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THEMATIC ISSUE

A comprehensive analysis of groundwater resources using GIS and multicriteria tools (Caldas da Cavaca, Central Portugal): environmental issues

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Abstract Hard-rock watersheds are essentially confined to fractured and weathered horizons, but they are a source of valuable water resources at a regional level, namely for domestic, industrial and agricultural purposes, and public supply. They commonly exhibit complex geological bedrock and morphological features as well as distinctive gradients in rainfall and temperature. Hydromineral and geothermal resources have relevant economic value both for the bottled water/thermal spas industry and for energy supply. A comprehensive evaluation and integrated groundwater resources study has been carried out for the Caldas da Cavaca hydromineral system in Central Portugal, using hydrogeomorphology and GIS mapping techniques. Thematic maps were organised from a geodatabase comprising several layers, namely lithology, tectonic lineaments density, slope, drainage density, rainfall, net groundwater recharge and water quality. Normalised weights were assigned to all these categories according to their relative importance to groundwater potential, based on their effectiveness factors. Hydrogeochemistry, natural radioactivity and intrinsic vulnerability assessment (GOD-S, DRASTIC-Fm, SINTACS, SI indexes) issues were also cross-checked. Based on all the compiled information, a hydrogeomorphological map was produced. This multidisciplinary approach highlights the importance of hydrogeomorphological mapping as a tool to support hydrological conceptualisation, contributing to groundwater decision-making process in different stages, like water resources management and territory planning, and thus, to environmental sustainability.

Keywords Applied cartography · Groundwater · Hydrogeomorphology · Infiltration potential index · Central Portugal

Introduction

Hard-rock aquifer systems are an important source for domestic, industrial, agricultural and public supply purposes. Moreover, these systems have a significant economic value, where groundwater is used in thermal bath spas. In these areas, geology, geomorphology, climatology and hydrological properties control the groundwater flow,

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storage and occurrence (e.g. Carvalho 1996; Jaiswal et al. 2003; Surrette et al. 2008).

In a complex hydrogeologic setting, hydrogeomorphology provides a very valuable approach on hard-rock aquifers characterisation, analysis and assessment (e.g. Tricart 1961; Sidle and Onda 2004; Babar 2005; Teixeira et al. 2013). In addition, the relationship with other related domains, such as, remote sensing, morphotectonics, structural geology, hydrogeology, applied geophysics, soil and rock geotechnics, climatology and natural hazards assessment usually provides original and useful insights. Hydrogeomorphology is also fundamental for understanding the linkage between hydrologic processes and landforms and earth materials, as well as the interaction of surface water and groundwater regimen in a given area (Bisson and Lehr 2004; Kudrna and Šindelářová 2006; Teixeira et al. 2013).

Sustainable development requires a better understanding of hydrogeological resources and their correct management in close relationship with the socioeconomic scope. The ecosystem goods and services provided by hydrogeological systems, such as freshwater provisioning, protection against salt water intrusion or floods and water quality issues, are fundamental for human welfare (e.g. NAP 1997; Wallace 2007). In order to correctly assess the georesource there are several factors controlling the occurrence and path flows of groundwater, such as, topography, lithology, structure, weathering grade, fracture extent, permeability, slope, drainage pattern, landforms, land use/land cover and climate (e.g. Jaiswal et al. 2003; Nilsson et al. 2006; Surrette et al. 2008; Yeh et al. 2008; Teixeira et al. 2010, 2013). Instead, intrinsic geological and hydrological variability and uncertainty data should be identified and properly characterised (e.g. Nilsson et al. 2006; Keaton 2013; Chaminé et al. 2013 and references therein).

The use of ground models and hydrological conceptual models based on hierarchical analysis of groundwater flow often provide significant contributions for understanding the complexity of Earth systems (e.g. Griffiths and Stokes 2008; Kresic and Mikszewski 2013; Chaminé et al. 2013; Griffiths 2014). In this context, good quality groundwater modelling requires hard-rock aquifer mapping and conceptualisation of hydrogeological systems (Chaminé et al. 2013; Teixeira et al. 2013). Groundwater-based mapping took advantage of the progress of geographical information systems (GIS) techniques, methods and analysis (e.g. Jaiswal et al. 2003; Jha et al. 2007; Yeh et al. 2008; Ballukraya and Kalimuthu 2010; Jha 2011; Teixeira et al. 2013). The multicriteria approach is greatly benefited by these GIS techniques when coupled with other decision tools (e.g. analytical hierarchy processes or fuzzy logic; Ettazarini 2007; Saaty 2008; Kim et al. 2009). Geovisualisation is another important issue to characterise hydrologic systems as it carries challenging approaches in map design (e.g. Dykes et al. 2005; Cascelli et al. 2012, and references therein).

This paper intends to present a comprehensive methodology of groundwater resources evaluation, based in GIS analysis and multicriteria tools. Remote sensing, hydrostructural cartography, hydrogeomorphological and vulnerability mapping, as well as hydrogeological field inventory and hydrodynamic features were key parameters to the assessment of Caldas da Cavaca hydromineral system (Central Portugal). This approach greatly contributes to the development of the hard-rock hydrogeological conceptual site model, and may provide valid guidelines for decision-making in the groundwater and surface water protection, planning and management, as well as to equitable and sustainable exploitation of water resources.

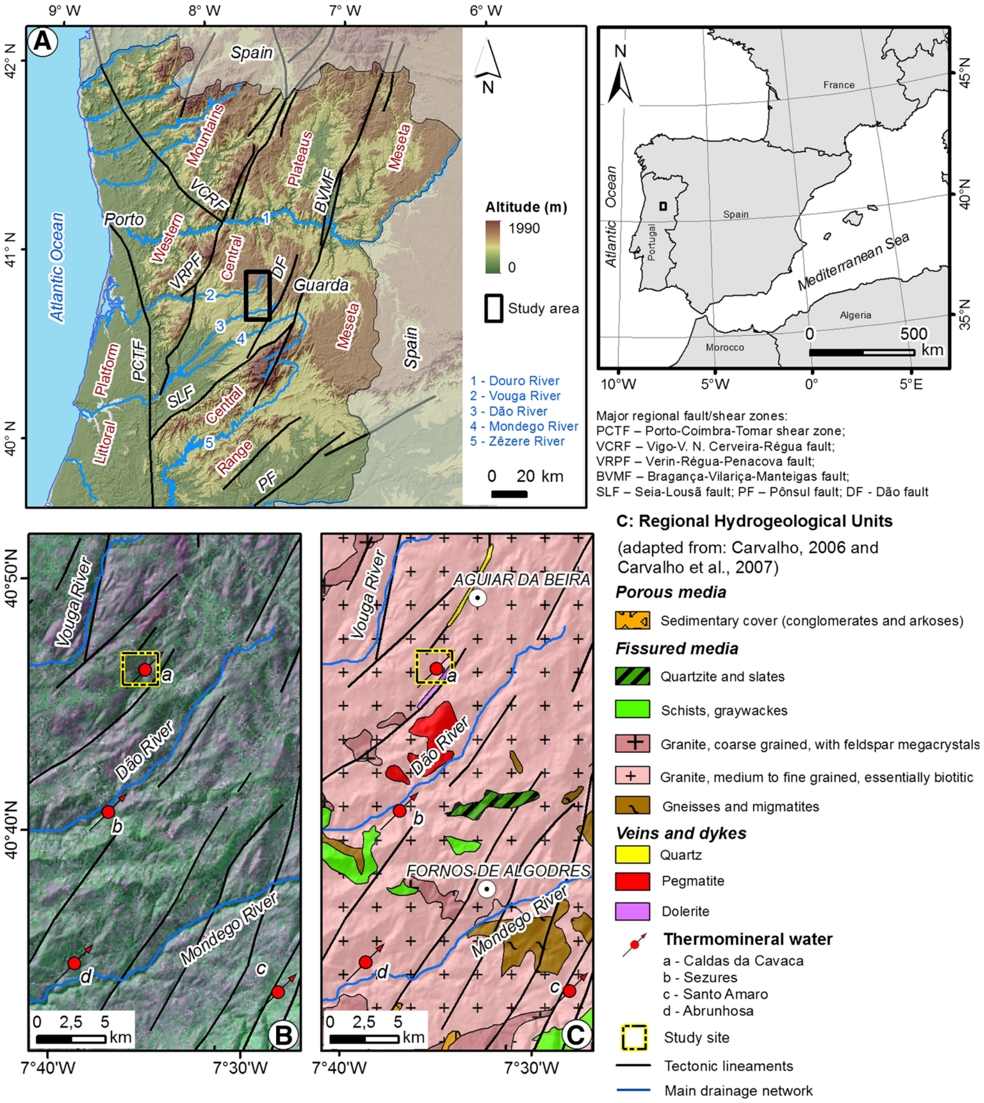
Caldas da Cavaca hydromineral system: regional framework

The Caldas da Cavaca area is sited in the municipality of Aguiar da Beira, Guarda district (Central Portugal). The study region is located in Beiras Variscan granitic belt—Dão complex granite (Boorder 1965)—of the Iberian Massif (Central-Iberian Zone), nearby the western border of the Bragança–Vilariça–Manteigas major fault zone, with a general trend of NNE–SSW (Brum Ferreira 1991; Ribeiro et al. 2007). The site belongs to the regional morphotectonic unit of the Central Plateau, in the northern part of the wide range of ridges, the so-called '*Cordilheira Central*' or Central Range (Ribeiro 1949; Brum Ferreira 1980), Fig. 1. The study area is mainly composed of coarse-grained porphyritic granite, alluvial deposits and doleritic dykes (Boorder 1965). The mafic dykes are mostly exposed over distances of less than 30 m and often highly weathered to fresh.

The drainage network in Caldas da Cavaca study site is part of the Dão River catchment, which is a tributary of Mondego River. The NNE–SSW Ribeira de Coja valley (bottom c. 521 m) is locally the main morphologic structure, with steep slopes and about 200 m of altitude difference. The surrounding area is mainly dominated by granitic rocks outcrops, some *Pinus pinaster* forest, and agriculture in small flattened areas. The slopes are generally covered by bushes/scrub.

The climate is generally temperate, corresponding to a Köppen–Geiger Cfb climate (McKnight and Hess 2000; Peel et al. 2007), which corresponds to a temperate humid climate, with a mild summer. The mean annual temperature is 13 °C, ranging from 6.2 °C in January to 20.1 °C in July. The average annual precipitation is 1,252.4 mm/year, being January the wettest month, with a mean rainfall

Fig. 1 Regional framework of the Caldas da Cavaca hydromineral system, Aguiar da Beira municipality: **a** location of study area; **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); **c** shaded relief, regional geology (adapted from Oliveira et al. 1992) and hydrogeology (adapted from Carvalho 2006; Carvalho et al. 2007) and main hydromineral springs (adapted from Carvalho 2006)



reaching 189 mm, and July the driest, with 16 mm. The Thornthwait and Mather (1955) water balance (field capacity of 150 mm) revealed a water deficit from June to September, especially during July and August, with a total deficit in the 4 months of 117 mm. The water surplus is registered from December to May, with total values around 743 mm (Teixeira 2011). The estimated recharge is about 175 mm/year, corresponding to 14 % of the mean annual rainfall (Carvalho et al. 2005a).

Caldas da Cavaca site is recognised in the region for the thermal spa tradition, which dates back to the late nineteenth century (e.g. Freire de Andrade 1937; Acciaiuoli 1952/53; Carvalho 1996). Lately, an entire rehabilitated thermal centre has re-opened, after many years of inactivity. The old thermal spring and former shallow well (Freire de Andrade 1935, 1938) used in the past for therapeutic purposes at the old spa, was replaced by two new wells. Their location resulted from the geological, geomorphological and hydrogeological studies carried out in the last years (Carvalho et al. 2005b; Teixeira et al. 2010; Teixeira 2011; and references therein).

The hydromineral waters from Caldas da Cavaca, with output temperatures around 29.8 °C, are characterised by (details in Teixeira et al. 2010; Teixeira 2011): (1) relatively high pH values (c. 8.3); (2) TDS contents in the range of 262–272 mg/L; (3) the presence of reduced sulphur species (HS-c. 0.9 mg/L); (4) high silica contents around 55 mg/L which represents a considerable percentage of total mineralisation (around 21 %); (5) Electrical conductivity (EC) measurements ranging 353–427 µS cm^{-1} indicating the presence of medium mineralised waters and (6) high fluoride concentrations up to 14 mg/L. These waters belong to HCO_3-Na facies.

Materials and methods

In this study, several data collection techniques and procedures mainly related to remote sensing, GIS mapping, structural geology, applied geomorphology, engineering geosciences, and hydrogeology have been used (e.g. Assaad et al. 2004; Dykes et al. 2005; Smith et al. 2011). In addition, the recommendations of the Geological Society Engineering Group (GSE 1995), the Committee on Fracture Characterisation and Fluid Flow (CFCFF 1996) and the International Society for Rock Mechanics (ISRM 2007) were followed. Topographic and geological maps, aerial orthophotos and also LandSat ETM+ and SPOT5 images have been used to build several thematic field maps to support all the exploration stages.

The data collection stage (Fig. 2) had great importance in this approach, and resulted in a large amount of information which was divided into two main groups: (a) basic cartographic description, which comprised topography, remote sensing, structural geology, morphotectonics, land use and hydroclimatology; (b) field and laboratory data, such as hydrogeological inventory, field hydrogeotechnics, and hydrochemical, isotopic and radiological analysis.

Hydrogeological parameters were measured during the field inventory (e.g. temperature, pH, electrical conductivity) using a multiparametric portable equipment (Hanna Instruments, HI 9828).

The water sampling sites (namely, springs, dug wells, water wells, water galleries, streams and fountains) were georeferenced with a high-accuracy GPS (Trimble GeoExplorer). In addition, the basic geological and geomorphological description of rock masses (e.g. lithology, weathering grade, structure, morphology) was recorded, as well as the hydrological and climatological features of the site region.

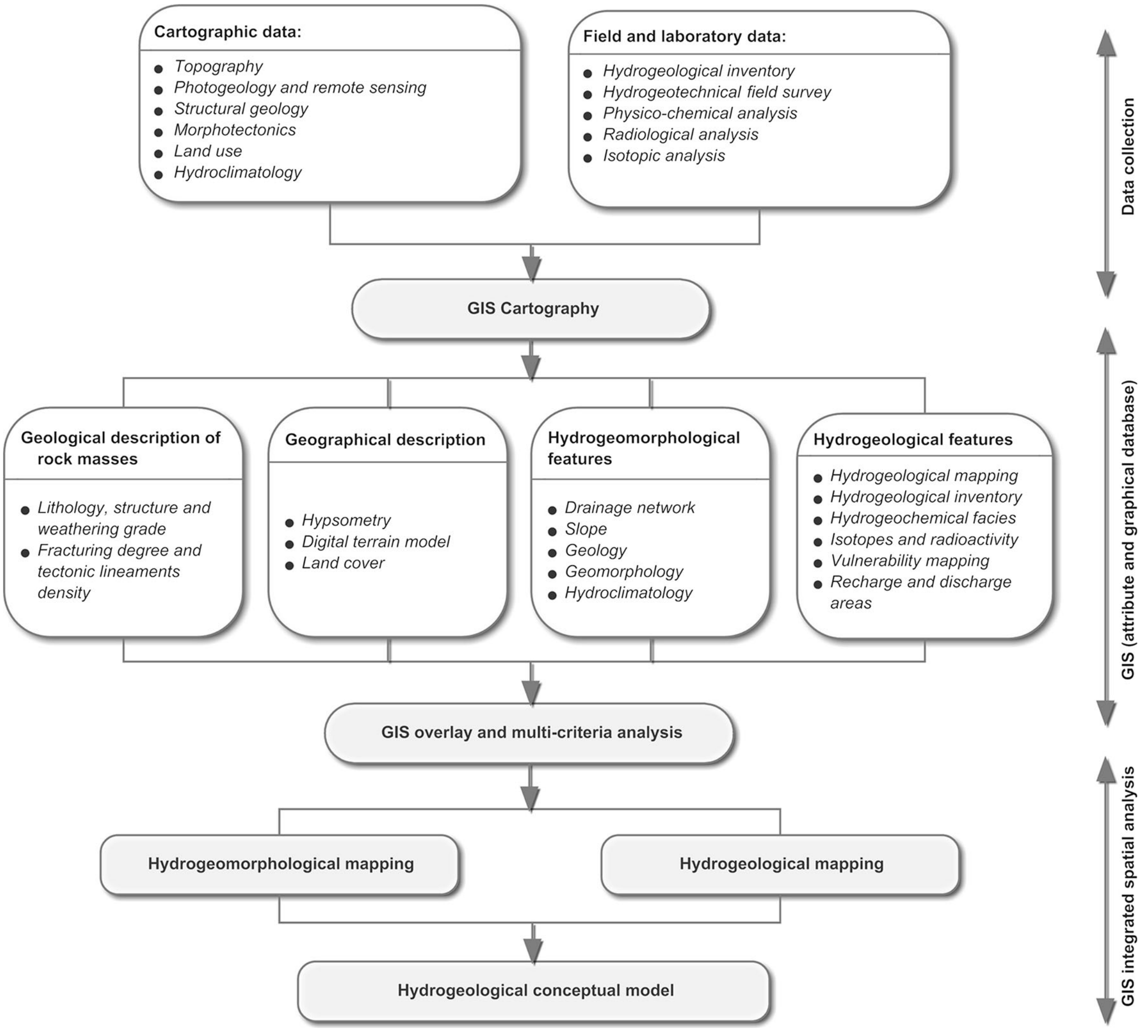


Fig. 2 Conceptual flowchart representing the methodologies used in this study

Hydrochemical parameters of each water sample were evaluated in a certified laboratory. Samples were conditioned and analysed according to standard field procedures (see details in Assaad et al. 2004). The δ^2H and δ^{18}O isotopes content were determined at the Stable Isotopes and Instrumental Analysis Facility (SIIAF) Laboratory, University of Lisbon (Portugal), by mass spectrometry continuous flow (CF-IRMS). The results are expressed as δ ‰ V-SMOW and the analytical accuracy is <0.1. In some water samples, ICP-MS analysis was made in Activation Labs (Canada). In order to evaluate the abundance and variability of radioisotopes in groundwater, as well as their impact on water quality, ^{238}U, ^{234}U, ^{226}Ra and ^{222}Rn were analysed in the Laboratory of Natural Radioactivity of University of Coimbra (Portugal). The radionuclide activity was measured by liquid scintillation counting techniques (LSC) using an ultra-low-level spectrometer Perkin Elmer Quantulus 1220 (see details in Gonçalves and Pereira 2007).

Cartographic, laboratory and field data were cross-checked and organised in a GIS environment, and a series of thematic maps was produced. This mapping was the base for the subsequent GIS overlay and analysis, namely the infiltration potential zoning and the groundwater vulnerability mapping. These maps were grouped in four main groups, namely the geological description of rock masses, geographical description, hydrogeomorphological and hydrogeological features of the study site.

The identification of the explaining factors for the calculation of the infiltration potential zoning index followed the methodology proposed by Teixeira et al. (2013). The relative weight and score for each factor was calculated using the analytical hierarchy process (AHP) method (e.g. Saaty 2008; Kim et al. 2009; and references therein), and the inner scores were mainly assessed from fieldwork data. The adopted grid data structure consisted of a pixel of 1 × 1 m. The GIS analysis resulted in a map displaying the spatial distribution of the infiltration potential index, ranging from 0 to 100, where the highest values represent a combination of favourable characteristics in most explaining factors. A more detailed explanation can be found in Teixeira et al. (2010, 2013).

The groundwater vulnerability assessment was made using several methods, some of them adapted and revised from the bibliography:

- GOD-S—Groundwater hydraulic confinement, Overlying strata, Depth to groundwater table, Soil media. The GOD-S vulnerability index is an evolution of GOD index, considering soil media properties (Foster 1987; Foster and Hirata 1988; Foster et al. 2002)
- DRASTIC-Fm—Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone, hydraulic Conductivity, Fractured media. Regarding the DRASTIC-Fm index, the original DRASTIC index (Aller et al. 1987) was slightly modified following the proposal by Denny et al. (2007), taking into account the specificities of the fissured hard-rock aquifers. The fractured media parameter (Fm) was derived from the tectonic lineaments density map, and grouped into four classes, with rating varying from 4 to 10, according to the tectonic lineament density. In the definition of the Fm factor weight, the approach by Denny et al. (2007) was followed, and a rating of 3 was given to this factor.
- SINTACS—depth to groundwater (S), recharge action (I), attenuation capacity of the vadose zone (N), attenuation capacity of the soil (T), hydrogeological characteristics of the aquifer media (A), hydraulic conductivity (C), and topographic slope (S). The SINTACS method, an evolution of the DRASTIC method, was applied to the study area, following the recommendations of Civita and De Maio (2000) and Civita (2010), using the normal strings for the multiplier weights.
- SI—susceptibility index. The susceptibility index (SI) proposed by Ribeiro (2005) and described in Stigter et al. (2006) was applied in the study area. This rating uses several parameters from the DRASTIC index (D, R, A, T), and takes into account the land use (LU), classified according to Land Cover and Land Use maps (*Corine Land Cover* 2006—Caetano et al. 2009; Painho and Caetano 2006; *Carta de Ocupação do Solo* 2007—IGP 2010), updated with more detailed information from high-resolution satellite imagery. This SI method is used, since 2012, in the Portuguese territory planning laws to identify and protect the aquifer recharge areas.

The integrated approach led to a great improvement in the understanding of the groundwater systems occurring in Caldas da Cavaca area, to a more detailed and accurate conceptual model, and thus to an efficient and sustainable management of groundwater resources.

Results and discussion

A geoscience interdisciplinary approach was employed to characterise and evaluate the Caldas da Cavaca aquifer systems. In fact, the petrophysical and hydrological properties of soil and rock masses are usually variable in spatial and temporal scales. This approach took advantage of multiple data sources including geology, morphotectonics, hydrogeology, hydrogeochemistry, environmental isotopes and radioisotopes, hydrogeomorphology and land cover. GIS-based mapping was used to produce an interactive geodatabase, to assess the spatial distribution of the field and analytical data, as well as to create intrinsic vulnerability maps (see details on the methodology approach in Teixeira et al. 2010, 2013, and references therein).

Geological description of rock mass: lithology, structure, weathering grade, fracturing degree

Locally, a coarse-grained granite dominates and was classified in three main groups, according to its exposure weathering degree (Teixeira et al. 2010; Teixeira 2011), Fig. 3a: (a) fresh to slightly weathered granite ($W_{1–2}$), occurring in the higher altitude areas (600–700 m) and, mostly, showing moderate (F_3) to very close to close fracturing degree ($F_{4–5}$). This unit has a great morphological importance, defining core stones shaped forms in the granitic outcrops of the area; (b) moderately weathered granite (W_3) is found at lower altitudes (500–650 m), in a wide corridor (ca. 500–1,000 m), with a general NE–SW

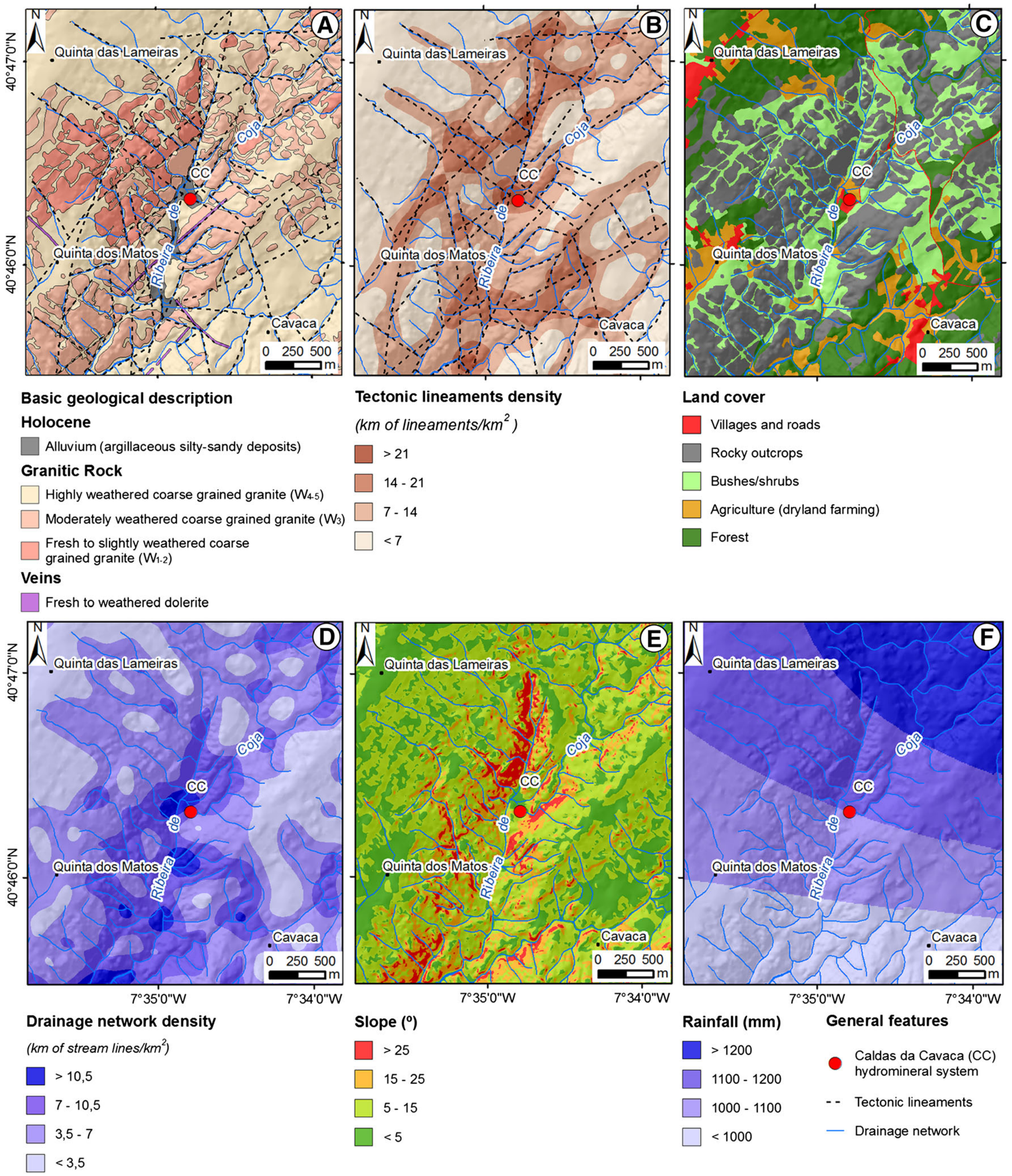


Fig. 3 Infiltration potential zoning factors: **a** lithology and weathering grade; **b** tectonic lineaments density; **c** land cover; **d** drainage network density; **e** slope; **f** rainfall

trend; (c) the last group is the most weathered granite ($W_{4–5}$), which dominates in plateau areas. The mineralogy and grain size of this granite results, locally, in intense arenisation. The rock masses ($W_{1–2}$/W_3) are generally bordered by faults and fracture zones, with NNE–SSW to NE–SW, and NW–SE trends. Along these depressed areas, several narrow corridors of highly weathered granite ($W_{4–5}$) surrounding the fresh rock masses were identified.

The weathering grade is very intense and may reach depths of about 50 m, especially in the NNE–SSW trending megastructure, the so-called Ribeira de Coja fault zone (Carvalho et al. 2005b). The dolerite veins and dykes follow the general structural pattern, namely NE–SW and NW–SE orientations. These mafic structures have different weathering grade ranges, but in most cases are altered and present light green to orange colour. In the Iberian Massif these structures are usually associated with deep fluid circulation (Carvalho 1996, 2006).

Finally, the sedimentary cover is more significant in the bottom of the Ribeira de Coja valley. The thickness of these silty–sandy deposits is small, ranging 3–5 m.

The regional and local structures were also confirmed at the very detailed rock mass scale, supported with hydrogeotechnical surveys related to the fracturing degree and hydrogeomechanical parameters. The structures (mainly faults) with orientations around N30°E to N60°E have a great importance at macroscale. The N45°–50°W trend structures are mainly joints, and have less continuity than the NE–SW ones.

The tectonic lineaments density (Fig. 3b) shows scatter behaviour, following predominantly the trending line of the structures mapped. However, a large corridor was identified, with a general NE–SW trend. Nearby the Caldas da Cavaca thermal site, a framework of tectonic lineament nodes was identified, conducting to a higher density fracture damage zone. In addition, the hydromineral fluid circulation is more favourable in a context of higher fracturing density.

Morphological and hydroclimatological features

Land cover (Fig. 3c) is an important factor controlling the surface water regimen, and thus, the infiltration (e.g. Sanford 2002; Shaban et al. 2006; Jha et al. 2007; Yeh et al. 2008). It is also a key parameter in some vulnerability indexes.

Thus, the site land cover mapping was updated with recent ortho-photomaps and high-resolution satellite imagery at a very detailed scale. In the study site, two main groups could be identified: (a) the forest and agricultural (dryland farming) areas are concentrated mainly in the NW area around the Quinta das Lameiras locality, and in the SE, around the Cavaca settlement; (b) the less weathered granite areas generally have correspondence, in the land cover, to the rocky outcrops. These outcrops are generally surrounded by bushes/shrubs, and sometimes by small forest or agricultural areas. Some agricultural areas, namely the one around Caldas da Cavaca (CC) site are presently abandoned.

The drainage network density (Fig. 3d) is also an important factor, that gives important clues about the surface and groundwater flows (e.g. Chowdary et al. 2003; Jaiswal et al. 2003; Sener et al. 2005; Sreedevi et al. 2005; Sander 2007; Ballukraya and Kalimuthu 2010; Elewa and Qaddah 2011). These key studies point that a higher density of stream lines is generally associated with less quantity of surface runoff available for infiltration, and thus, for groundwater flow, storage and occurrence. However, in some cases, when the aquifer has hydraulic connection to the stream lines, it could act in the opposite way.

In Caldas da Cavaca site, the higher drainage network density area follows the general trend of the main stream lines of the area, with a general direction approximately NE to SW. The higher values were registered in the SW area of Caldas da Cavaca.

About 80 % of the area has very low to low slope values (<5° and 5°–15°), which favours groundwater infiltration potential (Fig. 3e). These flattened areas are generally found around the settlements and are normally occupied by agriculture. The medium and high slope values (15°–25° and >25°) are mainly represented in the Ribeira de Coja valley, and are normally associated with rock outcrops.

According to the available official data from INAG (2013), the mean annual rainfall (Fig. 3f) has low spatial variation in Caldas da Cavaca area (around 950–1,300 mm/year). However, a general trend was identified, with the higher values in the NE sector.

Hydrogeology features: inventory, hydrogeochemistry, isotopic analyses

The hydrogeological inventory, acquired from the different field campaigns, is presented in Fig. 4. The water points of the area are not evenly distributed. Most of the shallow dug wells are located in the higher planned surfaces. They are related to the agricultural sites, which have in this area a high demand of water, mainly in the spring and early summer. These structures have small depths (normally <5 m), and are mainly fed by the unconfined aquifer (Carvalho et al. 2005b). The horizontal water galleries, usually hand-made, are located at lower altitudes (550–600 m). Springs are relatively rare and mainly located at altitudes between 650 and 700 m. These springs have very small yields (0.01–0.05 L/s), low temperature (<17 °C) and very low electrical conductivity (<50 µS/cm).

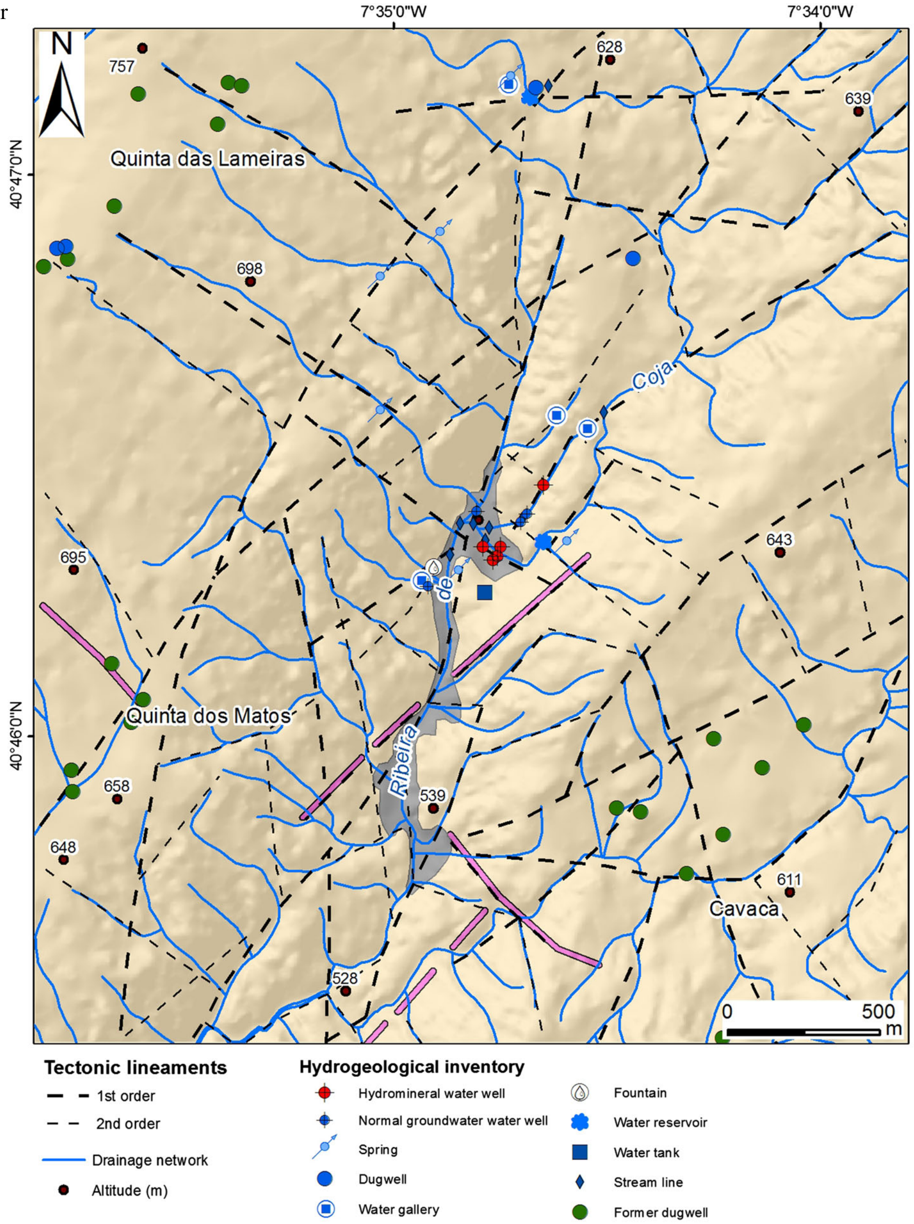


Fig. 4 Hydrogeological map and field water inventory in Caldas da Cavaca area

Hydrogeological units	Type of media		Shallow aquifer		Thermomineral aquifer	
	Porous	Fissured	Transmissivity (T, m^2/day)	Long term well capacity (Q, L/s)	Transmissivity (T, m^2/day)	Long term well capacity (Q, L/s)
■ Alluvium (sedimentary cover)	X		n.d.*	1 - 2	n.a.	n.a.
□ Granite, coarse grained, with feldspar megacrystals		X	<1	< 1	27 - 136*	1,5 - 6
■ Doleritic veins		X	<1	1 - 2	n.a.	n.a.

n.d. - not determined, very thin sedimentary cover; n.a. - not applicable.

* (Carvalho et al., 2005b)

The normal waters of the Caldas da Cavaca area can be divided into two main groups: (a) groundwater from weathered or fractured granitic areas, with a pH ranging from 5 to 6.5 and electrical conductivities between 20 and 50 µS/cm; (b) surface water and groundwater from alluvia, with pH ranging from 5.5 to 6 and electrical conductivities up to 20 µS/cm. In both groups, water temperature varies from 9 °C in the winter season to 17 °C in the summer season and is directly dependent on the air temperature. As for hydrodynamic features, this aquifer is characterised by transmissivity values below 1 m^2/day and long-term well yields below 1 L/s. However, springs have lower values, usually below 0.1 L/s.

The characteristics of Caldas da Cavaca hydromineral waters contrast with those from normal groundwater: emerging temperature around 30 °C, pH around 8.3 and electrical conductivity values ranging from 400 to 450 µS/cm. The hydromineral water wells are located in the bottom of the valley, intersecting the alluvia deposits in the first metres, and reaching a maximum depth of 220 m, with yields between 1 and 4 L/s and transmissivities ranging from 27 to 136 m^2/day (Carvalho et al. 2005b).

All the hydromineral water sites seem to be somehow related to the regional tectonic lineaments, and located very close (<100 m) to the tectonic lineaments. The context of hydrogeological trap is observed particularly in the bottom of the valley, where the hydromineral water wells are situated. This could be a key factor for the location of the former hydromineral spring, and was also an important issue for the location of the new hydromineral water wells built in the last years.

The hydromineral water of Caldas da Cavaca is part of the Portuguese Sulphurous Waters group (e.g. Acciaiuoli 1952/53; Machado 1988; Carvalho 1996; Calado 2001), having deep circulation and long residence time. Besides the relatively high pH, they have a high percentage of silica (ca. 15 % of total mineralisation), high fluoride values (around 14 mg/L), the presence of reduced forms of sulphur and sodium as the dominant cation.

These waters are mainly recommended for liver and intestine diseases (by ingestion), skin and rheumatic diseases (bath application) and respiratory diseases (by inhalation) (Pral 1965; Almeida and Almeida 1975).

The Stiff and Piper diagrams (Fig. 5a, c) show the results for the sampling sites in the study area (Fig. 5b). The hydromineral waters of Caldas da Cavaca can be considered as mesothermal, medium mineralised with alkaline reaction, sodium bicarbonate facies, fluoridated and sulphurous waters (Carvalho et al. 2005b). Their chemical composition is very stable, and is similar to the hydromineral water of the former spring (Freire de Andrade 1935, 1938). On the contrary, normal waters have very low mineralisation and generally a sodium chloride to sodium bicarbonate facies.

The main uranium decay chain isotopes occurring in natural waters (^{226}Ra and ^{222}Rn) are generally controlled by geological factors (Gonçalves and Pereira 2007). In Caldas da Cavaca site (Fig. 5b), the ^{222}Rn values in groundwater are generally within the variation interval observed in Portugal for granitic aquifers (104–373 Bq/L; Pereira et al. 2010). However, some values are much higher than the proposed interval, reaching 943 Bq/L. The mean value for Caldas da Cavaca samples is 392 Bq/L, and the values varying from <20 Bq/L to almost 950 Bq/L. This is a natural variation pattern for the radon gas in granitic rocks (Pereira et al. 2007). The higher values seem to be related to fault zones contexts, especially with orientations NNE–SSW to NE–SW.

The radon gas variations does not seem to be related to other groundwater features (pH, electrical conductivity, hydrogeochemical facies) either with the altitude or depth of the water wells. This is also pointed in other study areas (e.g. Choubey et al. 2003; Pereira et al. 2010). The local variations of the radon gas could be related to local variations of uranium concentrations, rock geochemistry, permeability or fracturing along the groundwater flow paths (LeGrand 1987; Choubey et al. 2003; Pereira et al. 2010).

The α particle activity values are low, ranging from 0.03 to 0.25 Bq/L. Also, the β particle activity is low, ranging from 0.03 to 0.99 Bq/L. These values are below the admissible values in natural waters for total α and β particle activities by the Portuguese legislation (0.5 and 1 Bq/L, respectively). Also, the low values of α and β indicates the probable presence, in these waters, of other radionuclides in insignificant concentrations (^{238}U, ^{234}U and ^{226}Ra).

The preliminary environmental isotopic data (Fig. 5d) for normal groundwater and hydromineral water show values of δ^{18}O (from −7.5 to −6.3 ‰) and δ^2H (from −48.1 to −36.3 ‰) close to the global (Global-MWL, Craig 1961) and regional meteoric (Regional-MWL, Carreira et al. 2006) water lines. Rain water from Vila Real (555 m.a.s.l.) shows −6.4 and −42.5 ‰, for δ^{18}O and δ^2H, respectively. This may indicate a similar recharge area, for normal and hydromineral groundwaters but different flow paths, given the hydrochemical and temperature characteristics. However, the hydromineral water shows lighter isotopic composition, probably related to slightly higher recharge area or water–rock interaction, like silicate hydration processes. Additional isotopic and hydrogeochemical studies are being carried on this subject.

The preliminary isotopic data (Fig. 5d) show relatively similar values of δ^{18}O and δ^2H for normal groundwater and hydromineral water, and also close to the global and regional meteoric water lines (Global-MWL and Regional-MWL, respectively). This may indicate a similar recharge area, for the normal and hydromineral groundwater. However, the flow paths for the normal and hydromineral groundwater must be different, given the hydrochemical and temperature characteristics. Additional studies are being carried on this subject.

Hydrogeomorphology and vulnerability mapping

The hydrogeomorphological map of Fig. 6 presents the main results of the calculation of the infiltration potential zoning, combining, in a GIS environment, the geologic, geomorphologic, climatic and hydrogeological factors. The spatial distribution of the infiltration potential becomes

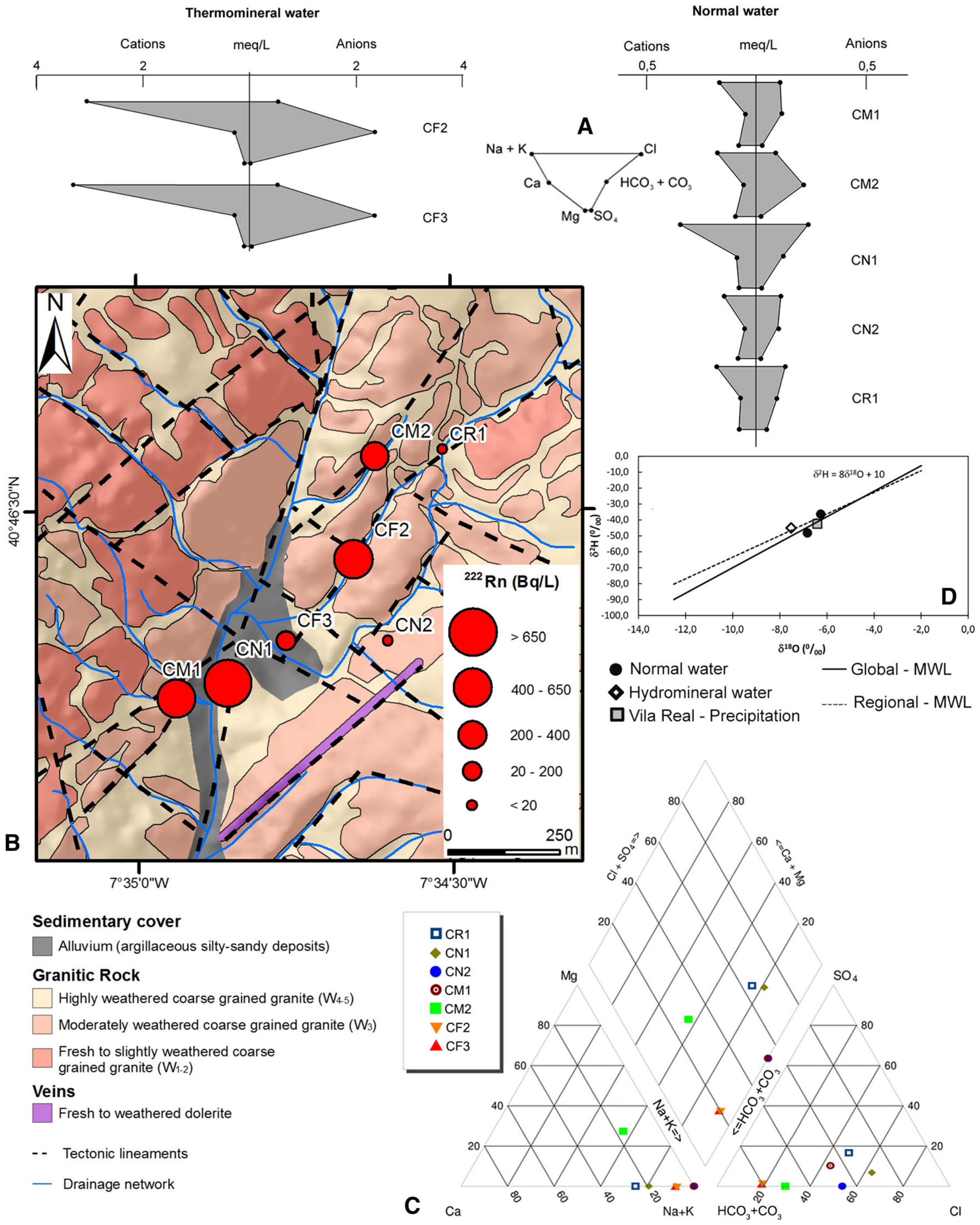


Fig. 5 Stiff diagrams (**a**), radon gas concentrations and location (**b**), Piper diagram (**c**) and preliminary isotopic data (**d**) for the water sampling points in Caldas da Cavaca study site

perceptible when using this type of hydrogeomorphological zoning (Teixeira 2011; Teixeira et al. 2010, 2013). The infiltration potential map (Fig. 6) showed that the most effective infiltration areas were located in the NW and SE sectors of the Caldas da Cavaca thermal site, namely near the settlements of Quinta dos Matos, Quinta das Lameiras and Cavaca. These zones correspond to highly weathered granite with a high thickness arenisation, and are located mainly in plateau areas. The less effective infiltration areas were found in an NE–SW corridor sub-parallel to the main tectonic valley and correspond to less weathered granites and higher slopes.

The valley bottom also presented high infiltration potential, resulting from the combination of lithology

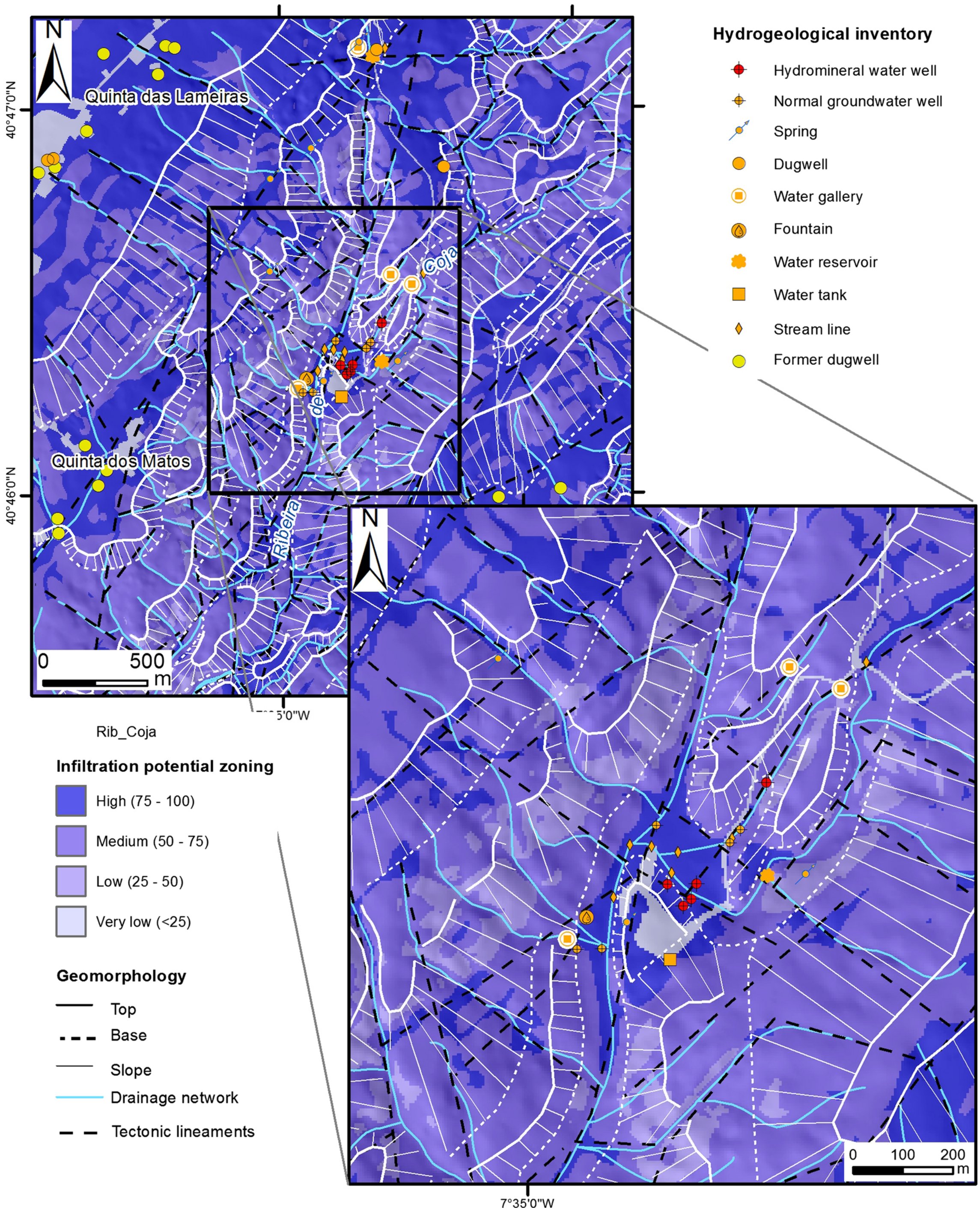


Fig. 6 Infiltration potential zoning, geomorphology and hydrogeological field inventory from Caldas da Cavaca aquifer system

(alluvial cover) and the very low slope (flattened valley bottom). However, the recharge area for hydromineral aquifer is probably located at higher altitudes (>675 m). The hydraulic connectivity between the alluvia deposits and the stream lines is very important to the groundwater recharge in this aquifer. The constructed areas in the Cavaca and Quinta das Lameiras settlements have the lowest infiltration potential.

The main features of the areas of higher infiltration potential were identified (Teixeira 2011; Teixeira et al. 2013): (1) moderately to highly weathered granitic rock (including arenisation layers); (2) moderate to close

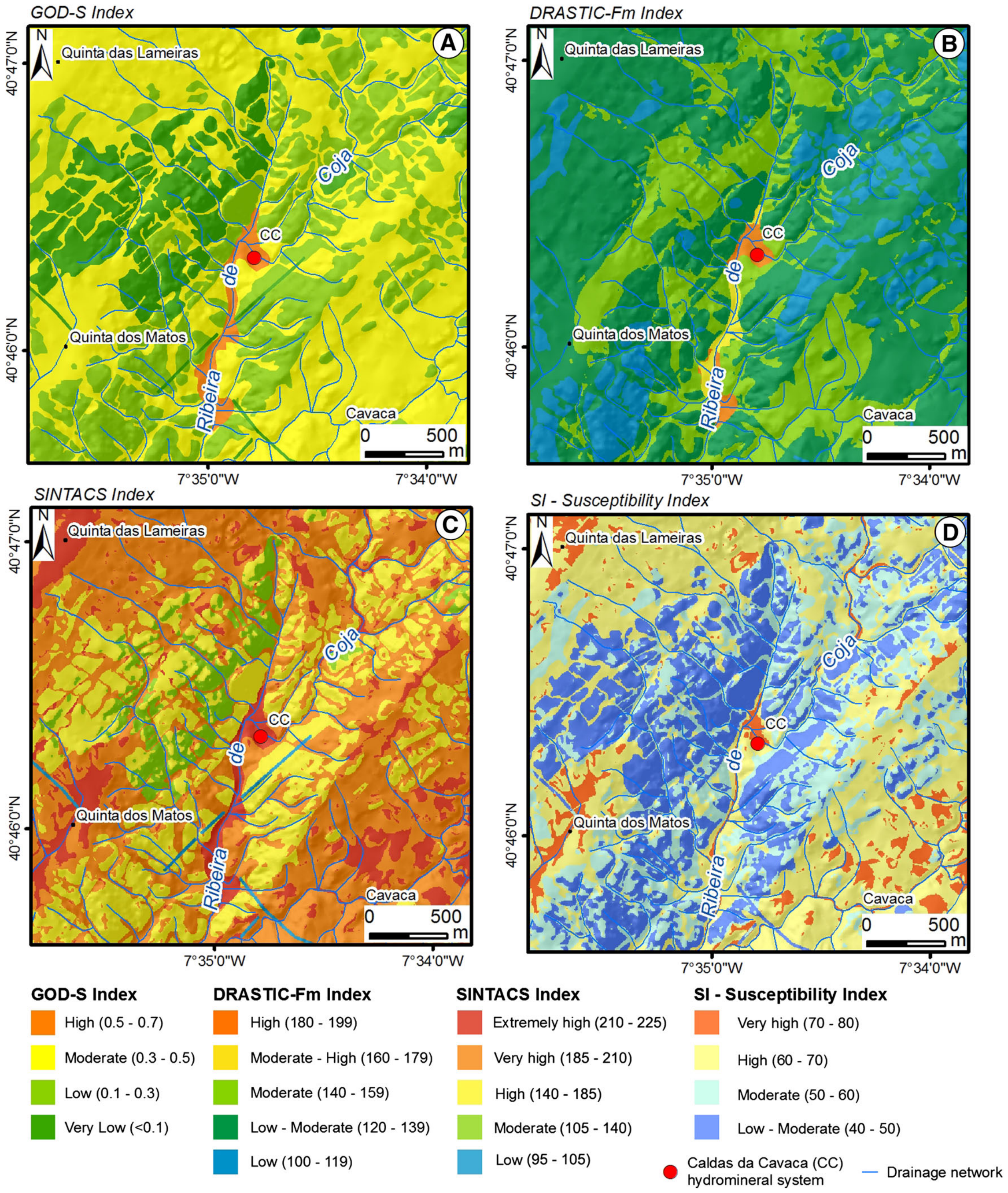


Fig. 7 Vulnerability indexes from Caldas da Cavaca aquifer systems and surrounding area: **a** GOD-S; **b** DRASTIC-Fm; **c** SINTACS; **d** SI

fracturing degree; (3) low slope areas at the highest elevations; and, (4) agricultural and forest areas.

Most of the water points (80 %) identified in Caldas da Cavaca study site are located in zones of high infiltration potential or in transition areas between the high and medium infiltration potential areas.

Figure 7 shows the results of the intrinsic vulnerability assessment based on GOD-S, DRASTIC-Fm, SINTACS and SI indexes. This type of vulnerability map evaluation has been successfully applied in many aquifer systems around the world.

According to GOD-S index (Fig. 7a), most of the Caldas da Cavaca area fits in a moderate vulnerability class. This class corresponds to the highly weathered granite ($W_{4–5}$). The low and very low vulnerability classes are related to the moderately weathered (W_3) to slightly weathered ($W_{1–2}$) granite and with the dolerite dykes. On the contrary, the high vulnerability class corresponds to the alluvia

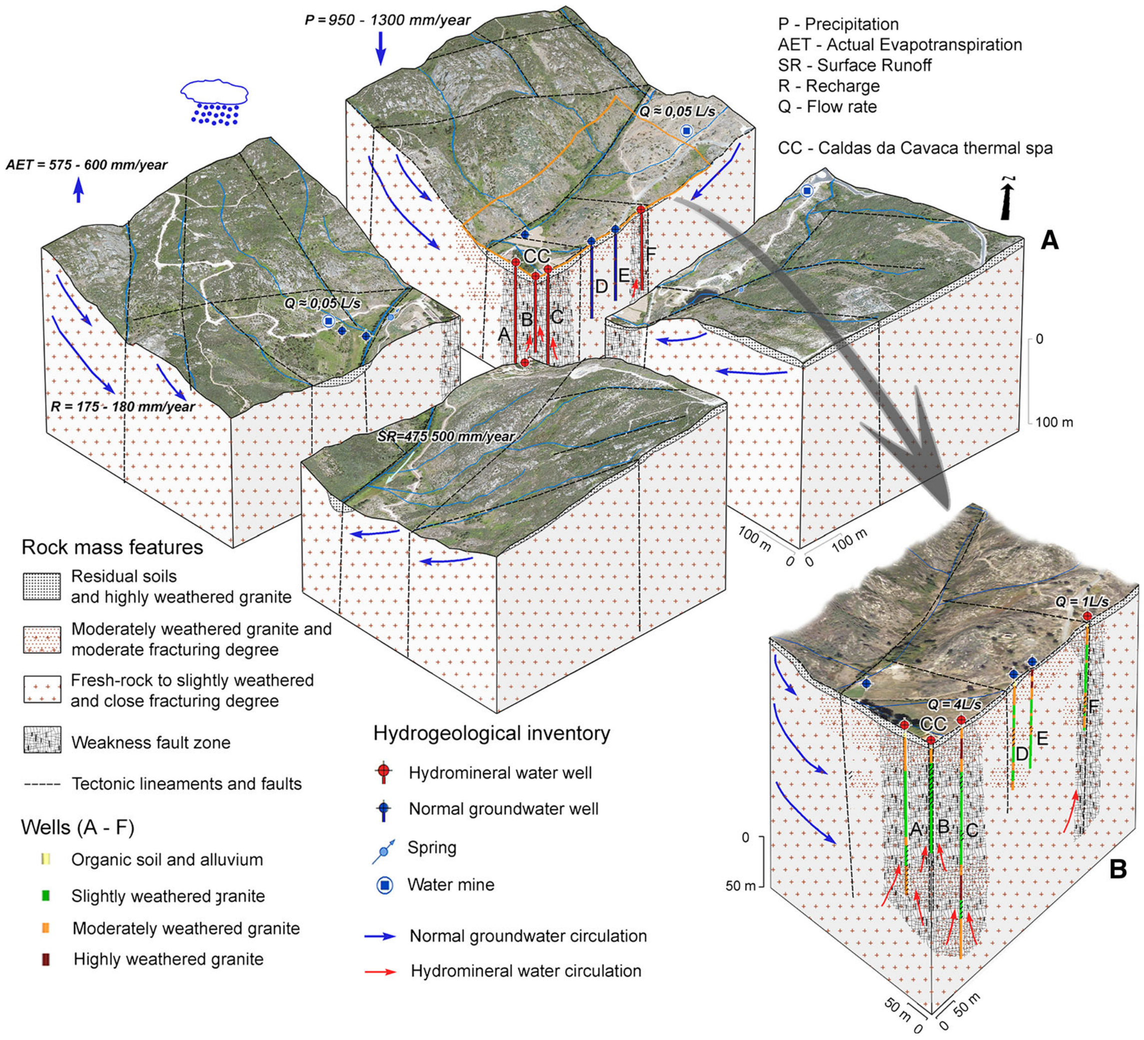


Fig. 8 General (**a**) and detailed (**b**) hydrogeological conceptual model from Caldas da Cavaca hydromineral system (updated from Teixeira et al. 2010; Teixeira 2011)

sedimentary cover, in a narrow strip along the bottom of the valley.

In the case of the DRASTIC-Fm index (Fig. 7b), a clear dominance from the lithology becomes apparent in the moderate-high and high vulnerability classes. Those classes are closely associated with the flat valley bottom, where the alluvia sedimentary cover prevails. The moderate vulnerability areas are located SE, N and NW of Caldas da Cavaca thermal site, mostly in large corridors with NE–SW trends. That is in relationship with the slope, the fracturing density and less weathered granite. Almost 50 % of the area has low-moderate and low vulnerability. Those areas are located mainly in the NW and SE areas of the study region, close to the Quinta das Lameiras and Cavaca localities.

The very high and extremely high SINTACS values (Fig. 7c) are located mainly near the settlements of the study site (Quinta das Lameiras, Quinta dos Matos and Cavaca), and in the bottom of Ribeira de Coja valley. The low slope values and lithology (alluvia or highly weathered granite) are the main controlling factors. Higher slope values and less weathered granite are the main features of the moderate-high vulnerability areas, mainly in a large NE–SW corridor, along the valley slopes. The lower index values correspond to the dolerite rocks, and are related to the argillaceous weathering of these dykes.

The SI index (Fig. 7d) reveals a similar pattern with SINTACS. However, land use can be clearly seen as an important parameter, namely around the settlements, where the buildings and agricultural areas are concentrated. Besides, these high to very high vulnerability areas have low slope values. The high slope, rocky outcrops and less weathered granitic areas have moderate or low-moderate vulnerability values. The high vulnerability area showed in the other indexes is not clearly seen in SI index; only a very small area has high vulnerability, in the N of the Caldas da Cavaca thermal site.

Conceptual site model: implications on aquifer systems

In the Caldas da Cavaca hydromineral system discharge zone, three aquifer types were identified, and an outline of the hydrogeological conceptual model of the area is shown in Fig. 8:

(a) A shallow, unconfined aquifer, related to the alluvia cover, and located in the valley bottom, near the Caldas da Cavaca thermal site; the groundwater in this hydrogeological unit has pH between 5 and 6.5 and electrical conductivity under 20 μS/cm (very low mineralisation). Water temperature is strictly dependent of the air temperature. This aquifer has high to very high vulnerability to potential load contamination.

(b) An unconfined to semi-confined aquifer, in the weathered rock mass and in fractured granite. These groundwaters have pH between 5 and 6.5 and electrical conductivity varying from 20 to 50 μS/cm (low mineralisation). The water yields, in the measured springs, are very low (<0.05 L/s), and the transmissivity is lower than 1 m^2/day. These normal waters have very low mineralisation, and generally a sodium chloride facies. In general, this aquifer has moderate to high vulnerability to potential load contamination.

(c) A deep confined hydromineral aquifer is clearly controlled by a deep fault zone, in the fresh granite. The hydromineral water has temperatures around 30 °C (mesothermal waters), higher electrical conductivities (350–400 μS/cm; medium mineralised waters) and pH around 8.4–8.6. These waters have an alkaline reaction, a sodium bicarbonate facies, fluoridated and sulphurous. The transmissivity in the hydromineral aquifer varies from 27 to 136 m^2/day. The Ribeira de Coja fault zone, with general NNE–SSW trend, mapped around Caldas da Cavaca area, has a regional cartographic expression, and locally, fault gouge was observed. This may be the main structure controlling the occurrence of hydromineral waters in this site. The two still working hydromineral water wells (wells C and D) are located along this fault. The other wells are not presently operational.

Conclusions

The multidisciplinary approach, based on GIS mapping tools, has proven its value and contributed to improve the knowledge on the groundwater storage and flow in the study area. These tools can provide an accurate method to assess the favourable hydrogeomorphological features that are favourable to infiltration and aquifer recharge or discharge. Also, its contribution is important to build and improve the hydrogeological conceptual model of the study area.

Thus, in Caldas da Cavaca site the main factors controlling the infiltration and recharge are the highly weathered granite, the close fracturing degree, as well as the planned surfaces in the higher areas, especially when the land use corresponds to agricultural or forest areas.

Regarding the discharge, it can be controlled by the fresh granite, in the areas with higher fracturing degree, and especially in the lower areas of the valleys.

As proven in this study, for a successful hydrogeological operation and development of the groundwater resources of a given area, it is fundamental the comprehensible integration of all data obtained at different scales (remote sensing, geology, morphotectonics, hydrogeochemistry, land cover, hydrogeological inventory, etc.). All data should be synthesised at adequate scale, and the comparative analysis of the results are improved by GIS integration and analysis (e.g. overlay analysis and/or multicriteria analysis). Also, all the results and the conceptual model may indicate, more accurately, priority areas to develop complementary studies (e.g. isotopic analysis and/or natural tracers). They can also contribute to a re-evaluation and/or redefinition of wellhead protection areas, both for hydromineral or normal groundwater.

The improved conceptual model of the site was very useful in the decision-making process regarding the integrated management of the water resources (surface water, normal groundwater and hydromineral water). In addition, it helped the planning of future hydrogeological investigations, and thus, reduce the costs of more advanced studies. Also, it may support the definition of the most vulnerable areas to contamination or the delineation of wellhead protection areas, as well as the sustainable management of the groundwater resources of the region.

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