

Research article

Evaluation of Entre-os-Rios Thermal Aquifer Vulnerability Using DRASTIC Index

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Abstract.

The “Entre-os-Rios” thermal aquifer has a protection perimeter buffer zone for avoiding water contamination. A vulnerability map was generated, using geographic information systems (GIS) tools and the DRASTIC index, to evaluate the risk of contamination of the perimeter area. The results showed that the protection perimeter buffer zone has an insignificant to moderate risk of pollution, with the DRASTIC index’s values ranging from 47 to 127 points, and an average pollution vulnerability of 79 points. The alluvium-covered land is vulnerable to moderate contamination but is located far from the catchment point. Areas of minimal risk correspond to locations where the granitic massif has not been altered significantly.

Keywords: geographic information systems, vulnerability map, protection perimeter buffer zone, DRASTIC index

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1. Introduction

The abundance of natural mineral waters and spring waters in Portugal has a high ecological heritage value. The undeniable added value that they have allowed, since 1928, Portuguese legislation established protection perimeter buffer zone. The delimitation of these zones integrates a resource management tool, with a view to its quantitative, qualitative, and ecological preservation. The importance of the “Entre-os-Rios” thermal aquifer in the life and economy of this area goes back to the 1920s when the thermal complex was raised. The current agreement for the exploration of natural mineral water has been signed with the “Instituto Nacional para o Aproveitamento dos Tempos Livres dos Trabalhadores” (INATEL) in 1997 [1]. In 2003, the Decree order n.º 203/2003 has defined the protection perimeter buffer zone for the “Barbeitos” borehole (immediate, closed, and distant zone), based on parameters that support a sustainable exploration of the resource [2]. Given the significance of this Thermal Complex to the local and regional economies, is essential to implement protective and planning measures adapted to the reality under consideration. By establishing a protection perimeter buffer zone, the risk of groundwater contamination is reduced [3].


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The need to protect groundwater involves considering an aquifer's vulnerability to pollution, which is determined by the continuous and diffuse pollutant loads that put pressure on its catchment area as well as its intrinsic characteristics [4]. Within this concept, there are two types of vulnerability concepts [5]: intrinsic vulnerability, which is determined by the aquifer's hydrogeological characteristics, and specific vulnerability, which includes a few outside variables in addition to the hydrogeological characteristics (e.g., land occupation, sort of contaminant). It is possible that aquifers with a high vulnerability, but a low pollution risk exist due to the absence of polluting loads, or that aquifers with a high pollution risk exist despite their low vulnerability [6].

The study of groundwater vulnerability allows the identification of areas with the highest potential for contamination, as well as the creation of the aquifer pollution vulnerability map [7]. Despite existing methodologies, there is no satisfactory way to represent aquifer vulnerability due to the difficulty in integrating all parameters that influence contaminant behavior [8]. The DRASTIC index is one of the most commonly used methodologies in this evaluation. Despite the varied amount of information available, its application is relatively simple, and it produces excellent results in areas with varying characteristics. The vulnerability of an aquifer with DRASTIC methodology is determined by seven parameters [4]: depth (D), recharge (R), material typology of the aquifer (A), soil type (S), topography (T), the impact of unsaturated/vadose zone (I) and hydraulic conductivity (C). Each parameter is subdivided into representative classes, which are assigned an index (i), ranging from 1 and 10 to order to correspond with the local hydrogeological characteristics (higher values correspond to greater vulnerability). The product of these values by a relative weight (p) of each parameter gives the value of the DRASTIC index (DI).

$$DI = D_i \times D_p + R_i \times R_p + A_i \times A_p + S_i \times S_p + T_i \times T_p + I_i \times I_p + C_i \times C_p \quad (1)$$

The use of Geographic Information Systems (GIS) has simplified the acquisition, processing, analysis, and manipulation of georeferenced data. GIS-based model development has become critical for studies of groundwater vulnerability and quality using hydrogeological parameters and anthropogenic activities [9]. The creation of thematic maps allows for better planning and management, both in terms of sustainable water use and the demarcation of places with the ability (or not) to implement various activities based on their potential impact on aquifers [10]. Map algebra operations enable mathematical operations to be performed between several thematic charts, resulting in composite charts, typically of vulnerability or susceptibility of a spatial nature.

Therefore, the main objective of this work was to create a vulnerability map for the “Entre-os-Rios” thermal aquifer using GIS interpolation tools based on the DRASTIC index.

2. Material and methods

The thermal aquifer is located in “Eja (Penafiel)” and the main point of the study was the “Barbeitos” borehole, which is located in the “Maciço Antigo”, in the Douro River Basin, where rivers converge (Figure 1-a) and 1-b)). The mineral water exploration exploitation concession has the registration number HM-23 and the name is named as “Entre-os-Rios (Quinta da Torre)”, with a surface area of 96.6 ha, coincident with the closed protection zone area of the protection perimeter buffer zone. The extended protection zone covers an area of 241.8 ha (Figure 1-c). The area is characterized by steep slope variations, which are primarily due to the presence of Ordovician quartzite rocks, which gave rise to ridges-oriented NW-SE due to differential erosion. On a local scale, the massif is dominated by discontinuities, which are typically sub-vertical N-S to NNE-SSW but, can also be horizontal to sub-horizontal. The most prevalent lithology is granite however, granites come in a wide range of textures and granularities. The springs appear to occur at the interface of the two types of granite and always in areas of great separation, primarily in the N20°E direction [11]. It appears that are the microgranite veins, installed throughout the area within the granitic masses that influence the emergence of water locally (at least in the “Torre” and “Termas de S. Vicente”). Except in the weathered superficial zones of the eruptive rocks and in the existing colluvium-alluvial patches, formations with secondary permeability due to granite fissures, predominate in the study area [12].

The waters of the thermal springs in “Entre-os-Rios” are cold, have deep circulation, and have a unique chemistry. The interaction with the massif granite rich in silica results in a pH of approximately 8.8. It is weakly mineralized water, sulphurous, fluoridated, with alkaline and soft reaction [13]. The water from the “Barbeitos” borehole has a low temporal fluctuation of its characteristics, allowing continuous monitoring to infer when contamination emerges in the aquifer. The “Entre-os-Rios” hydromineral system distinguishes the following aquifer systems [11]: at the surface, a highly altered and decomposed free aquifer that represents a critical role in the recharge of the underlying aquifers. A free to semi-confined aquifer with normal water circulation in altered zones and in most granite fissure zones (the pH is between 4.1 and 6; the electrical conductivity is less than 150 S/cm; flow rates are typically less than 0.2 L/s). A confined mineral

aquifer, located in depth near the catchment and conditioned by a zone of structural weakness in depth. The "Barbeitos" borehole, located in the granitic rock near contact with granodiorites at a maximum depth of 114 m, has an exploration flow of about 2.5 L/s, a pH of 8.4 to 8.9, and electrical conductivity of 550 to 620 S/cm. **a)**

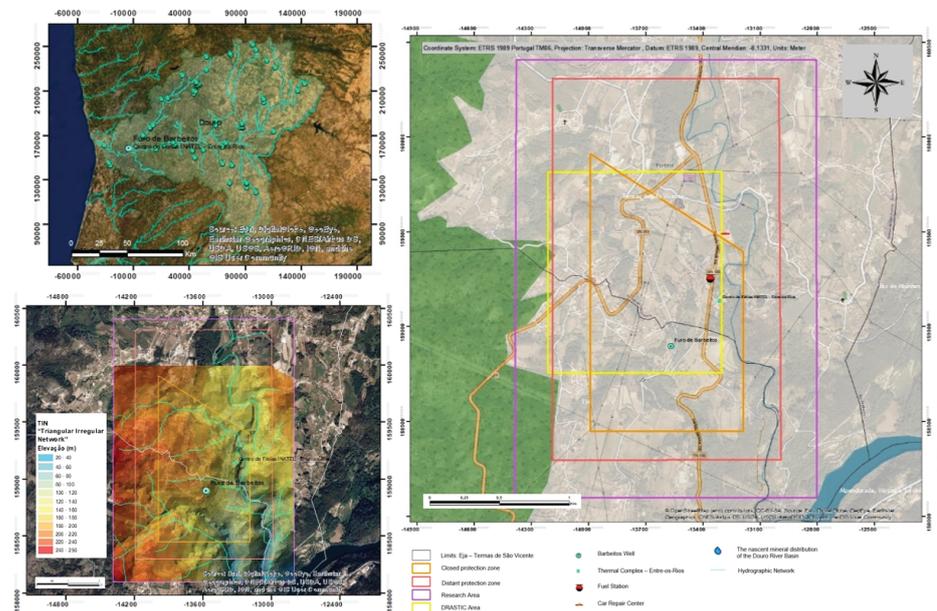


Figure 1: a) Location map of the “Barbeitos” borehole and mineral springs waters in the Douro River Basin [14]; b) Digital Elevation Model (DEM) of the study area surrounding the “Barbeitos” borehole [14]; c) Map of the geographical location of the “Barbeitos” borehole and the protection buffer zones and their conditions [14].

For attribute processing and vulnerability mapping, it was used ArcGIS 10.8 software from ESRI’s, which was based on the “PT-TM06/ETRS89”. For the construction of the seven thematic maps, a variety of data was collected and processed using ArcGIS tools. The parameter D was calculated using piezometric measurements from a set of 36 georeferenced water points taken in 2008 [11,15]. To interpolate the depth of the aquifer’s top, was applied the Inverse Distance Weighted (IDW) method resulted in mean values of less than 4 m, corresponding to an index of 9. The areas of greater susceptibility correspond to zones with shallower aquifer tops, indicating that it is a very sensitive attribute. The DEM was created using the “Carta Militar de Portugal”, scale 1:25000, N.º 135 of the “Centro de Informação Geoespacial do Exército” (CIGeoE), as shown in Figure 1-b). The Triangulated Irregular Network (TIN) interpolation model was used, which was converted into a matrix structure, allowing create the slope chart, flow direction, and curvature profile. The curvature profile shows the maximum slope direction and has an impact on flow acceleration and deceleration, as well as soil erosion and sediment deposition. The union of slope areas less than or equal to 6%, curvature profiles less

than or equal to 0, and areas that allow infiltration forms the map of infiltration potential zones. A recharge of 40 mm/year [11] was assumed using the precipitation values [11], resulting in an index value of 1. The values for quantifying the partial index A, I, and C were collected from the National Laboratory of Energy and Geology (LNEG) from the Geological Map of Portugal [16]. Parameters A and I assumed the prevalence of indexes 2 and 3, which are features of magmatic rocks in the research area. The attribution of greater susceptibility to microgranite outcrops, on the other hand, is cautious, because fissural percolation can endanger the aquifer. The partial index S was calculated using the Land Use and Occupation Map of Portugal (Cos2018) [17], from the Directorate General for Territory (DGT). Forest soil, as well as temporary crops and bushes, are more likely to be affected by pollution. The partial index T was obtained by considering the DEM and slopes map. The Slopes chart (%) confirmed that the study site ranges in altitude between 20 m and 250 m, with significant slope variations. In low-density areas, where pollutant infiltration is promoted, the vulnerability index is higher. The index C was created using an abacus that relates representative values of hydraulic conductivity for various types of rock [15,18], as well as values of effective porosity and porosity for certain types of rocks [19].

3. Results and discussion

Except in the weathered superficial areas of the eruptive rocks and in the current colluvium-alluvial patches, formations with secondary permeability due to cracking prevail in the study area. Underground water is circulated through fractures, and the greater the degree of fracture and the smaller the filling, especially with clay elements, the more interesting it is. The alteration can reach considerable thicknesses of several tens of meters in the most heavily weathered locations [11]. The vulnerability map for “Barbeitos” borehole (Figure 2-c) was generated by calculating the DRASTIC index (Eq. (1)), for each 5x5 m square, using the data of Table 1.

The cartography of intrinsic vulnerability in the study area was obtained as a result of the weighted sum, according to the DRASTIC methodology, of the various maps relating to each of the attributes. The risk of pollution includes the vulnerability and presence of pollution sources, and the environmental framework is reasonable in the study site where the catchment is located. The DRASTIC index’s values ranged from 47 to 127 points, ranging from insignificant to moderate, with an average pollution vulnerability of 79 points for “normal” pollutants. The alluvium-covered land is vulnerable to moderate contamination, however, it is located far from the catchment. Because of

TABLE 1: Values and weights used for calculating the DRASTIC index [4, 14].

Parameters	Characteristics	(i)	(p)	Range
D	3,9 m (average)	5 - 10	5	25 - 50
R	Deep recharge	0 - 1	4	0 - 4
A	Permeability	2 - 7	3	6 - 21
S	Change areas (< 2m)	1 - 6	2	2 - 12
T	Slopes map	1 - 10	1	1 - 10
I	Unsaturated zone lithology	2 - 6	5	10 - 30
C	Capacity to transmit water	1 - 2	3	3 - 6
Drastic Index (DI)				47 - 127

the conditions to which they are subject, the areas occupied by microgranites and where meteoric water infiltrates along with preferential recharge sectors hydraulically linked to deep fracturing represent a moderate vulnerability. Areas of minimal risk, on the other hand, could correspond to locations where the granitic massif has not been altered significantly.

The study location is situated in a sloping terrain (Figure 2-a) bounded by granitic outcrops, indicating a low vulnerability to contamination. However, as previously stated, fracturing can transport pollutants to great depths and/or distances (Figure 2-b).

The mineral water is of meteoric origin, with a long time of permanence in the deep system, classifying these waters among the slowest in the set of sulfuric waters in the country [19]. The pH value is around 8.8 being of basic character, resulting from the interaction with the granitic massif rich in silica. The temperature has an average value of 20.5 °C, which belongs to the class of hypothermal waters. According to [13,20] and to the traditional classification of the Lisbon Hydrology Institute, the water from the “Barbeitos” borehole is weakly mineralized, sulphureous, fluoridated water, with alkaline and soft reaction.

The use of several approaches to defining protection perimeters buffer zones allows for the long-term preservation of the quality of the hydromineral resource. For the immediate zone, a radius of 50 m is proposed, with the center of the circle representing the mineral water catchment. This is justified by the fact that it is an aquifer system whose lithological support is made up of igneous formations that range in the alteration from highly altered to little altered [21]. It has a total area of 0.785 ha and must be completely closed to any intrusion and always kept clean. The closed zone is defined by geological-structural, hydrogeological, and pollution vulnerability parameters. It coincides with the concession area, occupying an area of 96.6 ha. Its purpose is to protect the use of direct interference on the local emergency mechanism, particularly N-oriented fracturing and

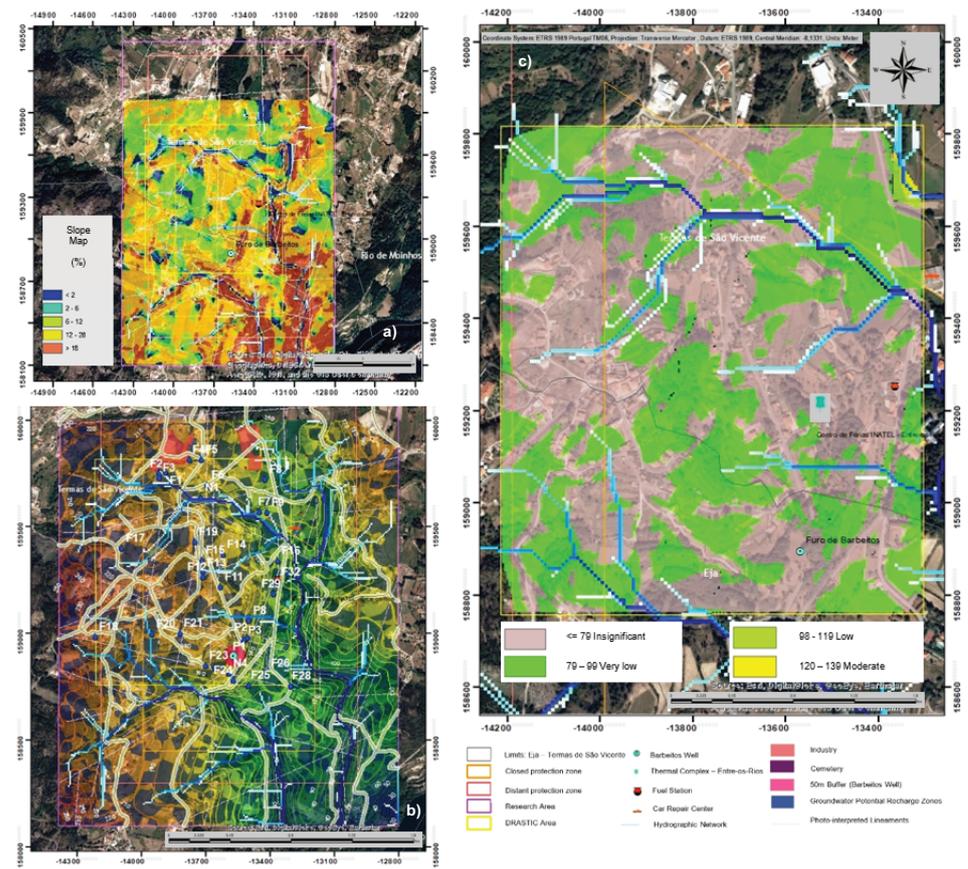


Figure 2: a) Slope map of the area around the “Barbeitos” borehole [14]; b) Map of areas with higher susceptibility to pollution around the “Barbeitos” borehole [14]; c) Map of the “Entre-os-Rios” Aquifer’s Pollution Vulnerability within DRASTIC methodology [14].

potentially ENE and NNE fracturing. The limits of the distant zone, which covers 241.8 ha, were established to include preferred recharge sectors that are hydraulically related to deep fracture. The favorable circulation of the aqueous system under study is related to the fracture N-S and NE-SW. The purpose of this area is to prevent contamination zones from developing, preventing further surface runoff and subsurface pollution.

4. Conclusion

This work allowed the determination of the intrinsic vulnerability of groundwater in the surroundings of the “Barbeitos” borehole through the calculation of a pollution vulnerability map, by applying the DRASTIC index. The vulnerability map shows that the protection perimeter buffer zone has a low vulnerability to pollution, which is partly related to the geological characteristics of the region, which tend to prevent polluting compounds from infiltrating. Although the areas are oversized, it is important to consider the heterogeneity of the underground environment in the study area, the

possibility of preferential flow through fractures to areas surrounding the catchment, and the uncertainty associated with method application due to the indeterminacy of some hydraulic parameters.

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