

Aquifer vulnerability and potential risk assessment: application to an intensely cultivated and densely populated area in Southern Italy

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Abstract The use of indices, describing aquifer vulnerability and the risk of groundwater pollution, is a basic tool for the implementation of a sound water management plan, especially in densely populated and intensely cultivated areas. In this study, the groundwater contamination risk of the Caserta Plain (Southern Italy) was assessed through the integration of hazards defined on the basis of the different land uses, of the intrinsic vulnerability calculated by applying the SINTACS model and of the groundwater value evaluated by considering water wells density. In order to evaluate the evolution of the risk of groundwater pollution, the proposed methods were applied in the study area for both 2001 and 2009. The resulting specific vulnerability (SINTACS-L) and the risk (GRA) maps, created in a GIS environment, were validated by the comparison with the nitrate concentration distribution. The application of the proposed approach to the study area highlighted the strengths and weaknesses of each method and, at the same time, showed that their combination can provide an overall view of the threats posed to groundwater resources by the human activities affecting the territory. Considering both the benefits and the issues of the proposed approach, overall, the groundwater risk map is thought to be a robust tool to support water managers in defining future plans for water resources exploitation and land use.

Keywords Intrinsic vulnerability · Land use · Water losses · Nitrogen losses · Groundwater · GIS

Introduction

Groundwater is considered an important resource to satisfy human requirements, such as drinking water supply and irrigation for agricultural purposes. This is mainly due to its relatively low susceptibility to pollution, with respect to surface water and to the big storage capacity of underground reservoirs. Nevertheless, diffuse and punctual sources of pollution mainly due to urbanization and growth in the agricultural sector are progressively harming groundwater resources so that groundwater quality deterioration is becoming a widespread problem (Morris et al. 2003), especially in the highly populated and cultivated alluvial plains (Billen et al. 2013; Lockhart et al. 2013; Mastrocicco et al. 2009, 2011a). Once groundwater has been contaminated, contaminants' fate within the aquifers is uncertain but, most of the times, long lasting, either because of the intrinsic complexity and site specificity of the soil-water-pollutant interactions (Foster and Chilton 2003) or because remediation is expensive and time consuming (Erickson et al. 2002; Khan et al. 2004; Sbarbati et al. 2015). Thus, pollution prevention and control should be a key component in groundwater management. In recent years, vulnerability and risk assessment studies aiming at the identification of areas that are more likely to be polluted as a result of human activities have been used as tools for groundwater pollution prevention and control (Shrestha et al. 2016).

Groundwater vulnerability is classified into intrinsic vulnerability, which considers the inherent geological, hydrological and hydrogeological features of an area but disregards the nature of the contaminant and the scenario of contamination (Vrba and Zaporozec 1994), and specific vulnerability, which

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considers the properties of a particular pollutant in addition to the inherent vulnerability of an area (Gogu and Dassargues 2000). Existing methods to assess groundwater vulnerability can be classified into three categories: (1) overlay index methods based on ratings and weights, such as DRASTIC (Aller et al. 1987) and SINTACS (Civita and De Maio 1997); (2) process-based mathematical models such as GLEAMS (Knisel and Davis 2000) and HYDRUS (Šimůnek et al. 2008); and (3) statistical models (Neshat and Pradhan 2015).

Compared to vulnerability assessment, there are fewer methods for groundwater risk assessment, which can be attributed to the diversity of contamination source types and scales and the unpredictability of contamination incidents. Most of the existing risk assessment methods only consider contamination hazards and aquifer vulnerability. Nevertheless, to properly assess the risk of groundwater pollution in addition to the potential surface contamination sources and to intrinsic vulnerability, groundwater value has to be accounted for (Ducci 1999; Saidi et al. 2011) to aid water managers in decision-making (Wang et al. 2012).

In view of the aforesaid literature, there is still a need for easy-to-use (not requiring model calibration) and flexible methodologies to assess the potential contamination risk of groundwater resources. The aim of this study is to propose a GIS-based groundwater risk assessment method (GRA), which combines low data requirements indices. The GRA was accomplished by integrating hazards, intrinsic vulnerability and groundwater value. The hazard was evaluated by land use parametrization, the intrinsic aquifer vulnerability was evaluated using SINTACS and the groundwater value was evaluated based on groundwater use.

The GRA was applied to an unconfined aquifer of the Campania Plain (Southern Italy) in order to estimate the potential pollution risk due to agricultural practice and high population density. Since the risk of pollution is determined both by the intrinsic vulnerability of the aquifer, which is a steady property, and by the hazards (namely land use) and the groundwater value, which may change with time, the GRA was calculated for both 2001 and 2009. In the attempt to validate the GRA here proposed, the resulting risk maps were then compared with the NO_3^- concentrations' distribution registered in the local unconfined aquifer in the monitoring campaign of 2010.

Study area

The study area is located in the province of Caserta ($41^\circ 05' \text{N}$ $14^\circ 13' \text{E}$) in the Campania region, Italy (Fig. 1). Morphologically, the Caserta Province is characterized by the Apennine Mountains in its eastern sector, oriented roughly NE–SW, while the western area host a coastal alluvial plain,

where the Volturno River flows. The Apennine chain comprises of a pile of nappes formed during the Miocene, overthrust towards N–NE (Patacca and Scandone 2007). The lithology is formed prevalently by sedimentary rocks, from Triassic to Holocene (Bonardi et al. 1998). The sedimentary rocks consist of limestone, dolostone and terrigenous sediments of Mesozoic age. These rocks represent the external Apennine domain, while the Neogene units are formed by siliciclastic, carbonatic and evaporitic sediments. The Quaternary sediments present mainly in the Campania Plain are formed by lacustrine, alluvial and coastal sediments. Finally, the Campanian Ignimbrite covers partially the Campania Plain. The underground digital terrain model (UDTM) was obtained by the interpretation of 54 stratigraphic surveys, selected among 120 boreholes; all those boreholes with a depth less than 50 m and/or too close to each other were not considered, since they do not provide information about the top and bottom of the aquifer. Four lithostratigraphic units have been identified: (i) a thin layer of alluvial sediments and/or soil, (ii) the Campanian Ignimbrite which is characterized by a considerable thickness and subdivided into four different facies (Cinerazzo, Semi Tufo, Pipernoide and Piperno, from top to bottom) as described by Di Girolamo (1968), (iii) the Pre-Ignimbrite made of pyroclastic deposits including the eruptive deposits of Flegrea's first stage and (iv) sea deposits made of sand and well-cemented clay with loamy layers.

Materials and methods

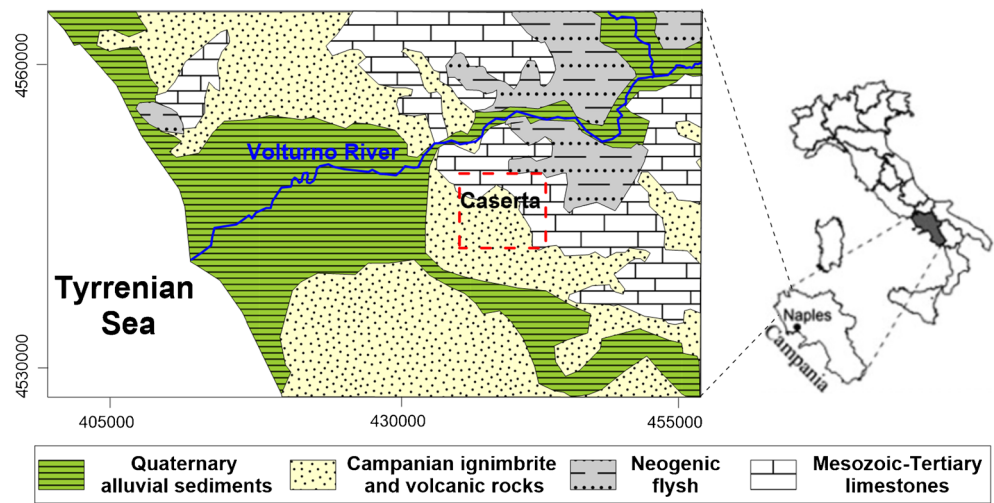
Methodological procedure to obtain the groundwater risk assessment map

Morris and Foster (2000) defined groundwater pollution risk “as the probability that groundwater in the aquifer will become contaminated to an unacceptable level by activities on the immediately overlying land-surface”. In this study, groundwater contamination risk maps for 2001 and 2009 were obtained by multiplying the specific vulnerability maps SINTACS-L (which, in turn, were obtained by multiplying the hazard and the intrinsic vulnerability maps), with the groundwater value maps (Mimi and Assi 2009), according to the procedure described in the following paragraphs.

Hazard assessment

In the context of groundwater contamination, a hazard is defined as a potential source of contamination resulting from human activities taking place at the land surface (Zwahlen 2004), which may alter the water quality (Babiker et al. 2005). There are a wide range of sources that are likely to generate a certain contaminant loads on the basis of land use

Fig. 1 Geological map of the area, in the dashed red square, where the study site is located



categories. In this study, the Corine Land Cover maps for 2001 and 2009 (Corine Land Cover 2000) were chosen as representative of the hazards affecting the study area (Fig. 2).

In order to make the hazard maps readily multipliable for the intrinsic vulnerability maps, a set of ratings and weights have been assigned to different land uses (Table 1), according first to Zaporozec (2002) and also to Kazakis and Voudouris (2015) to precisely account for N load requirement of different cultivation in the agricultural areas on the basis of the different amounts of fertilizers applied (FAO 2002) and/or estimated nitrogen inputs, like atmospheric deposition (Jia et al. 2016).

In the study area, most of the hazards come from the agriculture and urban classes. Therefore, the highest ratings are assigned to these classes. The detailed ratings for all the classes are given in Table 1. The land use/cover map is given a weighting of 5, due to the potential impact of this parameter on the groundwater (Secunda et al. 1998).

Intrinsic vulnerability assessment

Intrinsic vulnerability assessment allows describing innate features of specific hydrogeological conditions that provide some measure of defence against external contamination. In this study, the intrinsic vulnerability of the local unconfined aquifer was estimated using SINTACS.

SINTACS was established for hydrogeological, climatic and impact settings typical of the Mediterranean countries (Civita and De Maio 2004). The acronym SINTACS stands for the seven parameters included in the method: *soggiacenza* (depth to water), *infiltrazione efficace* (effective infiltration), *non saturo* (vadose zone), *tipologia della copertura* (soil cover), *acquifero* (aquifer), *conducibilità idraulica* (hydraulic conductivity) and *supeficie topografica* (slope of topographic surface). The rating assigned to each parameter is multiplied for a weight to describe the environmental impact or the particular hydrogeological situation.

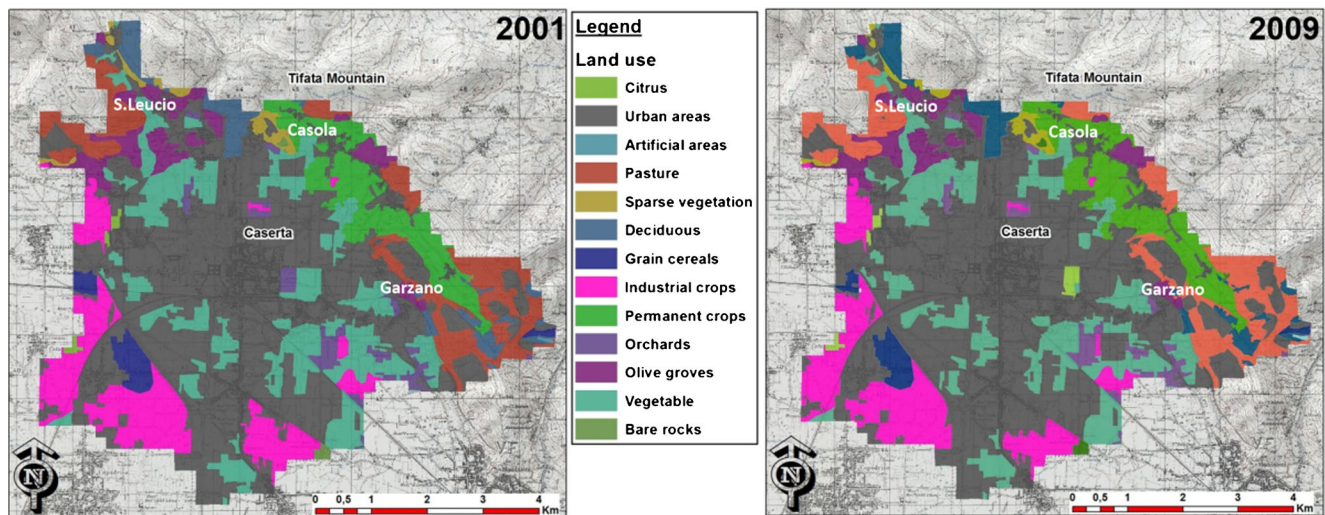


Fig. 2 Land use for the study site in 2001 (left panel) and 2009 (right panel)

Table 1 Land use ratings used in the hazard maps for 2001 and 2009

Land use	Ratings
Cereals and industrial crops	10
Orchards and citrus groves	4
Vegetable	3
Olive groves	2
Deciduous forests, pastures, sparse vegetation and bare land	1
Urban areas	6
Artificial areas	4

The form of the equation is the following:

$$I_{\text{SINTACS}} = \sum_{j=1}^7 P_j W_j$$

where P_j is the rating of each parameter and W_j is the corresponding weight.

The water depth (S), measured in 36 monitoring wells, ranges from 30 m in the southern area to more than 60 m in the northern area.

The effective infiltration (I) was calculated by multiplying the net recharge for texture coefficient derived from the type of soil cover. The net recharge was calculated by subtracting the actual evapotranspiration to the recorded rainfall using the climatological data of three meteorological stations, covering the period 1992–2012. To calculate the volumes of evapotranspiration, the Penman–Monteith formula was applied (Allen et al. 1998). The texture coefficients were set to 0.4 for soil B43, mainly located in the northern part of the study area, and to 0.2 for soil G1, which characterizes the Piedmont area. The resulting effective infiltration in the study area ranges from 69 to 138.5 mm.

From the analysis of the UDTM, the predominant units of the unsaturated zones (N) are the Campanian Ignimbrite and the Pre-Ignimbrite, which were demonstrated to be an important defence for the aquifer against pollutants (Bruno and Godio 1997).

The type of soil cover (T) plays an important role in mitigating the impact of pollutants and in the evaluation of the intrinsic vulnerability of aquifers. In the study area, two types of soil were identified using the thematic map “Lands of Campania” (Gennaro 2002). The soils are B43, which has a loamy sand texture and a good permeability, and G11, with a loamy silt texture and an average permeability.

Concerning the types of aquifer (A) in the northern area, a calcareous aquifer, fractured and/or karstified, can be found, while in the rest of the study area, the aquifer is hosted by alluvial and volcanic deposits.

The hydraulic conductivity (C) for the limestone formation is generally high, ranging from 1×10^{-3} to 5×10^{-5} m/s, while the volcanic complex has a medium to low permeability with

values ranging from 1×10^{-5} to 5×10^{-7} m/s (Allocca et al. 2007).

The slope of the topographic surface (S) affects the intrinsic vulnerability assessment mainly because it defines the amount of infiltration and runoff water with respect to an equal amount and rate of precipitation. More than 60% of the study area has very mild slope (0–2%), but moving north, the slope gradually increases from 10 to 15% in the piedmont area up to 30%. The investigated area covers about 68 km² with a population of 115,000 inhabitants. In the study area, the land use is very heterogeneous and varies with time. In particular, the urban area covers approximately a third of the territory, as well as the agricultural land, where a variety of different crops are cultivated (Fig. 2). The remaining territory, mainly the mountainous area, is occupied by forests (about 11 km²) and pastures (about 14 km²).

According to the description of the seven parameters taken into consideration by the SINTACS method and the ratings proposed by Civita and De Maio (1997), the vulnerability assessment in the study area was developed in the GIS environment and all the seven parameters were arranged in raster format, with a regular grid of 200 × 200 m (Fig. 3). In order to obtain the intrinsic vulnerability of the area (Fig. 4), the ratings of the seven parameters were multiplied by the string of weights proposed by Civita and De Maio (2004) for the *severe-impact* scenario, which emphasize the role of the first, second and fourth parameters among all the others.

Specific vulnerability assessment

Incorporating the land use parameter (namely the “hazard” factor) within the intrinsic vulnerability map, a specific vulnerability map to groundwater pollution was obtained and named SINTACS-L (Uricchio et al. 2004). Since in the study area the more important activities, from an economical perspective, are livestock farming and agricultural practices, which together with urbanization are likely to introduce in the ground mainly N-derived pollutants, the specific vulnerability map produced for the study site represents mostly the potential risk associated to nitrate percolation (Figs. 5 and 6).

Groundwater value

Valuing groundwater is an important component of groundwater resource protection schemes (Zaporozec 2002). Different researchers have used various factors to quantify groundwater value, such as (1) total economic value as measured by extractive value (National Research Council 1997); (2) socioeconomic value as measured by total extraction/groundwater recharge, variation in storage and groundwater quality (Saidi et al. 2011); and (3) estimated criteria measured by the current dependence on groundwater, the potential future dependence on

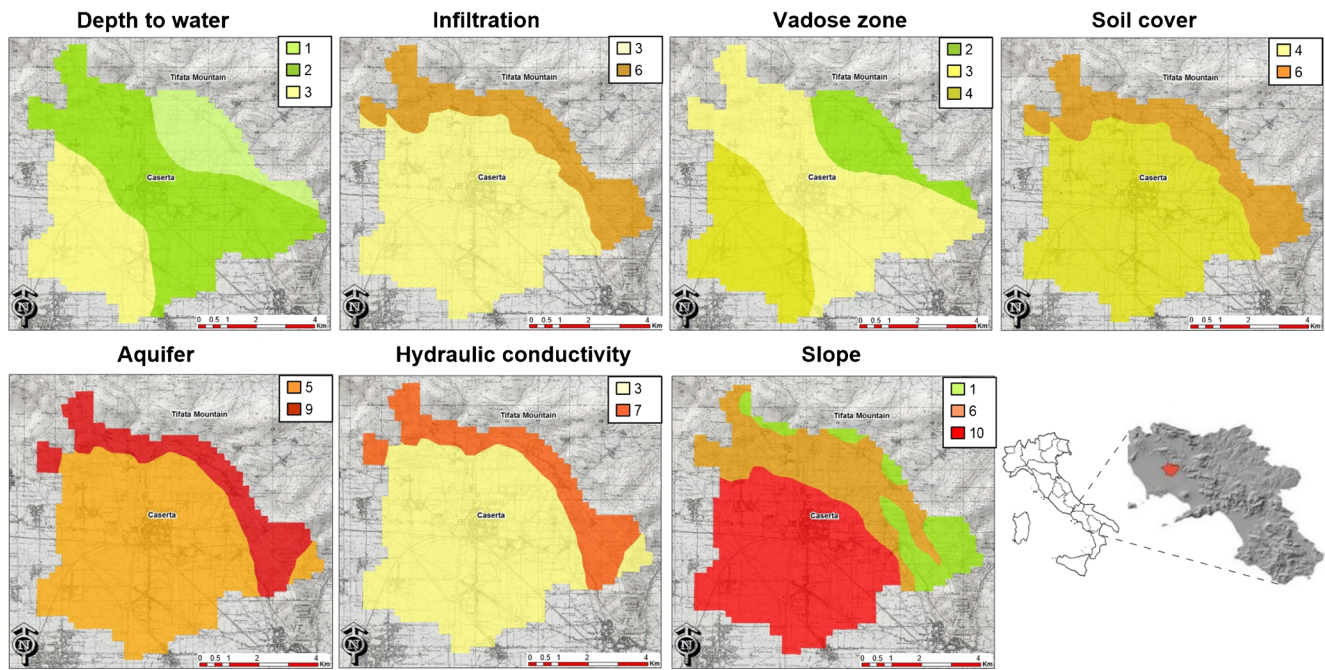


Fig. 3 Distribution of the ratings for each parameter considered in the SINTACS method for the study site. The location of the study site is shown in the bottom right panel

groundwater and the interaction with environmental resources (Fadlelmawla et al. 2011). In this study, the current dependence on groundwater was adopted to

parameterize the actual groundwater value. This was obtained by assigning a rating to the water wells density per square kilometre, in both 2001 and 2009 (Fig. 6).

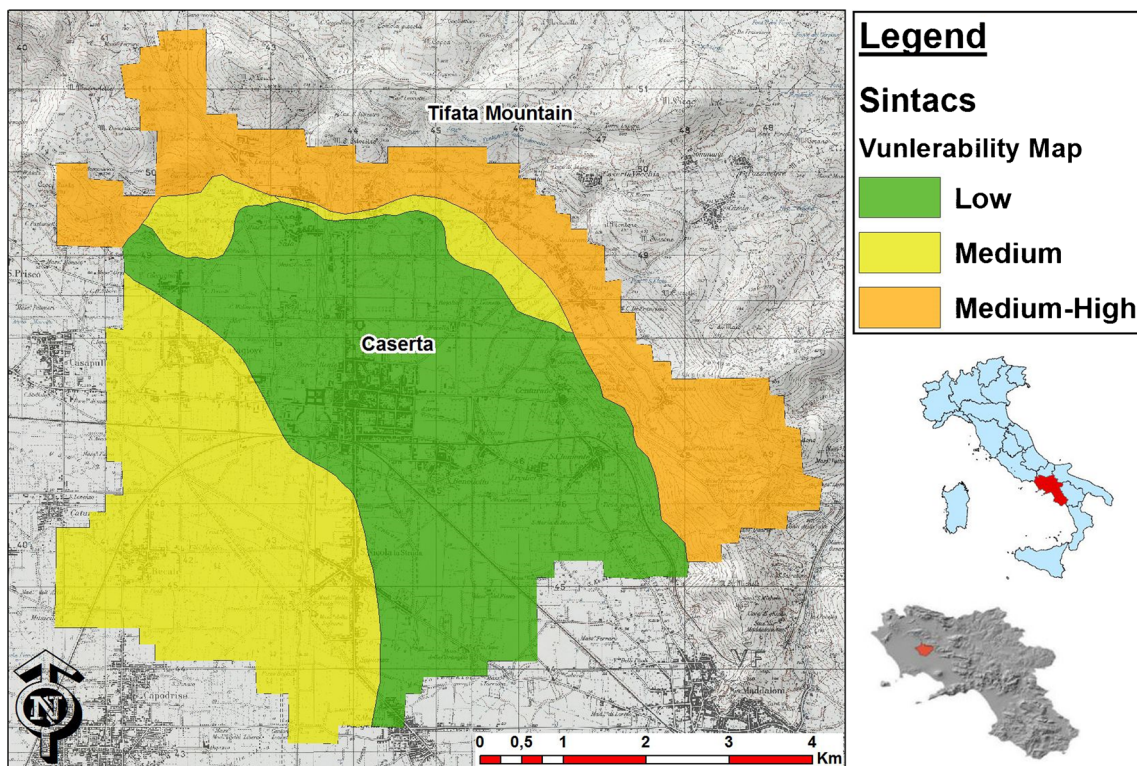


Fig. 4 Intrinsic vulnerability map of the study area calculated using the SINTACS method

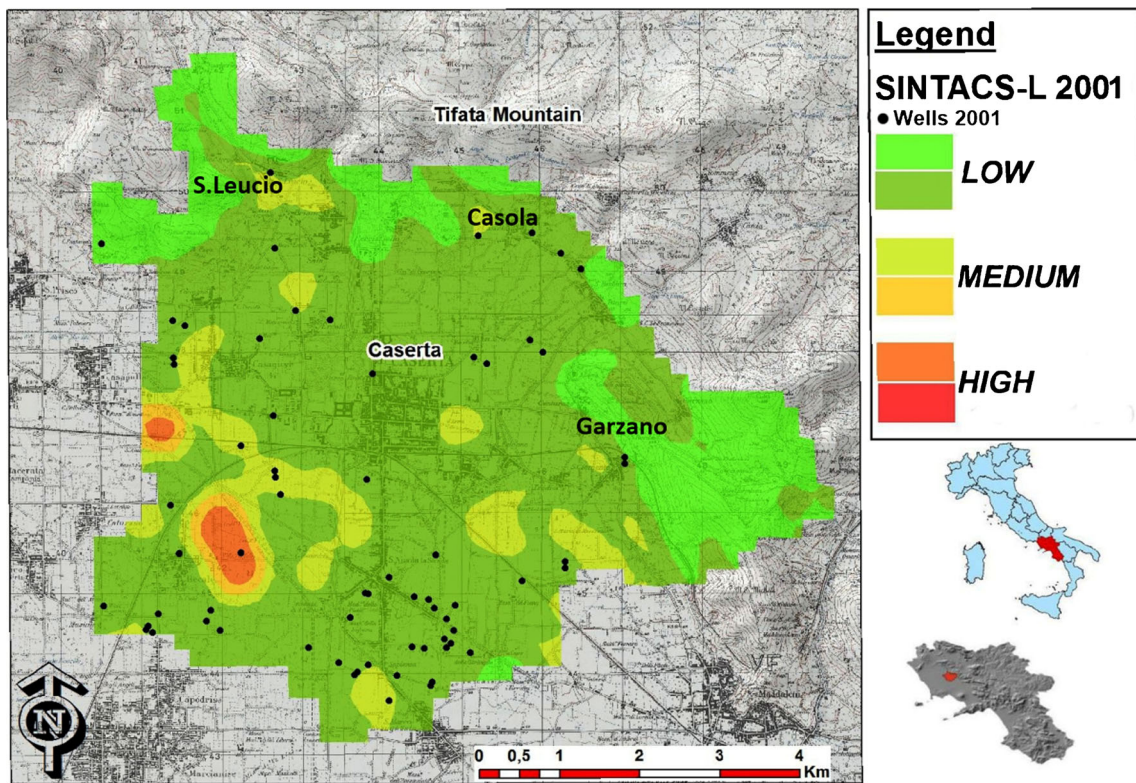


Fig. 5 Specific vulnerability map to nitrate pollution in 2001 calculated using the SINTACS-L method

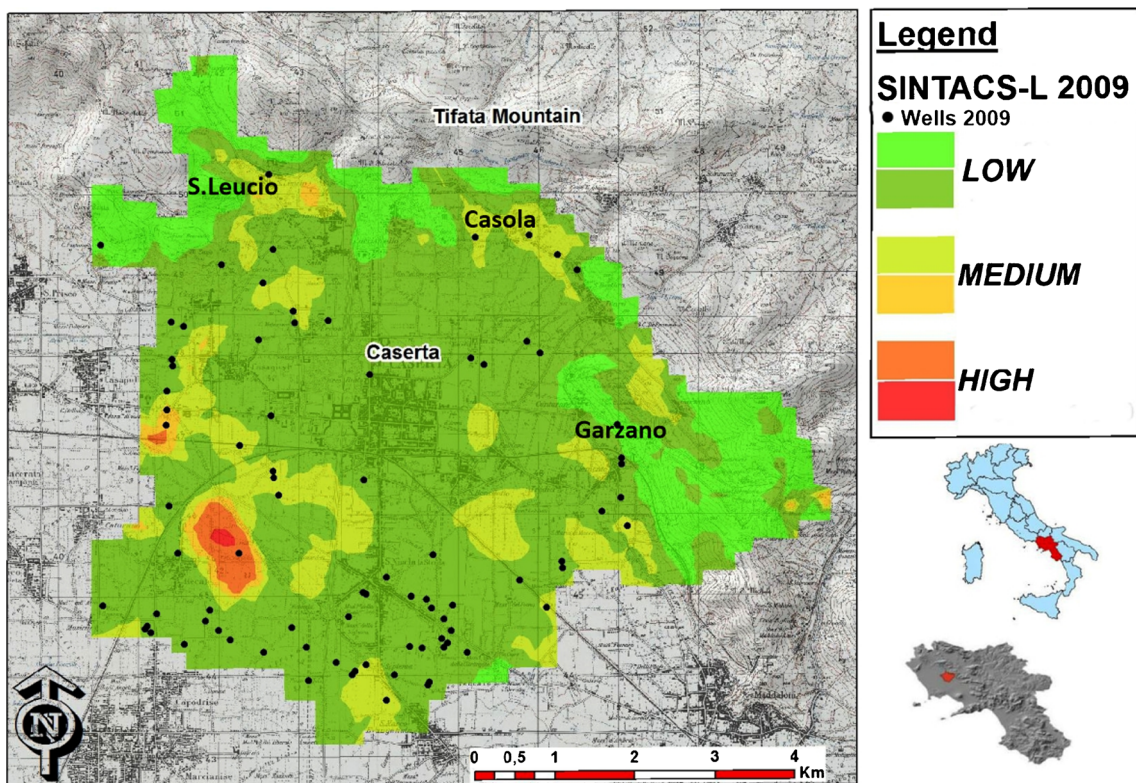


Fig. 6 Specific vulnerability map to nitrate pollution in 2009 calculated using the SINTACS-L method

Validation

The presence of nitrate in groundwater has been often used as an indicator in groundwater vulnerability and pollution risk assessment (Corniello et al. 2007; Huan et al. 2012). Nitrate contamination in groundwater very often occurs in a landscape with coexistence of urban, industrial and agricultural activities (Corniello et al. 2007; Cuoco et al. 2017). In fact, the use of nitrogen (N) fertilizers in agricultural fields represents one of the most important non-point sources of pollutant (Puckett et al. 2011). Moreover, the leachate of wastewater from septic tanks, wastewater treatment plants and solid waste disposal sites within urban areas may also increase NO_3^- concentration in groundwater and, consequently, deteriorate groundwater quality.

Thus, in this study, the validation of the GRA maps is performed using NO_3^- concentration in milligrams per litre, which is considered as a good indicator of the human interaction with the local groundwater environment (Ahmed et al. 2015). Moreover, the mobility of nitrate along with water also fulfils the assumption of the index overlay methods.

The GRA maps for 2001 and 2009 were compared with the NO_3^- distribution as derived by a geochemical characterization performed on 29 samples from the shallow unconfined aquifer, in the monitoring campaign of 2010 (Fig. 9). Water temperature, EC and pH were measured in the field. Major elements were analysed via ion chromatography (Dionex DX-120) on unfiltered (F^- , Cl^- , Br^- , NO_3^- and SO_4^{2-}) and filtered/acidified (Na^+ , K^+ , Mg^{2+} and Ca^{2+}) samples. The analytical precision and accuracy for repeated analyses of the groundwater and international standards were better than 5%.

Results and discussion

Vulnerability maps

For the study area, the intrinsic vulnerability ranges from 80 to 140. These values were then divided into three intervals of vulnerabilities: from 80 to 105, a low vulnerability class was identified; from 105 to 120, a medium vulnerability class was identified; and from 120 to 140, a medium–high vulnerability class was identified (Fig. 4).

By multiplying the land use (see Table 1) to the intrinsic vulnerability map, two specific vulnerability maps were obtained for 2001 and 2009 with respect to the potential pollution from NO_3^- . For the study area, the specific vulnerability to NO_3^- pollution (SINTACS-L) ranges from 40 to 1055 for 2001 and from 34 to 1352 for 2009. These values were then divided into three intervals of specific vulnerability: from 0 to 240, a low class was identified; from 240 to 500, a medium class was identified; and from 500 to 1400, a high class was identified (Figs. 5 and 6 for 2001 and 2009, respectively).

Most of the mountainous areas fall in the medium–high intrinsic vulnerability sector and show a low specific vulnerability for both 2001 and 2009. This is because no agricultural fields are present in this zone where only forested areas are reported. The only exception is constituted by two limited areas near the villages of S. Leucio, Casola and Garzano, where between 2001 and 2009, some areas that were covered by forests and/or meant for pasture have been converted to urban development with the creation of industrial and commercial areas. Due to the change in land use, the specific vulnerability to pollution from NO_3^- passed from the low class to the medium one (Fig. 6).

In the Caserta Plain, which is classified as a low intrinsic vulnerability area, according to the SINTAC method, the SINTACS-L maps for 2001 and 2009 show the existence of some area with a medium specific vulnerability due to the cultivation of crops requiring a considerable fertilization. Moreover, comparing the SINTACS-L maps for 2001 and 2009, an interesting change occurred in the central part of the study area, in proximity to the town of Caserta, where the extension of the medium class shrinks due to the conversion of arable land cultivated with cereals to industrial and commercial area. On the other hand, in the south-eastern part of the study site, the extension of the area presenting a medium specific vulnerability augmented due to the swop from vegetables to citrus crops.

Finally, in the south-western part of the study site, which is classified as a medium intrinsic vulnerability area, according to the SINTACS method, the SINTACS-L maps for 2001 and 2009 report a high specific vulnerability to pollution from NO_3^- , mostly because of the extensive cultivation of cereals.

In general, between 2001 and 2009, a slight worsening of the specific vulnerability has occurred in the study area, with a decrease in the percentage of territory falling in the low class and a corresponding increase of the territory falling within the medium class, while the extension of the territory falling in the high class remained almost unchanged (Table 2).

The SINTACS and SINTACS-L maps were compared with the distribution of NO_3^- concentrations (Fig. 7), obtained during a monitoring campaign that took place in 2010. This was done to determine if taking into consideration the land use when mapping for NO_3^- vulnerability would return a more accurate estimate on the exposure to NO_3^- contamination for the unconfined aquifer of the study area.

Table 2 Portions of land (%) falling into different classes of specific vulnerability to contamination from NO_3^- between 2001 and 2009

Specific vulnerability	2001 (%)	2009 (%)	Variation
Low	84	76.8	−7.2
Medium	12.6	20.4	+7.8
High	3.4	2.8	−0.6

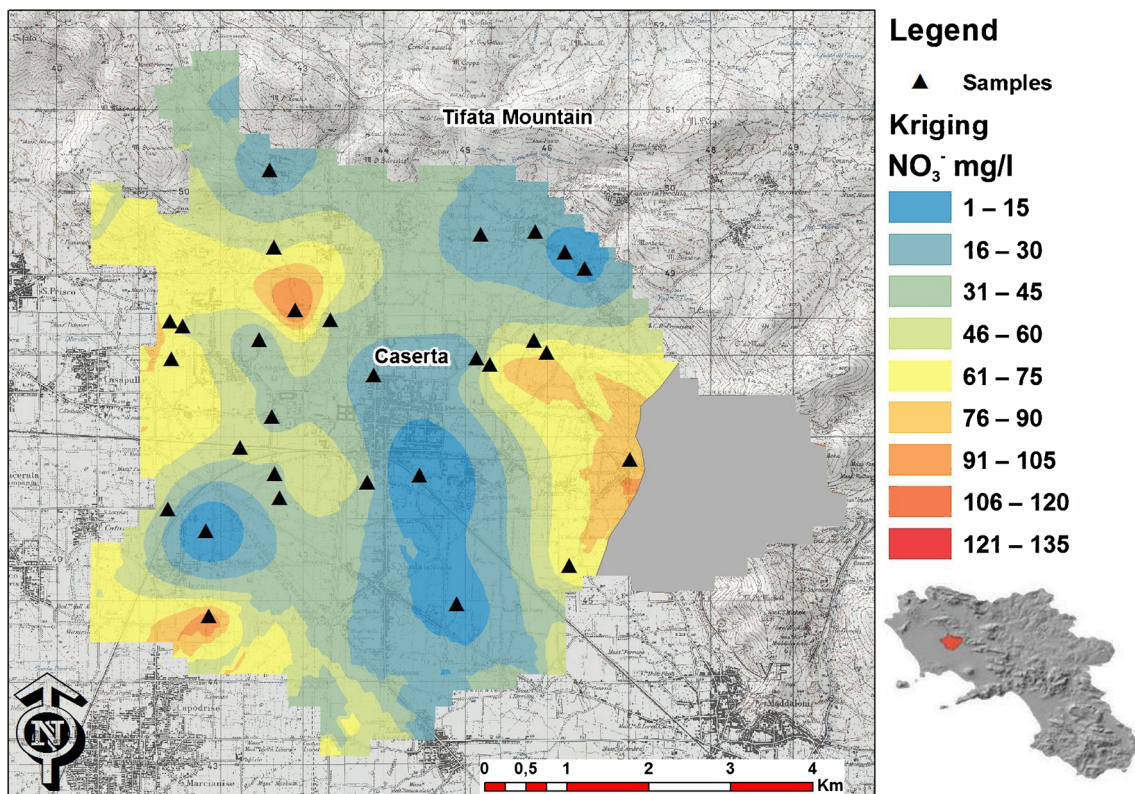


Fig. 7 Nitrate concentrations (mg/l) in the unconfined aquifer of the study area, from the monitoring campaign of 2010

The groundwater samples collected in 2010 mainly reflect the geological and hydrogeological situation of the area; in fact, while maintaining the characteristics of the catchment area, composed of carbonate rocks, groundwater flowing towards the plain undergoes a mixing with the water residing in the volcanic matrix that characterizes the plain. Together with the main natural dynamics, NO_3^- and SO_4^{2-} trends testify that the human activities present in the plain may play an important role in changing the groundwater geochemistry (Cuoco et al. 2017). For this reason, NO_3^- was chosen as an indicator of pollution.

In a pristine environment, NO_3^- concentration in groundwater is commonly in the order of a few milligrams per litre, while its presence in high concentrations can be related to the intensive use of fertilizers and/or losses from sewers and industrial waste. Figure 7 shows that the mountainous area and the central portion of the study area have low NO_3^- concentrations (up to 45 mg/l), never exceeding the threshold of 50 mg/l of NO_3^- in groundwater, established by the European Parliament (GWD 2006/118/CE) and subsequently adopted by the Italian Government. On the other hand, moving towards the western and eastern portions of the study area, there is a gradual increase in NO_3^- concentrations with peaks above 100 mg/l, in proximity to the municipalities of Recale and Casagiove.

The portion of land situated in the eastern part of the study area, represented in grey in Fig. 7, has been excluded from the interpolation, because data on NO_3^- concentrations were not available.

Comparing the SINTACS and SINTACS-L maps with the NO_3^- concentration map, it is clear that the addition of the land use ratings has largely improved the correspondence among the calculated values and the observed ones.

In particular, in the mountainous area and in the central portion of the study site, where the vulnerability to NO_3^- pollution was found to be low, the NO_3^- concentrations are generally below the threshold limit of 50 mg/l. Only few small areas with negligible NO_3^- concentrations fall in the medium class according to the SINTACS-L map of 2009, and this discrepancy is probably ascribable to the very thick unsaturated zone that prevents the percolation of NO_3^- even where the human activities deeply stress the territory. On the other hand, the high concentrations of NO_3^- recorded in the eastern and north-western portions of the study areas well match with the medium class contour of the 2009 SINTACS-L map.

The most evident discrepancy among the actual NO_3^- concentrations and the SINTACS-L map classification is restricted to the south-western corner of the study area where the highest specific vulnerability is calculated but extremely low NO_3^- concentrations are present. This behaviour may be due

to the presence of favourable conditions allowing denitrification, like for example the establishment of reducing conditions accompanied by the presence of a high content of readily available soil organic carbon in the top soil and/or through the whole aquifer thickness.

Though the inclusion of the land use ratings has improved the assessment of the propensity of the study area to suffer from NO_3^- pollution, in some cases, the risk of NO_3^- percolation towards the underlying groundwater may be underestimated, for example because of the presence of local factors, like leaking pipes and/or concentrated discharge through preferential pathways which readily transport dissolved NO_3^- from the ground surface downwards, which cannot be included in regional spatial analysis like the one hereby proposed. In other cases, probably the majority, the risk of NO_3^- percolation towards the underlying groundwater may be overestimated, for example because the attenuation capacity of the soil and sediments constituting the aquifer is not adequately taken into consideration (Mastrocicco et al. 2011b).

Pollution risk maps

Thus, a further step towards the improvement of the NO_3^- pollution risk assessment will be the inclusion of a parameter which refers to the soil organic matter content and, more specifically, to the amount of labile organic carbon available (Castaldelli et al. 2013), as recently proposed in the method from Aschonitis et al. (2013).

Moreover, the SINTACS-L maps only represent the specific vulnerability to contamination and not the actual risk of groundwater contamination in the study area. The risk of pollution is determined both by the specific vulnerability (intrinsic characteristics of the aquifer multiplied by the potentially

polluting activities) and by the actual groundwater exploitation rate (Saidi et al. 2010, 2011).

Thus, to further improve the analysis on the study area and to provide groundwater authorities a useful tool to support decision on water resources management, groundwater value maps were defined and multiplied to the SINTACS-L maps in order to obtain GRA maps, for both 2001 and 2009. To keep the procedure as simple as possible and to limit the amount of data required (Nguyet and Goldscheider 2006), the groundwater value has been expressed by calculating the actual water wells density, for both 2001 and 2009 (Fig. 8). The resulting groundwater value maps represent the actual value of the groundwater resource in the year taken into consideration; thus, the results are temporary and not predictive.

For the study area, the groundwater wells density (SINTACS-L) ranges from 0 to 12 units per square kilometre. These values were then divided into three intervals taking as reference scale the maximum water wells density registered in the whole Campania Plain: from 0 to 5, a low class was identified; from 6 to 11, a medium class was identified; and from 12 to 17, a high class was identified (Fig. 8).

In fact, from Fig. 8, it is evident that from 2001 to 2009, the human activities have increased their reliance on groundwater resources, since the water wells density increased in some part of the study area. While the water wells density has remained unchanged in the south-eastern portion of the territory, which shows the highest density in both 2001 and 2009, in the south-western portion, the water wells density passed from low to medium. The same occurred in the central eastern area and in the north-western region.

By multiplying the groundwater value maps (Fig. 8) to the specific vulnerability map SINTACS-L, the groundwater risk assessment maps (GRA) were obtained for 2001 and 2009 with respect to the potential pollution from NO_3^- . For the

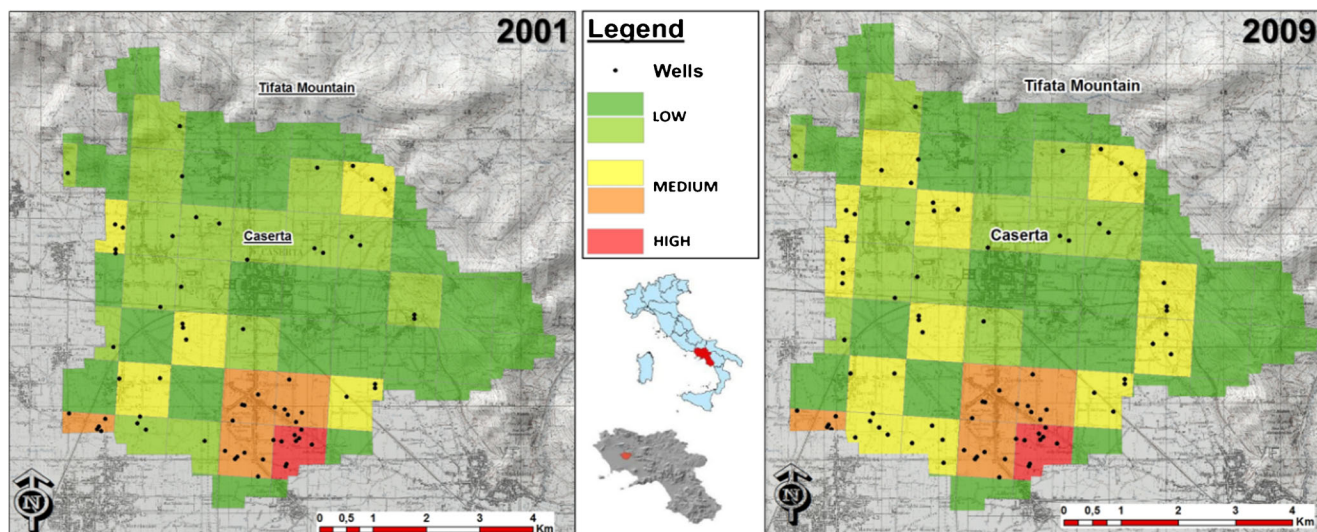


Fig. 8 Actual groundwater value map in 2001 (left panel) and in 2009 (right panel)

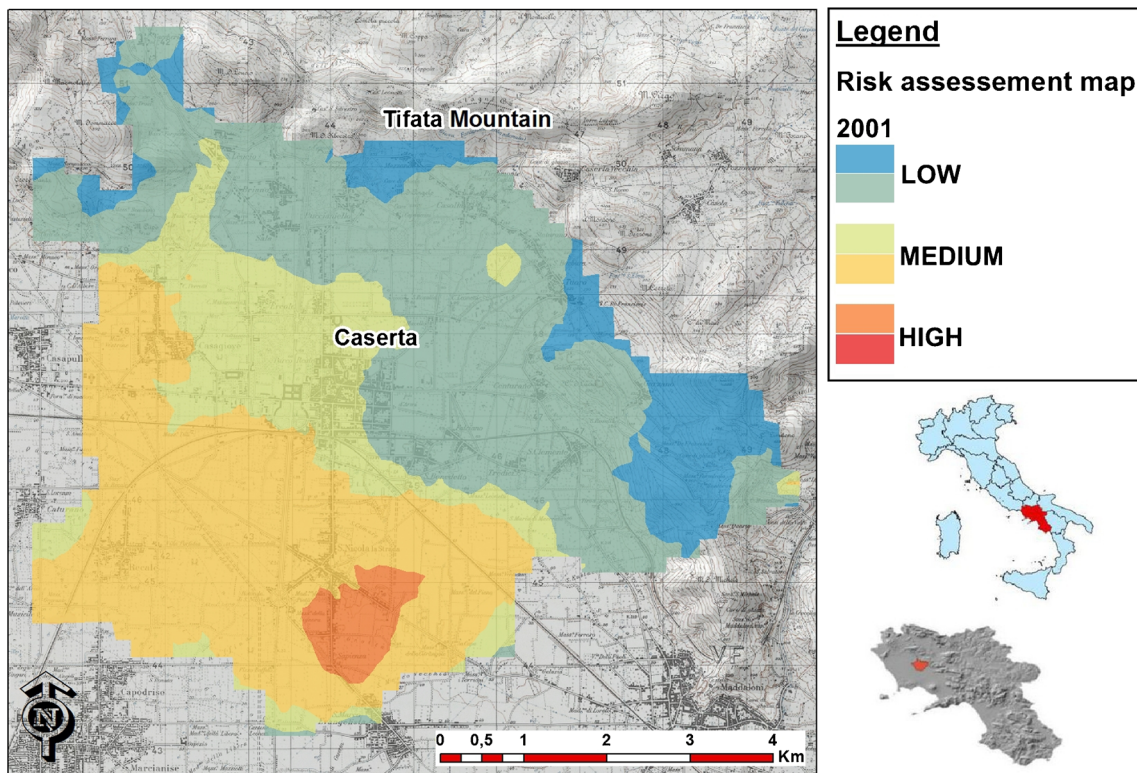


Fig. 9 Groundwater pollution risk assessment map (GRA) for the year 2001

study area, the GRA maps were divided into three intervals of low, medium and high risks (Figs. 9 and 10).

Most of the mountainous areas fall in the low-risk sector shown in both 2001 and 2009, since a low specific vulnerability

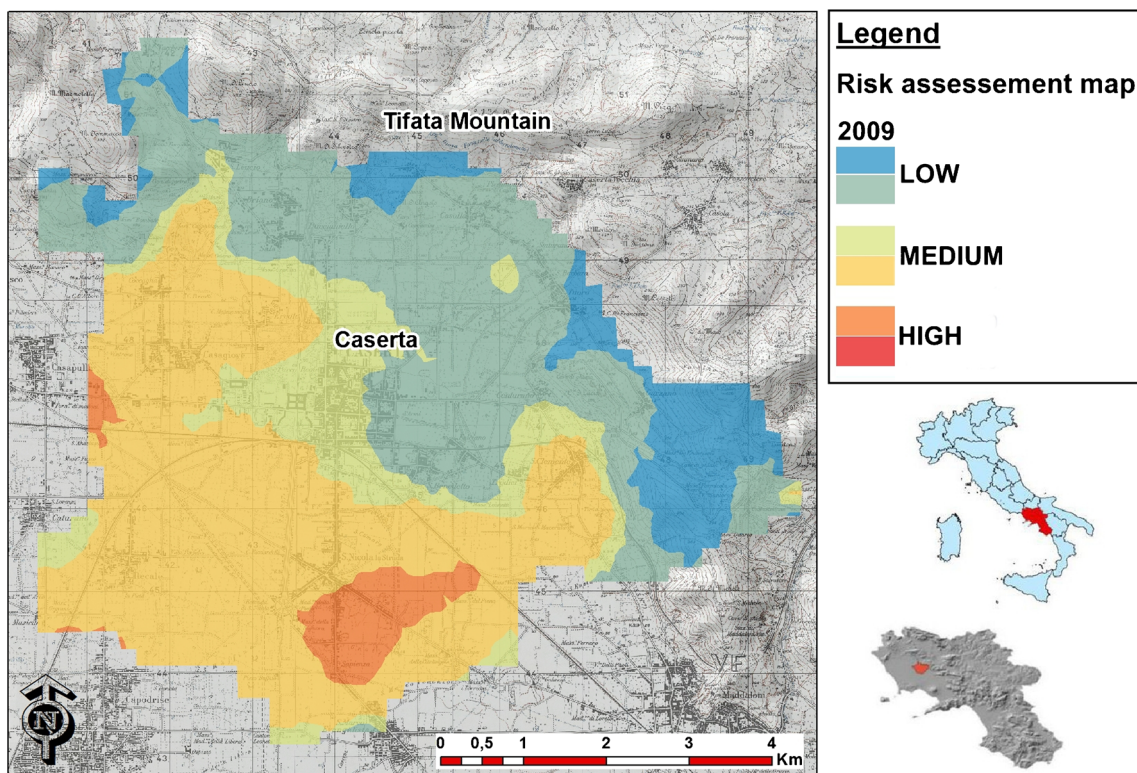


Fig. 10 Groundwater pollution risk assessment map (GRA) for the year 2009

was calculated for this area and the water wells density is generally low. The only exception is constituted by a limited area near the village of Casola, where despite the low specific vulnerability (Figs. 5 and 6), the groundwater value is higher (Fig. 8).

In the Caserta Plain, which is mostly classified as a low specific vulnerability area, the GRA maps for 2001 and 2009 show a medium risk of groundwater contamination due to the existence of a considerable number of water wells in the area. In particular, in 2009, the medium risk affects also the south-eastern area of the plain which was previously showing a low risk (2001 classification in Fig. 9) precisely because of the increased reliance on groundwater resources in that area.

Concerning the high-risk class, even if it involves a limited portion of the study area, an increase of its extension in the southern part of the territory is clearly identifiable between 2001 and 2009. Additionally, in 2009, a high risk of groundwater contamination also appears in a limited area located in the western part of the Caserta Plain, once more due to the drilling and activation of new water wells in that area.

In general, between 2001 and 2009, a slight worsening of the groundwater risk of contamination has occurred in the study area, with a decrease in the percentage of territory falling in the low class and a corresponding increase of the territory falling within the medium and high classes (Table 3).

As demonstrated by the analysis carried out in the Caserta Plain, the inclusion of a parameter concerning the actual groundwater exploitation, which, in turn, represents the groundwater value, gives a better notion on the groundwater risk to contamination with respect to both the intrinsic and the specific vulnerability of the local shallow aquifer. More in detail, while most of the study area is classified as low to medium vulnerable (SINTACS and SINTACS-L maps, Figs. 4, 5 and 6), due to the considerable reliance of the human activities on groundwater resources, the risk of loss or damage due to contamination problems resulted to be medium to high in a wide part of the study area, especially in the plains than in the mountains. Moreover, the increasing pressure on groundwater resources is testified by the worsening in the risk if the GRA maps of 2001 and 2009 are compared.

These findings suggest that it is necessary to do as much research as possible to identify the variations or trends when factors like land use and groundwater exploitation change in status.

Table 3 Portions of land (%) falling into different classes of potential risk of groundwater contamination from NO_3^- between 2001 and 2009

GRA	2001 (%)	2009 (%)	Variation
Low	39.2	32.4	-6.8
Medium	51.7	56.8	+5.1
High	9.1	10.8	+1.7

This would allow the risk map to be updated using the latest information to facilitate continued groundwater management and to raise awareness of the threats to groundwater resources (Mimi and Assi 2009).

Finally, while subjectivity is practically unavoidable when considering regional-scale schemes, a comprehensive application of the risk principles will enable more defensible land surface zoning schemes (Fadlilmawla et al. 2011), and an attempt of providing a validation of the results via comparison with the distributions of specific contaminants (such as nitrate) will enhance the reliability and applicability of the presented approach (Al-Adamat et al. 2003; Andreo et al. 2006; Saidi et al. 2010).

Conclusions

This study proposed a method for assessing groundwater contamination risk through the integration of hazards, intrinsic vulnerability and groundwater value, by means of a GIS platform. Two types of maps were produced for an intensively populated and cultivated area in Southern Italy, the specific vulnerability (SINTACS-L) and the risk (GRA) maps, and the validation of the results was done by comparison with the nitrate concentration distribution.

Large areas, especially in the mountainous portion of the study area, can be classified as a low-risk zone due to the absence of hazards and also due to low vulnerability and usage of the groundwater resources. These areas could consequently be interesting for future development as they are preferable in view of groundwater protection. The results of this study support the great utility of vulnerability and risk indexes as a robust and comprehensive tool for decision-making to promote the environmental and economic sustainability of agricultural systems and urbanization, by creating a sustainable water management plan via (i) a detailed monitoring programme in areas of known pollution threats, (ii) a flexible land use allocation and (iii) the definition of groundwater quality protection zones to prevent degradation of groundwater quality.

Moreover, the ease with which it is possible to dispose of the land use and of the water wells density means that the proposed approach can be easily employed in large-scale applications to other regions and environments.

Despite these positive aspects, it must not be forgotten that the proposed method could be further improved by including the processes involved in the transport, transformation and attenuation of reactive nitrogen species, updating regularly the thematic maps due to the dynamic nature of hazards and groundwater exploitation and taking into account the local conditions governing the water resources dynamic.

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