A., ABC Napoli and Alto Calore Servizi S.p.A.), and serves about five million inhabitants distributed among the Campania, Basilicata and Puglia regions (Fig. 1). Serino and Cassano Irpino springs, belonging to the Terminio Mt. karst aquifer, is one of the most productive springs groups of the Campania region. The Serino springs, divided into Acquaro-Pelosi group and Urcioli springs, outlet in the Sabato river valley, and are characterized by high water quality and discharge rate. The springs were tapped since Roman times (1st century AD) with the construction of the "Claudio" and "Sannitico" aqueducts. The first one tapped the Acquaro-Pelosi springs to supply Naples and Phlaegrean Fields, the second aqueduct tapped the Urcioli spring to supply the city of Benevento. This latter aqueduct was abandoned and partially destroyed during the two World Wars. The Cassano Irpino springs represent the other main sources that supply the Puglia region through the "Acquedotto Pugliese" (the main aqueduct of Italy) [27].

The primary goals to be achieved by the present study were: (1) to estimate and map groundwater vulnerability of the basal karst aquifer of Terminio Mt. by applying DRASTIC [19] and SINTACS [22] and specifically for

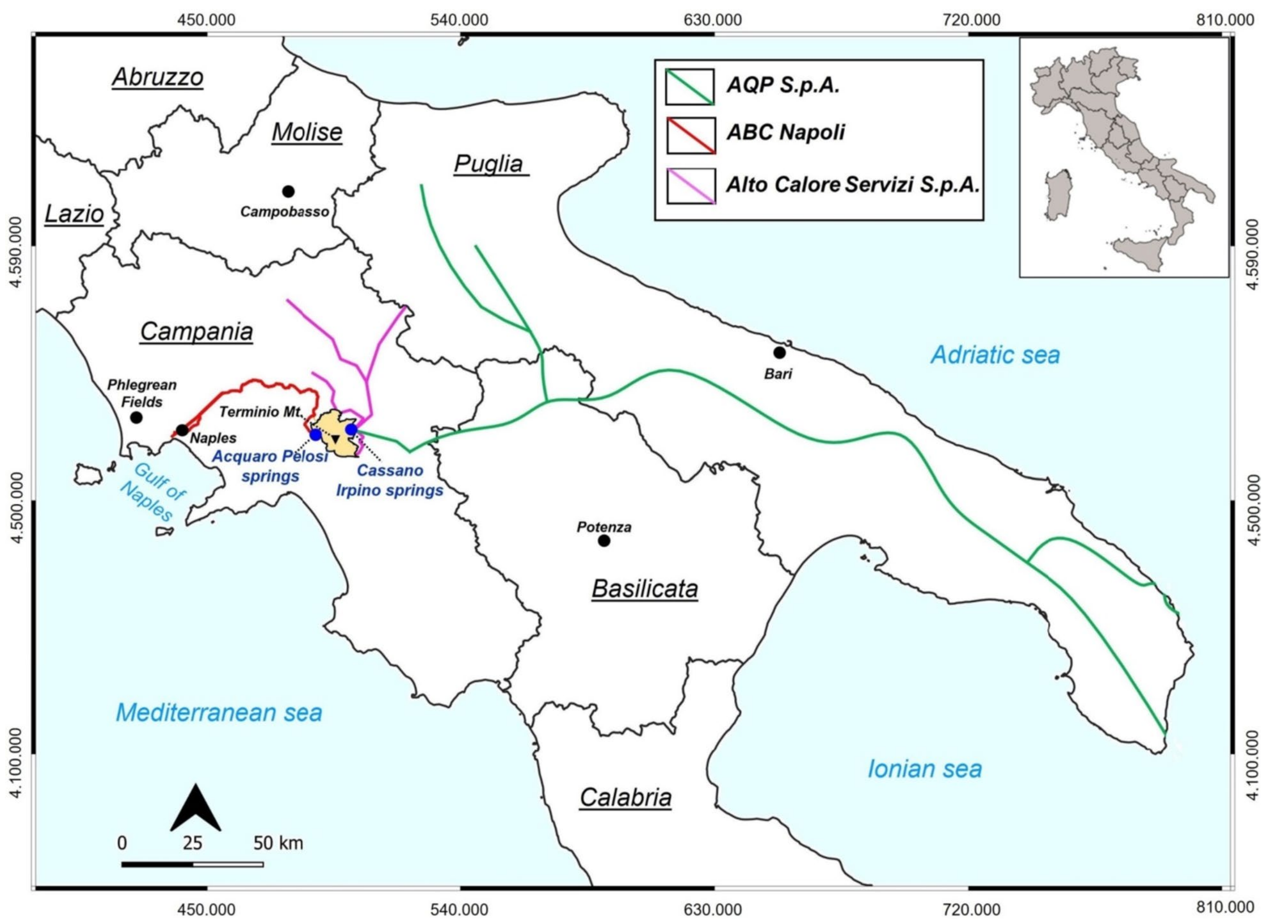

Fig. 1 Aqueduct systems supplied by Terminio Mt. karst aquifer

karst aquifers, such as DAC [28] and COP [26] methods; (2) to compare qualitatively and statistically results of four parametric methods to assess their applicability and reliability and; (3) evaluate the efficiency of the developed DAC and COP vulnerability approaches against the conventional SINTACS and DRASTIC models.

2 Description of the study area

The Terminio Mt., extended for about 170 km^2, is located (Figs. 1 and 2) in the Picentini Mts. Regional Park (Campania region) and hosts one of karst systems with a mean annual groundwater yield of 0.040 $m^3 \cdot s^{-1} \cdot km^{-2}$, the highest among the other karst aquifers of the southern Italy, which sustains a series of ecosystem services [13, 29]. The numerous environments, e.g. forests and grasslands, karst lakes and springs, swallow holes, poljes, and other karst forms [13, 29], contribute to its variegated geo- and bio-diversity. Groundwater resources play a primary role in the regulation of the hydro-ecological regime of Sabato and Calore rivers (Fig. 2). The Terminio Mt. karst aquifer has played a strategic role for socio-economic development of southern Italy since historical times. In Roman times, with the construction of the Augustan aqueduct (33 – 12 BC), some karst springs were used to feed cities such as *Neapolis, Puteoli, Pompeii*, *Cumae* and *Beneventum*, while currently they are tapped by three large aqueduct systems (Fig. 1) for the water supply of about 5 million inhabitants distributed across the Campania, Basilicata and Puglia regions [29].

From a hydrogeological point of view, the Terminio Mt. is a well-defined aquifer formed mainly by a fractured and karstified Cretaceous limestone series belonging to the "*Monti Picentini*" tectonic unit [30]. This carbonate series is hydraulically confined by low permeability terrigenous units, such as the Varicolored Clays (Sicilide Unit), which are juxtaposed by stratigraphic and tectonic boundaries. Moreover, other main hydrogeological lateral boundaries of the karst aquifer are low permeability zones related to faults acting as barriers to groundwater flow and it determines the existence of a basin-in-series aquifer system [29]. In such a hydrogeological framework, high altitude springs (Q_{mean} < 0.01 $m^3 \cdot s^{-1}$) are generally located in association with faults with lower permeability core zones, although hydraulic exchanges among groundwater basins are possible. The basal groundwater circulation outflows in four huge basal springs: Cassano Irpino, Serino, Sauceto - Lagno and Baiardo, located in the lowest point of hydrogeological boundary at the contact with low permeability deposits (Fig. 2a and b).

The aquifer system is subdivided into four main groundwater basins that are partially interconnected. The compressive tectonic line with east/west orientation, which puts in contact the carbonate series with the impermeable Varicolored Clays, allows to identify two karst subsystems, located on the southern and the northern side of the Dragone Plain respectively (Fig. 2a). In the southern sector of the karst aquifer, a fault system with north-south orientation separates the Cassano Irpino basin from the Serino basin. In the northern sector there are two other groundwater basins: the Baiardo basin to the east and the Sauceto-Lagno basin to the west (Fig. 2b).

Unlike other karst aquifers of Europe, the Terminio Mt. is characterized by large endorheic areas, poljes, swallow holes or ponors (Fig. 3d). These karst features play an important role for the groundwater recharge, which occurs by diffuse infiltration across the whole aquifer and with concentrated infiltration in the endorheic areas or ponors. The latter represents preferential pathways of the pollutants toward the saturated zone. Moreover, the karst aquifer is covered by alkali-potassic ash-fall pyroclastic deposits, derived mainly by the Somma-Vesuvio eruptive activity [13]. Such deposits can be found with thickness up to 0.50–0.60 m along slopes, where the slope angle is greater, while with a thickness up to 10–20 m in summit flat and endorheic areas due to both the primary and colluvial depositions (Fig. 3c). Along hillslopes, chestnut and beech deciduous forests are the predominant types of vegetation cover, while in karst endorheic areas grassland is the prevailing one (Fig. 3a and b).

The Terminio Mt. karst aquifer belongs to Mediterranean-mild climate (CSb) type [31] and is characterized by a mean annual rainfall up to 1500 $mm \cdot y^{-1}$and mean annual air temperature up to 8.4 °C. Fluctuations of interannual and decadal precipitations as well as groundwater recharge are controlled by the effects of the Nord Atlantic Oscillation [32].

(See figure on next page.)

Fig. 2 **a** Hydrogeological map of study area. Key to symbols:1) Colluvial unit; 2) Alluvional unit; 3) Silty clayey unit; 4) Marshy unit; 5) Pyroclastic fall unit; 6) Detrital unit; 7) YCT unit; 8) Gravelly-sandy-silty unit; 9) Conglomerate unit; 10) Arenaceous limestone unit; 11) Arenaceous sandy clayey unit; 12) Varicolored Clays unit; 13) Calcareous marly clayey unit; 14) Marly limestone unit; 15) Calcareous marly arenaceous unit; 16) Limestone unit; 17) Dolomite limestone unit; 18) Marly limestone unit; 19) Dolomite unit; 20) Groundwater divide with negligible hydraulic interchanges; 22) Groundwater divide with hydraulic interchanges; 22) Flow direction; 23) Borehole; 24) Main tapped basal springs; 25) Main untapped high altitude springs; 26) Faults; 27) Water table. Coordinate system: UTM WGS 84 33 N zone. 1:50.000 scale. **b** Hydrogeological sections of the study area

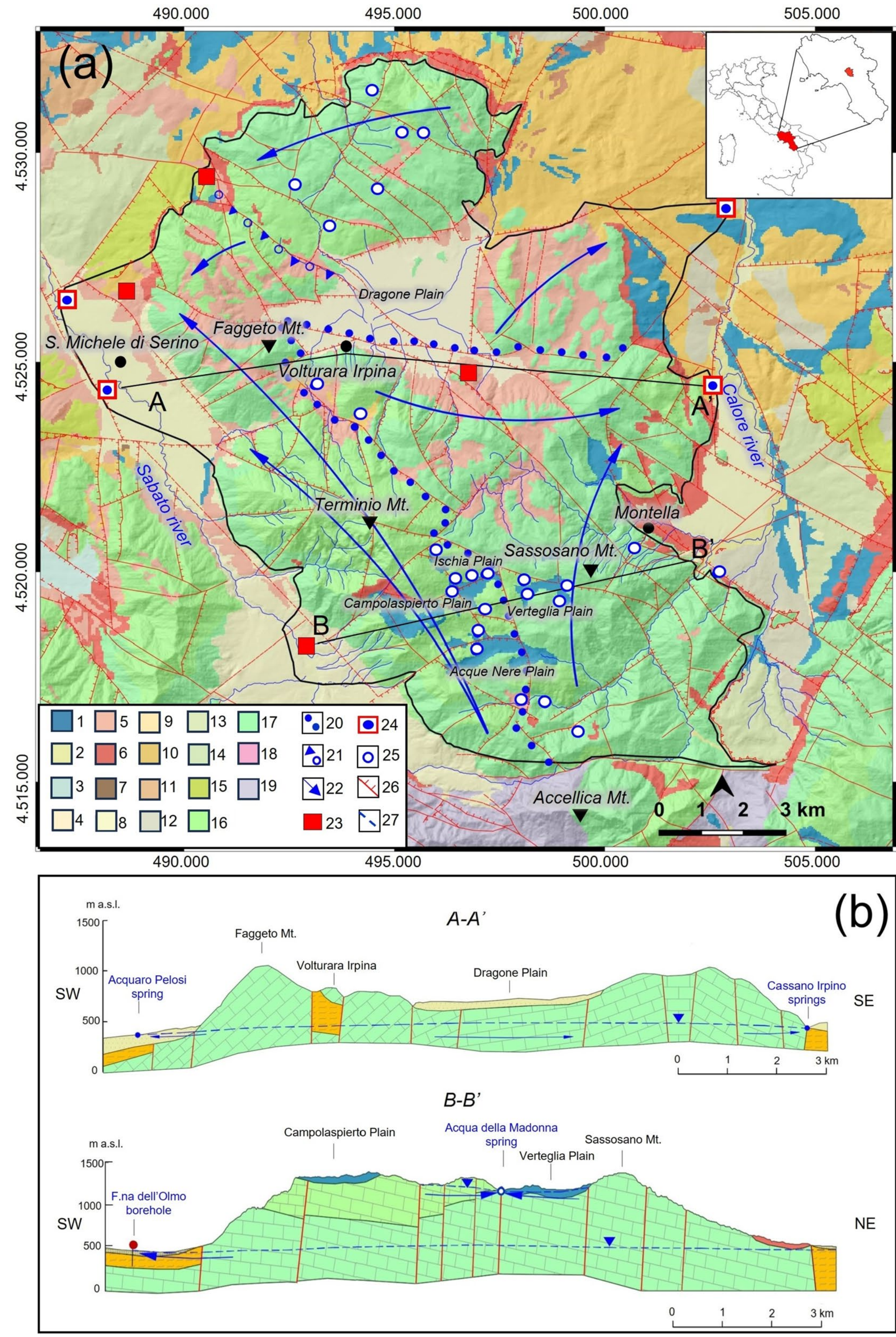

Fig. 2 (See legend on previous page.)

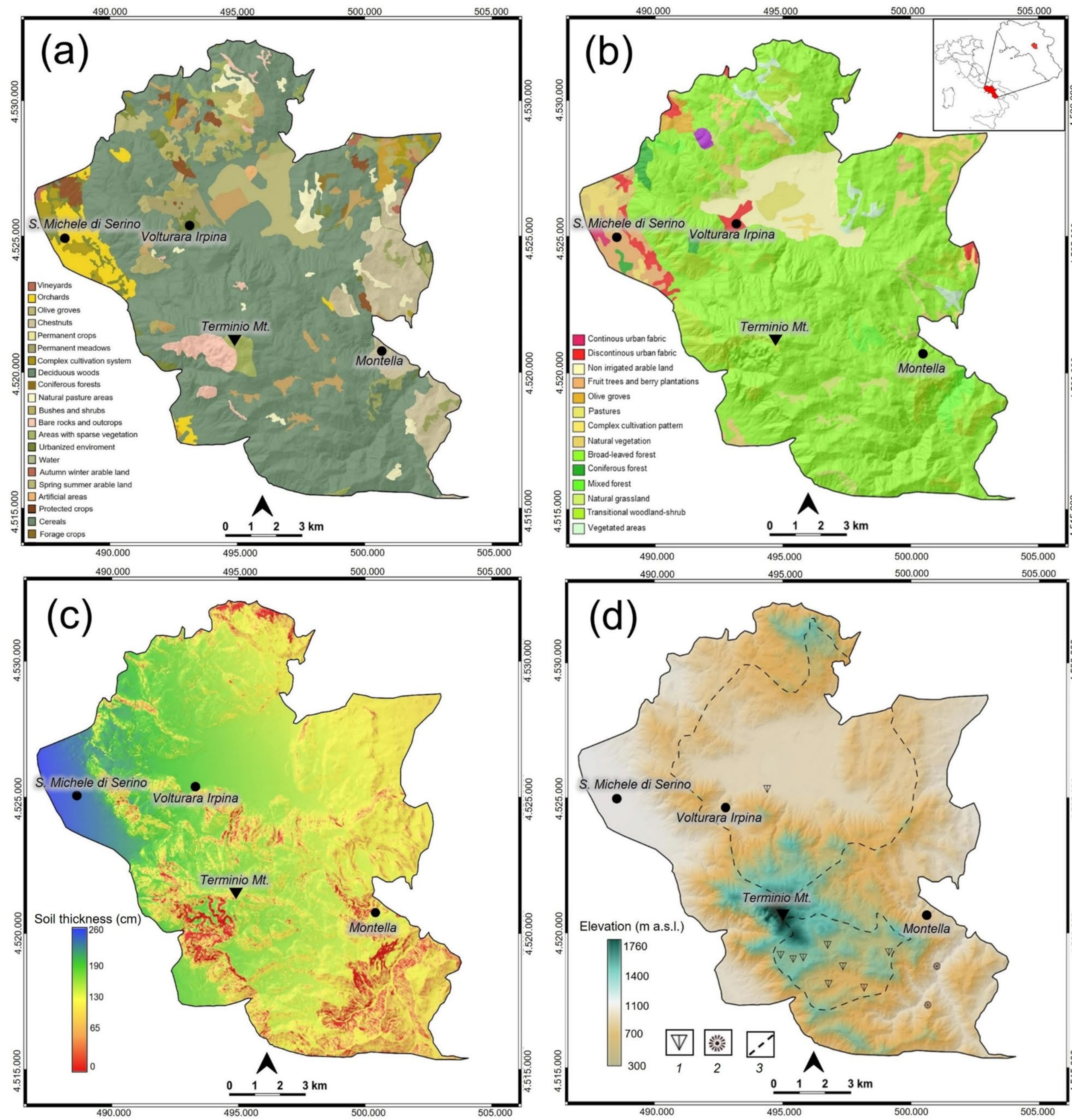

Fig. 3 **a** Corine Land Cover map (2018); **b** CUAS (Agricultural use map, 2009); **c** Soil thickness map; **d** Digital Elevation Model (%) with main karst features (1: Swallow hole; 2: Caves; 3: Endorheic basins). Coordinate system: UTM WGS 84 33 N zone. 1:50.000 scale

3 Overview of groundwater vulnerability assessment methods

Initially, there was no formal definition of groundwater vulnerability being it conceived as the relative susceptibility of aquifer systems to anthropogenic pollution. The concept of groundwater vulnerability was originally developed in France during 1960–70 to favor the awareness about groundwater contamination among land planners and public opinion [33]. During the 1980s, the concept of groundwater vulnerability gained momentum in the field of hydrogeology. Subsequently, the development of methods allowed the distinction between intrinsic and specific groundwater vulnerability [34]. The first is defined as the vulnerability of groundwater to contaminants generated by anthropogenic activities, taking into account the physical properties of aquifer system, i.e., geological, hydrological and hydrogeological characteristics, but not considering the nature and physical properties of contaminants. Instead, the *specific vulnerability* indicates the groundwater vulnerability depending on a specific pollutant (or a group of pollutants), depending on the pollutant properties (i.e. physical and biogeochemical attenuation processes) and taking into account the time of impact, its intensity and the interaction between the intrinsic vulnerability components and the contaminant itself [18].

Different approaches have been proposed in literature for estimating groundwater vulnerability. They can be grouped into three principal categories, depending on quality and quantity of data. The first group comprises the Hydrogeological Complex and Settings methods which is based on the assessment of groundwater vulnerability by the qualitative analysis of the hydrogeological media [35]. The second group is represented by the Parametric Systems, which 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 restricted number of hydrogeological parameters. To obtain a quantitative assessment of groundwater vulnerability, these parameters are mutually combined in different ways, being reliant on approaches developed by different research groups for local case studies such as the method selected for the Flemish Region of Belgium [36]. The RS methods provide a fixed range of index values for any parameter considered to assess groundwater vulnerability. The sum of the values results as the overall evaluation for a given area. The final numerical score is classified into intervals expressing a relative vulnerability degree. Examples are GOD system [20] and AVI method [21].

The PCSMs or Parameter Weighting and Rating Methods are also a rating parameters system. In this case, an additional multiplier value, identified as a weight, is assigned to each parameter to consider the specific impact on the assessment of groundwater vulnerability. Specifically, the scores attributed to each parameter are multiplied by the weight factor and the results of all products are summed to obtain the final score which provides a relative measure of groundwater vulnerability degree of an area. The first and representative method belonging to this group is the DRASTIC method [19], which has been largely applied worldwide and subsequently developed and improved in other methods such as the SINTACS [22]. To the same group, the DAC [28] and EPIK [24] methods also belong.

Finally, a third group of methods includes quantitative approaches based on numerical modeling which simulate the transport of pollutants in the vadose and saturated zones by considering physical, chemical and biological processes which control the dispersion, diffusion and attenuation of concentration [37].

4 Methods and data sources

In this paper, four parametric groundwater vulnerability methods (DRASTIC, SINTACS, DAC and COP) were applied and compared in the Terminio Mt. karst aquifer by analyzing geological, hydrogeological, geomorphological, piezometric, land use data and karst features. The first three methods provide an index which is directly proportional to the groundwater vulnerability. The COP methods instead, was specifically designed for carbonate aquifers and provides a protection index against aquifer contamination, whose values are inversely proportional to groundwater vulnerability. The study area was discretized using a grid with 20 m spatial resolution due to the amount of available data. All data were structured in a GIS environment as raster layers with the same resolution. Following, a brief outline of the parameters considered for each method applied, data sources and estimation approaches is described.

4.1 The DRASTIC method

The DRASTIC method proposed by the US Environmental Protection Agency [19] is a model that considers the main hydrogeological and geological factors exerting a potential impact on the aquifer pollution. Due to its versatile structure, the DRASTIC method is the most used worldwide in different geological and hydrogeological conditions and, at the same time, it has been subjected to several modifications and adaptations to specific conditions giving rise to a series of DRASTIC-like methods. It is based on the seven parameters described below:

4.1.1 Depth to water (D)

This parameter refers to the depth to the water table in an aquifer. It is important primarily because it determines the length of the percolation path through which a contaminant must travel before reaching groundwater. In general, there is a greater chance for attenuation of pollutants concentration as the depth to water table increases because deeper water levels infer longer travel times and more enhanced attenuation processes [19].

For the Terminio Mt. karst aquifer, the assessment of piezometric levels was carried out considering the altitude of the main basal springs and piezometric levels measured in some wells located mainly at the border of the aquifer. Subsequently the depth to water was reconstructed for the study aquifer calculating the difference between piezometric level and the Digital Elevation Model (DEM). Finally, for the Sabato river plain, characterized by alluvial deposits with shallow water table depth (less than 3 m), the depth parameter was assumed as constant and equal in average to 3 m, as observed for such hydrostratigraphic unit [38]. As a result of such estimations, this parameter resulted varying in the range between 3 and 1318 m. According to the DRASTIC method, the depth to water table map was classified into ranges to which scores ranging from 1 (minimum impact on vulnerability, corresponding to the areas characterized by deep water table depth) to 10 (maximum impact on vulnerability, corresponding to the areas characterized by shallow water table depth) were assigned. In detail, low scores were assigned to the main body of the study aquifer, higher scores were assigned to the river plains.

4.1.2 Net recharge (R)

It indicates the amount of infiltration per unit area which reaches the water table replenishing groundwater. For instance, groundwater recharge represents the principal vehicle for leaching and transporting solid and liquid contaminants to the water table. Therefore, the greater the recharge, the greater the potential for pollution [19]. To estimate mean annual groundwater recharge for the study area, firstly a distributed model of the mean annual effective precipitation (P-ETR) was reconstructed [29]. Subsequently, the Net recharge was estimated considering also the mean annual groundwater recharge coefficient [29, 38]. As a result, a mean value of 1200 $mm \cdot yr^{-1}$ a maximum value of 2036.8 $year^{-1}$ were obtained for the study area. Considered the high values of Net recharge obtained, a maximum score (9) was attributed to the entire map.

4.1.3 Aquifer media (A)

It refers to the consolidated or unconsolidated medium forming the aquifer. The aquifer medium exerts the major control over the ingestion of pollutants and their dispersion and diffusion throughout the saturated zone. Therefore, this parameter is important in determining also the time available for attenuation processes and the effective surface area of materials contacted by contaminated water in the aquifer [19]. Data of this parameter were obtained by the hydrogeological map and hydrostratigraphic sections of the study area (Fig. 2a and b) and considering the saturated zone of aquifers. Maximum score (10) was assigned to the main saturated aquifer consisting of limestone and dolomite limestone, characterized by high permeability grade and low attenuation capacity of propagation of pollutants.

4.1.4 Soil media (S)

It refers to the uppermost portion of the vadose zone characterized by significant biological activity. Soil has a significant impact on the amount of recharge which can infiltrate into the sub-surface and hence on the possibility of a contaminant to move vertically into the vadose zone [19]. It was estimated by the regional map of soil features, 1:250.000 scale, available for the Campania region [39] and subsequently cropped for the karst study area. Sandy loam is the prevailing soil type identified in the study karst aquifer, therefore a score equal to 6 was assigned to the soil media map, according to the DRASTIC method.

4.1.5 Topography (T)

This parameter expresses the slope angle of the land surface. Topography helps controlling the likelihood that a pollutant will run off or remain on the surface in an area favoring the infiltration. Therefore, the topograph parameter controls the soil development and exerts a control on the infiltration process favoring it in flat conditions and hampering it in opposite ones. It was estimated by the DEM (20×20 m). The highest value found is 49.1°. The slope angle map was calculated and scores were assigned according to the DRASTIC methods with values decreasing as the slope angle increases.

4.1.6 Impact of the vadose zone (I)

It corresponds to the characteristics of the unsaturated zone above the water table. The type of vadose zone controls the most important part of attenuation processes which depends on the lithology and permeability [19]. Therefore, it has been estimated by the hydrogeological map and hydrostratigraphic sections reconstructed for the study area with considering lithology of the unsaturated zone of aquifers. A maximum score (10) was assigned to the vadose zone of the aquifer consisting of limestone and dolomite limestone. A score ranging from 4 to 7 was attributed to the unsaturated media in the Sabato and Calore river plains and endorheic basins, consisting of coarse-grained gravel and sand and pyroclastic deposits.

4.1.7 Hydraulic conductivity of the aquifer (C)

It refers to the capability of the aquifer medium to transmit groundwater flow under a given hydraulic gradient. This parameter controls also the rate at which the contaminants move through the saturated zone of the aquifer medium [19]. This parameter has been estimated as the mean of values chosen from ranges known in literature [40, 22]. A score equal to 10 was assigned to the aquifer media, formed by limestone and dolomite limestone, which favor potentially the propagation of contaminants due to their high permeability grade.

The DRASTIC vulnerability index, ranging from less than 79 to 200 and above [19] is defined as a weighted sum of the scores assigned to the parameters according to Eq. (1):

Table 1 DRASTIC weight factors [19]

Parameter	DRASTIC weight	Pesticide DRASTIC weight
D	5	5
R	4	4
A	3	3
S	2	5
T	1	3
I	5	4
C	3	2

$$I_{DRASTIC} = DrD + RrR + ArA + SrS + TrT + IrI + CrC \tag{1}$$

Where Dr, Rr, Ar, Sr, Tr, Ir, Cr are the scores and *D, R, A, S, T, I* and *C* represent the corresponding weights. The DRASTIC method provides two series of weights (Table 1), one for normal conditions and the other for intense agricultural activity conditions. The method indicates eight classes of the $I_{DRASTIC}$ associating a color scale to them, even not providing their formal denomination. In order to make comparable the classes with those of other methods, we defined these classes as varying from invulnerable to extremely high.

4.2 The SINTACS method

The acronym SINTACS [22] derives from the Italian names of hydrogeological factors considered for the assessment of groundwater vulnerability: Depth to water table (S), Net recharge or Infiltration (I), Impact of the vadose zone (N), Soil media (T), Hydrogeological characteristics of the Aquifer (A), Aquifer's hydraulic conductivity (C) and Slope angle (S). The significance of parameters and data and elaborations considered for their estimation are described in the previous paragraph. A score between 1 and 10 was assigned to the above seven parameters considering the relevance of each of them in the overall assessment. In detail, for the Depth to water table (S) parameter, low scores, variable from 1 to 4, were assigned to the areas characterized by deep water table depth, corresponding to the permeable limestone and dolomite limestone lithologies. In the Sabato river plain, characterized by shallow water table depth, higher scores were attributed, ranging from 5 to 10. Scores ranging from 4.5 to 9 were attributed to the Infiltration map (I), considering the values and the spatial distribution of the Net recharge within the aquifer. According to the table proposed by the SINTACS method in relation to the Impact of the vadose zone (N) parameter, scores variable from 4 to 9 were attributed to lithologies constituting the vadose zone of the study aquifer. In detail, high scores (8 and 9) were attributed to permeable limestone and dolomite limestone lithologies, respectively. Low scores (ranging from 4 to 7) were assigned to the lithologies located in the Sabato and Calore river plains and endorheic basins. Sandy loam is the prevalent soil type identified in the study karst aquifer, therefore a score equal to 5 was assigned to the Soil media (T) map, according to the SINTACS method. Maximum scores (9 and 10) were assigned to the main saturated aquifer media (A) consisting of limestone and dolomite limestone, characterized by high permeability grade due to fracturing and karst. The hydraulic Conductivity (C) map was classified as mean representative values chosen from ranges known in literature [40, 22]. Based on these determinations, a score equal to 7 was assigned to high permeable limestone and dolomite limestone. Finally, according to the SINTACS method, the Slope angle (S) map was ranked in altitude ranges and assigned scores varying from 1 to 10.

The SINTACS groundwater vulnerability index is calculated according to Eq. (2):

$$I_{SINTACS} = \Sigma\ P_J\ (1,7)\ \times\ W_J\ (1,7) \tag{2}$$

Where Pj are the seven parameter and Wj the five lines of multiplying weights. The latter represent all five scenarios (natural, relevant impact, drainage, karst and fissured rocks) considered as raster maps. Weights for the normal and relevant impact scenarios were obtained by the regional map of agricultural land use [41]. Weights for drainage scenario were obtained by the areas with water table depth less than 3 m. Weights for karst (limestone aquifers) and fissured rocks (dolomite and volcanic rock aquifers) were assigned based on the hydrogeological map of southern Italy [38].

The lowest possible index score is 26 and the highest 260. Table 2 contains the values of weights provided in

Table 2 Multiplying weights considered by SINTACS for the five hydrogeological scenarios [22]

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

Civita and De Maio [22]. Finally, the SINTACS method provides six distinct vulnerability classes, from very low to extremely high.

4.3 The DAC method

The DAC (DRASTIC for Aquifers in Complex hydrogeological settings) methodology [28] was developed to assess groundwater vulnerability in fractured and karstified carbonate aquifers of southern Apennine. DAC comprises two different approaches:

a) a "classic" DRASTIC approach [19] that allows the assessment of pollution potential from diffuse infiltration of precipitation through the soil and fractured limestones;
b) the "new" DRASTIC-based approach that allows the assessment of the vulnerability from concentrated infiltration of surface water into swallow holes or topographically low areas [42].

The new approach considers runoff infiltrating both into swallow holes, with no interaction with unsaturated rocks, and through fractured unsaturated media with an interaction with rocks significant for the attenuation processes [42].

DAC can be considered as a DRASTIC-like method because it is based on the reinterpretation of the same parameters used by DRASTIC and aimed to not modify them, and the related weights, except for changing the range of values assigned. Specifically, for the karst aquifers of southern Apennine, considering their hydrogeological characteristics and peculiarities (i.e. the rainfall patterns, the high infiltration rates and the occurrence of soil coverings, which favor the percolation processes and then a widespread contamination), the range Net Recharge, Aquifer media, Hydraulic conductivity of the aquifer, Impact of vadose zone, and Topography, values assigned to parameters were limited to the highest values (7–10) only. Regarding the multiplying weights, the Table 1 was considered.

Similarly to DRASTIC and SINTACS, the DAC groundwater vulnerability index ranges between less than 65 to 219 and above, and it is estimated by the following Eq. (3):

$$I_{\mathrm{DAC}} = \Sigma\, P_J\,(1,7) \times W_J\,(1,7) \tag{3}$$

Finally, the DAC method provides seven distinct vulnerability classes, from extremely low to extremely high.

4.4 The COP method

The assessment of groundwater vulnerability of karst areas was tackled by the project COST Action 620 [25], whose principal outcome was the COP method. This method considers karst characteristics, such as the occurrence of swallow holes and their catchment areas as well as karst landforms, as factors which decrease the natural protection provided by overlying layers [26]. The COP acronym derives from the three initials of the factors used: flow Concentration, Overlying layers and Precipitation. As the method was conceived for groundwater resource protection, the karst network development inside the aquifer was not considered. The conceptual basis of this method relies on the natural protection of groundwater (O factor) determined by the properties of overlying soils and the unsaturated zone, and also to estimate how this protection can be modified by the infiltration process – diffuse or concentrated – (C factor) and the climate conditions (P factor – precipitation) [26]. The O factor considers the protection provided to the aquifer by the physical properties and thickness of the overlying layers above the saturated zone, therefore playing a critical role in the groundwater vulnerability. The C and P factors are used as modifiers that correct the degree of protection provided by the overlaying layers (O factor) [26]. The parameters used in the proposed COP method are described as follow:

4.4.1 Flow concentration (C factor)

It represents the potential for water to bypass the protection provided by layers overlying the saturated zone. Regarding this point, two scenarios may be differentiated:

> Scenario 1: It describes the situation within a catchment covered by a low permeability layer, where surface runoff infiltrates either into a swallow hole or in a specific area as the foot of a slope.
> Scenario 2: It describes the situation in areas where autogenic recharge occurs but not as concentrated infiltration via a swallow hole or at the foot of a slope [26].

Karst geomorphology, slopes and vegetation cover were considered in the estimation of the C factor. Areas with concentrated infiltration via swallow holes, where the overlying layer might be passed by infiltration water, were discriminated from the rest of the area. The areas of groundwater recharge through swallow hole (Scenario 1), recognized in the Dragone plain endorheic basin, in the northern part, and in a second endorheic basin in the southern sector, were identified by using the regional topographic map (CTR; 1:5.000 scale) and DEM with a resolution of 20 × 20 m. For the rest of the area (Scenario 2), the surface, slope and vegetation features were derived by the hydrogeological map (Fig. 2).

4.4.2 Overlying layers (O factor)

It refers to the protection of the aquifer from a contaminant event due to the attenuation effect of the unsaturated zone. It indicates the capability of unsaturated zone to attenuate and reduce the effects of contamination by dispersion and bio-geochemical degradation processes. Only two layers with important hydrogeological roles are used to evaluate the O factor: Soils [O_S] and the lithological layers of the unsaturated zone [O_L]. The first one deals with the biologically active part of the sub-surface, where attenuation processes occur and consequently, when present, should be considered in groundwater vulnerability mapping [26].

The lithology subfactor [O_L] reflects the attenuation capacity of each layer within the unsaturated zone and depending on the type of rocks, the degree of fracturing, the thickness of each layers considered and any confining conditions.

To obtain this parameter the entire study area was classified on the basis on the texture and thickness of the lithological layers of the unsaturated zone. The O factor was estimated by regional map of soil features, 1:250.000 scale, available for the Campania region [39] and subsequently cropped for the study area. Moreover, the soil texture map has been classified into three thickness ranges as reported by the COP method for the O factor. In addition, the thickness of each unsaturated layers and their properties such as lithology, fracturing degree and confining conditions were estimated by the regional hydrogeological map [38]. The O map was obtained by the sum of O_S and O_L and classifying the O score in different protection values.

4.4.3 Precipitation (P factor)

Considers the spatial and temporal variability of precipitation, which plays a role in the transfer of contaminants. To estimate the quantity of precipitation (P_Q), a distributed model of the P-ETR has been considered [29].

Furthermore, the temporal distribution of precipitation (P_I) ($mm \cdot d^{-1}$), which represents the intensity of precipitation, was estimated for the Terminio Mt. karst aquifer. The values obtained range between 12.01 and 14.8 $mm \cdot d^{-1}$. The application of the COP method to the Mt. Terminio karst aquifer is summarized in Table 3, which shows the parameters and factors observed and the scores assigned to each one.

The factors of the COP method have been combined to evaluate the protection of the groundwater resource, as proposed in the following formula:

$$COP_{Index} = C \times O \times P \tag{4}$$

The spatial distribution of the COP index was reconstructed by multiplying the scores of the three factors, namely C, O and P maps, because each of them is considered controlling the groundwater protection, and complementarily the groundwater vulnerability, of karst aquifers. The values for the COP $_{Index}$ range between 0 and 15 [26]. Finally, the COP method provides five distinct vulnerability classes, from very high to very low.

4.5 Comparison of groundwater vulnerability maps

In order to critically compare the vulnerability maps obtained, the normalized groundwater vulnerability indexes (NGVI) were calculated for each method. A linear normalization has been applied to the raw vulnerability values by attributing NGVI = 0% to the minimum groundwater vulnerability score and NGVI = 100% to the highest one, by using the following formula:

$$NGVI = \frac{I_v - I_{vmin}}{I_{vmax} - I_{vmin}} 100 \tag{5}$$

Where I_{vmin} and I_{vmax} are the minimum and maximum raw vulnerability indexes.

The resulting NGVI of each method were divided in five classes (very low, low, moderate, high and very high with values ranging from 0 to 20, 20–40, 40–60, 60–80 and 80–100%, respectively). For the COP method, the resulting normalized values were inverted to obtain a NGVI comparable with the other three methods, because the COP vulnerability index assesses the groundwater protection. The normalization procedure was applied because the four methods do not consider the same range for groundwater vulnerability indexes and a different number of vulnerability classes.

The Pearson correlation was used in order to assess how the values of groundwater vulnerability indexes obtained by each method are mutually correlated. The Pearson correlation coefficient ($r_{x,y}$) between two instances x and y that contain m attributes is defined as:

$$r_{x,y} = \frac{\sum_{i=1}^{m}(x_i - x)(y_i - y)}{\sqrt{\sum_{i=1}^{m}(x_i - x)^2}\sqrt{\sum_{i=1}^{m}(y_i - y)^2}} \tag{6}$$

Where x and y are defined as:

$x = \frac{1}{m}\sum_{i=1}^{m} x_i$

$y = \frac{1}{m}\sum_{i=1}^{m} y_i$

In this study the correlation between pairs of groundwater vulnerability indexes were expressed as correlation matrix in which each cell is the Pearson correlation coefficient of the different pairs [43].

5 Results

The four groundwater vulnerability maps obtained were compared and examined. Each map was statistically analyzed to assess the impact of the different parameters considered by single methods on the spatial variability of

Table 3 Scores for COP factors and variables in Mt. Terminio aquifer test site

Factor	Subfactor		Variable	Scores
C	Scenario 1 (shallow hole recharge area)	Distance to swallow hole	Between < 500 and 2000 m	0–0.3
		Distance to sinking streams	< 10 m	0
			10–100 m	0.5
			➢ 100 m	1
		Slope and vegetation	< 8%	1
			8–31% with vegetation cover	0.95
			31–76% with vegetation cover	0.85
			> 76%	0.75
	Scenario 2 (rest of the area)	Surface features	Fissured carbonate	0.75
			Non karstic terrains	1
		Slope and vegetation	< 8%	0.75
			8–31% with vegetation cover	0.8
			31–76% with vegetation cover	0.9
			➢ 76%	1
O	Soil (Os)	Texture and Thickness	Sandy loam and < 0.5 m	0
			Sandy loam and 0.5–1 m	1
			Sandy loam and > 1 m	2
	Lithology (O_L)	Layer Index (resulted from the multiplication of thickness and lithology of each layer)	0–250	1
			250–1000	2
			1000–2500	3
			2500–10,000	4
			> 10,000	5
P	Quantity (P_Q)	Average rainfall	> 1600 mm·yr^{-1}	0.4
			1200–1600 mm·yr^{-1}	0.3
			800–1200 mm·yr^{-1}	0.2
			400–800 mm·yr^{-1}	0.3
			< 400 mm·yr^{-1}	0.4
	Intensity (P_I)	Temporal distribution	10–20 mm·d^{-1}	0.4

the vulnerability indexes. Afterwards, the vulnerability classes were regrouped into five major categories in order to critically compare the four maps.

5.1 Groundwater vulnerability assessment

Four groundwater vulnerability maps (Fig. 4) were reconstructed, one for each of the methods applied. By the application of the DRASTIC method, 6 vulnerability classes were recognized, considering specific scores and weights. High values of groundwater vulnerability occupy 83.9% of the study area, while the 6.5% of the area is characterized by moderate values. Very high and extremely high values of groundwater vulnerability (6.2 and 1.7% of the entire area, respectively) were found in the Sabato river plain and in the Dragone Plain. Low and very low values of groundwater vulnerability occupy 1.6 and 0.1% of the territory (Figs. 4a and 5).

The SINTACS groundwater vulnerability map (Fig. 4b) allowed to evaluate that the Terminio Mt. karst aquifer is chiefly characterized by two classes of intrinsic vulnerability varying between the moderate and high grade (79.7 and 18.2% of entire area, respectively). Furthermore, high and extremely high values of groundwater vulnerability (1.6 and 0.3% of the entire area, respectively) were found in the Sabato river plain and in the surrounding of the Serino springs, both determined by the shallow depth of the water table. These areas are mainly characterized by alluvial deposits with high degree of primary permeability that resulted in the high scores assigned to the parameters *I, N, A, C*. Low values of vulnerability occupy 0.2% of the study area (Fig. 5).

The DAC groundwater vulnerability map (Fig. 4c) shows that the 83.8% of the study area is characterized by high values. Very high values of groundwater vulnerability (9.8%) were found in the Sabato river and in the Dragone plains. Moderate and low values of groundwater vulnerability occupy respectively 6.2 and 0.2% of the entire area (Fig. 5).

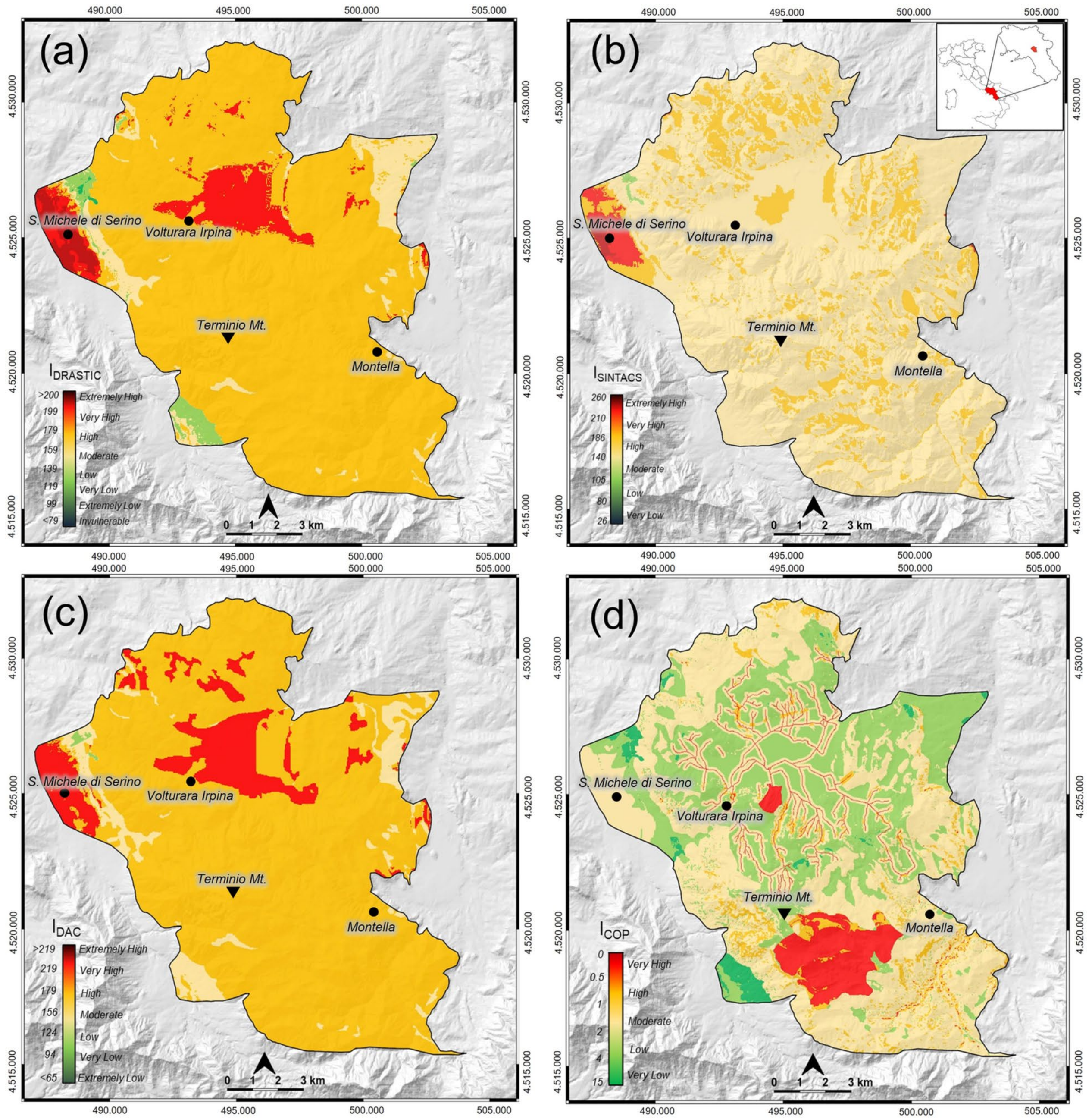

Fig. 4 Vulnerability maps obtained: **a** DRASTIC; **b** SINTACS; **c** DAC and **d** COP methods. 1:50.000 scale. UTM, WGS84 33 N zone

The COP Index map (Fig. 4d) shows that about 54.1% of the entire area was assessed as characterized with a moderate groundwater vulnerability; low values cover 30.7% of the study zone, while high and very high ones were assigned to the remaining 5.7 and 7.6% while 1.9% of the area is characterized by very low vulnerability grade (Fig. 5). In the areas with diffuse infiltration, which refer to the Scenario 2, groundwater vulnerability essentially depends on the "overlying layers" factor (O): raster cells with moderate groundwater vulnerability correspond to the areas of carbonate rock outcrops, while the karstic plains were classified as very highly vulnerable. As regards the areas of concentrated infiltration relevant to Scenario 1 (swallow holes recharge area), it is evident the influence of the C factor in determining a significant reduction of the protection

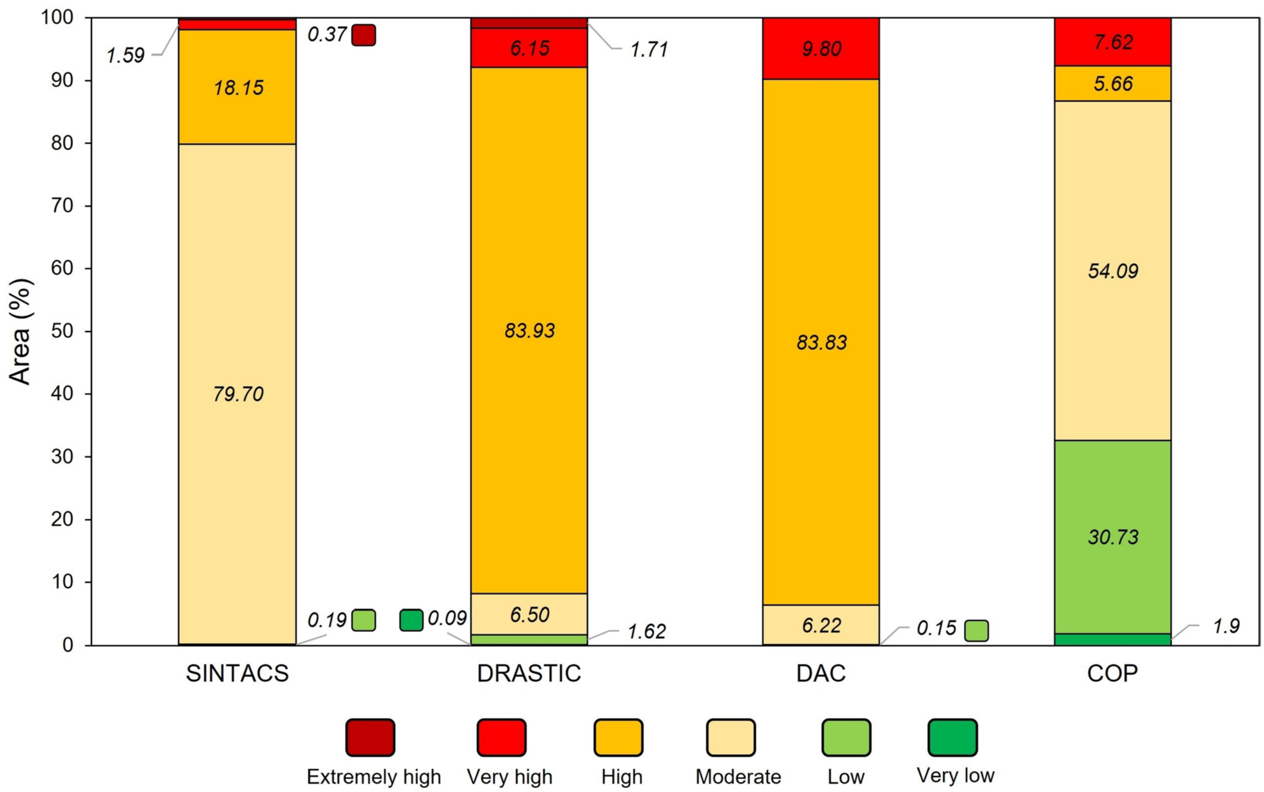

Fig. 5 Comparison between the areas representing the groundwater vulnerability classes obtained with the four methods (areas are expressed as percentage related to the entire study areas; 100% represents 167.1 km^2)

afforded by the O factor, which is reflected in the high scores calculated for the final COP vulnerability index. In this domain, oppositely to the previous Scenario, the areas ranging from moderate to very high vulnerability are largely predominant on the areas with low or very low vulnerability.

Within the aquifer, the O factor determines protection values ranging from 1 (very low protection) to 4 (moderate protection). The high degree of karstification and the occurrence of soil coverings, favour rapid infiltration from surface to the saturated zone. High protection values were found in the plains characterized by alluvial units, where the thickness of the soil is greater than 1 m. Lowest values of the C factor correspond to the calcareous outcrop where the prevailing slope promote runoff processes. The endorheic basins within the aquifer are characterized by high and very high groundwater vulnerability values, due to the occurrence of swallow holes and the slope/vegetation that favours infiltration.

The higher values of the *P* parameter, which were found in the Dragone Plain, indicate a lower impact on the level of protection afforded by the O factor and consequently a lower grade of groundwater vulnerability resulting in the COP Index map. However, lower values of the P parameter, which were found in the endorheic basin of the southern sector of the study area, indicate that precipitation decreases the aquifer protection given by the O factor and increase groundwater vulnerability. This is in accordance with Vias et al. [26].

The range of values and statistical parameters of raw vulnerability indexes were calculated (Table 4).

5.2 Comparison of groundwater vulnerability maps

The four methods used for assessing groundwater vulnerability resulted in maps showing some similarities as well as relevant differences. A regrouping of the raw vulnerability classes into new normalized categories was

Table 4 Statistical parameters of raw vulnerability index (I_v)

Statistical parameters of I_v	DRASTIC	SINTACS	DAC	COP
Minimum	108	89	103	0.4
Average	165	139	165	1.7
Maximum	219	222	208	4.9
Standard deviation	10.4	13.8	9.2	0.7

Table 5 Statistical parameters of normalized groundwater vulnerability index (NGVI)

Statistical parameters of NGVI (%)	DRASTIC	SINTACS	DAC	COP
Minimum	9.1	26.9	24.9	0
Average	52.1	48.4	64.9	37.3
Maximum	100	83.8	93.4	100
Standard deviation	9.5	5.9	5.9	17.8

performed in order to obtain a different interpretation. NGVI was calculated from the raw values of groundwater vulnerability index obtained from each of the methods applied. The range of values and statistical parameters of normalized groundwater vulnerability indexes were calculated (Table 5).

The NGVI values were divided into five main categories and for each of them the percentage of area was calculated and reported in Fig. 6 in the form of cumulative frequency. The $NGVI_{DRASTIC}$ and $NGVI_{COP}$ were recognized being distributed in the largest range of values (9.1–100%, and 0–100%) covering all five vulnerability classes, while $NGVI_{SINTACS}$ and $NGVI_{DAC}$ from the low, moderate, high and very high categories, showing a lower range of values (26.9–83.8, 24.9–93.4%, respectively) (Table 5). For the Terminio Mt. karst aquifer, these regrouped classes of vulnerability indicated two main trends in the assessment of groundwater vulnerability:

a) SINTACS and COP methods classify the study area as characterized by moderate, respectively 76.7 and 25.0%, and high, respectively 15.8 and 36.7%, groundwater vulnerability grade;
b) DRASTIC and DAC characterize the karst aquifer with high, respectively 84.7 and 85.4%, and very high, respectively 6.3 and 13.0%, groundwater vulnerability grade.

The relevant spatial variability of groundwater vulnerability among the four methodologies applied was assessed by calculating the Pearson correlation coefficient between pairs of groundwater vulnerability methods (Fig. 7). The analysis of correlation matrix revealed a general positive correlation for all methods compared.

The best correlation was found between DRASTIC and DAC (corr. = 0.60) with highest statistical significance, followed by SINTACS-DAC (corr. = 0.40) and SINTACS-DRASTIC (corr. = 0.37) correlations. In contrast, the correlation between COP and the other methods was found the poorest one (Fig. 7), due to different parameters involved in the vulnerability assessment.

6 Discussion

The protection of groundwater pollution represents a fundamental achievement aimed at the protection zoning and land-use planning. This topic is particularly relevant in the Campania region, which in the last two decades has

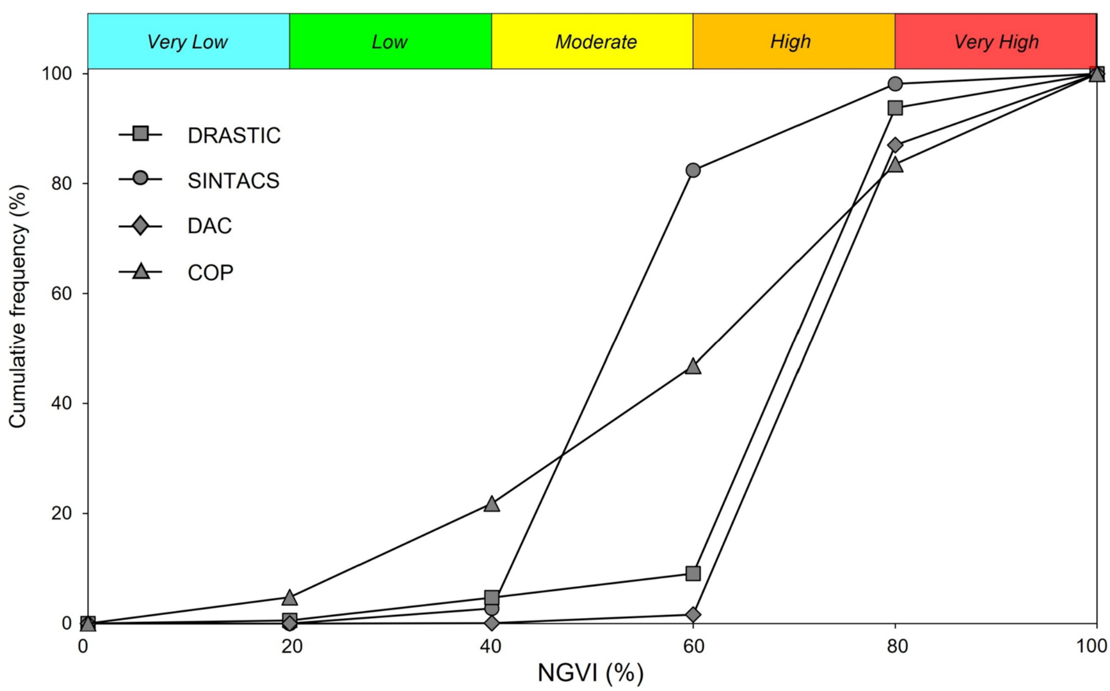

Fig. 6 Frequency distributions of normalized vulnerability classes of DRASTIC, SINTACS, DAC and COP

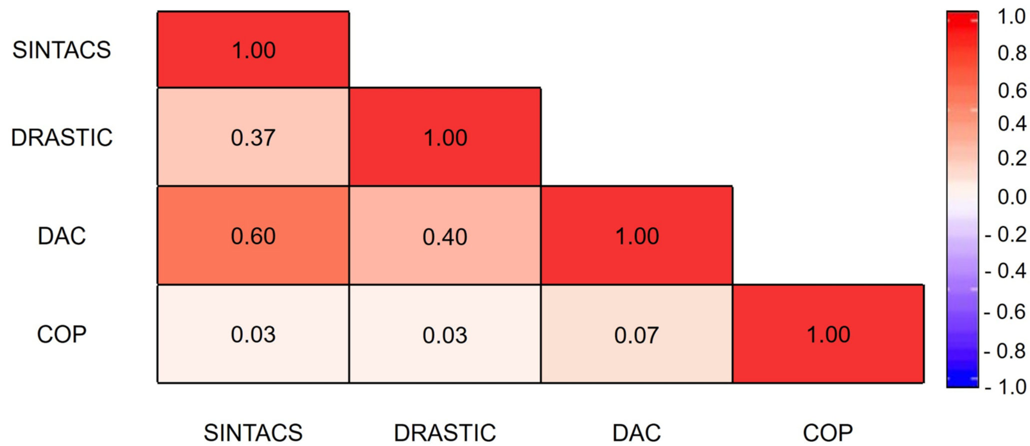

Fig. 7 Correlation matrix among the four vulnerability methods applied

been the focus of public debate regarding environmental issues and considered one of the most contaminated territories of Italy [44]. In such a view, the assessment of groundwater vulnerability has been considered mandatory for the Campania region due to the diffused supply of groundwater for drinking, agricultural and industrial scopes. In this study the assessment of groundwater vulnerability was performed for the Terminio Mt. karst aquifer, due to its high regional hydrogeological relevance and the highest mean annual groundwater yield of the region. The peculiar geological and hydrogeological settings of the study aquifer and in general of the karst systems of the Mediterranean areas, make it more vulnerable to contamination. Due to rapid infiltration processes and the flow concentration via swallow holes, contaminants can easily reach the groundwater and can be transported in karst conduits over large areas. Moreover, the industrial, agricultural and grazing activities in the in area represent potential source of contamination that may impact on groundwater quality [13]. For these reasons, the Terminio Mt. karst aquifer needs special attention.

To such a scope, four groundwater vulnerability methods (DRASTIC, SINTACS, DAC and COP) were used and compared.

The methods applied for the assessment of groundwater vulnerability consider similar factors which control the infiltration process and contaminants transport from the ground to the groundwater zone, even if their application to the study area produced different results. The mutual comparison of results obtained by different methods was intended giving hints concerning the performances in assessing groundwater vulnerability of karst aquifers.

The prevalent vulnerability grade results in the moderate class for SINTACS and COP methods and high one for DRASTIC and DAC. The DRASTIC method and its Italian modification SINTACS, which can be defined "any-aquifer "methods [45], evaluate the groundwater vulnerability of the study aquifer, indexing the seven parameters which have a potential impact on transport and diffusion of contaminants. Otherwise, DAC and COP methods were designed to evaluate the intrinsic vulnerability of the groundwater resources in carbonate aquifers and can be successfully used to consider diffuse and conduit flow system, under different climatic conditions, particularly in Mediterranean areas. The application of the four vulnerability methods in the karst hydrogeological system of the Terminio Mt. showed similarities and differences. For all the four methods applied, the karst Cretaceous limestone series were correctly classified ranging in the moderate/high groundwater vulnerability grade, due to their peculiar characteristics i.e. the high depth of water table, which implies high unsaturated thickness and then a long travel time for the pollutants. Nevertheless, the karst network characterizing carbonate karst aquifers, favors rapid infiltration from the ground to the saturated zone. The karstic summit plateau within the aquifer, as well as the Sabato and Calore river plains, were classified with a high and extremely high grade of groundwater vulnerability due to the occurrence of swallow holes that result in rapid travel times because bypassing rapidly the unsaturated zone. The shallow depth of water table and the occurrence of the complex surficial hydrogeological system "*soil covering-carbonate bedrock*" which favors the infiltration processes play also an important role in controlling groundwater vulnerability.

In this research, the assessment of groundwater vulnerability by DRASTIC and SINTACS provided different results. Both methods use the same parameters notwithstanding the different strings of weights applied by SINTACS, to describe the various environmental conditions. In fact, one of the advantages of SINTACS is the possibility of simultaneous use in different zones since each situation has assigned a specific weight [22]. This seems to give more relevance to the land-use parameter and provides a different and probably more reliable groundwater vulnerability assessment, from that obtained by applying the DRASTIC method. The different evaluation of the Depth to water table (S) and Net Recharge (I) parameters employed by SINTACS, make this method more complex than the DRASTIC one. Specifically, SINTACS considers a wider range of values for S and I parameters (0–100 m and 0–550 mm·yr^{-1} respectively; [22]) compared to the interval of DRASTIC approach (0–30 m and 0–25 cm respectively; [19]). Consequently, higher scores, which mean higher impact on groundwater vulnerability, were assigned to these parameters by DRASTIC. The correlation coefficient found between SINTACS and DRASTIC (0.37) confirms the different assumptions for the evaluations of parameters described above (S and N). On the other hand, the high correlation coefficient (0.60) resulted between DRASTIC and DAC confirms the similar methodology used for estimating groundwater vulnerability, which take into consideration a more conservative approach.

Among the methods used, COP provided the greater differentiation in term of groundwater vulnerability classes. This resulted from using factors that consider not only lithology, but also the influence of karst features on infiltration (diffuse or concentrated) as well as the rainfall pattern, unlike SINTACS, DRASTIC and DAC. This outcome represents a significant progress in karst groundwater vulnerability assessment, but comparative application of groundwater vulnerability methods in karst areas resulted in contradictory results, thus in agreement with Andreo et al. [46]. Furthermore, the low correlation coefficients found between COP and the other methods confirm the relevant difference in comparison to the other DRASTIC-like approaches for the assessment of groundwater vulnerability. Since autogenic and allogenic recharges occur in karst areas, the previous methods fail in areas with allogenic recharge. For examples, the swallow holes recharge area (the Dragone Plain and the karstic plains located in the southern sector of the study area) and the sinking streams were classified in the high vulnerability classes by the COP method only. This result is consistent to the occurrence of concentrated infiltration through karst features, such as swallow holes, that are directly connected with the saturated zone. In these areas, the attenuation capacity of the protective layers is ineffective, considering the high permeability of pyroclastic cover, derived mainly from The Somma-Vesuvius volcano [29].

Differently, SINTACS, DRASTIC and DAC consider the areas characterized by concentration of flow, partly as high vulnerability and partly as moderate vulnerability. According to Gogu et al. [47] most methods consider only vertical permeability, ignoring possible contamination coming directly from streams and bypassing the soil and unsaturated zone. In this way inaccurate assessment can arise from such misinterpretations. Considering the hydrogeological features of the Terminio Mt. karst aquifer, all the four methods applied provide reliable results, in terms of groundwater vulnerability assessment, but the COP method, which has been designed to be applied specifically in karst aquifers, particularly in Mediterranean type conditions, seems to be the more appropriate. In addition, the map obtained by using the COP method matches better with the hydrogeological characteristics of the test aquifer.

7 Conclusions

Among the specific outcomes regarding the assessment of groundwater vulnerability of the Terminio Mt. karst aquifer, which show a general high groundwater vulnerability, results obtained can be conceived as a useful tool supporting decision systems aimed at the protection of groundwater resources by a proper land use planning.

They provide a practical tool for decision makers implementing groundwater protection schemes against risk to groundwater pollution. Different studies in scientific literature show that no method developed for assessing groundwater vulnerability is the most reliable, each of them depending on the aquifer characteristics, land use, data availability, parameters involved in the model, weightings, and scores assigned to each parameter. Despite their popularity, the conventional methods (DRASTIC-like methods) introduce subjectivity and uncertainties in the determination of scores and weightings. These methods can be successfully used to identify areas where special attentions or protection efforts are warranted. The COP method considers specific factors and variables to be required in order to incorporate the additional attenuation processes into karst groundwater vulnerability assessment. In addition, the guidelines, tables and formulae for vulnerability assessment provided by COP are more consistent with the current hydrogeological understanding of karst aquifers. However, the results obtained by the COP approach can be used complementary to any methods for assessing intrinsic vulnerability.

The combination of the different methods can be used as a more robust tool for establishing detailed monitoring programs and the results of this kind of analysis represent a more efficient interpretation of the vulnerability index. Future extensions of the research will be aimed at validating and checking the reliability of index-based methods employed in this study, comparing the results here obtained with experimental data provided by hydrogeological and hydrogeochemical monitoring and tracer tests.

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Authors' contributions
Conceptualization, Vincenzo Allocca, Pantaleone De Vita and Silvia Fabbrocino; data curation, Delia Cusano, Francesco Fusco, Silvio Coda, Daniele Lepore, Rita Tufano, Federico Nicodemo, Antonio Pizzolante; formal analysis, Pantaleone De Vita; funding acquisition, Vincenzo Allocca and Pantaleone De Vita; investigation, Delia Cusano, Francesco Fusco, Vincenzo Allocca, Silvio Coda and Pantaleone De Vita; methodology, Delia Cusano, Francesco Fusco, Silvio Coda, Daniele Lepore, Rita Tufano, Vincenzo Allocca and Pantaleone De Vita; resources, Vincenzo Allocca and Pantaleone De Vita; software, Delia Cusano; supervision, Vincenzo Allocca and Pantaleone De Vita; visualization, Delia Cusano, Francesco Fusco, Silvio Coda, Daniele Lepore, Rita Tufano; writing—original draft, Delia Cusano, Francesco Fusco, Silvio Coda, Daniele Lepore, Rita Tufano, Vincenzo Allocca and Pantaleone De Vita; writing—review & editing, Vincenzo Allocca Pantaleone De Vita and Silvia Fabbrocino. All authors read and approved the final manuscript.

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Declarations

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All authors accept all ethical approvals.
All authors consent to participate.

Consent for publication
All authors consent to publish.

Competing interests
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