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VULNERABILITY ASSESSMENT OF THE KARST AQUIFER FEEDING THE PERTUSO SPRING (CENTRAL ITALY): COMPARISON BETWEEN DIFFERENT APPLICATIONS OF COP METHOD

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ABSTRACT
Karst aquifers vulnerability assessment and mapping are important tools for improved sustainable management and protection of karst groundwater resources. In this paper, in order to estimate the vulnerability degree of the karst aquifer feeding the Pertuso Spring in Central Italy, COP method has been applied starting from two different discretization approaches: using a polygonal layer and the Finite Square Elements (FSE). Therefore, the hydrogeological catchment basin has been divided into 72 polygons, related to the outcropping lithology and the karst features. COP method has been applied to a single layer composed by all these polygons. The results of this study highlight vulnerability degrees ranging from low to very high. The maximum vulnerability degree is due to karst features responsible of high recharge and high hydraulic conductivity. Comparing the vulnerability maps obtained by both methodologies it is possible to say that the traditional discretization approach seems to overestimate the vulnerability of the karst aquifer feeding the Pertuso Spring. Between the two different approaches of COP method, the proposed polygonal discretization of the hydrogeological basin seems to be more suitable to small areas, such as the Pertuso Spring hydrogeological basin, than the traditional grid mapping.

KEYWORDS: vulnerability assessment, COP, karst aquifer, Pertuso Spring, karst features.

I. INTRODUCTION

Groundwater vulnerability describes the susceptibility of an aquifer to contaminants that can reduce its quality. Intrinsic vulnerability only depends on the natural properties of the aquifer (soil, lithology, hydraulic properties, recharge, etc.) and is independent of the nature of the contaminant [1,2]. Thus, vulnerability assessment methods may be considered important tools for designing protection zones for water supply and highlighting areas, where the aquifer is more susceptible to pollution introduced at the land surface [3].

Karst groundwater protection is a prior environmental target for water sustainable management in Europe, where more than 30% of the water supply is obtained from these resources [4]. Karst aquifers are characterized by a heterogeneous distribution of permeability due to conduits and voids, developed by the dissolution of carbonate rocks, frequently embedded in a less permeable fractured rock matrix [5,6]. Water flow velocities into a well-developed karst system are extremely fast and contaminants can quickly reach the saturated zone [7]. This system may receive localized inputs from sinking surface streams and as storm runoff through sinkholes, dolines and karst features in general. For this reason, in a karst setting, the identification of these fast recharge areas is an important tool in order to protect groundwater resources [8]. Recently, in order to identify karst landscapes, to describe karst features and to detect geological structures, relevant to karst development, remote sensing and geographic information system (GIS) methods were used for karst research. Because of the computer low cost and processing speed, these applications have come out to be useful tools for karst feature mapping, providing detailed geomorphological info [9,10,11]. At the same time, as Geographic Information System technology (GIS) has improved in the last years, lots of approaches to groundwater vulnerability to pollution evaluation have been developed and worldwide applied [12,13,14]. Traditional approaches have strong limitations in vulnerability assessment of karst aquifer because the contaminants transport mostly occurs along preferential pathways (karst features). Other methods are especially designed for karst environment, taking into account the function of the epikarst and of the karstic network [1]. In this study, a new karst aquifer vulnerability approach has been set up, highlighting the karst features, outcropping in the study area. Two different approaches for the intrinsic aquifer vulnerability assessment have been tested in the case study, comparing their results.

This paper presents the intrinsic vulnerability maps obtained applying the COP method [15] to the karst aquifer, feeding the Pertuso Spring, sited in the Upper Valley of the Aniene River (Central Italy). This method is useful to identify the most vulnerable zones and the main processes controlling the evolution of groundwater in karst settings. The implementation of COP method has been carried out, starting from two different discretization of the study area. The aim of this work is to compare both results of the intrinsic vulnerability mapping, in order to evaluate which is the most suitable for the study area.

II. GEOLOGICAL AND HYDROGEOLOGICAL SETTINGS

The Pertuso Spring is an important karst spring located in the south part of Latium Region, in the Upper Valley of the Aniene River. This spring feeds the Comunacqua hydroelectric power plant, owned by ENEL group [16] and, with a discharge reaching up to 3 m^3/s, is now one of the main water resource for the South part of Rome district [17]. The study area lies in the Upper Valley of the Aniene River, in the Latium Region (Central Italy) and covers an area of about 50 km^2 [18]. The Pertuso Spring hydrogeological basin is located between latitude 41° 51’ to 41° 56’N and longitude 13° 13’ to 13° 21’E and belongs to the Special Area of Conservation (SAC) of the Aniene River Springs (EC Site Code IT6050029) established under Directive 92/43/EEC. The Aniene basin is made mostly of bare Mesozoic, highly fractured, karstified carbonate rocks of the central Apennine range [19]. The entire area is mostly made of highly permeable Cretaceous carbonate rocks, deeply fractured and mostly soluble (Figure 1). The base of the stratigraphic series is made of Upper Cretaceous carbonates, represented by the alternation of granular limestone and dolomites layers. Above these ones, Quaternary fluvial and alluvial deposits lie, downward pudding and Miocene clay and shale. Karst features in the aquifer feeding the Pertuso Spring are relatively well developed at the surface of the carbonate outcrops, mainly in the Cretaceous limestones, where karren, sinkhole, groove and shallow holes can be observed [20,21]. The lithostratigraphy, detected nearby Subiaco Station, confirms the outcropping of an extensive karst area, especially limestones and dolomites (Latium-Abruzzi succession, Upper Triassic-Upper Miocene) [22]. The karst surface is very permeable and allows the rapid infiltration of rainfall into the underground system, where the carbonate dissolution generates cavities [20,21]. Dissolution conduits strongly influence groundwater flow and evolve into complex networks, often crossing several kilometers, throughout the limestone matrix [23].

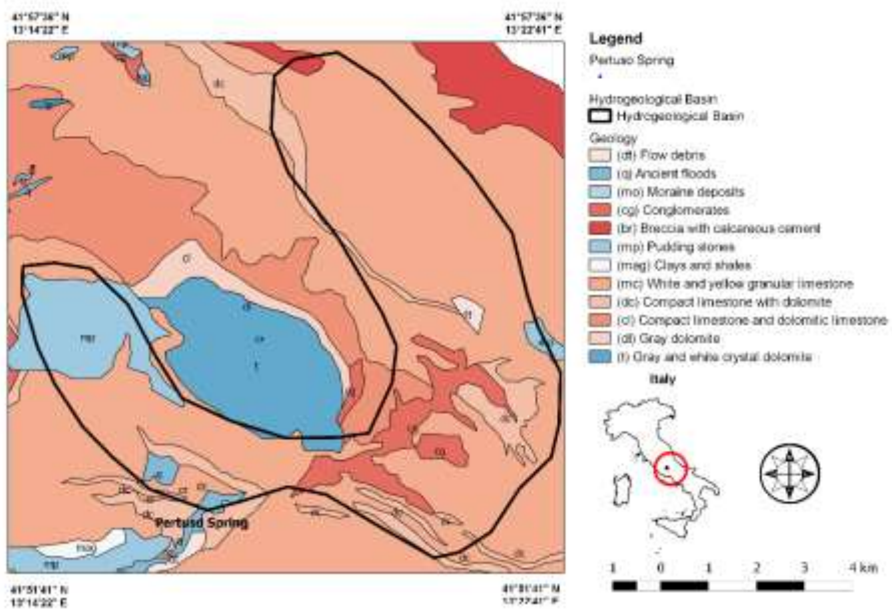

Figure 1. Geological map of the study area

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Thus, the Pertuso Spring is the natural outcrop of groundwater mostly discharging from these conduits showing an annual recharge of about 45 Mm^3/year [24].

The discharge is usually rapid and shows huge peaks following recharge events due to the receipt of a stormwater component, sourced via rapid preferential flow through karst features and fractures. The Pertuso Spring, located westward of Filettino (Figure 1), in the outcrop of limestone and dolomitic limestone of Upper Cretaceous age, flows into the Aniene River, close to the boundary of the carbonate hydrogeological system [25]. The most distinctive feature of the Pertuso karst spring is the branching network of conduits, whose size increases in the downstream direction. This conduit network is able to discharge very quickly large amounts of water, throughout the karst aquifer (up to 3 m^3/s) [16].

III. MATERIALS AND METHODS

The vulnerability of karst aquifer feeding the Pertuso Spring has been evaluated applying COP methodology, which focuses on the key role of karst features, responsible of the aquifer natural protection decreasing to pollution [15]. The COP method has been set up for the intrinsic vulnerability assessment of carbonate aquifers in the frame of the European COST Action 620 [7]. According to this method, the natural degree of groundwater protection is related to three parameters: the properties of the overlying soils and the unsaturated zone (O factor), the protection due to diffuse or concentrated infiltration processes (C factor) and the variable climatic conditions (P factor). The COP method provides for the C factor two different scenarios.

In Scenario 1, the C factor is calculated based on the following parameters: distance to the swallow hole (*dh*), distance to the sinking stream (*ds*) and the combined effects of slope and vegetation (*sv*) (Equation 1).

$$C = dh \cdot ds \cdot sv \qquad (1)$$

Scenario 2 is related to those areas, where the aquifer recharge does not occur through a sinkhole, so the C factor can be calculated on the bases of the parameters surface features (*sf*), slope (*s*) and the combined effects of slope and vegetation (*sv*) (Equation 2).

$$C = sf \cdot sv \qquad (2)$$

The COP vulnerability index (ICOP) is obtained by multiplying the three factors (Equation 3).

$$I_{COP} = C \cdot O \cdot P \qquad (3)$$

The COP vulnerability index classification defines five classes of vulnerability as shown in Table 1.

Table 1. COP index and corresponding vulnerability class

COP Index (I_{COP})	Vulnerability Class
0-0.5	Very High
0.5-1	High
1-2	Moderate
2-4	Low
4-15	Very Low

The tied relationship between rainfall and discharge rate, in the study area, is due to the preferential flowpaths of groundwater. For this reason, every concentrated recharge zone has been identified with the main karst features detectable from satellite images (Google Earth) (Figure 2) and about 50 different karst features in the hydrogeological basin have been plotted in GIS as polygons.

All these polygons, reported in a single GIS layer only related to the karst features, represent the direct recharge areas, where a possible contaminant may, directly and quickly, reach the aquifer with reasonable certainty. Before the vulnerability rating evaluation, the traditional vulnerability assessment approach would require the partition of the study area into Finite Square Elements (FSE) to which associate the Vulnerability Index calculated. However, in this study, with the aim of highlighting the presence of karst features, COP method has been applied starting from two different discretization approaches of the hydrogeological basin: polygonal layer

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and Finite Square Elements of 250 m per side (FSE). The polygonal layer is the result of an overlapping of two layers (Figure 3): the first one consists of the direct recharge area, related to the presence of karst features responsible of rainfall fast infiltration in the saturated zone, the second one coincides with the geology of the hydrogeological basin. Thus, the study area, of about 50 km^2, has been divided into 22 polygons, representative of different outcropping lithology and 50 polygons related to karst features. In this paper the aquifer vulnerability results, coming from both discretization application, are laid out, supported by QuantumGIS.

Figure 2. Karst features detection in the study area

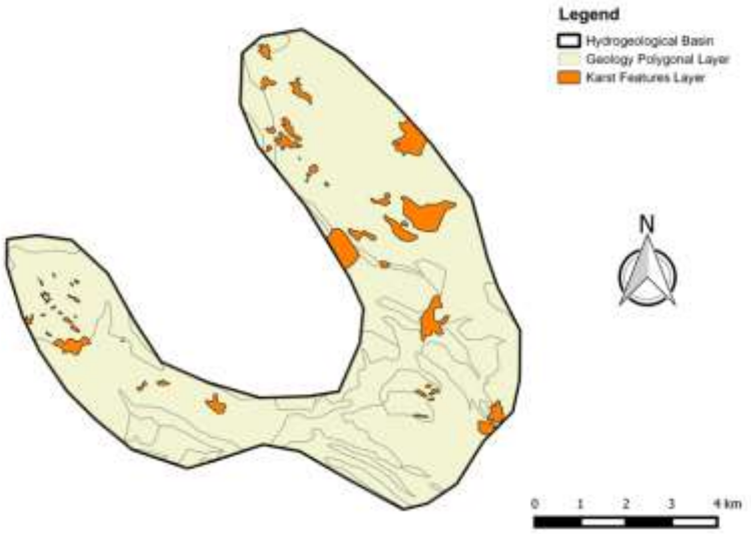

Figure 3. Polygonal layer discretization of the study area

The intrinsic groundwater vulnerability assessment requires data coming from the geological and hydrogeological settings of the aquifer, such as lithology, karst features, land use and land cover, soil, depth to groundwater, topography (slope) and climatic data (precipitation and temperature).

The study is based on the background data coming from previous studies [18,26] and results coming from the Environmental Monitoring Plan, carried out in the karst aquifer of the Upper Valley of the Aniene River, related to the catchment project of the Pertuso Spring. Data was collected from: (i) geological map, (ii) Digital Elevation Model (DEM), (iii) land use and land cover maps (iv) climatic data (precipitation and temperature),

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(v) airphotographs and satellite images of the study area to identify the position of the main karst features.Regarding to the evaluation of C factor, the COP method considers two scenarios: the first one includes the recharge area of karst features (Scenario 1) and the second one includes the rest of the area, where no surface karst features have been identified (Scenario 2). The C score for Scenario 1 is obtained by multiplying the values of the parameter referred to slope and vegetation (*sv*) by those related to the distances from recharge areas to the swallow hole (*dh*) or the sinking stream (*ds*). The C score for Scenario 2 is evaluated by the multiplication of two main factors: vegetation and slope (*sv*) and surface features (*sf*).

As a matter of fact, in this study, Scenario 1 for the evaluation of C factor has been applied in the higher permeability areas (karst features) and Scenario 2 in the lower permeability areas (aquifer lithology). The slope and vegetation (*sv*) came out by QGIS from the Digital Elevation Model (DEM) in percentage and divided into 4 classes (≤8%, 8% ÷ 31%, 31%÷75% and >75%), to which scores have been assigned, respectively from 0.75 to 1. Based on the land cover maps provided, land use has been divided into two main types, mainly "no vegetation" and "vegetation".In this study the distance to swallow holes (*dh*), consisting of a series of buffer zones with defined thickness, was not considered because the area belonging to each karst feature was assumed to be characterized by high vulnerability. According to the absence of sinking stream, the parameter (*ds*), referred to the distance to sinking stream, was assumed to be equal to 1. The surface features parameter (*sf*) takes into account the specific geomorphological features of carbonate rocks and the presence, or absence, of any overlying layers (permeable or impermeable), which influences the importance of runoff and infiltration processes. Ratings from 0.5 to 1 have been assigned to the surface features parameter (*sf*) according to the existing surface geology.The O factor represents the overlying layers, that is the soil cover (O_S), overlying the bedrock lithology (O_L). The O_S factor is related to the texture and thickness of the soil cover and in the case study, it has been evaluated starting from the soil map information. The O_L factor is representative of the unsaturated zone and it is the product of the layer index and the degree of confinement (*cn*). The layer index is the product of the type of lithology and fracturing (*ly*) and the thickness of the unsaturated zone. The O_S and O_L factors have been obtained using geological map and drilling profiles of the karst aquifer feeding the Pertuso Spring [17].The P Factor represents the climatic conditions in the catchment area and it is given by the sum of two sub-factors (P_Q and P_I) referring to, respectively, the amount and the intensity of yearly precipitation. P_Q represents the amount of precipitation and ranges between 0.2 and 0.4. The precipitation intensity (P_I) represents the ratio of precipitation amount and number of rainy days. Precipitation has been obtained starting from rainfall data, coming from four gauging stations inside the study area: Filettino, Vallepietra, Carsoli and Subiaco (Santa Scolastica). Data time series cover a period of 20 years, from 1992 to 2012 (Table 2) and they were applied to calculate the average annual rainfall module for each station. At last, a linear relation between the elevation and the average annual rainfall module was obtained in order to assign to each FSE a single precipitation value.

Table 2. Rainfall data about four different meteorological stations in the study area

Meteorological Station	**MPAM (mm/year)**	**Elevation (m asl)**	**Rainy days**
Vallepietra	1346.78	825	91
Filettino	1647.00	1062	107
Carsoli	1053.25	640	100
Subiaco (Santa Scolastica)	1147.88	511	100

IV. RESULTS AND DISCUSSION

C Factor

The estimation of the C factor, in the studied area, has been carried out according to Scenario 1 in areas, where the flow is concentrated towards karst features and Scenario 2 in the rest of the basin where the flow is diffuse.
The two C Factor maps generated (Figures 4a and 4b) present C score values ranging between very high to very low, with C Factor values ranging between 0 and 0.9 and it is very low (≤ 0.2) in the higher permeability area (karst features), whereas it is very high (0.9) in non-karstic terrains, such as pudding stone, conglomerate, alluvial soil. As a matter of fact, the mapping results clearly show a sound difference in vulnerability values between FSE version (Figure 4a) and the polygonal layer one (Figure 4b). The first one generally assigns a high vulnerability to the most part of the study area, whereas the second one assigns a moderate vulnerability value to the same part. This difference is related to the intrinsic choice of focusing on the Scenario 1 only for karst

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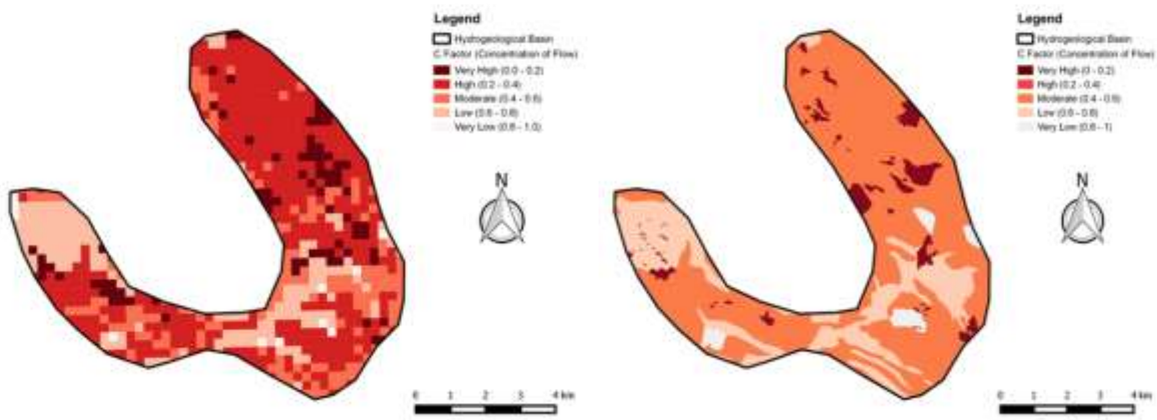
feature polygons and not out of these defined areas. On the other hand, FSE discretization allows a better precision on the finite square element elevation and leads to a more "conservative" vulnerability evaluation for the rest of area, but does not allow a clear identification of fast recharge areas due to karst features.



(a) (b)

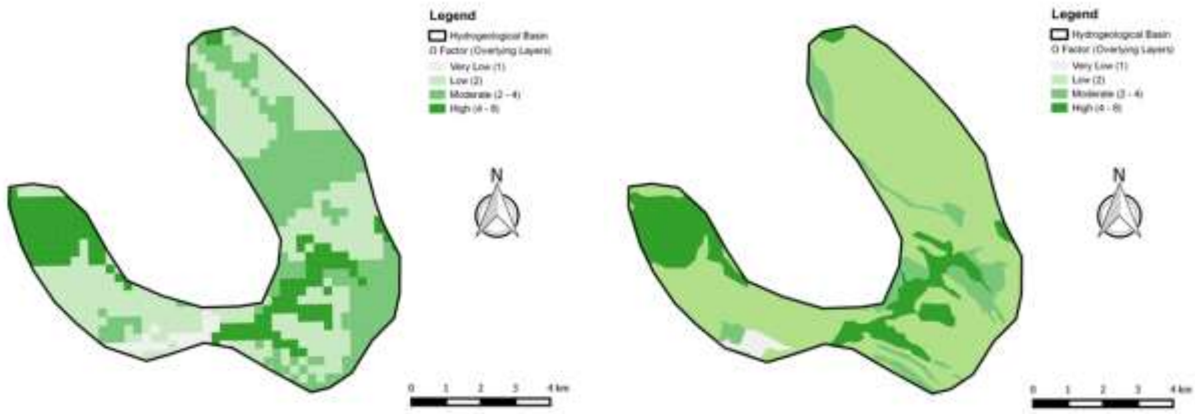
Figure 4. Map of the C Factor: (a) FSE and (b) polygonal layer

O Factor

The O factor ranges from 1 to 5, according to some properties as thickness of the unsaturated zone, soil type, aquifer confining conditions, lithology and its fracturation.

The higher protection areas (dark green) are related to the presence of conglomerates and pudding stones, which have a weaker state of fracturing. On the contrary, the lower ones are due to the presence of carbonate rocks, which are the dominant geological formations, in the study area, and present the highest fracturation. Hence, the O factor is low in most of the study area.

As it is shown in Figures 5a and 5b, there are no sensitive differences between the two discretization approaches. Karst features have no impact on the O factor and, consequently, most part of the area presents the same protection values in both maps.



(a) (b)

Figure 5. Map of the O Factor: (a) FSE and (b) polygonal layer

P Factor

P factor has been obtained using a linear relation, between elevation and average annual rainfall starting from data collected in Subiaco (Santa Scolastica), Carsoli, Vallepietra and Filettinometeorological stations, located nearby the study area. The number of rainy days in the study area ranges from a minimum of 91 to a maximum

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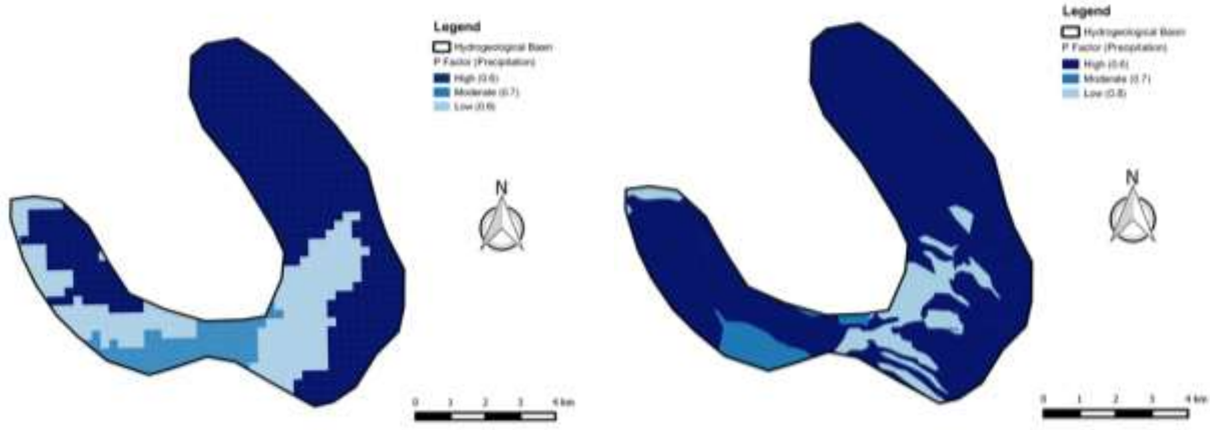
of 107 days per year, based on the analysis of precipitation data over a time series that goes from 1992 to 2012. The average value is 100 rainy days per year.P factor ranges between 0.6 and 0.8. Most part of the study area present a high value (dark blue) in both maps (Figures 6a and 6b). In particular, the polygonal layer discretization approach leads to obtain an enhanced coverage of high value. The reduction of protection is generally high (0.6) in mountain areas, because even if the precipitation quantity P_Q is higher there due to elevation values, the much wider temporal distribution is a key factor for contaminant transport and implies a decreasing protection.



(a) (b)

Figure 6. Map of the P Factor: (a) FSE and (b) polygonal layer

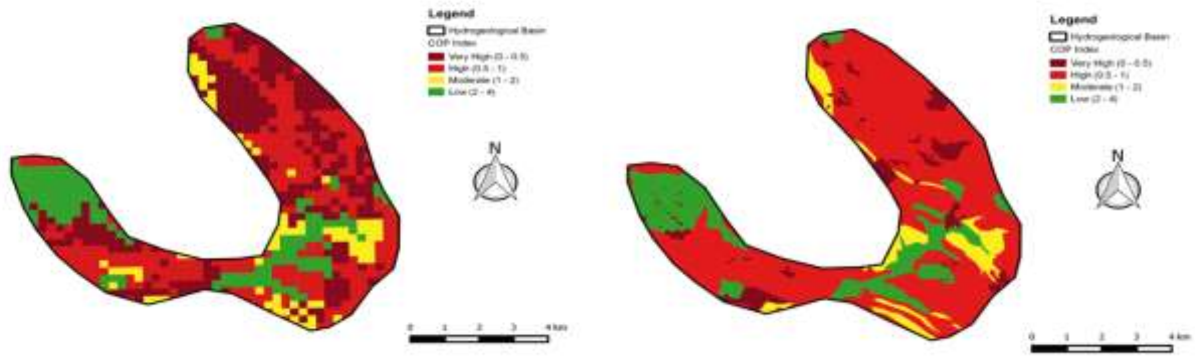
COP Index

Figures 7a and 7b shows the results of COP method in the hydrogeological basin of the Pertuso Spring, respectively for FSE and polygonal discretization.

The results obtained by COP vulnerability method, applied to FSE (Finite Square Elements) and polygonal layer, show different vulnerability degrees for several areas within the hydrogeological basin feeding the Pertuso Spring.

As expected, the COP vulnerability maps show generally the dominance of high vulnerability classes (shades of red) in the northern part of the basin, while the south-east and western part are characterized by low vulnerability class (shades of green) and moderate class (shades of yellow). There is no very low vulnerability class.

Details in percentages of area for each vulnerability class are given in Figure 8.



(a) (b)

Figure 7. Map of the COP Index: (a) FSE and (b) polygonal layer

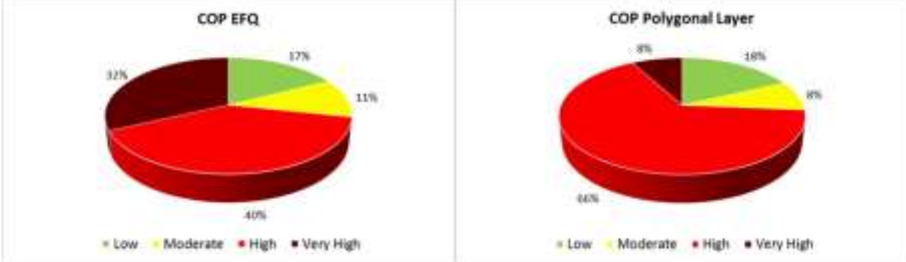


Figure 8. COP vulnerability classes percentage distribution: (a) FSE, (b) polygonal layer

The karst features, present in the study area, have been classified with the very high vulnerability degree (Very High: 0-0.5), due to the presence of swallow holes and dolines, that decreases the residence time of water in the unsaturated zone, reducing the potential attenuation capacity of the aquifer. This highest class of vulnerability index is due to the absence of an impermeable covering layer, which allowed rapid infiltration towards the saturated zone (C factor).

The low vulnerability class (Low: 2-4) covers similar percentages of the study area (17% and 18%) (Figure 13), mainly in the outcropping pudding stone, conglomerate and alluvial soil. In these areas, the low permeability of cover layers and the slope gradient are responsible of an increase of C and O factors and, consequently, of a vulnerability reduction.

The moderate vulnerability class (Moderate: 1-2) covers not more than 8 and 11% of the Pertuso Spring hydrogeological basin, respectively for polygonal layer and FSE discretization approaches (Figure 8). In these areas dolomitic limestone, compact limestone with dolomite and crystal dolomite outcrop, decreasing the protective capacity assigned to the unsaturated zone by the O factor. The COP method assigns the high vulnerability class (High: 0.5-1) to most part of the study area. This result is due to the presence of the karst Cretaceous limestone outcropping. Vulnerability maps obtained for both discretization approaches, result to be different just in the high and very high vulnerability degree assignment. The FSE discretization approach leads to a 32% of very high and 40% of high vulnerability rates, whereas in the polygonal layer discretization approach there is a lower presence of areas with the very high degree (8%) and a higher presence of areas with the high one (66%). This difference depends on the choice of using a polygonal layer, that allows identifying more precisely karst features and fast recharge area, assigning the potential contamination risk only to these areas and not to the rest. In this discretization hypothesis, karst features have a key-role for the C factor evaluation and their presence is predominant to each other consideration about vulnerability assessment. The FSE discretization approach, on the contrary, generally assigns COP index rates taking into account the lithology, the karst setting and the elevation, at the same level. As a consequence of it, in this case, a wider area of the whole basin has been considered very high vulnerable and the potential contamination risk result to be spread all over the study area, even out of karst features.

A comparison between the FSE discretization approach and the polygonal layer one is necessary to better understand which one is more suitable to the specific case study.

As to be expected, in a karst setting like the Pertuso Spring hydrogeological basin area, the presence of highly fractured rocks and most of all the specific permeability conditions, due to the local karst processes development, cause a spread high vulnerability degree to contaminants.

Even if the FSE discretization approach leads to a more cautionary vulnerability assessment in the study area, the polygonal layer shows a greater accuracy, defining all the areas interested by karst processes at local scale and assigning the higher vulnerability rate only to these ones. This choice allows to better highlighting protection areas, in order to protect groundwater quality. At the same time, the polygonal layer discretization approach needs a very detailed work, based on the detection and the outline representation of all the karst features. The visual detection and the graphic reconstruction of the areas, where karst features outcrop, is today easier to carry out, thanks to the remote sensing and the geographic information system (GIS) software. This process is strongly recommended for small basins as the Pertuso Spring one, but it may result to be not always suitable, above all in case of very wide areas.

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V. CONCLUSION

The aim of this paper was to carry on a comparative evaluation of vulnerability assessment of the karst aquifer feeding the Pertuso Spring, through the COP method application and starting from two discretization approaches: the Finite Square Elements (FSE) of 250×250 m and the polygonal layer, obtained from the overlapping of karst features and geology layers.

Regarding to the second approach, the study area, of about 50 km^2, has been divided into 22 polygons representative of outcropping lithology and 50 polygons related to karst features, which have been identified using satellite images.

The combined use of two vulnerability assessment approaches allows a better understanding of pollution vulnerability mechanisms in the study area.

The results of this study highlight that the vulnerability of the karst aquifer feeding the Pertuso Spring mainly ranges from low to very high in each approach.

Vulnerability maps show a high variability according to the environmental characteristics of the study area (e.g. geological, hydrogeological, morphological, climatic settings). The highest contribution to vulnerability is due to karst features such as karren, sinkhole, groove and swallow holes. The highly developed epikarst, the high recharge and high hydraulic conductivity minimizes the protective function of the unsaturated zone.

As to be expected, COP comes out to be a very suitable method for the vulnerability assessment in karst settings. As a matter of fact, the use of a polygonal layer as the basis for subsequent evaluations of the vulnerability is an effective option, because it allows to highlight the nature of outcropping lithology and the presence, shape and extent of karst features, responsible of fast infiltration and leakage.

On the other hand, the FSE discretization comes out to be more sensible to precipitation rates variations as well as to elevation and slopes, which are related to the water runoff. For these reasons, it is possible to say that the polygonal layer discretization is more recommended for small study areas such as the Pertuso Spring hydrogeological basin, whereas the FSE discretization is to be preferred for wide areas, where the higher range of precipitations and slope factors variations may play a key role in vulnerability assessment.

VI. ACKNOWLEDGEMENTS

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