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## Chapter – 14

# INTEGRATED APPROACH OF HYDROGEOMORPHOLOGY AND GIS MAPPING TO THE EVALUATION OF GROUND WATER RESOURCES: AN EXAMPLE FROM THE HYDROMINERAL SYSTEM OF CALDAS DA CAVACA, NW PORTUGAL

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ABSTRACT: Understanding the role of geomorphology is essential to accurately assess hydrogeological systems and groundwater resources. Hard-rock watersheds provide a source of valuable water resources. They commonly exhibit complex geological bedrock and morphological features as well as distinctive gradients in rainfall and temperature. A comprehensive evaluation and integrated groundwater resources study has been carried out for Caldas da Cavaca hydromineral system in NW Portugal, using hydrogeomorphology and GIS mapping techniques. Thematic maps were prepared from satellite imagery, topographical and geological mapping and other hydrogeological field data. These maps were converted to GIS format and then integrated using GIS software with the purpose of elaborating a hydrogeomorphological map intended to delineate the infiltration potential areas for the study region. Finally, this study highlights the importance of hydrogeomorphological cartography and groundwater GIS mapping as useful tools to support hydrogeological surveys, as well as for decision-making in the scope of management plans respecting to land and water resources and groundwater sustainability.

KEYWORDS: Applied Cartography, GIS, Groundwater, Hydrogeomorphology, Infiltration Potential Index, NW Portugal.

## 1. INTRODUCTION

Hydrogeomorphology is an emerging scientific domain, mainly based on the concepts of other scientific areas related to geosciences (e.g., geomorphology, geology, remote sensing, hydrogeology, applied geophysics, soil and rock geotechnics, hydrology, topography, climatology and natural hazards (e.g., Sidle and Onda, 2004; Bisson and Lehr, 2004; Babar, 2005). It operates in an interdisciplinary field focused on the linkage between hydrologic processes with landforms or earth materials, the interaction of geomorphic processes relating surface water and groundwater regimen (Sidle and Onda, 2004; Kudrna and Šindelářová, 2006). More recently, some interesting works stressed the importance of the relationships between geomorphology and groundwater approaches with other emerging scientific domains, such as hydroecology or hydrogeoecology (Loague et al., 2006; Hancock et al., 2009), hydrology modelling (Samper et al., 2007; Ebel and Loague 2008; Fujimoto 2008), hydropedology (Espinha Marques et al., 2006, 2007), urban hydrogeology (Afonso et al., 2006) and groundwater resources (Carvalho 1996; Marques et al., 2003; Carvalho et al., 2005).

The groundwater from hard-rock aquifer systems, for certain areas in Portugal, is an important water source for several domestic, industrial and agricultural purposes, as well as for public supply. Groundwater plays an important role in the economic activities and in the day life of the population. Public water supply of main towns is becoming increasingly reliant on surface water. However, several hundreds of villages still depend on groundwater supplies. In particular, small-scale agriculture and industry is highly dependent on groundwater resources. Sustainable development requires a better understanding of the hydrogeological resources, and its correct management in close relation with the socioeconomic sphere. The ecosystem goods and services provided by hydrogeological systems, such as water provisioning, protection against salt water intrusion or floods, are fundamental for human welfare (e.g., NAP, 1997; Wallace, 2007).

Thus, the groundwater and the surface water are linked components of the hydrologic system. Regarding that, groundwater recharge is the entry of water from unsaturated zone into the saturated zone, below the table surface (Freeze and Cherry, 1979; Sophocleous, 2002). There are many factors controlling the occurrence and path flows of groundwater, like topography, lithology, structure, weathering grade, fracture extent, permeability, slope, drainage pattern, landforms, land use/land cover and climate (Jaiswal et al., 2003; Surrete et al., 2008; Yeh et al., 2008). To achieve the quantification of these data it is necessary to identify and characterize the uncertainty data (Nilsson et al., 2006). In recent years, several techniques for land and water management have evolved, and remote sensing and Geographic Information Systems (GIS) have gained a great significance (Jha et al., 2007). According to Ettazarini (2007), the multi-criteria approach that encompasses various types of information (e.g., lithology, structure, slope, drainage) is greatly potentiated by the development of GIS techniques.

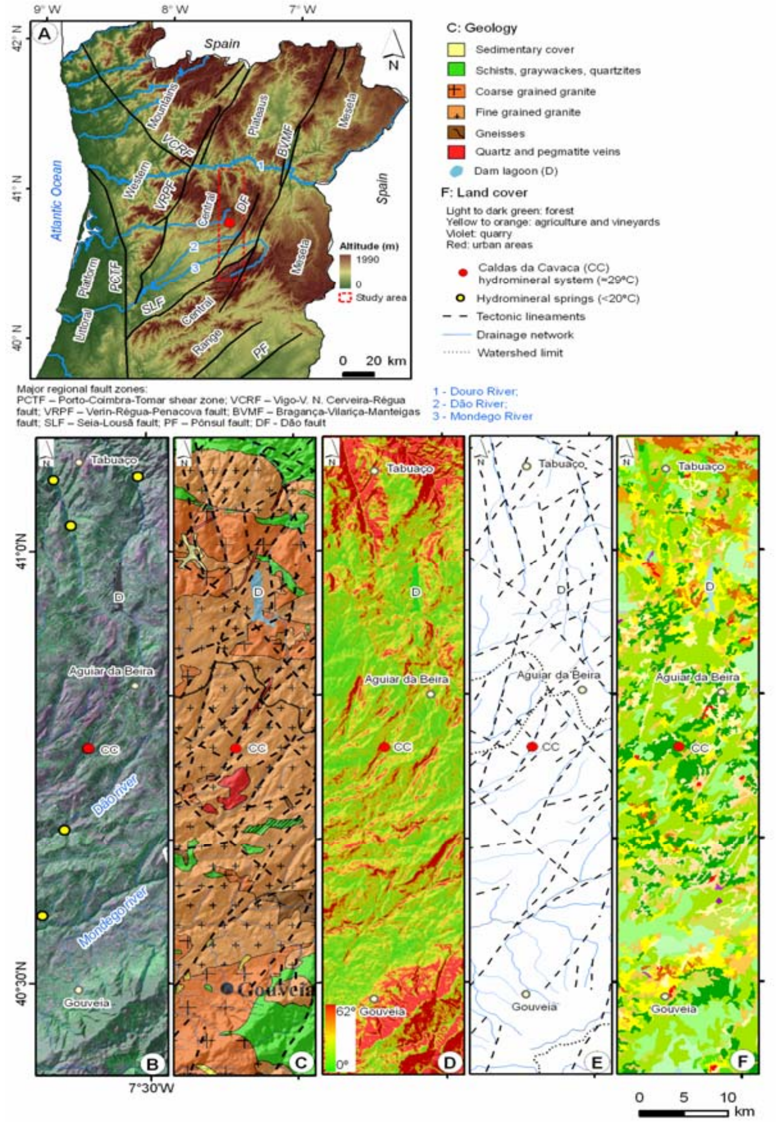

Figure 1. Regional framework of the study area (Caldas da Cavaca hydromineral system, Aguiar da Beira): A – Morphotectonic general features from Northern Portugal: i) Meseta surface, an almost perfect planation surface; ii) Central Plateaus and the Western mountains represent several stepped levels instead of a single planation surface (adapted from Brum Ferreira 1991); B – Satellite image (compiled from Landsat 7 ETM+ data, 2000/01; all IR colour, bands 7-4-5= RGB; adapted from Global Land Cover Facility) and main hydromineral springs (adapted from Carvalho 2006); C – Shaded relief and regional geology (adapted from Oliveira et al. 1992); D – Slope; E – Drainage network and tectonic lineaments; F – Land cover (adapted from CLC 2000).

In this paper we present a methodological approach, based on remote sensing, hydrostructural cartography and GIS hydrogeomorphological mapping, combined with hydrogeological field inventory and well hydrodynamic features, aiming at the assessment of fractured hydromineral systems. A hydrogeomorphological map and several derived geo-thematic maps were created in order to delineate the potential groundwater infiltration areas. This methodology was intended to enhance the understanding of hydromineral systems and can provide guidelines for decision making in the scope of water resources planning and management with respect to land and water resources exploitation in an equitable, sustainable and ethical manner.

## 2. CALDAS DA CAVACA HYDROMINERAL SYSTEM: A REGIONAL CONTEXT

The study region encompasses an area of about 10 km$^2$, and lies between 7º34'W– 7º35'W longitude and 40º44'N–40º47'N latitude (WGS84 coordinate system). It's located in Central Portugal, in the municipality of Aguiar da Beira, Guarda district. Caldas da Cavaca has a thermal tradition which dates back to the late 19th century (Acciaiuoli 1944, 1952/53). Recently, an entirely rehabilitated thermal centre has re-opened, after many years of inactivity. In this area, several geological, geomorphological and hydrogeological studies were developed, due to the need to increase the supply from the old thermal spring and former shallow well (Freire de Andrade 1935, 1938, unpublished reports) for therapeutic uses at the spa, and also provide additional freshwater in the surrounding area for domestic use. The hydromineral waters from Caldas da Cavaca (with output temperatures around 29.8ºC) are characterized by: i) relatively high pH values (c. 8, 3), ii) TDS contents in the range of 262 to 272 mg/L, iii) the presence of reduced sulphur species (HS- c. 0.9 mg/L), iv) high silica contents of 55 mg/L which represents a considerable percentage of total composition, v) Electrical conductivity (EC) measurements ranged from 353 to 427 µScm$^{-1}$ indicating the presence of medium mineralised waters and vi) high fluoride concentrations up to 14 mg/L. The waters belong to $HCO_3$-Na *facies*.

The study area belongs to the river Dão catchment, which is included in the Mondego drainage basin. Locally, the main morphologic feature is the NNE-SSW Ribeira de Coja valley (bottom *c*. 521m), with an altitude difference between top and bottom of about 170 meters, and steeping slopes. The landscape is mainly dominated by the rocky outcrops, *Pinus pinaster* forest, and agricultural areas. The Caldas da Cavaca area is located in the so-called Beiras Variscan granitic belt (Dão complex granite, Central-Iberian Zone; Boorder 1965) of the Iberian Massif and near the Western border of the deep crustal megastructure Bragança–Vilariça–Manteigas fault zone, with a general trend of NNE-SSW (Ribeiro et al. 1990, 2007). The study area is mainly composed of coarse grained porphyritic granite, alluvial deposits and doleritic veins and dykes (Boorder 1965). The mafic dykes are mostly exposed over distances of less than 30 m and often weathering to fresh. The main regional tectonic structure is the

NE-SW Dão fault zone and related fracture network systems, which control thermal water occurrences. All these structures have a great influence in the regional drainage network, revealed by its rectangular pattern.

The main hydrogeological division of Northern Portugal is determined by the mountain range associated to the major Verin-Régua-Penacova fault zone (figure 1), the Western Mountains. The mean annual rainfall to the West of this megastructure is over 1200 mm. Towards East, the precipitation declines, i.e., a minimum of 500 mm is attained in the Douro river valley, near the Spanish border (Daveau 1977). These pluviometric contrasts determine dramatic changes on the groundwater infiltration conditions. As could be expected, groundwater path flow is governed mainly by the geometry pattern and the hydraulic conductivity of the fractured medium, as well as weathering, resulting on non-continuous productive zones. Nevertheless, it is clear that in the Variscan Iberian Massif, lithology plays a major role on the productivity of regional geological units and related water wells (Carvalho et al. 2005).

The study area has a temperate climate, namely the Köppen–Geiger Cfb climate (McKnight and Hess 2000; Peel et al. 2007), which corresponds to a temperate humid climate, with temperate summer. The mean annual temperature is 13ºC, ranging from 6,2ºC in January and 20,1ºC in July. The average annual precipitation is 1252,4 mm/year, but is not constant trough the year. January has a mean rainfall reaching 189mm and July only 16mm.

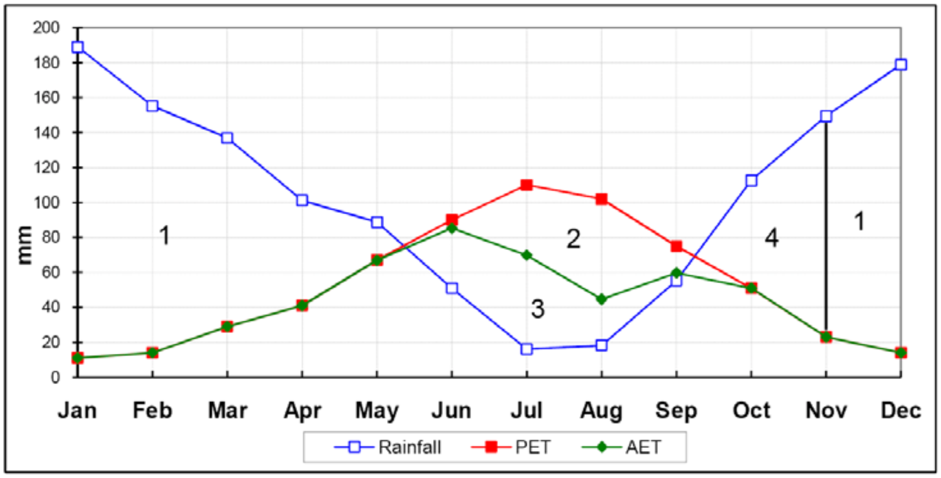

Figure 2. Annual water balance of Caldas da Cavaca area (data sources: Mendes and Bettencourt 1980; DRARN-Centro 1987): 1 – Water surplus; 2 – Water deficit; 3 – Soil moisture storage withdrawal; 4 – Soil moisture storage increase. (PET – Potential Evapotranspiration; AET – Actual Evapotranspiration).

According Thornthwait and Mather (1955) method, the annual water balance was calculated, with a field capacity of 150 mm. From June to September, the region has a water deficit, especially in July and August, with a total deficit in the four months of 117,4 mm. The full field capacity is only achieved in November, and from December to May, a total water surplus of

742,8 mm is registered (Figure 2). The estimative recharge rate is around 14% of mean annual rainfall (Carvalho et al., 2005). Considering the average annual precipitation of 1252,4 mm, thus the expected recharge is 175mm/year which is an acceptable scenario taking in account the water surplus.

The hydromineral system of Caldas da Cavaca, as other similar long circuit thermal waters in Northern Portugal (e.g., Marques et al., 2003; Carvalho et al., 2005; Espinha Marques et al., 2006), is recharged by meteoric waters that reach great depths and its emergence is controlled by tectonic traps. The knowledge of the possible recharge areas is an important instrument regarding the land use, as the design of the well head protection areas is of paramount importance for the management of this important geological resource.

## 3. METHODOLOGY

Recent technological advances have brought remote sensing and geographic information system (GIS) techniques to the forefront as tools for recommending conservation and management methods (Chowdary et al. 2003, 2008). Applying these new techniques, in a GIS environment, a geo-database was created, organised in different data layers, which include an evaluation mainly focused on present geology (i.e., lithology, structure, and weathering grade), land cover, drainage, slope, and rainfall. In this approach the different layers were overlaid, considering different weight factors. This GIS procedure allowed the generation of several thematic maps in order to achieve an integrated framework of the study area and the evaluation of potential groundwater infiltration areas (Figure 3). The factors influencing infiltration of groundwater (i.e., lithology, structure and weathering grade, tectonic lineaments density, land cover, drainage density, slope and rainfall), and their relative importance, are compiled and revised from previous literature (e.g., Krishnamurthy et al., 1996; Jha et al., 2007; Yeh et al., 2008 and references there in). The inner score of the different factors used are dependent of their own characteristics and are assessed mainly from data obtained during the field campaigns and by data gathered from the literature.

The different factors used to identify the potential groundwater infiltration areas, were grouped in three main basic categories: geological description of rock masses, geographical description, and hydrogeomorphological features. Each fundamental map, with his specific weight and inner score was used to calculate the groundwater infiltration potential area, applying the spatial analysis function of ArcGIS 9.3 software. The grid data structure (a rectangular block of cells with $25m^2$) was used, and each raster cell value is a result of the score sum from explanation factors. The GIS overlay of the explanation factors results in a map, that spatially reflects the index of infiltration potential, ranging from 0 to 100. The maximum value is achieved in cells where all of the factors have the higher score. This intermediate sketch map was then overlaid with the geomorphological map and with the hydrogeological field-data inventory, to achieve an integrated final GIS-base cartography, called hydrogeomorphological map.

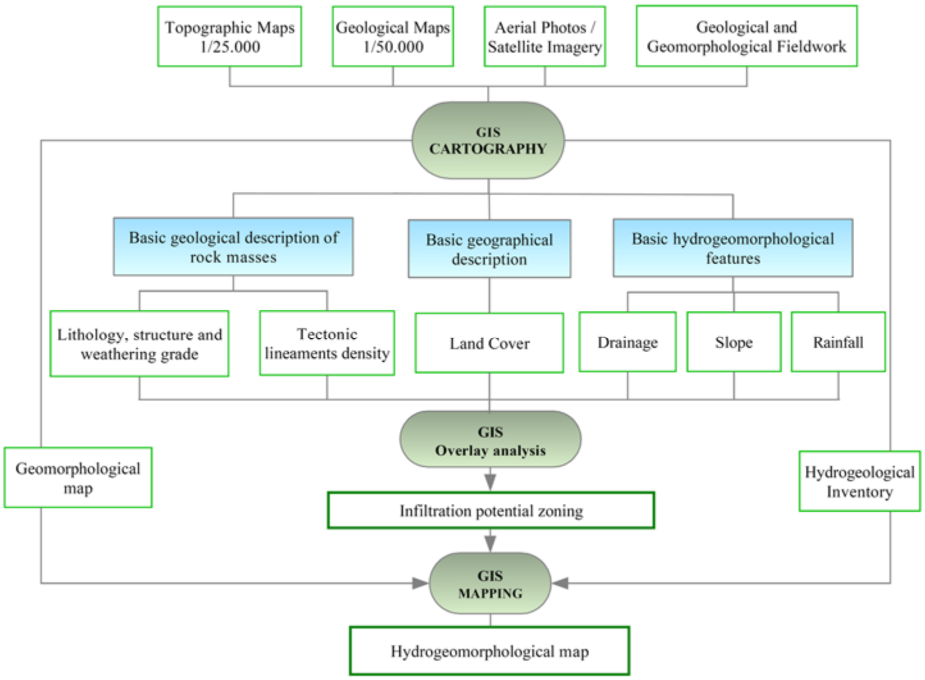

Figure 3. Conceptual flowchart of the hydrogeomorphological GIS mapping methodology applied on the Caldas da Cavaca hydromineral system.

### Infiltration potential explanation factors

Infiltration potential zoning was achieved in a GIS environment by means of a multi-criteria analysis in order to produce an index evaluation.

## 4. LITHOLOGY, STRUCTURE AND WEATHERING GRADE

The lithology, structure and the weathering grade of the rock masses, has great influence in groundwater infiltration. The intact rock and discontinuities introduce significant scale effects in hydrogeomechanical properties of granitic terrains (CFCFF 1996; Twidale and Vidal Romaní 2005; Vidal Romaní and Vaqueiro 2007). The type of lithology, structure and weathering grade implies different hydraulic conductivity, transmissivity and storage coefficient for diverse geological formations and affects the groundwater infiltration (El-Baz and Himida, 1995; CFCFF 1996; Shaban et al., 2006; Jha et al., 2007; Yeh et al., 2008).

In our case study, the dominant granitic rocks and mafic dykes exhibit different weathering grades, i.e., ranging from fresh to highly weathered, $W_{1\text{-}2}$–$W_{4\text{-}5}$, and the fracturing intercept degree is dominantly moderate to close, $F_3$–$F_{4\text{-}5}$. In addition, there is a small area of very low thickness of alluvium deposits. As a result of the fieldwork surveys we classify a weight factor of 20 of the total explanation (table 1). Besides, a score was given to each lithotype described in accordance with their geological and hydrogeotechnical characteristics (accordingly to ISRM 1978, 1981; GSE 1995; CFCFF 1996).

## 5. TECTONIC LINEAMENTS DENSITY

The density of tectonic lineaments is commonly used in hydrogeological studies, and several researchers gave a great importance to this subject (e.g., Lattman and Parizek, 1964; Krishnamurthy et al., 1996; Sener et al., 2005; Sander, 2007 and references there in). Lineaments may be used to infer groundwater's path flows and storage, as well as the transmissivity, hydraulic conductivity and storage coefficient of the geological formations. The tectonic lineament density is well correlated with secondary porosity and transmissivity indicating zones of higher groundwater infiltration and potential circulation (Yeh et al., 2008). In this study we have considered the lineament definition given by O'Leary et al. (1976), which defines lineament as the simple and complex linear properties of geological structures, such as faults, fractures, joints, and discontinuity surfaces, arranged in a straight or slightly curved line pattern. After the first lineaments map outline, the geological maps and fieldwork must be used to eliminate possible errors in the interpretation of the satellite and aerial photos. The tectonic lineaments, in this study, were classified according to their importance, and a population field value was defined in the density calculus. The 1st order tectonic lineaments have a double value of the 2nd order lineaments. The overall weight of this factor is 20 (Table 1).

In the ArcGIS 9.3 software, the line density function calculates the density of linear features in the neighbourhood of each point (Greenbaum 1985), in units of length per unit of area. Conceptually, with the line density function, a circle is drawn around each raster cell centre using a search radius. The length of the portion of each line that falls within the circle is multiplied by a population field value. These values are summed and the total is divide by the circle's area.

$$Density = ((L1 * V1) + (L2 * V2)) / (area\ of\ circle)$$

L1 and L2 represent the length of the portion of each line that falls within the circle. The corresponding Population field values are V1 and V2.

## 6. LAND COVER

Land cover is an important factor in groundwater infiltration. It includes the type of soil, the distribution of residential areas, and vegetation cover. Several studies in hydrogeology, and mainly those that focus in recharge, pointed out the land cover as a key factor (e.g., Sener et al. 2005; Sreedevi et al. 2005; Shaban et al. 2006; Jha et al. 2007). The different vegetation cover can benefit groundwater infiltration by the following ways (Yeh et al. 2008): (i) organic decomposition of the roots helps loosen the rock and soil, making easier the water percolation process; (ii) soil organic matter increases the formation of structural aggregates resulting in higher hydraulic conductivity; (iii) vegetation prevents direct evaporation of water from soil; (iv) Plants absorb most of their water through their roots, thus preventing water loss; (v) vegetation delays direct runoff increasing the possibility of infiltration.

In this study, land cover was derived from the former existing Portuguese Land Use Cartography (*http://snig.igeo.pt/COS/*), from Ministry for Environment, Spatial Planning and Regional Development, and also from the Corine Land Cover Map (*http://www.eea.europa.eu/*). Since this data is old to our purposes of estimating the groundwater potential, an important update to this land use maps was made, recurring to aerial photos, from the last flight available, made in 2006. The overall weight considered for this factor was 15, and a higher score was given to forest and agricultural areas (Table 1).

## 7. DRAINAGE DENSITY

The structural analysis of a drainage network helps assessing the characteristics of the groundwater infiltration zones. The quality of a drainage network depends on lithology, which provides an important index of the percolation rate. The drainage density was calculated in the same way as the lineament density, and measures the density of linear features in the neighbourhood of each point (Greenbaum, 1985), in units of length per unit of area. Many studies have integrated drainage maps to infer the groundwater infiltration potential zone (Edet et al., 1998; Shaban et al., 2006; Jha et al., 2007). As the water surface circulation can be considered an inverse function of the groundwater circulation, in this study, an overall weight of 15 was given to this factor, and a higher score was given to the lower drainage density (Table 1).

## 8. SLOPE

Slope is one of the most important factors controlling the groundwater infiltration (Jha et al., 2007; Yeh et al., 2008). Since the rainfall is the main recharge source for groundwater infiltration, the permanence of time of surface water in a given place, and consequently the time available to infiltration, is an inverse function of the slope values. Regarding that, a weight of 20 was given to slope, and the higher scores were given to the lowest slope values (Table 1).

## 9. RAINFALL

Rainfall plays a major role in the hydrologic cycle, and is the main source for groundwater infiltration. Since the water balance results reveal a water surplus from November to May (Figure 2), and the spatial variation of annual rainfall is very discrete, the overall weight for rainfall was only 10, and the high scores were given to the higher values of rainfall (Table 1).

## 10. FIELDWORK AND GEOMORPHOLOGICAL MAPPING

The hydrogeological models serves to analyse, qualitatively and quantitatively, subsurface flow and transport at a site in a way that is useful for review and performance evaluation (Neuman and Wierenga, 2003). To achieved this modelling the basic field techniques of geology, geomorphology and hydrogeology were applied (e.g., Fetter 2001; Assaad et al., 2004). The terminology and the criteria used in the rock mass characterisation and weathering grade studies was the recommended either by the International Society for Rock Mechanics (ISRM 1978, 1981), the Geological Society Engineering Group (GSE, 1995) and the Committee on Fracture Characterization and Fluid Flow (CFCFF, 1996). In this study, the topographic maps (from the Portuguese Army Geographic Institute), the geological maps (former Portuguese Geological Survey), aerial orthophotos and LandSat ETM+ and SPOT5 images were used to construct a series of geo-thematic maps, regarding the basic geological description of rock masses, basic description of geography and basic hydrogeomorphology features.

Table 1. Weights and values of the affecting factors of infiltration potential.

| Spatial features | | Value | Max. Weight | Explanation | References |
|---|---|---|---|---|---|
| Lithology, structure and weathering grade | Alluvium terraces, alluvial plains | 20 | 20 | Favourable sites for groundwater storage | ISRM (1978, 1981); GSE (1995); Jha et al. (2007); Yeh et al. (2008) |
| | Fresh to low weathered granitic rocks | 5 | | Low infiltration potential | |
| | Moderate weathered granitic rocks | 10 | | Medium infiltration potential | |
| | Highly weathered granitic rocks | 18 | | High infiltration potential | |
| | Vein and dyke structures | 15 | | High infiltration potential | |
| Tectonic lineaments density | High lineament density (> 21/km$^2$) | 20 | 20 | High infiltration potential | CFCFF (1996); Sener et al. (2005); Sreedevi et al. (2005); Jha et al. (2007); Sander (2007); Yeh et al. (2008) |
| | Medium lineament density (14-21/km$^2$) | 15 | | Medium infiltration potential | |
| | Low lineament density (7-14/km$^2$) | 10 | | Low infiltration potential | |
| | Very low lineament density (< 7/km$^2$) | 5 | | Very low infiltration potential | |
| Land cover | Roads | 0 | 15 | Impermeable sites | Sanford (2002); Shaban et al.(2006); Jha et al. (2007); Yeh et al. (2008) |
| | Villages / urban areas | 0 | | Impermeable sites | |
| | Rock outcrops | 5 | | Low infiltration potential | |
| | Forest | 15 | | High infiltration potential | |
| | Agriculture (upland conditions) | 12 | | Medium infiltration potential | |
| | Grass / Bushes | 10 | | Medium infiltration potential | |
| Drainage | Very low drainage density (< 3,5/ km$^2$) | 15 | | High infiltration potential | Sener et al. (2005); Sreedevi et al. (2005); |

| | | | | | |
|---|---|---|---|---|---|
| | Low drainage density (3,5 - 7/ km$^2$) | 13 | 15 | Medium infiltration potential | Jha et al. (2007); Sander (2007) |
| | Medium drainage density (7 - 10,5/ km$^2$) | 10 | | Low infiltration potential | |
| | High drainage density (> 10,5 / km$^2$) | 8 | | Very low infiltration potential | |
| Slope | Very low slope values (0º -5º) | 20 | 20 | High infiltration potential | Sener et al. (2005); Sreedevi et al. (2005); Jha et al. (2007); Sander (2007); Yeh et al. (2008) |
| | Low slope values (5º - 15º) | 15 | | Medium infiltration potential | |
| | Medium slope values (15º - 25º) | 10 | | Low infiltration potential | |
| | High slope values (> 25º) | 5 | | Very low infiltration potential | |
| Rainfall | > 1200 mm/year | 10 | 10 | High infiltration potential | Sener et al. (2005); Jha et al. (2007); Sander (2007); Yeh et al. (2008) |
| | 1100 – 1200 mm/year | 8 | | Medium infiltration potential | |
| | 1000 – 1100 mm/year | 6 | | Low infiltration potential | |
| | < 1000 mm/year | 4 | | Very low infiltration potential | |

## 11. RESULTS AND DISCUSSION

In Caldas da Cavaca the field petrophysical properties of soil and rock masses are usually variable in spatial (vertical or horizontal dimension) and often also in temporal scale. The geological and geomorphological studies based on fieldwork as well as remote sensing and photogeology techniques allowed differentiating the bedrock according to lithology, weathering grade and tectonic features. The cartographic expression of these features is presented in figure 4.

The coarse grained granite can be divided in three groups, according to its weathering grade. The first group is a fresh to slightly altered granite ($W_{1-2}$), occurring in the higher areas (from 600 to 700m). Its fracturing intercept degree (ISRM 1981) is, dominantly, moderate ($F_3$) to very close to close ($F_{4-5}$). This unit has a strong effect on the landscape shaping, and a pattern of rounded rocky outcrops are visible. The second group presents medium weathering grade ($W_3$). This unit is mainly present in a large corridor, with medium trend NE-SW, in lower areas than the first unit (500 to 650 m). Finally, the third group corresponds to the higher weathering grade ($W_{4-5}$), with more intense arenisation. This unit is dominant in the plateau areas away from the tectonic valley of Ribeira da Coja. The less weathered units ($W_{1-2}$ and $W_3$) are delimited by faults and fractures, with general direction NNE-SSW to NE-SW, and NW-SE. Several corridors corresponding to the $W_{4-5}$ weathering follow these fracture patterns and surround the outcrops of the less weathered units. The weathering is very intense and deep (around 40 m) in the vicinity of the brittle structures, especially near the NNE-SSW main structure, the so-called Ribeira da Coja fault zone (Carvalho et al. 2005). The mafic dykes follow the broad structural pattern, with general directions of NE-SW and NW-SE. These structures have different weathering grades, but in most cases, are weathered and present light green to orange colour. Generally, in the Portuguese part of the Iberian Massif, these structures are associated to deep fluid circulation (Carvalho 1996). The sedimentary cover is especially important in the bottom of the Ribeira da Coja valley. These silty-sandy deposits have thickness ranging from 3 to 5 meters.

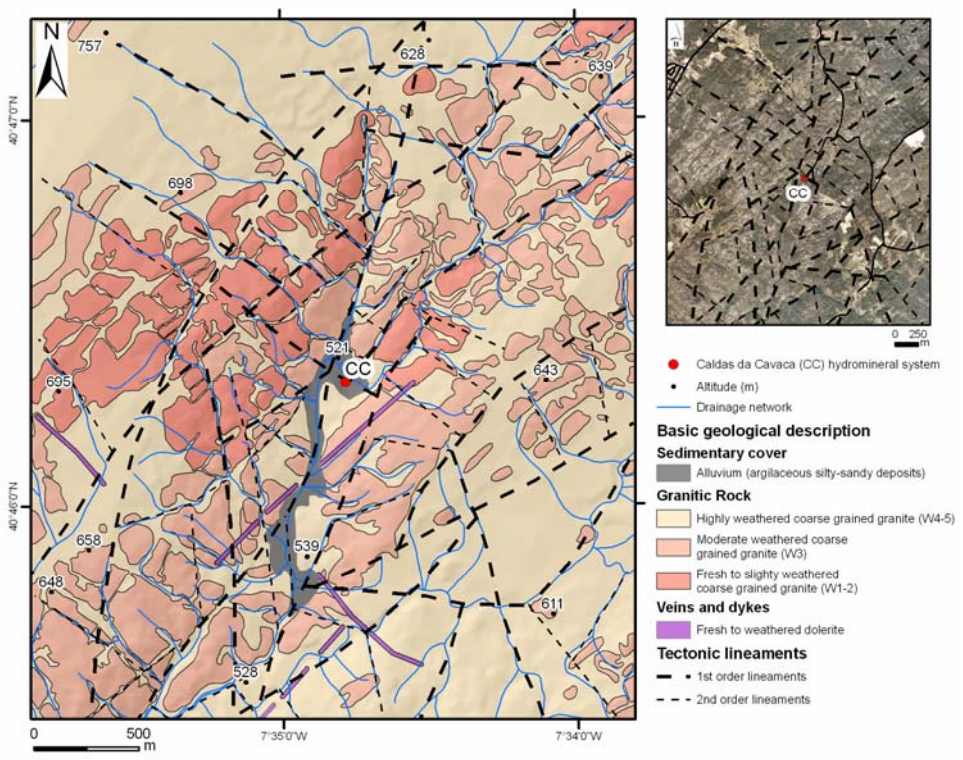

Figure 4. Geology, ground structure, weathering grade and tectonic lineaments of Caldas da Cavaca hydromineral system.

About 80% of the area has very low to low slope values (0º-5º and 5º-15º), which favours groundwater infiltration potential. The medium and high slope values (15º-25º and >25º), are mainly present in the Ribeira da Coja valley, and are normally associated to the rocky outcrops of the lower weathering grade granite.

The different phases of the hydrogeomorphological approach applied in Caldas da Cavaca hydromineral system are illustrated in Figure 6 and Table 2. The infiltration potential zoning (Fig. 6C) is a result of all the factors listed in the previous section: lithology, structure, weathering grade, tectonic lineaments density, land cover, drainage density, slope and rainfall. The overlay of the explanation factors results in a map showing the potential groundwater infiltration in the Caldas da Cavaca area. The overall calculation was qualitatively reclassified into four infiltration potential classes, from very low (index <25) to high (index 75-100).

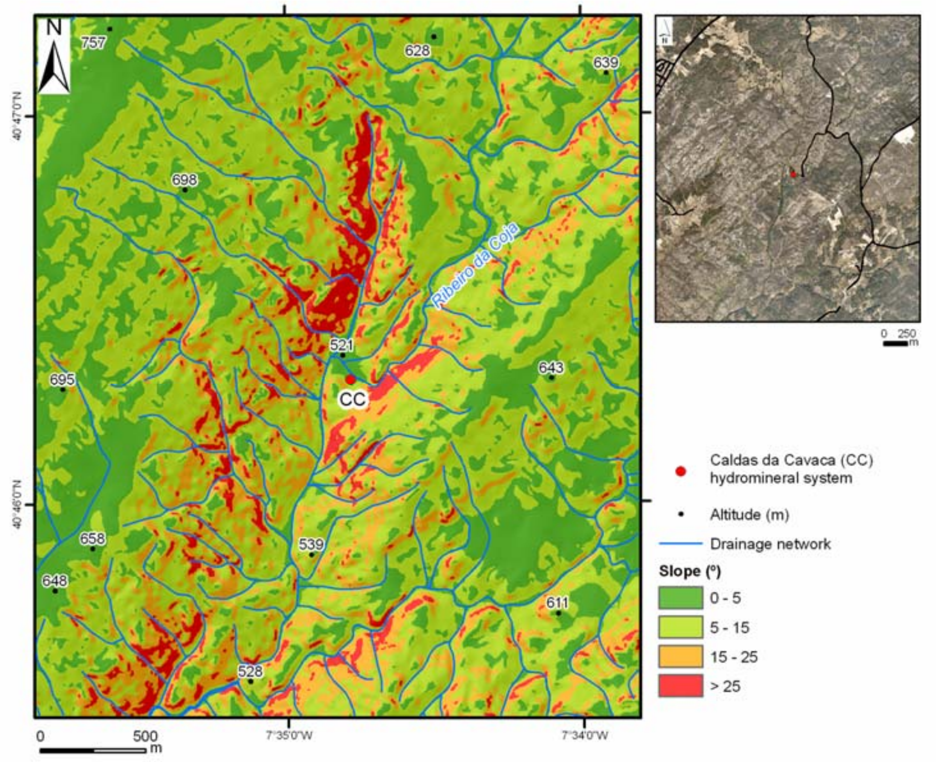

Figure 5. Slope map of the Caldas da Cavaca hydromineral system.

Table 2. Hydrological and hydrogeomorphological favourability for the potential infiltration fissured hard-rock, focused in to groundwater recharge/ discharge, to Caldas da Cavaca area.

| Parameters | Recharge | Discharge |
|---|---|---|
| Weathering grade | | |
| *$W_{1-2}$ to $W_3$* | – | + |
| *$W_{4-5}$ (arenisation layers)* | + | + |
| Ground structure | | |
| *$F_{1-2}$* | – | – |
| *$F_3$ to $F_{4-5}$* | + | + |
| Tectonic lineaments | + | + |
| Topography/slope | | |
| *Flat top* | + | – |
| Topography/slope | | |
| *Bottom valley* | – | + |
| Topography/slope | | |
| *Steep convex/rectilinear* | – | – |

| | | |
|---|---|---|
| Drainage network | | |
| *Low to medium density* | − | − |
| *high density* | + | + |
| Land cover | | |
| *Forest and agricultural areas* | + | − |
| Rainfall | + | + |

(**ground fracture intercept**: $F_{1-2}$: wide; $F_3$: moderate; $F_{4-5}$: close; **weathering grade**: $W_{1-2}$: fresh to low; $W_3$: moderate; W4-5: high)

The areas of high infiltration potentials are mainly located in three major areas (Figure 6c): (i) Quinta das Lameiras site; (ii) Cavaca village and (iii) Quinta dos Matos site. These areas are characterized by low slope values, higher weathering grade granite and higher extension of tectonic lineaments. The area of Caldas da Cavaca is also characterized by high infiltration potential, which in this case is due to the influence of the lithology (sedimentary cover) combined with low slope values (valley bottom landform). Medium to low infiltration potentials are mostly explained by the presence of fresh to slightly weathered granitic rock, with scarce fracturing and low concentration of lineaments. Very low infiltration potentials correspond to building areas in the local settlements.

## 12. GEOMORPHOLOGY AND FIELD HYDROGEOLOGICAL INVENTORY

The local geomorphology clearly reflects the regional morphological context (see Figure 1), specially the main planation surface of the Iberian Central Plateaus, as defined by Brum Ferreira (1980, 1991). This surface is characterized by a very regular top surface comprehending altitudes between 700 and 750m, which is largely present in the study area. The regular surfaces are more extense in the NW and in the SW sectors. A small ridge is noticed in the W sector, with two planation levels, around 650 and 700m. This regional morphological unit is also characterized by the presence of some embedded levels, from the top planned level, about 700m, to the bottom of the Ribeira da Coja valley, around 521m. The watercourses play a determinant role, creating an important morphological feature, i.e., an entrenched valley, with high slope values. The slopes show different patterns, related with their altitude, and topographic position. Near the top, between 650 and 700 m, the slopes are convex and have lower slope gradient; close to the valley bottom they are concave, leading also to the higher slope values of the study area (Figure 7).

The hydrogeological inventory was carried out in field campaigns. The water points were georeferenced with a high-accuracy GIS data collection system (GPS Trimble GeoExplorer), and several parameters were measured, like water temperature, electrical conductivity, pH and yield. Additionally, the topographic, geomorphological and geological conditions of each water point were registered in a field datasheet, and added to the GIS database. The water points of the area are not uniformly distributed. A large number of shallow dug-wells are present in the plannation surfaces of 600, 650 and 700m, especially in the agricultural sites (upland conditions), which have a strong need of water. In general, these water

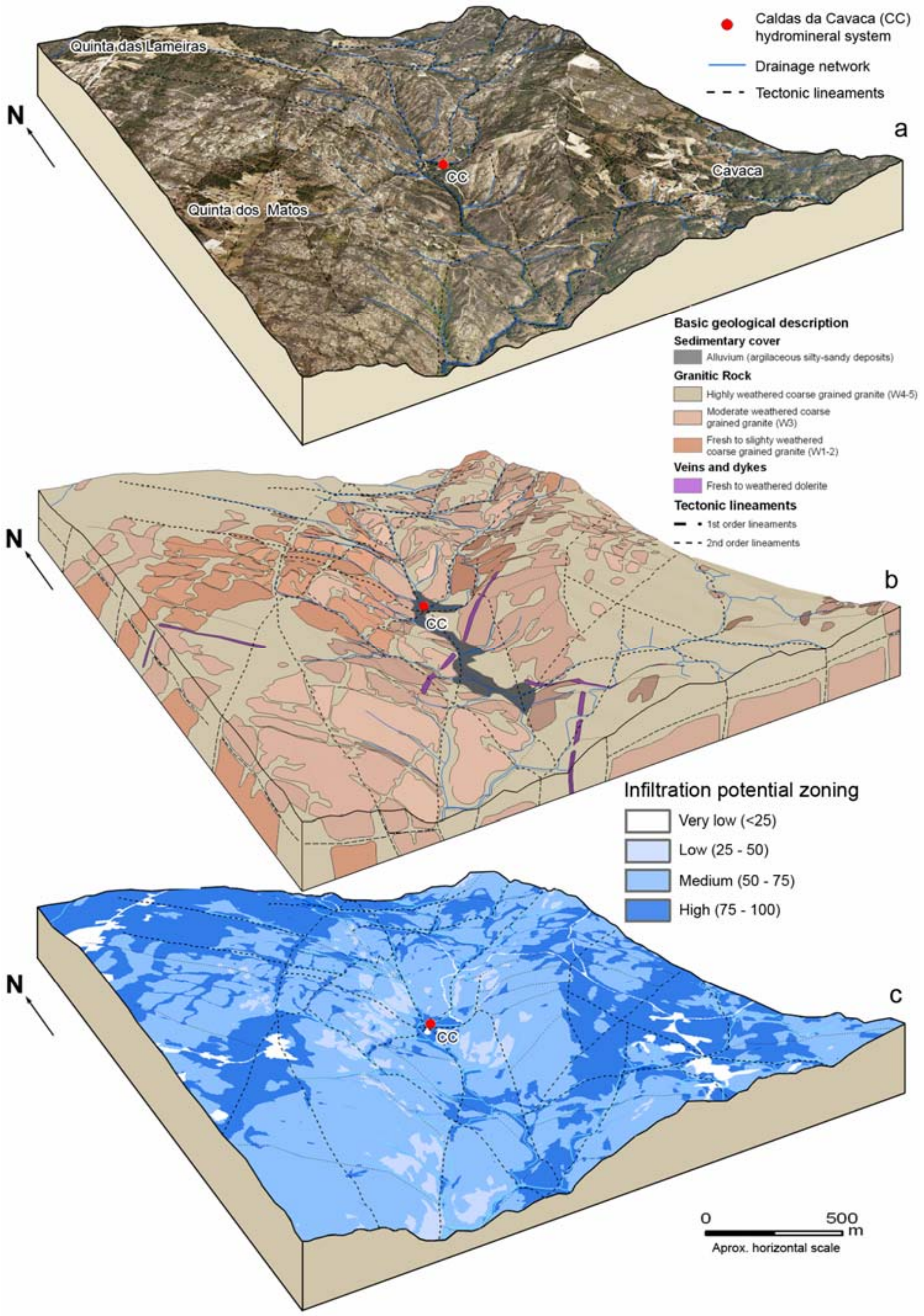

Figure 6. Block diagrams illustrating the different phases of the hydrogeomorphological approach applied in Caldas da Cavaca hydromineral system. a) Digital Terrain Model bearing aerial photography; b) Basic geological features: lithology, rock structure, weathering grade and morphotectonics; c) Groundwater infiltration potential zoning.

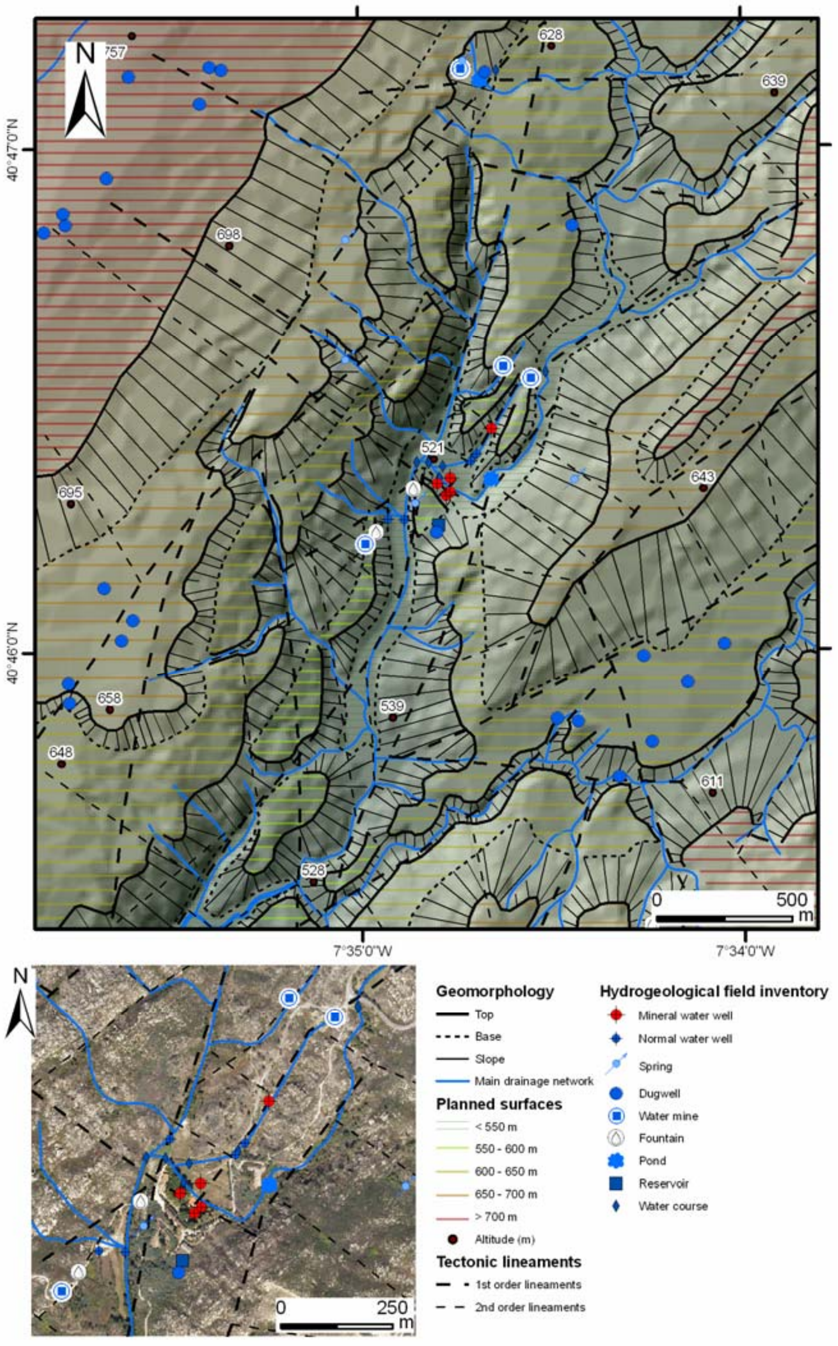

Figure 7. Geomorphological map and hydrogeological field inventory of the Caldas da Cavaca hydromineral system.

points have small depths. The main water origin seems to be the upper unconfined aquifer (Carvalho et al., 2005). The horizontal hand-made water galleries, are mainly located between 550 to 600m, also in the unconfined aquifer. The few natural springs in the area are generally located at the altitudes of 650 to 700m. These water sources have small yields (0.05 to 0.01 l/s), low temperature (<17ºC), and low electrical conductivity values (<100 µScm$^{-1}$). The mineral water wells are located in the bottom of the valley of Ribeira da Coja, and achieve a maximum depth of 220m (Figure 8). Two of these wells extract water from the hydromineral aquifer, which has higher temperature (around 29.8ºC) and electrical conductivity values (400–450 µScm$^{-1}$). In these wells the hydromineral system has transmissivities ranging from 27 to 136 m$^2$/day. The other wells are unproductive for practical purposes without mineral or "normal" water. The median transmissivities, outside the hidromineral flow paths, are <1 m$^2$/day. The storativity is 6.7 x 10$^{-3}$ denouncing semi-confined conditions (Carvalho et al., 2005).

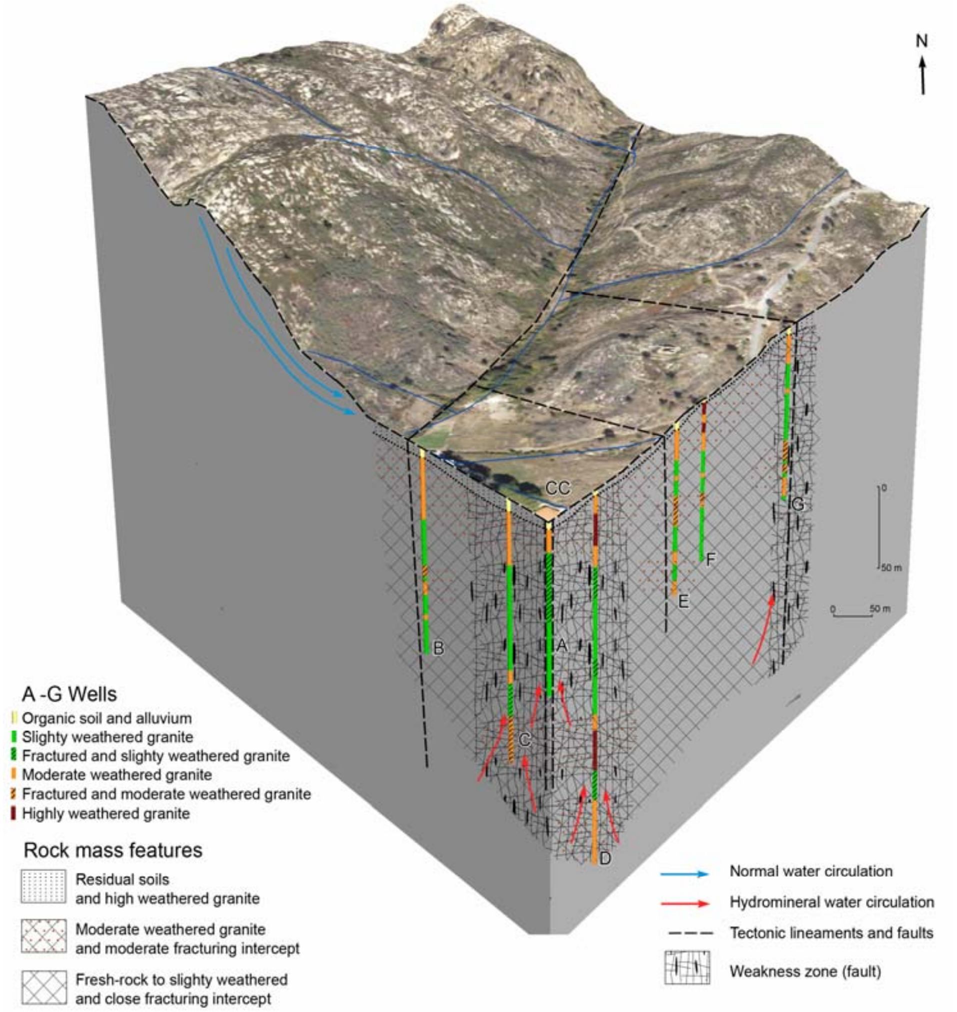

Figure 8. 3D block diagram with well geological and hydrogeomechanical features from Caldas da Cavaca (CC) area.

The hydrogeomorphological map of Figure 9 presents the main result of the application of the applied methodology, which combines geological, hydrogeological and geomorphological factors. The location of potential infiltration areas becomes perceptible when using this type of hydrogeomorphological zoning. The study produced an infiltration potential zoning showing that the most effective infiltration areas are located in the NW and SE sectors of the Caldas da Cavaca region. These zones correspond to highly weathered granite with deep arenisation mantles, namely in plateau areas. The less effective infiltration areas are present in a NE-SW corridor sub-parallel to the main tectonic valley and correspond to less weathered granites.

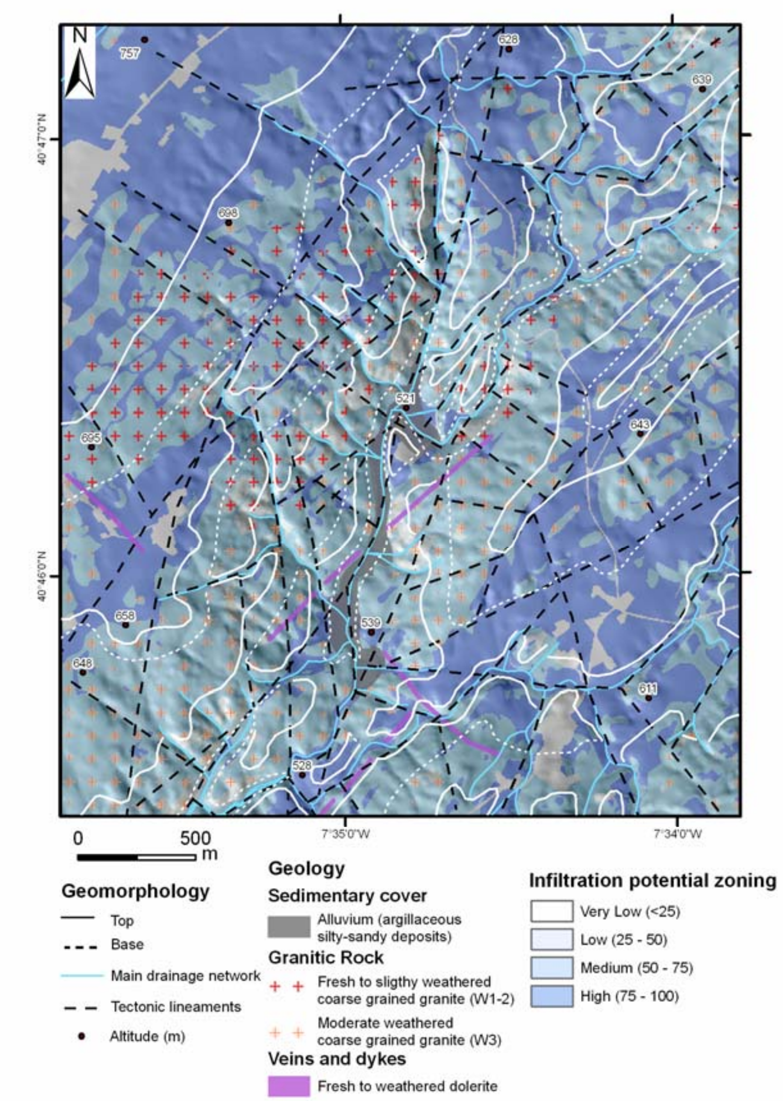

Figure 9. Hydrogeomorphological map of the Caldas da Cavaca hydromineral system.

## 13. CONCLUDING REMARKS

Hydrogeomorphological analysis supported by GIS mapping techniques may be a very useful tool in the assessment of infiltration potential. The Caldas da Cavaca hydrogeological system corresponds to a hard-rock watershed with a complex granitic bedrock and distinctive morphological and climatic features. In this study, a geo-database was created, in a GIS environment in order to carry out a multi-criteria analysis intended to produce an index evaluation of infiltration potential. This geo-database, organised in different layers, includes data reinterpreted from published cartography, such as topography, geology and image data (like aerial photos and satellite imagery), and also geomorphological, geological, and hydrogeological data from fieldwork campaigns. Several geo-thematic maps were created using a grid model, regarding the basic geological description of rock masses and the basic description of hydrogeomorphological characteristics. The basic maps, incorporating several features (e.g., lithology, structure, weathering grade, tectonic lineaments, slope, drainage, rainfall, land cover, hydrogeological inventory) and having different values of significance, were overlaid, leading to a final hydrogeomorphological map of infiltration potential zoning.

The connection of the geomorphological and hydrogeological features with the hydrological characteristics of these areas provided a simple and efficient way to understand the groundwater and surface water circulation model, and to contribute to the decision-making process in different areas, like the water resources management and the territory planning. This is particularly important regarding the hydromineral aquifer, a resource of high economical importance considering its utilisation in the thermal spa.

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