Vulnerability of the Territory of São Tiago Medical Spa Area in Relation to the Preservation of its Mineral Water Quality

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Abstract. The world is becoming more and more demanding in the quality of life of the common citizen. One way to achieve this quality is to enjoy health tourism. Medical Spa are an excellent equipment in this sense, because they allow practices of health treatment, or relaxation and well-being, aqualudic, focused on the use of natural mineral water, and with direct or indirect monitoring of health professionals (doctors). Thus, in Portugal, for a medical spa to function as such, it must have mineral water of stable quality. For this to be possible, it is necessary to comply with a set of procedures in the exploitation of water, and to impose restrictions on certain types of activities and due limitations on the occupation of the territory, in accordance with the implementation of the Protection Perimeter of groundwater abstraction of the medical spas. The maps of vulnerability to groundwater contamination are excellent instruments to contribute in the elaboration of the aforementioned Protection Perimeter. Thus, this paper presents the fundamental hydro-environmental elements in order to present the vulnerability map of the São Tiago medical spa territory. The General DRASTIC method is used, with a set of adaptations, called Specific DRASTIC, in order to preserve the areas most sensitive to the potential contamination of natural mineral water, and to liberate other areas that are not of potential danger to its contamination. It is also presented the map of occupation of the territory with registration of the main sources of potential pollution, making an analysis of the relationship between the results of the vulnerability map and the types of occupation. Finally, some conclusions are briefly presented.

1. Introduction
São Tiago medical spa is a very recent health spa, starting its activity in 2017. It corresponds to a case, where in the place of its implantation, there had never before been any ancient spring with thermalism traditions, nor ruins of ancient baths. There was nothing physically in anthropogenic terms in that sense, except the "will" of a businessman, in partnership with the local political power, to build a medical spa there in order to contribute to local and regional development. That wish would only be possible if, in fact, there was adequate groundwater, both in quality and quantity, that would permit it to be licensed, at the highest level (recognized by the State), as natural mineral water.

Some bureaucratic procedures were developed and several technical studies were carried out, from hydrogeo-environmental field works, mechanical prospecting works, with search drill holes, one of which was transformed into the definitive groundwater abstraction, the Well P1 [1]. In the follow-up, several technical reports were made, the main elements of which were presented in Ferreira Gomes [2,3]. In order to preserve the quality of the aquifer system that supplies the new medical spa, among
other actions, the characterization of the vulnerability of the lands in the associated territory is fundamental, in order to harmonize various actions and occupation of that territory, and establish the protection perimeter of natural mineral water abstraction (Well P1). So, the main objective of this paper is to present the vulnerability map of São Tiago medical spa territory, to present some technical-scientific discussions in the establishment of the methodology to assess the adequate vulnerability of the different geological formations of those territories, besides making a synthetic discussion about the current occupations of the surrounding territory.

The study area is located immediately south of the urban area of Penamacor, a border town between Portugal and Spain, municipality of Penamacor, about 47 km to the NE of its district capital, Castelo Branco, interior-centre region of Portugal, in the SW zone of Europe.

Regarding the classification of land in terms of vulnerability, there are several methods in the literature, notably DRASTIC [4], GOD [5], and AVI [6] indices. It is the first that in the present work deserves full attention with some local adaptations. Situations of use of the DRASTIC method with some adaptations were also used by several authors, deserving reference to the case applied to Egirdir Lake basin (Isparta) in Turkey [7], and also the case applied to the zone of Águas Medical Spa, also in the Penamacor Municipality, Portugal [8].

2. Geoenvironmental aspects of the territory
Geomorphological, geological, hydrogeological and other elements, with some detail were explained in an inedited report [9], presented to the Portuguese state, to propose the legalization of the new natural mineral water: "Termas de São Tiago". The main aspects on those themes were presented in Ferreira Gomes in 2020 [2]. The local geological sketch of the area of greatest interest to the abstraction of the groundwater under study is presented in Figure 1; it should be noted that the units that are preponderant to this study are: i) river alluviums - actuals; ii) Granites - hercinic; and iii) Shist-metagreywacke complex, ante-ordovician.

The alluviums have thin strata, generally less than 5m thick, and are essentially sandy, with a extensive grain size, with the coarsest fraction predominating. The granites, preponderant to the aquifer system that supplies the natural mineral water of São Tiago medical Spa, are medium to coarse grain, with little alteration in the urban area of Penamacor, that is, in the areas of higher altitude, and of very coarse grain, porphyroid, of two micas, generally very altered and sometimes even sanded in the lower areas, including in the area where the mineral water abstraction is installed (Well P1). The Shist-metagreywacke complex is understood to be of no significant importance in the context of this study. Still from the geological point of view, it is important to point out that the granite massif, and especially in the higher areas, urban area, is extremely fractured, besides some relatively extensive faults occur, with predominant NNE-SSW directions; these situations favor the recharging of water in depth, in order to supply the area of Well P1.

The conceptual hydrogeological sketch of the area of interest to this study is presented in Figure 2. The horizontal distance, from the Well P1, to the most upstream area, in the centre of Penamacor village, is about 1200m. The highest altitudes are around 605m asl and the lowest are around 461m asl.

In hydrological terms, it should be noted that the region has average annual temperatures in the order of 14.3°C, and average annual rainfall (from records of 30 years) in the order of 834mm. The monthly sequential hydrological balance results in annual surpluses of 382.5 mm, of which 133.9 mm correspond to the underground flow [2].
From a hydrogeological point of view, considering the geological framework of the region and in particular of the basin where Well P1 is installed, the following hydrogeological units are considered, from top to bottom [2]:

- Unit Af: unconfined or phreatic aquifer, consisting of alluviums, of medium permeability, of normal groundwater;
- Unit Gsup: unconfined or phreatic aquifer, consisting of geological formation consisting of very altered granites, of low permeability and of the mixed type (interstitial in the most altered zone and fissured in particular in the less altered zones), with normal groundwater;
- Unit Gdepth: > 65m: semi-confined aquifer, consisting of granite little altered to unaltered, with very low permeability of the fissured type, with groundwater of the special characteristics, that resurfacing in the Well in fractures that are understood to be relatively extensive.

For the aquifer system of natural mineral water, the following hydraulic parameters have been advanced [2]: Hydraulic conductivity - \( K = 1.45 \times 10^{-7} \) m/s; Transmissivity - \( T = 1.1 \times 10^{-6} \) m²/s; Storage coefficient - \( S = 3.0 \times 10^{-2} \). The mineral aquifer system is explored by Well P1, with 324m of depth, and with an allowable flow of 0.7 L/s. Natural mineral water in ionic terms, is classified by sodium-calcium-magnesian bicarbonated water [3].

3. Vulnerability and the Occupation of Territory

3.1. Vulnerability: methodological considerations

The present proposal is to apply the DRASTIC [4] method in a first stage, considering the general index, i.e. the index independent of the polluting load; in a second stage some additions are made to that classification which are considered to be suitable for mineral water aquifers, of crystalline rock massifs, such as the present case, with fissured granitoid type rocks.
Figure 2. Sketch of the conceptual hydrogeological model to supply the abstraction of the São Tiago Medical Spa – Penamacor. Note: the location of the AB section is shown in Figure 1 [2].

3.1.1 General DRASTIC
The general DRASTIC vulnerability index \( I_D \) corresponds to the weighted sum of 7 values corresponding to 7 hydrogeological parameters or indicators, as shown in Table 1. Each parameter \( P_i \) will have a partial index \( I_P \) that varies between 1 (lower vulnerability) and 10 (higher vulnerability) based on its relative effect on the aquifer (Table 2). The \( I_D \) values vary between 23 and 226, indicating the minimum and maximum vulnerability, respectively. Using this method, can result DRASTIC vulnerability maps, with the colours referred to in Table 3.

Table 1. Definition of the general DRASTIC vulnerability index \( I_D \) and respective parameters and weights (from [4]).

| Definition | Parameter – \( P_i \) | weight - \( w_i \) |
|------------|------------------------|------------------|
| \( I_D = \sum \left( P_i \times w_i \right) \) | \( D \) = Depth to the water table | 5 |
|            | \( R \) = Recharge      | 4 |
|            | \( A \) = Aquifer material | 3 |
|            | \( S \) = Soil type      | 2 |
|            | \( T \) = Topography – slope | 1 |
|            | \( I \) = Impact of the vadose zone | 5 |
|            | \( C \) = hydraulic Conductivity of the aquifer \((k)\) | 3 |

3.1.2 DRASTIC adaptation
The general DRASTIC index \( I_D \) classes represent an average vulnerability of the characterized geological formation and in the cases of fissural aquifers, associated with mineral waters, all the local geological-structural aspects, from the area close to the abstraction that supplies the medical spa, are fundamental and should be carefully considered in order to re-evaluate the vulnerability of the geological formation, depending on the potential contamination of the natural mineral water to be explored. Thus, the mapping on vulnerability in mineral aquifer zones proposes the following methodology:
(i) in a first step, classify the lithological units in terms of the general DRASTIC index (I_D) and assign the same units a Potential Vulnerability, a Vulnerability Degree and a Qualitative Vulnerability Class, according to the various degrees presented in Table 4;

(ii) in a second step the various units are subject to a second reclassification, depending on two types of factors, in relation to the position of the mineral water abstractions and mineral springs; the factors to be considered are:

a) Occurrence of Geological Singularities (OGS), with actual or potential connection to the mineral water aquifer, such as lithological contacts, faults, veins, fractures and others;

b) Location of the Geological Unit (LGU) to be classified, in relation to the mineral water discharge zone.

Detailed reclassification can lead to lower or increase the degree of classification, according to the situations presented below, designating the final classification, as Specific DRASTIC, to differentiate from common situation.

Regarding the OGS Factor, the following situations are considered:

(i) if there is no discontinuities with actual or potential connection to the mineral aquifer, then the unit should maintain the vulnerability class according to the general DRASTIC index (I_D);

(ii) if there are discontinuities, or sites with mineral water springs, then these are proof of the actual existence of discontinuities with connection to the mineral aquifer; these sites are considered zones with a very high to extremely high vulnerability (G= 7 to 8, Table 4);

(iii) if there are discontinuities or locations with mineral water springs potential, then these places are considered zones with medium to high vulnerability class (G= 5 to 6, Table 4).

Table 2. Partial Indices (Ip) to be assigned for the calculation of the general DRASTIC Index (I_D), function of the various parameters and their classes [4].

| D | Depth (m) | Ip | 0.5 = 10 | 1.5-4.6 | 4.6-9.1 | 9.1-15.2 | 15.2-22.9 | 22.9-30.5 | >30.5 |
|---|-----------|----|----------|---------|---------|----------|-----------|----------|-------|
| R | Recharge (mm/year) | Ip | <51 | 51-102 | 102-178 | 178-254 | >254 |
| A | Aquifer material | Ip | clayey schist, claystone | metasomatic / igneous rock | metamorphic / igneous altered rock | glacial deposits | sandstone, limestone and claystone, stratified | Sandstone | limestone | sand and gravel | basalt | carsified limestone |
| S | Soil type | Ip | thin or absent | gravel | sand | peat | consistent clay and/or expansible | sandy | Powerfull | silty | clayey | muddr | non-expansive clay |
| T | Slope (%) | Ip | <2 | 2-6 | 6-12 | 12-18 | >18 |
| I | Unsaturated zone | Ip | confining layer | clay/silt | clayey schist, claystone | limestone | sandstone | sandstone, limestone and claystone, stratified | sand and gravel with many fines | metamorphic / igneous rock | sand and gravel | basalt | carsified limestone |
| K | (m/day) | Ip | <4.1 | 4.1-12.2 | 12.2-28.5 | 28.5-40.7 | 40.7-81.5 | >81.5 |
Table 3. General DRASTIC Index (I_D) and corresponding color classes [4].

| General DRASTIC Index - I_D | Class color |
|-----------------------------|-------------|
| <80                         | violet      |
| 80-99                       | anil        |
| 100-119                     | blue        |
| 120-139                     | dark green  |
| 140-159                     | light green |
| 160-179                     | yellow      |
| 180-199                     | orange      |
| >199                        | red         |

Regarding the LGU Factor, the following situations are considered:

(i) if the location of the unit to be characterized is upstream of the actual or potential areas of natural mineral water discharge, the unit should maintain the vulnerability class according to the general DRASTIC index (I_D);

(ii) if the location of the unit to be characterized is downstream of the actual or potential areas of natural mineral water discharge, the unit class should be lower in relation to the general DRASTIC Index, depending on the detailed analysis of each case, and may even in some situations go from high vulnerability to low vulnerability, being aware that, if the lands are classified as very high vulnerability, they may be out of access to other occupations in the territory, and often in areas close to the medical spa there is a need to do use of the entire territory, provided that the quality of the resource, mineral water, is not endangered.

3.2 Results: Application to the case study

For the application of the case study, it is emphasized that the fundamental focus is the preservation of the water quality of the mineral aquifer system under study, which allows to obtain natural mineral water to be used, with stable quality, in São Tiago medical spa, from the exploitation of the resource by the Well P1. The geological and hydrogeological situation has been previously presented, namely in the figures 1 and 2. The results obtained for the main hydrogeological units of the study area and surroundings, in terms of the general DRASTIC index, are presented in Table 5. It should be noted that in this table are classified the outcropping units of the area near the medical Spa (units 1 and 2), unit 3a, especially in the higher altitude zone (Penamacor urban area), and unit 3b, in depth, in the area of Well P1.

Following the application of the general DRASTIC index (I_D), the necessary adjustments are made to the present study, designating the final result as the Specific DRASTIC Index (I_D_E), with the 8 degrees presented in Table 4. This application resulted in the map shown in Figure 3.

Table 4. General DRASTIC Index (I_D) classes and categorization into classes with qualitative vulnerability classification, to be used in natural mineral water aquifer systems in crystalline rock massifs, after the respective adaptations, being called Specific DRASTIC Index.

| I_D [4] | Potential Vulnerability P_v (%)(*) | Vulnerability Degree - G | Qualitative Vulnerability - V_Q |
|---------|-----------------------------------|-------------------------|--------------------------------|
| <80     | <30                               | 1                       | Practically null                |
| 80-99   | 30-39                             | 2                       | Extremely low                  |
| 100-119 | 40-49                             | 3                       | Very low                       |
| 120-139 | 50-59                             | 4                       | Low                            |
| 140-159 | 60-69                             | 5                       | Medium                         |
| 160-179 | 70-79                             | 6                       | High                           |
| 180-199 | 80-89                             | 7                       | Very high                      |
| >199    | >90                               | 8                       | Extremely high                 |

(*) Potential vulnerability classes were established by considering 0 % for I_D=23 and 100 % for I_D=226.
Table 5. Vulnerability assessment for hydrogeological units in the study area, based on the general DRASTIC index (I_D).

| Unidade (*) | P | I_P | w | I_w | I_D | Vulnerability |
|-----------|---|-----|---|-----|-----|---------------|
| **Unit Af:** | | | | | | |
| River alluviums (unconfined aquifer) | D | 0.5 to 4.6 m | 9 | 5 | 45 | Usually very high. |
| | R | 178 – 254 mm/year | 8 | 4 | 32 | The pollution can spread with some facility to large distances |
| | A | sand and gravel | 8 | 3 | 24 | |
| | S | sandy | 6 | 2 | 12 | |
| | T | 2 - 6 % | 9 | 1 | 9 | |
| | I | sand and gravel | 7 | 5 | 35 | |
| | C | 41 – 82 m/day | 8 | 3 | 24 | |
| **Unit G_{sup}:** | | | | | | |
| Altered granites (unconfined aquifer) | D | 1.5 – 4.6 m | 9 | 5 | 40 | Usually Low |
| | R | 102 – 178 mm/year | 6 | 4 | 24 | |
| | A | igneous altered rock | 4 | 3 | 12 | |
| | S | sandy | 6 | 2 | 12 | |
| | T | 2 - 6 % | 9 | 1 | 9 | |
| | I | igneous rock | 4 | 5 | 20 | |
| | C | < 4.1 m/day | 1 | 3 | 3 | |
| **Unit G_{sup}: (3a*)** | | | | | | |
| Little altered to unaltered granite (unconfined aquifer) | D | < 1.5 m | 10 | 5 | 50 | Usually Medium |
| | R | 102 – 178 mm/year | 6 | 4 | 24 | |
| | A | igneous rock | 3 | 3 | 9 | |
| | S | thin or absent | 10 | 4 | 40 | |
| | T | 12 - 18 % | 3 | 1 | 3 | |
| | I | igneous rock | 4 | 5 | 20 | |
| | C | < 4.1-12.2 m/day | 2 | 3 | 6 | |
| **Unit G_{depth}: (3b*)** | | | | | | |
| Little altered to unaltered granite (semi-confined aquifer) | D | >30,5 m | 1 | 5 | 5 | Usually Practically null |
| | R | 102 – 178 mm/year | 6 | 4 | 24 | |
| | A | igneous rock | 3 | 3 | 9 | |
| | S | non-exp. clay | 1 | 4 | 4 | |
| | T | 2 - 6 % | 9 | 1 | 9 | |
| | I | igneous rock | 2 | 5 | 10 | |
| | C | < 4.1 m/day | 1 | 3 | 3 | |

(3a*) the classification of this unit, refers to *little altered to unaltered granite*, but in superficial outcropping, typical in the urban area of Penamacor;
(3b*) this unit corresponds to the classification of the same type of granites of 3a*, but in depth in the zone of Well P1.

In the application, the example stands out of Unit Af, which has a Very high vulnerability by general ID (equivalent to G = 7, Table 4), however considering the area of occurrence of Af, downstream of Well P1, and for long distances from this, there is no risk of contamination of the mineral aquifer. So, that area, taking into account the potential for contamination of the aquifer that supplies Well P1, it was considered to be of lower vulnerability than that considered for upstream, proposing to have Medium vulnerability (equivalent to G = 5, Table 4). Thus, by acting in this way, are not preserved excess areas of the territory, as they may be needed for other occupations in the future.

The mineral water discharge zone, in the Unit G_{sup} (Altered granites - unconfined aquifer), the general I_D Index points to Low Vulnerability (equivalent to G=4, Table 4), but being a very fissured system, the fluids can circulate locally in fractures that being very open, the vulnerability can be extremely high and especially if the situation of downward flows is possible, when pumping in Well P1. Thus, in areas where this type of situation occurs locally, the vulnerability of the hydrogeological unit under analysis is considered higher than that obtained by the general I_D Index.

Analysing the vulnerability map by Specific DRASTIC, for the area of São Tiago Medical Spa, it turns out that the most vulnerable area presents G= 7, Very high vulnerability, corresponding to the abstraction area and proximity zones upstream of it. That zone includes the Unit Af and essentially the G_{sup} Unit with altered granite, with some fractures; this zone also includes in its interior several water points with characteristics in chemical quality close to the water of the mineral aquifer. It should also
be noted that there is no zones with G of values 1, 2 and 8, being particularly important not to occur the highest degree, for the good of the resource.

![Figure 3. Vulnerability Map for the São Tiago Medical Spa based on the Specific DRASTIC Index](image)

**Figure 3.** Vulnerability Map for the São Tiago Medical Spa based on the Specific DRASTIC Index

### 3.3 Occupation of the Territory and Potential Pollution Sites

Having need to analyze the actual or potential pollution risks of the mineral aquifer system where Well P1 is installed, in order to obtain natural mineral water, it became necessary to organize the zone of influence, in areas with different occupations, based on the designations presented in the Municipal Master Plan [10]. Thus, from that document for the zone under study there are the following areas (Figure 4): a - Urban Zone; b - Urban Expansion Zone; c - NAR, National Agricultural Reserve; d - NER - National Ecological Reserve: i) Water Line Headers; and ii) Flood Zones; iii ) Erosion Risk Zones.
Considering the various areas in terms of territorial planning and crossing with the same areas in the vulnerability map (Figure 3), there are favorable and less favorable situations. The favorable situations correspond to the fact that around the urban area of Penamacor, namely the NW and SW of the village, there are areas of NER classified as headwaters of water line and areas of potential erosion; this situation is favorable because these sectors are already limited to urban occupation, and therefore are favorable situations because they are in areas of medium vulnerability, and of recharge to the mineral aquifer. The less favorable situations are organized into two groups: i) the situation of the Urban Area, which is located in an area of medium vulnerability, and despite the distances to Well P1 being relatively considerable, but because it is in an area of groundwater recharge, there should be very good sense, in the sense that there should be no infiltrations of contaminated fluids in that area; in particular, there should be great care with the sewage system in the sense that it should function normally, without infiltration it from ruptures or leaks, in a continuous regime; ii) the situation of the NAR area that is found in the NW of the São Tiago Medical Spa area, and being part of this area of high vulnerability, the use of agriculture could lead to outbreaks of contamination, as it is already understood to happen, when verifying the water quality of some water points that occur in that area, and for that reason, it is advisable, that in future alteration of the PDM, this area loses its status current, remaining only as a NER area, as this situation is favorable. Other situations to mention is the fact that the area of the Medical Spa and the nearest surroundings has no limitation. This fact can be favorable or unfavorable, pointing out that if there is at first some "freedom" of occupation, any project for the area should always be the target of much attention on the potential contamination of the aquifer system, not least because the majority of the area has very high vulnerability. It should be noted that the Wastewater Treatment Plant (WWTP) and a small lake of semi-stopped water, not being serious emergency situations, will be important in future interventions to move south, at least about 700m downstream of Well P1.

Figure 4. Map of Territory Occupation from the PDM Map of Penamacor Municipality (from [10]).
4. Conclusions
The general DRASTIC Index ($I_D$) is an excellent method to classify the territory in terms of vulnerability to potential contamination of aquifer systems, as it is based on a panoply of factors and parameters that are very useful in this type of situations. Its application results as a classification in average terms for each hydrogeological unit classified, leading to a situation where its application to mineral aquifers fissured crystalline rock systems is not totally satisfactory. Thus, in this case study, considering a complement to that classification (item 3.1.2), it allows more rigorous vulnerability classifications, leading that the global classification obtained by $I_D$ can change, either to higher or lower vulnerability. The application according to the methodology used, was designated as Specific DRASTIC to mineral aquifer systems.

It should be noted that the vulnerability mapping according to the Specific DRASTIC index, will favor the optimization of the Protection Perimeters of groundwater abstraction, namely in the definition of Immediate Protection Zone, which should initially include all areas classified with the Degree of Vulnerability (G) greater than or equal to 7 (Table 4), which generally tend to be close to mineral water abstractions.

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