

Insights from a comparative GIS-MCDA groundwater vulnerability assessment in a granitic and metasedimentary fractured rock media

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Abstract

This work proposes a comprehensive methodology for evaluating fissured hard-rock groundwater resources through an integrative approach based on fieldwork techniques, Geographic Information System (GIS)-based mapping, geospatial analysis and multiple-criteria decision analysis (MCDA). The study sites comprise distinct geological settings and geographic contexts, i.e. granitic rocks (NW Portugal) and metasedimentary rocks (SW Spain). A similar methodological approach was used in both areas to compare and assess the methodological approaches' effectiveness. The cartographic, field, and laboratory data were analysed through GIS overlay and multi-criteria spatial analysis. This GIS-integrated analysis allowed the calculation of the Infiltration Potential Index (IPI) and groundwater vulnerability indexes: GOD-S, DRAS-TIC-Fm, SI and DISCO, as well as the development and improvement of the hydrogeological conceptual models. At the Entre-os-Rios site (NW Portugal), the IPI index showed that the most favourable areas for infiltration are the fractured granitic regions, where the slope has the lowest values, combined with forest areas. The recharge values are around 70 to 90 mm/year. Considering hydraulic connection with the borehole data, the DISCO index identified the geostructures with the most important trending to NNE-SSW, NE-SW and WNW-ESE in the area. The highest IPI values were identified in the regional aquifer quartzite unit at Herrera del Duque (SW Spain). The recharge values are around 60 to 80 mm/year. The DISCO index identified zones where discontinuities have a higher hydraulic connection to the borehole, mainly trending NW-SE and NE-SW. The models developed could be helpful for decision-making and sustainable water resources management regarding the planning of hydrogeological investigations, delineating potential contamination areas, and the definition of catchment protection areas.

Keywords Groundwater · Vulnerability · GIS · MCDA · Geovisualisation techniques · Iberian Peninsula

1 Introduction

In a climate-changing world, groundwater is a valuable resource to improve the resilience of the territories and communities. UN-Water [1] stated that groundwater is vital to domestic, agricultural and industrial use. In many regions, groundwater resources are vital to face water scarcity during dry or drought seasons [2]. In other territories, some

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important ecosystems rely upon groundwater availability [3, 4]. Groundwater could also be an essential source of drinking water and, in some cases, mineral water used in thermal spas (e.g., [5, 6]).

Despite their high importance, water resources are constantly threatened by anthropic activities, such as agricultural, industrial, or recreational activities. Therefore, new practices and behaviours could be adopted by the users to reduce water consumption, as well as to improve the efficiency of their domestic uses (e.g., [7–10]), services (e.g., [11, 12]), agriculture (e.g., [13, 14]) or industrial use (e.g., [15–19]).

Conversely, decision-makers have the difficult task of defining policies and rules to balance the increasing demand with a limited resource such as groundwater [20, 21]. Also, the most recent groundwater management policies consider a geoethical approach, which means the interaction between human activities and earth systems, particularly the hydrosystems, should be sustainable and responsible, promoting a linkage between nature, society, ecosystems, geodiversity, heritage and geoethics (e.g., [22–28]). UNESCO also recognised the importance of groundwater as a vital and strategic natural resource, promoting World Water Day, which focused on “Groundwater: making the invisible visible” [1].

Groundwater is essential for achieving Sustainable Development Goals (SDG). By providing access to clean and safe water, groundwater can help to reduce poverty and hunger and improve health outcomes. It is also a primary source of irrigation for food production [29]. In addition, groundwater can be used as an energy source, helping to reduce greenhouse gas emissions and promote energy security. Finally, by protecting and restoring groundwater resources, countries can promote biodiversity and reduce the risk of floods and other natural disasters [29]. Also, Agenda 2030 calls for improved water-related infrastructure, increased access to safe drinking water and improved water-use efficiency. To achieve SDGs, countries must invest in better monitoring, management, and regulation of groundwater resources [30]. It includes improving the understanding of groundwater systems, developing and implementing effective policies, and strengthening the capacity of stakeholders to manage and protect groundwater resources [31].

Hydrogeological and groundwater models are conceptual and/or numerical-based models that are expectably reliable for supporting sustainable groundwater management [32]. The potential groundwater models use various data sources, such as geologic, morphotectonic, hydrologic, and climatological information, to calculate the probability of groundwater occurrence in a particular site or region [33]. In addition, groundwater potential models inform water resource management, development, and public health decisions in areas where groundwater is used for drinking water [34].

Geographical Information Systems (GIS) based mapping for groundwater models is valuable as they allow for the geovisualisation of potential groundwater resources and can be used to identify areas of groundwater potential recharge/discharge and contamination hazard/risk [35]. In addition, these models can also be used to identify and map potential groundwater infiltration areas, which can help define the recharge/discharge areas and sustainable water resources management strategies (e.g., [36–38]).

The Analytical Hierarchy Process (AHP) is one of the most commonly used Multiple-Criteria Decision Analysis (MCDA) techniques in groundwater models [33]. AHP is a hierarchical decision-making approach that involves splitting the criteria into smaller sub-criteria and assigning weights to each criterion to determine each criterion's relative importance. AHP is an effective tool because it allows users to evaluate various criteria systematically [39, 40]. For example, in mainland Portugal, several studies have been made for peri-urban and urban areas (e.g., [41–43]), rural and mountain areas (e.g., [35, 44, 45]) in different geological contexts.

This work proposes a comprehensive methodology for evaluating fissured hard-rock groundwater resources through an integrative approach based on fieldwork techniques, GIS-based mapping, geospatial analysis and multicriteria tools. Remote sensing, structural geology, hydrogeomorphology and vulnerability studies, hydrogeological field inventory, and hydrodynamic features were used to assess the Entre-os-Rios (NW Portugal) and Herrera del Duque (SW Spain) groundwater systems. Entre-os-Rios is a fissured granitic hydromineral system, while Herrera del Duque is a fissured metasedimentary media. Thus, the effectiveness of the methodological approaches in both environments is compared. This approach significantly helps develop the hard-rock hydrogeological conceptual site model. Consequently, it can offer helpful guidance for making decisions relating to protecting, planning, and managing groundwater systems and surface water interactions, as well as contributing to equitable and sustainable water resources management.

2 Study sites: regional and local background

2.1 Entre-os-Rios Site (Penafiel, Northwest Portugal)

The Entre-os-Rios study site is located in Lugar da Torre (Eja), municipality of Penafiel, district of Porto (NW Portugal). The thermal waters tradition in the region has been well-known since the middle of the 16th century (e.g., [46–53]). Currently, there are two operating thermal baths: Entre-os-Rios thermal baths (formerly Torre thermal baths) and S. Vicente thermal baths (outside the study area).

The region has a CSB climate type [54], corresponding to a temperate climate with dry and hot summers. The available climatic data (1981–2000) shows precipitation reaching 1300 to 1350 mm/year, the average annual temperature around 14 °C, and the estimated yearly evapotranspiration around 500–550 mm [55].

The granitic rocks in the study area are part of a Variscan granitoid belt with an NW-SE trend, extending from the Alto Minho region (Northern Portugal) to the Beiras region (Central Portugal) [56]. Locally (Fig. 1A1), the geology of the study area is outlined [55, 57–61]: (a) sedimentary rocks, namely alluvial deposits and river gravels, appear along river valleys; (b) fresh to slightly weathered porphyritic granodiorites and biotitic quartz-diorites, dark to greyish coloured, and fine-grained; (c) porphyritic granite, coarse to medium-grained, two-mica, but essentially biotitic. This granite is high to very highly weathered near the surface and reaches up to 10–15 m depth; (d) two-mica microgranites, very fine-grained and biotite's dominance, presenting a dark to greyish colour when fresh, with thickness exceeding 0.5 m. These microgranites may structurally control the emergence of mineral waters.

The geometry of the geo-structures dominates the regional morphology. That can also be seen locally (Fig. 1A2), with geological faults trending from N-S to NNE-SSW separating blocks with different altitudes. Also, some NW-SE to WNW-ESE lineaments were identified. In addition, more discrete tectonic lineament sets were recognised, trending from ENE-WSW to NE-SW. The geometric pattern of the hydrographic network corresponds to aligned fracture valleys, typical of this granitic region (e.g., [62–65]).

2.2 Herrera del Duque site (La Siberia, Southwestern Spain)

The second study site is in Herrera Del Duque municipality, Badajoz province, Extremadura (SW Spain). The quantity and quality of the former *El Borbollón* spring are well known in the region (e.g., [66–71], and references therein).

The region has a Bsk climate type [54], corresponding to a cold semi-arid climate commonly found in the inner of the Iberian Peninsula. This climate tends to have warm to hot, dry summers and cold winters. The available climatic data (1980–2010) shows precipitation of around 660 mm/year, an average annual temperature of about 16 °C, and yearly evapotranspiration of about 450 mm [71].

The regional geotectonic background of the Dehesa de las Navas area comprises a middle-upper Palaeozoic meta-sedimentary fissured basement substratum which is deformed and overthrusts the late Proterozoic schist-greywacke complex. The studied area is part of the Dehesa de las Navas mega-synclorium, with a trending regional axis of NW-SE. This faulted megastructure has regional faults transversal and subparallel to the axial orientation (e.g., [72, 73]).

Locally (Fig. 1B1), the main geological units are (e.g., [72, 74–78]): (a) an upper Tertiary/Quaternary sedimentary cover unit, including alluvium deposits and hillslope deposits (“Raña” deposits); (b) an Upper Ordovician sequence, composed of clayey and quartzitic units called “Canteras shales” and “Botella quartzite”. At the base of this unit occurs a microconglomeratic and ferruginous horizon. These formations are overlaying alternating shales, sandstones and siltstones, the so-called “Bancos mixtos”; (c) a Middle Ordovician sequence of sandstone units (“Los Rasos’s sandstones”). These horizons are richly fossiliferous dark shales and sandstones, occasionally with nodules; (d) a Lower-Middle Ordovician sequence of alternating darkish black shale, sandstone and siltstone horizons, the so-called ‘Pochico beds’; (e) a Lower Ordovician megasequence disconformably overlying over upper Proterozoic rocks (“Herrera del Duque plateau”). This unit is mainly light-coloured thick-bedded mature sandstones and quartzite with shaly or silty intercalations. In addition, an alternating unit of interbedded conglomerate, sandstone and quartzite is found below this dominant unit; (f) an Upper Proterozoic metasedimentary sequence, forming part of the schist-greywacke unit.

The regional fracture network defines some preferential orientations (Fig. 1B2): NW-SE to NNW-SSE are the dominant set, and more discreetly, NE-SW to N-S. The geomorphology of the studied area is controlled by the steep-rigid

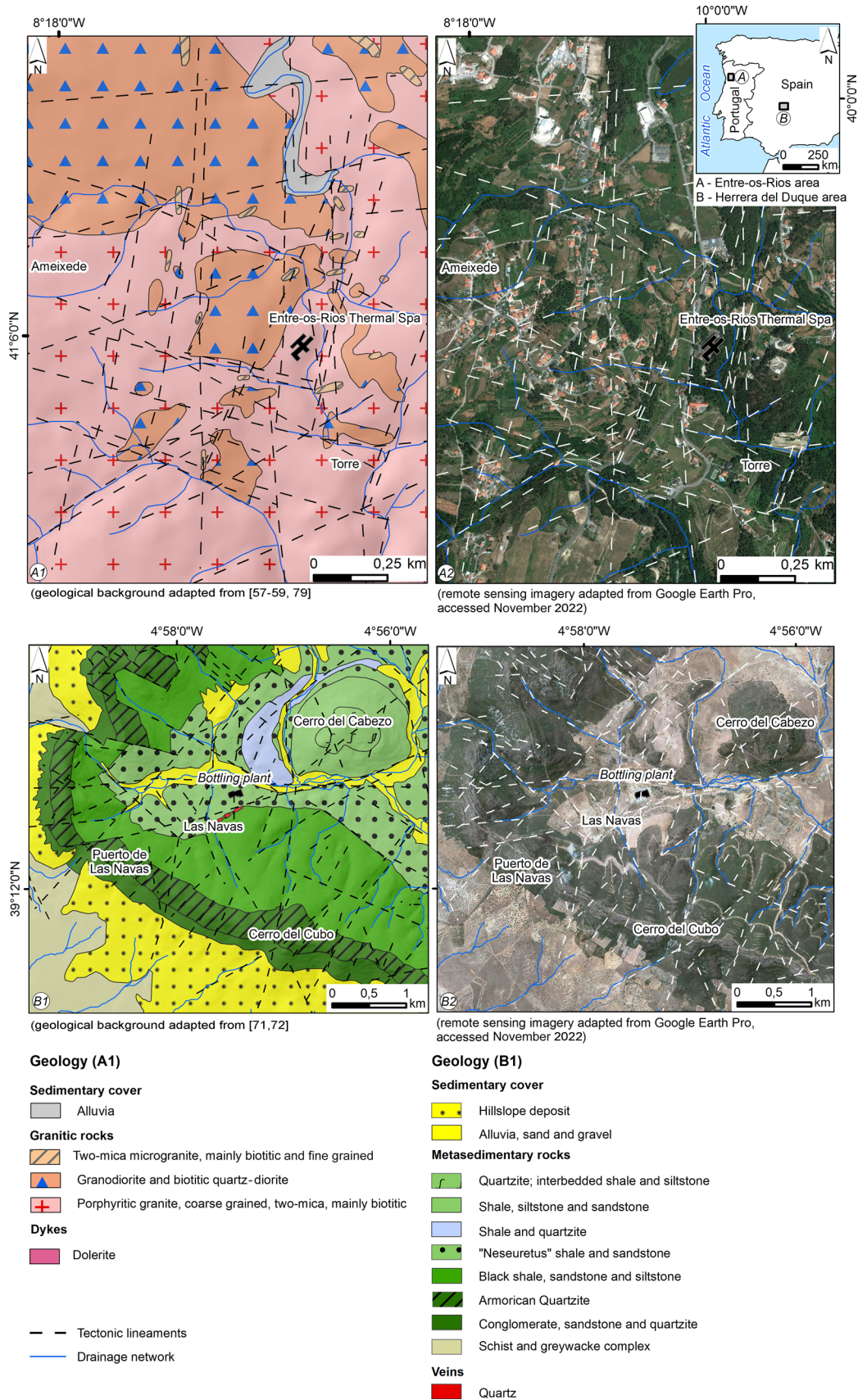


Fig. 1 Regional geological framework (A1) and tectonic lineaments (A2) of the Entre-os-Rios site, NW Portugal (adapted from [57–59, 79]) and regional geological framework (B1) and tectonic lineaments (B2) of Herrera del Duque site, SW Spain (adapted from [71, 72])

outcrops of the Armorican quartzite, reaching elevations of about 750 m, decreasing gradually from SE to NW (elevation of 700 m at Puerto de las Navas). The drainage network shows this tectonic control, which imposes morphostructural features on the region.

3 Materials and methods

This study comprises data collection techniques, GIS geospatial analysis, MCDA multicriteria evaluation, and geovisualisation techniques. Standard procedures were used for applied geomorphology, structural geology, hydrogeology, engineering geosciences, and GIS mapping (e.g. [80–82]). Also, the guidelines from the Geological Society Engineering Group [83], the Committee on Fracture Characterisation and Fluid Flow ([84]) and the International Society for Rock Mechanics [85] were followed. In addition, the Portuguese and Spanish topographic and geological maps, orthophotomaps and satellite images were used in an exploratory stage. GIS and multicriteria analysis are commonly used in groundwater studies. This study uses an updated and revised methodology used by [36, 44] and [43, 86].

The first stage was the definition of the data sources and collection (Fig. 2). Then, all of this basic information was gathered into two sets: (a) the cartographic data, comprising topography, photogeology and remote sensing, structural geology, morphotectonics, land use/cover and climatology; (b) field and laboratory data, such as hydrogeological mapping, hydrogeological inventory, along with hydrogeochemistry, hydrodynamic and water wells data.

The georeferencing of the water samples during the hydrogeological inventory (springs, dug wells, wells, water mines, streams and fountains) was performed using a high-accuracy GPS (Trimble Geo-Explorer). In addition, the water parameters (e.g., temperature, pH, electrical conductivity) were measured using multiparametric portable equipment, Hanna Instruments (HI-9828). Along with this information, the fundamental geological and geomorphological description of rock masses (e.g. lithology and weathering grade, structure, morphology) and the hydrological and climatological features were also collected.

A dynamic geodatabase was built and designed to organise the spatial data for each study site. The raster data has a spatial resolution of 5×5 m (25 m^2) to ensure a correct overlay in the subsequent GIS-based mapping analysis. Inside the geodatabase, some datasets were created in a multi-scale approach: (a) geological characteristics of the rock masses, describing lithology, geostructure, weathering grade and tectonic lineaments; (b) geographical description, comprising the altitude (hypsometry and DSM—Digital Surface Model) and land cover; (c) hydrogeomorphological features, explaining the drainage network, slope, geomorphology and hydroclimatology; (d) hydrogeological features, comprising the hydrogeological units, hydrogeological inventory, hydrogeochemistry, and hydrodynamic data.

The third stage was the preparation of various thematic maps in the GIS environment to support the following GIS overlay and multicriteria analysis. Those maps are the base for the Infiltration Potential Index (IPI) map calculation and the integrative vulnerability assessment.

The GIS integrated spatial analysis allowed calculating the IPI map based on partial maps of lithology and hydrogeology, tectonic lineaments density, drainage density, slope and land cover. Those base maps were selected following the proposed IPI calculation procedures [36]. The analytical hierarchy process (AHP) method (e.g. [39, 40, 87, 88]) was used to calculate the importance (relative weight) of each factor, as well as the inner scores. After [89], an accurate Consistency Ratio (CR) is computed by dividing the Consistency Index for the set of judgments by the index for the corresponding random matrix. Then, the judgment set is inconsistent if that ratio exceeds 0.1 [40]. In practice, when $\text{CR} < 0.1$, the consistency of the judgment matrix is acceptable; when $\text{CR} \geq 0.1$, the judgment matrix needs to be subsequently tested (e.g., [87–89]). The resulting map shows the spatial variation of the IPI. A combination of high values in most explaining factors will result in more favourable areas for infiltration. [36, 44] offers a more detailed methodological description of the IPI. The resulting maps were combined with average rainfall and infiltration rates for each study site, and the recharge values were calculated.

The groundwater vulnerability assessment followed the proposed methodologies from the bibliography:

- GOD-S: a development of GOD index, considering Groundwater hydraulic confinement, Overlying strata, Depth to the groundwater table, and Soil media (e.g., [90–92]);
- DRASTIC-Fm: an update of the DRASTIC index [93, 94] considers the properties of the fissured hard-rock aquifers. It ponders depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone, Hydraulic Conductivity and Fractured media [95]. The fractured media parameter (Fm) resulted from the tectonic lineament

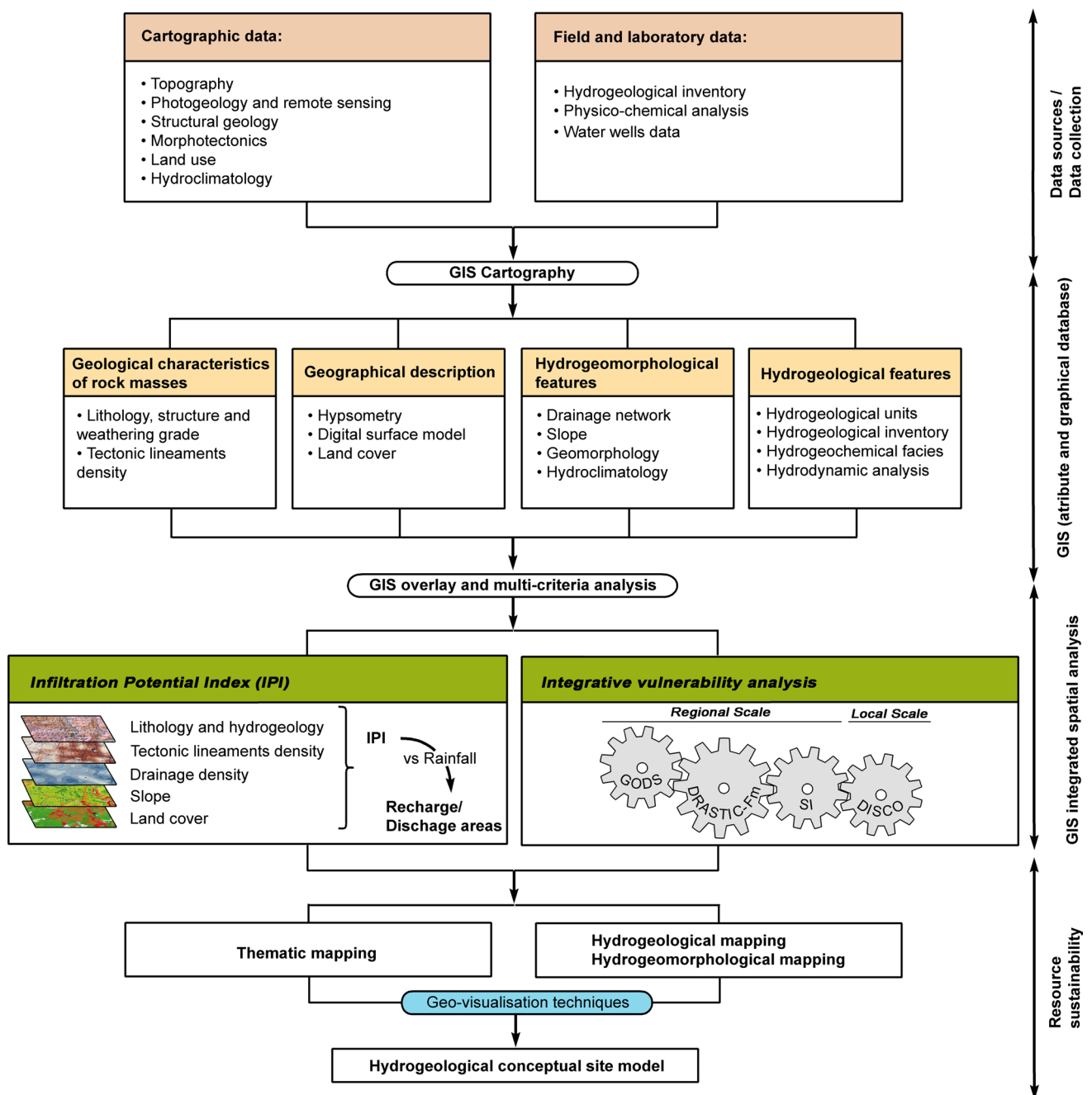


Fig. 2 Methodological flowchart of the present study

density map and was grouped into five classes, with ratings varying from 4 to 18, following the weight and rating proposed by [95];

- SI: the susceptibility index [96, 97], from which the weight and ratings were followed. It relies on the DRASTIC index's D, R, A, and T parameters and includes the Land Use/Land cover map. Since 2012, a simplified version of this index (without the LU—Land Use parameter) has been used in the Portuguese municipality masterplans to recognise and protect the aquifer recharge areas (Resolution of the Council of Ministers n.º 81/2012, revised and updated by Ministry Orders no. 336/2019 and no. 264/2020).
- DISCO: the index proposed by [98] evaluates the intrinsic vulnerability in fractured media and vulnerable springs or well-head protection areas. This index considers the heterogeneity of the environment and comprises the characterisa-

tion of the hydrogeological properties of the aquifer (DIScontinuities parameter) and the thickness and permeability evaluation of the protective cover (protective COVer parameter) (details in [86, 98, 99]).

The final integrated approach helped improve the conceptual hydrogeological site models, contributing to better design, solutions and protection for environmentally sustainable management of groundwater resources in the study areas.

4 Results and discussion

The multidisciplinary geoscience approach of this study relies on GIS-based analysis and advanced geovisualisation techniques. In fact, a correct characterisation and analysis of the hydrogeological environment, the hydrogeomorphological features, and the geological and geographic characteristics are essential to a better understanding of the study sites' groundwater systems. GIS analysis effectively integrates all this data for both study sites. Furthermore, the methodological approach was similar in both geological environments—granitic and metasedimentary background—allowing the comparison and assessment of the methods' effectiveness in different site investigations.

4.1 Entre-os-Rios Site (Penafiel, Northwest Portugal)

The hydrogeological units of the Entre-os-Rios site are formed mainly of granitic rocks (Fig. 3A). The granodiorite, quartz-diorite, and coarse-grained porphyric granite unit cover more than 95% of the area. The inner scores for these units are similar but slightly higher for the granodiorite and quartz-diorite units. The weathering is relatively higher in these units and can reach 5–10 m depth. The resulting weathering materials are generally more clayey in the porphyritic granite than the ones from granodiorite, resulting from the feldspar alteration. Sometimes, the granodiorite unit is covered by a topsoil layer. The alluvia unit has the higher inner scores. However, the topographic location along the bottom of the valley makes this unit less relevant for recharging the water points at higher altitudes. The microgranite and the dolerite veins were assigned the lower inner scores, given by their impervious characteristics.

The tectonic lineaments identified (Fig. 3B), concerning their direction and continuity, could be divided into three groups with different importance: first, an N-S to NNE-SSW set, with the most significant continuity and many tectonic lineaments; two more discrete groups can be identified with trending orientations of NW-SE to WNW-ESE and ENE-WSW to NE-SW. For groundwater infiltration and circulation, a higher lineament density is more favourable and, thus, reflected in the inner score of this parameter. The calculus of the lineaments density reveals a higher concentration to the west of the thermal spa, between Torre and Curveira localities. These are the areas where the mineral water wells and springs are located.

The drainage network density is fundamental, giving necessary inputs about the surface and groundwater circulation (e.g. [100–106]). These studies point out that a higher density of streamlines is generally associated with higher surface runoff values; thus, less water remains for infiltration, groundwater flow, storage and occurrence. At the Entre-os-Rios study site, the higher drainage density values are concentrated in the Torre locality to the North of the thermal spa and the Abol de Cima locality to the west of Ameixêde (Fig. 3C). Regarding the IPI index calculus, all of these variations were reflected in the inner score of this factor.

The slope is another important factor controlling water infiltration. Rainfall is the primary source of groundwater infiltration. The water residence time influences the vertical infiltration. Several field and laboratory studies indicate that vertical infiltration decreases with increased slope values (more details in [107]). This variation is reflected in the inner score of the slope factor. The slope classes $< 5^\circ$ and 5° – 10° are dominant at this study site. Some planned surfaces could be identified in the northern area, while the southern area is dominated by the trenching of the stream valleys, where the high slope values are located (Fig. 3D).

Land use plays a significant role in determining surface water behaviour and consequently affects groundwater infiltration [108, 109]. The land use (Fig. 3E) reflects the characteristics of this territory [110]. The urban fabric is discontinuous, composed mainly of dwellings, generally with backyard gardens. Its elongated shape results from a concentration along the main roads, namely the Ameixêde, Curveira and Torre localities. Small industrial areas can be found North of Curveira, mainly related to stone transformation industries. The agricultural, orchard and vineyard areas are primarily found around the localities in the central and eastern parts of the site. The forest areas are located mainly in the western

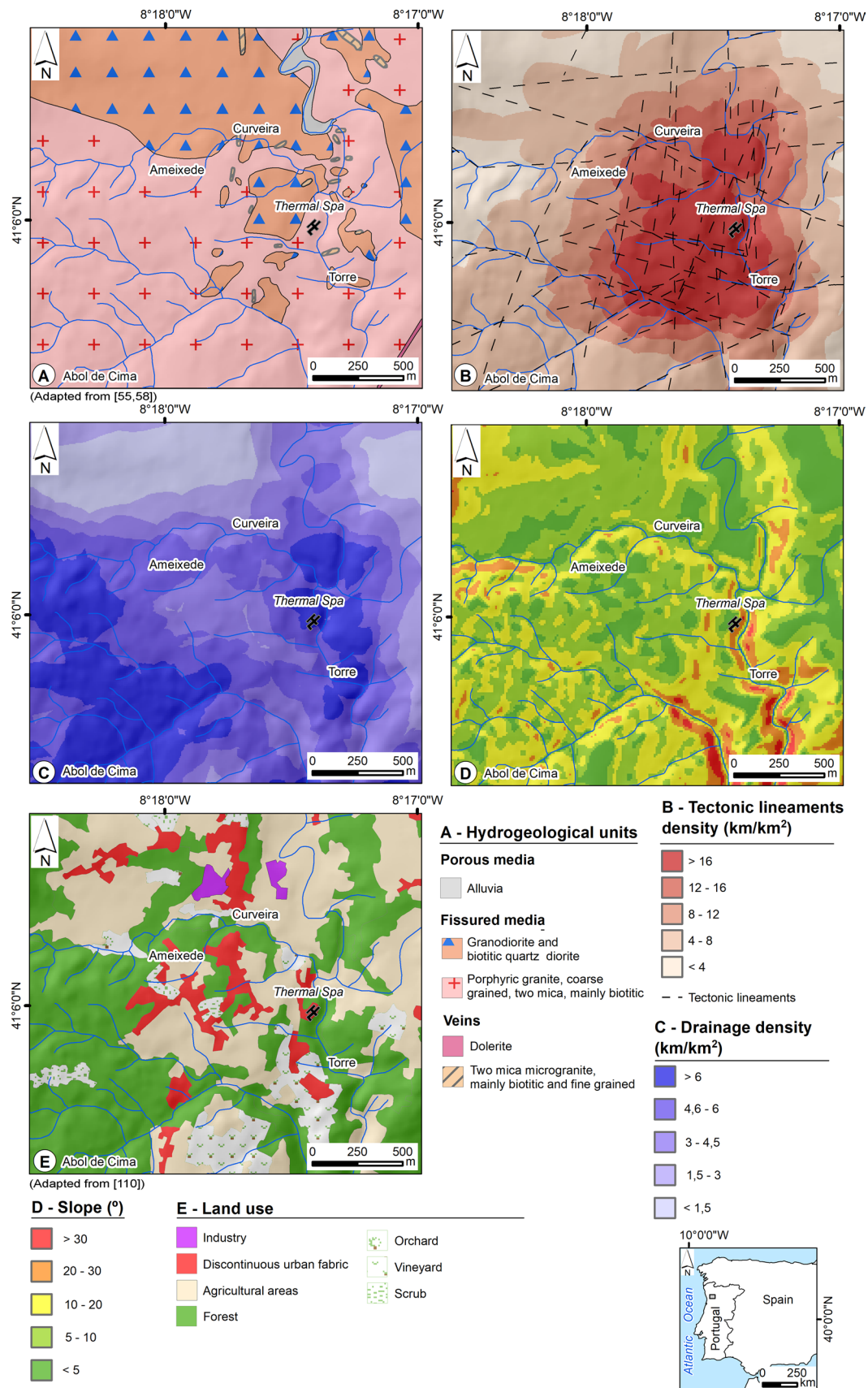


Fig. 3 Thematic mapping to obtain the IPI parameters for the Entre-os-Rios Study site: **A**—hydrogeological units; **B**—tectonic lineaments density; **C**—drainage density; **D**—slope; **E**—land use

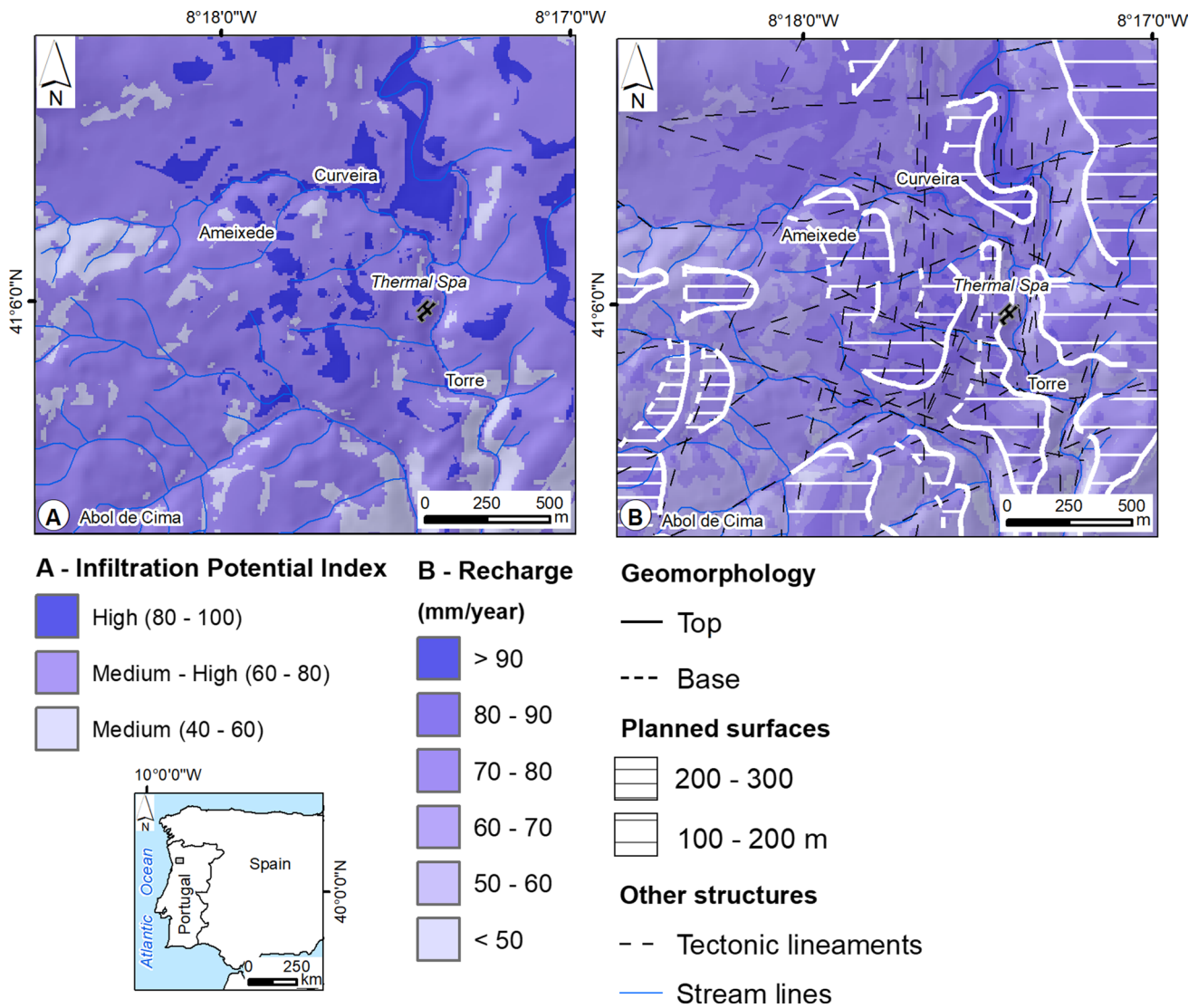


Fig. 4 Entre-os-Rios study site: Infiltration Potential Index zoning map (A); recharge and hydrogeomorphological map (B)

part of the area and at higher altitudes, which is favourable to groundwater recharge. These characteristics were reflected in the inner scores of this factor.

The maps in Fig. 4A and B represent the IPI zoning and the recharge combined with the main geomorphological features of the area. As a result of the combination of all factors and inner scores, most of the study area has medium to medium-high IPI values. The higher values could be found in the alluvia deposits to the North and some areas where the slope has the lowest values, combined with forest areas. The recharge values for the granodiorite and the quartz-diorite regions range mainly between 70 and 90 mm/year, while in the porphyric granite, the values are generally lower (less than 70 mm/year). The highest values (over 90 mm/year) are in the alluvia areas.

The vulnerability was assessed (Fig. 5) by regional scale indexes (GOD-S, DRASTIC-Fm and SI) and a local scale index (DISCO). The higher values in all indexes are found in the valley's bottom, where the alluvia sedimentary cover dominates. The high to very high vulnerability values registered are significantly reduced in their possible outcomes due to this limited extension, altitude, thickness and connection to the deeply fractured mineral aquifer. As for DRASTIC-Fm and SI indexes, most of the site has low to very low vulnerability values, which is related to the protective characteristics of the granitic hydrogeological units. On the other hand, there are various groundwater potential contamination activities in the area: a petrol station, car repair shops, stone transforming industries, and a dense road network.

The DISCO index contributes to the groundwater safeguard zones centred in the Barbeitos borehole, where four classes were defined. Class S1 (very high vulnerability) corresponds to zones where discontinuities with a higher hydraulic

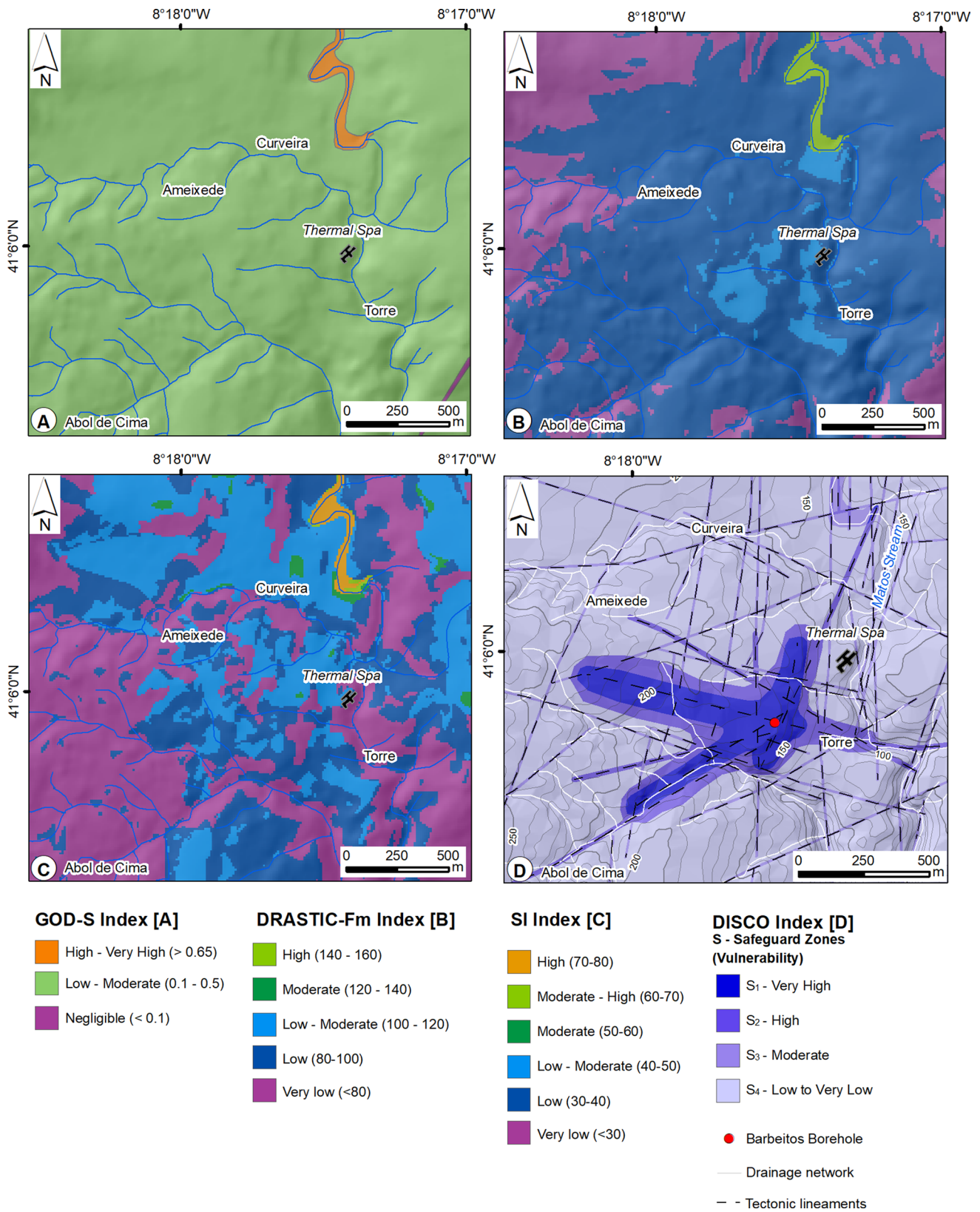


Fig. 5 Vulnerability indexes for Entre-os-Rios Study site: **A**—GOD-S Index; **B**—DRASTIC-Fm Index; **C**—SI Index; **D**—DISCO Index

connection to the borehole, mainly by NNE-SSW, NE-SW and WNW-ESE structures. Class S2 (high vulnerability) is characterised by lower connectivity between the second-order tectonic lineaments and the borehole. Class S3 (moderate vulnerability) comprises a small area of the alluvia North of the Thermal Spa, with low connectivity to the borehole. Finally, class S4 (low to very low vulnerability) corresponds to the rest of the area, characterised by a reduced or absent hydraulic connection to the borehole.

4.2 Herrera del Duque site (La Siberia, Southwestern Spain)

The geological units at Herrera del Duque comprise metasedimentary rocks and a sedimentary cover, grouped by their hydrogeological characteristics (Fig. 6A). The hillslope deposits in the southwest and west of the study site cover a large area. Although their detrital characteristics are relatively favourable to infiltration, they are mainly located in a different hydrogeological drainage basin than the former *El Borbollón* spring. The alluvia deposits are located along the streamlines on the valley bottom. Although the small area this unit covers and a relatively small thickness, they have a high value regarding infiltration potential due to the granulometric characteristics. Only the quartzite unit presents some favourable characteristics for groundwater circulation from the metasedimentary units. Sometimes, some interbedded shales and conglomerates are found in this quartzitic unit. The quartzites are generally highly fractured, presenting high transmissivity. The other metasedimentary units are generally composed of shales, sandstones or siltstones, with very low transmissivities. All of these characteristics were reflected in the inner scores of the IPI index.

The tectonic lineaments identified (Fig. 6B) could be categorised in some dominant trending orientations: (i) NW-SE and NE-SW, mostly with less continuity, and (ii) E-W orientation, with high continuity, crossing the map from W to E near the bottling plant. The tectonic lineaments' density shows an irregular pattern. However, the highest values are found along the E-W area, from south of Cerro del Cabeço to North of Puerto de las Navas. This area continues North of the bottling plant, around Cerro del Cabeço, a small round hill. The SW area has the lowest values, mainly in the schist and greywacke bedrock. A background of higher fracture density is generally more favourable for groundwater circulation. Thus, these variations were reflected in the inner scores of the IPI Index.

Drainage density can be critical when evaluating groundwater infiltration. Higher drainage density generally means more surface runoff; thus, less water is available for infiltration. The higher drainage density values (Fig. 6C) are found in a W-E area near the bottling plant and the eastern part of the study area. Therefore, these conditions are also reflected in the IPI inner scores for this factor.

At the Herrera del Duque study site, the areas with higher slope values are focused mainly on the flanks of the quartzite ridges, from Cerro del Cubo to the North of Puerto de Las Navas and around the Cerro del Cabezo hill (Fig. 6D).

Land use is a crucial factor in controlling surface water regimen and, thus, the conditions for groundwater infiltration [97, 108, 109]. The land use (Fig. 6E) is dominated mainly by forests and areas with mixed vegetation [111]. These areas are the most favourable for infiltration and have the higher values assigned for IPI calculation. The top of the quartzite ridges is mostly rock outcrops. Although the quartzites are relatively fractured in this area, there are no soils or vegetation to retain the rainfall. Thus, this area has a lower inside score. The impervious areas are almost non-existent. They can be found only in the bottling plant and on a small road connecting the Herrera del Duque site to the bottling plant.

The maps in Fig. 7A and B represent the IPI map zoning and the recharge combined with the main geomorphological features of the area. As a result of the grouping of all factors and inner scores, most of the study area has medium to medium-high IPI values. The higher values could be found in the hillslope deposits in the SW and the sedimentary cover along the valley to the North of Las Navas. The most crucial area for groundwater recharge lies on the top of the quartzite ridge, from Cerro del Cubo to Puerto de Las Navas. This area was identified as the recharge area of the wells located near Las Navas. The calculated recharge values for the top of the quartzite ridges range between 70 and 80 mm/year, while in the other metasedimentary areas, these values are around 60–65 mm/year.

The former *El Borbollón* spring is over a conspicuous fault, filled partially with brecciate quartz veins. This vein underlines the fault contact between the 'Pochico beds' and 'black shales and sandstones' units (generally impermeable). This means that the high transmissivities registered are probably related to those structures. The *El Borbollón* fault zone conveys much of the area's groundwater flow, acting as a significant hydrogeological trap. Another important tectonic feature is the *Saucillo* fault, an NW-SE tectonic lineament well identified on the landscape (see Fig. 6), cutting the syncline from the Armorican quartzite to the *El Borbollón* fault zone. Considering structural and lithological settings, the recharge zone is located mainly at the Armorican quartzite and 'Pochico beds', with 70–80 mm/year values. The 'Pochico beds' unit values are slightly lower (60–65 mm/year). Some sandstone layers in the 'black shales' unit could also increase recharge and constrain the discharge.

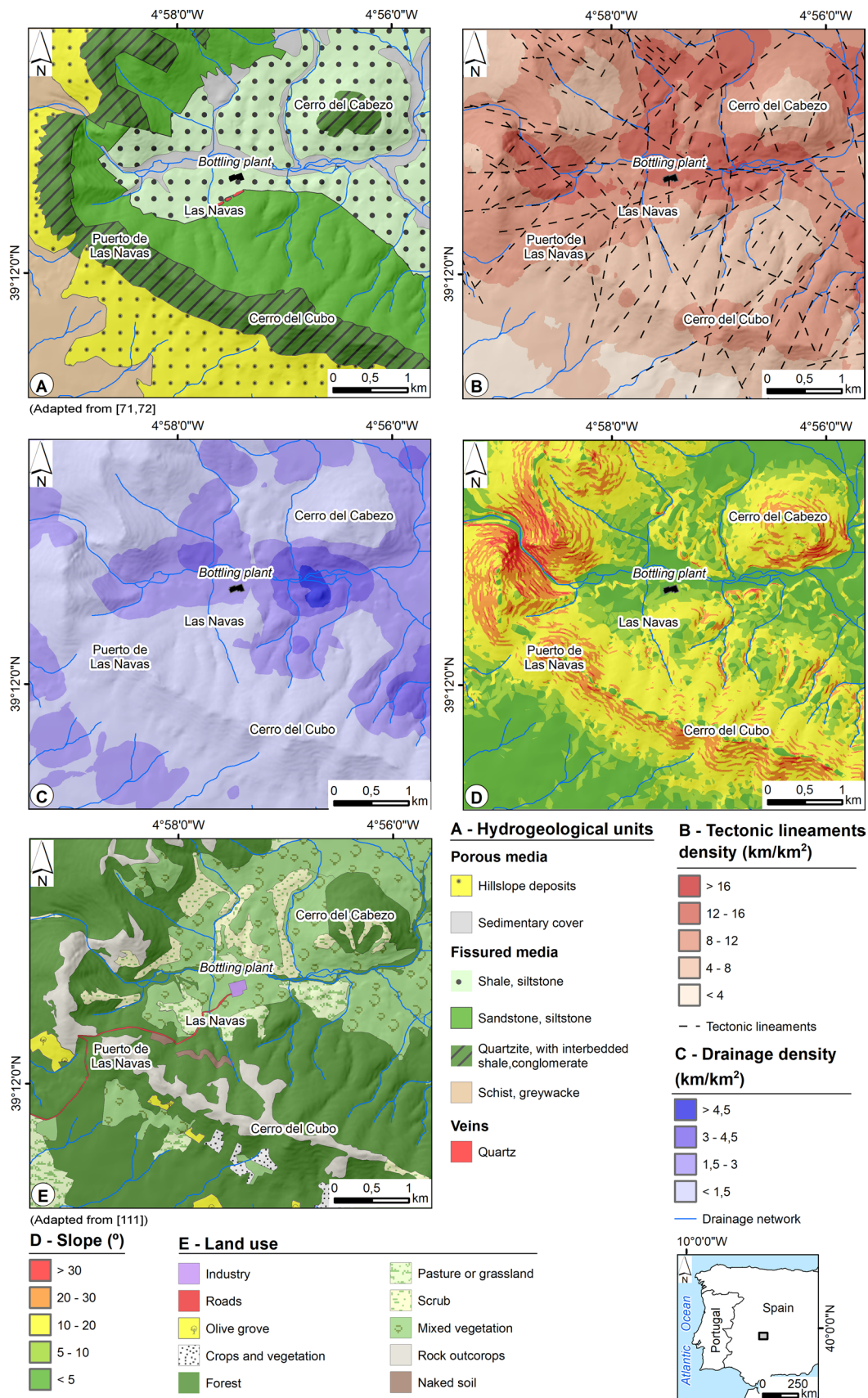


Fig. 6 Thematic mapping to obtain the IPI parameters for the Herrera del Duque study site: **A**—hydrogeological units; **B**—tectonic lineaments density; **C**—drainage density; **D**—slope; **E**—land use

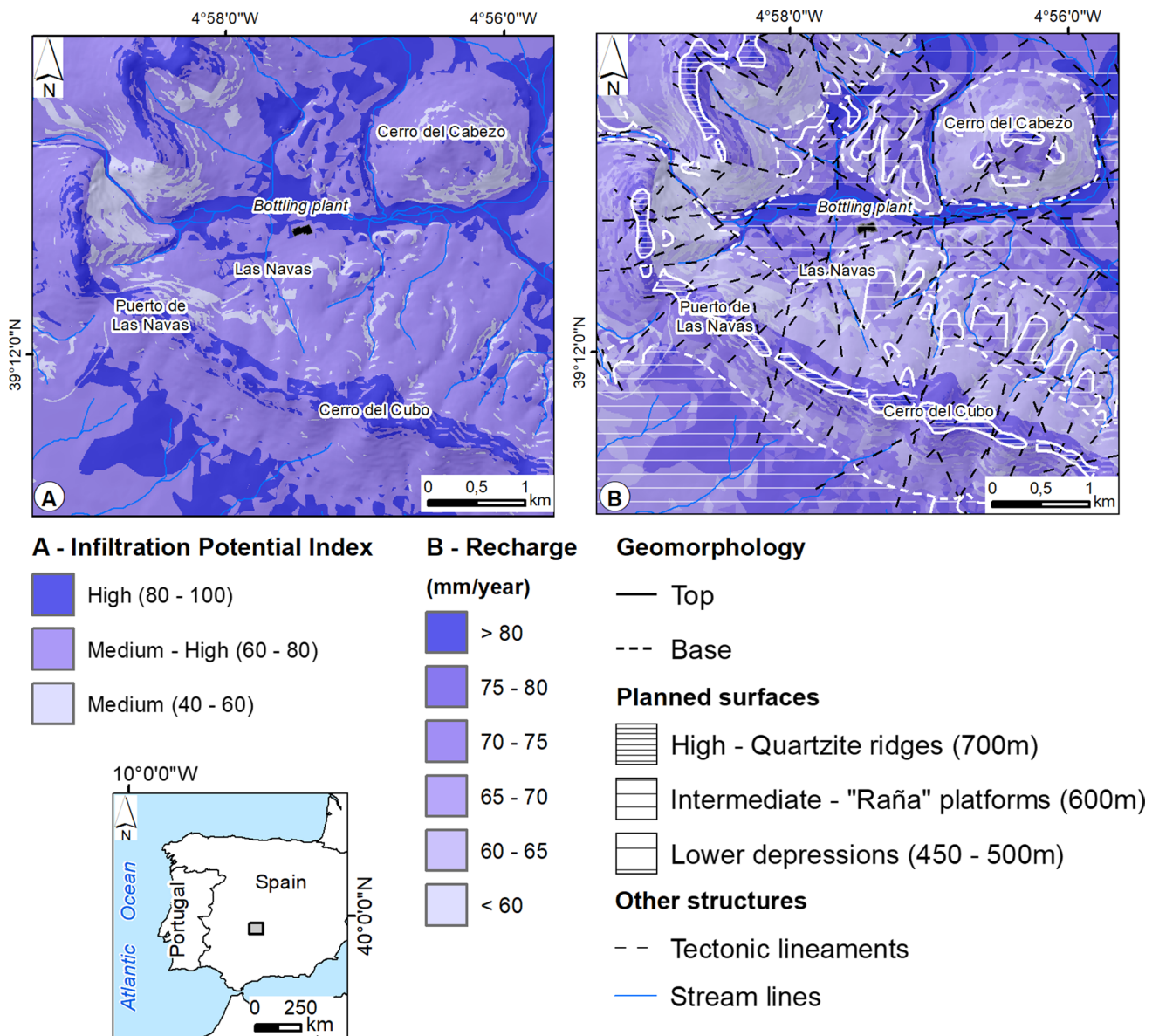
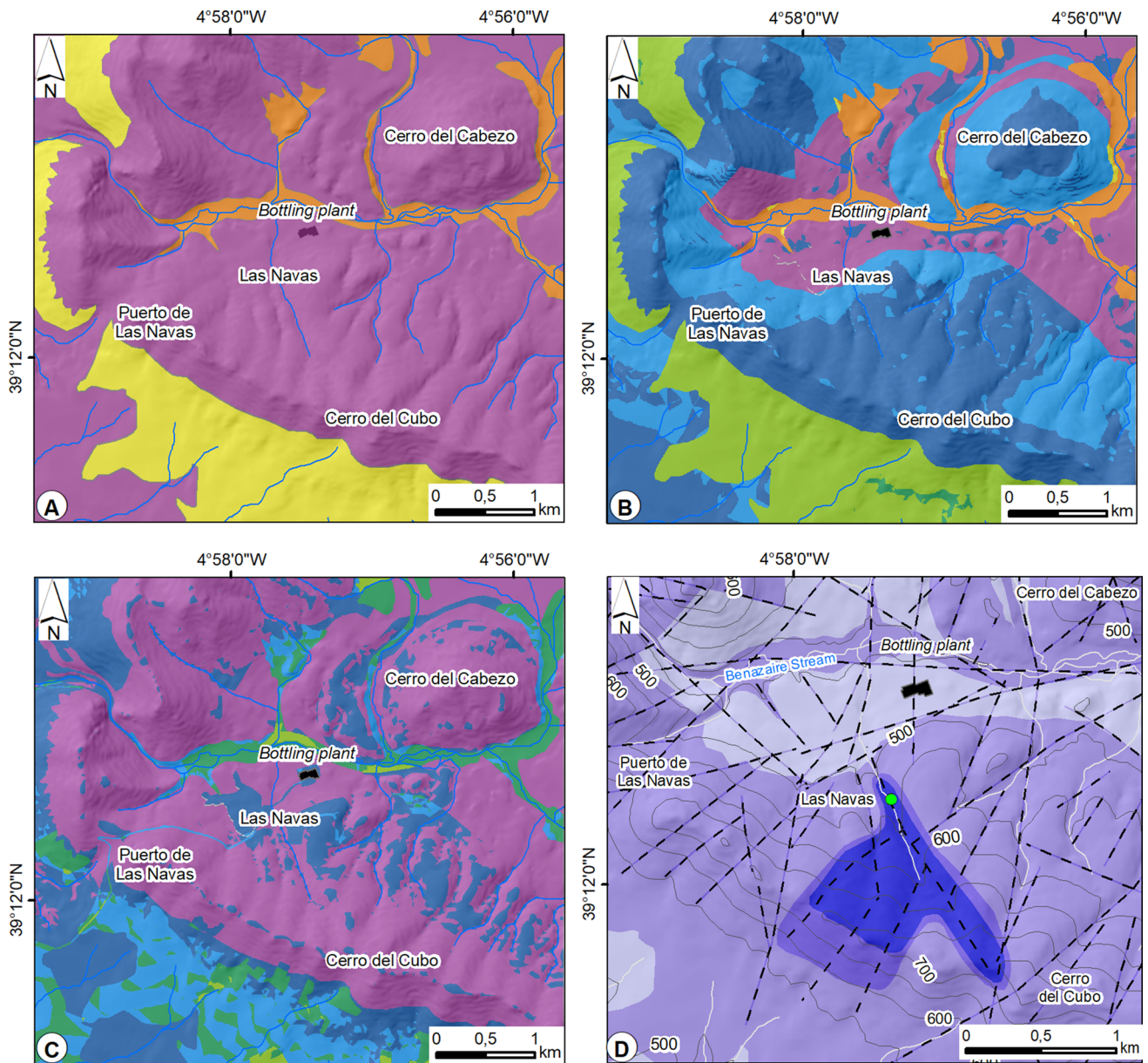


Fig. 7 Herrera del Duque study site: Infiltration Potential Index zoning map (A); recharge and hydrogeomorphological map (B)

The following indexes evaluated the vulnerability susceptibility to contamination with an integrative approach (Fig. 8): the GOD-S, DRASTIC-Fm, SI and DISCO. The higher values of the indexes are related to the sedimentary cover at the valley's bottom. That restricted morphological area with a shallow thickness significantly decreases the impacts of the high to very high vulnerability values recorded. Also, the higher vulnerability values found in the SW of the study area are related to the hillslope detrital deposits. However, they belong to another drainage basin, so their importance is insignificant for the studied groundwater systems.

On the contrary, it is essential to register that the most important unit for the aquifer system, the quartzite unit, has a relatively low vulnerability value in all the indexes. All the other metasedimentary units have, in general, low vulnerability values. Only a minor groundwater potential contamination activities are found in the area (e.g., local road network and small-farm livestock).

At the Herrera del Duque study site, the DISCO index also contributed to delineating the groundwater protection zones, where four classes were defined. Class S1 (very high vulnerability) corresponds to zones where discontinuities have a higher hydraulic connection to the borehole, mainly by NW-SE and NE-SE structures. It is limited to the south by the water divide on top of the quartzite ridge. Class S2 (high vulnerability) is characterised by lower connectivity to



GOD-S Index [A]

- High - Very High (> 0.65)
- Moderate - High (0.5 - 0.65)
- Negligible (< 0.1)

DRASTIC-Fm Index [B]

- Very high (180 - 200)
- High - Very high (160 - 180)
- High (140 - 160)
- Moderate (120 - 140)
- Low - Moderate (100 - 120)
- Low (80-100)
- Very low (<80)

SI Index [C]

- High (60-70)
- Moderate (50-60)
- Low - Moderate (40-50)
- Low (30-40)
- Very low (<30)

DISCO Index [D]

- S - Safeguard Zones (Vulnerability)**
- S₁ - Very High
 - S₂ - High
 - S₃ - Moderate
 - S₄ - Low to Very Low
 - Borehole
 - Drainage network
 - Tectonic lineaments

Fig. 8 Vulnerability indexes for Herrera del Duque study site; **A**—GOD-S Index; **B**—DRASTIC-Fm Index; **C**—SI Index; **D**—DISCO Index

the borehole and is limited to the south by the limits of the quartzite unit. Class S3 (moderate vulnerability) comprises a large area surrounding the first two classes, mainly in sandstone and siltstone units, with minimum connection to the borehole. Class S4 (low to very low vulnerability) is dominant in the lower areas, corresponding to the absence of a hydraulic connection to the borehole.

4.3 Hydrogeological conceptual site models

Hydrogeological conceptualisation and geovisualisation techniques have become crucial in comprehending groundwater and hydromineral systems. The design of good conceptual models will allow, in advanced studies, better results, which can be carried out with less resource consumption and, for sure, will decisively support subsequent mathematical models and even back-analysis of aquifer systems. The conceptual site modelling of the hydrogeological systems benefited from an integrative, multi-scale and interdisciplinary approach, which allowed for the high complexity of natural systems (e.g., [32, 112, 113]).

The definition of the unique groundwater systems in the Entre-os-Rios area and the previous studies have aided in enhancing the hydrogeological conceptual model site, as shown in Fig. 9. Three types of aquifers can be distinguished in the Entre-os-Rios region (details in [55, 114]):

- i) A shallow and unconfined aquifer in the superficial, highly weathered to decomposed granitic rock and granitic residual soil will play a critical role in recharging the underlying aquifers.
- ii) An unconfined to semi-confined aquifer with normal water circulation in the weathered areas and most of the fissured zones of the granite; the waters of this aquifer have a pH of 4.1 to 6 and an electrical conductivity of fewer than 150

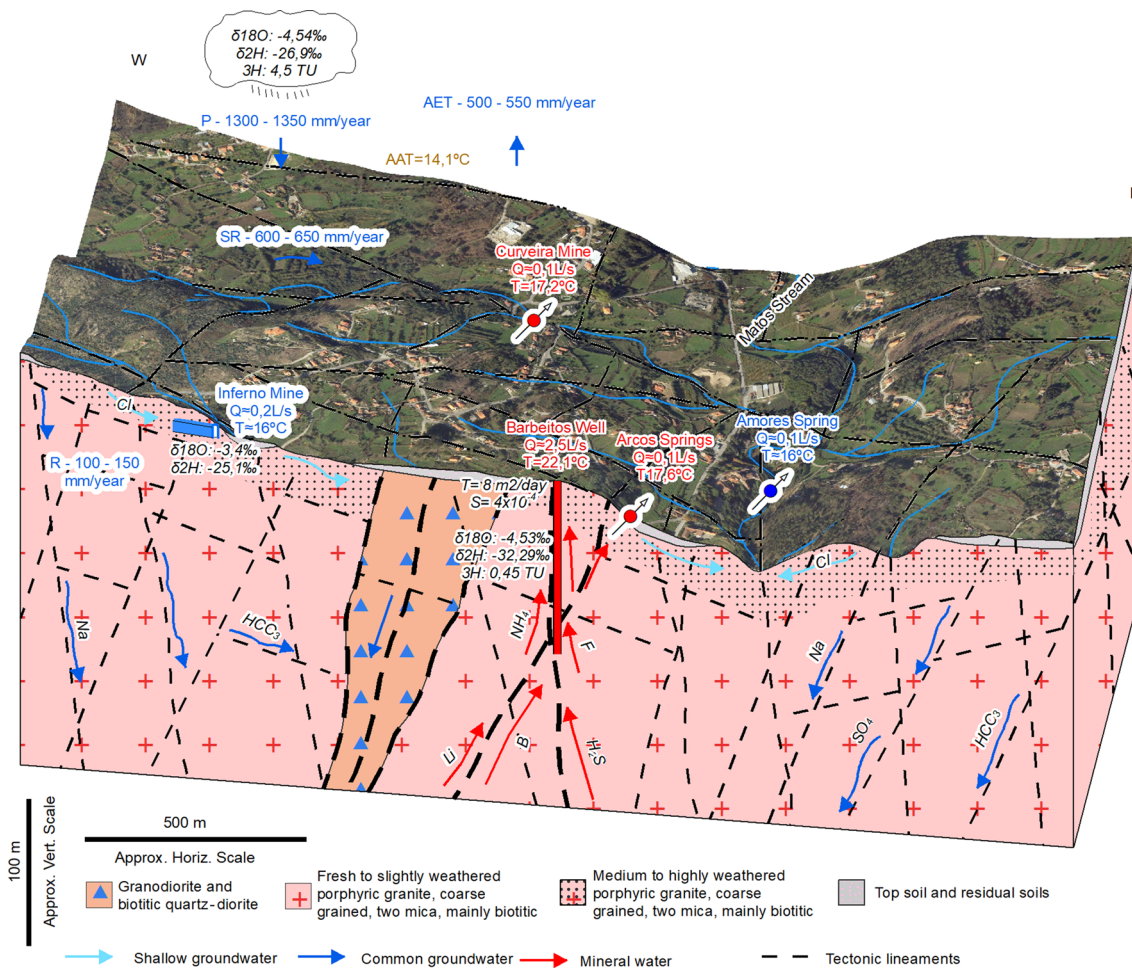
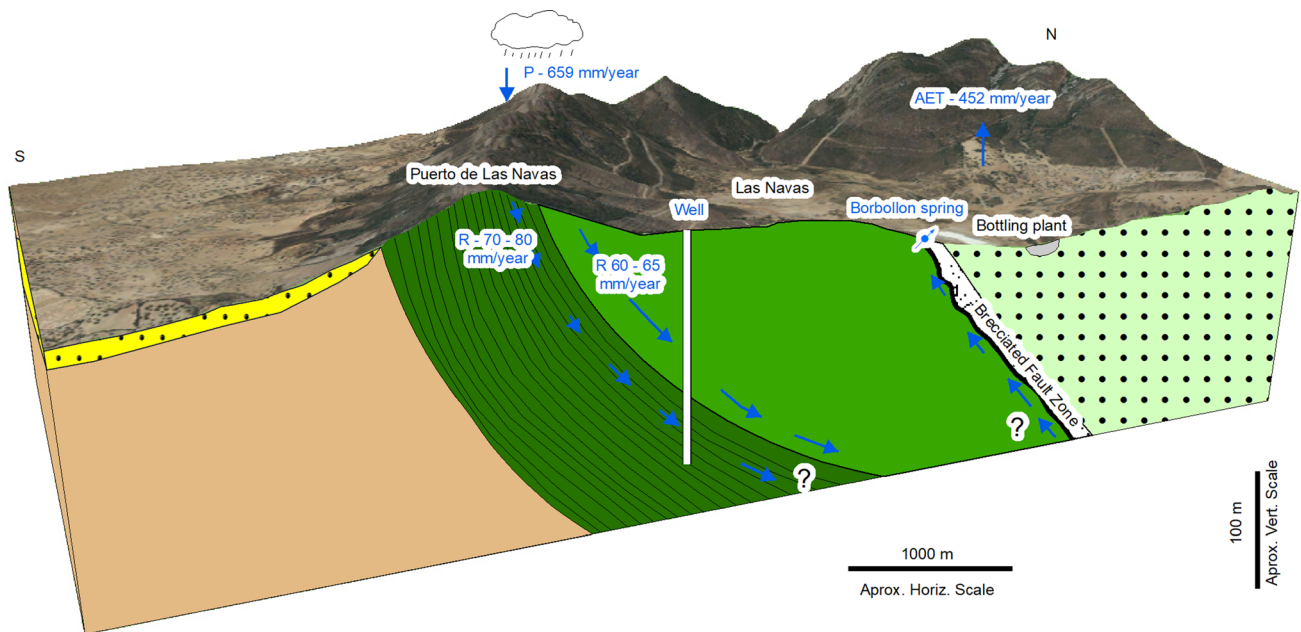


Fig. 9 Updated hydrogeological conceptual model for Entre-os-Rios study site (revised from [55, 114])

$\mu\text{S}/\text{cm}$. The flow rates are generally less than 0.2 L/s. The normal waters of the region are characterised by a very low mineralisation, mainly sodium chloride.

- iii) A confined mineral aquifer, located at depth, except at the point of emergence, close to the catchments, conditioned by an area of structural weakness at depth. The mineral water borehole (Barbeitos) is located in the coarse-grained porphyritic granite, close to the granite, close to contact with the hydrogeological unit of granodiorites, reaching a maximum depth of 114 m in the granitic rock, with an exploration flow of 2.5 L/s. The flows in the remaining mineral water springs do not exceed 0.1 L/s. The water extracted from the Barbeitos borehole presents a low temperature, that is, around 22 °C, being of the order of 17 to 18 °C in the remaining springs (Nascentes dos Arcos and Mina da Curveira). The pH varies between 8 and 9, and the electrical conductivity is between 650 and 750 $\mu\text{S}/\text{cm}$. The mineral waters of Entre-os-Rios are characterised by being hypothermic, weakly mineralised, with alkaline reactions, sulfidric, sodic bicarbonate, carbonated, and very fluorinated.

The classical springs (Torre, Arcos, Curveira and Ardias) are interrelated with lithological contacts, mainly coarse-grained porphyritic granite and fine-grained granodiorites/quartz-diorites. Furthermore, the microgranitic structures constrain the Curveira and Ardias springs. The combination of the geological and morphotectonic features (in particular, tectonised lithological contacts, a convergence of fracture systems, and morphostructural landscape control) lead to tectonic knots that create favourable hydrogeological traps, which result in the current abstractions and natural mineral springs in the Entre-os-Rios Thermal Spa area.



Hydrogeological units	Type of media		Transmissivity (T, m ² /day)	Long-term well capacity* (Q, L/s)		
	Porous	Fissured		Q < 1	1 < Q < 2	2 < Q < 10
Sedimentary cover						
Hillslope deposits	X		n.a.	n.a.	n.a.	n.a.
Metasedimentary rocks						
Shale, siltstone		X	n.a.	Aquitard, Q<1		
Sandstone, siltstone		X	n.a.	Aquitard, Q<1		
Quartzite, with interbedded shale, conglomerate		X	25			X
Schist, greywacke		X	n.a.	Aquitard, Q<1		

* Median long-term well capacity
n.a. - not available

Fig. 10 Updated hydrogeological conceptual model for Herrera del Duque study site (revised from [113])

In SW Spain, *El Borbollón* spring (e.g., [68–70]) is about 2 km North of the Armorican quartzite ridge, close to the Benazaire river banks at an elevation of 470 m. The local hydrogeological units could be identified in the improved hydrogeological conceptual model for the Herrera del Duque study site (Fig. 10) (revised and updated from [113]):

- a) Sedimentary cover: A shallow and unconfined aquifer in detrital deposits with quartzitic clasts and clayey matrix with very low interstitial permeability.
- b) Metasedimentary fissured basement with an aquitard performance, most likely with productivity lower than 1 L/s: (i) Alternating sedimentary beds (interbedded layers of shales, slates, sandstones and quartzite with secondary permeability); (ii) Black shales and interbedded sandstones/siltstones layers, with brecciated quartz veins with a 0.5–1 m thickness (mainly, dark clayey shales richly fossiliferous and sandy shales beds mostly impermeable, primarily due to the presence of fault gouges and argillaceous matrix); (iii) 'Pochico beds': coarse interbedded layers of quartzite, sandstones and slates on the top. This hydrogeological unit is less permeable than the Armorican quartzite. However, this unit has typical fracture permeability over singular fractured zones.
- c) Armorican quartzite: almost pure ortho-quartzite fractured with well-developed secondary permeability. The transmissivity could reach 25m²/day, and the hyposaline water flow could vary from 2 to 10 L/s. Considering its regular discontinuity network, this unit could be considered a regional aquifer. In addition, quartz veins increase the hydraulic conductivity locally of the aquitard units and contribute to the occurrence of thermal water resulting from the deep circulation in the Armorican quartzite aquifer.

5 Conclusions

The unique tools made available by GIS and MCDA analysis, widely used in this study, have proven extremely useful in cross-referencing and synthesising the immense amount of data available in the study areas. This promptly and effectively allows the production of essential GIS-based mapping documents for sustainable water resources management, clearly identifying the areas of groundwater infiltration, flow and discharge.

At the hydrogeological level, it is shown that the coherent integration of all the geological elements obtained at different scales, such as regional and local geology and geomorphology data, photogeology and remote sensing, tectonics and land use, is fundamental to groundwater resources development operations. As far as possible, all this information should be cross-referenced and synthesised at appropriate scales and, thus, represented in georeferenced thematic maps, if possible overlaid, to perform a comparative analysis of the results.

The Entre-os-Rios study site (NW Portugal) predominantly comprises a granitic rocks suite, including granodiorite, quartz-diorite, and coarse-grained porphyric granite. The combination of all factors and inner scores in the study area results in moderate to medium-high IPI values, with higher values in alluvia areas and in zones where the slope has the lowest values, combined with forest areas to the west of the thermal spa.

The vulnerability assessment of the study sites was assessed using GOD-S, DRASTIC-Fm, SI and DISCO indexes. At Entre-os-Rios, the valley's bottom, dominated by alluvia sedimentary cover, exhibits higher vulnerability values on regional GOD-S, DRASTIC-Fm, and SI indexes. However, the limited extension and thickness, low altitude, and connection to the deeply fractured mineral aquifer mitigate the potential outcomes. On the contrary, the DISCO index evaluates the local vulnerability and focuses on the groundwater borehole. Thus, it highlights the importance of the NNE-SSW, NE-SW and WNW-ESE structures in defining the most vulnerable areas for the Barbeitos Borehole.

At the Herrera del Duque study site, the combination of factors and inner scores in the study area results in medium to medium-high IPI values, with higher values in hillslope deposits, sedimentary cover, and the top of quartzite ridges. The recharge area is located on the top of the quartzite ridge. Vulnerability assessment with the regional indexes indicates higher vulnerability values in the sedimentary cover at the valley bottom, but the limited area and shallow thickness mitigate their impacts. The quartzite unit, crucial for the aquifer system, has relatively low vulnerability values. The local approach of the DISCO index shows the most vulnerable areas located to the south of the borehole, highlighting the importance of NW-SE and NE-SE structures.

Hydrogeological conceptualisation and geovisualisation techniques have become essential in understanding groundwater and hydromineral systems. In the Entre-os-Rios area, the hydrogeological conceptual model has been enhanced based on the definition of various aquifer systems. Three types of aquifers were identified: a shallow and unconfined aquifer in the weathered granitic rock and residual soil, an unconfined to semi-confined aquifer with normal water circulation in the weathered and fissured zones of the granite, and a confined mineral aquifer at depth conditioned by

structural weakness. Conversely, the Herrera del Duque study site (SW Spain) consists of metasedimentary rocks and a sedimentary cover with distinctive hydrogeological characteristics. Alluvia deposits along the valley bottom have high infiltration potential, while the quartzite unit exhibits favourable characteristics for groundwater circulation due to its high transmissivity. Other metasedimentary units, composed of shales, sandstones, or siltstones, have low transmissivity.

The proposed GIS-based methodology has proven its value in granitic and metasedimentary contexts. With the increased knowledge of the nature and functioning of the aquifers provided by the hydrogeological studies and GIS–MCDA approach, the conceptual models are more robust and realistic. It is also expected that the models developed will be helpful for decision-making on the management of the water resources of the areas presented, namely regarding the planning of hydrogeological investigations, the hierarchisation of potential contamination areas, the reduction of the cost of more advanced studies, the definition of catchment protection areas, as well as a follow-up of the management of the georesource itself in an environmentally sustainable way.

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Author contributions JT and HIC designed the research. JT, HIC, JMC, APA and FR gave input on field surveys and hydrogeological inventory, remote sensing, hydrogeomorphology, hydrogeochemistry, and GIS mapping of the study sites and the surrounding region. All authors contributed to the data analysis and interpretation and discussed the results. JT and HIC wrote the manuscript with the contributions of all authors. JT and HIC edited the final revised version. All authors read and approved the final manuscript.

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Data Availability All data generated or analysed during this study are included in this published article.

Code Availability Not applicable.

Declarations

Competing interests No potential competing interests was reported by the authors.

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