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Research article

# Assessment of groundwater vulnerability to nitrates from agricultural sources using a GIS-compatible logic multicriteria model

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A B S T R A C T

In the present study an overlay method to assess groundwater vulnerability is proposed. This new method based on multicriteria decision analysis (MCDA) was developed and validated using an appropriate case study in Aragon area (NE Spain). The Vulnerability Index to Nitrates from Agricultural Sources (VINAS) incorporates a novel Logic Scoring of Preferences (LSP) approach, and it has been developed using public geographic information from the European Union. VINAS-LSP identifies areas with five categories of vulnerability, taking into account the hydrogeological and environmental characteristics of the territory as a whole. The resulting LSP map is a regional screening tool that can provide guidance on the potential risk of nitrate pollution, as well as highlight areas where specific research and farming planning policies are required.



## 1. Introduction

The increasing international concern about nutrient overload into the environment has resulted in the introduction of strict regulations for the protection of water resources. Within this context, groundwater contamination by nitrates ($NO_3^-$) from agricultural sources is one of the most widespread threats worldwide (Addiscott and Benjamin, 2004; Karr et al., 2001; Weyer et al., 2001). Due to this threat the EU drew up the Nitrate Directive 91/676/EC concerning the protection of waters against nitrate from agricultural sources.

Since the EU Nitrate Directive was adopted, important differences have been observed in the methods and approaches used to identify Nitrate Vulnerable Zones (NVZs) (European Commission, 2013). Although criteria for identifying the NVZs were established in the Nitrate Directive, the specific procedure for the delimitation of these vulnerable areas is still unclear. Furthermore, recent research has shown that an inadequate designation of NVZs can generate unsatisfactory results in the contamination reduction of affected water bodies (Arauzo and Martínez-Bastida, 2015; Arauzo and Valladolid, 2013; Worrall et al., 2009).

In Spain, the regional administrations are responsible for identifying NVZs from agricultural practices. In general, analysis of water quality data from networks of monitoring stations has been used to designate vulnerable zones, and administrative boundaries and groundwater bodies have been used to delineate the shape of these areas. Furthermore, the emphasis on the evidence of environmental damage, rather than on a proactive planning, can hinder successful conservation of water resources. Therefore, it is necessary to develop a more rational, rigorous and systematic approach.

Until now, several methods for groundwater vulnerability and risk mapping have been proposed. They range from complex deterministic models of the physical, biological and chemical nitrate leaching processes occurring in vadose zone and saturated zone (De Paz and Ramos, 2004; Lasserre et al., 1999; Ledoux et al., 2007; Srinivasan and Arnold, 1994), to methods that are based on overlay and index techniques to obtain a final vulnerability score. Index methods are based on combining rated maps of various physiographic factors (e.g., depth to water table, aquifer type, soil organic carbon content) of the region by assigning a subjective numerical score to each factor. Models of index methods include DRASTIC (Aller et al., 1987); GOD (Foster, 1987); AVI (Van Stempvoort et al., 1993); EPIK (Doerfliger et al., 1999); SINTACS

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(Civita, 1994); ISIS (Civita and De Regibus, 1995); SI (Ribeiro, 2000) and IPNOA (Padovani and Trevisan, 2002).

The traditional GIS-based multicriteria decision analysis (GIS-MCDA) approaches, i.e. the Boolean overlay and the weighted linear combination (WLC) have two fundamental problems with their use and interpretation. The first is related to the standardization of factors, where the common approach is to rescale the original criteria into comparable units by simple linear transformation, although in some cases a non-linear standardization would be more appropriate. The second problem stems from the logics aggregation. WLC approach is based on a "permissive" procedure of aggregation that allows a full trade-off among factors, given that in actual situations this compensation would only take place to a certain extent, while the Boolean overlay approach uses a Boolean AND or a Boolean OR to obtain a strict outcome with no trade-off (Drobne and Lisec, 2009; Eastman, 1999).

Real decision-making about "vulnerability," however, is shaped by a variety of conditions, including not only simultaneity and replaceability, but also mandatory, desired and sufficient requirements. The Logic Scoring of Preferences (LSP) method (Dujmović, 1996), unlike traditional MCDA approaches, expresses flexible logic conditions observed in the nature of environmental factors (Dujmović and Scheer, 2010; Dujmović and Tré, 2011; Dujmović et al., 2010, 2008). Consequently, it is realistic to expect that the inherent flexibility of the LSP approach can provide highly accurate and justifiable models for GIS applications (Dujmović and Scheer, 2010; Dujmović et al., 2009).

The aim of this work is to develop a territory-wide approach to assess groundwater vulnerability with the use of GIS in order to combine spatial information on hydrogeological characteristics, the natural attenuation (denitrification capacity of soil) and the effect of topography and climate (infiltration potential). Since the ultimate objective of NVZs designation is to prevent nitrate contamination from agricultural sources, the agricultural nitrogen loads are included in the risk assessment. In order to consider the complex relation between these different environmental and hydrogeological factors, and to overcome the weaknesses of traditional MCDA approaches, LSP was selected as aggregation technique. To facilitate the understanding of the study, Vulnerability Index to Nitrates from Agricultural Sources (VINAS-LSP) was applied to a case study in Aragon (Northeast of Spain).

## 2. Study area and problem definition

The geographic region of Aragon, situated in NE of Spain, covers an area of 47.719 km$^2$. Aragon can be divided into three distinct areas from north to south; the central Pyrenees in the north, the Ebro depression in the centre and, the Iberian system mountain in the south (Fig. 1).

The Ebro River system is one of the most significant river basins in the Iberian Peninsula. The region has a Continental Mediterranean climate, with warm summers and cold winters. The mean annual temperature varies between 6 °C (in the colder regions of Pyrenees) and 15 °C (in central zones). The precipitation levels vary along the territory. The mountainous regions present the higher mean precipitation levels (between 800 and 1200 mm yr$^{-1}$), while the central zones present lower rainfall levels (between 300 and 400 mm yr$^{-1}$) (DGA, 2007).

According to the report from the Commission to the council and the European Parliament on the implementation of Council Directive 91/676/EEC, in Aragon, all groundwater bodies are affected or at risk of being so by nitrates from agricultural sources (European Commission, 2013). In 2010, nitrate concentrations in groundwater exceeded the "Maximum Acceptable Level" (MAV) equal to 50 mg $NO_3^-$ L$^{-1}$ at 20% of monitored sites of Aragon. Moreover, quality at 57% of groundwater monitoring points was above 15 mg $NO_3^-$ L$^{-1}$, suggesting that these control points could be subjected to nitrogen inputs from human activities (Hinsby et al., 2008; Panno et al., 2006).

The designation of NVZs implies that in these areas, farmers are required to comply with the measures laid out by local/regional water quality protection and restoration programs. It is therefore reasonable, from a methodological point of view, to propose a new method for the designation of these NVZs based on hydrogeological and environmental factors, instead of on administrative boundaries (municipal, provincial, etc.), which is the case of Spain.

## 3. Development of the spatial multicriteria model

The different GIS-MCDA approaches differ significantly in the details of how values are assigned and combined, but the common purpose of these diverse methods is to provide a specific criterion function for computing an overall degree of suitability (Dujmović et al., 2009). In this study, the criterion function describes the relationship between inputs (environmental and hydrological factors) and a complex output related to vulnerability, where each cell value should indicate the continuous degree of membership [0, 1] that elementary criteria as a whole have within a fuzzy "vulnerability" class. This calls for a framework to integrate factual information on groundwater vulnerability with rational and structured preferences of decision-makers.

Fig. 2 shows a high-level view of major steps followed in this study. First, the problem and the purpose of the study must be clearly defined. The next step is the selection of elementary criteria (factors) that will be used in the evaluation. In this point, the statistical independence between the set of selected factors is verified by Pearson's correlation coefficient technique. Afterwards, the standardization process is carried out by transforming the different measurement units of the raster datasets (e.g. soil organic carbon content, pH, terrain slope, mean rainfall, etc.) into a comparable range [0, 1] using fuzzy membership functions. In the next point, a preliminary LSP-system factor tree is established for decomposing the complex decision problem. Then, a pairwise comparison questionnaire was made for eliciting expert opinions. Consequently, Analytical Hierarchy Process (AHP) (Saaty, 1980) was selected to obtain the factor weights (relative importance). After that, the next step involves selecting an appropriate LSP aggregation structure to combine the elementary criteria (factors). At the end of the study, a Global Sensitivity Analysis (GSA) was carried out to quantify the output uncertainty due to the uncertainty in the elementary criteria. Finally, a statistical technique was used to test the validity of the spatial multicriteria model output.

### 3.1. Selection of elementary criteria (factors)

In a regional planning context, groundwater vulnerability depends on the degree of aquifer vulnerability to $NO_3^-$ leaching (intrinsic vulnerability) as well as on a range of environmental factors involved both in the natural attenuation and water infiltration processes.

The inclusion of factors used here is based mainly on an extensive literature review and the judgment of the authors and environmental consultants. In order to perform the study, eleven factors were selected and clearly classified into four main groups according to their participation in the main processes involved in the evaluation. A brief description of VINAS-LSP factors is shown in Table 1 and described below.

The first group comprises factors related to intrinsic vulnerability (hydrogeological factors, HF), i.e. aquifer type ($HF_{AT}$), permeability of vadose zone ($HF_{PV}$) and water table depth ($HF_{WD}$).