Role of hydrogeological mapping in groundwater practice: back to basics

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Maps are of key importance in groundwater professional practice and hydrogeology research, mainly in field data synthesis and communication related to a number of fields: regional hydrogeology, exploration hydrogeology, groundwater engineering, hydrogeophysics, hydrogeomorphology, urban groundwater, military geology/engineering, thermal water resources, planning, management and decision making on the water resources. This paper highlights the importance and necessity of accurate ground field surveys at several scales, water resources inventory and an integrated groundwater mapping as useful tools to support hydrogeological conceptualisation. Selected sites are highlighted to demonstrate the importance of groundwater mapping for assessment of water resources. Conceptualisation of groundwater systems must be grounded on Earth-based models and mathematical modelling to outline predicting scenarios. Thus, going back to basics is important to create a reliable conceptualisation on groundwater systems established on cartographic reasoning.

Les cartes sont d'une importance clé dans les applications professionnelles pratiques de l'eau souterraine ainsi que dans le cadre de la recherche hydrogéologique, principalement dans le champ de la synthèse des données de terrain et de communication liées surtout: hydrogéologie régionale, prospection hydrogéologique, ingénierie de l'eau souterraine, hydrogéophysique, hydrogéomorphologie, hydrogéologie en milieu urbain, géologie/ingénierie militaire, ressources en eaux thermales, planification et gestion intégrée des ressources en eau. Cet article met en évidence et à plusieurs niveaux l'importance et nécessité d'une cartographie de terrain précise, de l'inventaire des ressources en eau souterraine et d'une cartographie intégrée en tant qu'outils indispensables à la conceptualisation hydrogéologique. Certains sites ont été sélectionnés pour mettre en évidence l'importance de la cartographie de terrain dans l'évaluation des ressources en eau. Il s'ensuit que, pour décrire les scénarios de prédiction, la conceptualisation des systèmes d'eau souterraine doit être basée sur des modèles de terrain ainsi que sur des modèles mathématiques. Ainsi, il est essentiel de revenir à l'essentiel si l'on veut créer une conceptualisation établie sur un raisonnement cartographique des systèmes d'eau souterraine qui soit crédible.

Los mapas tienen importancia fundamental en la práctica profesional de las aguas subterráneas y en la investigación hidrogeológica, principalmente en la síntesis de datos de campo y en la comunicación relacionada principalmente con: hidrogeología regional, prospección hidrogeológica, ingeniería de aguas subterráneas, hidrogeofísica, hidrogeomorfología, aguas subterráneas en medio urbano, geología/ingeniería militar, recursos de aguas mineromedicinales y termales, planificación, gestión y apoyo a la toma de decisión de recursos hídricos. Este trabajo pone de relieve la importancia de los estudios de campo en varias escalas, los inventarios de recursos hídricos y la cartografía de las aguas subterráneas, integrado todo ello como herramientas útiles para apoyar la conceptualización hidrogeológica. Se han seleccionado algunos lugares elegidos para demostrar la importancia de la cartografía del terreno en la evaluación de recursos hídricos. Posteriormente, la conceptualización de los sistemas de aguas subterráneas debe sustentarse en modelos del terreno y en modelos matemáticos, para describir escenarios de predicción. Así, es importante volver a lo básico para conseguir una conceptualización fiable de los sistemas de aguas subterráneas, apoyada en el razonamiento cartográfico.

Groundwater, mapping, and practice: towards a cartographic reasoning

In 33 BC the Roman military engineer Marcus Vitruvius wrote in *De Architectura*, 'we should also consider the nature of the place when we search for water' [The Ten Books on Architecture – Book VIII: Water Supply, translated by M.H. Morgan, 1960, Dover Publications]. This inspirational quotation is the motto for the first approach to any study for groundwater purposes, i.e., a professional hydrogeologist and or researcher must place firmly his feet in the groundwater itself. Since water-related data are usually organised in tables, graphs and maps, it is crucial that the field techniques of observation and applied mapping for hydrogeology be carried out correctly. Hopefully, nowadays skilled groundwater-related professionals (e.g., hydrogeologists, engineering geologists, applied geomorphologists, hydrologists, groundwater engineers, drilling engineers, or military geologist/engineers) involved in the practice are sensitised to such an approach.

This paper highlights the importance of mapping as one of the effective tools for supporting groundwater resources studies. The long history of hydrogeology demonstrates that its practitioners contribute decisively to the exploration, the protection, and the economic and hopefully sustainable management of groundwater resources (e.g., Chaminé *et al.*, 2013; Margat and van der Gun, 2013; Gilbrich and Struckmeier, 2014), as well as dealing with landslides, dewatering, foundations, groundwater inflow into tunnels, underground excavations or mines, and the effects of water within soil and rock slopes from an engineering perspective (e.g., Chaminé *et al.*, 2010; Gustafson, 2012; Griffiths, 2014). To achieve this a sound knowledge of geology, geomorphology, geochemistry and hydraulics is required. Some of the reasons for this were identified by Griffiths (2014) for the correlate field of engineering geology. In his words, 'this knowledge has to be acquired through training and experience, and is firmly based on well-honed observational field skills' (p. 137). That is the key topic of applied geoscience activity, and the testing, analytical and numerical methods for collecting data, monitoring, predicting scenarios and back analysis studies that we use are derived from it.

Through the ages, map-making procedures and design, as well as the conceptuali-

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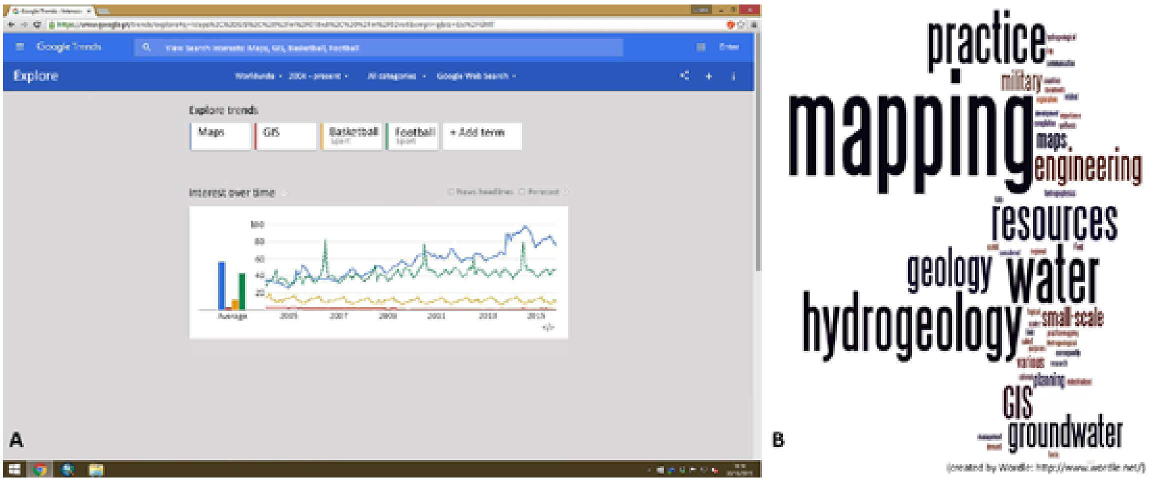


*Figure 1: A) Google Trends (***https://www.google.com/trends***) comparison of searchers for the terms (2004–present; accessed in August, 2015): maps, GIS, basketball and football (adapted and updated from MacEachren, 2013); B) Cloud diagram based on keywords about hydrogeological mapping in practice.*

sation of maps, have developed enormously (e.g., Andrews, 1996; Dykes *et al.*, 2005, and references therein). Kraak (2013) stated a basic issue: cartography first of all means "maps". New trends exploring geovisualisation analysis integrate approaches from different disciplines, including scientific visualisation, image analysis, information visualisation, exploratory data analysis and GIScience (Dykes *et al.*, 2005). According to Kraak (2013), geovisualisation combines the strength of the computer (automated analysis techniques and geo-computation) and of the human (interactive visualisations for effective understanding, reasoning and decision making). In addition, geovisual analytics focuses on visual interfaces of analytical and computational methods that support reasoning with and about geo-information – to enable insights about something for which place matters. Maps are typically central to geovisual analytics, but the emphasis is not on maps as representation but on maps as interface (MacEachren, 2013).

MacEachren (2013) argues that in current days maps have become a ubiquitous component of many technologies that support a wide range of activities from advancing science, through responding to emergencies, to location-based coordination on a given meeting point. ***Figure 1*** shows the *Google Trends* search queries for "maps" category make those for "GIS [Geographic Information Systems]" appear imperceptible and even swamp those for "basketball" and "football", which only surpassed "maps" during the 2006 and 2010 world cups and UEFA Europe league (namely Euro 2004 and 2008). Consequently, well-designed maps shape daily life and are everywhere in numbers unparalleled till now, thanks to new technological developments (Kraak, 2013; MacEachren, 2013). Hydrogeological maps play a major role in practice (e.g., Struckmeier and Margat, 1995; Margat and van der Gun, 2013; Kresik and Mikszewski, 2013; Gilbrich and Struckmeier, 2014; Chaminé, 2015). Hydrogeological mapping needs to advance towards an insightful cartographic reasoning concept established, among others, in geomatic techniques, geoscience fieldwork, applied hydrogeology, Earth-based systems conceptualisation and numerical groundwater modelling. So a significant return to basics is required to create reliable designs for groundwater systems and water resources.

An important issue was highlighted in the report *"50 years of hydro(geo)logical mapping activities under the auspices of UNESCO, CGWM, IAH and BGR"*: "Before the middle of the past century the increasing demand for water, particularly in the industrialised countries, called for a rational planning of water resources. Hydrogeological maps were considered useful basic documents in this development and, consequently, compilation of hydrogeological maps at various scales and for various purposes…" took place (Gilbrich and Struckmeier, 2014: 18). That is the basis for the key role of hydrological, hydrogeological and groundwater maps in a dual perspective focused on the main purposes and on end-users (e.g., Castany and Margat, 1965; Struckmeier and Margat, 1995; Chaminé *et al.*, 2013; Gilbrich and Struckmeier, 2014): i) general hydrological and hydrogeological maps (generally, regional scale to continental and global scales), often simplified, are produced to communicate with politicians, the general public and students; and ii) hydrogeological and groundwater maps, at several scales (mainly, large scale to local and regional scales) are created by practitioners and or researchers for the exploration, characterisation, description and evaluation of groundwater resources.

Groundwater-related activities (hydrogeological site investigations, hydrogeological inventory, hydrogeophysics, identification of potential contamination areas and definition of wellhead protection areas, water well drilling, and hydrogeological conceptual site models, among others) are considerably improved by terrain mapping methods, including the recently sophisticated unmanned aerial vehicles (UAV), remote sensing, high-resolution photogrammetry, geographic information systems (GIS), global position systems (GPS), and geovisualisation analysis (e.g., Dykes *et al.*, 2005; Cascelli *et al.*, 2012; Kresik and Mikszewski, 2013; Teixeira *et al.*, 2013; Chaminé, 2015). Subsequently, the conceptualisation of groundwater systems must be grounded on Earth-based models and mathematical modelling to outline predicting scenarios using diverse integrated approaches. Useful models must be robust, calibrated and supported on a permanent back-analysis scale based on a logical understanding of the real hydrological functioning framework. Models for decision making must incorporate the intrinsic geological ground variability and uncertainty of Earth-based systems, as well as geological risk management in a multi-hazard environment approach (Chaminé *et al.*, 2013; Chaminé, 2015 and references therein). GIS technologies provide an accurate tool to improve databases of water resources and the overall functioning of the groundwater systems, as well as aiding decision makers and managers to achieve environmentally sustainable use. The multi-analysis approach provides useful information regarding the coupling of groundwater resources and GIS mapping.

This paper highlights the importance of accurate ground and or sub-surface field surveys, hydrogeological inventory and GIS mapping as useful tools to support hydrogeological conceptualisation, as well as for supporting a balanced decision-making focus on sustainable groundwater resources management. Some selected sites are highlighted to demonstrate the importance of ground mapping for the assessment and modelling of water resources or groundwater. Thus, it is important to get back to basics in order to create a reliable conceptualisation of groundwater systems.

Back to basics: the role of mapping in ground and conceptual hydrogeological models

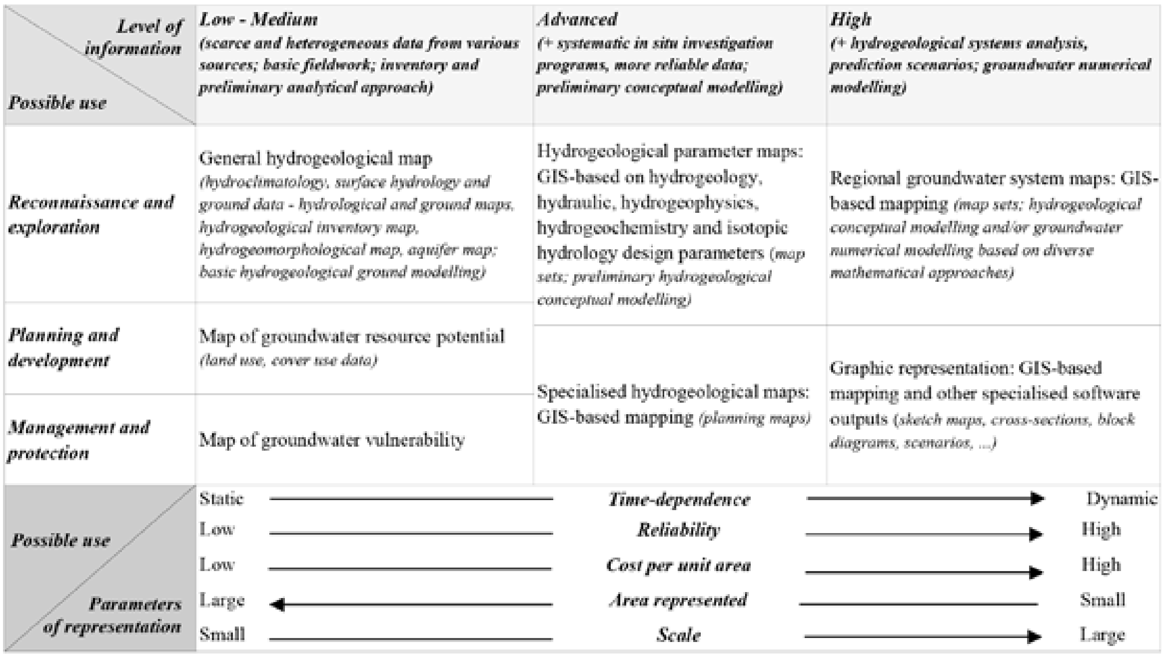
Field surveys have been the backbone of geological studies both in practice and research. Field maps are of key importance in groundwater practice and hydrogeology research, particularly in data synthesis, analysis and communication. The remarks of Wallace (1975) are still topical: 'There is no substitute for the geological map and section — absolutely none. There never was and there never will be. The basic geology still must come first — and if it is wrong, everything that follows will probably be wrong' (p. 34). This impressive thought is perfectly complemented by the words of Şengör (2014): 'properly made geologic maps are the most quantitative data in geoscience: while we may debate the nature of a contact, the contact and dip-strike measurements, if properly located, should be there 100-200 years hence and are therefore both quantitative and reproducible, something that cannot be said of experiments in some of the other sciences' (p. 44). Both thoughts are the key issue to avoid an often used phrase among geo-professionals: the so-called 'unforeseen ground conditions'. Consequently, the central issue in this approach should be the effort to make a reliable comprehensive geology to any applied geoscience or geoengineering study.

In that approach, mapping (including general or sketch maps, geological maps, hydrological maps, hydrogeomorphological maps, hydrogeological maps and hydrogeomechanical maps, at diverse scales) assumes a fundamental importance in further stages of groundwater investigations and modelling (e.g., Chaminé *et al.*, 2013; Chaminé, 2015). It is important to emphasise the value and cost-effectiveness of field mapping in site investigation compared with other activities or operations (Griffiths, 2014). Thus, mapping plays a key role in field data synthesis related to regional hydrogeology, exploration hydrogeology, water management and planning, urban hydrology, hydrogeophysics, hydrogeomorphology, groundwater engineering, engineering geology, rock engineering, and military geology/engineering (e.g. Struckmeier and Margat, 1995; Gustafson, 2012; Mather and Rose, 2012; Kresik and Mikszewski, 2013; Chaminé *et al.*, 2010, 2013; Teixeira *et al.*, 2013; Griffiths, 2014; Chaminé, 2015, and references therein).

Margat and van der Gun (2013) authoritatively highlight some basic issues related to the groundwater systems mapping: 'maps are very effective for showing variations and patterns […]' (p. 4) and also 'derived from geological maps, hydrogeological maps have the objective of showing the composition and structure of the subsoil in relation to the occurrence and movement of groundwater. They do so by combining data on the container (aquifer) and the content (groundwater)' (p. 39). Hydrogeological maps address the following (Margat and van der Gun, 2013): i) a classification of formations in relation to the productivity of groundwater abstraction works, or sometimes in relation to the infiltration capacity of water-table aquifers, using an *ad hoc* typology; ii) data on groundwater dynamics (piezometric levels, potential field and outflow in discharge zones on a given date) and the relationship between groundwater and surface water; iii) the presentation of observed or inferred structural elements at depth (possibly supplemented by cross-sections, sketches or three-dimensional drawings), in particular those of delineated aquifer systems which form the framework for assessing and managing the groundwater resources; and iv) information on groundwater recharge by infiltration of excess rain water, on water quality and on abstraction works can be added to these basic elements, depending on the state of knowledge.

However, the accuracy of hydrogeological field survey and mapping in groundwater practice must meet the following purposes (Struckmeier and Margat, 1995; Margat and van der Gun, 2013; Gilbrich and Struckmeier, 2014): i) hydrogeological or groundwater maps that are of immediate use to the hydrogeologist, groundwater engineer or water-related professionals; ii) maps that are easily understood, including a comprehensive explanation, hydrogeo-

Table 1: Classification system for hydrogeological maps (updated from Struckmeier and Margat, 1995).



Level of information / ***Possible use***	***Low - Medium*** ***(scarce and heterogeneous data from various sources; basic fieldwork; inventory and preliminary analytical approach)***	***Advanced*** ***(+ systematic in situ investigation programs, more reliable data; preliminary conceptual modelling)***	***High*** ***(+ hydrogeological systems analysis, prediction scenarios; groundwater numerical modelling)***
Reconnaissance and exploration	General hydrogeological map *(hydroclimatology, surface hydrology and ground data - hydrological and ground maps, hydrogeological inventory map, hydrogeomorphological map, aquifer map; basic hydrogeological ground modelling)*	Hydrogeological parameter maps: GIS-based on hydrogeology, hydraulic, hydrogeophysics, hydrogeochemistry and isotopic hydrology design parameters *(map sets; preliminary hydrogeological conceptual modelling)*	Regional groundwater system maps: GIS-based mapping *(map sets; hydrogeological conceptual modelling and/or groundwater numerical modelling based on diverse mathematical approaches)*
Planning and development	Map of groundwater resource potential *(land use, cover use data)*	Specialised hydrogeological maps: GIS-based mapping *(planning maps)*	Graphic representation: GIS-based mapping and other specialised software outputs *(sketch maps, cross-sections, block diagrams, scenarios, …)*
Management and protection	Map of groundwater vulnerability		
Possible use / ***Parameters of representation***	Static	***Time-dependence*** →	Dynamic
	Low	***Reliability*** →	High
	Low	***Cost per unit area*** →	High
	Large ←	***Area represented***	Small
	Small	***Scale*** →	Large

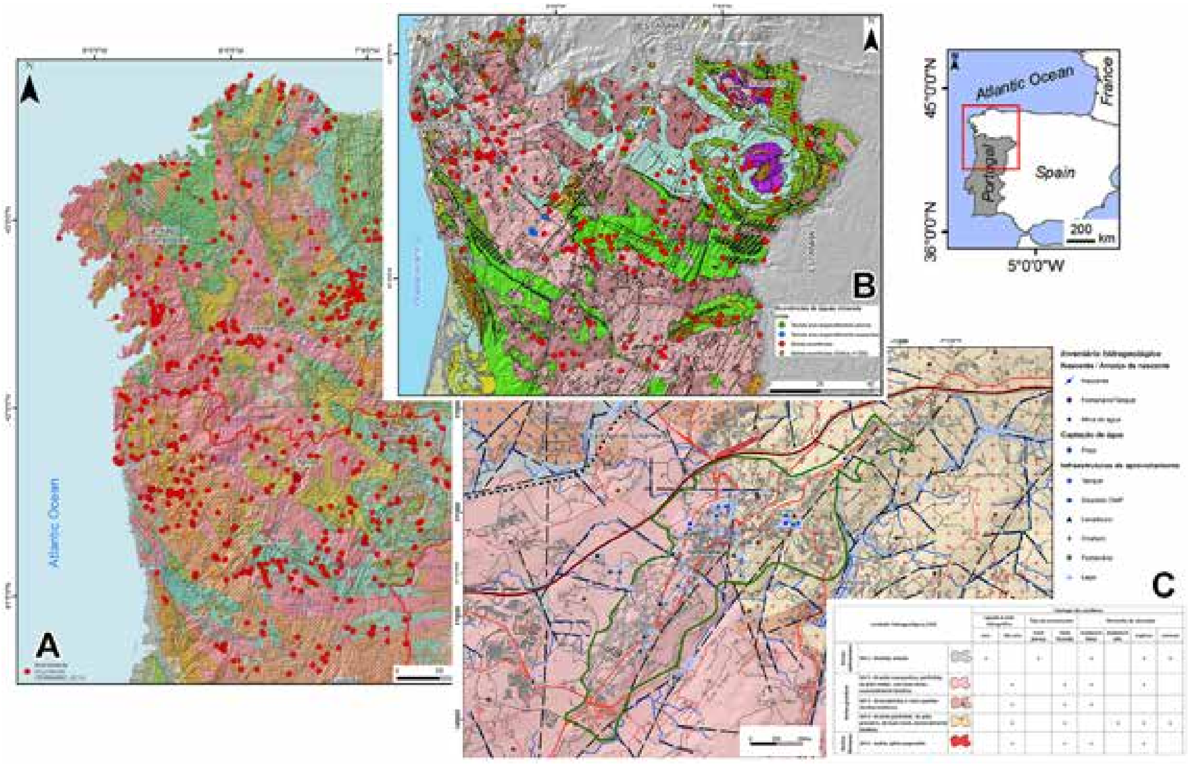


Figure 2: Examples of hydrogeological maps at several scales and for diverse purposes (archives of LABCARGA|ISEP and TARH Lda): i) large-scale mapping – A) hydromineral resources inventory for Northern/Central Portugal and Galicia (Spain); B) hydrogeological map and hydromineral occurrences for Northern Portugal; ii) small-scale mapping – C) hydrogeological inventory map of the Penafiel urban area (NW Portugal).

logical cross-sections and complementary information (for example, geology and morphotectonics, hydrogeochemistry, groundwater quality, hydrodynamics, drilling, etc.); and iii) maps on different scales, since mapping for hydrogeological *in situ* investigation purposes requires both large scale maps (detailed surveys: ranging 1:50 to 1:250; local framework: 1:1000 to 1:10 000) and small-scale maps to illustrate regional to global groundwater conditions for national, regional or continental summary maps (regional background: 1:25 000 to 1:50 000; general framework: 1:100 000 to 1:500 000; global framework: 1:1000 000 to 1:25 000 000). The maps use diverse legends and explanatory notes, but an effort to promote a uniform mapping methodology was launched over 50 years ago by UNESCO, IAH, BGR and associated institutions (see details in Struckmeier and Margat, 1995; Gilbrich and Struckmeier, 2014; also see WHYMAP – World-wide Hydrogeological Mapping and Assessment Programme (***http://www.bgr.de/app/fishy/whymap; http://www.whymap.org***). ***Table 1*** outlines a general classification system for hydrogeological mapping and ***Figure 2*** shows diverse types of hydrogeological maps in practice.

The optimal development of water resources embraces the use of the surface and groundwater resources as a single integrated system. The conceptual site model serves as the basis for modelling groundwater flow systems. Hydrogeological conceptualisation and geo-visualisation techniques have become essential tools in understanding groundwater systems at *in situ* investigations (Kresik and Mikszewski, 2013; Chaminé *et al.*, 2013, and references therein). Peeters (2015) stated critical thoughts about the applicability of the groundwater models, highlighting their subjectivity in practice. However, a conceptual site model integrates the overall knowledge of the features and dynamics of the system based on existing data interpretation. In addition, the core elements are conceptual development based on available information, data collection at the site-specific level, spatial data analysis, and data visualisation to achieve the conclusions drawn by the study (Kresik and Mikszewski, 2013). A model additionally involves the assumption of practical simplifications, which are crucial to enable its applicability despite geologic variability and uncertainty. Nevertheless, simplification should be restricted as far as possible to ensure the accuracy of the conceptualisation (Chaminé *et al.*, 2013).

Hydrogeological conceptual site models can be outlined as (details in Chaminé *et al.*, 2013; Chaminé, 2015): i) *ground models focused on hydrology*: such models integrate climatic, topographic, geologic, tectonic, geomorphological, hydrological and land use data with basic hydroclimatic, hydrochemical, hydrodynamic, hydropedological, rock and soil hydrogeotechnics and hydrogeomorphological characteristics and parameters; ii) *hydrogeological models:* ground models with predicted performance based on design hydrogeological, hydraulic, hydrogeochemical, hydrogeophysical and isotopic hydrological parameters; or iii) *numerical groundwater models:* hydrogeological models based on numerical modelling to create predicting scenarios (i.e., based on probabilistic, deterministic or stochastic approaches).

Figure 3 shows a generic outlook of the role of field mapping and GIS-based mapping techniques in the development of conceptual site models as a primary tool to synthesise the field, laboratory and analytical data in order to generate a ground model and a hydrogeological model and for numerical modelling. The key issue in building a robust hydrogeological conceptual model is the accuracy of the source field and analytical data (including the field techniques of observation, collecting and integration data) and a permanent system of back analysis to validate the data assessment and assumptions. In addition, the conceptualisation of hydrogeological systems must be dynamic and should be continuously updated to reflect the latest advances in the knowledge of the groundwater reservoir and parameters involved, including the geological processes.

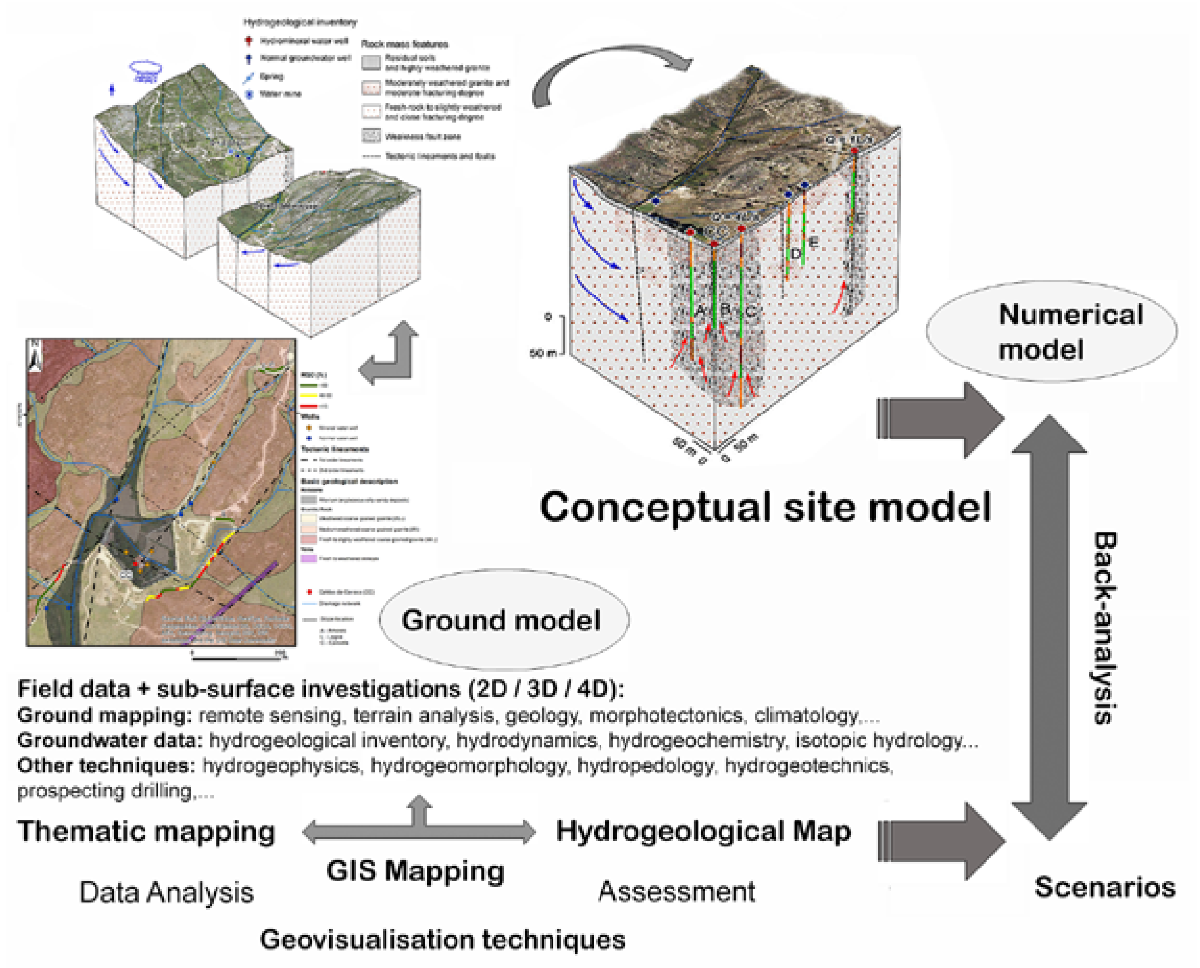


Figure 3: The role of mapping in development of conceptual site models in practice based on hydrogeological in situ investigations has focused on terrain analysis (remote sensing, geology, morphotectonics, surface hydrology, etc.), characterisation of surface outcrops (geology, hydrogeotechnics, hydropedology, etc.), hydrogeological inventory, borehole data providing information on geology and hydrogeology (namely, hydrodynamics and hydraulics), as well as often being complemented by hydroclimatic analysis and hydrogeomorphological, hydrogeophysical, hydrogeomechanical data and numerical studies.

Selected sites: hydrogeological maps on groundwater practice

This paper demonstrates the need to study complex groundwater-related systems with an integrated approach, i.e. the selected sites are grounded in fieldwork and desk studies where the mapping emerged. Thematic maps are prepared from multi-source geodata, namely satellite imagery, topographic, morphotectonic and geological mapping, as well as from hydrological and hydrogeological field surveys and laboratory data. These maps are converted to GIS format and then integrated with the purpose of elaborating groundwater resources or hydrogeological maps intended to support the conceptual site model and thus assisting prospecting and or exploitation drilling programs. In addition, the GIS-based mapping approach incorporates hydrogeological uncertainty and variability issues, for example, GIS interpolations between data points and accuracy or groundwater parameters/testing in relation of measured, estimated and projected conditions (e.g., Chaminé *et al.*, 2010; Gustafson, 2012; Kresik and Mikszewski, 2013). Three examples are presented to show different scale approaches to mapping outputs. The first example is a small-scale mapping related to a hydromineral resources inventory (1:500 000) to support the publication of a natural selected springs catalogue (TERMARED, 2011). An example of large-scale mapping is presented for a hydrogeological inventory mapping (1:25 000) integrated in a multidisciplinary geological resource evaluation of the Cela site, Castro Daire region (N Portugal). Finally, a detailed mapping (1:1 000) is shown that is related to a hydrogeomechanical assessment integrated into an underground rock engineering study at Aveleiras mine (Braga, NW Portugal).

Small-scale mapping: NW Iberia region, Northern Portugal and Galicia (Spain)

A comprehensive integrated hydromineral resources study was carried out in the scope of the TERMARED project (INTERREG IV–B SUDOE programme). Its main objective was the publishing a catalogue of selected natural springs which have a potential background for balneotherapy/balneological purposes in the SUDOE region – N Portugal; Galicia, Spain and SW France (TERMARED, 2011). In addition, regional mapping studies were realised for inventorying hydromineral resources in the northern-western part of the Iberian Peninsula, particularly in Northern Portugal and Galicia (Spain) territories, with an area covering over 50,800 km^2. The regional hydrogeological framework of those areas is very similar. To achieve the goal of identifying springs for further economic and tourism development, an extensive study was carried out, with collection, updating and organisation of all previous data.

The general assessment mapped over 590 groundwater occurrences for the two key regions of NW Iberia. That small-scale inventory was supported by a carefully selected bibliographical analysis, fieldwork and desk studies. This combined methodology allowed the cross-checking and GIS analysis of several levels of information, namely climatology, geology, geomorphology, hydrogeology, hydrogeochemistry, hydrodynamic and hydrohistorical issues about the hydromineral record. Data from field hydrogeological inventories were integrated into a database that coupled GIS thematic mapping and hydromineral water occurrences. The geodata were loaded into a spatial database, which allowed the design of a datasheet for each sampling occurrence (***Figure 4***).

The 23 natural springs selected for NW Iberia were based on several criteria integrating, for example, water quality and hydrodynamic characteristics of the resource, land use and accessibility, proximity of the location of natural parks or protected areas, thermal architecture heritage, awareness of the owners and or entities related to sustainable management. In addition, the catalogue included various physical and chemical types of waters which are representative of the genuine sulphurous and sparkling waters, but also hyposaline waters, as these are included in the thermal tradition of that territory (details in TERMARED, 2011).

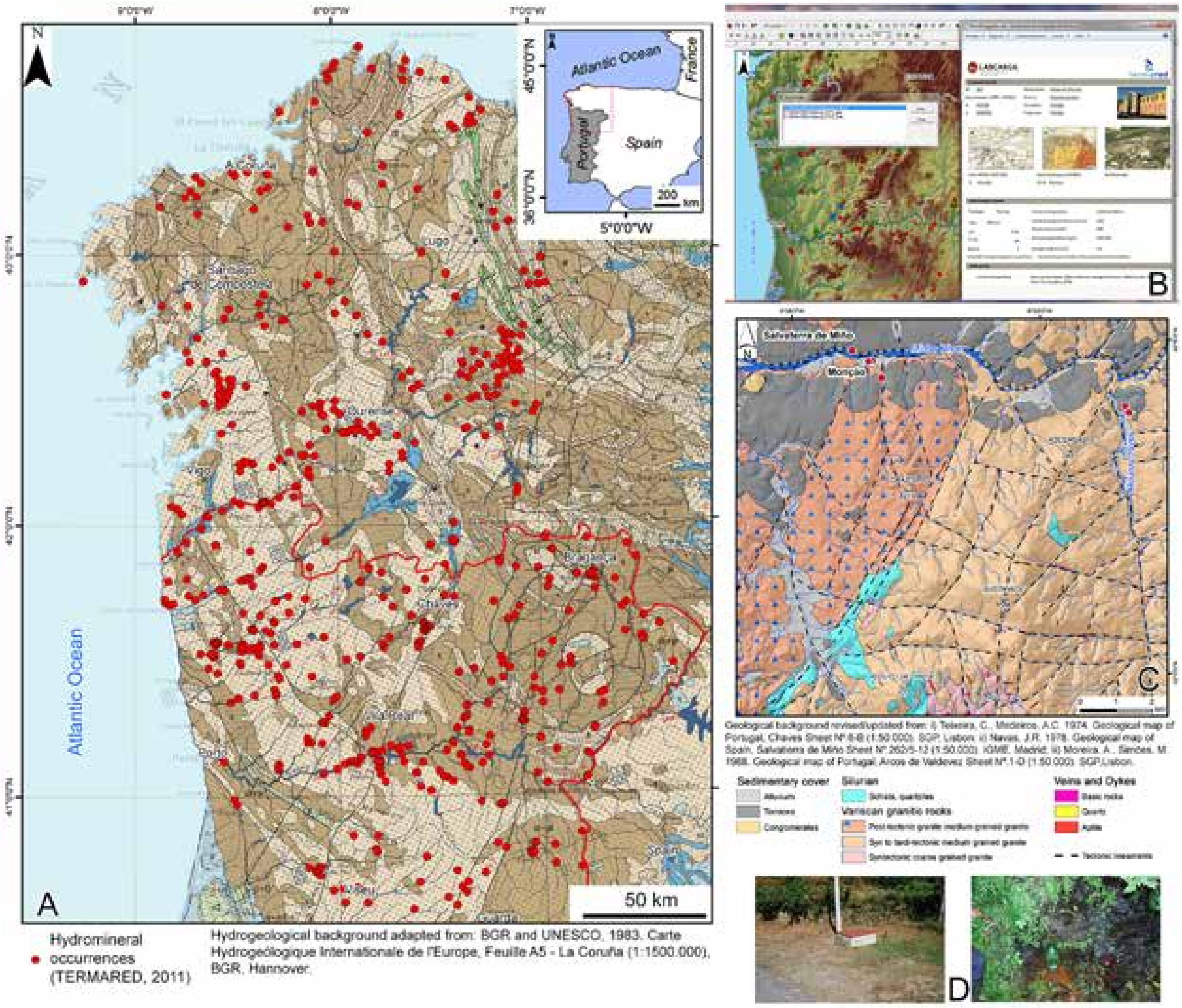
Large-scale mapping: Cela area (Castro Daire, N Portugal)

The selected study site, the Cela area (Castro Daire), is located in a crystalline fractured bedrock of Variscan granitic rocks (***Figure 5***). The rock mass comprises porphyritic two-mica granite, medium grained, and light grey colour (Pendilhe granite). A fine-grained, dominantly biotite granite outcropping also lies in the northeast of the region, the Lamas granite. Trends of three dominant tectonic lineament sets (NW-SE, NE-SW to NNE-SSW and WNW-ESE to W-E) were mapped. The granitic basement is also crosscut by albite-dolerite dykes and quartz veins. Locally, the geomorphology is characterised by flattened surface areas (600-500 m) and some entrenched valleys (300-350 m).

The hydrogeological setting and inventory are presented in ***Figure 5***. The drilled and hand-dug wells are mostly situated in the higher flattened surface. The dug wells are related to agricultural sites. These structures have shallow depths (normally 6–10 m). The springs inventoried are essentially located in lower areas and have very small yields (0.01–0.05 L/s). The local groundwaters are characterised by median low temperature (15 ºC), majority acidic pH (5.4), and low electrical conductivity (190 µS.cm^{-1}). The waters have very low mineralisation and commonly are calcium chloride facies. The hyposaline chemical composition of the groundwater indicates a surficial to very shallow circulation.

Detailed mapping: Aveleiras mine, S. Martinho de Tibães site (Braga, NW Portugal)

The study area is located in the S. Martinho de Tibães Monastery and its surroundings, near the Braga urban area. This monastery was the mother house of



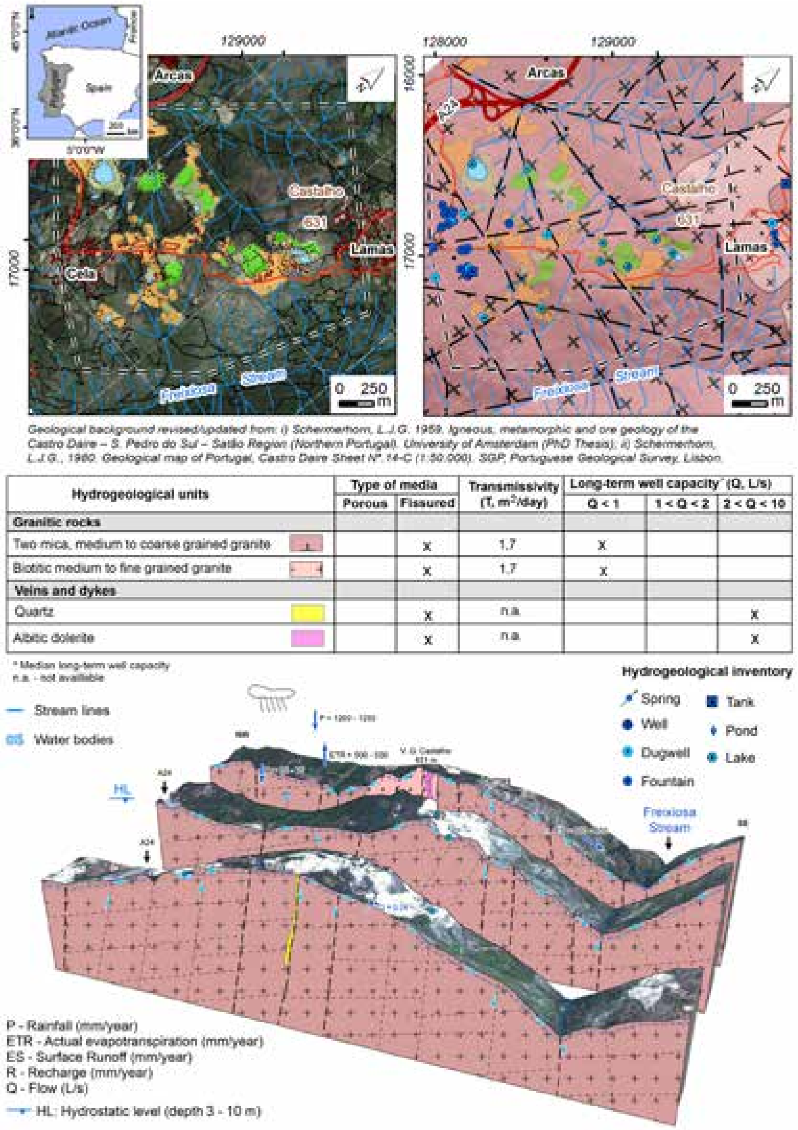
Hydrogeological background adapted from: BGR and UNESCO, 1983. Carte Hydrogéologique Internationale de l'Europe, Feuille A5 - La Coruña (1:1500.000), BGR, Hannover.

Geological background revised/updated from: i) Teixeira, C., Medeiros, A.C. 1974. Geological map of Portugal, Chaves Sheet Nº 6-B (1:50 000). SGP, Lisbon; ii) Navas, J.R. 1978. Geological map of Spain, Salvaterra de Miño Sheet Nº 262/5-12 (1:50 000). IGME, Madrid; iii) Moreira, A., Simões, M. 1988. Geological map of Portugal, Arcos de Valdevez Sheet Nº 1-D (1:50 000). SGP,Lisbon.

Figure 4: Northern Portugal and Galicia (Spain) framework: hydromineral resources inventory from the TERMARED project. A) Hydromineral resources inventory map for NW Iberia, over 590 hydromineral occurrences mapped; B) application tool to create hyperlinks between features (line, point or polygon) and other files; hyperlink addressed to a file (image or text); and hydrogeological inventory datasheet (field and desk data); C), D) examples of mapping from Monção (NW Portugal) – Salvatierra de Miño (Galicia) and Corga do Vergueiral (ACP1 well) and Angueiro (NW Portugal) hydromineral systems (TERMARED, 2011).

the Order of Saint Benedict for Portugal and was founded in the late 11th century. Some abandoned water mines were part of an impressive water supply system of the monastery between the 17th and 19th centuries. In this area several natural springs were reported, such as S. Bento spring (TERMARED, 2011). Some of these water mines were used for ore prospecting. The presence of wolfram-bearing quartz shear veins in the study area led, in the 1930s, to the exploitation of these hydrothermal deposits for over 23 years. Such is the case of the Aveleiras mine, also known as the Tibães mine. The geotectonic framework comprises a middle Palaeozoic metasedimentary highly fractured and folded basement rock mass. The subsurface rocks are composed by micaceous clayish phyllites, metagreywackes interbedded with metasiltites, metapelites and quartz hornfels, and granitic rocks. The underground rock mass is crosscut by a well-exposed network of mineralised quartz masses and veins.

The underground constraints of the Aveleiras groundwater systems were assessed by integrating several techniques taking benefit of GIS-based mapping. Underground geological and hydrogeomechanical mapping (scale 1:1 000) permitted the assessment of the Aveleiras rock mass (galleries network around 376 m long and a maximum depth of -30 m below ground level). An extensive hydrogeological inventory was made at surface and underground. The hydrogeological level is characterised by median low temperature (13.9 ºC), pH acid (6), and low electrical conductivity (83 µS.cm^{-1}). The waters are sodium chloride to sodium-chloride sulphated facies. The dominant metasedimentary rocks have an aquitard performance, with productivities usually lower than 1.5 L/s. Quartz veins increase locally the hydraulic conductivity of the formations. The hydrogeomechanical zoning map was performed using GIS-based techniques integrating the previous information, data collected and interpreted from hydrogeotechnical and hydrogeological surveys. ***Figure 6*** shows the detailed mapping of the hydrogeomechanical indexes (Hydro-Potential, HP-value and Joint Water Factor, J_w) integrated *in situ* rock engineering investigations of mining gallery 2 (188 m) from the Aveleiras/Tibães site.



Geological background revised/updated from: i) Schermerhorn, L.J.G. 1959. Igneous, metamorphic and ore geology of the Castro Daire – S. Pedro do Sul – Satão Region (Northern Portugal). University of Amsterdam (PhD Thesis); ii) Schermerhorn, L.J.G., 1980. Geological map of Portugal, Castro Daire Sheet Nº 14-C (1:50.000). SGP, Portuguese Geological Survey, Lisbon.

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
Granitic rocks							
Two mica, medium to coarse grained granite	▨		x	1,7	x		
Biotitic medium to fine grained granite	▨		x	1,7	x		
Veins and dykes							
Quartz	🟨		x	n.a.			x
Albitic dolerite	🟪		x	n.a.			x

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

Figure 5: Cela area (Castro Daire, N Portugal) framework: hydrogeological mapping and conceptual model site.

Concluding remarks

In hydrogeological practice accurate mapping is a fundamental tool for a comprehensive understanding of site conditions. Mapping has wide-ranging uses, such as military operations, geosciences, water resources, engineering, environment, and planning. This study highlights the importance of coupling field mapping and hydrogeological site modelling to better understand the evolution of water resources or groundwater systems. This approach encompasses combined field and desk studies to support various types of modelling. Hydrogeological site conceptualisation is improved by this integrated approach and should contribute to the environmental sustainability of water resources. However, the key issue in groundwater practice is the reliable source of field and laboratory data, in terms of quality and quantity. Further interpretation, analysis and conceptualisation could be compromised if the data are not consistent and representative.

In recent years, a new focus has emerged in the collection, analysis, integration and visualisation of field data, made possible by high-resolution photogrammetry, unmanned aerial vehicles, global position systems, visualising geographic information and geospatial data. For the approach presented in this paper to meet its aims, we must stress the need to acquire better groundwater field data and to better define hydrogeological design parameters. These play a key role in the economics of the resource and in their sustainable management and environmental protection. In combination, these approaches show the importance of mapping, GIS and visualisation techniques involuting to cartographic reasoning. The actions concerning geovisualisation (e.g., open formats, interactive online tools, multisensory interfaces, etc.) appear as an enabler to cross-disciplinary communication and cooperation with diverse scientific and technical fields (Dykes *et al.*, 2005). New groundwater mapping possibilities for innovative and dynamic representations are emerging in practice (e.g., Cascelli *et al.*, 2012; Chaminé *et al.*,

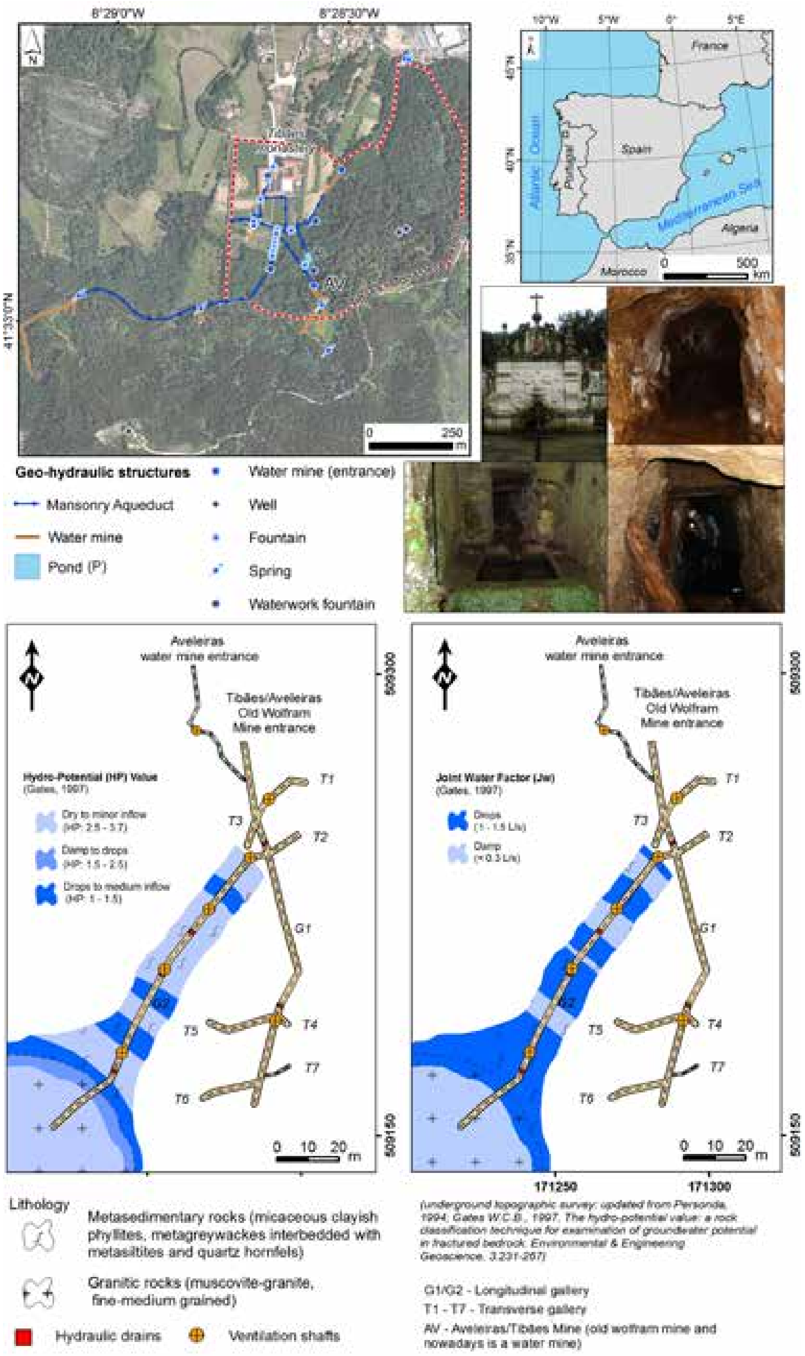


Figure 6: Aveleiras mine, S. Martinho de Tibães (Braga, NW Portugal) framework: detailed hydrogeomechanical zoning map for mining hydrogeology and hydrogeotechnics in situ investigations.

2010, 2013; Kresik and Mikszewski, 2013; Teixeira *et al.*, 2013).

A hydrogeology map is an invaluable tool for communication with practitioners, researchers, water-related professionals and society. Indeed, cartographic reasoning and groundwater mapping are amazing tools for supporting a full-scale integrated analysis of reciprocal global actions and local concerns contributing to a balanced sustainable water resources evaluation, protection, management and governance. Finally, if images are worth a thousand words, how about maps? The hydrogeologist Dr. Willi Struckmeier adapted that saying in an unusual way: *"a picture can tell more than thousand words; a map more than thousand pictures"*.

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