On a dialogue between hard-rock aquifer mapping and hydrogeological conceptual models: insights into groundwater exploration

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Groundwater is a dynamic and renewable resource, but in hard-rock terrains its availability is rather limited compared to other types of aquifer formations. Groundwater systems require a comprehensive understanding of geology, morphotectonics and hydrology, which are controlled by ground characteristics like weathering grade, fracturing degree, permeability, slope, drainage pattern and density, land cover, and climate. GIS-based integrative cartography provides an accurate way to improve knowledge on water circulation models and on the global functioning of aquifer systems. The groundwater conceptual model based in Earth systems has proven its value in water resource studies. This approach highlights the importance of groundwater exploration mapping as a useful tool to support hydrogeological conceptualisation of fractured hard-rock terrains, contributing to the sustainability of water resources.

Les eaux souterraines constituent une ressource dynamique et renouvelable, mais leur présence dans les roches du socle est plus limitée que dans d’autres types de formations aquifères. Les systèmes d’eaux souterraines étant contrôlés par des caractéristiques du sol comme l’altération, la fracturation, la perméabilité, la pente, le drainage, la couverture du sol et le climat, leur compréhension exige une connaissance approfondie de la géologie, de l’hydrologie et de la morphotectonique. La cartographie SIG intégrative fournit un moyen précis d’améliorer les connaissances portant sur les modèles de circulation d’eau et le fonctionnement global des systèmes aquifères. Les modèles hydrogéologiques conceptuels ont fait leur preuve dans l’étude des ressources hydriques. Contribuant ainsi à la conservation de ces ressources, cette approche met en évidence l’importance de la prospection des eaux souterraines dans la conceptualisation hydrogéologique des roches dures fracturées.

Las aguas subterráneas son un recurso dinámico y renovable, pero en formaciones de rocas duras su disponibilidad es muy limitada, en comparación con otras formaciones acuíferas. Los sistemas de aguas subterráneas requieren un conocimiento profundo de la geología, hidrología y morfotectónica, controladas por las características del terreno, como: grado de alteración, grado de fracturación, permeabilidad, pendiente, patrón de drenaje y densidad, cobertura del suelo y clima. La cartografía SIG integradora proporciona una forma precisa para mejorar el conocimiento de los modelos de circulación del agua, y el funcionamiento global de los sistemas acuíferos. Los modelos conceptuales basados en los sistemas geológicos han demostrado su valor en los recursos hídricos. Este enfoque pone de relieve la importancia de la cartografía de las aguas subterráneas, como herramienta útil para apoyar la conceptualización hidrogeológica de rocas duras fracturadas, contribuyendo a la sostenibilidad de los recursos hídricos.

Geosciences, Water and Modelling

In 1802 J. B. Lamarck wrote: *“En un mot, l’écoulement des eaux vers les lieux bas, comme celui des torrens, des ruisseaux, des rivières, des fleuves, des eaux pluviales de tous les genres; enfin, des sources et des fontaines.”* [*“In short, they correspond to the downflow of water toward the lowlands, as done by torrents, brooks, streams, rivers, rain water, and finally, by springs and rock springs.” – translated by A.V. Carozzi*, 1964, Univ. Illinois Press]. This impressive quote about the action of terrestrial waters in Earth, from the interesting book under the title of *Hydrogeólogie*, illustrates the conceptual framework of this paper: water dynamic systems. On this aspect, ***Fig. 1*** represents the main water flows affecting groundwater in a hydrogeological reservoir.

Understanding the role of conceptual site models is essential to accurately assess hydrogeological systems and water resources. Hard-rock watersheds are essentially limited to fractured and weathered horizons, and they are a source of valuable water resources on a regional level, namely for domestic, industrial and agricultural purposes, and also for public supply. In particular, hydromineral and geothermal resources have a relevant economic value in the bottled water/thermal bath industry and in energy supply, respectively. Groundwater conditions are also of primary significance for the construction and maintenance of subsurface engineering structures (e.g., tunnels, sewers, underground storage facilities and building foundations) and may additionally influence urban drainage. Recent technological advances have brought remote sensing and geographic information system (GIS) techniques to the forefront as tools to develop and recommend sustainable conservation and management measures of geosciences (e.g., Kresic and Mikszewski, 2013; Teixeira *et al.*, 2013). GIS tools are also useful in providing accurate ways to improve knowledge about groundwater, surface water circulation models and the overall functioning of aquifer systems.

In the past decades, the practise of intensive water resource exploitation has had a large impact on hydrological systems on several scales. Thus, accurate evaluation of

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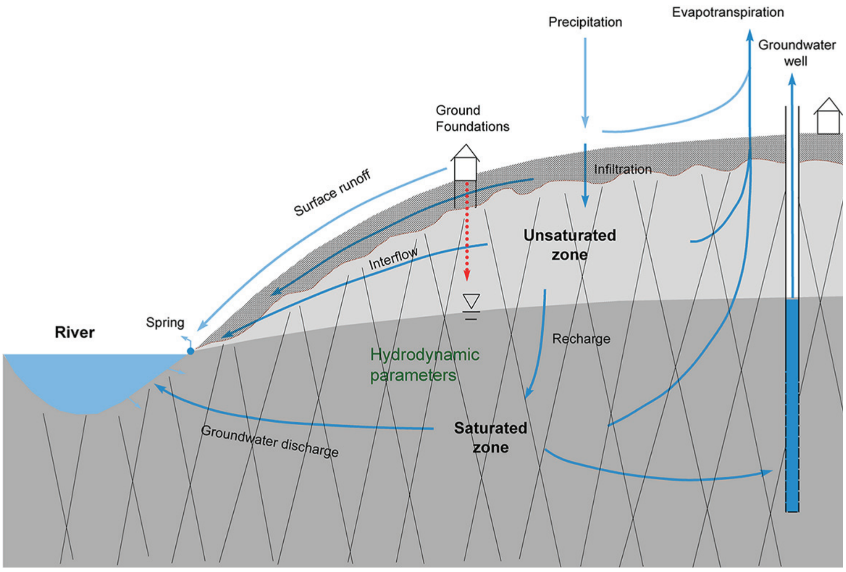


Figure 1: Water flows affecting the groundwater in a hard-rock fissured framework: an outlook for water resources and geoengineering issues (updated from Fitts, 2013).

the present state of these systems requires studies ranging from hydrogeological site investigations to watershed scales. Particularly, hydrogeological modelling plays a key role in the protection and management of groundwater resources.

Understanding the complexity of Earth systems is possible through the use of ground models (Griffiths and Stokes, 2008). Several types of model approaches can be used (e.g., Bredehoeft, 2005; Carvalho *et al.*, 2005; Marsily *et al.*, 2005; Renard and Allard, 2013; and references therein): geologic, analytic, numeric, deterministic and stochastic. These approaches differ in various aspects, though they also show some feature similarities, depending on their use and application domains. According to Kresic and Mikszewski (2013), a conceptual site model accomplishes an overall knowledge of the features and dynamics of the system based on existing data interpretation. The key elements are conceptual development based on available information, data collection at the site-specific level, spatial data analysis, and data visualisation to achieve the study conclusions (Kresic and Mikszewski, 2013). A model additionally involves the assumption of practical simplifications, which are crucial to enable its applicability despite of geologic variability and uncertainty (Keaton, 2013). Nevertheless, simplification should be restricted as far as possible to ensure the accuracy of the conceptualisation.

The conceptualisation process is an initial main step in the hierarchical analysis of groundwater flow. In addition to this, there is a clear need to accommodate the relationship between hard-rock aquifer mapping and conceptualisation of hydrogeological systems, for an effective construction of the groundwater models (Teixeira *et al.*, 2013). A hydrogeological conceptual model is primarily a description of various natural and anthropogenic factors that govern and contribute to movement of groundwater in the subsurface (Kresic and Mikszewski, 2013). The conceptualisation of hard-rocks aquifer systems involves an overall balanced understanding of geological behaviour, petrophysical features and hydraulic processes. The standardisation of procedures, methodologies and techniques addresses many such hydrological issues. Hence, groundwater modelling has become standard practice for professional hydrogeologists.

The modelling techniques have been used to achieve several goals (e.g., Bredehoeft, 2005; Marsily *et al.*, 2005; Kresic and Mikszewski, 2013, Teixeira *et al.*, 2013; and references therein): i) to predict short-term recharge/discharge areas and assess their role in relation to the evaluation of water resources; ii) to identify constraints related to groundwater management towards long-term sustainable exploitation, iii) to identify potential groundwater contaminants and estimate their transport in space and time; and iv) to aid better decision making about climate change and variability.

Hard rocks occupy large regions throughout the world, particularly in Africa, Europe, America, Asia and Oceania. The crystalline rocks have a very low porosity; the secondary porosity is thus developed across the geological and geomechanical characteristics of the discontinuities (i.e., fissures, fractures, joints, faults, shear zones, vein-structures, etc.), which are responsible for most permeability and groundwater path flows (e.g., Assaad *et al.*, 2004; Carvalho *et al.*, 2005; Fitts, 2013). On a local scale, the main factors that control the groundwater flow in saturated zones are: fracture network density and tectonic patterns (which promote crustal fault damage zones), opening and filling of discontinuities, weathering grade, and lithology features.

The hard-rock hydrogeological conceptual model should include, at least: the geostructure of the reservoir, its lithological

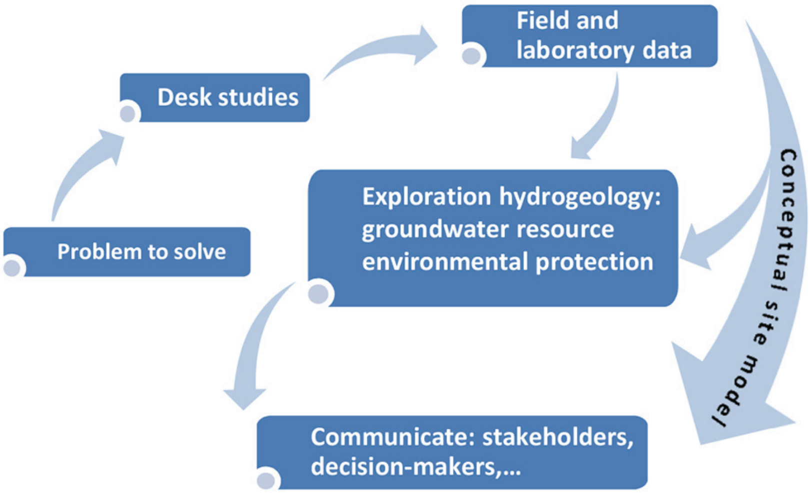


Figure 2: Conceptual site model: a flow path for an integrated exploration hydrogeology approach.

heterogeneities, petrophysical properties, permeability, hydrodynamics, hydrogeological structures that affect the circulation and their distribution in space, hydrogeochemistry and isotopic behaviour, and evaluation of the water discharge conditions.

The conceptualisation of hydrogeological systems focused on groundwater exploration must be dynamic and should be continuously updated to reflect the latest advances in the knowledge of the groundwater reservoir. In addition, it is vital to outline possible scenarios for further interventions. The next step is to transform the information about the hard-rock fractured reservoir into mathematical modelling to check various scenarios using different approaches (i.e., probabilistic, deterministic or stochastic). All the models must be robust, calibrated and supported on a permanent retro-analysis scale based on a logical understanding of the real hydrogeological framework, as well as capable of communicating information to all agents (practitioners, researchers, stakeholders and decision makers) involved (*Fig. 2*).

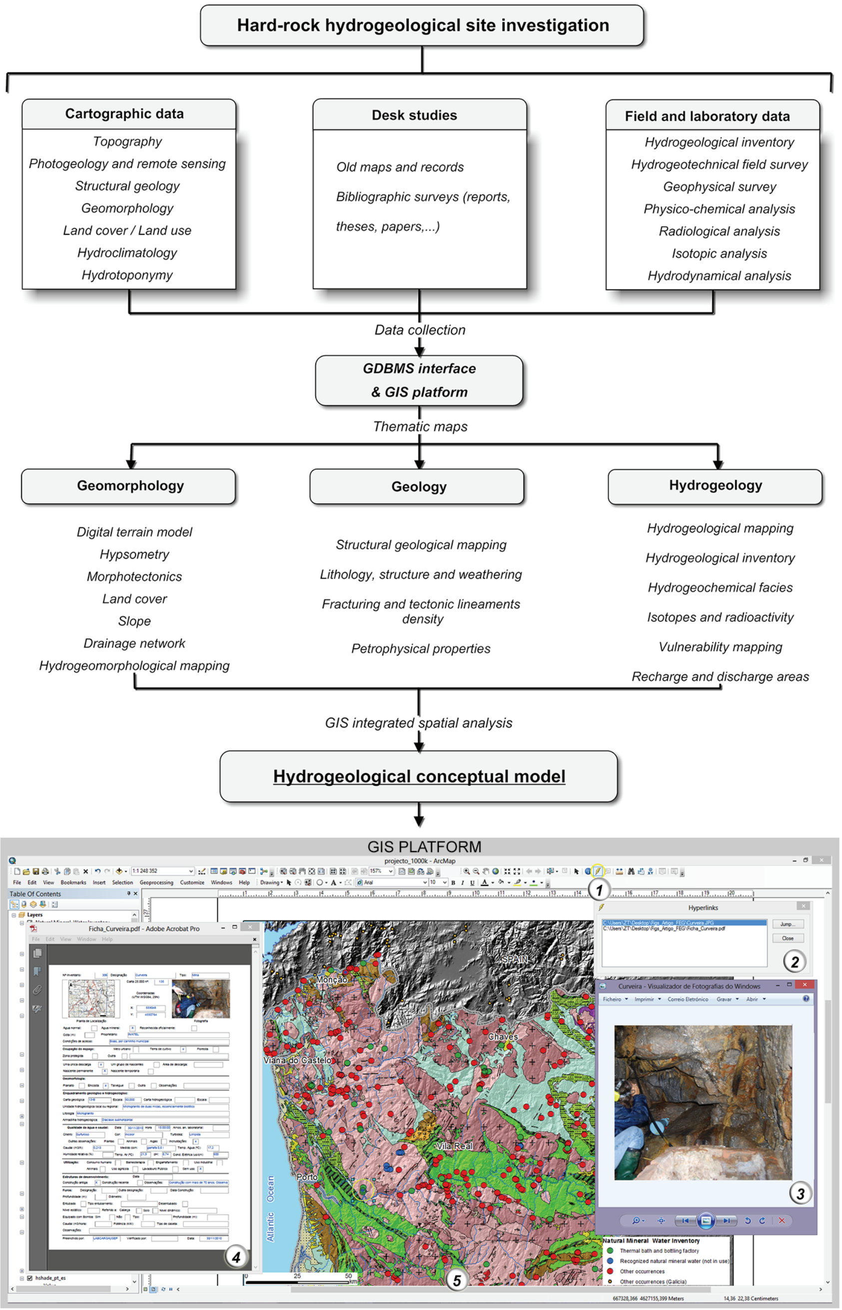


Figure 3: Conceptual flow chart of the hard-rock hydrogeological site investigation. 1. Application tool to create hyperlinks between features (line, point or polygon) and other files; 2. Hyperlink addressed to a file (image or text); 3. Visualisation of photo details for the water inventory; 4. Hydrogeological inventory datasheet (field and desk data); 5. Regional hydrogeological mapping.

In this work GIS-based mapping was used to produce groundwater exploitation models under different hydrogeological frameworks. The hydrogeological conceptualisation of these fractured hard-rock terrains was enhanced by this integrated approach and should contribute to the environmental sustainability of water resources in the study areas.

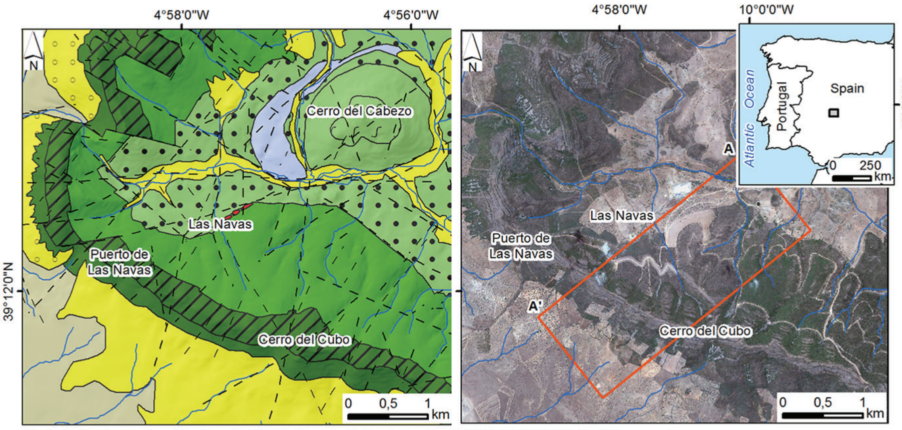
Selected sites: examples from Iberian Peninsula

The thermal baths and bottled water industry are highly related to hard-rock hydrogeology in the Iberian Peninsula (Carvalho *et al.*, 2005). A comprehensive integrated study of groundwater resources was carried out at two selected sites of Portugal and Spain. The study coupled GIS-based mapping with hydrogeological assessments. Thematic maps were prepared from multi-source geodata, namely satellite imagery, topographic and geological mapping and hydrogeological field surveys. These maps were converted to GIS format and then integrated with the purpose of elaborating a hydrogeological map intended to support the groundwater conceptual site model and further exploration and exploitation drilling. The basic techniques of geology, geomorphology and hydrogeology were applied in the study sites (e.g., Assaad *et al.*, 2004; Teixeira *et al.*, 2013). ***Figure 3*** presents a flow chart of the hard-rock hydrogeological site investigation.

Herrera del Duque site (La Siberia, South-western Spain)

The studied site is located in the middle-upper Palaeozoic metasedimentary sequences of the south-western Spain, in the Dehesa de las Navas synclinorium area (Herrera del Duque municipality). The geotectonic background comprises a middle-upper Palaeozoic metasedimentary fissured basement which is deformed and overthrusted late Proterozoic Schist-Greywacke Complex. This megastructure with axis trending NW-SE is faulted, with the main regional faults being transversal and sub-parallel to the axial orientation. In "Neseuretus shale" richly fossiliferous beds (mainly trilobites, brachiopods, echinoderms and graptolites) brecciated quartz veins were mapped with a thickness of 0.5-1 m. The Ordovician megasequence disconformably overlies late Proterozoic rocks (Herrera del Duque plateau). The most famous and extensive lithological unit is the Armorican quartzite, which occurs also in other regions of the Iberian Peninsula (e.g., the Valongo anticline and Monfortinho syncline, in Portugal; the Tamames syncline, in Spain) and in the Armorican Massif of western France. This unit consists mainly of light-coloured thick-bedded mature sandstone and orthoquartzite with some grey shaly or silty intercalations. The drainage network reveals this tectonic control, which imposed morphostructural features on the region.

At the hydrogeological level the main aquifer is placed over the Armorican quartzite, containing hyposaline water and transmissivities values of up to 25 m²/day, determined using pumping tests in drilled wells. All the other metasedimentary units have an aquitard performance, probably with productivities generally lower than 1 L/s and with a very low rate of success. Quartz veins increase locally the hydraulic conductivity of the aquitard formations and allow the occurrence of thermal water resulting from the deep circulation in Armorican quartzite aquifer (*Fig. 4*).



Geological background: updated from ITGE 1989, Mapa geológico de España, 1/50.000. Nº 733/15-29; Castilblanco and Carvalho et al, 2010. Proceedings V Congresso Nacional de Geomorfologia, APGEOM, Porto. pp. 257- 259

Hydrogeological units		Type of media		Transmissivity (T, m²/day)	Long-term well capacity * (Q, L/s)		
		Porous	Fissured		Q < 1	1 < Q < 2	2 < Q < 10
Sedimentary cover							
Alluvia, sand and gravel	🟨	X		n.a.	n.a.	n.a.	n.a.
Hillslope deposit	🟨	X		n.a.	n.a.	n.a.	n.a.
Metasedimentary rocks							
Quartzite; interbedded shale and siltstone	🟩		X	n.a.	Aquitard, Q<1		
Shale, siltstone and sandstone	🟩		X	n.a.	Aquitard, Q<1		
Shale and quartzite	🟦		X	n.a.	Aquitard, Q<1		
"Neseuretus" shale and sandstone	🟩		X	n.a.	Aquitard, Q<1		
Black shale, sandstone and siltstone	🟩		X	n.a.	Aquitard, Q<1		
Armorican Quartzite	▨		X	25			X
Conglomerate, sandstone and quartzite	🟩		X	n.a.	Aquitard, Q<1		
Schist and greywacke complex	⬜		X	n.a.	Aquitard, Q<1		
Veins							
Quartz vein	🟥		X	Locally increase the hydraulic conductivity.			

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

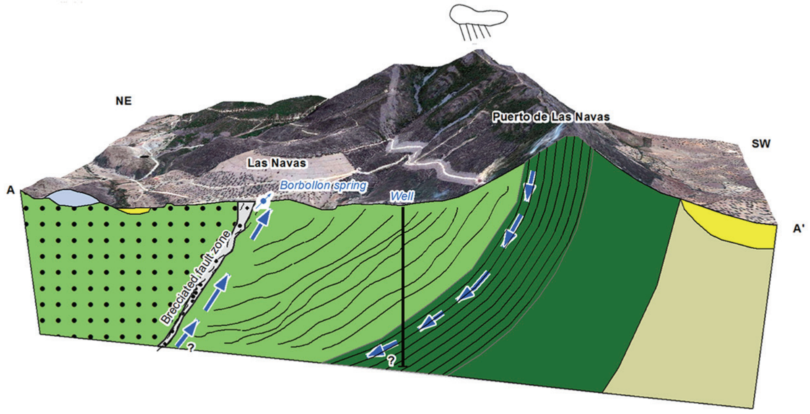


Figure 4: Herrera del Duque site (La Siberia, South-western Spain) framework: hydrogeological conceptual model site.

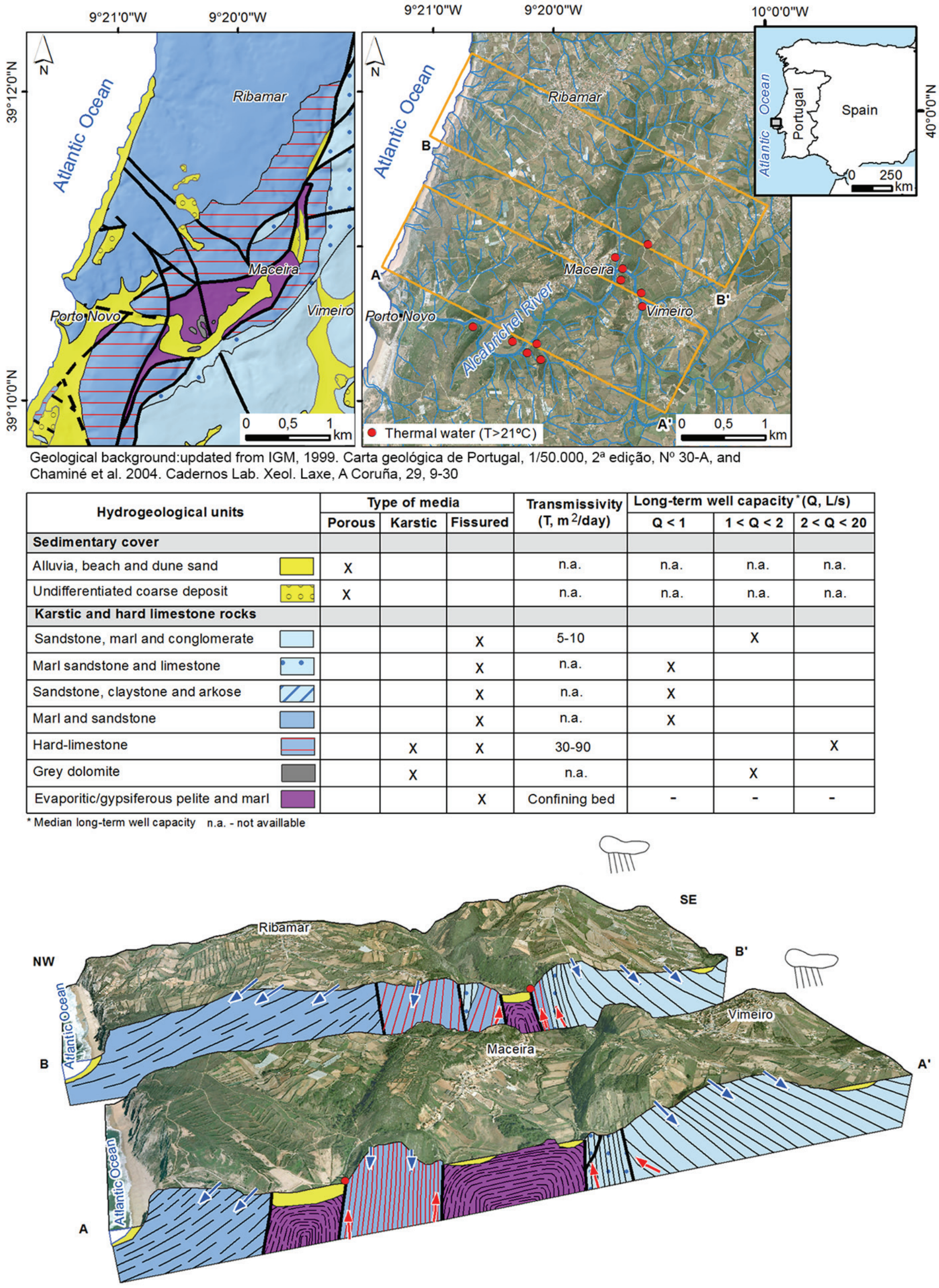
Vimeiro site (Torres Vedras, Central Portugal)

Hydrogeological studies were performed at the Vimeiro hydromineral discharge and the surrounding Maceira–Porto Novo area (Torres Vedras municipality). The studied site encompasses an area of about 23 km², including the Alcabrichel River catchment. Vimeiro has a balneological and balneotherapy tradition which dates back to the early 18th century. The studies were due to the need to increase the supply from the thermal springs and former shallow well for therapeutic uses at the thermal bath, as well as to provide additional drinking water in the surrounding area for domestic use.

The thermal water from the Vimeiro diapiric structure is characterised by: i) output temperatures around 26 ºC; ii) relatively high pH values (6.9 to 7.1), iii) TDS content in the range of 900 to 1100 mg/L, but TDS content ranging from 3300 to 6000 mg/L (Frades Spring) was also reported, iv) electrical conductivity (EC) measurements ranging from 1.550 to 4.830 μScm^{-1} (Santa Isabel Spring and Frades Spring), indicating the presence of high mineralised water. The groundwater belongs to sodium bicarbonate-chloride facies. This chemical composition and the existing thermal waters denote deep circulation and a final circulation trough in the karstified hard limestone at the contact with the evaporitic marls. In the area the only regional aquifer is placed in the karstified hard limestone (with transmissivity up to 900 m²/day), the other units acting for practical purposes as aquitards (*Fig. 5*).

Concluding remarks

This work highlights the importance of groundwater GIS mapping as a useful tool to support hydrogeological conceptualisation, as well as for decision-making at the



Geological background:updated from IGM, 1999. Carta geológica de Portugal, 1/50.000, 2ª edição, Nº 30-A, and Chaminé et al. 2004. Cadernos Lab. Xeol. Laxe, A Coruña, 29, 9-30

Hydrogeological units		Type of media			Transmissivity (T, m^2/day)	Long-term well capacity* (Q, L/s)		
		Porous	Karstic	Fissured		Q < 1	1 < Q < 2	2 < Q < 20
Sedimentary cover								
Alluvia, beach and dune sand	🟨	X			n.a.	n.a.	n.a.	n.a.
Undifferentiated coarse deposit	🟨	X			n.a.	n.a.	n.a.	n.a.
Karstic and hard limestone rocks								
Sandstone, marl and conglomerate	🟦			X	5-10		X	
Marl sandstone and limestone	🟦			X	n.a.	X		
Sandstone, claystone and arkose	▨			X	n.a.	X		
Marl and sandstone	🟦			X	n.a.	X		
Hard-limestone	▤		X	X	30-90			X
Grey dolomite	⬛		X		n.a.		X	
Evaporitic/gypsiferous pelite and marl	🟪			X	Confining bed	-	-	-

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

Figure 5: Vimeiro site (Torres Vedras, Central Portugal) framework: hydrogeological conceptual model site.

basin master plan level regarding land use, water resources and sustainability. In hydrogeological practice an accurate conceptual modelling process is the basic tool for developing a correct and essential understanding of site conditions. This multidisciplinary approach involves decision making regarding water supply, ecosystems and environmental protection.

The conceptual model provides the primary understanding of how a hydrogeological system or process operates, which is usefully expressed quantitatively as a mathematical approach. According to Konikow and Bredehoeft (1992), models cannot be proven or validated, but only tested and invalidated. Nevertheless, because of its ability to synthesise and model a wealth of information, if used cautiously a model is quite advantageous to groundwater exploration (Bredehoeft, 2005; Carvalho *et al.*, 2005). The conceptual site model serves as the basis for modelling groundwater flow systems. Many difficult questions that arise in the development of hydrogeological investigations have been answered using groundwater modelling. At present, hydrogeological conceptualisation has become an indispensable tool in understanding and effectively managing hard-rock aquifer systems (***Fig. 6***).

New challenges are emerging related to conceptualising and modelling heterogeneities in aquifer connectivity. Under this framework, connectivity metrics are becoming significant tools to describe subsurface flow and transport (Renard and Allard, 2013). Thus, innovative approaches are needed in the collection and integration of data. This will improve the simulation of real conditions for a better development of models for hard-rock aquifer systems (Teixeira *et al.*, 2013).

Last, but not least, a hydrogeological conceptual model is an invaluable instrument for communication with practitioners, researchers, other professionals (e.g., stakeholders and decision makers) and society. These groups can jointly contribute to identifying strategies, policies, targets, and funding for implementing water resources programmes within an environmental, sustainable and ethical framework.

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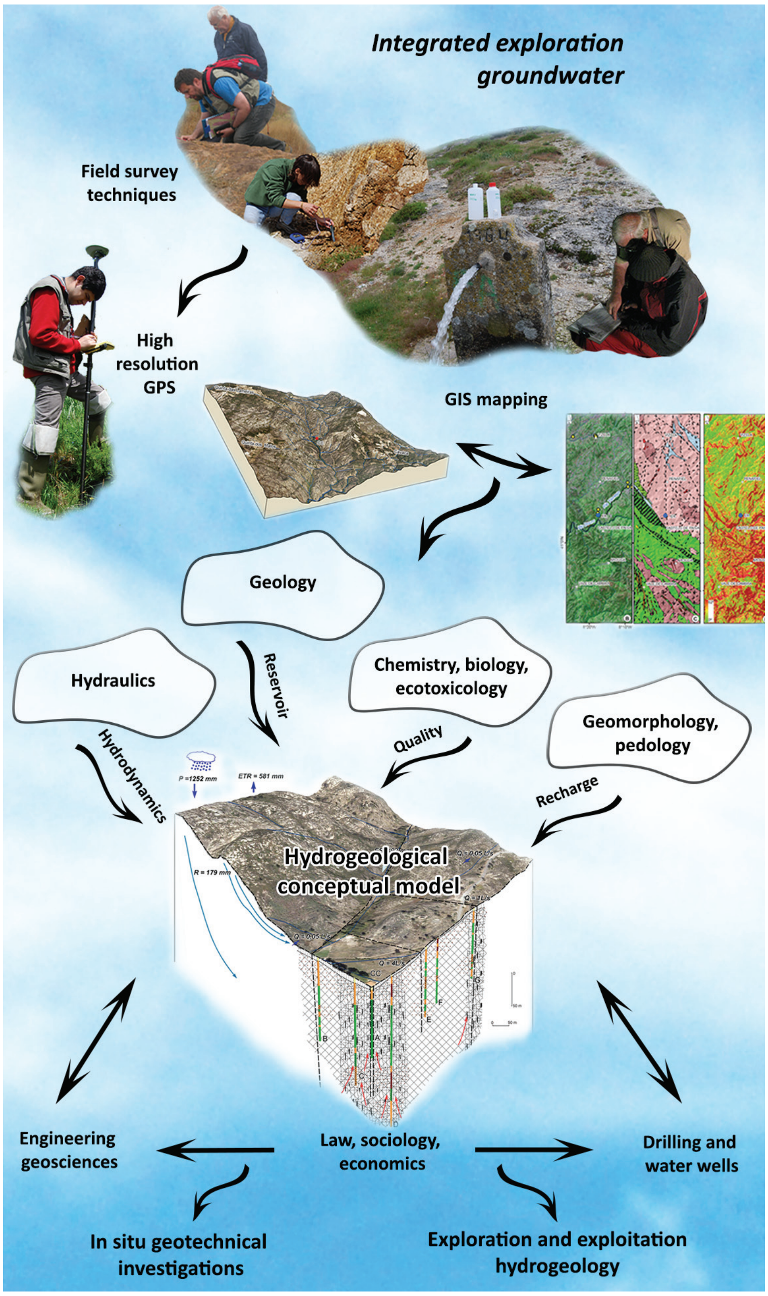

Figure 6: Hydrogeological conceptual model: a general outlook on an integrated exploration groundwater framework.

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