# Expert based DRASTIC adaptation to mineralized aquifer vulnerability assessment – Penamacor, Portugal

Ferreira Gomes, L M, Albuquerque, M T D, Antunes, I M H R

***Abstract*— Hydrotherapy and bottling mineral water exploitation requires a detailed placement of the catchment and the aquifer's vulnerability assessment for further protection perimeter design. The DRASTIC methodology was the starting point index used for the herein introduced "specific DRASTIC". It is possible to say that hydrogeologically the area suggests a predominant low vulnerability. However, hydrogeological and structural characteristics (e.g., granitic fracturation), indicate an extremely high vulnerability in which concerns to the Termas de Fonte Santa catchment. The "specific DRASTIC" index is held by local parameters in order to downscale the key properties for local vulnerability mapping and further quantification of the potential for contamination of the aquifer. The Termas de Fonte Santa is classified as very high to extremely high vulnerable and in need of protection and conservation**

***Index Terms*— Vulnerability, DRASTIC, "specific DRASTIC", mineralized aquifer.**

## I. Introduction

The study area is a thermal medical spa (spa mineral water), located at Central Portugal (Termas de Fonte Santa; Penamacor). The area is a small village with a local development potential and, consequently, requires a mineral water stable quality to be used by human community and contribute to the national economy.

Actually, the thermal mineral water from Termas de Fonte Santa is obtained in a well (reference AM4) with 328 m depth and a water exploitation of about 3.6 $m^3/h$. The thermal mineral is sulphurous and bicarbonate-sodium water type.

The boundary line of protection perimeters and associated restrictions have become essential instruments in the preservation of natural water sources. The potential contamination of mineral water from Termas de Fonte Santa will be minimized with the delimitation of a protective perimeter for the catchment AM4.

Vulnerability assessment and groundwater contamination have been studied by many researchers [1, 2], resulting several proposed classifications. Some developed methodologies could be indicated such are: the DRASTIC index [3], the index of vulnerability to pollution GOD [4], the AVI index (Aquifer Vulnerability Index) [5] and the DWSAP method [6].

Nevertheless, the DRASTIC index have been widely used and will be applied to Termas de Fonte Santa area with some adjustments/adaptations identified and designated. DRASTIC index with adjustments have also been used by other authors 7, 8].

## II. Study Area

### A. Geographical Setting

The study area is located in the Central Iberian Zone, central Portugal (Fig. 1). Fonte Santa thermal area (AM4 well) occurs in the village of Águas, approximately located at 42 km NE from Castelo Branco and 5 km south of Penamacor (Fig. 1). This region contains about 300 inhabitants and an area of 15 km², where it is possible to enjoy the Fonte Santa SPA complex.

### B. Geomorphology and Geology

The geomorphology of the region represents approximately an elliptical shape with 19 km by 9 km, with a major axis elongated NW-SE. This area is located in the geomorphological unity called "Planura de Castelo Branco" [9], which is relatively flattened with an elevation of 400 m.

Altogether the area is situated in the granitic rocks from Penamacor-Monsanto pluton, with an expanse of approximately 140 $km^2$ (Fig. 1).

The Penamacor-Monsanto pluton consists of granitic rocks, which are more permeable than the intruded schist-graywacke complex (Grupo das Beiras) [10]. The schist-graywacke complex is dominated by impermeable schists, leading an aquifer groundwater recharge essentially by surface waters and water infiltration from the granitic rocks. However, it should also be noted an infiltration from outside to inside drainage recharging groundwater reserves.

In structural terms, there is a dominant N40ºE, vertical system of geological fractures, mostly very open, smooth and stretch over a big region. The fractures from that system may correspond to recent faults that traverse the granite and country rocks. The granitic rocks where resurfaces mineral water is apparently limited and located between two faults, N40ºE, vertical (Fig. 2).

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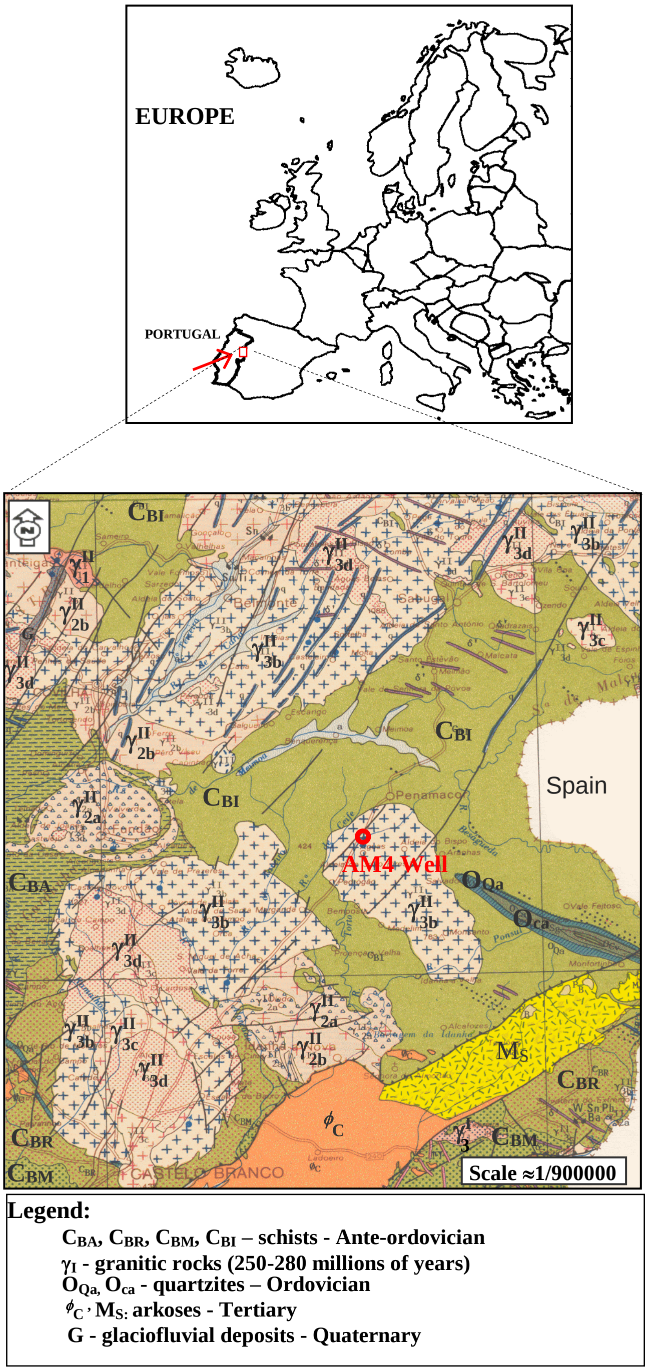


Fig. 1. Geographical and geological setting of the study area and AM4 well location [adapted 10].

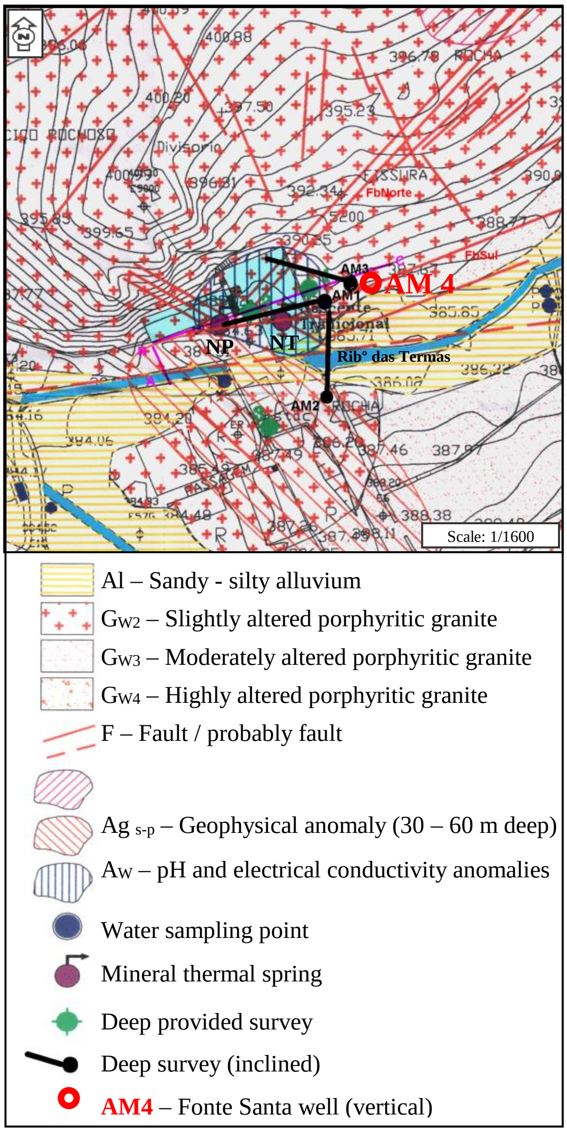


Fig. 2. AM4 well location in the local geology map [11].

### C. *Geohydrology*

Almost Penamacor-Monsanto pluton area records an annual average daily temperature between 13.5 and 15.5ºC, approximately. The lowest values occurred in the NW of the pluton, while the highest ones in the SE. The mean annual rainfall registered value ranges between 750 and 850 mm. The estimated water balance to the Fonte Santa area indicates the occurrence of a dry season and a wet period [11].

The dry period occurs between May and October, with water deficits (DH), achieving its maximum during July. Differently, the wet period, evidenced by water surplus (SH), occurs between November and April of the following year, with a maximum excess of water in January.

During the wet period, SH receives two contributions: runoff (R) and groundwater flow (G) according to:

$$SH = R + G = 327.3\ L/m^2$$

The Penamacor-Monsanto granitic pluton has modest slopes (<10%), sometimes with very fractured and altered areas covered with a thick flora, which enables the occurrence of orientated infiltration processes and, therefore, the aquifer recharge. According to the background experience, it was considered a "G / SH" ratio of 35% [12]. This ratio leads an infiltration rate of 115 $L/m^2$ per year, to the aquifer recharge which allows a global annual recharge of $16x10^6\ m^3$ for an area of 140 $km^2$ to the Penamacor-Monsanto pluton.

On a hydrogeological point of view, in the vicinity of Fonte Santa (AM4 well) occurs mainly granites, locally covered by thin alluvium located in the stream of Ribeira das Termas (Fig. 2). Nevertheless, in that location is a complex arrangement of fractures associated with semi-horizontal veins which promotes the occurrence of mineral water in a very restricted zone (Fig. 3).

are 0.25, 0.5 and 1.0 L/s, in a permanent and stationary model, using Thiem equation. According to Lambe and Whitman classification [13], Fonte Santa thermal area contains sulphurous water and could be sorted out as a low permeability aquifer (Table I).

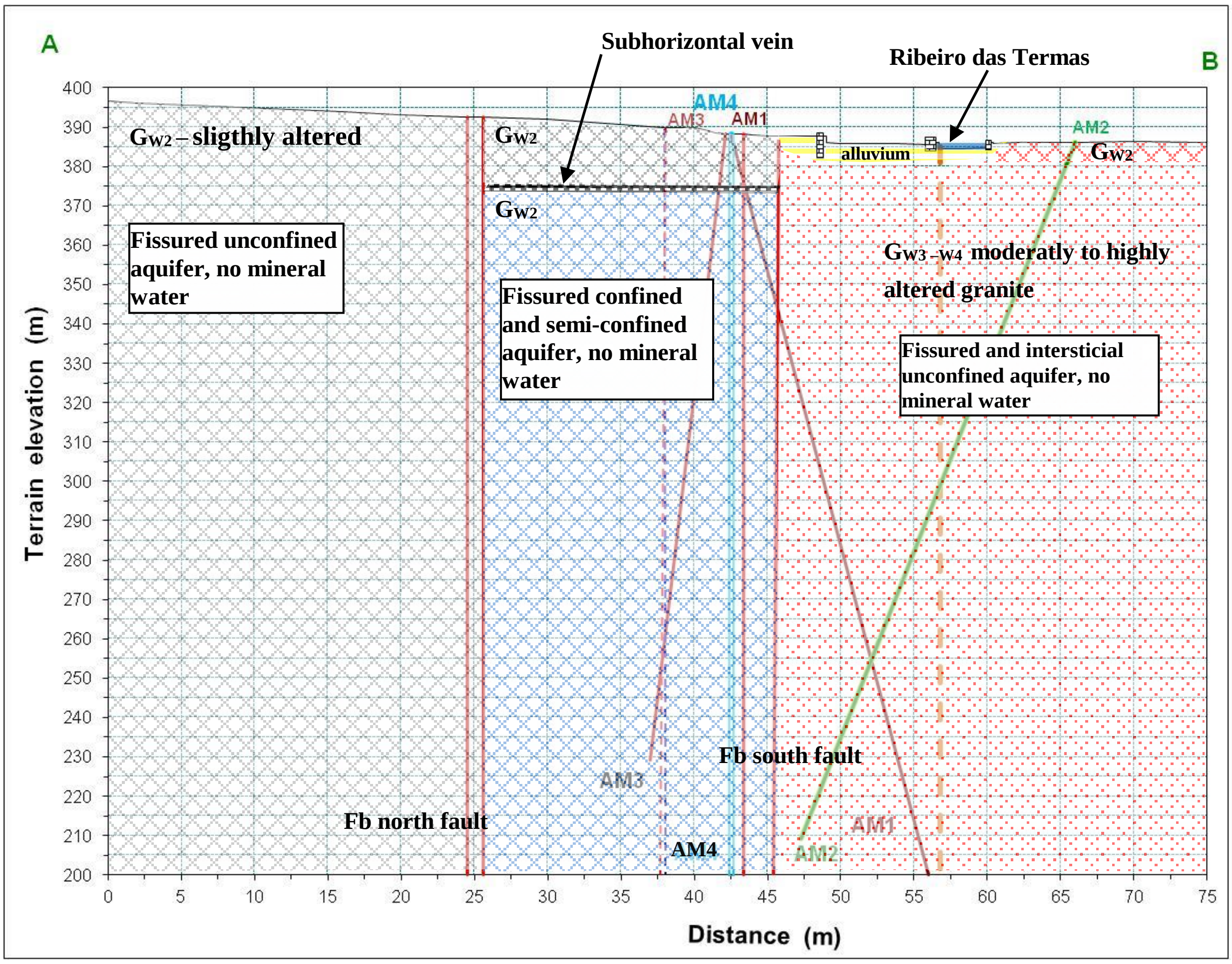


Fig. 3. Hydrogeological model of aquifer system from Fonte Santa (Penamacor, Portugal) [12].

The mineralized aquifer area comprises slightly altered granitic rocks (GW2), mainly fractured, which constitutes a confined to semi-confined fissured aquifer. The aquifer deep water layer is around 3 m and effectively develops below 20m deep, with a vein structure system at the height of the aquifer.

The hydraulic parameters of the mineralized aquifer were obtained [11]:

$k = 0.28$ m/day ($3.2 \times 10^{-4}$ cm/s) - permeability coefficient

and $S = 26.6 \times 10^{-4}$ – storage coefficient.

These parameters should be taken as a magnitude order value because represent an average of test flow obtained by two different methods, in a confined aquifer (AM3 well; Fig. 3). The applied model is continuous and representing a porous medium, in a productive zone located between 20 and 120 m. In a second phase, were considered modest flow rates, such

TABLE I: PERMEABILITY COEFFICIENTS FOR PENAMACOR-MONSANTO PLUTON

| Permeability Classification [13]. | k (cm/s) | | |
|---|---|---|---|
| Almost impermeable | | $< 10^{-7}$ | |
| Very low (reduced) | $10^{-7}$ | - | $10^{-5}$ |
| Low | $10^{-5}$ | - | $10^{-3}$ |
| Average | $10^{-3}$ | - | $10^{-1}$ |
| High | | $> 10^{-1}$ | |

The granitic rocks that are not included in the mineralized aquifer from Fonte Santa are organized into two groups (Fig. 3). The first group is represented by slightly altered granites (GW2), corresponding to an unconfined aquifer in the first 60m deep, generally with a lower to medium permeability increasing with the fractured system. The second group contains moderately to highly altered granites (GW3-W4-W5; Fig. 3), corresponding to a normal aquifer, in the first 60 m deep, fissured and locally interstitial type in highest altered granitic zones. The group is an unconfined aquifer with variable permeability, ranging from low to medium permeability, increasing locally with granite fracturation.

In the study area, there is also an unconfined aquifer associated to the highest permeability of alluvium from the Ribeira das Termas stream, but not extended more than 3 m.

## III. Aquifer Vulnerability to Mineral Waters

The presented proposal includes, in a first phase, the application of the DRASTIC method [3] to define vulnerability zones at the Fonte Santa area. After that, the DRASTIC index will be presented with some adjustments related to mineralized water from crystalline rocks, such are the granitic rocks from Penamacor-Monsanto pluton. The adapted DRASTIC methodology – "specific DRASTIC" - will be applied to the mineralized aquifer from Fonte Santa (Penamacor) such a study case and will be presented the obtained results.

### *A. DRASTIC index*

The acronym DRASTIC stands for the parameter included in the method: Depth to water (D), net Recharge (R), Aquifer media (A), Soil media (S), Topography (T), Impact of vadose zone (I) and hydraulic Conductivity (C) of the aquifer. The calculated DRASTIC indices are roughly analogous to the likelihood that contaminants released in a region will reach groundwater, higher score translates into a higher likelihood of contamination [3].

The DRASTIC method includes a numerical index computed as a weighted sum of the seven model parameters. The significant media types or classes of each parameter range between 1 (lower vulnerability) and 10 (higher vulnerability) based on their relative effect on the aquifer. The seven parameters are then assigned weights between 1 and 5 reflecting their relative importance [3].

The DRASTIC index values range between 23 and 226, corresponding to a minimum and maximum vulnerability, respectively, and assigned by different color classes (Table II).

TABLE II: DRASTIC INDEX AND CORRESPONDING VULNERABILITY COLOR CLASSES

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

### *B. Expert Issues and DRASTIC's adaptation*

The obtained DRASTIC index for Fonte Santa area – "specific DRASTIC"- indicate an intermediate vulnerability class mainly related to the geological formations and associated structural characteristics. In the study area, the geological and structural aquifer catchment characteristics should be detailed weighted in order to reassess its vulnerability depending on potential contamination of the exploited resource (mineral water).

To increase the sensitivity of this process and facilitated visual result interpretations were assigned a qualitative vulnerability to DRASTIC indexes (Table III).

TABLE III: DRASTIC INDEX AND ASSOCIATED VULNERABILITIES IN MINERALIZED AQUIFER SYSTEMS

| DRASTIC index [3] | Potential vulnerability (%) | Degree | Qualitative vulnerability |
|---|---|---|---|
| <80 | <30 | 1 | Nonexistent |
| 80-99 | 30-39 | 2 | Very very low |
| 100-119 | 40-49 | 3 | Very low |
| 120-139 | 50-59 | 4 | low |
| 140-159 | 60-69 | 5 | Intermediate |
| 160-179 | 70-79 | 6 | High |
| 180-199 | 80-89 | 7 | Very high |
| >199 | >90 | 8 | Extremely high |

The vulnerability mapping areas from mineralized aquifers intends to adopt the following methodology:

i) In a first stage, identification and classification of different rocks according to DRASTIC index and the corresponding qualitative vulnerability class (Table III);
ii) in a second phase, the different rock is subject to a second reclassification, according to two factors relatively to mineral water catchment spatial location:
a) singular or topic geological occurrences with potential connection to the mineralized aquifer (such as: lithological contacts, faults, veins or other diaclases);
b) spatial location of the hydrogeological formation.

This detailed reclassification leads to a reduction or increase in the classification stage, according to the follow specific characteristics, and the final result will be called as "specific DRASTIC" to Fonte Santa mineralized aquifer.

The singular or local geological occurrences should be considered if:

i) there is no discontinuity with actual or potential binding to mineralized aquifer and the qualitative vulnerability class must be the same as the original DRASTIC index;

ii) there are local discontinuities or mineral waters upwelling sites, that will indicate discontinuities with the mineralized aquifer and these areas must be classified as high to extremely high vulnerability (degree 6 to 8; Table III);

iii) there are discontinuities or potential mineral waters upwelling sites and these areas must be classified as intermediate to high vulnerability (degree 5 or 6; Table III).

Otherwise, the spatial position of the hydrogeological formation should consider if:

i) the litological unity is located upstream of real or potential discharge areas from natural mineral water and the qualitative vulnerability degree class must be the same as the original DRASTIC index;

ii) the litological unity is located downstream of real or potential discharge areas from natural mineral water; the qualitative vulnerability degree class must be lower than the original DRASTIC index. This reclassification will depend on a detailed analysis of the survey region and its local utilization and exploitation without decrease water resources quality and quantity.

## IV. Results

The mineralized aquifer from Fonte Santa area allows to explore and obtain sulphurous natural mineral water to be used as medical spa waters in the local AM4 catchment (Termas de Fonte Santa, Penamacor; Portugal). Geological and hydrogeological characterization is presented in figures 1, 2 and 3.

The DRASTIC indexes and respectively vulnerability classification of the different litological units from the study area are presented in Table IV.

According to singular or topic geological occurrences, the obtained results indicate an extremely low vulnerability associated with the mineralized aquifer (Gw2; Table IV). All the same, this classification could be not realistic because the granite contains different fractures allowing water infiltration. This outside fluids could contain dissolved contaminants that will extend to the mineralized aquifer and will be a possible pollution source. According this, the surrounding AM4 catchment must be classified as an extremely high vulnerability area and calculated "specific DRASTIC" index will increase from degree 2 to 8.

Another particularly relative to the hydrogeological spatial location, from alluvium of the study area, the DRASTIC index attributes a high vulnerability (degree class 6; Table IV). However, the alluvium is located in a large distance downstream the mineralized aquifer from Fonte Santa and would be considered having a lower vulnerability than similar materials located upstream. So, alluvium must bear a different class classification according to its spatial location and distance relative to the AM4 Fonte Santa catchment (degree class 6 – upstream; degree class 5 or 4 – downstream).

Attending to the local study area, there is no exceeding preservation areas without relevant particularities that could be used as support infrastructure to the spa area from Fonte Santa, such as parking, residential or recreative areas.

The final results include a comparation of DRASTIC indexes and "specific DRASTIC" proposed to Fonte Santa mineralized aquifer (Table V) and a detailed map of the study area with associated vulnerability classification (Fig. 4).

TABLE V: DRASTIC INDEX AND SPECIFIC DRASTIC CLASSIFICATION OF THE HYDROGEOLOGICAL UNITS FROM TERMAS DE FONTE SANTA (PENAMACOR, PORTUGAL)

| Hydrogeological units | DRASTIC index | Specific DRASTIC (*) |
|---|---|---|
| **Al – Alluvium** | High | High, intermediate, low |
| **$G_{W3-W4}$ - Unconfined aquifer** | Very low | Very low, low, intermediate |
| **$G_{W2}$ - Unconfined aquifer** | Very low | Low, intermediate, high, very high, extremely high |
| **$G_{W2}$ - Confined and semi-confined aquifer** | Extremely low | Extremely high |

(*) presented in Figure 4.

## V. Conclusion

The DRASTIC index [3] is an excellent method to identify and classify vulnerability areas and potential aquifer contamination. This assessment vulnerability methodology is supported by detailed and specific parameters associated to the study area.

The DRASTIC index is interpreted as a general vulnerability of an area and is not specific to a local hydrogeological unity. So, this methodology is not accurate and precise to be applied in the local mineralized aquifer from Fonte Santa (Penamacor, Portugal). According this, the presented study has applied the DRASTIC index to the mineralized aquifer – "specific DRASTIC" – with the inclusion of two relevant factors: i) the occurrence of pontual or local geological units and ii) the spatial location of the hydrogeological formation relative to discharge areas of the mineralized aquifer. The inclusion of these two features of the field will leave a more accurate and precise vulnerability classification. The application of this particular methodology has been sorted out as "specific DRASTIC" to be applied in mineralized aquifers, such is Termas de Fonte Santa (Penamacor, Portugal).

The vulnerability map obtained with "specific DRASTIC" will promote the optimization of groundwater protection perimeters, including the definition of immediate and extended protection zones. The mineralized aquifer catchment is situated in the immediate protection zone and will be classified as very high to extremely high vulnerability zone allowing groundwater protection and preservation.

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TABLE IV: DRASTIC INDEX AND VULNERABILITY OF HYDROGEOLOGICAL UNITS FROM TERMAS DE FONTE SANTA AREA (PENAMACOR, PORTUGAL)

| Hydrogeological unity | Parameter (*1) | Classes | Degree | weight | Partial index | DRASTIC index | Vulnerability |
|---|---|---|---|---|---|---|---|
| Al - Alluvium | 1 | < 1.5 m | 10 | 5 | 50 | 169 | High |
| | 2 | 102 – 178 mm/year | 6 | 4 | 24 | | |
| | 3 | sand and gravel | 8 | 3 | 24 | | |
| | 4 | silty | 4 | 2 | 8 | | |
| | 5 | 2 - 6 % | 9 | 1 | 9 | | |
| | 6 | sand and gravel (fine) | 6 | 5 | 30 | | |
| | 7 | 41 - 82 m/day | 8 | 3 | 24 | | |
| **$G_{W3-W4}$** Moderately to highly altered granite Unconfined aquifer | 1 | 1.5 - 4.6 m | 9 | 5 | 40 | 110 | Very low |
| | 2 | 102 - 178 mm/year | 6 | 4 | 24 | | |
| | 3 | Altered igneous rock | 4 | 3 | 12 | | |
| | 4 | silty | 4 | 2 | 8 | | |
| | 5 | 12 - 18 % | 3 | 1 | 3 | | |
| | 6 | igneous rock | 4 | 5 | 20 | | |
| | 7 | < 4.1 m/day | 1 | 3 | 3 | | |
| **$G_{W2}$** Slightly altered granite (Termas de Fonte Santa) Unconfined aquifer | 1 | 15.2 - 22.9 m | 3 | 5 | 15 | 104 | Very low |
| | 2 | 102 - 178 mm/year | 6 | 4 | 24 | | |
| | 3 | igneous rock | 3 | 3 | 9 | | |
| | 4 | thin or absent | 10 | 2 | 20 | | |
| | 5 | 12 - 18 % | 3 | 1 | 3 | | |
| | 6 | igneous rock | 6 | 5 | 30 | | |
| | 7 | < 4.1 m/day | 1 | 3 | 3 | | |
| **$G_{W2}$** Slightly altered granite (Termas de Fonte Santa) Unconfined aquifer Confined and semi-confined aquifer | 1 | 15.2 – 22.9 m | 3 | 5 | 15 | 86 | Extremely low |
| | 2 | 102 – 178 mm/year | 6 | 4 | 24 | | |
| | 3 | igneous rock | 3 | 3 | 9 | | |
| | 4 | confining layer | 1 | 2 | 2 | | |
| | 5 | 12 - 18 % | 3 | 1 | 3 | | |
| | 6 | igneous rock | 6 | 5 | 30 | | |
| | 7 | < 4.1m/day | 1 | 3 | 3 | | |

(*1) Parameters: 1 – Deep to water; 2 - net Recharge; 3 - Aquifer media; 4 - Soil media; 5 – slopes; 6 – unsaturated zone; 7 - Conductivity of the aquifer.

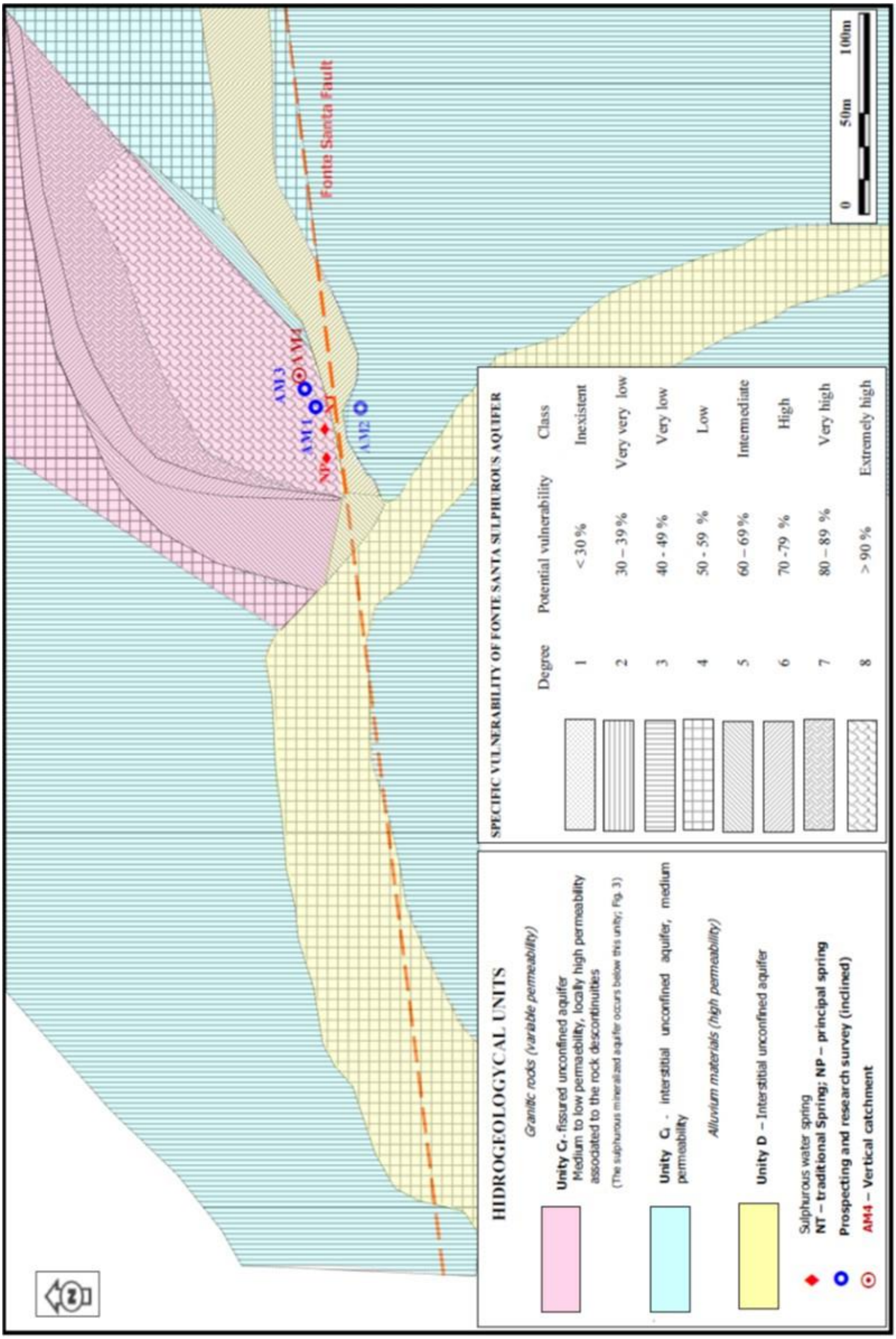


Fig. 4. “Specific DRASTIC” vulnerability map for Termas de Fonte Santa (Penamacor, Portugal).

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