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Modifying SINTACS method to assess groundwater vulnerability and pollution risk to nitrate

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Abstract: Groundwater as a source of water supply and ecological asset has drawn a growing attention in order to meet the increasing demand of water resources due to fast demographic growth and urbanization, and to economic and agricultural activities intensification. In particular, the assessment of agrochemicals losses from cultivated land and the potential of groundwater contamination, especially from nitrogen species, is a serious issue to effectively meet the measures established in the European Water Framework Directive (Directive 2000/60/EC). The use of indices, describing the intrinsic and the specific groundwater vulnerability are widespread methods to characterize areas affected by non-point agricultural sources. In the present study, the SINTACS method was applied in order to estimate the intrinsic vulnerability of the aquifer underlying the Campanian Plain, an intensively cultivated and densely populated coastal plain located in Southern Italy. Nitrogen losses from the top soil were estimated based on climatic, soil and topographic data using LOS indices. By combing the SINTACS and the LOS indices in a GIS environment, the specific vulnerability of the local unconfined aquifer to nitrogen losses was calculated. Results show that the inclusion of an estimate of the potential percolation of nitrogen species below the agricultural fields, can improve the vulnerability classification of the study area allowing a more detailed and targeted management of groundwater resources and a wiser allocation of land use.

Key words: vulnerability indices, N leaching, GIS, Non-point source pollution

1. INTRODUCTION

Groundwater is considered an important resource to guarantee human and environmental needs, but it is increasingly affected by diffuse and punctual sources of pollution (Morris et al. 2003). The use of nitrogen (N) fertilizers is one of the most widespread non-point sources of pollutant (Mastrocicco et al. 2009; Puckett et al. 2011). Treatment of groundwater pollution is often unpractical, so groundwater vulnerability assessment is a valuable tool for the implementation of agrochemicals management strategies to prevent groundwater pollution. A wide variety of methods has been developed in the past decades to assess groundwater vulnerability (Foster 1987; Gogu and Dassargues 2000; Kazakis and Voudouris 2015). These methods can be broadly grouped in two main categories: (i) process-based mathematical models which are powerful tools to predict pollutants fate but need a the large number of input data; (ii) overlay indices methods based on ratings and weights which can be easily applied at regional scale via GIS because they require less and more accessible data. Although, the indices methods are often strongly affected by subjectivity.

In this study, a combined method was used by applying indices of low data requirements, which can describe separately the vulnerability of the topsoil and of the aquifer system. After applying the SINTACS method (Civita and De Maio 2004) to an unconfined aquifer to gain its vulnerability, in order to estimate the potential pollution risk due to agricultural practice within the same area, the LOS indices (Aschonitis et al. 2012; 2013) were calculated to obtain the vulnerability of the topsoil (30 cm) to nitrogen losses.

The separate analysis and combination of the aforementioned compartments can provide a more robust and detailed description of the response of the whole hydrogeological systems to pollution.

2. SITE DESCRIPTION

The Campanian Plain, which covers approximately 1400 km^2 with a population of more than 1 million inhabitants, shows an heterogeneous land use: the urban area covers approximately 30% of the territory, the agricultural land is about 40% (where a variety of different crops are cultivated) and forests and pastures occupy the remaining 30% of the territory, mainly in the mountainous area.

The Campanian Plain is limited by Massico Mountain and Roccamonfina Volcano to the North, by the carbonatic ranges of Maggiore, Tifatini and Avella Mountains to the Est and by the volcanic systems of Phlegrean Fields and Vesuvio to the South. While on its western side, the Campanian Plain overlooks the Tyrrhenian Sea. The geological evolution of the Campanian Plain begun in the upper Pliocene and proceeded in the Quaternary with a critical extensive-tectonic stress, which brought to a large graben development. The tectonic stretching allowed the development of important volcanic centres (Roccamonfina, Phlegrean Fields and Somma-Vesuvio) in the most depressed areas at the graben borders. Such geological conditions lead to the accretion of thick continental, marine and volcanic deposits (Ortolani and Aprile 1985; Romano et al. 1994). The deepest unit is made by marine clays and sands with an upper limit between -90 m and -20 m above sea level (a.s.l.). The overlying unit is composed by Phlegrean volcano-clastic and volcanic sediments, constituted by pyroclastic sands and cinerites reworked in subaqueous environment. The Campanian Ignimbrite emission took place in different eruptive events (Civetta et al. 1997) and consisted in the emplacement of a pyroclastic rock layer formed by a trachytic-phonolithic flow. The Holocenic sediments, outcropping in the middle of the plain, are irregular successions of clays, silts and peat beds (Barra et al. 1996), while toward the coast dunes and sandbars parallel to coast are present. In the Southern part of the plain, the outcropping unit is an irregular succession of pozzolans, cinerite and sandy pyroclastite due to the Phlegrean activity.

3. MATERIALS AND METHODS

The Underground Digital Terrain Model (UDTM) was obtained by the interpretation of 447 stratigraphic surveys. From the analysis of the UDTM, the predominant units of the unsaturated zones are the Ignimbrite Campana and the Pre-Ignimbrite, which were demonstrated to be an important flow barrier to prevent pollutants migration toward the aquifer (Bruno and Godio 1997).

The water depth, measured in 1000 monitoring wells, ranges from 1 m to more than 70 m.

The effective infiltration was calculated multiplying the recharge for texture coefficient derived from the type of soil cover, identified using the thematic map "Lands of Campania" (Gennaro 2002). The recharge was calculated subtracting the actual evapotranspiration to the recorded rainfall using the climatological data of 6 meteorological stations, covering the period 2006-2016. To calculate the volumes of evapotranspiration the Penman–Monteith formula was applied (Allen et al. 1998). The resulting effective infiltration in the study area ranges from 85 to 348 mm.

Concerning the types of aquifer, 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 (Ruberti et al. 2014).

The hydraulic conductivity for the limestone formation is generally high, ranging from $1x10^{-3}$ m/s to $5x10^{-5}$ m/s, while the volcanic complex has a medium to low permeability with values ranging from $1x10^{-5}$ m/s to $5x10^{-7}$ m/s (Allocca et al. 2007).

The slope of the topographic surface is mild (0-1%) in the coastal area and in the centre of the plain, but moving inland the slope gradually increase, from 15-20% in the piedmont area up to 45% in the mountains.

SINTACS, established for hydrogeological, climatic and impact settings typical of the Mediterranean countries (Civita and De Maio 2004), was applied to evaluate groundwater vulnerability of the study area on the base of the aforementioned data. 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), 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.

The form of the equation is the following:

$$I_{SINTACS} = \sum_{J=1}^{7} P_J W_J \tag{1}$$

where P_J is the rating of each parameter and W_J is the corresponding weight.

According to the description of the seven parameters taken into consideration by the SINTACS method and the ratings proposed by Civita and De Maio (2004), the vulnerability assessment in the study area was developed in GIS environment and all the seven parameters were arranged in raster format, with a regular grid of 200×200 m (Fig. 1).

In order to obtain the intrinsic vulnerability of the area, on the base of the aforementioned data, 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 forth parameter among all the others.

The LOS indices (Aschonitis et al. 2012) estimate the intrinsic vulnerability of agricultural land to water and nitrogen losses in the top 30 cm of soil. LOS indices, calibrated via multiple regression analysis using the GLEAMS model (de Paz et al. 2002), quantify (i) the annual losses of the percolated water beneath the root zone (LOSW-P), (ii) the annual losses of the surface runoff (LOSW-R), (iii) the annual losses of N leaching beneath the root zone (LOSN-PN) and (iv) the annual losses of N through the surface runoff (LOSN-RN).

In the study area to estimate the annual N losses, on the base of the aforementioned data, the LOSN-PN map (Fig. 2) was calculated according to the following formula:

$$\text{LOSN-PN} = \left\{ \begin{array}{l} -0.1536\sqrt{\text{OM}}+2.6981\sqrt{\text{T}}+0.0439\sqrt{\text{Ks}} \\ -0.2046\sqrt{\text{S}}+0.0471\sqrt{\text{PCP}}-0.2515\sqrt{\text{PE}} \\ -0.0116\sqrt{\text{IR}} \end{array} \right\}^2 \tag{2}$$

where LOSN-PN is the amount of N losses beneath the top 30 cm of the soil profile (kg/ha/ year), OM is the organic matter (%) and T is the mean annual temperature (°C), Ks is hydraulic conductivity (mm/day), S is the surface slope (%), PCP is the total annual precipitation (mm/year), PE is the total annual potential evapotranspiration (mm/year), IR is the total annual irrigation amount (mm/year).

The SINTACS and LOSN-PN maps were then combined to gain the potential impact to groundwater resources due to N percolation below the top soil (Fig. 3), according to Uricchio et al. (2004).

4. RESULTS AND DISCUSSION

For the study area, the intrinsic vulnerability ranges from 85 to 205. These values were then divided into 4 intervals of vulnerabilities: from 85 to 115 a low vulnerability class was identified, from 115 to 145 a medium vulnerability class was identified, from 145 to 175 very high vulnerability class was identified and from 175 to 205 very high vulnerability class was identified (Fig. 1).

According to the SINTACS classification, the most vulnerable area of the Campanian Plain coincides with the coastal area where the modern and relict dune systems are located; while the less vulnerable portions of the territory are located in the foothills in the North eastern and southern part of the study area (Fig. 1).

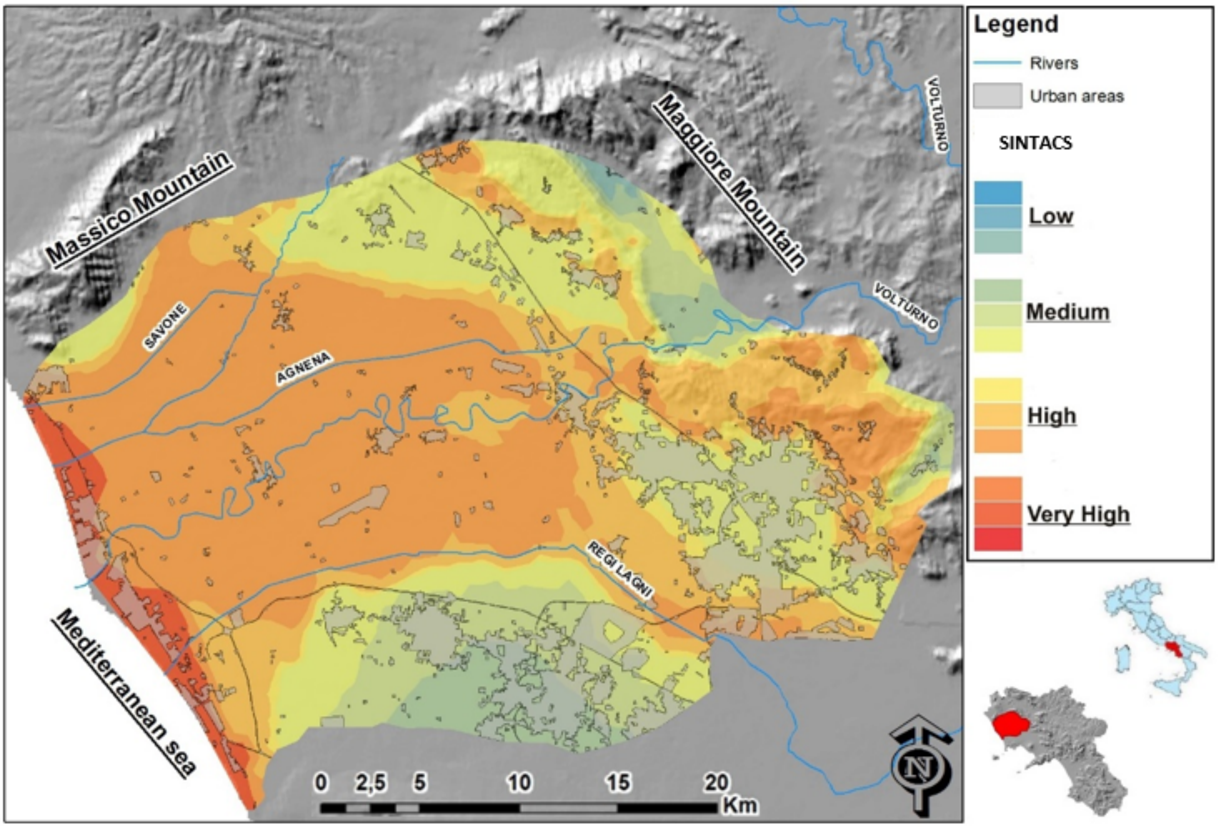

Figure 1. SINTACS map for the Campanian Plain

On the other hand, the annual losses of N leaching beneath the root zone, calculated according to the LOSN-PN index, range from 4 up to 54 kg-N/ha/year (Fig. 2). Also in this case, as with the SINTACS classification, the zone that shows the highest value of leaching is the coastal area. High values of leaching characterize even the southern portion of the study area, which was instead classified as a low vulnerability zone. Small values of N leaching are calculated for the mountainous area at the North eastern and eastern part of the study area. While the North eastern portion also falls in the a low vulnerability area, the eastern portion of the territory was classified as a medium to highly vulnerable area.

Combining the SINTACS and LOSN-PN maps, the potential impact to groundwater resources due to N percolation below the top soil was calculated and represented in Figure 3. The combination of the two indices shows that the coast is still the most endangered portion of the study site but the area interested by a very high impact is wider than the one calculated with the SINTACS method. The same happen in the southern part of the study area, where the specific vulnerability to N leaching is higher than the intrinsic vulnerability of the aquifer. The latter was in fact classified as medium according to the SINTACS method. On the contrary, the mountainous area shows a low specific vulnerability to N leaching either in the North eastern part either in the eastern part of the territory, which was instead classified as highly vulnerable according to the SINTACS method, thus giving a substantial widening of the low vulnerability area. The central portion of the territory does not show a remarkable change in its classification among the SINTACS and the combined method.

5. CONCLUSIONS

This study verifies the suitability of combining different vulnerability indices in the assessment of the potential threat to groundwater resources due to N leaching in an intensively populated and cultivated area in southern Italy.

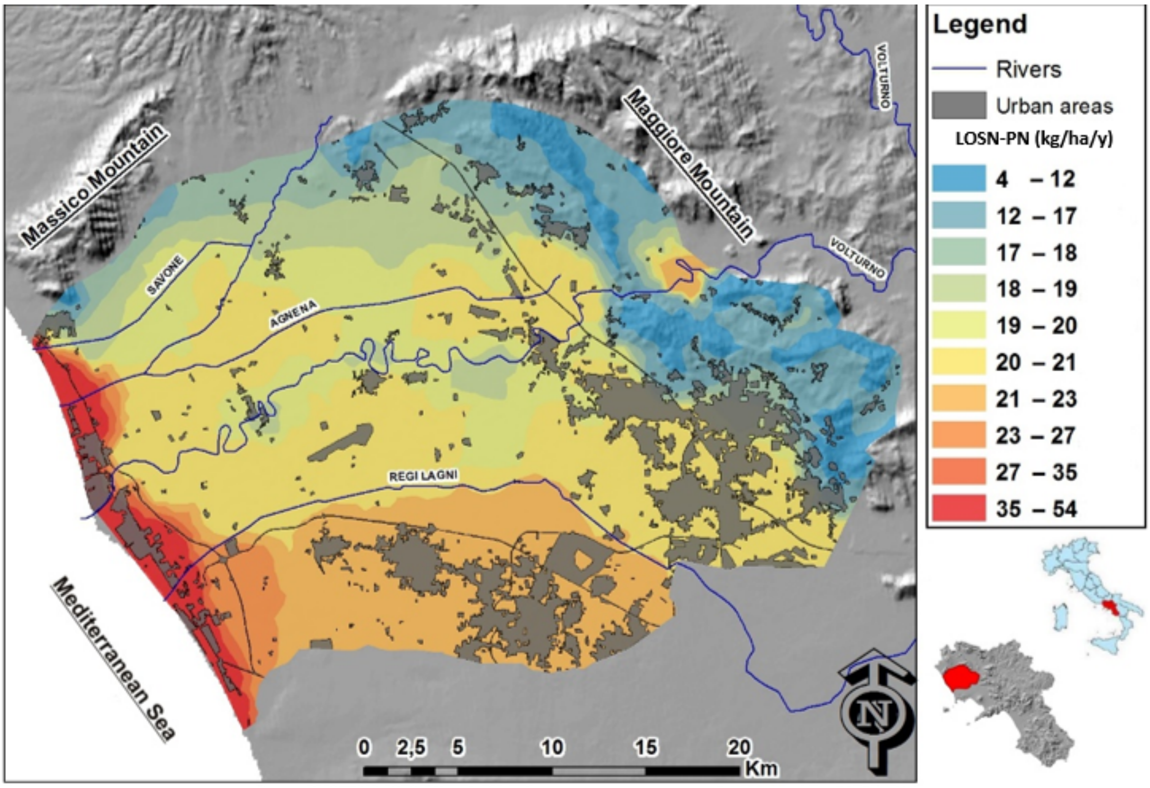

Figure 2. LOSN-PN (kg-N/ha/year) for the Campanian Plain

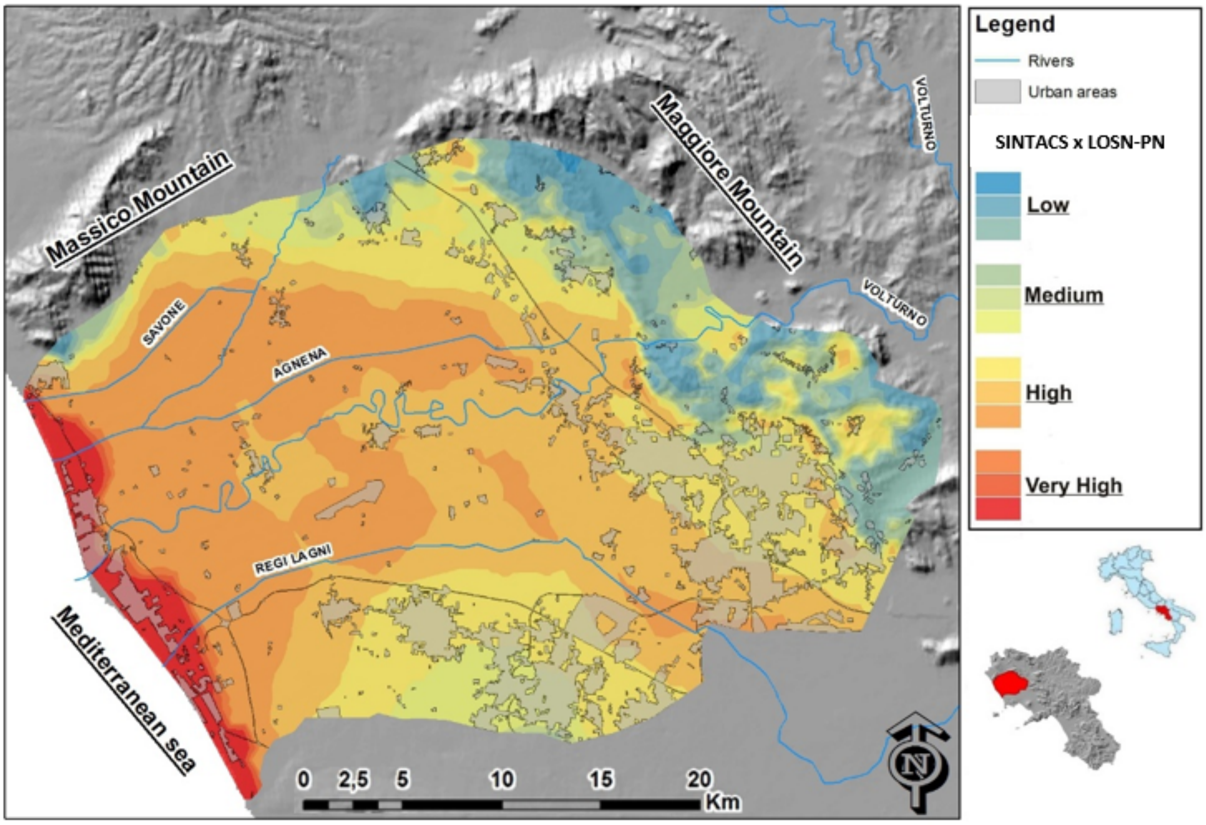

Figure 3. Combination of the SINTACS and LOSN-PN indices for the Campanian Plain.

The SINTACS method was applied to gain the intrinsic vulnerability map for of the local unconfined aquifer while the LOS method was applied to gain the potential percolation of N below the topsoil.

The specific vulnerability to N losses, resulting from the combination of the two indices in a GIS environment, returns a more reliable representation of the distribution of the vulnerable zones in the study area, allowing a more detailed and targeted management of land use at the ground surface and a better allocation and exploitation of the groundwater resources.

The ease with which it is possible to dispose of the basic input parameters to calculate both the SINTACS and the LOS methods, suggests that the proposed method is widely applicable to many other regions and environments, aiming to create a sustainable water management plan, flexible land use allocation, and define groundwater quality protection zones in unconfined aquifers.

Despite these positive aspects, it’s worth to note that the combined application of these two indices could be further improved by the inclusion of the processes involved in the transport, transformation and attenuation of reactive nitrogen species from the topsoil towards the underlying unconfined aquifer.

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