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Article

DRASTICAI, A New Index for Groundwater Vulnerability Assessment – A Portuguese Case Study

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Abstract: Groundwater vulnerability assessment has become a useful tool for groundwater pollution prevention. Groundwater vulnerability maps provide useful data to protect groundwater resources. The identification of agricultural patterns is an important issue for optimized land management. The Tagus river watershed is the backbone of this survey. Naturtejo UNESCO Global Geopark, in central inland Portugal, corresponds to a rural territory. Intensive agricultural practices showed a rising tendency in the last decades. The most internationally used method for vulnerability evaluation is the DRASTIC index. In this survey, the DRASTICAI index is introduced. A new attribute - Anthropogenic Influence - is here added. Five levels of growing vulnerability, from low to high, can be here acknowledged. Idanha-a-Nova municipality is the most affected by intensive farming activities. A robust assessment of groundwater quality has a key role. Climate change scenarios and water scarcity are important issues in years to come. Therefore, optimized groundwater management is essential to consider in policy-making strategies.

Keywords: Naturtejo Geopark; groundwater; vulnerability; DRASTIC; DRASTICAI; GIS

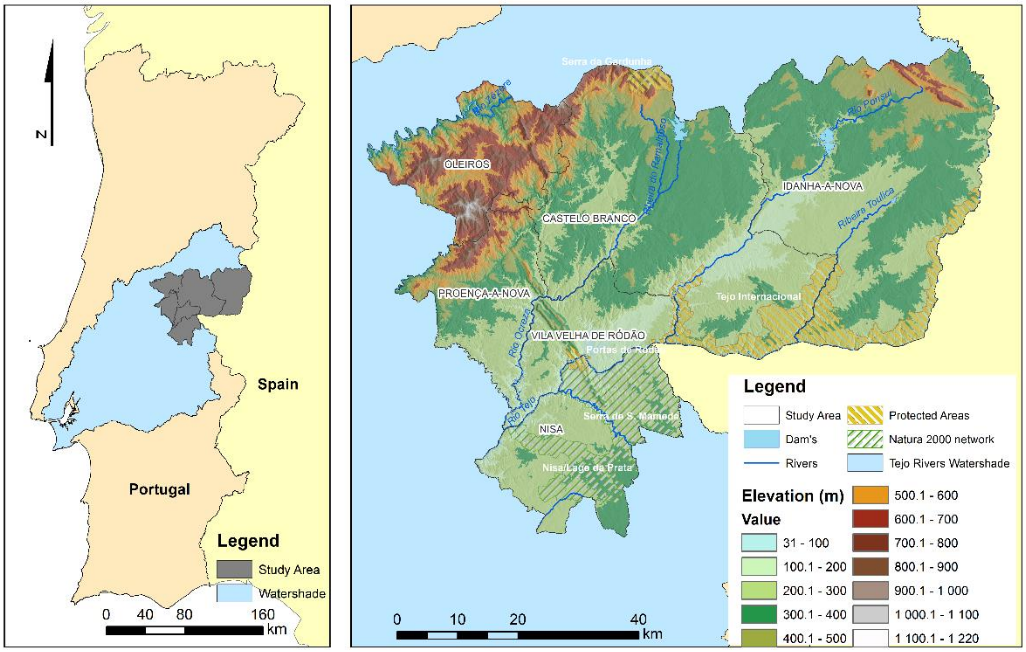
1. Introduction

Nowadays, groundwater vulnerability assessment has become a useful tool for groundwater pollution prevention. Groundwater vulnerability maps provide useful data to protect groundwater resources and to work as a tool for water management, allowing to consider changes in agricultural practices and, therefore, land use optimization [1–7]. Several authors acknowledge two different types of groundwater vulnerability, intrinsic and extrinsic or specific [8]. The first is a function of hydrogeological factors and the second is defined through the addition of attributes defining the potential anthropogenic influence. The most widely used method of intrinsic vulnerability assessment is the DRASTIC index [9], as it is easy to compute with minimum data requirement.

The study area is in the center of inland Portugal, close to the Spanish border and included in the district of Castelo Branco. This area overlaps the most of the area of Naturtejo UNESCO Global Geopark, created in 2006, a territory with an outstanding geological heritage, that comprises 176 geosites, 9 of them with hydrogeological importance, such as springs, hot springs, fountains, or medicinal water sources [10]. Geographically located, within the Central Iberian Zone of the Iberian Massif, lies at the transition between the Central Cordillera (to the North) and the Alentejo peneplain (to the South).

This surveyed zone is in the hydrographic watershed of the Tagus River, one of the largest hydrological system of Western Europe that cross almost the whole Iberian Peninsula. This basin includes rivers such as Zêzere, Erges, Ocreza, Ponsul, or Tagus (that establishes the southern limit of the district) and streams like Meimoa, Aravil, or Sertã.

The oldest bedrock comprises mainly Neoproterozoic and lower Cambrian rocks, with impermeable metasediments (shales and metagrauvaks) from Beiras Group [11,12] forming wide flattened areas. The catchment is cut off by Lower Ordovician Armorican Quartzite Formation [13,14]. Quartzites characterized by cracks and fissures, with minor intercalations of pelite, are the most abundant lithology. These rocks are found in thick quartzite beds in the ridges of Penha Garcia, Monforte da Beira, Muradal, Unhais-o-Velho ou Talhadas, with the main NW–SE direction directly related with the Variscan deformation. Variscan and late-Variscan magmatic bodies intruded the Beiras Group bedrock in Castelo Branco [15], Penamacor-Monsanto [16], Fundão [17], Covilhã [18] and Oledo [19]. Continental sediments of Cenozoic age with variable permeability can be found (arkoses, conglomerates, and breccia), in Sarzedas and Lower Tagus intermountain basins [20].



a) b)

Figure 1. a) Study area, included in the Naturtejo Geopark, and Tagus watershed; b) Municipalities; Main rivers; Dams; Protected areas; Natura 2000 Network and Elevation map.

The main aim of this study was the evaluation of the groundwater vulnerability to pollution, Tagus river's watershed more properly in the Naturtejo Geopark (Fig. 1), using a modified DRASTIC method in a GIS environment. The modified DRASTIC index (DRASTICAI) was made by appending a new attribute designated as Anthropogenic Influence.

2. Materials and Methods

The DRASTIC model was developed by the U.S. Environmental Protection Agency (EPA) to evaluate the groundwater contamination potential for the entire United States. This model is based on the concept of the hydrogeological setting, which is defined as a composite description of all the major geologic and hydrologic factors that affect and control the groundwater movement into, throughout, and out of the area. The acronym rep-

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resents seven hydrogeological parameters taken into consideration in the evaluation procedure on Depth to groundwater (D), Aquifer Recharge (R), Aquifer media (A), Soil media (S), Topography (T), Impact of the Vadose Zone (I), and Hydraulic Conductivity (C) of the aquifer. Each DRASTIC parameter is evaluated concerning the others to determine the relative importance of each and is then assigned a relative weight, ranging from 1 to 5. The most significant parameters are given a weight of 5, while the least significant receive a weight of 1 [9]. The purpose of the DRASTIC index implies multiplying each factor weight (Table 1) by its category rating (Table 3), where rating (r) reflects the significance of classes and weight (w) designates the importance for the parameter, as follows:

$$DRASTIC = (D_r \times D_w) + (R_r \times R_w) + (A_r \times A_w) + (S_r \times S_w) + (T_r \times T_w) + (I_r \times I_w) + (C_r \times C_w) \quad (1)$$

In this study, one extra parameter was added to the DRASTIC model to map groundwater vulnerability more accurately by, including the Anthropogenic Influence (AI). This new parameter, was assigned a weight value equal to 5, and the modified DRASTIC index, DRASTICAI, computed using the following equation:

$$DRASTICAI = (D_r \times D_w) + (R_r \times R_w) + (A_r \times A_w) + (S_r \times S_w) + (T_r \times T_w) + (I_r \times I_w) + (C_r \times C_w) + (AI_r \times AI_w) \quad (2)$$

Where D is the depth to groundwater, R is the recharge rate (net), A is the aquifer media, S is the soil media, T is the topography (slope), I is the impact of the vadose zone, C is the conductivity (hydraulic) of the aquifer, and AI is the Anthropogenic Influence (Table 1):

Table 1. Assigned weights for DRASTIC parameters (Source: [9]) and DRASTICAI.

Parameters	Weight
Depth	5
Recharge	4
Aquifer media	3
Soil media	2
Topography	1
Impact of vadose zone	5
Hydraulic conductivity	3
Anthropogenic Influence	5

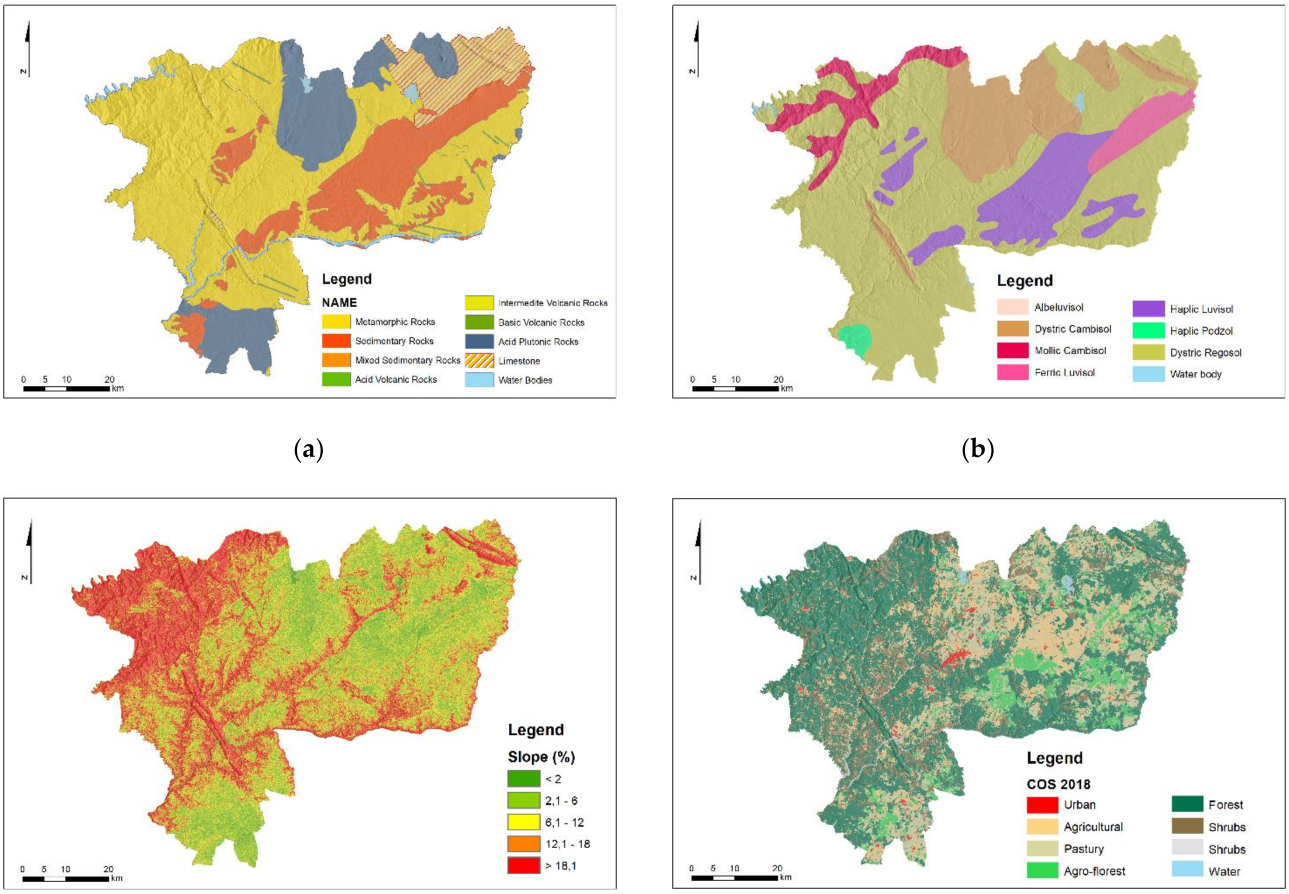
For the mention parameters, different data sources were used (Table 2). Geographical information was projected using EPGS (European Petroleum Survey Group - Geodetic Parameter Dataset) code 4326 | WGS 84 as the reference system. The maps were clipped using the study area borders.

The Global Lithological Map, the FAO Harmonized Soil Map, the SRTM Elevation Map, and the Land-use Map (Figure 2) were used to produce the input attributes' layers. ArcGIS 10. was used to process the datasets and compute the eight input variables.

Table 2. Data type, source, format, and respective references of the DRASTIC /DRASTICAI parameters.

Parameters	Data Type	Source	Format	Reference
Depth	Interpolation	SNIRH and IGEM	Table	[21,22]
Recharge	Location Map	ARH Tejo	Raster	[23,24]
Aquifer media	Geology Map	Global Lithological Map database v1.1	Polygon	[25]
Soil media	Soil Map	FAO	Polygon	[26]
Topography	Elevation Map	Global Digital Elevation Model	Raster	[27]
Impact of vadose zone	Geology Map	Global Lithological Map database v1.1	Polygon	[25]
Hydraulic conductivity	Driven Soil Map	FAO + 3D Hydraulic DB	Raster	[26,28,29]
Anthropogenic Influence	Land use 2018	COS 2018	Polygon	[30]
Study Area	Administration	CAOP 2020	Polygon	[31]

Depth point information was collected from the Spanish and Portuguese piezometers network using the dataset from 1986 to 2020, in a total of 23 locations [21,22], 13 in Portugal, and 10 in Spain. The Inverse Distance Weighted (IDW) algorithm was used for interpolation purposes and, finally, a raster data file produced corresponding to a continuous Depth layer, along the surveyed area. The Recharge rate layer was obtained from the ARH Tejo database [24] and it is expressed in mm/year. The Hydraulic conductivity (KS) layer used the SoilGrids (FAO)and the EU-SoilHydroGrids ver1.0 [29] and downloaded for a 2 m depth.



(**a**) (**b**)

(**c**) (**d**)

Figure 2. Base Map variables of the study area: **a**) Lithology; **b**) Soil; **c**) Slope and **d**) Anthropogenic Influence.

The obtained layers were reclassified and transformed into raster files, considering the adopted set of ranges and rates indicated (Table 3).

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Table 3. DRASTIC (Source:[9]) and DRASTICAI parameters.

DRASTIC/DRASTICAI	Range	Rating
	30.5	1
	22.9 – 30.5	2
Depth to groundwater (m)	15,2 – 22.9	3
	9.1 – 15.2	5
	4.6- 9.1	7
	< 50	1
	50 – 100	3
Recharge rate (net) (mm)	100 – 150	6
	150 – 300	8
	> 300	9
	Metamorphic rocks	3
	Sedimentary Rocks	
	Acid volcanic rocks	
Aquifer media	Intermediate Volcanic Rocks	3
	Basic Volcanic Rocks	
	Acid Plutonic Rocks	4
	Limestone	6
	Coarse	6
Soil media	Medium	9
	Null / No information	10
	> 18	1
	12 – 18	3
Topography (slope) (%)	6 – 12	5
	2 – 6	9
	< 2	10
	Metamorphic rocks	4
	Sedimentary Rocks	
	Acid volcanic rocks	
Impact of the vadose zone	Intermediate Volcanic Rocks	4
	Basic Volcanic Rocks	
	Acid Plutonic Rocks	4
	Limestone	6
	< 4.1	1
Hydraulic Conductivity of the aquifer (m/d)	12.2 – 28.5	4
	> 28.5	6
	Water body and Waste land	1
	Forest and Shrub land	2
	Built up with very low density	5
Anthropogenic Influence	Agriculture	
	Built up with low density	7
	Built up with medium density	8
	Built up with high density	9

For the further computation of DRASTIC and DRASTICAI indices, the eight thematic maps were gathered as shown in Figure 3.

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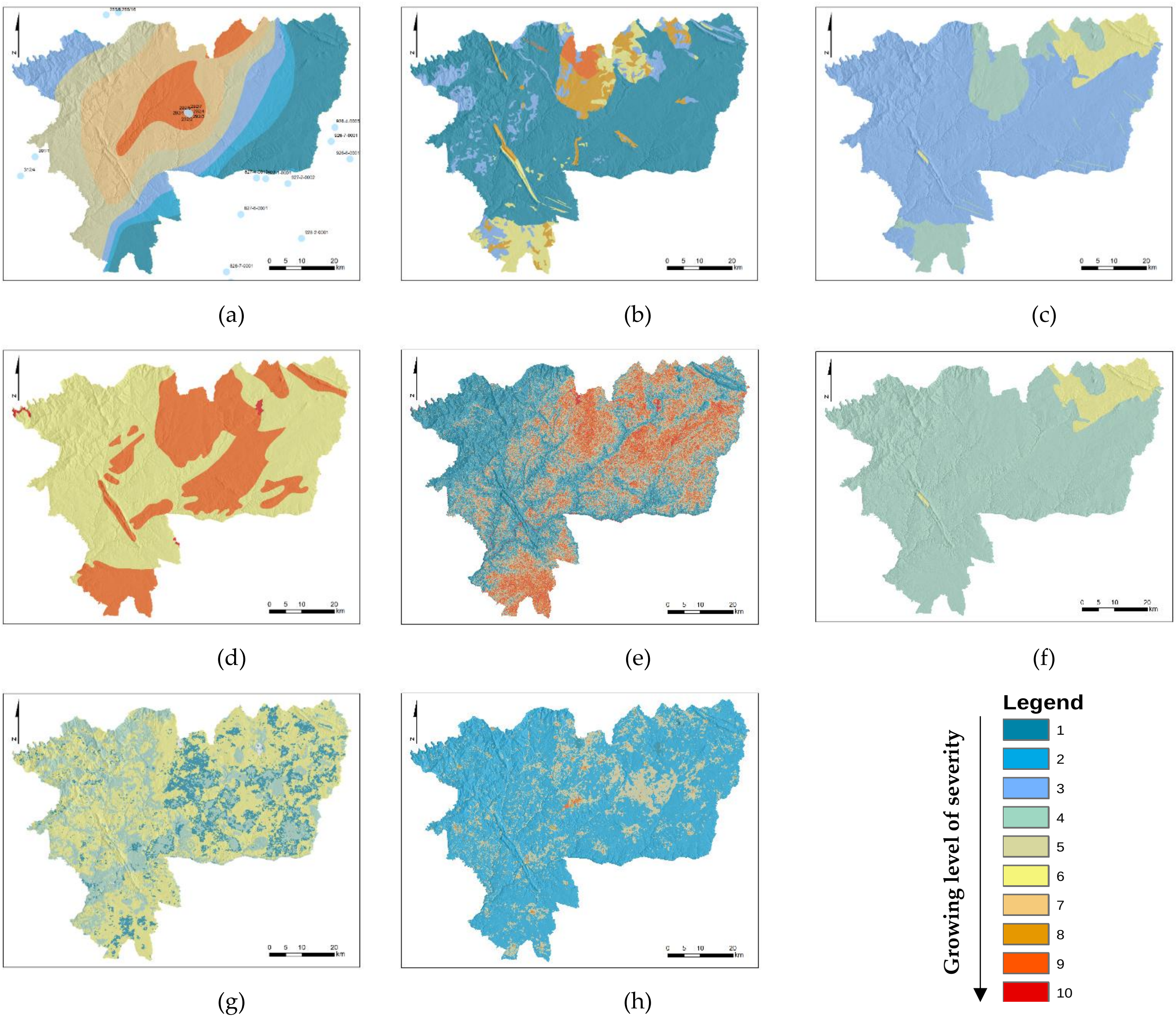

Figure 3. DRASTIC and DRASTICAI layer attributes: (**a**) Depth; (**b**) Recharge; (**c**) Aquifer media; (**d**) Soil media; (**e**) Topography (slope); (**f**) Impact of the vadose zone; (**g**) Hydraulic Conductivity and (**h**) Anthropogenic Influence.

3. Results

The DRASTIC index was constructed using equation (1). The obtained results were reclassified in different classes, corresponding to the low vulnerability (54-119, 87.9 %), medium/intermediate vulnerability (119-149, 10.4 %), and high vulnerability (> 149, 1.7 %; Figure 4a). The DRASTICAI index was composed based on the DRASTIC index using the equation (2). The DRASTICAI index considers the reclassification of the obtained results in different classes, corresponding to a low vulnerability (53-119, 65.8 %), medium/intermediate vulnerability (119-149, 28.4 %), and high vulnerability (> 149, 5.8 %; Figure 4b).

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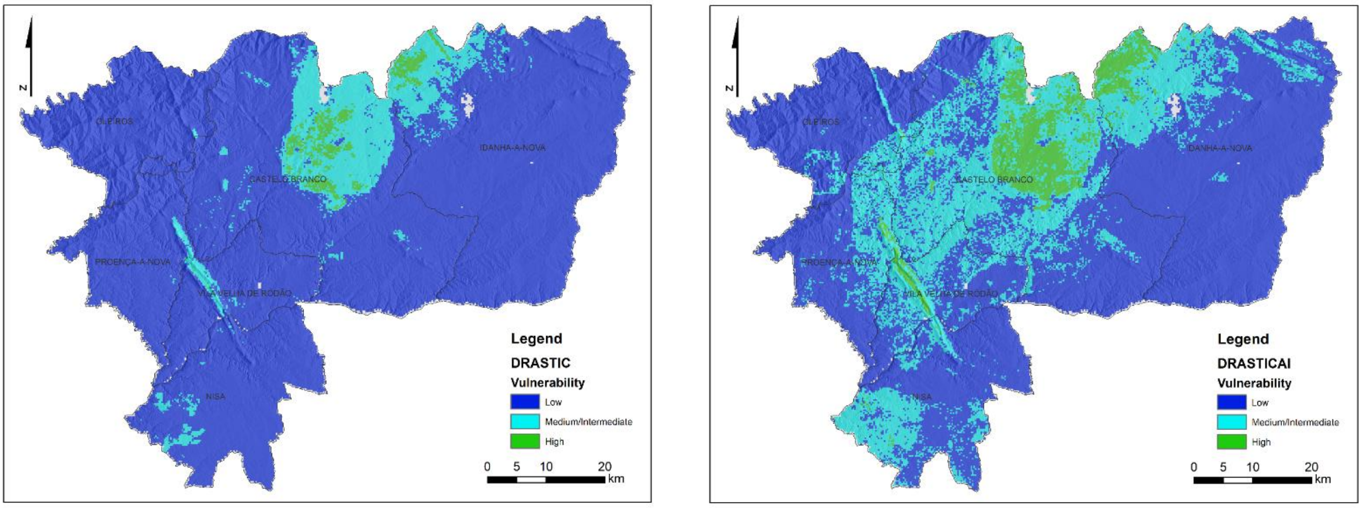

(**a**) (**b**)

Figure 4. DRASTIC (**a**) and DRASTICAI (**b**) maps.

The DRASTIC risk map highlights two different levels of vulnerability: low (87.9% of the total area) and moderate (10.4% of the total area) (Figure 4a). The northern Idanha-a-Nova and Castelo Branco areas show low vulnerability (105–119) as the remaining territory is moderately vulnerable (120–138). However, when analyzing the DRASTICAI map it is possible to identify considerable changes in the spatial patterns of vulnerability (Figure 4b). Indeed, three levels of growing vulnerability, from low to high, can be acknowledged. Idanha-a-Nova municipality is the most affected by the anthropogenic influence due to intensive farming activities.

4. Discussion

Land use parameters can significantly affect groundwater quality. Anthropogenic factors affecting water quality in rural areas differ from those in urban areas. In rural areas, they include agriculture practices, e.g. use of fertilizers, herbicides, and pesticides; river siltation due to erosion; nutrient loading in waters; run-off from degraded forestall areas; and animal husbandry. Changes in land cover and more specifically in soil use patterns play an important role in water flow and consequently, in water quality [32] The surveyed area is mainly dedicated to intensive agriculture which poses important questions regarding groundwater monitoring and quality assessment (Figure 3). Indeed, groundwater resources in areas that are significantly dedicated to agricultural activities, generally display higher nitrate content, resulting in deterioration of water quality and a high non-carcinogenic risk to human health [33–35]. Therefore, increasing attention is globally dedicated to identifying effective approaches aiming at the prevention and management solutions for groundwater pollution assessment and water safety [36].

The DRASTIC index highlights a predominant low/moderate vulnerability (87.9 %), and, thus, reassuring a geological and hydrogeological framework providing natural protection against groundwater contamination. However, when considering the anthropogenic influence, using land-use parameters, the obtained index (DRASTICAI) showed a moderate-high vulnerability increasing from 12.1% to 34.2%, and, therefore, indicating a high level of risk caused by human hazards. Thereby, more vulnerable areas are coincident with agricultural and urban land cover areas.

The algebraic subtraction between the DRASTIC and DRASTICAI maps shows an important contribution of the anthropogenic influence (Figure 5). It is possible to mention all over the surveyed area, but specifically, in Idanha-a-Nova municipality, a raising effect from low/moderate up to highly vulnerable.

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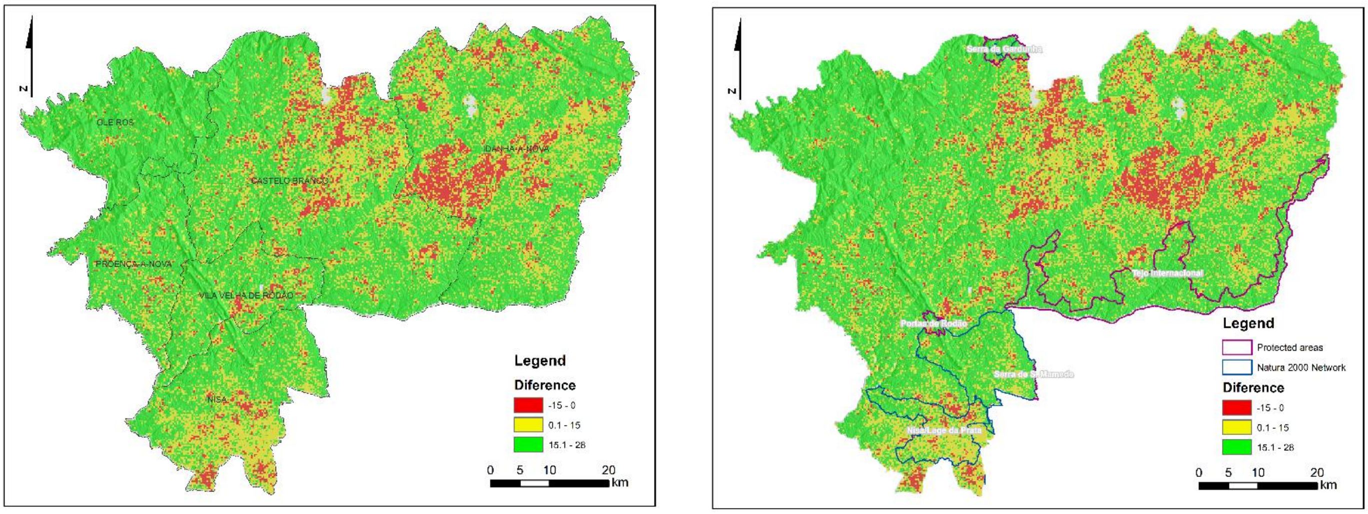

(a) (b)

Figure 5. Algebraic subtraction between the DRASTIC and DRASTICAI (**a**) municipalities within the study area, (**b**) Protected areas, and Natura 2000 Network areas overlap.

Finally, to stress that the understanding of field conditions coupled with human activities allows a robust assessment of groundwater quality and plays a fundamental role in decision-making and the definition of efficient management strategies for groundwater monitoring and abstraction.

Future developments will include an extension of the explored methodologies to other neighbor areas aiming at groundwater quality assessment at a regional scale [37–42].

5. Conclusions

Groundwater is an essential and strategic resource for social and human sustainable development, especially in regions of water scarcity and cyclic drought periods under climate changes scenarios.

There is an urgent need to develop efficient management strategies for the sustainable use and protection of groundwater resources. To this aim, it is imperative to have suitable tools for effective monitoring and assessment of groundwater resources at the watershed scale. Effective management is pivotal for the sustainable management of groundwater resources.

This survey aimed the evaluation of the groundwater vulnerability to pollution, in the Naturtejo Geopark area, using a modified DRASTIC index - DRASTICAI. This new index was constructed by adding a new attribute designated as Anthropogenic Influence. The DRASTICAI spatial patterns indicate a clear influence of anthropogenic activities, mainly in the Idanha-a-Nova municipality.

Water is one of the most strategic resources in the world. Portugal has important resources of groundwater that may be strategic to face the expected dry years to come.

Supplementary Materials: The following are available online Fig.S1. Source Parameters layers.

Author Contributions:. Conceptualization, Teresa Albuquerque and Natália Roque. methodology, Teresa Albuquerque and Natália Roque, software, Natália Roque, validation, Teresa Albuquerque, Natália Roque; formal analysis, Teresa Albuquerque and Natália Roque; investigation, Teresa Albuquerque, Natália Roque, Joana Rodrigues, Margarida Antunes and Catarina Silva .; resources, Teresa Albuquerque, Natália Roque, Joana Rodrigues, Margarida Antunes and Catarina Silva.; data curation, Teresa Albuquerque.; writing— Teresa Albuquerque, Natália Roque, Joana Rodrigues, Margarida Antunes and Catarina Silva, visualization, Teresa Albuquerque, Natália Roque, Joana Rodrigues, Margarida Antunes and Catarina Silva.; supervision, Teresa Albuquerque, project administration, Teresa Albuquerque.; funding acquisition, Teresa Albuquerque and Margarida Antunes. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: data supporting reported results can be found:

Source	Links	Reference
SNIRH	https://snirh.apambiente.pt/	[21,22]
IGEM	http://info.igme.es/BDAguas	
ARH Tejo	https://sniamb.apambiente.pt/content/cat%C3%A1logo	[23,24]
Global Lithological Map database v1.1	https://www.geo.uni-hamburg.de/en/geologie/forschung/geochemie/glim.html	[25]
FAO - Harmonized World Soil Database v 1.2	http://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/	[26]
Global Digital Elevation Model	https://lpdaac.usgs.gov/products/astgtmv003/	[27]
3D Hydraulic DB	https://esdac.jrc.ec.europa.eu/content/3d-soil-hydraulic-database-europe-1-km-and-250-m-resolution	[26,28,29]
COS 2018	https://www.dgterritorio.gov.pt/Carta-de-Uso-e-Ocupacao-do-Solo-para-2018	[30]
CAOP 2020	https://www.dgterritorio.gov.pt/cartografia/cartografia-tematica/caop	[31]

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