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Vulnerability of groundwater resources to nitrate pollution: A simple and effective procedure for delimiting Nitrate Vulnerable Zones

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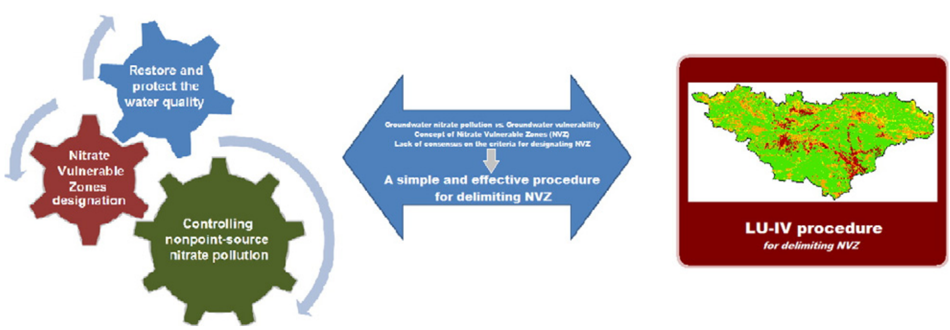
HIGHLIGHTS

- A simple and effective procedure (LU-IV) was developed for delimiting the NVZ.
- LU-IV procedure combines intrinsic vulnerability and risks associated with land use.
- 100% of the alluvial aquifers were affected by or at risk from nitrate pollution.
- High to extreme vulnerability to NO_3-pollution was found in 7% of the territory.
- The current officially designated NVZ should be extended from 328 to 1728 km^2.

GRAPHICAL ABSTRACT



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ABSTRACT

This research was undertaken to further our understanding of the factors involved in nonpoint-source nitrate pollution of groundwater. The shortcomings of some of the most commonly used methods for assessing groundwater vulnerability have been analysed and a new procedure that incorporates key improvements has been proposed. The new approach (LU-IV procedure) allows us to assess and map groundwater vulnerability to nitrate pollution and to accurately delimit the Nitrate Vulnerable Zones. The LU-IV procedure proved more accurate than the most widely used methods to assess groundwater vulnerability (DRASTIC, GOD), when compared with nitrate distribution in the groundwater of 46 aquifers included in the study (using the drainage basin as the unit of analysis). The proposed procedure stands out by meeting the following requirements: (1) it uses readily available parameters that provide enough data to feed the model, (2) it excludes redundant parameters, (3) it avoids the need to assign insufficiently contrasted weights to parameters, (4) it assess the whole catchment area that potentially drains N-polluted waters into the receptor aquifer, (5) it can be implemented within a GIS, and (6) it provides a multi-scale representation.

As the LU-IV procedure has been demonstrated to be a reliable tool for delimiting NVZ, it could be particularly interesting to use it in countries where certain types of environmental data are either not available or have only limited availability.

Based on this study (and according to the LU-IV procedure), it was concluded that an area of at least 1728 km^2 should be considered as NVZ. This sharply contrasts with the current 328 km^2 officially designated in the study area by the Spain's regional administrations. These results highlight the need to redefine the current NVZ designation, which is essential for an appropriate implementation of action programmes designed to restore water quality in line with Directive 91/676/EEC.

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1. Introduction

What do we really understand by "Nitrate Vulnerable Zones"? According to the Nitrates Directive of the European Union (91/676/EEC; Council of the European Communities, 1991) Nitrate Vulnerable Zones (NVZ) are areas of land that drain into waters affected by nitrate pollution. Nitrate from nonpoint sources has been identified as the main cause of groundwater degradation in Europe (Sutton et al., 2011). Of these nonpoint sources, nitrogen fertilization represents the most important input of nitrate into groundwater and may cause a significant change in groundwater geochemistry (Menció et al., 2016). Farmers in designated NVZ are therefore required to comply with measures laid out in action programmes designed to restore water quality.

The Nitrates Directive establishes that both surface freshwater and groundwater should be considered affected by nitrate pollution when their nitrate contents exceed 50 mg L^{-1}. Nitrate levels above this threshold are considered dangerous to human health and to the environment (Sutton et al., 2011). Within the range of 25–50 mg L^{-1} of nitrate, water can be considered at risk of becoming polluted if no protective measures are taken (European Commission, 2000).

Although the EU has made significant efforts to reduce nitrate pollution, there are still important discrepancies in the way that NVZ are designated in different European regions and countries (European Commission, 2010). In fact, recent studies have shown that inadequate designations of NVZ can lead to unsatisfactory results in attempts to reduce water pollution caused by nitrate (Arauzo and Martínez-Bastida, 2015; Arauzo et al., 2011; Worrall et al., 2009).

One major obstacle to a more efficient implementation of EU environmental policies for nitrate pollution control is the lack of consensus on the criteria to be used for designating NVZ (De Clercq et al., 2001). To address this complex issue, it is first necessary to examine the elusive concept of groundwater vulnerability. It is usually defined as "the sensitivity of an aquifer to being adversely affected by an imposed contaminant load" or "the intrinsic susceptibility of an aquifer to contamination" (Witkowski et al., 2007). Two different types of groundwater vulnerability assessment are generally considered: intrinsic and specific assessments. Intrinsic vulnerability is based on an assessment of natural climatic, geological and hydrogeological attributes, whereas specific vulnerability is mainly assessed in terms of the risk of the groundwater system becoming exposed to contaminant loading (Witkowski et al., 2007). In the case at hand, assessing specific groundwater vulnerability to nitrate pollution involves analysing the risk of exposure to N-compounds in areas where there is a considerable degree of intrinsic vulnerability.

Foster (2007) asserted that "there is little doubt that the concept of aquifer vulnerability (and its practical manifestation in land surface mapping) is a valuable tool for groundwater quality protection". Even so, no consensus has yet been reached as to which environmental factors must be considered in assessments of groundwater vulnerability. Aquifer recharge, aquifer media, topography, soil properties, hydraulic conductivity, the lithology of the overlaying strata, groundwater hydraulic confinement and the depth to the water table, all tend to be key attributes for both intrinsic and specific vulnerability. Several authors have also considered groundwater flow, the travel time of the contaminant and local land use in assessments of groundwater vulnerability (Witkowski et al., 2007). On the basis of these parameters, a variety of groundwater vulnerability indexes have been proposed in recent decades (Aller et al., 1987; Anjali et al., 2015; Dixon, 2005; Foster, 1987; Huan et al., 2012; Lubianetzky et al., 2015; Martínez-Bastida et al., 2010; Neshat and Pradhan, 2015; Secunda et al., 1998; Witkowski et al., 2007; Wachniew et al., 2016). Of these, the DRASTIC index (Aller et al., 1987) and the GOD index (Foster, 1987; Foster et al., 2002) have been the most widely used to assess intrinsic groundwater vulnerability.

The DRASTIC model uses seven media parameters (depth to the water table, aquifer recharge, aquifer media, soil media, topography, impact of vadose zone and hydraulic conductivity) in an additive formulation. These parameters are weighted according to their relative importance to the pollution potential. The GOD model incorporates three parameters (groundwater confinement, overlying strata and depth to groundwater) into a multiplicative algorithm. Martínez-Bastida et al. (2010) observed a great similarity between intrinsic vulnerability maps obtained using both the DRASTIC and GOD approaches, underlining the simplicity of the latter. The same authors also suggested that the ratings that DRASTIC assigns to the hydraulic conductivity parameter (which increase with the velocity of the groundwater flow) reflect the ability of the system to transport the pollutant through the saturated zone, but do not assess its vulnerability. Moreover, Hamza et al. (2015) demonstrated that all the DRASTIC parameters are equally significant irrespective of their assigned weights. Stigter et al. (2006) suggested two additional weaknesses of the DRASTIC model: the excessive emphasis on the attenuation capacity of the unsaturated zone and the difficulty of obtaining accurate estimates of aquifer recharge and hydraulic conductivity. With regard to the GOD index, Arauzo (2014) pointed out that the model only provides information about the area above the aquifer and not about the entire aquifer catchment area (given that its G and D parameters are assigned a zero value in areas where there is no groundwater). This imposes a limitation for sloped areas in which advective N-transport can take place in the vadose zone by subsurface runoff, until the water reaches the aquifer.

Debernardi et al. (2012), Holman et al. (2005) and Stigter et al. (2006) all expressed doubts about the reliability of estimations of groundwater vulnerability because of the discrepancies that were sometimes observed between vulnerability maps and nitrate pollution maps. However, Arauzo and Martínez-Bastida (2015) suggested that such discrepancies can be adequately explained by considering advective N-transport and accumulation/dilution processes in the saturated zone and/or N-transport by subsurface runoff in the vadose zone. They highlighted the importance of distinguishing between the NVZ (areas of the catchment area of an aquifer from which N-leaching occurs) and the zones of the aquifer in which groundwater is polluted by nitrate. Unfortunately, on many occasions these two concepts have been mistakenly taken as interchangeable in scientific and technical literature and this has sometimes adversely affected NVZ designations.

In short, the assessment of groundwater vulnerability to nitrate pollution and the delimiting of NVZ could be improved by: (1) using parameters that provide enough useful data to feed the model, (2) eliminating redundant parameters, (3) eliminating the assignment of insufficiently contrasted weights to parameters, and (4) assessing the entire catchment area that could potentially drain waters polluted by nitrate into the receptor aquifer. It should also be implementable in a geographic information system (GIS) and provide a multi-scale representation (ranging from the local to the regional scale).

The primary aim of this study was, therefore, to develop a new method for assessing and mapping groundwater vulnerability to nitrate pollution that meets the above-mentioned requirements. The proposed method includes two steps: (1) applying a new algorithm that improves the assessment and mapping of intrinsic groundwater vulnerability and (2) incorporating a new procedure, based on logical evaluation, for assessing and mapping the specific groundwater vulnerability to nitrate pollution.

The present investigation also sought to further our understanding of the factors involved in the nonpoint-source nitrate pollution of groundwater resources. This was conducted through a joint analysis of groundwater nitrate distribution in a diverse range of aquifers and the NVZ (delineated by the aforementioned method) potentially draining into them. The study area (the upper River Ebro basin, north of Spain) presents great variety in terms of its geology, topography, hydrology, weather conditions and land use. More specifically, the following objectives were established: (1) to model the spatial distribution of nitrate content in the 46 main aquifers of the upper River Ebro basin on an aquifer by aquifer basis, (2) to analyse the relationship between groundwater nitrate distribution, water table elevation and flow direction, (3) to develop a methodology for assessing and mapping intrinsic groundwater vulnerability (the new IV index) and specific groundwater vulnerability to nitrate pollution (the new LU-IV procedure) in a way that improves previous approaches, (4) to generate thematic maps of intrinsic and specific