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Towards 2020: groundwater research in Europe

Contents

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Foreword

EurGeol. Vítor Correia, EFG President

“Water, like religion and ideology, has the power to move millions of people. Since the very birth of human civilization, people have moved to settle close to it. People move when there is too little of it. People move when there is too much of it. People write, sing and dance about it. People fight over it. And all people, everywhere and every day, need it.”
Mikhail Gorbachev

This edition of *European Geologist* is dedicated to groundwater. Groundwater lies in the hidden part of the water cycle, which may explain why it is so difficult to attract the attention of the general public and decision makers to this critical resource. This effect is visible in the work programs of Horizon 2020 for 2016-2017, adopted by the European Commission in October 2015. Horizon 2020 is the most important and biggest research funding instrument in Europe (and probably in the world at this time) and, despite evidence on the need for more research and better coordination to cope with water scarcity in many regions of Europe, water is no longer present as a stand-alone topic, as was the case in the period 2013-2015.

In addition, Europe is struggling to manage its worst refugee emergency since World War II, and the social and political implications of this crisis cannot be predicted (the crisis itself was not foreseen one year ago). If the trend towards nationalism continues to grow, it can affect transnational cooperation across Europe, simply because many people do not realise that political boundaries have nothing to do with water basins or geological aquifers.

In a world that faces climate change and a growing population (there were 7 billion of us in October 2011 and we will reach 8 billion by the spring of 2024, according to the most recent United Nations estimate), access to clean water will become the main key challenge to mankind in this century.

The role of geoscientists in this context is well illustrated by several articles included in this issue. Investigating and mapping the subsurface, evaluating groundwater geochemistry and modelling water flow are fundamental contributions to manage water quality and supply.

But, with the increasing competition among various water users, we have additional responsibilities: we must provide objective information; we must inform policy makers that preventing groundwater depletion and changes in groundwater quality demands a holistic approach, combining local and regional scales; we must explain that sustainable groundwater development also means protecting the soil from contaminants (including pesticides) and avoiding adverse effects such as land subsidence or sea water intrusion.

To be effective, sustainable management practices for groundwater must be incorporated into regulations. And, because the Water Framework Directive is now being revised, this is the right time to draw the attention of the general public and regulators to the intrinsic value of groundwater, explaining that preserving clean water for future generations is an ethical obligation.

This demands co-operation among all stakeholders. I am sure geoscientists are ready to play their role. And I trust all stakeholders will come along. As Gorbachev said about water, ‘all people, everywhere and every day, need it’.

PS: Isabel Fernandez, our efficient Executive Director, just pointed out to me that this is the 40th issue of European Geologist (the first number was printed in June 1995), which means European Geologist is celebrating 20 years. To top this, in November we will have the 70th Council Meeting of EFG. In this context, I invite you to raise your glass (you choose the drink) to EFG and all the people who have made it what it is today. Cheers!

The KINDRA project: a tool for sharing Europe's groundwater research and knowledge

Marco Petitta, Balazs Bodo, Mariachiara Caschetto, Nicolò Colombani, Vítor Correia, Adrienn Csekő, Maria Di Cairano, Isabel Fernández, Clint Garcia Alibrandi, Éva Hartai, Klaus Hinsby, Tamás Madarász, Viktória Mikita, Mercedes García Padilla, Péter Szűcs and Peter van der Keur*

Hydrogeology-related research activities cover a wide spectrum of research areas at EU and national levels. The KINDRA project (Knowledge Inventory for hydrogeology research, Grant Agreement No. 642047) seeks to create a critical mass for scientific knowledge exchange of hydrogeological research, to ensure wide applicability of research results - including support for innovation and development - and to reduce unnecessary duplication of efforts. A new terminology and classification methodology for groundwater R&D results and activities (Hydrogeological Research Classification System: HRC-SYS) has been developed based on a hierarchical structure using keywords derived from EU directives and scientific journals. This classification allows the population of a European Inventory of Groundwater Research (EIGR) of research results, activities, projects, and programmes to be used to identify critical research challenges and gaps, for better implementation of the Water Framework Directive.

Les activités de recherche en Hydrogéologie couvrent un large éventail de domaines tant au niveau européen que national. Le Projet KINDRA (Knowledge Inventory for hydrogeology research, Grant Agreement No. 642047) vise à créer une "masse critique" pour déclencher un processus d'échange des connaissances scientifiques au niveau de la recherche en Hydrogéologie, pour garantir l'application la plus large des résultats de la recherche – incluant un soutien à l'innovation et au développement, en limitant les efforts consacrés aux activités redondantes. Une nouvelle méthodologie pour les eaux souterraines, concernant la terminologie et la classification des résultats et activités de R&D (Système de Classification en recherche hydrogéologique : HRC – SYS) s'est développée, basée sur une structure hiérarchique utilisant les mots clefs dérivés des directives EU et des revues scientifiques. Cette classification permet à la population d'un Inventaire européen de recherche en eau souterraine (EIGR), d'utiliser les résultats, les activités, projets et programmes de recherche pour identifier les défis et les manques pour une mise en œuvre plus complète dans le cadre de la Directive sur l'Eau.

Las actividades de investigación relacionadas con hidrogeología cubren un amplio espectro de áreas de investigación tanto al nivel europeo como nacional. El proyecto KINDRA (Knowledge Inventory for hydrogeology research, Grant Agreement No. 642047) tiene la intención de crear una masa crítica que permita el intercambio de conocimientos científicos en el área de la investigación hidrogeológica, asegurar la aplicacion de los resultados de investigación por tanto apoyando a la innovación y el desarrollo, y reducir la duplicación innecesaria de esfuerzos. Una nueva terminología y metodología de clasificación para los resultados y actividades dentro de la I+D de las aguas subterráneas (Hydrogeological Research Classification System: HRC-SYS) ha sido desarrollada sobre la base de una estructura jerárquica utilizando palabras claves derivadas de las directivas de la UE y de revistas científicas. Esta clasificación permite rellenar un Inventario Europeo de Investigación sobre las Aguas Subterráneas (EIGR) con los resultados de investigación, actividades, proyectos y programas que se utilizarán para identificar los desafíos y lagunas en la investigación, que permitirá una mejor aplicación de la Directiva Marco del Agua.

Water is a key topic in modern society: not only is it a pivotal human, biological and environmental requirement, it also represents the engine for several research topics which are interconnected, covering the water-food-energy-climate nexus, and it has even a fundamental impact on urban systems. Groundwater is the hidden component of the water cycle, difficult to assess and evaluate, and therefore its importance is difficult to communicate. It plays a fundamental role by sustaining the health of our ecosystems, ourselves and our industrial and agricultural production. Practical and scientific knowledge related to hydrogeology research and innovation is scattered amongst various actors in Europe. With respect to the water cycle, a specific focus on hydrogeology has not been looked into until now, in spite of its utmost importance as a renewable, high-quality, naturally protected (but still vulnerable) resource. In this context, the KINDRA project (EC framework program H2020, Grant Agreement No. 642047) has the aim of creating an inventory of this knowledge base and then using the inventory to identify critical research challenges, in line with the implementation of the Water Framework Directive (WFD) and new innovation areas, within integrated water resources management based on the latest research. This approach will promote the correct management and policy development of groundwater at the EU scale, as recommended also by the Blueprint Document (EC, 2012).

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The main goal of the KINDRA project (***www.kindraproject.eu***) is to create a unique knowledge inventory, i.e. a database of groundwater research results, activities, projects and programmes deemed essential for the identification of the state-of-the-art, future perspectives and research gaps in the groundwater field. The framework requires (i) the identification of keywords and categories for an effective and useful classification system, and (ii) the definition of a common terminology allowing the recognition of the pertinence of groundwater related topics in the field of general water research. For these reasons, a new terminology and classification methodology on groundwater R&D results and activities (Hydrogeological Research Classification System: HRC-SYS) and a European Inventory of Groundwater Research (EIGR) have been developed as the main outcomes of the KINDRA project. These have a common methodological base for classifying the results according to a harmonised terminology and give the possibility of access to the classification system by different external users. This paper presents a description of the adopted terminology and classification methodology (HRC-SYS), with related hierarchical structure on groundwater R&D results and activities, based on keywords derived from EU directives and the most relevant scientific journals dedicated to groundwater research. This classification constitutes the basis for the implementation of the European Inventory of Groundwater Research, which will contain information from each European country covered by the project partners (in particular EFG Third Parties at the national scale), including research and innovation results and knowledge improvements derived from projects directly or indirectly supported by the EC.

Keyword selection for the Hydrogeological Research Classification System (HRC-SYS)

The adoption of a classification system is necessary and clearly stated as a preliminary step in the KINDRA project, in order to gain a comprehensive understanding of the groundwater theme, by creating an overview of the scientific knowledge covering European countries. Such comprehensive coverage will result in an accurate assessment of the state of the art in hydrogeology research in various geographical and geo-environmental settings, allowing for a direct comparison and exploitation of existing synergies. The first step in identifying research gaps and formulating recommendations for the future is to build a harmonised approach for classifying and reporting European groundwater research efforts.

Keywords are necessary for performing searches using search engines and in creating and populating the inventory: they are the means for defining queries in the EIGR (European Inventory of Groundwater Research). The information and the inventory need to be searchable and comparable at any given time to past and ongoing research activities, to assess the suitability and relevance of policies and research agendas, the groundwater quantitative and chemical status and the implementation of the WFD and GWD and other key directives (the nitrate directive, REF, etc.).

The use of keywords identified in the Water Framework Directive (WFD) and Groundwater Directive (GWD), and the recent Blueprint to Protect Europe's Water Resources (BWR, European Commission, 2012) for the classification of groundwater research (covering the periods 2000-2006 and 2006-2015 for citation analyses) is a factor ensuring that this approach provides information that can be used for the assessment of the directives' importance as research drivers.

This approach also helps evaluate the relevance of groundwater research in relation to the objectives of the WFD/GWD and the societal challenges defined in the EU research programme Horizon 2020, group them by categories and evaluate science-policy feedback within water research, policy and management. Additionally, the integrated perspective of the WFD and GWD provides a good possibility for demonstrating the important links in the water-food-energy nexus among surface and subsurface waters and dependent or associated terrestrial and aquatic ecosystems. Hence, it emphasises the importance of groundwater in the hydrological cycle, not only for drinking water and other legitimate uses but also for sustaining terrestrial and aquatic ecosystems in a changing climate where freshwater availability is under pressure. In this way, about 100 relevant keywords have been identified and extracted from the Water Framework and Groundwater Directives and the Blueprint to protect Europe's Water Resources for the development of the HRC-SYS.

This approach cannot stand alone, however, as it does not cover all relevant groundwater research areas, especially the most recently developed topics. Therefore, it has to be supplemented by the identification of important keywords and topics from the most important scientific journals publishing groundwater research, which can be identified by use of sources such as the Journal Citation Reports. In scientific journals keywords are essential; this is the second most frequently searched field after the title. The main keywords are identified by analysing the data from searches of the most important international peer-reviewed journals dealing with groundwater resources. Clearly, there are many journals dealing with hydrogeology. The most convenient approach is to identify which are the groundwater journals with the highest impact or are the most influential. Based on an international ranking comparison, a list was made of the highest impact factor ("reputation") journals.

After having selected the most relevant scientific journals in the field of hydrogeology, detailed searches were carried out to identify the most frequently used and most relevant keywords in these scientific journals focusing on the volumes throughout the period 2006-2015. For the identification of keywords the list of the most commonly used keywords adopted by the *Hydrogeology Journal* (published by Springer) was considered. Comparing this proposed list with the search results obtained, it turned out that the 80 most relevant keywords from the scientific journals with high impact factor were also present in the keyword list of the *Hydrogeology Journal*. This is a very convincing match and verification of the applied approach. Therefore a keyword list was selected by KINDRA as a reference for relevant keywords from scientific journals, adding new keywords. The two lists, one derived from the EU policy documents, and the second derived from the scientific journals – including remarks from the Joint Panel of Experts of the project – have been merged into a final list that includes about 240 selected keywords, which is expected to be updated as new keywords arise in the research fields dealing with groundwater, for instance as a result of continuous technological development.

The hierarchy of the Hydrogeological Research Classification System (HRC-SYS)

For classifying groundwater research and knowledge, the KINDRA project group has defined the categorisation of all groundwater research according to three main categories: 1) Horizon 2020 societal challenges, 2) Operational Actions and 3) Research Topics (***Figure 1***). Each of these three main categories includes five overarching groups allowing for an easy overview of the main research areas, as described below.

Horizon 2020 defines seven main categories of Societal Challenges (SCs) for which

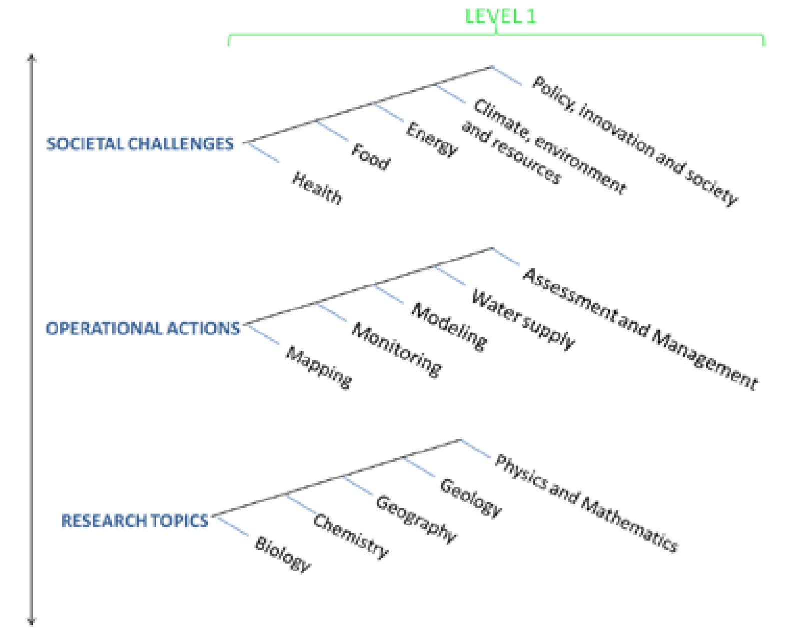

Figure 1: Tree hierarchy diagram.

research programmes for 2014-2020 will be defined and developed according to identified research needs. Groundwater research may be conducted under all of these SCs except for SC4 (Smart, green and integrated transport), which is not relevant. Furthermore, we consider SC6 (Europe in a changing world - inclusive, innovative and reflective societies) and SC7 (Secure societies - protecting freedom and security of Europe and its citizens) similar in scope, as both consider issues related to the development of secure and prosperous societies and EU policies to ensure such a development. Therefore SCs 6 and 7 are grouped into one SC with the title "Policy, Innovation and Society". The resulting final five societal challenges selected as overarching themes for categorisation of groundwater research are therefore: 1. Health; 2. Food; 3. Energy; 4. Climate, environment and resources; 5. Policy, innovation and society.

The five main Operational Actions adopted as overarching actions or activities – intended to include all identified activities in the identified keywords – are based partly on literature searches in the Web of Science, Scopus (SciVal) and Google Scholar, and their results on the number of papers published in each category, and partly based on expert judgment, used to determine how the different Operational Actions are related. The five overarching activities covering all operational actions, taking into account the results of an end-user survey performed during the project, have been identified as: 1. Mapping, 2. Monitoring, 3. Modelling, 4. Water Supply, 5. Assessment & Management.

The research topics constitute by far the largest group of keywords, and it was impossible to identify five of the selected research topics as overarching research topics that include all of the more than 150 identified research topics. Based on the understanding that hydrogeology or groundwater research is a natural science discipline and generally relates to one or more of the other main natural science disciplines, the following five overarching groundwater research topics have been selected: 1. Biology, 2. Chemistry, 3. Geography, 4. Geology, 5. Physics & Mathematics.

The identification of the three main categories (Societal Challenges, Operational Actions and Research Topics) and the subdivision of each of these into five overarching groups give us the tree hierarchy classification shown in ***Figure 1***. The adopted merged list of keywords consisting of about 240 terms has also been organised in a tree hierarchy, where the overarching groups represent Level 1, followed by Levels 2 and 3. Subsequently, items from the complete merged list of keywords have been distributed under pertinent categories.

The classification system previews the interaction among the three main categories through a 3D approach, where along each axis the five overarching groups are indicated. Societal Challenges (SC) as put forward by the EC policy priorities of the Europe 2020 strategy are represented by the vertical (z) axis in ***Figure 2***, while Operational Actions (OA), which are instrumental

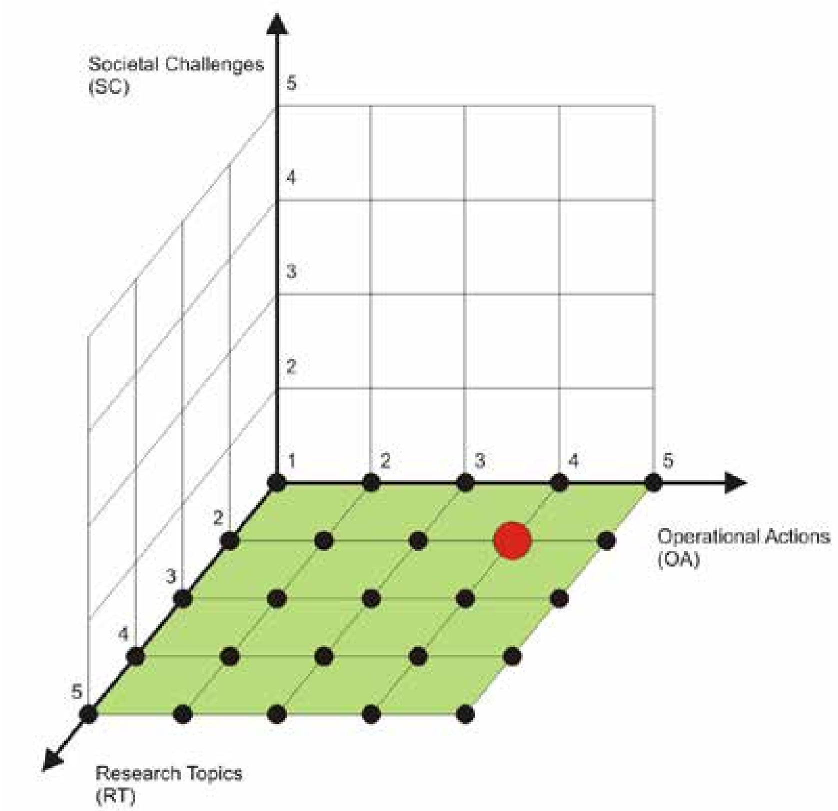

Figure 2: Two- and three-dimensional representation of the HRC- SYS. The 2D level corresponding to SC1 Health is shown in green. The red dot shows the intersection of OA4 (Water supply) with RT2 (Chemistry).

actions required for implementing groundwater related activities (e.g. implementation of the Water Framework directive and the development of river basin management plans) correspond to one of the horizontal axes (x). Finally, Research Topics (RT) – identified from (a) the EC policy document, Water Framework Directive and its daughter the Groundwater Directive, and (b) the scientific literature – are represented by the other horizontal axis (y).

This also results in a 2D representation for each of the Societal Challenges, where Operational Actions and Research Topics intersect in a 5x5 matrix. The 2D structure of each one of the five Societal Challenges allows for a 2D analysis and report of the relationships between the three main categories. Taking for instance ***Figure 2***, let us consider one of the five selected 'Societal Challenges", say, Health (SC1); it is then possible to identify all possible intersections for 'Operational Actions' and 'Research Topics' within this layer. Each sub-category on Research Topics and Operational Actions for the same Societal Challenge SC1 Health can be represented and analysed at a more detailed level. At this point it becomes easier, as well as friendlier to the end user, to use two-dimensional representations, i.e. tables, to study intersections on different levels (1, 2 & 3). An example of this detailed 2D representation is shown in ***Figure 3***.

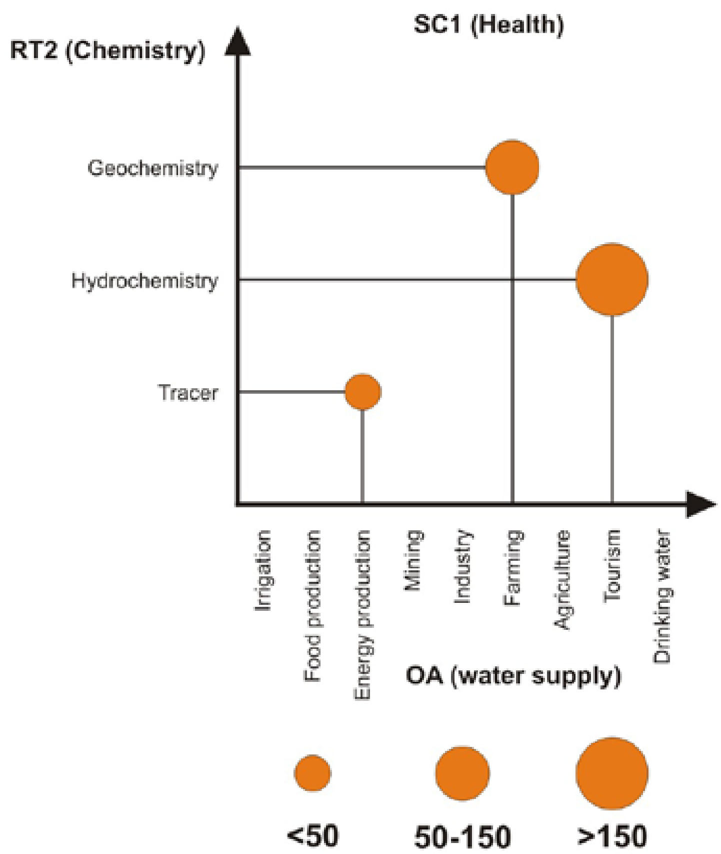

Figure 3: Two-dimensional representation of the HRC- SYS for SC1-Health: example related to the intersection between Research Topic 2 (Chemistry) with Operational Actions 4 (Water Supply) (see Figure 2). Circle size represents number of publications for each of the third-level intersections.

4. Conclusions

In order to develop the common terminology on which to base the EIGR through the HRC-SYS, a merged list of keywords characterising research on groundwater has been selected. Through this list, the KINDRA project group defined the categorisation of all groundwater research according to three main categories: 1) Societal Challenges, 2) Operational Actions and 3) Research Topics. Each of these three main categories includes five overarching groups, allowing for an easy overview of the main research areas. The classification system previews the interaction among the three main categories through a 3D approach, where along each axis the five overarching groups are indicated. This also results in a 2D representation for each of the Societal Challenges, where Operational Actions and Research Topics intersect in a 5x5 matrix. The 2D structure of each of the 5 Societal Challenges allows for a 2D analysis and report of the relationships between the three main categories. In detail, for each vertical layer (Societal Challenges), a first-order table is built intersecting the five Operational Actions with the five Research Topics. Each of these intersections, also at lower levels (2, 3 and 4), facilitates summarising the state of the art of the corresponding groundwater research and knowledge. This HRC-SYS classification system will be implemented and tested in the following steps of the project, when developing the EIGR tool.

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From arsenic in groundwater in SE Asia to implications of climate change in Danish catchments - A brief review of current and past groundwater research in Denmark

Lisbeth Flindt Jørgensen, Klaus Hinsby, Jens Christian Refsgaard, Flemming Larsen, Kurt Klitten, Lærke Thorling, Verner H Søndergaard, Walter Brüsch, Dieke Postma and Peter van der Keur*

Denmark has a long history of groundwater research strongly related to the increasing importance of the groundwater resources. As societal awareness of issues of groundwater quantity and quality arose, especially during the second half of the twentieth century, a number of serious knowledge gaps were recognised in integrated (ground) water resources management, leading to a large number of research projects. The new knowledge and tools arising from this research has fuelled increasing exports of groundwater related technologies internationally. The purpose of this paper is to highlight and give a brief summary of key ongoing groundwater research studies nationally and abroad.

Depuis très longtemps, le Danemark associe usage de l'eau et recherche de l'eau souterraine. Comme la prise en compte sociale des questions touchant la quantité et la qualité de l'eau souterraine s'est développée, en particulier pendant la seconde moitié du vingtième siècle, un nombre de défauts majeurs au niveau des connaissances a été reconnu dans le cadre de la gestion intégrée des ressources en eau, conduisant à un grand nombre de projets de recherche. Les nouvelles connaissances et outils dérivés de cette recherche ont alimenté l'exportation croissante de technologies liées aux eaux souterraines sur le plan international. Le but de cet article est de mettre en évidence et de résumer brièvement les études actuelles de recherche sur les eaux souterraines, au niveau national comme international.

Dinamarca tiene gran experiencia en el uso de las aguas subterráneas asociado fundamentalmente con la investigación hidrogeologica. Debido al aumento de la conciencia social sobre los problemas de cantidad y calidad del agua subterránea, sobre todo durante la segunda mitad del siglo XX, se indentificaron importantes lagunas de conocimiento en la gestión integrada de los recursos hídricos, dando lugar a un gran número de proyectos de investigación. Los nuevos conocimientos y herramientas que surgen de esta investigación han impulsado el aumento de las exportaciones de tecnologías relacionadas con las aguas subterráneas a nivel internacional. El propósito de este artículo es de recalcar y dar un breve resumen de los principales estudios de investigación sobre las aguas subterráneas en curso tanto al nivel nacional como internacional.

Since the adoption of what is probably the oldest national water supply act in the world in 1926, Danish water supply has been increasingly based on groundwater and today virtually all drinking water supply is based on groundwater resources. Groundwater suitable for drinking water production can be found almost all over the country at depths from a few meters down to a few hundred meters below surface, and the abstracted groundwater ranges in age from a few years, with anthropogenic impacts, to more than 10,000 years old, without human impact. Denmark has a decentralised water supply structure with many (>2,500) small and a few larger water supply utilities equally distributed across the country. This has called for and ensured common efforts and a long tradition of research on groundwater management, mapping and protection.

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Background

Denmark (43,000 km^2, 5.5 million inhabitants) is geologically dominated by soft sediments such as clayey or sandy tills, and meltwater deposits originating from Quaternary glaciations, the latest ending only around 10,000 years ago. The topography is modest, ranging from a few meters below to around 170 meters above sea level. The climate is temperate with moderate temperatures, monthly averages from 1 °C to 18 °C, and abundant precipitation during most of the year, 37-91 mm/month (2001-2010, DMI 2015). Thus, groundwater aquifers and surface waters are usually replenished sufficiently although abstraction takes places from around 20,000 irrigation wells and 10,000 water supply wells. However, this has not always been the case; with increasing industrialisation during the 1960s and 1970s, which also brought available and affordable technology for the Danish farmers to establish irrigation wells, water consumption rose to almost 1.4 billion m^3 a year, about twice as much as today (***Figure 1***). The use in the 1970s was well beyond what in a recent study was estimated as a sustainable abstraction of 1 billion m^3 a year, taking ecosystem protection (e.g. environmental flows) into account (Henriksen *et al.*, 2008). However, rising energy prices, water saving campaigns, and requirements on cleaning of waste water during the 1980s and 1990s encouraged (or forced, though legislation and gradually increasing levies) industry, agriculture and private consumers to reduce water use. This has led to a significant decrease in the water use since the 1980s, as shown in ***Figure 1***, although the population has grown from 4.5 million in the mid-1970s to 5.5 million today.

This does, however, not imply that the groundwater abstraction in Denmark always is sustainable, as heavy abstraction does not necessarily take place where groundwater is abundantly present. This may, especially in dry seasons, result in unacceptable local effects on streams, lakes and wetlands that are not in line with the

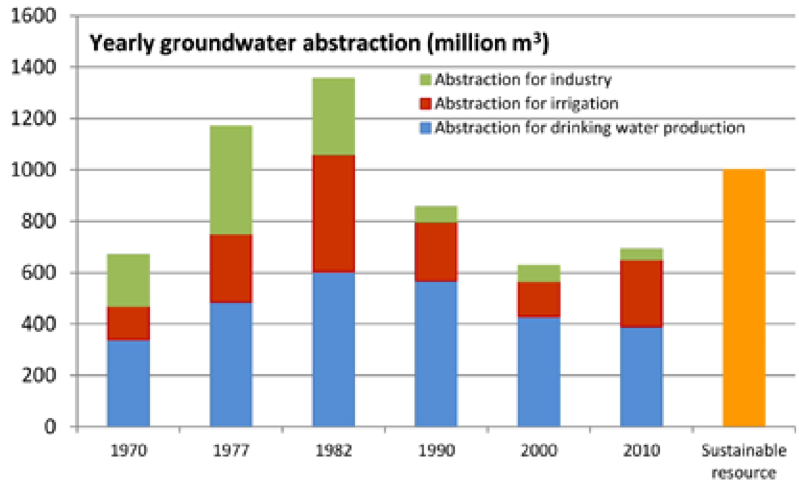

Figure 1: Water use by sectors from 1970 to 2010 (Jørgensen et al.*, 2015) compared to an estimate of the sustainable groundwater resource in Denmark (Henriksen* et al.*, 2008). Data from 1970, 1977 and 1984 are estimates made by the Environmental Agency as there was no mandatory reporting of abstraction before 1989. Data from 1990, 2000 and 2010 are averages of 5 years around each year.*

good status objectives of the European Water Framework Directive. In addition, quality aspects play an important role, as Denmark has a long tradition of performing only simple treatment (aeration followed by filtering through sand/gravel to remove iron, manganese, etc.) of groundwater before distributing it to consumers as clean drinking water. As good quality in line with national and international quality standards are of utmost importance for the water supply utilities, and for dependent terrestrial and associated aquatic ecosystems, the protection of the Danish groundwater resources are of interest for all parties involved. The amount, location, and protection of the quantitative and chemical status of the Danish groundwater is crucial for the Danish society, and this fact has for several decades been the catalyst for initiating Danish strategic groundwater research in collaboration among research institutes, national and regional authorities, and private companies.

Historical development

Probably the first to investigate Danish groundwater was Johan Georg Forchhammer (1794-1865), a German-Danish geologist. He was a director at Copenhagen Polytechnic Institute, today known as the Technical University of Denmark, and later professor at the Mineralogical Museum in Copenhagen. He studied the water-bearing chalk layers under a lake in the vicinity of Copenhagen and concluded that the artesian groundwater had a very positive influence on the water quality of the lake, which at that time was a very important drinking water reservoir for Copenhagen. Forchammer's experiences were later used by the state engineer for Copenhagen, Ludwig August Colding (1815-1888), when he was given the responsibility of managing the establishment of the Copenhagen Water Supply Company constructed after the British example, following a severe cholera epidemic in the 1853. With this, the citizens of Copenhagen could enjoy clean drinking water based on groundwater.

Groundwater investigations continued at Copenhagen Polytechnic Institute while the Geological Survey of Denmark (DGU, today Geological Survey of Denmark and Greenland - GEUS) was established in 1888. However, groundwater research as a discipline was not defined until the 1930s, when groundwater chemistry caught the interest of a few geologists at DGU working with mapping of underground resources. The research area slowly grew, mainly driven by the requests from local and regional authorities in charge of water supply. From DGU, groundwater research spread to the University of Copenhagen as well as Aarhus University and also strengthened the groundwater investigations at the Technical University of Copenhagen; these four research institutes are the main actors in groundwater research in Denmark today. Denmark participated in the UNESCO initiated 'International Hydrological Decade' (1965–1975) giving rise to the first hydrological cooperation between research institutions, followed by a large project on a regional river catchment in the Eastern part of Denmark starting in the mid-1970s (the Susaa project) as the Danish contribution to the International Hydrological Programme. At that time focus was mainly directed towards the quantity of groundwater, though also acknowledging the interactions between surface and groundwater. Rather comprehensive studies on the chemical and isotopic composition of precipitation, groundwater and streams were also conducted. In the 1980s the first strategic research programmes began with funding targeting directly groundwater quantity and quality, giving rise to more solid cooperation between the different research institutes, also involving semi-private technology institutes/companies.

Highlights from current Danish groundwater research

In the following, we will present a selection of a few recently completed or ongoing research projects illustrating the diversity of Danish research initiatives. It should be noted that this does not in any way reflect the total portfolio of groundwater research carried out in Denmark, as the scope of this paper does not allow for that. Thus, issues such as e.g. groundwater dating, groundwater–surface water interaction, groundwater and medical geology, biogenic degradation of pesticides or other xenobiotic substances are not included.

Research activities related to groundwater quantity

Mapping of the Danish subsurface with geophysical techniques started as a research discipline at DGU in the 1940s and has since been used to locate and delineate our most important groundwater resources. From the late 1960s onwards Aarhus University intensified its research activity, particularly regarding further development of electric and electromagnetic mapping methods. In the late 1990s, a new water supply act set the scene for a comprehensive and still ongoing hydrogeological mapping task, covering 40% of the Danish area. This was encouraged by promising mapping results obtained during the 1990s using improved geophysical methods. However, the ambitious plan of mapping a significant part of Denmark with ground-based geophysics combined with drilling would be quite time consuming. This inspired researchers at the Aarhus University experienced in the progress and improvement of ground-based transient electromagnetic methods (TEM) to carry out further developments. In 2002/2003 they were able to present a new and more efficient TEM system, the SkyTEM-system (Sørensen and Auken, 2004) being the first **airborne TEM system** developed specifically for **hydrogeological mapping purposes**. The Danish SkyTEM system covers a depth range down to 400-500 m below ground surface, and the spatially dense SkyTEM data combined with borehole information are used to produce 3D models of the geological layers, to determine freshwater/saltwater boundaries, etc. Today, SkyTEM is a commercial system used worldwide and provided by the company SkyTEM Surveys (***http://skytem.com***), still being further developed and used in research projects (see e.g. ***www.nitrat.dk***, Schamper *et al.*, 2014).

Groundwater modelling in Denmark started in the 1970s with a few research and commissioned studies, but it was not until the 1990s that groundwater modelling became a regular activity in advisory tasks for the authorities. The focus was initially on groundwater flow and quantity, while research related to groundwater quality emerged in the 1980s. Today, groundwater modelling is a supporting activity in the above-mentioned detailed mapping of groundwater resources, launched in the late 1990s. Private companies conduct the mapping, while research institutes are involved to ensure best practices. In addition, GEUS has developed a **national water resources model (DK-model)** (see Henriksen *et al.*, 2003, 2008; Højberg *et al.*, 2013, or visit ***www.vandmodel.dk***). The DK-model is a coupled surface water/groundwater model using data from national databases on geology, soils, climate, land use, and water abstraction. The model has a 500 m spatial grid, 10-15 geologically based layers and 16,000 km of water courses. Today, this national model is used as a research platform, e.g. to assess climate change impacts on water resources using different future CO_2 emission scenarios. In addition, the DK-model supports the governmental and local authorities in implementing the Water Framework Directive in Denmark.

A river catchment with an area of 2,500 km^2 in the western part of Denmark was selected as the site for a **hydrological observatory** (HOBE) in 2007. The research is headed by the University of Copenhagen with contributions from Aarhus University and GEUS. HOBE provides a site for integrated and interdisciplinary measurements and experiments at multiple spatial and temporal scales with the opportunity to establish high-density, multiscale, high-quality, and long-term data sets that can provide a platform for hydrological research with interdisciplinary focus. This can improve the scientific basis for better water resources management decisions and for reducing the uncertainty in the water balance at catchment scale. A number of novel measurements have been established to supplement the existing state-of-the-art monitoring of climate, streamflow and groundwater. The new measurements include eddy flux measurement of evapotranspiration, soil moisture measurements by *in situ* sensors, cosmic ray and satellite based techniques, a variety of natural tracers, unmanned aerial vehicles and new techniques to measure stream-aquifer interactions The collected data form the basis for development **of integrated and physically based models** for different scales. Validated integrated hydrological models will be applied for predicting the effects of climate change and land-use changes. For more information, see Jensen and Illangasekare (2011) or visit ***www.hobe.dk***.

Research activities related to groundwater quality

As groundwater use for drinking water grew during the 1960–80s, focus on groundwater quality also raised, and a research programme on nitrate, phosphorous and organic matter in the aquatic environment was launched in 1986, including a groundwater part. Following this, a **national groundwater monitoring programme** was established in 1988 as a part of a national programme for monitoring the aquatic environment to document effects of nutrients regulations to improve water quality in general in fresh surface water, groundwater and in the marine environment surrounding Denmark. The still existing programme is regularly adjusted to fit the current (political) challenges, and currently the objective and monitoring design of the groundwater part is being adapted to fit the requirements of the Water Framework Directive and the Groundwater Directive. One of several challenges is how and where to monitor the quality of the groundwater that flows into the Danish freshwater bodies and wetlands. Today, the monitoring programme is defined as a non-research programme; however, data and findings from the programme are continuously used in research activities. For more information, see Jørgensen and Stockmarr (2009) or Hansen *et al.* (2012), or visit ***www.grundvandsovervaagning.dk***.

Groundwater quality is also monitored in the **Danish Pesticide Leaching Assessment Programme** (PLAP), an early warning system aimed at assessing the leaching risk of pesticides and their degradation products under field conditions. The programme was initiated by the Danish Government in 1998, and is still ongoing in both monitoring and research activities, carried out by Aarhus University and GEUS. The objective is to provide a scientific foundation for decision making in Danish regulation of pesticides by analysing whether approved pesticides applied in accordance with current regulations will result in leaching of pesticides and/or their degradation products to groundwater in unacceptable concentrations (usually above 0.1 µg/L).The programme focuses on pesticides used in arable farming and monitors leaching in five agricultural fields, selected to be representative of Danish conditions as regards soil type and climate. Given the monitoring design of the fields, pesticides and degradation products appearing in groundwater below and downstream of the fields can be related to the pesticides applied in accordance with current approval conditions (Rosenbom *et al.*, 2015). For more information on the programme, visit ***www.pesticidvarsling.dk***.

Historically, Denmark has been a farming society due to its favourable climate, topography, and soil conditions, and today still two-thirds of the country is agricultural land with an average farm size of more than 60 ha. This poses a perpetual threat to the aquatic environment, including groundwater quality. Supported by comprehensive research and monitoring programmes, regulation of agricultural practices has led to a 50% reduction in nitrate leaching from agriculture between 1980 and 2005. This has been based on uniform regulations implying that the same regulation has taken place in all areas, irrespective of the fact that more than half of the nitrate leaching from the root zone is reduced on the travel path between the root zone and the streams and that the location of this reduction varies greatly depending on topography, geology and functioning of drain pipes. Uniform regulations are not cost-effective, as many nitrate reducing measures are located in areas where nature will reduce nitrate anyway. Therefore, a government commission recommended introducing spatially differentiated nitrate regulations so that measures to reduce nitrate leaching would be located in areas where the natural reduction is low, implying that regulations can be relaxed for areas with high natural reduction. As this regulatory paradigm shift from uniform, national based regulation to spatially differentiated regulations requires new knowledge on local scale conditions, a number of new research projects on **nitrate transport and regulation** have been initiated (Refsgaard *et al.*, 2014, or visit ***www.nitrat.dk***, ***www.soils2sea.dk***).

Salt water intrusion is an increasing problem in coastal aquifers globally, and the problems will increase in the future due to increasing population, abstraction, climate change and sea level rise (Hinsby *et al.*, 2011). Mapping, monitoring and modelling of saltwater intrusion is ongoing in many coastal aquifers around the world and the results show that there is a need for developing new innovative tools for mapping, monitoring and controlling salt water intrusion in fresh aquifers supplying drinking water for millions of people as well as for food production (irrigation of farm lands, etc.). These are among the main research topics of some recently completed Danish-headed international research projects: 'Vietas' (Tran *et al.*, 2012), 'CLIWAT' - ***www.cliwat.eu*** (Hinsby *et al.*, 2011; Jørgensen *et al.*, 2012), 'Water4Coast', 'BaltCica' - ***www.baltcica.org*** (Rasmussen *et al.*, 2013), as well as in a recently initiated EU Horizon 2020 project called 'SUBSOL'.

Groundwater contaminated with **arsenic of natural origin** in concentrations exceeding the WHO drinking water limit of 10 μg/L is a threat to the health of millions of people in Bangladesh, West Bengal and Vietnam, and since 2004 GEUS has worked together with Vietnamese universities on capacity building and research activities in the Red River delta plain in Vietnam. One of the research themes has been to study the geochemical processes controlling the occurrence of elevated arsenic (As) in shallow, Holocene aquifers, and the groundwater chemistry has been investigated in a transect of 100 piezometers (Postma *et al.*, 2012) The research in this topic is ongoing, and recently a large ERC Advance Grant from the EU has been granted to GEUS on a project entitled 'Predicting the arsenic content in groundwater in the floodplains in SE-Asia'.

Future challenges

On a 5–10 year perspective, the groundwater research areas mentioned above are believed to be still relevant. Additionally, some upcoming challenges are foreseen in relation to scaling and parameterisation in modelling activities, quantification of uncertainty, and optimisation of solutions e.g. in relation to climate change adaptation, or emerging contaminants. Further, we see a challenge for the research community in general to adapt to requirements of the funding bodies, who seem to favour supporting the development of innovative solutions over funding process studies.

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Water quality and water-rock interaction in the Harz Mountains (Germany)

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The Harz Mountains, known for ancient silver and base metal mining, are an important drinking water supply region for northern Germany today. The water quality of the Harz Mountains is mainly influenced by atmospheric depositions, water-rock interactions and biological activities. Anthropogenic influences are minor. Springs, creeks, lakes and reservoirs have relatively low mineralisation. Measured as specific electrical conductivity, the mineralisation of the different water bodies ranges from about 15 to 650 µS/cm. Only deep springs and mine waters reach higher values. Despite dilution effects due to different rainwater amounts, water-rock interaction can be retraced by the chemical water composition, especially by trace metals and rare earth element concentrations. Examples of water-rock interaction are discussed for granite, greywacke and limestone.

Les montagnes du Harz, célèbres pour les anciens travaux miniers de recherche d'argent et de métaux non précieux, représentent une région importante, au sein de l'Allemagne du Nord actuelle, pour l'alimentation en eau potable. La qualité de l'eau des montagnes du Harz est conditionnée principalement par la déposition atmosphérique, les interactions eau-roche et les activités d'ordre biologique. Les influences anthropogéniques sont faibles. L'eau des sources, ruisseaux, lacs et réservoirs est relativement peu minéralisée. Mesurée en tant que conductivité électrique spécifique, la minéralisation des différentes eaux varie entre 15 et 650 µS/cm. Les sources profondes et les eaux en relation avec les secteurs miniers sont les seules à fournir des valeurs de conductivité élevées. Malgré les effets de dilution liés à l'abondance des différents régimes de pluie, l'interaction eau-roche peut être déterminée par la composition chimique de l'eau, en particulier par les concentrations en éléments-traces métalliques et en éléments de terres rares. Des exemples d'interaction eau-roche font l'objet de discussions pour le granite, la grauwacke et le calcaire.

Las montañas del Harz, conocidas por la minería antigua de plata y de metales básicos, son hoy una región de suministro de agua potable importante para el norte de Alemania. La calidad del agua de las montañas del Harz está influenciada principalmente por las deposiciones atmosféricas, las interacciones agua-roca y las actividades biológicas. Las influencias antropogénicas son menores. Manantiales, arroyos, lagos y embalses tienen una mineralización relativamente baja. Medida como conductividad eléctrica específica, la mineralización de los diferentes cuerpos de agua varía entre aproximadamente 15 y 650 µS/cm. Solamente los manantiales profundos y aguas de mina alcanzan valores más altos. A pesar de los efectos de dilución por el agua de lluvia, la interacción agua-roca se puede reconocer por la composición química del agua, especialmente por metales traza y concentraciones de elementos de tierras raras. Ejemplos de la interacción agua-roca se discuten para el granito, grauvaca y piedra caliza.

Transport and geochemical modelling in drainage basins are based on the understanding of water-rock interactions, which include many natural geochemical processes like weathering, dilution, precipitation and sorption, as well as microbiological interactions and anthropogenic influences (Oelkers and Schott, 2009). These basic processes can be easily studied in mountains ranges where surface waters (e.g., lakes, reservoirs and springs) are situated in relatively small drainage basins with well-known rock compositions and low anthropogenic impacts.

Mountain catchments in Germany are characterised by high precipitation rates. Surface waters from these catchments are often stored in water supply dam reservoirs.

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The Harz Mountains are an important drinking water supply region for northern and eastern Germany today. A number of hydrogeochemical studies have been carried out in this area with a special focus on spring water quality, nitrogen dynamics and atmospheric inputs (e.g., Alicke, 1974; Matschullat *et al.* 1994; Bozau *et al.*, 2013; Mueller *et al.*, 2015). Long term measurements are also performed by the companies which are responsible for reservoirs in the Harz Mountains and the drinking water supply (e.g., Lange, 2012; Mehling *et al.*, 2012).

In this study, data of several projects are examined and combined to understand major hydrogeochemical processes, especially water-rock interaction, in the different geological units of the Harz Mountains. Geochemical details and indicators such as rare earth element (REE) and trace metal concentrations are discussed.

Study area

The Harz Mountains, situated in the north of Germany, are about 120 km long and about 40 km broad. The highest mountain - Mount Brocken with 1,141 m a.s.l. - is part of a granite pluton dated at about 283 million years (Zech *et al.*, 2010). The entire mountain range consists of Palaeozoic rocks, which can be divided in several regional geological units. Most of the rocks have low permeability, causing a strong discharge at the surface, soil and weathering zone (Jordan and Weder, 1995). Therefore, there are many springs connected to different rock layers and fractures. Aquifers are not well developed and are of minor importance for water use.

The precipitation rate increases with altitude. At the highest elevations (700 to 1,100 m a.s.l.) mean annual precipitation rates range between 1,400 to 1,800 mm (***http://***

Table 1: Hydrogeochemical characteristics (pH value, specific electrical conductivity and main ions) of waters in the Harz Mountains.

	Sampling year (number of samples)	pH	SEC µS/cm	Na^+ mg/l	K^+ mg/l	Ca^{2+} mg/l	Mg^{2+} mg/l	SO_4^{2-} mg/l	Cl^- mg/l
Rainwater Clausthal-Zellerfeld*	2013-2014 (n=35)	4.4-6.8	5-43	<0.05-1.6	<0.05-1.2	<0.05-2.0	<0.05-0.20	0.32-3.3	0.06-3.4
Lake "Oderteich" near Mount Brocken	2013 (n=1) 2015 (n=1)	4.6 4.7	59 58	 6.0	 0.9	 1.6	 0.5	 3.7	 9.2
Lake "Blauer See" near Elbingerode	2015 (n=1)	9.9	330	7.6	1.8	34	0.7	37	15
Spring "Bode"** near Mount Brocken	2010-2012 (n=4)	4.2-7.5	16-43	0.8-1.4	0.1-0.8	0.3-4.3	0.1-0.9	0.7-1.1	0.5-1.7
Creek "Bode" at Treseburg and Neinstedt leaving the Harz Mountains	2015 (n=1) 2015 (n=1)	7.8 7.8	200 240	12	1.4	25	3.2	12	22
Spring "Innerste"** near Clausthal-Zellerfeld	2010-2014 (n=14)	5.8-7.3	63-97	3.0-9.9	0.5-1.2	5.2-9.8	1.4-2.8	13-21	1.6-4.3
Creek "Innerste" at Langelsheim leaving the Harz Mountains	2014 (n=1)	8.1	191	12	1.2	21	3.9	26	33
River "Innerste" at Hildesheim (about 40 km away from the Harz Mountains)	2012 (n=1) 2014 (n=1)	8.1 8.1	825 840	64 57	5.2 4.9	126 81	15 12	115 96	104 96
Reservoir "Innerste-Stausee"	2012 (n=1)*** 2014 (n=1)	7.7 8.2	160 172	 9.9	 1.1	 19	 3.5	 23	 13
Spring "Eisenquelle" near Clausthal-Zellerfeld	1972-1973****(n=7) 2010-2015**(n=6)	5.1-6.5 5.0-7.8	61-94 73-115	5.8-8.1 7.6-10	1.8-2.3 0.5-1.1	2.3-4.0 3.3-8.0	2.6-3.2 1.5-3.3	8.0-28 5.5-8.4	4.9-14.3 7.1-17.5
Mine water "Rammelsberg" near Goslar	2013 (n=1)	6.5	1870	48	9.0	313	95	1,100	38
Deep springs (North of Harz Mountains) Bad Harzburg***** Bad Suderode*****	 2003 (n=1) 2001 (n=1)	 7.6 7.5	 34,700 26,500	 7,523 3,835	 115 60	 1,138 2,560	 200 4.6	 3,845 16	 11,200 9,320

**Bozau* et al. *(2015), **Bozau* et al. *(2013), ***Mehling* et al. *(2012), ****Alicke (1974), *****Kübeck (2004)*

www.dwd.de). Acid rain and atmospheric deposition in the Harz Mountains have led to increased metal mobility in soils and metal concentrations in drainage water. Detailed effects of air pollution are discussed in several studies (e.g., Matschullat *et al.*, 1994; Roostai, 1997). Due to air pollution control measures, the ecosystem has started to recover. This effect can be seen in the decrease of sulphate concentrations in spring waters (Bozau *et al.*, 2013).

Because of several yielding mineralisations, mining activities in the Harz Mountains have a long history. Mining is thought to have started as early as the Bronze Age (Matschullat *et al.*, 1997) and has been widespread since the Middle Ages. Mining activities have consequently caused contamination of surface waters as well as recharge areas. But the majority of waters are not chemically affected by mining. Most of them are involved in the "Oberharzer Wasserregal", which is an old system of dams, adits, reservoirs and ditches. It was constructed from the 16th to 19th centuries to deliver water to the water wheels of the mines. Reservoirs for flood protection, energy production and drinking water supply were built in the 20th century. The biggest reservoir of the eastern Harz Mountains is the Rappbode-Stausee reservoir, with a total water volume of 109,000,000 m^3. The six big reservoirs of the western Harz Mountains (Ecker-, Innerste-, Grane-, Oder-, Oker- and Söse-Stausee) have a water storage capacity of 182,000,000 m^3. Investigations in the drainage basins of the reservoirs and creeks show that the annual water runoff has been nearly constant since 1941, when measurement started. However, the seasonal runoff volume is changing. Summertime is getting drier, resulting in lower runoff, whereas during the winter runoff volumes from the Harz Mountains are rising (Lange, 2012).

Deep thermal springs near Bad Suderode and Bad Harzburg at the north boundary of the Harz Mountains are in contact with Mesozoic rocks. They are used for balneotherapeutical purposes. According to their main anions, Na or Na + Ca, the deep springs can be related to upper Triassic rocks or lower Triassic rocks (Buntsandstein) and Permian layers (Bozau and van Berk, 2014).

Water sampling

Water samples of the Harz Mountains are taken regularly during student excursions and for different scientific projects by all authors of this study. The samplings started in 2010 and span all seasons. For the purpose of showing the effects of water-rock interaction, data of several sampling campaigns are combined in this study (***Table 1***).

Generally, pH, temperature and specific electrical conductivity (SEC) are measured during sampling. The main ions are analysed after filtration (0.45 µm) using ion chromatography, while trace elements and REE are determined using ICP-MS. For further analytical details see Bozau *et al.* (2013).

Water quality and water-rock interaction

In order to characterise the water-rock interaction and its influence on the water quality, three main geological units of the Harz Mountains are considered (***Figure 1***):

- granite of the Upper Harz around the Mount Brocken,

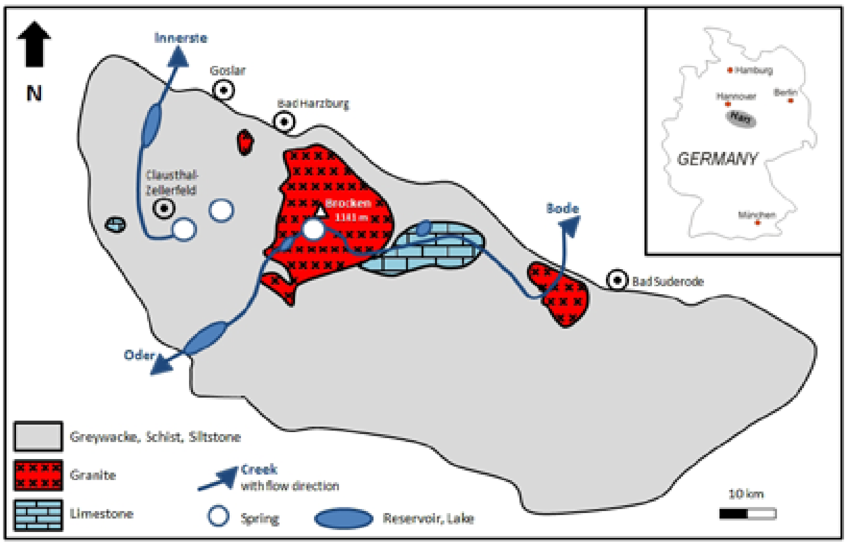

Figure 1: Simplified sketch of the Harz Mountains with the considered rock units and the sampling locations of this study - springs (Innerste, Eisenquelle, Oder, Bode), creeks (Innerste, Oder, Bode), lakes (Oderteich, Blauer See) and dam reservoirs (Innerste-Stausee, Oder-Stausee).
For detailed geographical and geological information on the Harz Mountains see: http://www.geopark-harz.de.

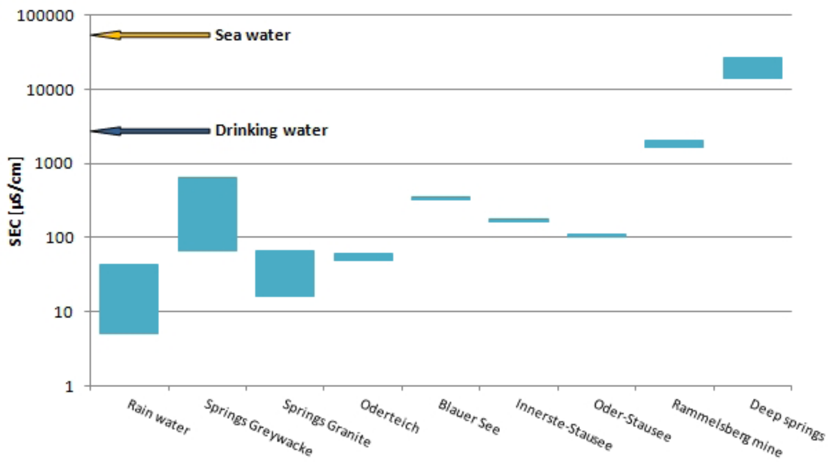

Figure 2: Specific electrical conductivities measured in waters of the Harz Mountains, sea water (52,000 µS/cm) and the German threshold value for drinking water (2,500 µS/cm). Data on rain water and springs are from Bozau et al. *(2015, 2013) and data of deep springs are from Kübeck (2004).*

- limestone of the geological unit "Elbingeröder Komplex" in the Middle Harz,
- greywacke, schist and siltstone of the Western Harz.

The mineralisation of the waters from all these areas is relatively low. Some springs and lakes are characterised by ion concentrations no higher than rainwater. Measured as SEC, the mineralisation of the different water bodies ranges from about 15 to 650 µS/cm (***Figure 2***). Due to the rainwater dilution, the springs formed in the granitic region of the upper mountains with higher precipitation rates have lower SEC values than the springs of the lower areas dominated by greywacke, schist and siltstone. Only deep springs (e.g., at Bad Harzburg and Bad Suderode) and mine waters (Rammelsberg mine near Goslar) reach values >1,000 µS/cm; these values are still lower than sea water mineralisation and can be explained by intensive water-rock interaction with the surrounding Mesozoic rocks at the northern boundary of the Harz Mountains and with the ore minerals of the old adits, respectively.

Despite dilution effects due to different rainwater amounts, water-rock interaction can be retraced by the chemical water composition in all investigated waters. Seasonal changes are observed especially in spring waters. Some springs around Mount Brocken which are strongly dependent on surface water supply can dry out in summer or are frozen in winter. These springs are also characterised by a high amount of organic materials measured as dissolved organic carbon (DOC) originating from the numerous peat bogs in this area (Bozau *et al.*, 2013). The investigated creeks show an increase of ion concentrations downstream due to rising biological activities and further water-rock interactions. The highest concentration in the creeks is measured when they are leaving the mountain range (***Table 2***). The SEC of the creek "Innerste" rises from 87 µS/cm at the spring to 191 µS/cm at the boundary of the Harz Mountains in Langelsheim. In Hildesheim, 40 km away from the mountains, a SEC value of about 820 µS/cm is measured in the Innerste river. The Bode and Oder creeks leave the Harz Mountains with a SEC of about 200 and 100 µS/cm, respectively.

Table 2: Specific electrical conductivity of the creeks "Innerste", "Bode" and "Oder" sampled at and downstream of the spring (distance in km).

Innerste September 2014	*SEC µS/cm*
Spring	*87*
Wildemann, 12 km	*145*
Reservoir, 25 km	*173*
Langelsheim, 30 km	*191*
Bode June 2015	***SEC µS/cm***
Spring	*dry*
Elend, 10 km	*60*
Treseburg, 38 km	*200*
Neinstedt, 50 km	*240*
Oder July 2013	***SEC µS/cm***
Spring	*35*
Oderteich, 4 km	*59*
Inflow 1/2, 19 km	*94/117*
Reservoir, 22 km	*106*

Due to the high amount of rainwater and the low ion concentrations of rainwater, water-rock interaction of the considered rock units can be better seen in the minor and trace element concentrations deriving from rock minerals than in the concentrations of the main elements. If trace elements are detected in spring water they must originate from the soil or rock, because trace element concentrations of rainwater are very low and often below the detection limits for trace elements. Therefore, trace metals and REE are useful tracers of water-rock interaction.

Some of the major rainwater ions, e.g. NH_4^+, are already degraded within the soil zone. The average rainwater concentration of NH_4^+ is 0.9 mg/l (Bozau *et al.*, 2015), but NH_4^+ is not detected in the spring water. According to the biological processes within the soil zone, organic matter is degraded and the CO_2 content rises, changing the ratios of the main ions from the rainwater, too.

Depending on time and environmental conditions, water in contact with a rock will equilibrate with the minerals of that rock. The main minerals of granite are quartz, feldspar minerals and micas. Greywacke, schist and siltstone consist mainly of quartz and clay minerals. Calcite is the main component of limestone. The dissolution of calcite will increase the pH value of water faster than biological activities in the soil zone and the water bodies. Surface waters also equilibrate with the oxygen and carbon dioxide content of the atmosphere. Waters of the ore mines are influenced by the dissolution of ore and secondary ore minerals. These waters can be enriched in metals and if sulphide minerals are weathered under oxygen supply, the sulphate contents will rise. Combined with the precipitation of iron oxyhydroxides, this process can lead to the formation of acid mine drainage.

Water of the granitic area around Mount Brocken

The springs of the creeks „Bode“ and „Oder“ originate in the peat bogs around Mount Brocken (***Figure 3a***). These bogs get most of their nutrients by atmospheric deposition. The water draining the bogs and contacting the weathered granite boulders is rich in organic matter (fulvic and humic acids) and iron. All waters from the granitic area have relatively high Al and Fe concentrations. Compared to the spring "Innerste" (a non-granitic area) the trace metal concentrations (e.g., Cu, Pb) are also enriched. The highest U concentration (0.2 µg/l) is found in the creek "Oder" (***Table 3***).

The spring "Oder" and some other little creeks feed the lake "Oderteich" with a holding capacity of 1,700,000 m^3. The lake "Oderteich" was built in 1722 as a part of the water management system "Oberharzer Wasserregal" and is characterised by a very low pH value (about 4.6) combined with high Fe concentrations (***Figure 3***). The concentrations of the main ions Ca^{2+} and K^+ are not much higher than the ion concentrations measured in rainwater. The sulphate concentration slightly exceeds rainwater concentration. Acidification due to outflow of peat bogs and acid rain found in the upper part of the mountain range is compensated by buffering processes downstream the creeks.

The REE concentrations and the REE pattern of the creek "Oder" and the lake "Oderteich" can be attributed to the interaction with the granite, which displays the same REE pattern with the typical negative Eu anomaly and the enrichment of heavy REE. The shale normalised REE pattern of the water samples is shown in ***Figure 4***. North American Shale Composite (NASC; Taylor and McLennan, 1985) was used for normalisation.

The outflow of the lake "Oderteich" leaves the granitic environment, and together with several further creeks runs into the reservoir "Oder-Stausee". The reservoir, as well as many creeks of the western and eastern shore flowing into it, are situated in Carboniferous, non-granitic

Figure 3: Waters and bogs around Mount Brocken: a) Peat bog, origin of the spring "Oder"; b) Sampling at the creek "Oder" that flows around granite boulders; c) Lake "Oderteich" near Torfhaus; d) The red brown water colour of the lake "Oderteich" shows the high iron concentrations (up to 1 mg/l).

Table 3: Minor and trace element concentrations of waters [µg/l] connected to different geological units from the Harz Mountains.

Rock	Granite				Greywacke, schist, siltstone			Limestone
Sample	Spring "Bode"	Spring "Eule"	Creek "Oder"	Lake "Oderteich"	"Oder-Stausee" inflow 1/2	Spring "Innerste"	Rammelsberg Mine	Lake "Blauer See"
Date	Spring 2013	Spring 2013	Summer 2013	Summer 2013	Summer 2013	Spring 2013	Autumn 2013	Spring 2015
Al	121	244	228	235	34/19	36	n.a.	28
Fe	121	10	710	845	213/16	5	4	9
Mn	10	73	29	82	60/3	11	12	0.4
Cd	0.09	0.24	0.23	0.21	0.02/0.05	0.19	11	0.003
Cu	1	0.4	4	3	3/3	0.5	35	0.5
Pb	10	3	16	12	2/2	2	<3	0.02
Zn	8	14	12	14	3/14	9	15,300	1.1
U	0.026	0.034	0.18	0.14	0.02/0.04	0.009	1	0.002
B	2	2	5	4	9/13	3	140	11
Li	0.13	1.4	1.3	1.2	2.2/1.6	0.81	111	6
Sr	2	4	15	10	23/36	27	2,300	66

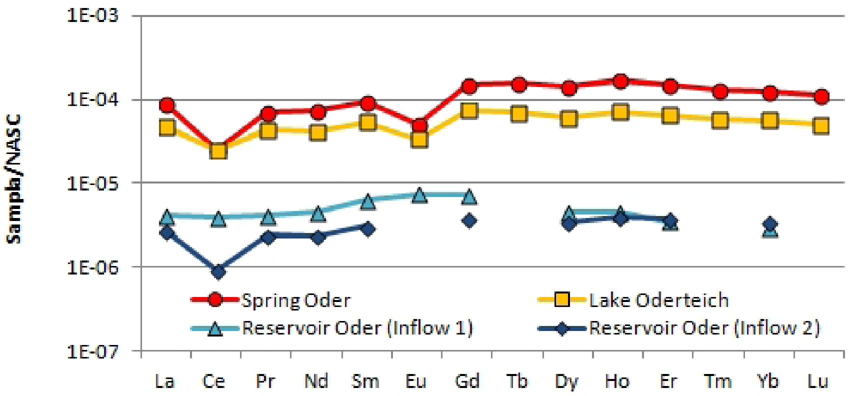

Figure 4: Shale normalised REE pattern of water from the Oder catchment. Spring "Oder" and lake "Oderteich" show the typical pattern for granitic rocks, whereas the inflows to the reservoir "Oderstausee" have lower REE concentrations and a pattern typical for greywacke, schist and siltstone.

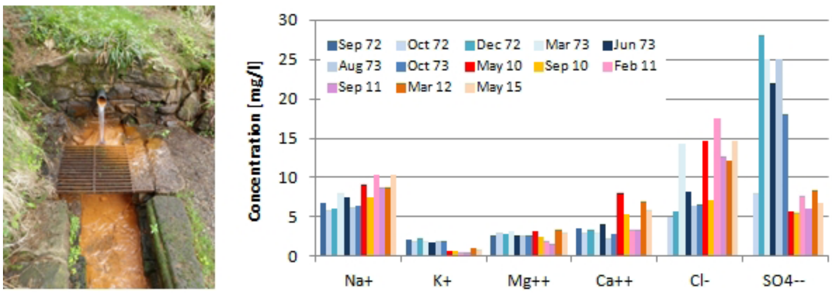

Figure 5: Spring "Eisenquelle" with the precipitation of brownish iron oxide-hydroxides. Main ions of the spring "Eisenquelle" (Data from Alicke, 1974 and Bozau et al.*, 2013).*

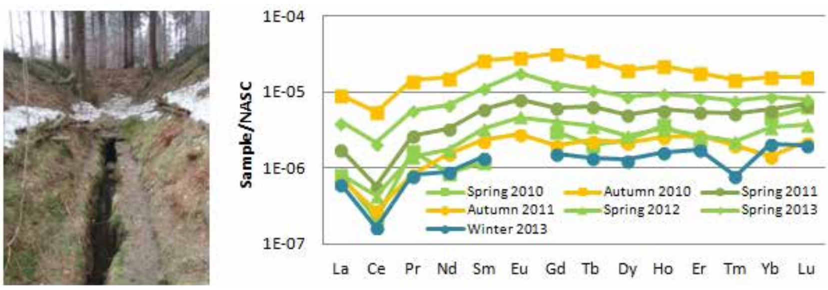

Figure 6: Spring "Innerste". Temporal variations of the REE pattern of the spring "Innerste" from May 2010 to December 2013. Autumn 2010 was very dry and the REE concentrations reached their highest values.

rocks. The REE concentrations of the reservoir inflows are lower than that of the lake "Oderteich" and the pattern is nearly flat. The influence of the water coming from the lake "Oderteich" is not seen in the REE pattern of the main inflow (***Figure 4***) and the reservoir. The REE concentrations of the reservoir are lower than the detection limit and therefore not shown in ***Figure 4***. These REE pattern and concentrations are typical for waters from greywacke, schist and siltstone, as described in Roostai (1997) and Bozau *et al.* (2013), and are also presented in the next section (see ***Figure 6***) for the spring "Innerste". The negative Ce anomaly seen in the REE pattern of the spring "Oder", the lake "Oderteich" and inflow 2 to the reservoir "Oder-Stausee" can be explained by the oxidation of Ce^{3+} and the precipitation of CeO_2 when the spring water comes in contact with the oxygen of the air (Elderfield *et al.*, 1990). From the Ce anomaly it can be concluded that water of inflow 1 has less contact with oxygen than the other sampled waters.

Waters connected to greywacke, schist and siltstone of Palaeozoic rock units

The spring of the river "Innerste" (south-east of Clausthal-Zellerfeld) and the spring "Eisenquelle" (east of Clausthal-Zellerfeld) are connected to Carboniferous strata consisting of greywacke, schist and siltstone. Both springs are involved in the water management system "Oberharzer Wasserregal". The ion concentrations of the springs vary with the amount of rainwater. The typical concentration range of the main ions is shown in ***Figure 5*** for the spring "Eisenquelle". Due to the atmospheric oxygen supply, brownish iron(III) oxide-hydroxides precipitate from the spring water, which is characterised by total iron concentrations from 0.5 to 5 mg/L. Data from 1972 and 1973 compared to actual data allow the conclusion that only the sulphate concentration was reduced after the air control measures in the 1990s. The differences in the K^+ and Na^+ concentrations can be explained by the change of the analytical method (1972-1973: atom absorption spectrometry, 2010-2015: ion chromatography).

REE concentrations are generally lower here than in waters from granitic areas. The crust normalised REE pattern of the waters is nearly flat as the REE pattern of the hosting rocks. But they also reflect the dilution effects with changes in the amount of rainwater (***Figure 6***). The typical Ce anomaly for water in contact with atmospheric oxygen has already been explained in the previous section.

Rammelsberg mine near Goslar

Rammelsberg mine, a sedimentary exhalative deposit, is situated in the south of the town Goslar. The orebody, with 7,000,000 t metal content (mainly Zn, Pb, Cu, Ag and Au), is situated in middle Devonian schists consisting of dark shales and tuff bands (Pohl, 1992).

After more than 1,000 years, mining activities ended in 1988 due to depletion. Many adits and the dewatering system are still accessible. A water sample was collected in the pumping shaft and represents a mixture of the water flowing through the mine. According to observations, the water amount can be correlated to the rainwater height. Water chemistry is influenced by water-ore interaction (***Tables 1 and 3***). High sulphate concentrations (1,100 mg/l) and Zn concentrations (15.3 mg/l) point to the weathering of sulphide minerals. Cu (35 µg/l), Pb (<3 µg/l) and Fe (4 µg/l) concentrations are surprisingly low for an ore mine. Compared to the other water samples B, Li and Sr concentrations are enriched. The formation of secondary minerals like copper and zinc sulphates (***Figure 7***) can be seen during a museum tour in the main adits. It seems to be possible that the dissolution of these secondary minerals are mainly responsible for the water composition. REE concentrations in the mine water are low. The REE pattern is comparable to that of the spring waters deriving from greywacke, schist and siltstone, as shown for the spring "Innerste" (***Figure 7***).

Lake "Blauer See" connected to limestone of the geological unit "Elbingeröder Komplex"

The geological unit "Elbingeröder Komplex", a fossil Devonian reef, is situated east of Mount Brocken and consists of limestone. Typical karst phenomena including caves developed in this area, which belongs to the barrier reef zone of the Variscan mountain range. The limestone has been industrially exploited for a long time, starting in the 19th century. Today, active open pit mines are found near the town Elbingerode. Furthermore, there are some submarine exhalative iron mineralisations which were mined until the end of the last century. Today some of these pits are show mines, e.g. the Büchenberg mine, where the formation of calcite precipitation can be observed (***Figure 8***). The lake "Blauer See" is formed by rain, leakage and groundwater which are filling the lowest level of an old open pit limestone mine. Mining in the pit started in 1885 and was abandoned in 1945. The water has the typical blue colour of lakes in karstic environments, which contain many calcite particles. Calcite precipitation indicating a decreasing water table can be seen at the shore of the lake. During summer and autumn, the water colour changes to green due to algae growth (***Figure 8***). Sometimes the lake also dries out.

Water chemistry should be determined by the equilibrium of rainwater with calcite and atmospheric CO_2, leading to an expected pH value of about 8.2. However, a pH value of 10 was measured in June 2015 (***Table 1***), leading to the conclusion that CO_2 is biologically consumed within the lake water so that the mineral calcite alone is buffering the system. In July 2015, the pH increased to 10.6, which could be explained by high evaporation leading to changes in the aqueous complexes (HCO_3^- is replaced by $CaCO_3^0$) and intense microbiological activities (e.g., photosynthesis, uptake of nitrate, denitrification).

Compared to both the waters from the granitic area and the area of greywacke, schist and siltstone (***Table 3***), the lowest trace metal concentrations are found in the water of the lake "Blauer See". Its water has relatively high concentrations of B, Li and Sr, indicating that the Devonian limestone formed from sea water which is enriched in these elements. The REE pattern of the water should retain the REE pattern of the limestone. As a result of the very low REE concentrations in the limestone, the REE concentrations of the water are below the detection limits of our analytical method.

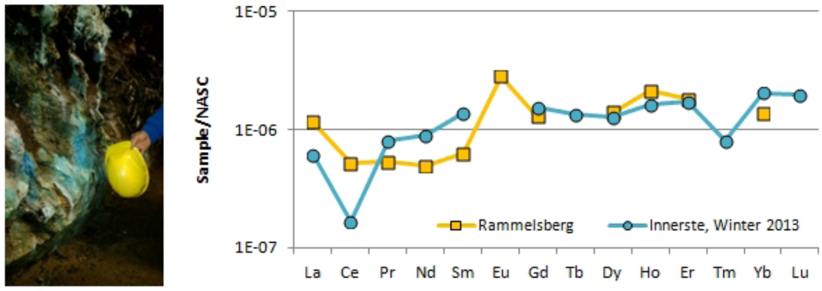

Figure 7: Rammelsberg mine underground (Formation of secondary copper sulphates). REE pattern of mine water is compared to the spring "Innerste" for a sampling date with high rain water dilution.

Summary

The investigated waters show that water-rock interaction is an important process leading to different typical water compositions. REE pattern and trace element concentrations can be used as indicators for the interaction of the water with different rocks. Waters connected to granite display higher REE concentrations, an enrichment of heavy REE and the typical negative Eu anomaly, whereas waters from geological units dominated by greywacke, schist and siltstone or by limestone show lower REE concentrations and an almost flat REE pattern. Mine waters have an increased concentration of Zn, Cu and further trace elements deriving from the ore minerals. Uranium concentrations of mine water and waters from the granitic areas are higher than the uranium concentrations of water connected to limestone and geological units consisting of greywacke, schist and siltstone. Sea water derived elements, e.g. Li and B, are enriched in mine waters and waters connected to limestone.

The surface water of the Harz Mountains is mainly derived from rainwater, and ion concentrations are influenced by biological and geochemical processes within the soil and rock as well as within the water body itself. The mineralisation of these waters is relatively low compared to water from other regions. These waters are the main basis for sustainable drinking water production in the dam reservoirs of the Harz Mountains. Only mine water and deep springs with contact to ore minerals and highly mineralised rock units reach higher concentrations. These locally occurring waters must be observed and mixing with the surface water used for drinking water supply must be avoided. In order to sustain the drinking water quality and evaluate the anthropogenic influence the hydrogeochemical data of springs and surface waters in the Harz Mountains should be continuously monitored. As is known from industrial sites and highly populated cities, the concentration of micropollutants in waters including trace elements, REE and pharmaceuticals passing waste water plants is rising worldwide. Japanese rainwaters are already enriched in REE (Iwashita *et al.*, 2011). To minimise an overlapping of natural indicators for water-rock interaction by anthropogenic inputs – even if they are

Figure 8: Limestone of the geological unit "Elbingeröder Komplex": a) Lake "Blauer See" in June 2015 (pH 10.0); b) Lake "Blauer See" in July 2015 (pH 10.6); c) Calcite precipitate on the shore of the lake "Blauer See" after water table decrease in July 2015; d) Stalactites (length about 2–5 cm) in the Büchenberg mine.

not toxic for the environment - attempts should be made to reduce anthropogenic changes in the water concentrations as much as possible.

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EGG: European Groundwater Geochemistry

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A model geochemical study of bottled mineral water in Europe, as a proxy to groundwater, found that wide variations occur in element distribution. Here, bottled mineral water results are compared with surface-, tap- and ground-water survey data, and the role of different geological terrains is considered. In order to produce harmonised hydrogeochemical databases, all samples of each data set were analysed in a single laboratory, following a very strict quality control protocol. Since reliable maps can be obtained from only 1,000 to 2,500 samples evenly distributed across Europe, it is recommended to carry out similar studies for different water sources or types; the resulting harmonised hydrogeochemical databases would provide an excellent resource for European decision makers and scientists.

Une étude de modèle géochimique concernant l'eau minérale embouteillée, en Europe, en tant qu'élément représentatif des eaux souterraines, a démontré qu'il existait de grandes variations dans la distribution des éléments chimiques. Les résultats fournis par l'eau minérale en bouteille sont comparés ici avec les données d'étude venant des eaux de surface – au robinet – et des eaux souterraines, en tenant compte du rôle joué par les différents terrains géologiques. Pour obtenir des bases de données hydrogéochimiques comparables (harmonisées), tous les échantillons de chaque lot ont été analysés par un seul laboratoire, suivant une procédure très stricte de contrôle qualité. Puisque les cartes significatives peuvent être obtenues seulement à partir de 1000 à 2500 échantillons, régulièrement distribués à travers l'Europe, il est recommandé d'effectuer des études analogues pour différentes origines de l'eau ou "types"; les bases de données hydrogéochimiques harmonisées constitueraient un excellent outil pour les décideurs et les scientifiques.

En representación de las aguas subterráneas, un estudio geoquímico del agua mineral embotellado en Europa, encontró que se producen amplias variaciones en la distribución de los elementos. Aquí los datos del agua mineral embotellado se comparan con los datos de sondeo de aguas superficiales, en la toma de datos del estudio del agua subterranea se considera el papel de los diferentes terrenos geológicos. Para producir bases de datos hidrogeoquímicas armonizadas, todas las muestras de cada conjunto de datos se analizaron en un solo laboratorio, siguiendo un protocolo de control de calidad muy estricto. Dado que mapas fiables se pueden obtener con solamente 1.000 a 2.500 muestras distribuidas de manera uniforme en toda Europa, es recomendado llevar a cabo estudios similares para diferentes fuentes o tipos de agua; las bases de datos hidrogeoquímicas armonizadas obtenidas proporcionarían un excelente recurso para los responsables políticos y científicos europeos.

For the last 60 years or so, humans have had the capacity to influence groundwater chemistry on both global and countrywide scales. For example, the atmospheric testing of atomic bombs in the late 1950s led to the enrichment of recharging rainfall with tritium, allowing this isotope to be used as a dating tool in groundwater on a global scale (e.g., Carmi and Gat, 2000). As a consequence of the intensification of agriculture across Europe in the 1960s and '70s, with the accompanying unregulated disposal of farm effluents, national legislation was required to prevent nitrate pollution of shallow unconfined groundwater aquifers (e.g., Meinardi *et al.*, 1995).

To monitor groundwater chemistry, and so prevent deterioration in groundwater quality, there is an immediate need to document the current natural variation of the chemical composition of groundwater in Europe. Future groundwater analyses can then be compared with this and anthropogenic impacts identified. To be of any use to the regulator and the practitioner, such documentation must reflect the diversity of groundwater environments (and use) across Europe, and be able to verify reference values for the variation in (ground)water composition naturally present in aquifers.

The results of the EuroGeoSurvey's Geochemistry Expert Group's project entitled European Groundwater Geochemistry were published as an atlas with the title *Geochemistry of European Bottled Water* (Reimann and Birke, 2010). These data are a useful first step in providing the natural range of variation for over 70 chemical parameters in groundwater, namely Ag, Al, As, B, Ba, Be, Bi, Br, Ca, Cd, Ce, Cl, Co, Cr, Cs, Cu, Dy, Er, Eu, F, Fe, Ga, Gd, Ge, Hf, Hg, Ho, I, K, La, Li, Lu, Mg, Mn, Mo, Na, Nb, Nd, NH_4^+, Ni, NO_2^-, NO_3^-, PO_4^{3-}, Pb, Pr, Rb, Sb, Sc, Se, Si, Sm, Sn, SO_4^{2-}, Sr, Ta, Tb, Te, Th, Ti, Tl, Tm, U, V, W, Y, Yb, Zn, Zr, electrical conductivity, pH and total alkalinity.

This survey has shown that it is possible, by analysing bottled natural mineral water from across Europe, to provide useful guidance on the chemical composition of deep natural groundwater. It also provided important insights about problems related to collection and analytical methodologies and associated costs. More importantly, it showed that by using the analytical results from bottled mineral water samples from just 884 locations, we can gain a good statistical overview of groundwater quality in terms of natural variation at the European scale – quite comparable to the results of general statistical polls.

At the European scale, it is not necessary, therefore, to analyse every single aquifer, as it is possible to get a good impression of water quality by just collecting 1,000-2,500 representative samples across Europe. The validity of the low sample density approach has already been demonstrated by the Geochemical Atlas of Europe (Salminen *et al.*, 2005), and more recently for agricultural

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and grazing land soil in the GEMAS project (Reimann *et al.*, 2014). It is suggested, therefore, to follow the GEMAS approach of one sample site per 2,500 km^2, resulting in just over 2,000 samples covering Europe. A number of such 'water polls' could thus be carried out at the European scale, for instance for:

a. springs, providing a chance to get an excellent overview of natural shallow groundwater quality, untouched by human interference via, e.g., well installations;
b. surface water – a repetition of the FOREGS stream water geochemical survey (Salminen *et al.*, 2005) at double the sample density;
c. tap water, providing a good idea about what the European population really drinks; recent publications on the geochemistry of tap water prove that this would work (e.g., Banks *et al.*, 2015), and
d. groundwater from wells, collecting also additional geological information about each well.

Background

Two key objectives of the EU Water Framework Directive 2000/60/EC are to prevent deterioration in groundwater quality and, if contaminated, to implement measures to reverse the situation in order to bring groundwater quality back to a 'good' status. The successful implementation of these objectives requires (a) knowledge about naturally occurring element concentrations in groundwater, and (b) comparison of groundwater analyses with the mapped natural variation. To date, individual Member States publish their own guidance lists, without considering the natural variation in chemical composition in relation to toxicological and health data. As groundwater, and potable water in general, is very important to the good health status of the human population, maximum admissible determinand concentrations in groundwater must be based on toxicity data, which assess the relationship between chemical elements and compounds and their effect on human health (USEPA, 2011).

However, while the process of setting up threshold or limit values appears quite simple, as they should be based on toxicological and health data, there are a number of points that should be considered for the establishment of the natural variation of groundwater chemical composition across Europe. As has already been suggested, representative groundwater samples can be collected using a sample density of one site per 2,500 km^2. The samples should be collected, according to the same specifications, from groundwater wells, which:

i. have been in operation for many years;
ii. are located in a wide variety of aquifers, and
iii. are stable in natural chemical composition.

Finally, the analyses should be carried out in a single laboratory for consistency and repeatability.

By harvesting the groundwater analytical data from such an evenly spaced network of groundwater wells across Europe, it would be possible to establish not only the normal variation in elemental composition of groundwater, but perhaps also – and more importantly – the variation that can occur with individual aquifer types, such as sedimentary, igneous, and metamorphic aquifers. It should be noted, however, that this approach is prone to contamination from well installations, and the degree of contamination can be different from country to country.

Geochemistry of European Bottled Water

The atlas *Geochemistry of European Bottled Water* (Reimann and Birke, 2010) presents the results from the detailed analysis of 1,785 bottled mineral water samples collected from 38 European countries, representing 1,247 different sources at 884 locations. The bottled mineral water samples were analysed in a single laboratory for more than 70 determinands by ICP-MS, ICP-OES and IC, including pH, alkalinity, etc. (***Table 1***), thus producing the first harmonised geochemical data set for European groundwater. The bottled mineral water data set, therefore, provides a first impression of variability and the regional distribution of groundwater chemistry at the continental scale.

The maps identify the influence of geology on water composition, as well as other factors (e.g., bottling effects, leaching of elements from bottles). Furthermore, enormous natural variation in concentration (up to 7 orders of magnitude) of many of the analysed chemical elements in groundwater is documented. The bottled water data are plotted against European surface water (Salminen *et al.*, 2005), tap water (this study; Banks *et al.*, 2015) and Norwegian bedrock groundwater (Frengstad *et al.*, 2000) in cumulative probability plots that highlight the similarities and differences between these different water types (***Figure 1***); it is worth noting that all samples of each data set were analysed in the same laboratory.

In general, the four data sets shown in ***Figure 1*** are surprisingly comparable for most elements (e.g., Cd, Cl, Cr) with respect to concentration and variation. Cerium shows two distinct trends between the bottled-tap water and the ground–surface water; the Norwegian groundwater is undoubtedly affected by the variable geological terrain and the higher Ce values are due to granitic, granodioritic and gneissic terrains; its similarity with the stream (surface) water leads to the assumption that this trend is also due to the variable geological terrain of Europe. Caesium in bottled mineral water shows a different atypical trend for groundwater, which is most likely due to a higher number of samples sourced from granitic terrains in comparison to other terrain types. Copper seems to display a strong impact of contamination from well installations; this is indicated by the shift towards higher values over the whole concentration range for tap water and Norwegian groundwater. However, bottled mineral water from high production wells most likely shows the 'true' (background) variation of Cu in groundwater, as it is assumed that there is too short a time to 'acquire' a contamination signal from well installations.

Natural Mineral Water

To obtain and maintain the status of a certified natural mineral water a source must have been sampled for many years prior to recognition, and must remain bacteriologically pure and within set limits for a range of parameters according to European Directives 80/777/EEC and 2003/40/EC.

EU Council Directive 80/777/EEC (Annex 1, p. 6) defines a *"natural mineral water"* as a water that is *"microbiologically wholesome, originating in an underground water table or deposit and emerging from a spring tapped at one or more natural or bore exits"*. It moreover states, *"natural mineral water can be clearly distinguished from ordinary drinking water:*

- *by its nature, which is characterised by its mineral content, trace elements or other constituents and, where appropriate, by certain effects" and*
- *"by its original state".*

Table 1: Instrumental analytical method, detection limits, precision, number of samples <RDL, % of samples <RDL, and basic statistical parameters of bottled mineral water data set used for mapping (n=884)

Parameter	Method	Unit	IDL*	RDL**	PDL***	N<RDL	%<RDL	P%[a]	Min.	Percentiles							Max.	MAD[f]	Powers[g]
										5	10	25	50	75	90	95			
Ag	ICP-QMS	µg/l	0.001	0.002	0.002	637	72	13	<0.002	<0.002	<0.002	<0.002	<0.002	0.002	0.012	0.1	112	0	6
Al	ICP-QMS	µg/l	0.2	0.5	0.2	158	18	5	<0.5	<0.5	<0.5	0.59	1.2	4.2	13	30	966	1.3	4
As	ICP-QMS	µg/l	0.01	0.03	0.001	45	5.1	10	<0.03	0.017	0.041	0.09	0.24	0.75	2.8	5.1	90	1.5	4
B	ICP-QMS	µg/l	0.1	2	0.2	12	1.4	4	<2	4.7	6.6	13	39	162	730	1618	120000	1.8	6
Ba	ICP-QMS	µg/l	0.005	0.1	1[c]	0	0	5	0.05	1.2	2.7	10	29	78	221	390	26800	1.5	7
Be	ICP-QMS	µg/l	0.001	0.01	0.005	636	72	5	<0.01	<0.01	<0.01	<0.01	<0.01	0.015	0.1	0.51	64	0	5
Bi	ICP-QMS	µg/l	0.0005	0.005	0.003	856	97	-[e]	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	0.69	0	3
Br^-	IC	µg/l	3	3	-[d]	43	4.9	-	<3	3	4	12	35	91	343	1015	21700	1.5	5
Ca	ICP-OES	mg/l	0.005	0.01	-[d]	0	0	-	0.43	3.7	9.1	32	66	115	239	377	611	0.92	4
Cd	ICP-QMS	µg/l	0.001	0.003	0.002	420	48	29	<0.003	<0.003	<0.003	<0.003	0.003	0.008	0.02	0.037	1.1	1.1	4
Ce	ICP-QMS	µg/l	0.0005	0.001	0.0001	449	51	13	<0.001	<0.001	<0.001	<0.001	<0.001	0.007	0.024	0.052	6.2	0	5
Cl^-	IC	mg/l	0.01	0.01	-[d]	0	0	-	0.18	0.82	1.4	4.6	13	41	162	378	3627	1.6	5
Co	ICP-QMS	µg/l	0.002	0.01	0.002	138	16	5	<0.01	<0.01	<0.01	0.013	0.023	0.047	0.12	0.36	16	0.93	5
Cr	ICP-QMS	µg/l	0.01	0.2	0.014	592	67	7	<0.2	<0.2	<0.2	<0.2	<0.2	0.28	0.76	1.5	27	0	3
Cs	ICP-QMS	µg/l	0.0005	0.002	0.004[c]	59	6.7	3	<0.002	<0.002	0.003	0.007	0.039	0.51	6.9	24	415	2.8	6
Cu	ICP-QMS	µg/l	0.01	0.1	0.029	139	16	2	<0.1	<0.1	<0.1	0.13	0.27	0.61	2.4	4.7	100	1.1	4
Dy	ICP-QMS	µg/l	0.0002	0.001	0.001	362	41	16	<0.001	<0.001	<0.001	<0.001	0.001	0.003	0.01	0.016	0.39	1.3	4
EC	conductometric	µS/cm	-	-	-[d]	0	0	-	18	88	181	337	588	1256	2580	3582	26500	0.94	4
Er	ICP-QMS	µg/l	0.0002	0.001	0.0004	468	53	13	<0.001	<0.001	<0.001	<0.001	<0.001	0.003	0.008	0.016	0.77	0	4
Eu	ICP-QMS	µg/l	0.0002	0.001	0.001	473	54	18	<0.001	<0.001	<0.001	<0.001	<0.001	0.002	0.005	0.008	0.45	0	4
F^-	IC	mg/l	0.003	0.003	-	2	0.23	-	<0.003	0.024	0.039	0.084	0.19	0.43	1.1	1.6	11	1.2	5
Fe	ICP-QMS	µg/l	0.01	0.5	0.08	381	43	4	<0.5	<0.5	<0.5	<0.5	0.69	3.3	15	43	13500	1.5	6
Ga	ICP-QMS	µg/l	0.0005	0.005	0.005	611	69	4	<0.005	<0.005	<0.005	<0.005	<0.005	0.006	0.013	0.02	3.9	0	4
Gd	ICP-QMS	µg/l	0.0002	0.002	0.001	530	60	22	<0.002	<0.002	<0.002	<0.002	<0.002	0.004	0.009	0.018	0.66	0	3
Ge	ICP-QMS	µg/l	0.005	0.03	0.02	461	52	6	<0.03	<0.03	<0.03	<0.03	<0.03	0.094	0.53	2	110	0	5
Hf	ICP-QMS	µg/l	0.0001	0.002	0.001	722	82	28	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	0.005	0.008	1.6	0	4
Ho	ICP-QMS	µg/l	0.0001	0.001	0.0003	645	73	19	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	0.003	0.005	0.12	0	4
I	ICP-QMS	µg/l	0.01	0.2	0.09	1	0.11	15	<0.2	0.83	1.3	2.4	4.8	11	31	76	4030	1.1	5
K	ICP-OES	mg/l	0.05	0.1	-[d]	4	0.45	-	<0.1	0.3	0.5	0.9	2.1	6.5	18	33	558	1.4	5
La	ICP-QMS	µg/l	0.0001	0.001	0.001	264	30	9	<0.001	<0.001	<0.001	<0.001	0.002	0.007	0.021	0.047	10	2.1	5
Li	ICP-QMS	µg/l	0.01	0.2	0.14	24	2.7	5	<0.2	0.33	0.75	2.6	10	54	298	744	9860	2.3	5
Lu	ICP-QMS	µg/l	0.00005	0.001	0.0002	729	82	16	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.002	0.004	0.41	0	4
Mg	ICP-OES	mg/l	0.005	0.01	-[d]	1	0.11	-	<0.01	0.87	2	5.7	16	32	68	92	4010	1.3	7
Mn	ICP-QMS	µg/l	0.005	0.1	0.111	265	30	2	<0.1	<0.1	<0.1	<0.1	0.54	11	98	249	1870	3.5	6
Mo	ICP-QMS	µg/l	0.001	0.02	0.017	55	6.2	4	<0.02	<0.02	0.031	0.089	0.28	0.82	2.1	4	74	1.6	4
Na	ICP-OES	mg/l	0.02	0.1	-[d]	0	0	-	0.4	1.5	2.3	6	16	76	306	620	8160	1.7	5
Nb	ICP-QMS	µg/l	0.001	0.01	0.001	784	89	15	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.011	0.025	0.54	0	3
Nd	ICP-QMS	µg/l	0.0001	0.001	0.001	258	29	18	<0.001	<0.001	<0.001	<0.001	0.002	0.007	0.019	0.041	5.1	2.1	5
NH_4^+	photometric	mg/l	0.005	0.005	-[d]	573	65	-	<0.005	<0.005	<0.005	<0.005	<0.005	0.028	0.3	0.89	60	0	5
Ni	ICP-QMS	µg/l	0.005	0.02	0.01	39	4.4	4	<0.02	0.022	0.029	0.063	0.18	0.64	2	4.3	95	1.7	4

NO_2^-	IC	mg/l	0.1	0.1	-[d]	854	97	-[e]	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	3	0	3
NO_3^-	IC	mg/l	0.01	0.01 – 1.0[b]	-[d]	387	44	-	<1	<1	<1	<1	1.3	3.9	9.2	15	995	1.4	4
P	ICP-OES	µg/l	0.01	0.01	-[d]	121	14	-	<6.5	<6.5	<6.5	9.8	33	62	95	150	2863	1.4	4
Pb	ICP-QMS	µg/l	0.001	0.01	0.003	340	38	6	<0.01	<0.01	<0.01	<0.01	0.016	0.067	0.17	0.31	2.3	1.7	4
pH	potentiometric	-	-	-	-[d]	0	0	-	4	4.9	5.1	5.5	6.8	7.7	8	8.2	9.9	0.21	1
Pr	ICP-QMS	µg/l	0.00005	0.001	0.0002	601	68	15	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	0.004	0.01	1.5	0	5
Rb	ICP-QMS	µg/l	0.001	0.01	0.30[c]	0	0	6	0.015	0.18	0.27	0.61	2.1	7.7	39	114	631	1.9	5
Sb	ICP-QMS	µg/l	0.001	0.01	0.0001	47	5.3	6	<0.01	<0.01	0.02	0.14	0.27	0.41	0.54	0.68	4.4	0.69	4
Se	ICP-QMS	µg/l	0.005	0.02	0.009	289	33	19	<0.02	<0.02	<0.02	<0.02	0.054	0.18	0.46	0.74	371	2.4	5
Si	ICP-OES	mg/l	0.03	0.03	-[d]	0	0	-	0.42	2	2.7	4.1	6.5	11	17	25	59	0.73	3
Sm	ICP-QMS	µg/l	0.0001	0.001	0.001	360	41	23	<0.001	<0.001	<0.001	<0.001	0.001	0.003	0.007	0.013	0.67	1.4	4
Sn	ICP-QMS	µg/l	0.001	0.02	0.003	718	81	12	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.037	0.096	1.8	0	3
SO_4^{2-}	IC	mg/l	0.01	0.01	-[d]	0	0	-	0.01	1.4	2.8	7.5	20	64	305	809	20342	1.6	7
Sr	ICP-OES	µg/l	0.001	0.001	-[d]	0	0	-	2	20	38	112	326	1035	2906	6906	25500	1.7	5
Ta	ICP-QMS	µg/l	0.0005	0.005	0.002	839	95	-[e]	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	0.005	0.037	0	2
tAlk	titration	mg/l	0.1	0.1	-[d]	2	0.23	-	<2	24	56	152	286	429	1172	1785	16110	0.75	5
tAlk	titration	meq/l	-	-	-[d]	2	0.23	-	<0.03	0.4	0.93	2.5	4.7	7	19	29	264	0.75	5
Tb	ICP-QMS	µg/l	0.00005	0.001	0.0002	778	88	23	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	0.003	0.077	0	3
Te	ICP-QMS	µg/l	0.001	0.03	0.01	777	88	-[e]	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	0.035	0.056	0.32	0	2
Th	ICP-QMS	µg/l	0.0001	0.001	0.0004	635	72	33	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	0.003	0.005	0.15	0	4
Ti	ICP-QMS	µg/l	0.005	0.08	0.04	626	71	52	<0.08	<0.08	<0.08	<0.08	<0.08	0.093	0.25	0.39	6.3	0	3
Tl	ICP-QMS	µg/l	0.0005	0.002	0.001	264	30	6	<0.002	<0.002	<0.002	<0.002	0.0041	0.011	0.035	0.087	2.2	1.7	4
Tm	ICP-QMS	µg/l	0.00005	0.001	0.0002	761	86	22	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	0.003	0.19	0	4
U	ICP-QMS	µg/l	0.00005	0.001	0.006[c]	14	1.6	2	0.001	0.003	0.006	0.028	0.23	0.92	2.3	4.3	229	2.5	7
V	ICP-QMS	µg/l	0.01	0.1	0.02	292	33	6	<0.1	<0.1	<0.1	<0.1	0.17	0.41	1.1	2.1	49	1.8	4
W	ICP-QMS	µg/l	0.002	0.05	0.009	671	76	1	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.14	0.39	28	0	4
Y	ICP-QMS	µg/l	0.00005	0.001	0.002	27	3.1	7	<0.001	0.001	0.002	0.005	0.012	0.038	0.11	0.21	3.5	1.5	5
Yb	ICP-QMS	µg/l	0.0001	0.001	0.001	447	51	17	<0.001	<0.001	<0.001	<0.001	<0.001	0.003	0.01	0.021	1.8	0	5
Zn	ICP-QMS	µg/l	0.01	0.2	0.11	177	20	3	<0.2	<0.2	<0.2	0.25	0.89	3.4	9.2	19	651	1.9	4
Zr	ICP-QMS	µg/l	0.0001	0.001	0.013	81	9.2	7	<0.001	<0.001	0.001	0.002	0.008	0.05	0.3	1	165	2.2	7

*IDL - Instrumental detection limit; **RDL - Reported detection limit; ***PDL - Practical detection limit

(a) P% - Precision at the 95% confidence level

(b) Depends on total dissolved solids (TDS)

(c) Too large concentration range and too many high values to reliably calculate PDL

(d) No duplicate/replicate pairs for the estimation of PDL

(e) Insufficient number of sample values above detection limit to estimate precision

(f) Median Absolute Difference calculated for the log transformed data

(Note: No MAD can be calculated if the median is below the detection limit)

(g) Orders of magnitude

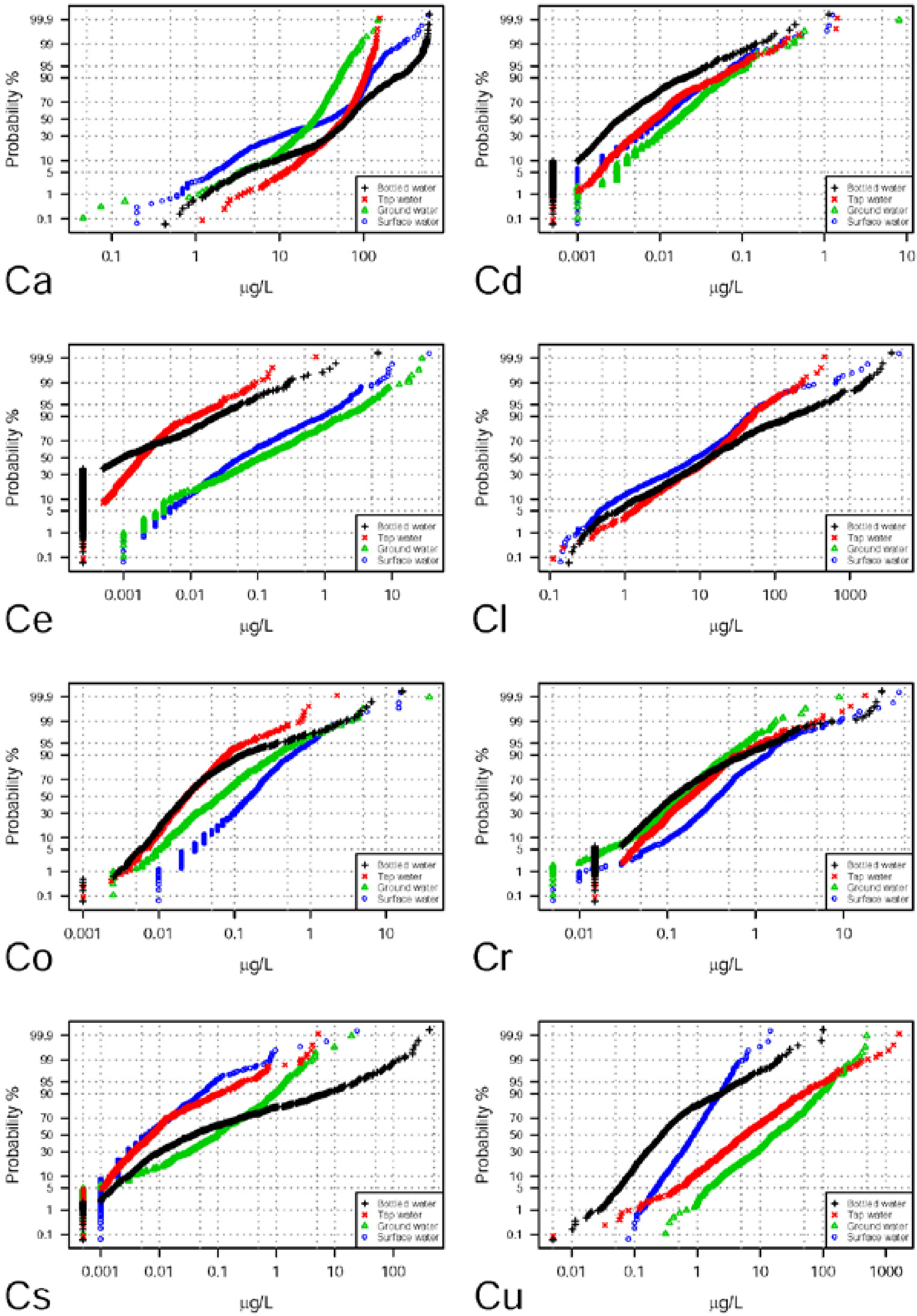

Figure 1: Cumulative probability plots for selected elements in bottled mineral water (n=884) data set (black plus). For comparison values for European tap water (red x – this study), European surface water (blue circle – from Salminen et al.*, 2005) and Norwegian hardrock groundwater (green triangle – from Frengstad* et al.*, 2000) are added to the plots (Source: Reimann and Birke, 2010, Fig. 26, p.55). It is noted that all samples of each data set were analysed in the same laboratory.*

Both characteristics having been preserved intact, because of the underground origin of such water, which has been protected from most pollution risks.

The "natural mineral water" at source must be free from pathogenic microorganisms, and its total bacterial content should comply with strict criteria. It must be of such high microbiological quality that no disinfection is required. Its composition and temperature must remain stable within the limits of natural fluctuation and must not vary with flow rate. A natural mineral water source must have been fully characterised in terms of its geology and chemistry and should be protected against pollution.

The mineral water producers usually print the concentration of some of the major elements on the bottle label. This information provided an ideal opportunity to compare the analytical results produced in this project with those on the labels, which are, in some cases, much older. Mostly, the chemical composition on the labels fits surprisingly well with the produced analytical results (***Figure 2***). Thus, the condition set by EU Council Directive 80/777/EEC of stable composition within the limits of natural fluctuation is met.

Analysis and Quality Control

For the production of a harmonised database of high integrity all samples must be analysed in the same laboratory, over a short period, and under a strict quality control programme. Experience has shown that without exceptionally strict quality control from sampling to laboratory analysis, data sets will never be comparable (Salminen *et al.*, 2005; Demetriades *et al.*, 2014).

The benefits of using a single laboratory are that one deals with a single point of contact for all laboratory requirements, and that all determinations are made under the same roof, using the same instruments, sample preparation, reagents, and technical staff. Optimal laboratory conditions are thus achieved, enabling good repeatability and reproducibility of analytical results. Finally, one deals only with the evaluation of a single set of quality control results. Therefore, the most cost- and time-effective way of producing harmonised, compatible,

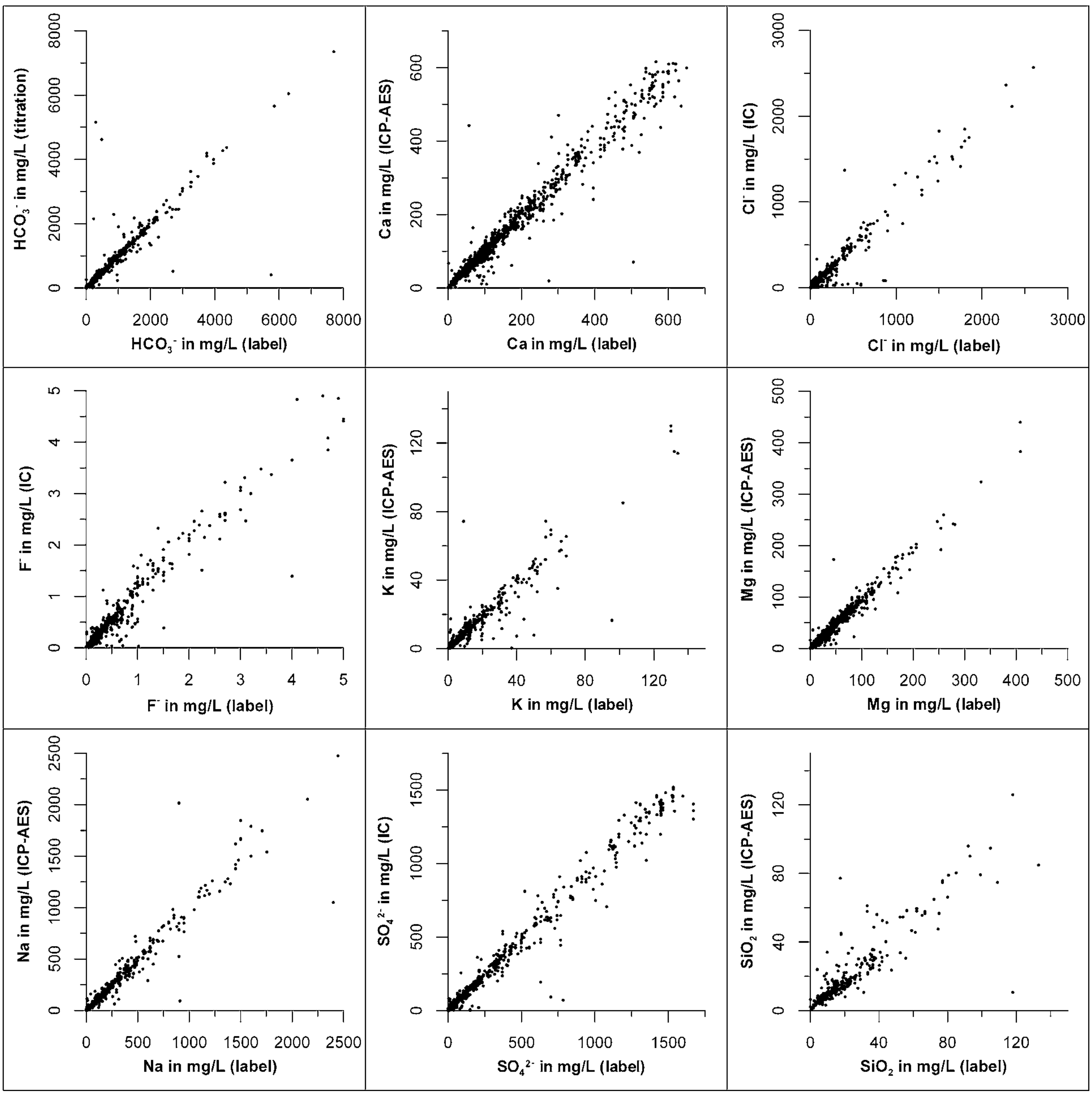

Figure 2: Comparison of the chemical composition displayed on the bottle labels with the measured concentrations of this study (Source: Reimann and Birke, 2010, Fig. 20, p.44).

and reliable analytical results is to collect a manageable number of representative samples, and to use the same laboratory for the analysis of the same suite of determinands.

The 1,785 bottled mineral water samples were all analysed at the chemical laboratory of the Federal Institute for Geosciences and Natural Resources (BGR) in Berlin. Details of sample preparation and the extensive analytical programme are reported in Reimann and Birke (2010) and Birke *et al.* (2010).

Influence of Geology on Groundwater Chemistry

The output from the sampling of bottled mineral water across Europe has clearly shown the influence that geology has on the composition of the natural mineral water of Europe. Geology is one of the key factors influencing the observed element concentrations for a significant number of elements. Examples include:

- high values of Cr, clearly related to ophiolite complexes (***Figure 3***);
- Be, Cs, Li showing high values in areas underlain by Hercynian granite masses (***Figure 4***);
- F, K, Si (***Figure 5***) related to the occurrence of alkaline rocks, especially near the volcanic centres in Italy, and
- V indicating the presence of active volcanism (***Figure 6***).

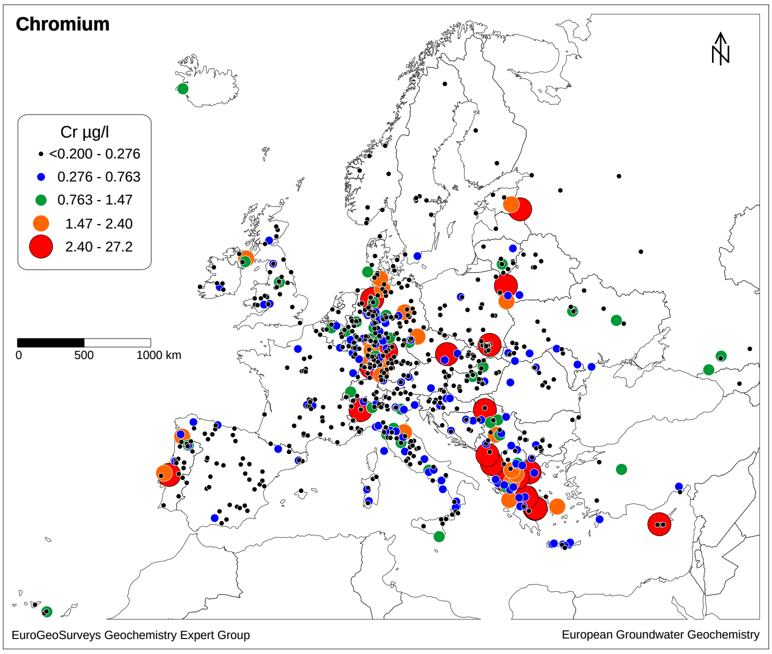

Figure 3: Map of Europe showing the distribution of chromium (µg/l) in bottled mineral water (N = 884).

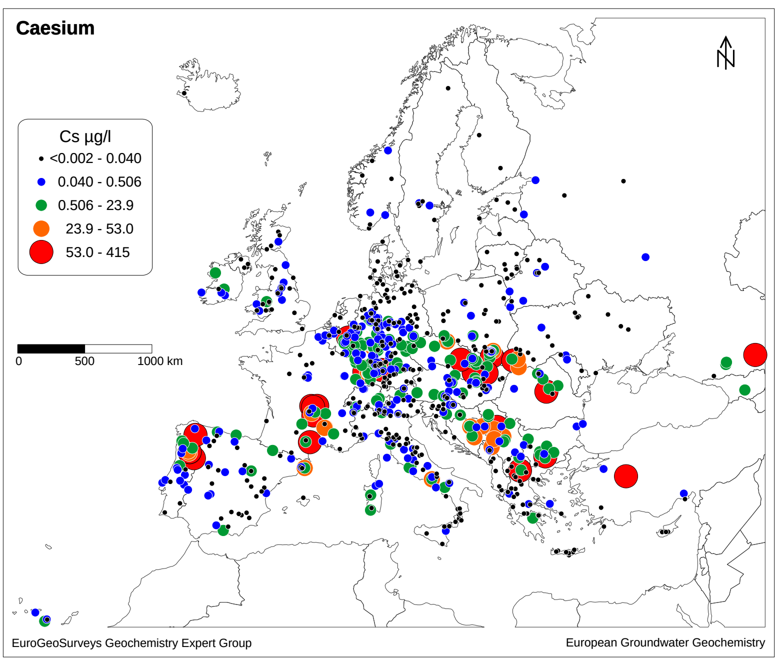

Figure 4: Map of Europe showing the distribution of caesium (µg/l) in bottled mineral water (N = 884).

As is quite apparent, geological components are basically the same across the continent, i.e., a limestone or a granite in one country is essentially similar in chemical composition as in other countries. In fact, the background variation of chemical elements in the same rock unit, depending on the degree of weathering, should be quite comparable from one country to the next.

Discussion

The data presented in the atlas *European Groundwater Geochemistry* (Reimann and Birke, 2010) can be used to gain a first impression of the natural variation of the analysed elements in water at a European scale. Natural variation is enormous, usually spanning three to four and occasionally up to seven orders of magnitude. Several elements for which no potable water standards are defined in Europe (e.g., Be, Bi, Br, Cs, Ga, Ge, I, Li, P, Rb, Sr, Te, Tl, V, Zr) show surprisingly high concentrations in bottled mineral water samples. In terms of health effects, more attention at both ends of the concentration range (deficiency as well as toxicity) may be required for quite a number of elements (e.g., deficiency: I, Se, Zn; toxicity: As, B, Ba, Li, Th, Tl, U, V).

Geology is one of the key factors influencing the observed element concentrations for a significant number of elements. As has already been shown, high values of Cr are clearly related to ophiolite complexes; Be, Cs and Li show high values in areas underlain by Hercynian granite; F, K and Si are related to the occurrence of alkaline rocks, especially near the volcanic centres in Italy, and V indicates the presence of active volcanism. Some elements observed in bottled mineral water are clearly not representative for 'normal' shallow groundwater, but tend to exhibit unusually high concentrations, typical for 'mineral water', e.g., B, Cs, F, Ge, Li, Na, Rb, Te, Tl and Zr.

In terms of water standards, the vast majority of samples fulfil the requirements of the European Union legislation for mineral (and drinking) water. For some elements, a few samples exceed the potable water standards, e.g., the maximum values observed for Al, As, Ba, F^-, Mn, Ni, NO_2^-, NO_3^-, Se and U. It must be noted that the maximum admissible concentration (MAC) for F^- in mineral water is set very high (5 mg/l instead of the 1.5 mg/l valid for drinking water) in order to avoid too many compliance failures (about 5 % of all mineral water samples report F^- concentrations above 1.5 mg/l); this practice is questionable in view of the fact that bottled mineral water is increasingly replacing tap water as general drinking water. European tap water, on the other hand, returned considerably higher concentrations of Cu, Pb and Zn than the bottled mineral water – a likely indication of contamination from plumbing and well installations.

With very few exceptions, all values reported in this study are well below the MAC values, as defined by European legislation. There exist, however, a number of elements that have been indicated as having health effects in the international literature, but for which no MAC values are defined in the European Union. Some of these (e.g., Be, I, Li, Th, Tl and U) exhibit a very large natural variation in bottled mineral water.

Overall, it can be concluded that the idea of using bottled water as a first proxy for groundwater quality at the European scale was not as absurd as it might have appeared at first glance. Despite all the potential problems, it has been shown that natural variation in groundwater quality at the European scale is much larger than the impact of any secondary consideration. Thus, on many hydrogeochemical maps, the importance of geology and other natural processes (e.g., climate) affecting the chemical composition of groundwater is clearly visible. In any case, this continental-scale survey provides valuable experience, and should provoke productive proposals for a more systematic investigation of groundwater quality at the European scale, as this database does not cover evenly the whole of Europe.

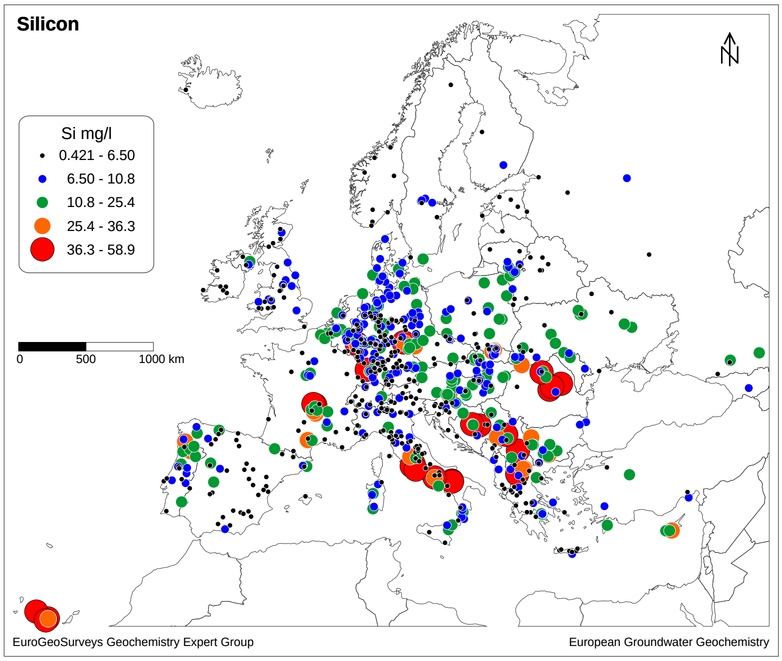

Figure 5: Map of Europe showing the distribution of silicon (mg/l) in bottled mineral water (N = 884).

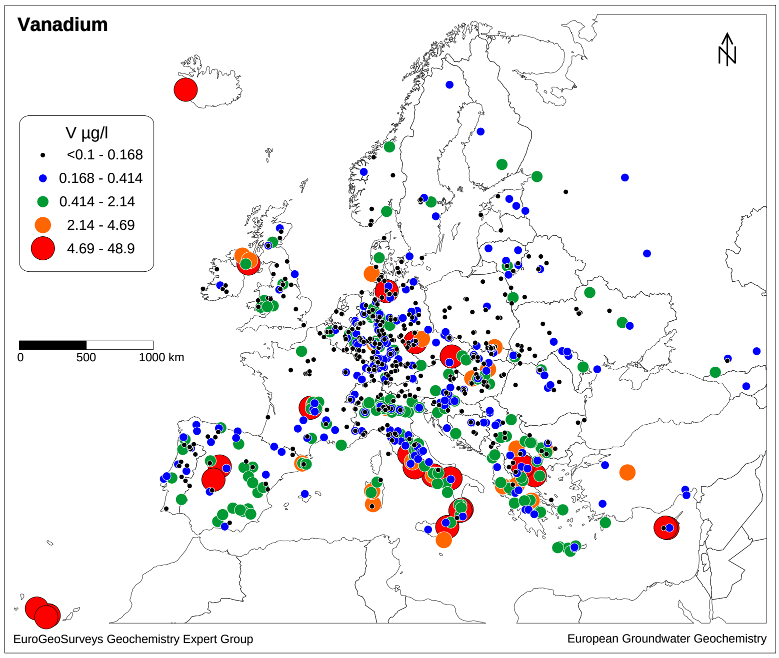

Figure 6: Map of Europe showing the distribution of vanadium (µg/l) in bottled mineral water (N = 884).

Proposal

A continental-scale low-density groundwater survey (e.g., 1 sample site/2,500 km²) should be carried out, based on regular low-density grid cells evenly spaced across the entire continent, with all samples analysed at a single laboratory, and under a strict quality control programme. This is a cost-effective survey, as approximately 1,000 to 2,500 samples will be collected, compared to the very elaborate sampling of all groundwater aquifers with hundreds of thousands of samples, and many laboratories involved. Using this affordable low sample density approach, different water surveys, each covering different sources or water types, can easily be carried out, e.g., for natural spring water, surface water, tap water or water at source from water works. Wherever possible, additional information should be collected about the aquifer type, its lithology, and depth of sampling, and on site-site measurements should be made of pH, Eh, electrical conductivity, and alkalinity. The resulting databases would provide an excellent overview of 'normal' concentrations of chemical elements in different water types and geological settings at the European scale. Such harmonised hydrogeochemical data sets would undoubtedly be very useful for the European legislative process, as well as in a multitude of other applications, e.g., for epidemiological studies.

Whatever the arguments, the first step is to collect harmonised hydrogeochemical data in the proposed systematic way, and to look at the range of concentrations that can occur in 'natural water' at the European scale. The resulting hydrogeochemical atlases, and associated geological interpretation, will certainly help to identify new risks and risk areas and elements that need attention, with respect to both toxicity and deficiency. Public health authorities and European legislators will have, therefore, the necessary background information for sound decision-making.

Until such systematic and harmonised hydrogeochemical data are available at the European scale, it would be beneficial if the present groundwater geochemical database, which resulted from the analysis of bottled mineral water, were complemented with information about the geological setting and well depth.

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Long-term impact of transboundary cooperation on groundwater management

Teodora Szocs, György Tóth, Annamária Nádor, Nina Rman, Joerg Prestor, Andrej Lapanje, Ágnes Rotár-Szalkai, Radovan Černák, Gerhard Schubert*

The Pannonian Basin is Europe's largest intracontinental basin, with numerous transboundary aquifers and groundwater bodies shared by eight neighbouring countries. Good management and governance of shared water resources is essential to ensure regional political and economic stability, as well as the long term sustainable use of groundwater for a wide range of purposes. The delineation of a new transboundary thermal groundwater body (Mura-Zala; 4,974 km²) between Slovenia and Hungary and a much larger aquifer (Upper Pannonian Transboundary Thermal Aquifer; 22,128 km²), extending between Austria, Hungary, Slovakia and Slovenia, is proposed in the west Pannonian Basin. Nine benchmarking indicators were tested to compare management of these aquifers in several countries, as an aid to implementing their joint and harmonised management.

Le Bassin Pannonien est le bassin intracontinental le plus vaste d'Europe, avec de nombreux aquifères transfrontaliers et réservoirs souterrains partagés entre huit pays voisins. Une saine gestion et planification de ces ressources partagées est essentielle pour garantir une stabilité régionale sur les plans politique et économique ainsi que l'utilisation à long terme, à la fois responsable et pérenne, de l'eau souterraine pour un large éventail d'objectifs.
La délinéation d'un nouveau réservoir thermal souterrain transfrontalier (Mura-Zala; 4,974 km²) entre la Slovénie et la Hongrie et d'un aquifère beaucoup plus vaste (l'Aquifère thermal transfrontalier du Pannonien Supérieur; 22,128 km²), s'étendant entre l'Autriche, la Hongrie, la Slovaquie et la Slovénie, est programmée dans la partie ouest du Bassin Pannonien. Neuf indicateurs de référence ont été testés pour comparer la gestion de ces aquifères dans plusieurs pays, en tant qu'aide à la mise en œuvre d'une gestion coordonnée et harmonisée.

La cuenca de Panonia es la cuenca intracontinental más grande de Europa, con numerosos acuíferos transfronterizos y masas de aguas subterráneas compartidos por ocho países vecinos. Una buena gestión y gobernanza de los recursos hídricos compartidos es esencial para asegurar la estabilidad política y económica regional, así como el uso sostenible a largo plazo de las aguas subterráneas para un amplio abanico de propósitos.
La delimitación de una nueva masa de agua subterránea térmica transfronteriza (Mura - Zala; 4.974 km²) entre Eslovenia y Hungría y un acuífero aún más grande (Upper Pannonian Transboundary Thermal Aquifer; 22.128 km²) que se extiende entre Austria, Hungría, Eslovaquia y Eslovenia se propone en el oeste de la Cuenca de Panonia. Nueve indicadores de evaluación comparativa se pusieron a prueba para comparar la gestión de estos acuíferos en varios países, como una ayuda para la implementación de su gestión conjunta y armonizada.

The European Union has set a target of gaining 20% of its energy needs from renewable sources by 2020. This goal, with different individual targets in the member states, is represented in the National Renewable Energy Action Plans. As the Pannonian Basin is a hot sedimentary basin an increase is expected in the utilisation of geothermal energy, and subsequently of thermal groundwater. An increase in the use of thermal water for agricultural and other purposes has also been observed over the past 15-20 years; these developments are currently uncoordinated on a regional and sectorial scale. Good management and governance of shared water resources is essential to ensure regional political and economic stability, as well as the long term sustainable use of groundwater for a wide range of applications.

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Aquifers generally range in size from a few to thousands of square kilometres and in many cases they are transboundary. Eleven important transboundary groundwater bodies have been delineated by the International Commission for the Protection of the Danube River (ICPDR) at the level of the Danube River Basin. As Hungary is situated in the middle of the Pannonian Basin, 7 important transboundary groundwater bodies out of the 11 in the Danube River Basin are shared by Hungary. Although the delineation of these groundwater bodies was done with the aim of common water/groundwater management, no real common bilateral or multilateral actions were taken. If we consider that there are also bilateral agreements related to cross-border water/groundwater issues, the lack of common surveys or long-term sustainable management of groundwater resources is even more conspicuous. The only good example of an operating management plan in the Danube River Basin is for the Austrian-German Jurassic thermal karst groundwater body, where a common hydraulic model was developed which is used by both countries' regional authorities in order to be able to manage the thermal water resources in a sustainable way.

The transboundary character of aquifers in the west Pannonian Basin was previously investigated in the framework of the TRANSTHERMAL project (Götzl *et al.*, 2008), and in the ENWAT project (Brezsnyánszky *et al.*, 2008). The first project focussed on the geothermics of the Eastern and Southern Alps, the second on the environmental state and sustainable management of three Hungarian-Slovakian transboundary groundwater bodies.

The European Union recently co-funded two international projects focusing on the implementation of good groundwater governance. A proposal for a joint aquifer management plan across the Hungarian-Slovenian border has been demonstrated within the framework of a bilateral Hungarian–Slovenian project "Thermal Joint Aquifer Management (T-JAM)" to be an effective model for common aquifer management (Prestor *et al.*, 2011). Moreover, the TRANSENERGY project provided support for a harmonised thermal water and geothermal energy utilisation management strategy for Austria, Hungary, Slovakia and Slovenia (Nádor *et al.*, 2013). The Upper Pannonian Transboundary Thermal Aquifer was one out of 199 aquifers incorporated into the comparative assessment of transboundary aquifers within the framework of the continuation of the Transboundary Waters Assessment Programme (TWAP) project, funded by the Global Environment Facility (GEF).

Although these projects forecast a rapid increase in thermal water demand (Rman *et al.*, 2015) and investigated its possible environmental impact on the status of groundwater resources, the project results have not yet been implemented.

Surveys and bilateral or multilateral characterisation of transboundary thermal aquifers

The results of joint surveys of the transboundary thermal aquifers in the western part of the Pannonian Basin carried out by national geological surveys within the framework of the T-JAM and TRANSENERGY projects are presented below. This includes a proposal for delineating a transboundary groundwater body together with guidelines for joint cross-border thermal groundwater management.

Hungarian–Slovenian porous intergranular thermal aquifer – A proposed Transboundary Thermal Groundwater Body 'Mura-Zala'

On the basis of joint geological, hydrogeological and geothermal models, and related hydrogeochemical evaluation, a Slovenian–Hungarian cross-border thermal water flow was identified and simulated by a numerical hydraulic model. Based on the data interpretation it was proposed to define a common Transboundary Thermal Groundwater Body (TTGWB) between Slovenia and Hungary with the tentative name of 'Mura-Zala'. It covers an area of 4,974 km2, of which 1,151 km^2 fall in the territory of Slovenia and 3,823 km^2 in Hungary (***Figure 1***). As it is larger than 4,000 km^2, it is also important on the level of the Danube River Basin. The length of the shared international boundary of the proposed Mura-Zala TTGWB is 108 km.

The delineation of the proposed Mura-Zala TTGWB was based on the geological extent of the major thermal aquifer system, the major recharge and discharge areas, as well as the potential impact areas and state borders.

In the Hungarian part the borders of the porous thermal groundwater bodies delineated for the EU Water Framework Directive River Basin Management Plan were followed, wherever possible. As the Hungarian porous (intergranular) thermal groundwater bodies are large, the eastern and southeastern boundary was defined based on the potential impact territory. In the Hungarian part Lake Hévíz and its vicinity was also included, because it is closely connected to the investigated thermal groundwater flow system and it is an important, entirely groundwater-dependent ecosystem in this region.

In Slovenia, the proposed Mura-Zala TTGWB is delineated by the Slovenian–Croatian state border in the south and by the Slovenian–Austrian state border to the north. In the northwest this is defined by the pinching out of the Upper Pannonian (Mura) Formation, and in the west by the surface water divide between Mura and Drava rivers at the Slovenske Gorice Hills. The surface water divide does not affect the thermal groundwater flow, but hydraulic modelling showed that the abstractions lying to the west of the divide have negligible impact on the hydraulic head and water budget at the Hungarian–Slovenian border. This delineation was also chosen to ease the administrative and management strategies of the proposed Mura-Zala TTGWB.

The upper boundary of the proposed intergranular Mura-Zala TTGWB was proposed to be delineated at 500 m below surface because the majority of geothermal wells are screened below this depth. Its bottom, which is proposed to be delineated at 2,200 m below the surface, can be considered as a no-flow boundary due to the clayey aquitard-aquiclude complex of the Upper Miocene delta slope facies. Hydrodynamically, it is open to the neighboring cold and thermal intergranular, fissured and karstic aquifers from where it recharges and discharges.

The regional groundwater flow occurs from west to east (***Figure 1***), and the water balance before the main thermal water abstraction was strongly positive for Hungary, with a 59.5 l/s water surplus from Slovenia. At an average abstraction as in 2009 (61.8 l/s in the Slovenian and 67.3 l/s in the Hungarian part), this cross-border groundwater flow decreased to 50.1 l/s, but this does not endanger the good regional quantity status of the Hungarian thermal groundwater body. Based on the hydraulic modelling it was demonstrated that an extreme production scenario (five times the 2009 abstraction rate) would result in only a 7.5 l/s surplus flowing from Slovenia to Hungary.

The general environmental objective of the Water Framework Directive is to maintain the good status and to prevent deterioration of the actual status of groundwater bodies. Therefore, a critical groundwater level and a critical abstraction value were defined for the Mura-Zala TTGWB. The critical groundwater level was defined as a maximum regional drawdown measured in observation wells. Its value was set at 30 meters below the original potential values that were characteristic before the thermal water abstraction phase. The critical thermal water abstraction value was set at the maximum of a 3.5-fold increase of abstraction rate in comparison to 2009 in

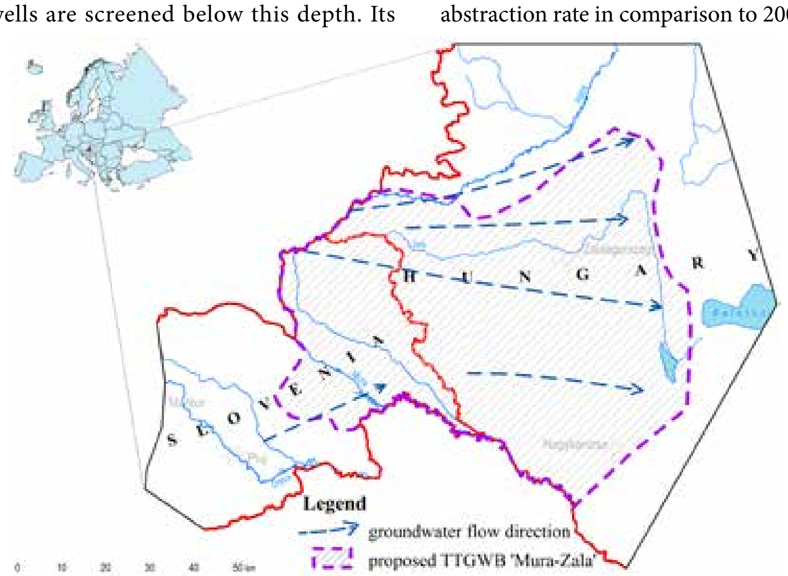

Figure 1: The proposed 'Mura-Zala' Transboundary Thermal Groundwater Body with the regional groundwater flow directions.

the area up to 20 km from the state border. These values shall be restricted locally if deterioration of the aquifer state becomes evident.

Regarding the sustainable management of the proposed Mura-Zala TTGWB, an increase in thermal efficiency and re-injection technology should be prioritised in order to gain more geothermal energy independence from higher thermal water abstraction. "Sensitive areas" for further development are suggested for delineation in 10-15 km zones around the major production sites. A transboundary monitoring system of representative (existing) wells should be established with yearly exchange of production and monitoring information. Thus we selected 17 observation wells according to the areal proportion, 5 observation wells from the Slovenian part and 12 from the Hungarian part of the Mura-Zala TTGWB. In the border area between Lendava and Lenti a co-funded and jointly-operated representative monitoring well was also proposed, because this area has the highest geothermal potential in the region and the main flow path of thermal water is expect to cross the border from Slovenia towards Hungary here. This observation well would provide regional hydraulic head measurements and also quality data on the cross-border thermal water flow. The numerical hydraulic model should be updated at least every 6 years based on the data exchanged yearly between Hungary and Slovenia. These recommendations for joint transboundary management and monitoring were presented to the Permanent Hungarian-Slovenian Water Management Committee in 2011.

Hungarian-Slovenian-Austrian-Slovakian porous intergranular thermal aquifer – The Upper Pannonian Transboundary Thermal Aquifer

Based on the lessons learnt in the framework of the T-JAM project, 3D geological, hydrogeological and geothermal models developed by the geological surveys of Hungary, Slovenia, Austria and Slovakia within the TRANSENERGY project enabled identification of a large Upper Pannonian transboundary thermal aquifer (TTA). It was delineated in Austria, Hungary, Slovakia, and Slovenia, but its continuation into Croatia was not investigated (Nádor *et al.*, 2013). The Upper Pannonian aquifer extends over 22,128 km^2 (***Figure 2***) in the first four countries based on a three-dimensional geological model. It is composed of the whole Upper Pannonian (Upper Miocene) sequence of clastic sandy and silty sediments, both those deposited in the delta

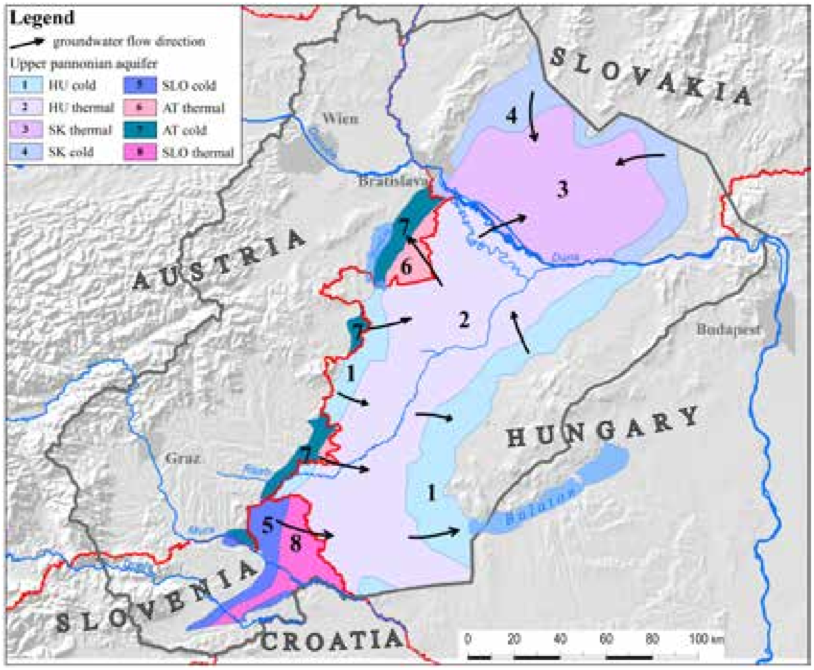

Figure 2: Delineation of Upper Pannonian Transboundary Thermal Aquifer and predominant groundwater flow directions (after Tóth et al.*, 2012).*

front as well as the delta plain environment.

Due to continuous delta progradation the interconnectivity of sand bodies is very good. They have good permeability and the sandy-silty sequence behaves as one hydrostratigraphic unit and forms a regional, highly productive intergranular aquifer. In the same way as the proposed Mura-Zala TTGWB, the bottom of the aquifer is defined by the clayey aquitard-aquiclude complex of the Upper Miocene delta slope facies. Except for its no-flow boundary bottom, it is hydrodynamically connected to the upper and to the horizontally neighbouring units (***Figure 2***). It has an open hydrodynamic connection also with groundwater-dependent ecosystems at Lake Hévíz (HU) and Lake Neusiedl (AT). The regional groundwater flow is generally directed from Slovenia and Austria to Hungary, from west to east in the southern part of the aquifer. In its northern part the groundwater recharged in Slovakia flows from the cold-water-bearing Upper Miocene aquifer mainly to the south and partly from NE to SW to Hungary. One flow component is directed from SW to NE from Hungary to Slovakia, in the south part of the Danube basin. Hydraulic modelling has simulated discharge along the Danube River and Lake Neusiedl (AT).

In total, the current thermal water abstraction from the Upper Pannonian thermal aquifer was calculated to be approximately equivalent to 48% of the original infiltration, being roughly 1 mm/year. This abstraction has already caused the regional groundwater level to decline by up to 10 m, but near the production sites the drawdown is even higher (***Figure 3***). Based on regional hydraulic modelling (Tóth *et al.*, 2012) the transboundary drawdown cones extend several tens of kilometres into the neighbouring countries. The hydraulic simulation forecasts that most changes in groundwater flow rate and direction will occur at the Slovenian-Hungarian and Hungarian-Slovakian border (decreasing the water budget towards Hungary), but changes at the Austrian-Hungarian border are also likely to occur (decreasing towards Austria).

Measures to prevent depletion of this thermal aquifer are very similar to those proposed for the 'Mura-Zala' TTGWB. Additionally, a set of benchmarking indicators for use as a tool to identify strengths and weaknesses of current management of thermal water abstraction has also been developed, tested and subsequently recommended to the relevant authorities.

Benchmarking methodology – indicators for (transboundary) thermal water abstraction management

An objective and transparent method is needed in order to quantify and evaluate the different parameters of thermal water utilisation that are critical for the sustainable use of geothermal aquifers exploited by several users or neighbouring countries. A concept developed for the better management of the region around Lake Geneva (Lachavanne

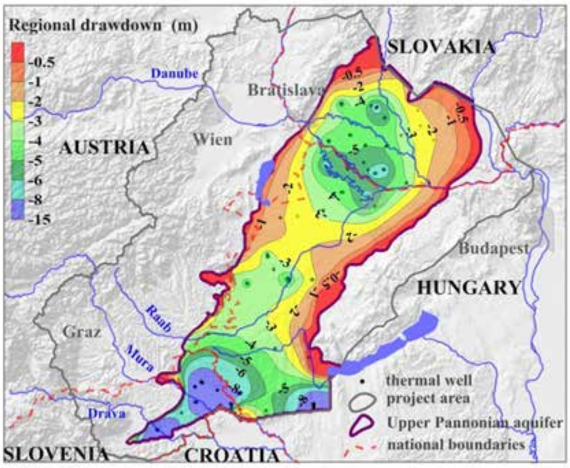

Figure 3: Simulated regional drawdown in the Upper Pannonian aquifer at the current thermal water abstraction rate (after Tóth et al. *2012).*

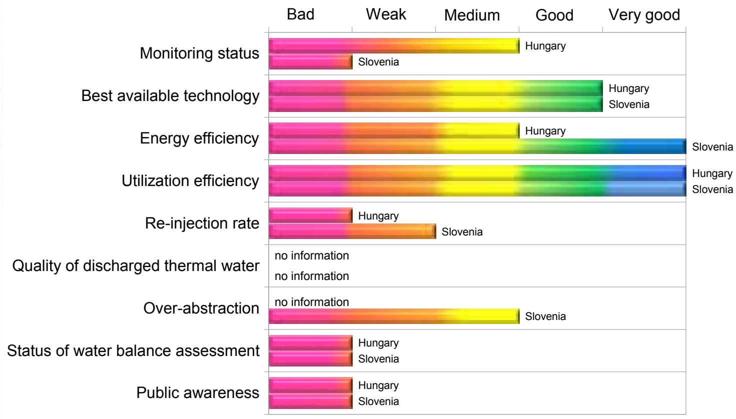

Figure 4: Comparison of management practices in the Upper Pannonian Transboundary Thermal aquifer between Hungary and Slovenia in the Mura-Zala basin based on benchmarking parameters.

and Juge, 2009) was adapted and extended in order to be applicable to thermal water management. Originally 10 indicators were defined within the TRANSENERGY project, later modified to nine based on the results of data, information availability and their relevance (Prestor *et al.*, 2015). These indicators are based on an objective calculation method which requires detailed information on individual wells, including their operation. The results are classified in five descriptive categories: bad, weak, medium, good and very good, which allows fast and transparent comparison between regions or states, as shown for the Mura-Zala region in ***Figure 4***.

The nine benchmarking indicators are:

1. Monitoring status (if mandatory, unified and integrated monitoring exists),
2. Best available technology (if appropriate technical parameters of well installations, their documentation and cascade use are applied),
3. Thermal efficiency (ratio between used and available annual heat energy),
4. Utilisation efficiency (ratio between the average annual and maximum allowable water production),
5. Re-injection rate (ratio between the reinjected and produced volume of thermal water used for geothermal energy production),
6. Quality of discharged thermal water (how many wells fulfil the legislative standards for wastewater emissions),
7. Over-abstraction (status of the aquifer based on the impact of thermal water production),
8. Status of water balance assessment (depth and reliability of information on the quantity status of the aquifer),
9. Public awareness (open-access information on monitoring, BAT, aquifers' quantity status and thermal efficiency).

These indicators need to be checked both when water permits are issued and when they are renewed, including concessions on thermal water use. A detailed description of the methodology is presented by Prestor *et al.*, (2015).

As ***Figure 4*** shows, utilisation efficiency, energy efficiency and best available technology are mostly good or very good in the Mura-Zala basin, while monitoring and over-abstraction indicators should be improved. Development of re-injection is crucial for the long term sustainable use of thermal waters not just in this basin, but in the whole Upper Pannonian TTA. In the framework of this investigation we only checked whether re-injection is applied or not. In the future, it will be necessary to differentiate between re-injection into the aquifer from where the water is being abstracted and re-injection into other aquifers or at different depths of the same aquifer. There is a lot to do regarding knowledge on the depth and reliability of information on the quantity status of the aquifer, and public awareness should also be increased.

All countries have legislation in which the monitoring procedures and standards for the discharged waste (thermal) water are regulated, concerning direct emissions into the environment or indirect through sewer systems and water treatment plants. Since this type of information was not collected within the surveys of water utilisation, we could not test the applicability of this indicator in the Mura-Zala basin, but in fact information was either absent or difficult to obtain at the study areas.

Conclusions

Very important steps have already been taken by the four neighbouring countries in the west Pannonian Basin towards establishment of a joint and harmonised management of transboundary thermal groundwater bodies. A Transboundary Thermal Groundwater Body 'Mura-Zala' – also important on the Danube River Basin level – between Slovenia and Hungary was proposed for delineation. The Upper Pannonian Transboundary Thermal aquifer was also delineated and then characterised in the framework of the Transboundary Waters Assessment program in 2014 (TWAP).

The nine benchmark indicators defined within the framework of the TRANSENERGY project and tested at different transboundary regions within the Upper Pannonian Transboundary Thermal aquifer are seen to be a useful tool in transboundary groundwater management. Some of the indicators referring to geothermal investigations can be complementary to the Guidelines published by IGRAC and UNESCO-IHP (2015).

Based on our surveys we can conclude that:

- Priorities in groundwater usage have to be defined.
- Harmonised datasets and information should form the basis of common understanding and evaluation of resources.
- The joint and harmonised evaluation applied here can be seen as good

examples for other regions sharing transboundary resources.

- Well operating monitoring is required.
- Benchmarking criteria can be a tool to achieve a better evaluation of the use of the hydro geothermal transboundary resources.
- Re-injection development should be promoted.
- In addition to national management, sustainable long-term governance of transboundary aquifers is essential in the Pannonian Basin.

It also became clear that due to the geological setting of the Upper Pannonian transboundary geothermal aquifer, joint investigation and management need to be extended into other parts of the basin. We plan to expand our cooperation based on lessons learnt. As a first step a data availability survey for geothermal energy utilisation development through the use of thermal water is being carried out through the START Danube Region Project Fund. This includes the geological surveys of Bosnia & Hercegovina, Croatia, the Czech Republic, Romania, and the University of Belgrade under the coordination of the Geological and Geophysical Institute of Hungary. Further joint transboundary survey and thermal water and geothermal energy management plan guidelines are planned within the Danube Transnational Programme, extending our studies to the south and south-eastern part of the Upper Pannonian aquifer and an aquifer in the basement between Serbia and Bosnia-Hercegovina.

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Role of hydrogeological mapping in groundwater practice: back to basics

Helder I. Chaminé, José Martins Carvalho, José Teixeira and Liliana Freitas*

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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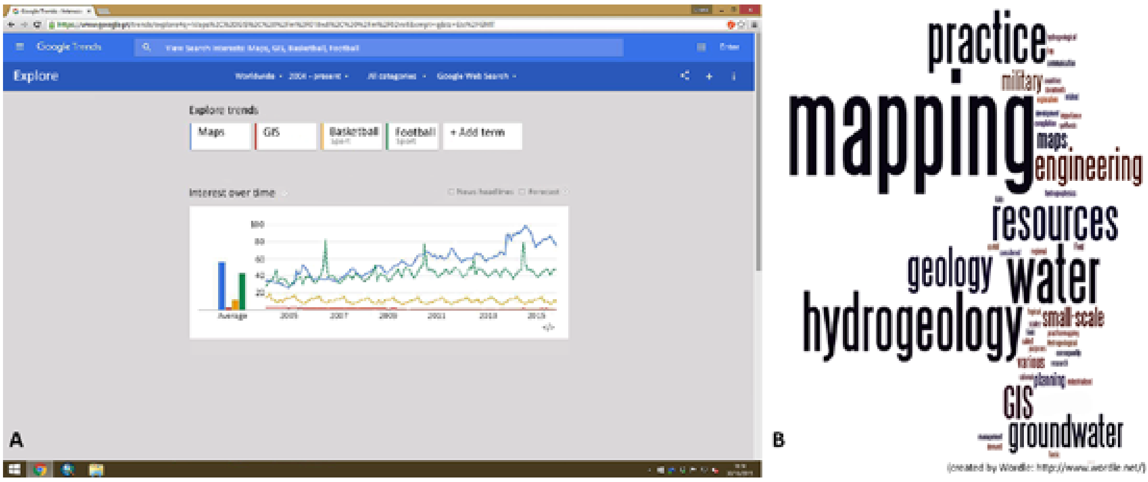


*Figure 1: A) Google Trends (***https://www.google.com/trends***) comparison of searchers for the terms (2004–present; accessed in August, 2015): maps, GIS, basketball and football (adapted and updated from MacEachren, 2013); B) Cloud diagram based on keywords about hydrogeological mapping in practice.*

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

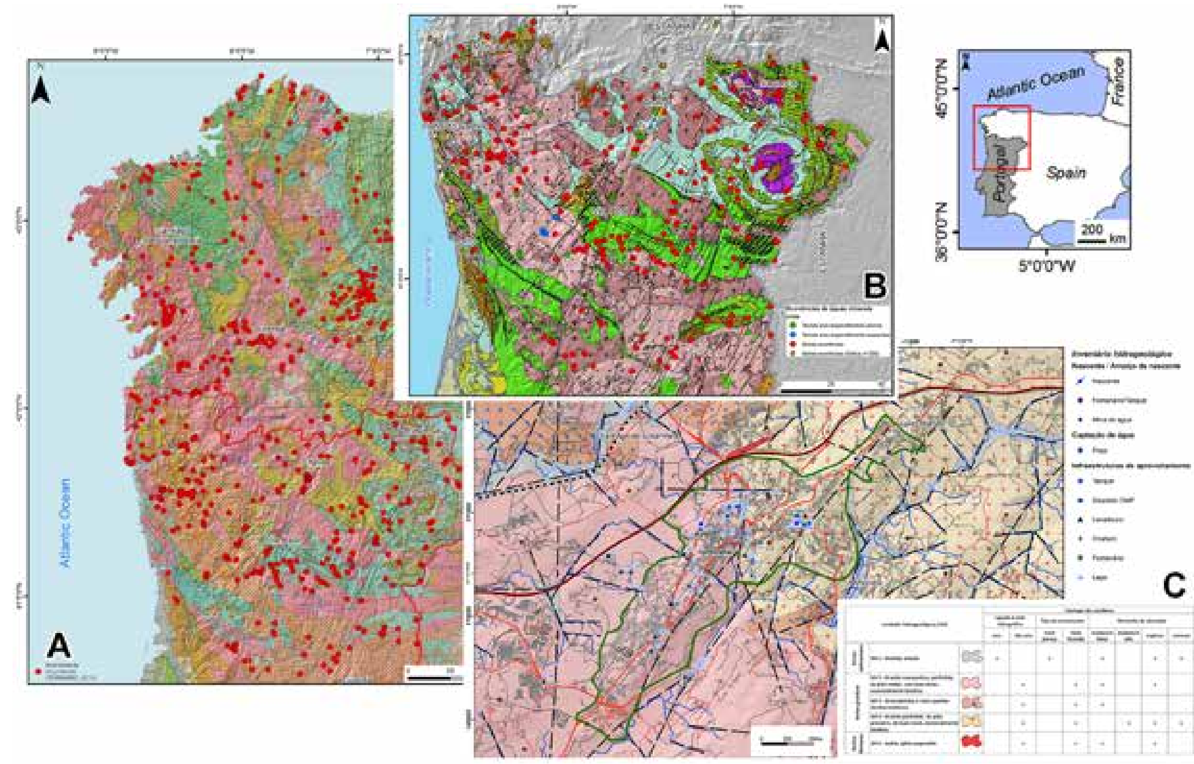


Figure 2: Examples of hydrogeological maps at several scales and for diverse purposes (archives of LABCARGA|ISEP and TARH Lda): i) large-scale mapping – A) hydromineral resources inventory for Northern/Central Portugal and Galicia (Spain); B) hydrogeological map and hydromineral occurrences for Northern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

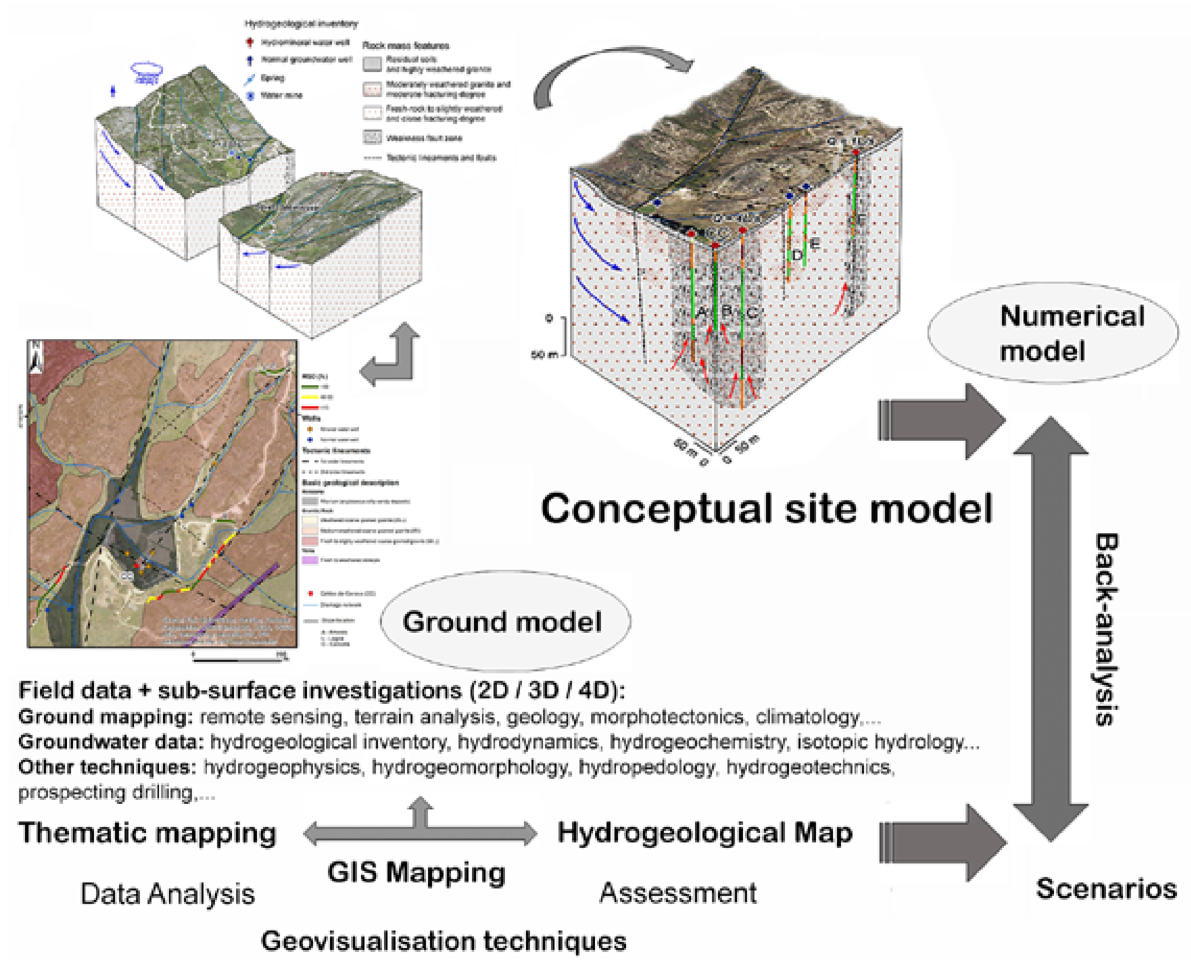


Figure 3: The role of mapping in development of conceptual site models in practice based on hydrogeological in situ investigations has focused on terrain analysis (remote sensing, geology, morphotectonics, surface hydrology, etc.), characterisation of surface outcrops (geology, hydrogeotechnics, hydropedology, 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

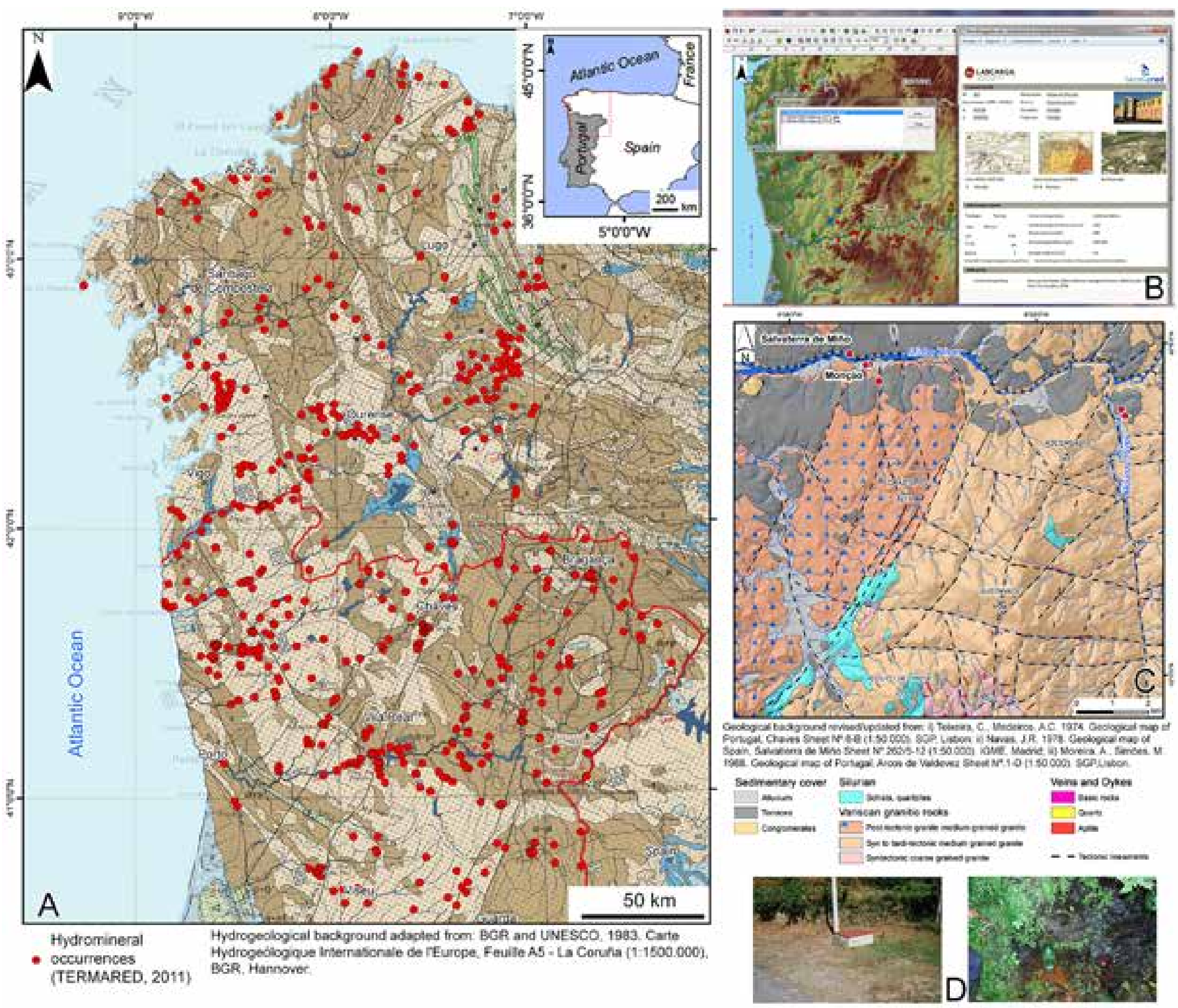
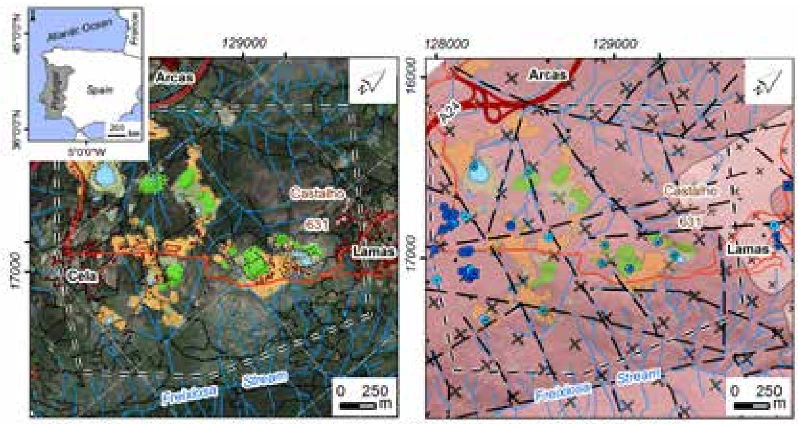


Figure 4: Northern Portugal and Galicia (Spain) framework: hydromineral resources inventory from the TERMARED project. A) Hydromineral resources inventory map for NW Iberia, over 590 hydromineral occurrences mapped; B) application tool to create hyperlinks between features (line, point or polygon) and 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, m²/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

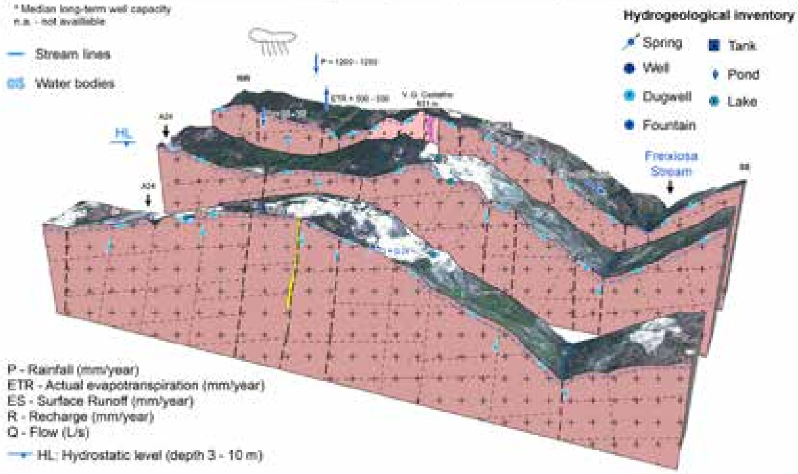


Figure 5: Cela area (Castro Daire, N Portugal) framework: hydrogeological mapping and conceptual model site.

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.*,

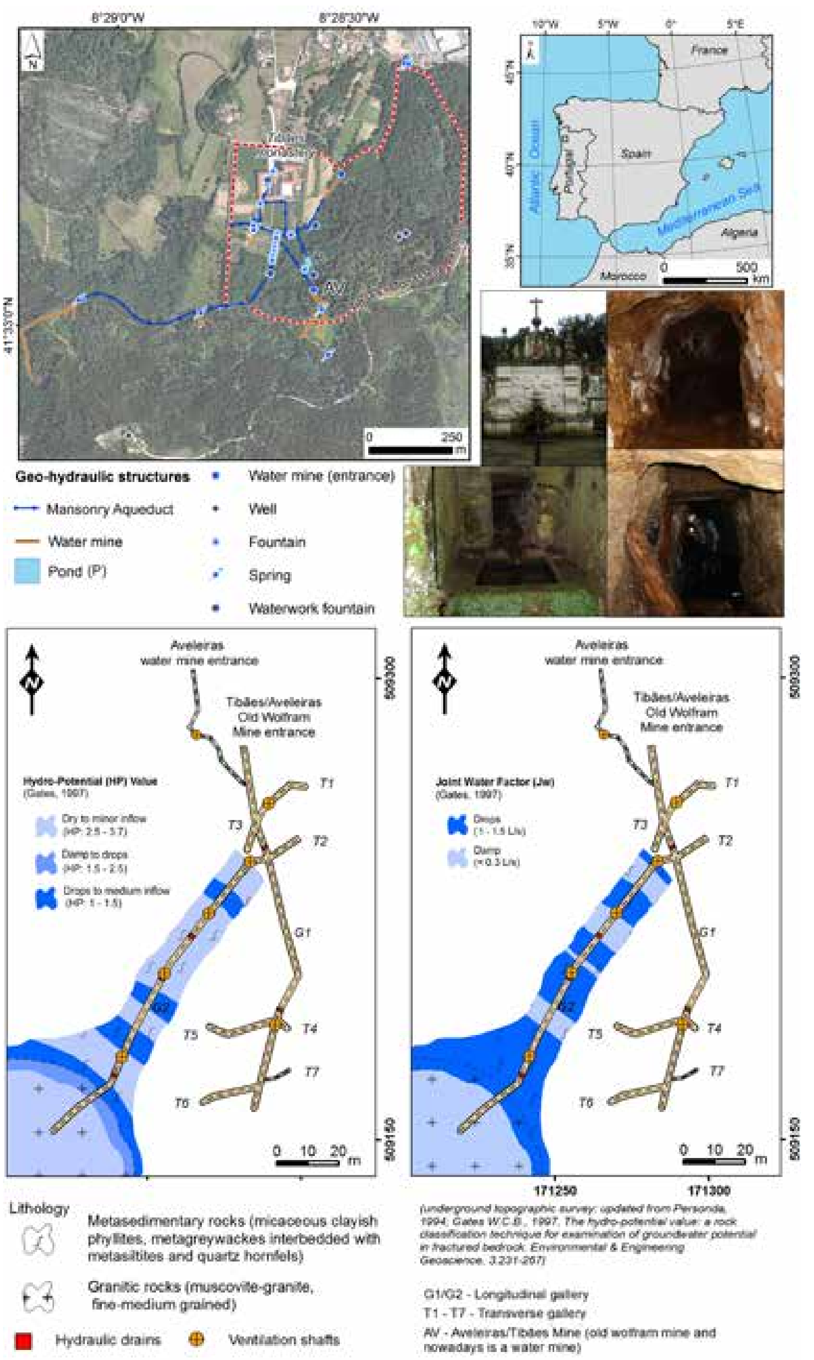


Figure 6: Aveleiras mine, S. Martinho de Tibães (Braga, NW Portugal) framework: detailed hydrogeomechanical zoning map for mining hydrogeology and hydrogeotechnics in situ investigations.

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"*.

Acknowledgements

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Equalising flow in water wells: from theory to practical results

*Jordi Pujadas-Ferrer**

Well ageing processes (loss of yield, sand pumping, turbidity, mineralogical incrustation and biofouling) area related to a non-uniform, high flow regime in the well. In that paper we review flow equalisation, a technique which counteracts non-uniform flow pattern, and present results from two experiences with Spanish water wells. In this study previously published results for equalisation were reproduced and equalization's applicability was extended to highly incrusted wells. In a time when economic and environmental aspects lead to increasing interest in rehabilitation techniques, equalisation deserves attention for its results in the improvement of well hydrodynamics and reduction of well ageing processes.

*Des signes de vieillissement de puits (perte de débit, sable dans pompage, turbidité, incrustation minérale et accumulation de micro-organismes), sont liés à un régime de puits non uniforme et de débit de crue. Dans cet article, nous examinons le contrôle de débit (*équalisation*), une technique qui régule le modèle de débit non uniforme, et présentons les résultats fournis par deux expériences réalisées sur des puits, en Espagne. Lors de cette étude, des résultats publiés précédemment pour l'*équalisation *ont été reproduits et les conditions d'applicabilité de ce contrôle de débit ont été étendues à hauteur de puits fortement incrustés. Au moment où les critères économiques et environnementaux contribuent à un regain d'intérêt pour les techniques de réhabilitation, l'*équalisation *mérite une attention particulière pour ses résultats dans l'amélioration des caractéristiques hydrodynamiques et la réduction des phénomènes de vieillissement des puits.*

Los procesos que deterioran los pozos (pérdida de rendimiento, arrastres, turbidez, incrustación y biofouling) están estrechamente relacionados con la existencia de un régimen de flujo heterogéneo con velocidades elevadas. En éste artículo se presenta una revisión de la ecualización del flujo, una técnica que corrige el régimen de flujo, y se presentan los resultados de dos experiencias en pozos en España. En ellas se han reproducido resultados publicados y se extiende la aplicabilidad de la ecualización a pozos fuertemente incrustados. En una época en la que la rehabilitación de pozos gana aceptación por criterios económicos y ambientales, la ecualización es una técnica de interés por sus resultados, al mejorar el régimen de flujo y reducir los procesos que causan el envejecimiento de los pozos.

1. Introduction

The utilisation of fresh water, especially groundwater, has been increasing all over the world. This is why the maintenance of wells and development of new techniques for sustainable operation and well diagnostics are very important. Well ageing processes are related to the flow regime. The aim of this paper is to focus on the importance of flow regime in the well ageing process and to show practical results using a technique that improves flow regime and reduces well ageing.

1.1. The basics of well hydraulics

The general approach to well hydraulics (Driscoll, 1986) assumes that the flow enters the well uniformly distributed along the screen. Flow entrance velocity is simply estimated as the ratio between discharge and the open area of the screen without any consideration of other variables. Traditional well design considers low entrance velocity a key factor in order to maintain laminar flow, reduce head losses, allow better well development and reduce ageing (Sterrett, 2007; Wenling *et al.*, 1997).

But well hydraulics are actually more complex, as has been outlined by theoretical analyses and laboratory simulation since the 1960s. Pump suction creates a lower pressure area that modifies the original schema of a uniform vertical flow distribution (***Figure 1***). Assuming a pump located above the screen area, the flow is characterised by:

- a maximum inflow velocity zone in the upper area of the screen, located close to the pump and decreasing exponentially downwards (Kirschmer and Ueker 1966, Kirschmer 1977).
- a vertical flow component in the gravel pack created by the unequal flow distribution along the screen (Truelsen, 1958). These vertical flows could increase the inflow velocity by up to 50 times (Ehrhardt, 1986).

As a result of this flow distribution, water flows mainly across the uppermost part of the screen, whereas water from the lowest part of the well flows through the gravel pack, also rising to the upper part of the screen, so that the rest of the screen acts weakly or does not act at all (Pelzer, 1991).

1.2. Flow pattern and well ageing processes

The presence of areas of high velocity creates zones prone to several processes that cause the ageing of wells and also affect the water quality: sand pumping and increased turbidity, mineral incrustation and biofouling.

For these flow patterns, it is very common for the upper part of the screen to display more development of incrustations. When the pump is located at the

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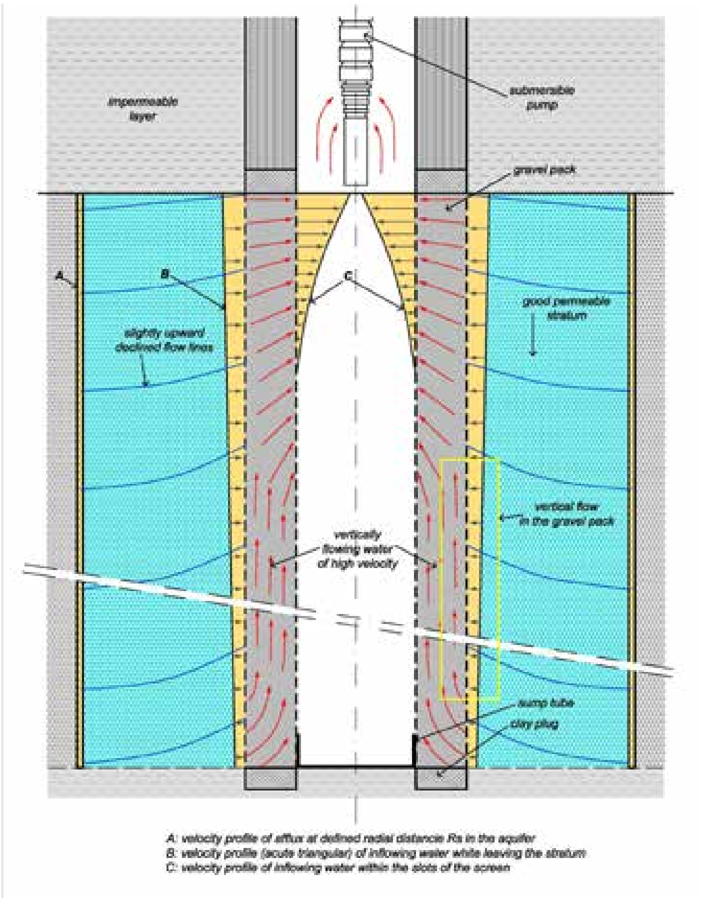

Figure 1: Flow distribution inside a well: flow concentrates in the area closest to the pump; this unequal distribution along the screen creates a vertical flow through the gravel pack located in the annular space (modified from Pelzer, 1991).

bottom, incrustations develop from the pump upwards. Caliper measurement and camera inspection allow quantification of the thickness of incrustation, which helps to describe the flow pattern inside the well (***Figures 2 and 3***). In the first example (***Figure 2 and 3, left***), the process of incrustation has led to complete clogging from the pump area to the bottom. The well bottom is filled with sediments due to the failure of the bottom concrete pad because of suffusion. In the second example (***Figure 2 and 3, right***), the caliper measurement shows a first area (***arrow in Figure 2, right***) of thick incrustations at 50 m depth, related to the initial position of the pump, while a main incrusted area is near the second pump position. .

Houben and Treskatis (2007) describe a gradual pattern of incrustation that starts in the area of high velocity (usually the area closest to the pump) and, as incrustation closes the openings, the area of maximum flow displaces downwards to less incrusted areas, until the screen is completely incrusted.

1.3. Equalisation and SFCD

Equalisation is a technique which tries to counteract the asymmetrical flow pattern in the well described above, creating a uniform distribution of flow over the total length of the well screen. The first ideas for equalisa-

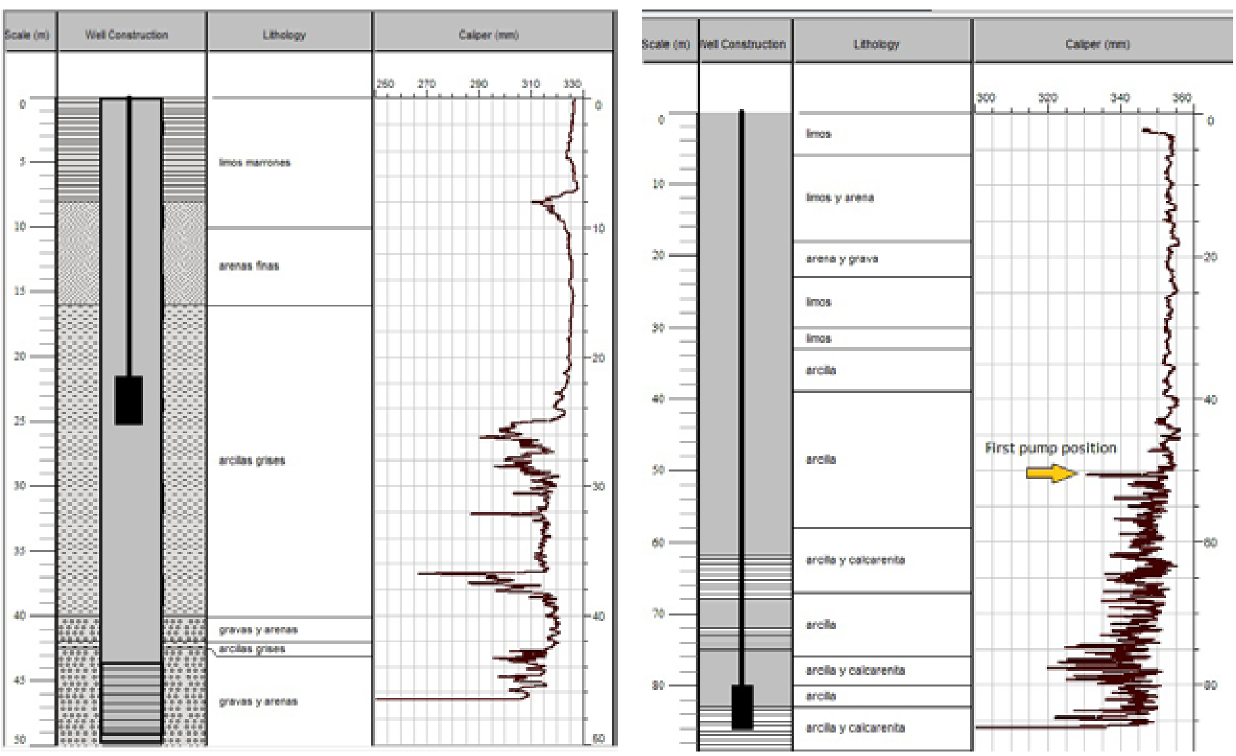

Figure 2: Well profile and caliper measurement of wells with a different pump position. The left-hand example is comparable to Well B and the right-hand profile corresponds to Well A, as shown below.

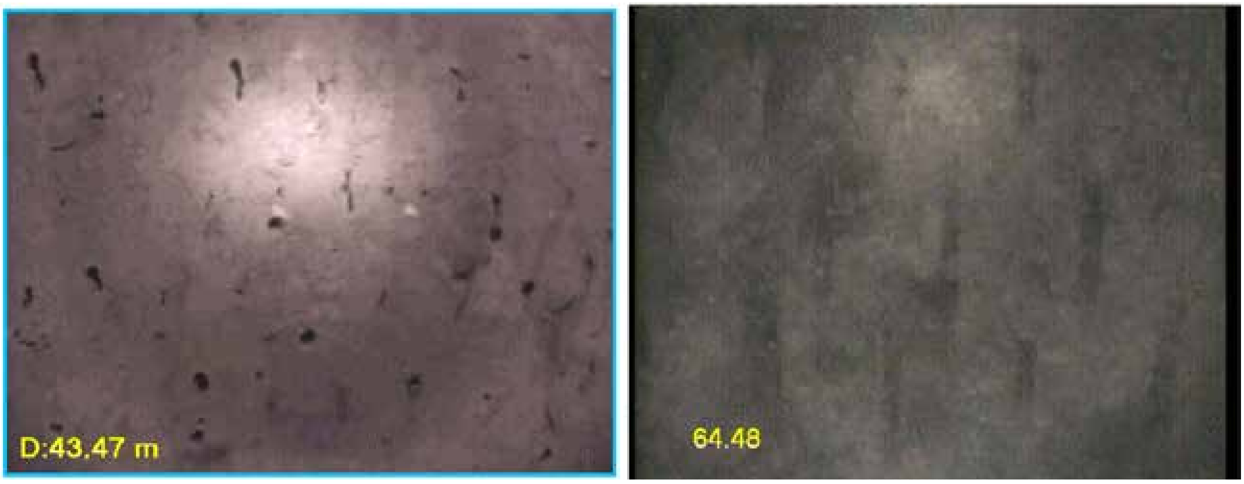

Figure 3: Images of a highly incrusted screen in a well comparable to Well B (left) and of the highly incrusted screen of the above-mentioned Well A (right). Source: Construcciones Iniesta.

Figure 4: Installation of a suction flow control device (SFCD) in a water well.

tion came from Truelsen (1958), and were later developed by Pelzer and others.

Equalisation is performed by a Suction Flow Control Device (SFCD) (called Sistema Ecualizador del Flujo (SEF) in Spain). An SFCD is an engineered slotted pipe inserted inside the well casing that carries all the water pumped. Slot distribution tends to equalise the velocity of the water across the screen, thus tending to a more laminar and less turbulent flow and reducing the vertical flow component in the annular space.

The original device (late 1970s-80s) consists of two concentric thick-walled pipes closed at the bottom, with uniform slotted jackets and an infilling of plastic granulate in the annulus. It was designed on the principle of increasing high flow resistance to counteract the natural flow areas. The device was easily affected by incrustation (Ehrhardt and Pelzer, 1992) and abandoned in Europe, though a comparable design with a resin-bound gravel pack is still used in the USA. An improved design (late 1980s onwards) consists of only one thin-walled pipe closed at the bottom with perforations that increase from the upper part to the bottom. The device can hang on the rising mains with the well pump inside or rest on the bottom of the well. The latter is the current standard (***Figure 4***).

Although SFCDs were designed several decades ago, their use in Europe has been very limited, probably due to the limited results of the first designs and the need for a specific design for each well, calling for a diagnosis of the well. For these reasons experience with those devices is very limited, despite the sound hydraulic criteria on which they are based.

2. Experiences and results

In this paper we present the first results of the installation of SFCD devices in Spain. The work has consisted of the preliminary diagnosis of the water well, the installation of SFCDs and the monitoring of the equalised well in order to evaluate well performance.

2.1. Well Diagnosis

Well A, in the Valencia area, is a 25-year-old well, 90 m deep and 350 mm in diameter, drilled by percussion with 18 m of screen in the lower part (***Figures 2 and 3***). The well is constructed in a confined granular aquifer.

Well A was diagnosed by geophysical testing and a pumping test. The well was highly incrusted with 2-3 cm of hardened iron-manganese incrustations. The last 4 m were full of gravel from the gravel pack, indicating the bottom concrete pad had been broken by suffusion phenomena. An SFCD was installed with no rehabilitation, simply using an air-lift to remove sediment from the bottom. A 3-year record of monitoring is available.

Well B, in the Barcelona area, is a 51-year-old well, 50 m deep and 600 mm in diameter, drilled by percussion with a 6 m screen

Figure 5. Well A, heavily incrusted rising main (left). Accumulation of fresh Iron precipitates on the rising main after a 12-hour pumping test (right).

in the bottom. The well has been rehabilitated several times and in 1994 was partially recased with 500 mm steel casing from the top to above the screen area.

Well B has been diagnosed with a pumping test only, but data from other wells in the same area show heavy incrustation of the screen with 1-2 cm of hardened iron-manganese incrustation (***Figures 2 and 3***). An SFCD device was installed without any previous rehabilitation. From monitoring we have a 6-month record of post-installation performance.

2.2 Results

2.2.1. Observed changes in well losses

The introduction of an SFCD is physically equivalent to the installation of a second casing inside a well (recasing). Recasing tends to create additional friction, which causes extra head loss and consequently a decrease in specific discharge or yield (ratio discharge/drawdown). In our experience the recasing of a well with a screened commercial PVC pipe could cause a reduction in specific discharge of around 20%.

Although it might seem counter-intuitive, the SFCD does not cause head losses (Pelzer, 1991; Wathelet, 1994) because the effect of equalisation reduces dynamic head losses (turbulence and the vertical flow component) and this counteracts the head losses created by the friction of the new pipe.

In Well A, immediately after the installation of SFCD, there was a first period of three months (from Q2 2012 to Q3 2012) where a sharp loss of yield occurred (-45 % in the first weeks, -20% on average). In a second period (from Q4 2012 to Q4 2013), yield increased with a gain of up to +30% on the original yield. In a third period (from Q1 2014 to present) yield decreased to the values prior to installation. The same loss in yield was also observed in the control well, where loss in yield of about -5% was observed (***Figure 6***).

Well B had lost -30% of its yield in the last 30 years. After installation no change in yield was observed. Two months later a +10% increase was observed (***Figure 7***). Because of the recent installation data (beginning in 2015), few results are available for the evolution of well performance due to this device.

2.2.2 Observed changes in incrustations

None of these units has been video inspected since installation so we do not

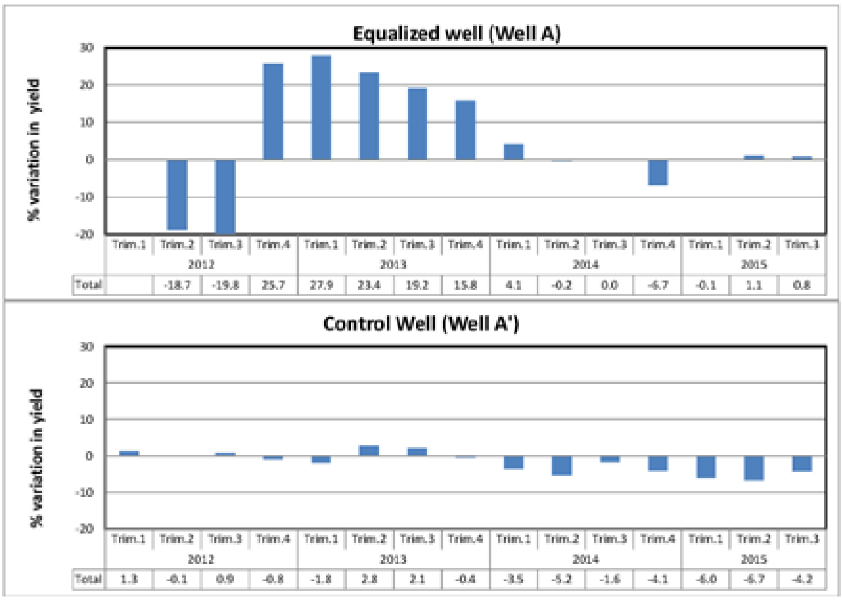

Figure 6: Evolution of yield in two old incrusted wells in a well field in the Valencia area. Well A was equalised with an SFCD in June 2012. Well A' is the control well. Values correspond to a quarterly average based on daily values.

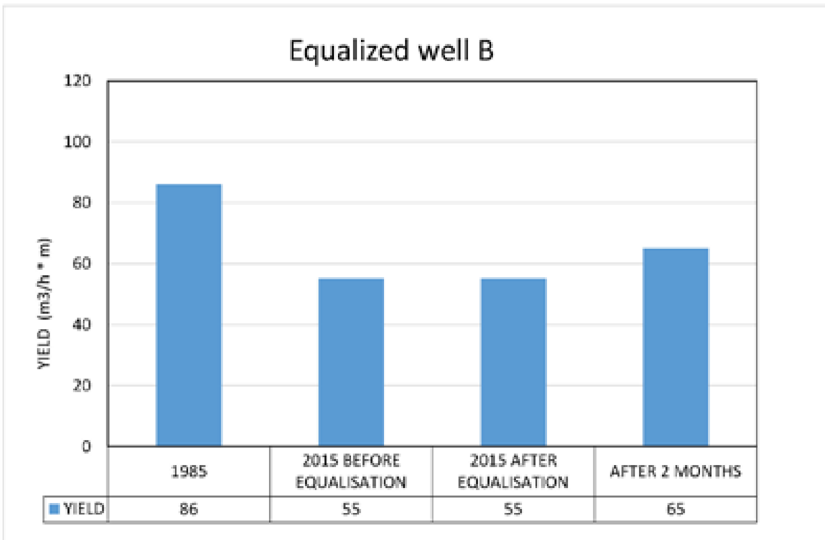

Figure 7: Changes in yield in equalised Well B in Barcelona area. Values correspond to specific tests.

Figure 8: Comparison of fouling of dataloggers in an equalised well (Well A probe, left) and in a non-equalised well (Control well A', cable and probe, right) one year after installation.

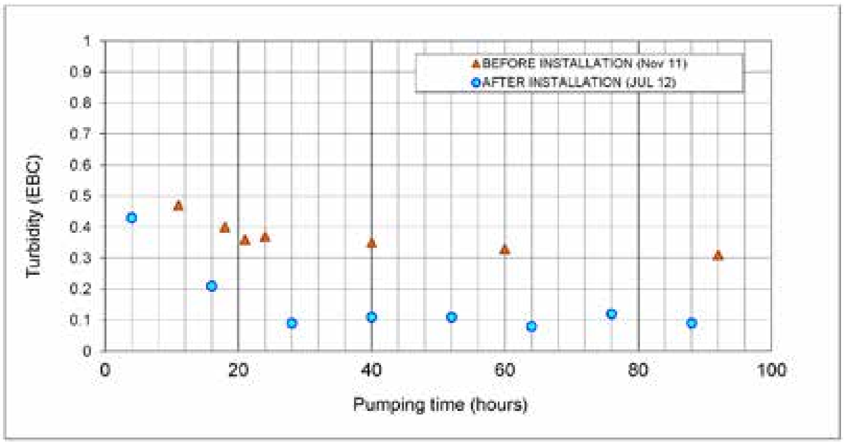

Figure 9: Comparison of turbidity in Well A before and after equalisation.

have direct observation of new incrustation on the wells and on the installed SFCD. The degree of soiling of dataloggers and communication cables installed inside the wells is an indirect way to estimate the progress of incrustation in the well. The probe and cable in Well A (installed in July 2014) remain clean one year later whereas in the control well (Well A') both probe and cable (installed in September 2014) accumulated fresh iron precipitates (***Figure 8***).

2.2.3. Observed changes in turbidity

In Well A turbidity was monitored in the pumping tests before and after installation of the SFCD. Before installation, turbidity was stable at 0.3 EBC; after installation turbidity reduced to 0.1 EBC (***Figure 9***). Sand pumping was also reduced but was not systematically measured. The parameter *Silt Density Index* (SDI) records the ability of water to clog a filter and was systematically recorded in Well A. After SFCD installation the SDI in Well A improved (***Figure 10***), showing a reduction of 0.5 units (a 25% reduction).

In equalised Well B no sand pumping or low turbidity occurred before installation. Water maintained its quality and probable improvements need a longer time to be verified.

3. Discussion

3.1 Interpretation

In both of the cases discussed an increase in yield was observed after the installation of SFCD. That increase confirms the general assumption that device flow improvement (reduction of turbulence and annular vertical flow) counteracts head losses that cause friction in the new pipe installed (Pelzer, 1991).

In the first case (Well A) we observed an initial period (from Q2 2012 to Q3 2012) of initial strong loss of yield followed by a progressive yield increase, in Q4 2012 reaching a +30% increase compared to the original level (***Figure 6***). This evolution could be related to a slow process of redistribution of the flow paths across the screen and the gravel pack. In the second case (Well B) increased losses did not occur and a moderate increase in yield (+10%) occurred after 2 months (***Figure 7***). This behaviour is probably related to a lesser degree of incrustation in the well and a shorter screen length that makes equalisation difficult.

In the first case, Well A, a 3-year data track is available (***Figure 6***). Gains persist over time, with a moderate decrease after two years. In the third year (from Q1 2014 to Q3 2015), yield is down, close to the original pre-installation values. This reduction is also observed in the control well, where a -5% loss of yield occurs, so it is not directly related to SFCD. This reduction in yield could be related to the progression of new incrustation in both wells (both Well A and the control well) or more probably to the drought period affecting eastern Spain.

Yield improvement data demonstrates that equalisation is also possible in the case of wells affected by hardened incrustations. Equalisation could also be inferred from the reduction in turbidity and SDI in Well A. The reduction in mobilisation of very fine particles must be related to a reduction in flow velocity and/or to a reduction in the vertical flow component. The persistence over time of a higher yield in Well A could be related to a reduction in the formation of new precipitates. Also the difference in the degree of fouling of the probes between Well A (clean) and the control well (soiled) must be interpreted in the same way. This point will be confirmed in the future by camera inspection of the wells.

Our results for non-rehabilitated wells seem to contradict another case study (Houben, 2006) in which the performance of two equalisation devices were compared, one in a rehabilitated well and the other in a well without rehabilitation. In that study, measured yield losses were -1.2% in the first case, and after some months a loss of -7.8% was recorded in the second. From these results the author concludes that SFCD increases well incrustation. The lack of any gain in yield after SFCD installation could indicate that equalisation had not been fully achieved. This fact could be related to well characteristics and also to the type of device used: the tail-pipe model, which has since been discarded due to poor results. The lack of equalisation made these results hard to extrapolate from.

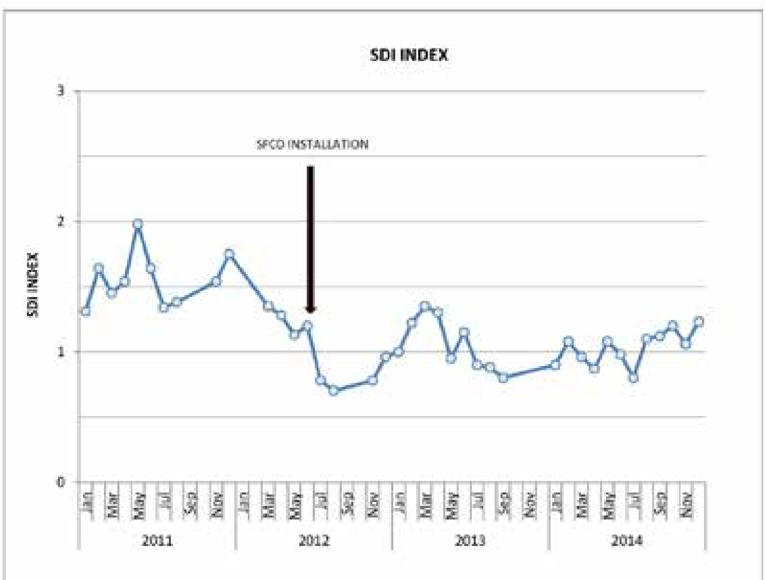

Figure 10: Evolution of silt density index in Well A: SDI is reduced after equalisation.

3.2. General points

The results for non-rehabilitated, heavily incrusted wells are in line with earlier results of increased yield linked to equalisation in new and rehabilitated wells. In the non-rehabilitated wells an initial period of temporary deterioration could occur. These initial short-lived deteriorations are interpreted as a dynamic adaptation of the well to the new flow pattern.

The results also confirm a lower mobilisation of fine particles with a reduction in turbidity and the silt density index, as well as giving clear indications of a reduction in the formation of new incrustations.

4. Conclusions

Many processes related to well ageing and the water quality of pumped water (loss of yield, sand pumping, turbidity, mineral incrustation and biofouling) are related to a high flow regime and turbulence related to a non-uniform distribution of flow in the well. Equalisation is a technique defined in the 1960s which tries to counteract the non-uniform flow pattern in the well by creating a uniform distribution of flow over the total length of the well screen. Equalisation is achieved with an SFCD device, an engineered slotted pipe inserted inside the well casing through which all the pumped water flows.

The results presented for non-rehabilitated, heavily incrusted wells are in line with earlier results of increased yield linked to equalisation in new and rehabilitated wells. In the non-rehabilitated wells an initial period of temporary deterioration could occur. Additionally, equalisation leads to less mobilisation of fine particles, with a reduction in turbidity and silt density index and a reduction in the formation of new incrustations.

As a result, we confirm that flow equalisation improves well hydrodynamics and deserves more attention in order to fully understand its potential to improve well hydraulics and mitigate ageing processes, especially those related to particle erosion and incrustation.

At present, for economic and environmental reasons, rehabilitation techniques are increasing in importance, as they are an alternative to the construction of new wells. Equalisation opens up new ground for the improvement of well hydrodynamics and new strategies in well maintenance and rehabilitation. In this technique the role of the hydrogeologist is maximised because proper equalisation requires a sound diagnosis and monitoring of the wells.

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Groundwater flooding research and mapping in the UK

*Andrew McKenzie**

The winter of 2013/14 was one of the wettest on record in the Southern part of the UK. This led to extensive and prolonged flooding, and refocussed attention on groundwater's role in flood events. Rising water levels in bedrock aquifers, especially the Chalk aquifer in Southern England, caused localised but long lasting floods and affected infrastructure. Along river valleys high groundwater levels exacerbated fluvial flooding events. Prior to a similar extreme event during the winter of 2000/01 groundwater flooding was not widely recognised as a significant issue in the UK, but over the last 15 years a combination of research, data compilation, mapping and modelling has improved our understanding of how groundwater floods develop, which areas are most vulnerable and the impacts on buildings and infrastructure. Significant challenges remain, especially in understanding the frequency of flood events and the interactions between fluvial flooding and groundwater flooding. Regulatory reform in recent years has devolved much of the responsibility for managing groundwater flood risk to local administrations who must communicate the risk, of what remains a rare event, to vulnerable communities.

L'hiver de 2013/2014 fut l'un des plus humides d'après les données existantes dans la partie sud de la Grande Bretagne (UK). Cela a conduit à des inondations de grandes ampleur et durée, et, à nouveau, a remis en exergue le rôle de l'eau souterraine dans le cas d'inondations. La montée des niveaux piézométriques au sein des aquifères de socle, en particulier, pour l'aquifère de la Craie dans le Sud de l'Angleterre, a provoqué des inondations localisées mais durables et affecté les infrastructures.
Avant l'événement semblable et extrême, advenu pendant l'hiver de 2000/01, le phénomène d'inondation n'était pas reconnu par tous comme une question importante en UK, mais pendant les quinze dernières années, l'association entre la recherche, le traitement des données, la cartographie et la modélisation a amélioré notre compréhension sur le comment du développement d'une inondation souterraine, sur la localisation des zones les plus vulnérables et sur les impacts affectant les bâtiments et les infrastructures. Des défis significatifs demeurent, spécialement dans la compréhension de la fréquence des inondations et des interactions entre crue fluviale et inondation souterraine. Une réforme réglementaire, ces dernières années, a transféré l'essentiel des responsabilités de la gestion des risques d'inondation souterraine aux administrations locales qui doivent faire part du risque, de ce qui reste un événement peu fréquent, aux communautés vulnérables.

El invierno de 2013/14 fue uno de los más húmedos en el registro de la parte sur del Reino Unido. Esto dio lugar a inundaciones extensas y prolongadas y reenfocó la atención sobre el papel de las aguas subterráneas en las inundaciones. El aumento de los niveles de agua en los acuíferos de roca firme, especialmente el acuífero de yeso en el sur de Inglaterra, povocó inundaciones localizadas pero duraderas y afectó la infraestructura. A lo largo de los valles fluviales, altos niveles de agua subterránea agravaron los episodios de inundaciones fluviales. Antes de un fenomeno extremo similar que ocurrió durante el invierno de 2000/01, las inundaciones subterráneas no fueron reconocidas como un problema importante en el Reino Unido, pero en los últimos 15 años la investigación, recopilación de datos, cartografía y modelización de forma conjunta ha mejorado nuestra comprensión de cómo inundaciones de aguas subterráneas se desarrollan, qué áreas son más vulnerables y cuales son los impactos en edificios e infraestructuras. Retos importantes subsisten, especialmente en la comprensión de la frecuencia de las inundaciones y las interacciones entre las inundaciones fluviales y las inundaciones de las aguas subterráneas. La reforma de regulacion recientes ha transferido gran parte de la responsabilidad de la gestión del riesgo de inundación de las aguas subterráneas a las administraciones locales que deben comunicar el riesgo, a las comunidades vulnerables, aunque se trata de un acontecimiento raro.

Groundwater plays an important role in many flood events, although this may be overlooked, hydrogeologists have historically focussed on resource scarcity rather than abundance. Increasingly researchers and authorities responsible for flood defence and management are recognising that understanding the complex interactions between rivers and aquifers can be important in designing effective flood defences, while episodically high groundwater levels can cause flooding directly, or impact the functioning of vital infrastructure.

Groundwater flooding, as a distinct mode of flooding, distinguished from fluvial or pluvial flooding, received little attention in the UK until a major flood event in the winter of 2000/2001. Since that event it has been the focus of government planning, regulatory attention and academic research. This paper outlines our current understanding of groundwater flooding in the UK, the major research initiatives that have developed that understanding and how groundwater flood vulnerability has been mapped, and how groundwater flooding has been embedded in current regulatory frameworks for flood management.

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Groundwater and flooding

Groundwater influences many aspects of flooding; for example soil saturation affects pluvial floods; groundwater in hydraulic continuity with rivers or lakes both responds to and controls heightened stage; and rises in groundwater level in an aquifer can be a direct cause of flooding. The emergence of groundwater at the

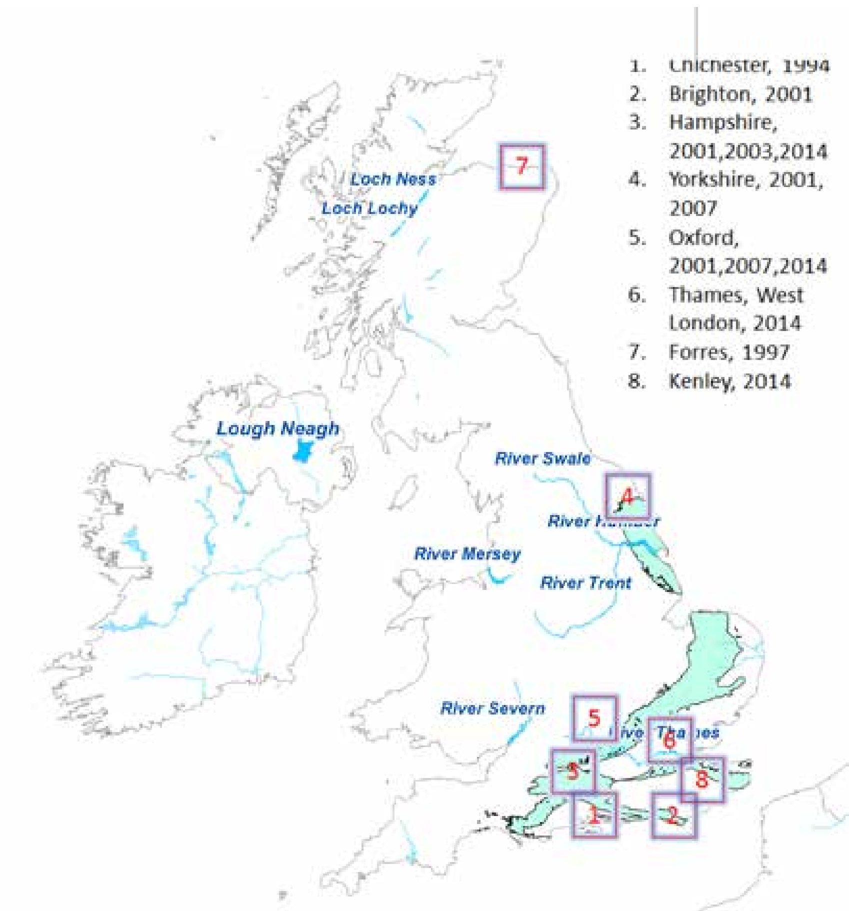

Figure 1: Outcrop of Chalk and location of groundwater flooding events, Map data © NERC 2015.

ground surface away from perennial river channels or the rising of groundwater into man-made ground, under conditions where the 'normal' ranges of groundwater level and groundwater flow are exceeded has been defined as groundwater flooding (MacDonald *et al*, 2008).

If pathways for rises in the water table, resulting in water reaching the land surface, are driven by natural processes of recharge and head driven flow, the flooding is often described as 'clearwater' flooding – because the flood water has been filtered by the aquifer. In the UK this is often associated with Chalk aquifers in Southern England, a dual porosity aquifer where flow occurs predominantly in solution enlarged fractures. Low effective porosity and high fracture permeability results in large seasonal water level fluctuations. These give rise to ephemeral streams or 'bournes'. As groundwater rises and intersects the land surface in response to increased recharge during winter months the flowing portion of the bournes migrate up catchment, and water may rise to the surface in low spots away from water courses. Some bournes flow every winter, others only flow in response to exceptional recharge. When groundwater reaches houses or infrastructure, or when natural drainage is impeded or inadequate for the volumes of water discharged, bourne flow becomes a flood event.

Groundwater flooding also occurs when aquifers receive recharge from streams and rivers. In shallow, permeable, sedimentary deposits in river valleys, the water table responds to rises in river stage and the aquifer can form a pathway for flood waters to impact infrastructure without direct overland flow or a river breaking its banks. Identifying the precise role of groundwater in these situations is difficult – during any flood episode there may be periods when water flows from river to aquifer and periods when the aquifer is flowing to the river. A property might flood initially because of rising groundwater, and then the river may overtop its banks and cause flooding directly.

Other pathways for groundwater flooding are associated with man's modification of natural groundwater flows. These can include leakage from canals, diversion of natural flows by underground construction and the rebound of water tables after long periods of abstraction. In London tunnels and building foundations constructed between 1850 and 1960 have had to deal with a rising water table as water levels rose because of reduced abstraction.

Groundwater flood events

The episodic nature of bournes, and their response to variations in rainfall, was documented by early hydrogeologists (e.g. Whitaker, 1912), though their flow was largely considered a natural phenomenon, and consequent flooding a minor inconvenience. Groundwater was largely ignored by hydrologists focussed on fluvial flood events.

In 1994 there was a major flood event on the chalk-fed River Lavant, and widespread flooding of buildings and transport infrastructure in the town of Chichester. In analysing the causes of the flood and options for future flood defence the importance of groundwater was highlighted (Taylor, 1995). ***Figure 1*** shows the location of this flood, and others referenced in this paper.

During the winter of 2000/2001 much of Britain experienced exceptional winter rainfall, 166% of the normal rain fell in the 8 months from September 2000 to April 2001. Antecedent groundwater levels in Chalk aquifers were high and in early 2001 bournes were flowing and the rising water table and associated flows began to cause flooding, disrupted transport and affected the operation of sewer systems. The combination of fluvial, pluvial and groundwater floods caused damage estimated at 1.35 B€. The extended period of flooding, media attention and quantified costs galvanised the regulatory and research communities to explicitly consider groundwater flooding, especially when there was another, smaller, flood in the winter of 2002/2003.

These events were dominated by 'clearwater' flooding on Chalk aquifers, but in July 2007 a period of intense rainfall focussed attention on the interactions between rivers and streams in hydraulic continuity with shallow sedimentary aquifers. Many communities were flooded by intense rainfall and surface runoff, but in some, notably Oxford, high permeability sands and gravels channelled recharge from rainfall and from local streams, leading to rising groundwater levels and the flooding of basements and low lying land.

In the winter of 2013/2014, prolonged winter rainfall in the southern part of the UK again raised groundwater levels in the Chalk and activated bournes. The event was most severe in Southern England,

Figure 2: Flooding in Hampshire, February 2014. Photo © NERC 2014.

and some communities were impacted that had escaped flooding in 2000/2001. While few properties were inundated there was extensive disruption to transport and other infrastructure (***Figure 2***). Inflows to sewers led to blockages and overloaded some rural treatment plants. High stage in rivers prevented the drainage of water from saturated superficial deposits, and led to complex flood events where groundwater emergence, drainage failures and fluvial flooding affected large areas, especially in the Thames valley.

Research Initiatives

With groundwater flooding established as a distinct issue a range of initiatives started after 2000. These included research commissioned by central government and regulators, academic programmes and a range of institutional responses.

Government sponsored research

A review of groundwater flooding was commissioned by the Department of Environment and Rural Affairs (DEFRA) that led to an initial report and an outline map of vulnerable areas. This was followed up by a programme of commissioned research, including projects on modelling and mapping, early warning and data collation that reported between 2006 and 2008, and set the framework for current institutional approaches (Cobby *et al*, 2009).

Academic research

One of the first research programmes in the UK to explicitly focus on was Flood1, a 3 year EU-INTERREG programme, this studied the 2000/2001 event in England and France, examining unsaturated zone processes in the Chalk. Instrumentation and imagery in experimental boreholes was used to capture these processes during high rainfall events (Adams *et al*, 2010).

The understanding of Chalk flooding processes was developed further during a major initiative on lowland catchment hydrology (LOCAR) which instrumented and investigated a number of flood prone catchments in the Chalk of southern England (Hughes *et al*, 2011).

This was followed by research specifically focussed on flooding, the NERC Flood Risk from Extreme Events (FREE) programme. An important element of this research was developing groundwater models that can be used to simulate groundwater floods. (Upton and Jackson, 2011).

Following the 2013/2014 floods ongoing research is examining the effects of flooding on the quality of public water supply, the interactions between groundwater and sewer flows and on quantifying groundwater driven overland flows.

Institutional responses

Important contributions to understanding and managing groundwater flooding originated within regulatory agencies, research institutions, consultants and local authorities. The Environment Agency in England focussed on mapping groundwater flood incidents and on developing early warning systems for affected communities. The British Geological Survey concentrated on understanding aquifer behaviour in a number of key flood prone catchments, and on developing national assessments of flood hazard. Consultants have been active in refining approaches to estimating risk and forecasting flood events. Several local authorities commissioned detailed studies of flood risk, and groundwater was addressed explicitly in flood alleviation schemes in Scotland, and in schemes being developed for Oxford.

Mapping groundwater flooding

The first stage of assessing the magnitude of groundwater flooding issues has been to map affected areas; however the rarity of events has hampered direct observation. Some incident data has been recorded systematically by regulators and local authorities since the 2000/2001 flood, and during the 2014 flood event aerial photography was collected over many flooded communities to document inundation.

Direct observation has been supplemented by models of potential flooding. Modelling approaches range from simple GIS based models to detailed numerical flow models. The simple models have generally sought to a) identify geological conditions where flooding may occur, b) interpolate a groundwater surface from monitoring data and c) model how the surface may vary during extreme events. National mapping (***Figure 3***) at 1:50,000 scale has been used for the preliminary flood risk assessments mandated by the EU Floods Directive and by local authorities and other stakeholders as a screening tool (Cobby *et al* 2009). Simple models tend to identify large areas as susceptible to flooding; it is likely that only 3% to 10% of properties and infrastructure in a susceptible zone are actually vulnerable (McKenzie and Ward, 2015).

Models have been improved locally by incorporating greater geological detail, by using information on river stage to condition water levels, and by using observed groundwater flood events for validation.

Groundwater flow models have been used to simulate aquifer response in flood events, and can be used to map and predict groundwater emergence, and to understand how flooding may change in the future in response to climate change, land use or infrastructure development. This approach allows groundwater models to be linked to fluvial models or to simulations of urban drainage (Morris *et al*, 2015). The expense of calibrating models to accurately simulate high groundwater levels has limited wide application of this approach.

Understanding risk

A key question for hydrogeologists is to quantify the risk of groundwater flooding. With few observed events return frequencies can only be estimates In areas prone to clearwater flooding monitored or simulated observations of groundwater level have been used to estimate flood frequency and where groundwater interacts with rivers fluvial flood frequency estimation has been used.

The lack of recorded groundwater flood events before 2000/2001 invites the following questions: Has the frequency of events changed in recent decades. If so, have these changes in frequency been a response to climate variability, changes in land use or changes in management of aquifers?

Long time series, of both rainfall and groundwater, don't provide compelling evidence of large changes in natural groundwater levels in the UK, but there are few aquifers that have not been impacted by abstractions and lowland rivers regulation. Water tables lowered by pumping may have contributed to a reduction in flood events during the last century, but reductions in abstraction to meet higher standards of environmental protection may reverse this trend.

Apparent changes in frequency may be a reflection of the way in which groundwater flood events were recorded, and understood by the local communities. During the 2013/2014 event flooding on the Kenley bourne received national attention when flood waters threatened an important water treatment plant. Frequent flooding on this bourne was documented in the 19th century, but wasn't widely reported in the 20th century, so a superficial analysis could suggest that the latest event represented a change or a reversion to previous behaviour. However local records (***Figure 4***) show that flooding occurred regularly during the 20th century. Local newspapers recorded significant impacts, but the floods were understood as failures in drainage infrastructure that had been developed since the 1850s to manage bourne flows.

Adaptations to groundwater flooding are very common in flood prone communities, often comprising drainage channels that lower groundwater levels and divert flows. Sewers and road drainage may have a similar, if unplanned, effect in densely populated areas. Where drainage is not an option a common adaptation is to raise buildings above flood levels. Many of the problems associated with groundwater flooding occur when the purpose of these adaptations is forgotten in the interval between flood events and they fall into disrepair or are removed.

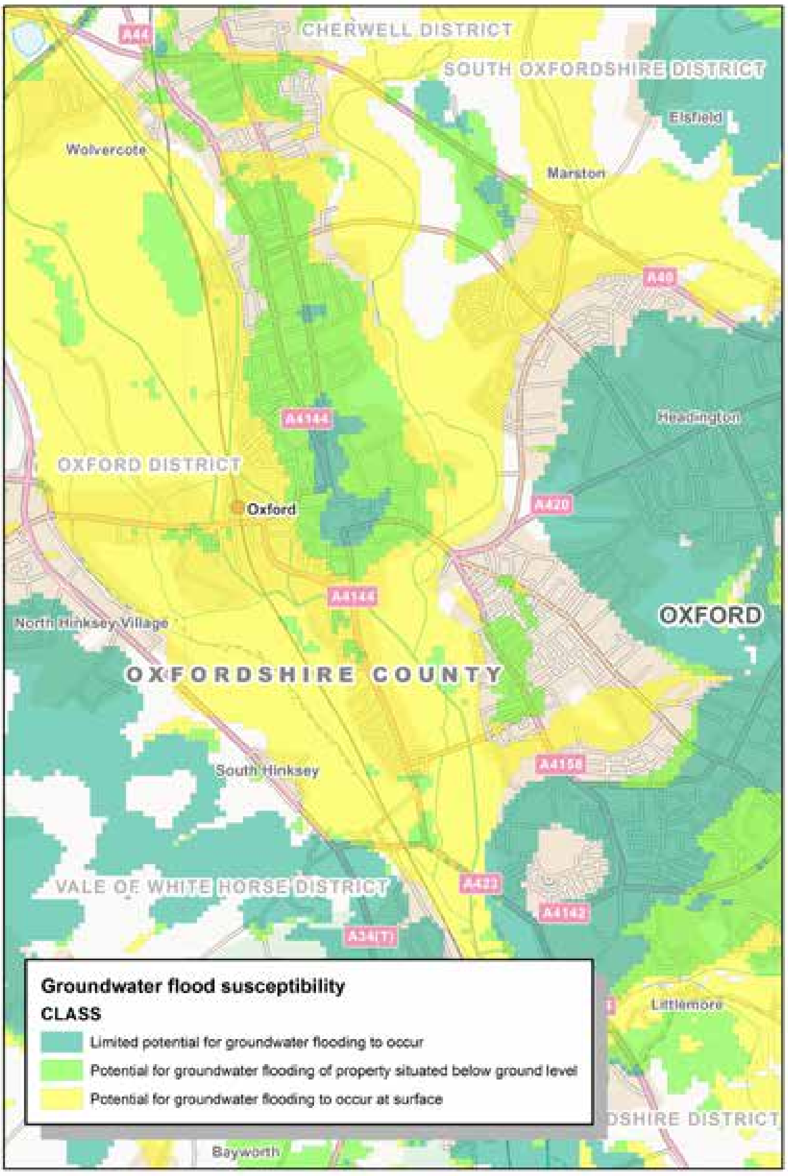

Figure 3: Extract of national groundwater flood susceptibility mapping. Map data © NERC 2015, Contains OS data © Crown copyright 2015.

Regulation

The UK has a longstanding framework for managing the risk of flooding from major rivers and the sea, but groundwater and pluvial flooding were historically excluded from this framework.

The current approach to managing groundwater flooding evolved after the 2000/2001 event and were given greater impetus following the 2007 summer flooding, and by the requirements of the EU Floods Directive, 2007. New legislation included the Flood and Water Management Act 2010, covering England and Wales, the Flood Risk Management Act, 2009 covering Scotland and the Water Environment (Floods Directive) Regulations (Northern Ireland) 2009. In England, where most groundwater flooding occurs, legislation has set up a hierarchical structure, with central government defining policy, the Environment Agency managing flooding on the coast and major rivers, and local authorities responsible for other sources of flooding, including, explicitly, groundwater.

The 2014 event was the first major test for the groundwater aspects of the new legislation and while the immediate institutional response was largely judged effective, it highlighted the fact that the Environment Agency, which has hydrogeologists with detailed local knowledge, has a limited remit to address local issues. Local authorities rely on external consultants for specialised hydrogeological advice. Communities and households are often confused as to where responsibility lies and the structure can complicate decisions over long term investment in flood warning and alleviation.

Challenges

Many aspects of groundwater flooding remain as challenges for the hydrogeological and regulatory community in coming years. These include:

Understanding interconnected systems: The complex interplay of flooding from different sources on the floodplains of major rivers is still poorly understood. Reliably distinguishing between sources of flooding, for instance by measuring chemical signatures, will be important.

Mapping of risk: Existing national mapping does not provide the precision required to assess risk at local level, and may not identify communities that haven't experienced flooding in recent events. Better mapping should allow targeted interventions, for instance to control inflows to sewers.

Food frequency: Major uncertainties in defining the return period of groundwater flood events need to be addressed through the compilation of historical data and modelling of historic events and future climate variability.

Communicating risk: How information about risk is communicated, how events are forecast, and how infrastructure owners and communities manage this risk requires interdisciplinary cooperation between researchers, regulators and other stakeholders.

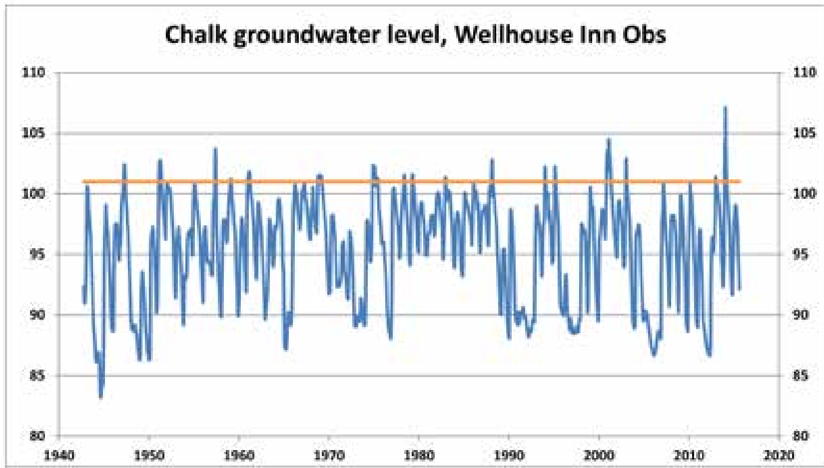

Figure 4: Groundwater flooding occurs on the Kenley Bourne when water levels in this observation borehole exceed 101 metres . Graph © NERC 2015, Contains EA data © Crown copyright 2015.

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News from the German Association of Professional Geoscientists

Hans-Jürgen Weyer*

The BDG (German Association of Professional Geoscientists) organised two outstanding events in 2015:

1st Days of Raw Materials in Meggen

Meggen (Germany) is well known as one of the leading mines of zinc and sulphur in the 20th century. With the "Meggener Days of Raw Materials" BDG ties into the history of this site. From September 17th to September 19th BDG carried out a workshop (especially for European Geologists) about the European reporting system PERC, a conference on mineral exploration in Germany and Europe and a demonstration of modern drilling techniques.

Our special guest was the President of EFG, Vitor Correia, from Portugal. He gave the opening speech about current mineral exploration in Europe.

The 2nd Days of Raw Materials in Meggen are to be held in 2016.

German Association of Professional Geoscientists

BDG is the national organisation of professional geoscientists (geologists, geophysicists, mineralogists) in Germany. BDG represents the profession and is the central contact point for all kinds of needs and issues of geoscientists – in practice and in education – within Germany.

More information: ***www.geoberuf.de***

9th German Day of Geologists

The second event of national significance was the 9th German Day of Geologists (October 29th and 30th). This event comes along with the trade fair GEC Geotechnik expo & congress, held in Offenburg (***www.gec-offenburg.de***). The German Day of Geologists, the fair and the congress are the central meeting point of this important section of applied geosciences in Germany.

An important part of the Day of Geologists (carried out every two years) is the general meeting of the BDG (German Association of German Professional Geoscientists) and several meetings of BDG working groups. BDG expects several hundred participants. The speech section deals with geohazards, a topic to which the last issue of the BDG magazine "BDG-Mitteilungen" (No. 125, July 2015) was also dedicated.

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Announcing – 2016, the Year of Water!

Florence Bullough*

As the Year of Mud at the Geological Society of London comes to a close, we are excited about next year's Year of Water! Themed years are at the heart of the Society's science strategy, and throughout 2016 we will explore a wide range of water-related geoscience through research conferences, public lectures, our education programme and other activities.

An understanding of groundwater and hydrogeology is crucial to addressing a wide range of societal challenges, from securing fresh water supplies and mitigating flood risk to extracting shale gas and other hydrocarbons and safely disposing of our nuclear waste. But water also plays an important role in fundamental geological processes, many of which are the subject of continuing research. Dewatering is key to the formation of sedimentary rocks. Studying the isotopic signatures of ancient waters and the organisms that were formed in them can help us characterise and understand past environments. Water affects deep mantle processes, and fuels volcanic eruptions, determining explosivity and propelling eruption columns into the atmosphere. Water is also at the heart of our efforts to look for life on Mars and elsewhere.

The Year of Water will provide an opportunity to share and debate emerging research, and to communicate to policymakers and the wider public the vital role of water in how our planet works and how we can live sustainably on it.

The Society is currently inviting proposals for conferences to take place during 2016 on any geoscience topic related to water. To suggest events and activities for next year and see listings for confirmed events, please visit our website ***http://www.geolsoc.org.uk/water16***

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Geosciences Research, Resource Development, Monitoring and Evaluation through Nanoscanner/Drone Technology

*Barney P. Popkin**

Over the past decade or more, the development and application of nanoscanner (small-scale sensor, or nanosensor) and drone technology for medical and health, energy and water management, physical infrastructure and antiquities, military surveillance, warfare, defense, and security purposes has mushroomed. These technologies are rapidly expanding to agriculture and food quality and safety and security, environmental, and natural resource research, development, and management. Their use is changing the way traditional practices are moving forward to increase understanding, productivity, and value on a new and higher scale. They have gone way beyond aerial photography and geophysical technologies for resources management.

IBM's Chief Innovation Officer and Vice President, Bernard Meyerson, summarized the top 10 emerging technologies of 2015 in a Scientific American note, based on the World Economic Forum's Meta-Council on Emerging Technologies. He included autonomous drones ("flying robots") as "better able to process and respond to visual cues, much more powerful and intelligent cameras and smartphones, and data-crunching on a scale that may help unlock the secrets of financial markets or climate forecasting. Computers will be able to anticipate and learn, rather than merely respond in pre-programmed ways."

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For geosciences, these applications include, for example, study and monitoring of landforms and features, glaciers and ice sheets and ice bergs, greenhouse gases, avalanches and landslides, volcanic eruptions, urban heat islands, building energy, floods and droughts, drainage, sea level changes, advancing and retreating coasts, weather patterns, mechanical weathering and erosion, geothermal resources, and mineral deposits and mining. The basic principles are as follows:

1. Collection of accurate, real-time data, such as high-fidelity sensing (scouting or monitoring) and precise positioning (location) through high-resolution, on-demand visual and electro-optical/ thermal infrared mapping to obtain a detailed view from nanoscanners feeding back information to drones (unmanned aircraft), manned aircraft, satellites, or other stationary or mobile air or land centers
2. Centralization of collected data (often called "big data")
3. Massaging collected data in a form to identify spatial and temporal trends, anomalies, inconsistencies, and comparison to established specifications, standards, and deviations
4. Decision-making to identify appropriate action alternatives and recommend actions
5. Implementation of appropriate actions
6. Reassessment through monitoring and evaluation

Unfortunately, much of the best technology is confidential, proprietary, and security sensitive, but entrepreneurs are rapidly licensing and developing commercially available technologies.

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News corner:
Compiled by Isabel Fernández Fuentes and Anita Stein, EFG Office

EFG strategy and Horizon 2020 projects

Horizon 2020 is the biggest EU Research and Innovation programme ever, with nearly €80 billion of funding available to secure Europe's global competitiveness in the period 2014-2020. Following its *Initiative Looking Forward*, the EFG Board put a lot of energy in developing and participating in several project proposals within the Horizon 2020 programme. EFG is glad to report that its efforts have been fruitful. From the beginning of 2015 the Federation is already involved in four Horizon 2020 projects: INTRAW, KINDRA, MINATURA2020 and ¡VAMOS!. Three new projects will start at the beginning of 2016: UNEXMIN, CHPM2030 and MICA.

INTRAW, fostering international raw materials cooperation

As part of the European Commission's Horizon 2020 Programme for Research & Innovation (R&I), the 36-month project INTRAW, which started in February 2015, aims to map best practices and develop new cooperation opportunities related to raw materials between the EU and technologically advanced countries (Australia, Canada, Japan, South Africa and the United States) in response to similar global challenges. The European Federation of Geologists (EFG) is the coordinator of a consortium of 15 partners from different countries including Australia, the United States and South Africa. Most of EFG's members are also part of the consortium as EFG third parties.

The outcome of the mapping and knowledge transfer activities to be conducted in the first two years of the project will be used as a baseline to set up and launch the European Union's International Observatory for Raw Materials as a permanent raw materials knowledge management body. The experts appointed to the three INTRAW Panels on "Research & Innovation", "Education & Outreach" and "Industry & Trade" gathered in Bled (Slovenia) on 15 and 16 September 2015 to provide their views on international raw materials policies and the key factors that are most influential in developing and sustaining successful raw materials sectors. For more information: ***www.intraw.eu***

MINATURA2020, Safeguarding Mineral Deposits of Public Importance

MINATURA2020, a new EU project funded within the scope of the European Commission's Horizon 2020 Programme for Research & Innovation (R&I), was launched in February 2015 as a response to social needs to safeguard mineral deposits of public importance for the future. The overall objective of this three-year project is to develop a concept and methodology for the definition and subsequent protection of "Mineral Deposits of Public Importance" (MDoPI) in order to ensure their best use in the future with a view to being included in a harmonised European regulatory, guidance or policy framework. Providing a policy-planning framework that comprises the sustainability principle for mineral exploitation, as it exists for other resource/land use sectors, is thus the key driving force behind MINATURA2020. EFG is involved in the establishment of the Council of Stakeholders and leads the Work Package on Dissemination. For more information: ***www.minatura2020.eu***

¡VAMOS!, Developing a Revolutionary Underwater Mining System

The aim of the EU-funded ¡VAMOS! (Viable Alternative Mine Operating System) project is to design and build a robotic, underwater mining prototype with associated launch and recovery equipment, which will be used to perform field tests at four EU mine sites. The project consortium passed a major milestone in September 2015 with the successful delivery of conceptual design plans of the prototype and all associated equipment.

EFG supports the project through stakeholder engagement and dissemination activities.

More information is available at: ***http://vamos-project.eu***

KINDRA, Knowledge Inventory for hydrogeology research

Groundwater and hydrogeology-related research activities cover a wide spectrum of research areas at EU and national levels. However, groundwater issues are quite often either ignored or considered only in insufficient detail and separated from the associated surface water bodies, despite groundwater's critical importance as renewable, high-quality, naturally protected (but still vulnerable) resource that has significant impacts on both surface water bodies and ecosystems.

The EU-funded KINDRA project (Knowledge Inventory for hydrogeology research, Grant Agreement No. 642047) seeks to take stock of our current knowledge of hydrogeology through an inventory of research results, activities, projects and programmes.

A stakeholder workshop is organised by the European Federation of Geologists (EFG) and Sapienza University on behalf of the KINDRA project consortium on 24 and 25 November 2015 in Brussels. The first day of the KINDRA Workshop is intended as an open session with introduction to the "state of the knowledge for hydrogeology research in Europe", including presentations on relevant European water policy and H2020 activities. The audience for the first day is open to hydrogeologists, companies and associations related to groundwater in Europe. The second day will be focused on the training of national experts (delegates from the EFG KINDRA Third Parties) who will actively take part in the KINDRA activity "Data collection and processing".

For more information: ***http://www.kindraproject.eu***

New EFG member: Geological Society of Denmark

During its June meeting, the EFG Council approved unanimously the application of the Geological Society of Denmark to become a full member. The Geological Society of Denmark was founded in 1893 to promote interest in geology and to establish a forum for geologists and others with an interest in geology. The Society arranges meetings with lectures and discussions, arranges excursions, and publishes two publication series - one international: the Bulletin of the Geological Society of Denmark.

More information can be found at: ***http://2dgf.dk/dgf_uk/main.html***

International collaboration

On 17 September 2015, EFG signed a Memorandum of Understanding (MoU) with the International Association for Geoethics (IAGETH). The memorandum was signed by EFG President Vítor Correia and IAGETH President Jesús Martínez-Frías in Bled (Slovenia).

The objective of this MoU is to bring the two IUGS-affiliated organisations (IAGETH and EFG) together to focus attention on the conjunction of geoethical aspects and best practices in the context of geosciences, through joint actions, including professional and institutional cooperation on different subjects and the production of training material, roadmaps and protocols at different levels.

More information on IAGETH: ***http://www.icog.es/iageth***

More information on EFG's global network: ***http://eurogeologists.eu/global-network***

Endorsed training courses

EFG's training course endorsement programme is a free service with benefits to both course providers and EurGeol title holders. Applications are welcomed from the providers of short training courses, seminars, workshops, etc. Course endorsement will raise your company's profile and foster recognition within the European and international geoscience community. To apply for endorsement of your event(s) please download the application form and return it to ***info.efg@eurogeologists.eu***. A decision will be taken within a few weeks following the receipt of your application. Endorsement is valid for three years, subject to receipt of satisfactory feedback from EurGeol title holders.

More information: ***http://eurogeologists.eu/training/***

EFG Medal of Merit awarded to Peter Styles

During the summer council meeting of the European Federation of Geologists (EFG), held on 13 and 14 June 2015 at Newcastle (UK), Professor Peter Styles was awarded the 2014/2015 Medal of Merit for exceptional and distinguished contributions to the Federation and to the geological profession in Europe. Peter Styles is one of Europe's leading applied and environmental geophysicists. He has fully engaged with professional development and academic excellence within his field for some 40 years.

He has served the profession in many ways, with considerable beneficial impact. As the Geological Society's Professional Secretary, he was the UK's delegate to the EFG Council, serving the development of the profession in Europe from 1997 to 2000. He was President of the Geological Society of London from 2004 to 2006, and has served at a high level on government bodies, spending two terms on the board of the British Geological Survey. He has advised the UK government on the underground storage of nuclear waste. His work has raised the profile of geoscience within government and with the public, as well as through the advice he has given to industry. He was also President of the British Association for the Advancement of Science (Geology Section) for 2007. He is Editor-in-Chief of Geoscientist and currently conducting a global lecture programme as the first Distinguished Visiting Lecturer in Environmental Geophysics for the European Association of Geoscientists and Engineers (EAGE).

More widely, Peter has made a major contribution to the current debate on shale gas and the associated hydraulic fracturing, making sure that policy makers and the public are informed of the facts that relate to shale gas exploration. His work in this regard is one reason why the UK Government supports shale gas exploration. Peter also applies his knowledge of microseismic activity to geothermal exploration, where again factual knowledge of this process is vital to the safe management of exploration and production.

He was awarded the William Smith Medal of the Geological Society of London in 2014 for outstanding research in Applied Geosciences and the Medal of Merit of the European Federation of Geologists in 2014/2015 for persons who have provided exceptional and distinguished contributions to the Federation or to the geological profession in Europe.

Geology for Society report launch

In the light of the major role geology plays (often unknowingly) in a multitude of economic areas, the Geological Society of London (GSL) produced in 2014 a major report named "Geology for Society" that has been translated into 14 languages so far, thanks to the collaboration of the European Federation of Geologists (EFG) and its national membership associations. This European report was officially launched at the European Parliament on 2 June 2015 with the aim of outlining to MEPs and EU policy makers the importance of geology and qualified professionals to our society, covering areas such as energy, minerals, water, waste management, construction, land contamination and natural hazards. The session, hosted by MEP Carlos Zorrinho (Group of the Progressive Alliance of Socialists and Democrats in the European Parliament, Member of the Committee on Industry, Research and Energy), intended to promote dialogue between policy makers and geoscientists at a European and national level. Read more about this event at ***http://eurogeologists.eu/geology-for-society-launch/***

EAGE/EFG Photo Contest 2015

After the success of last year, EFG and the European Association of Geoscientists and Engineers (EAGE) again jointly organised the Photo Contest 2015. Once again, the theme was 'Geoscientists at work' and members of EFG and EAGE were invited to submit their photos in the following subcategories:

1. Education & training
2. Landscapes & environment
3. Fieldwork
4. Energy

A huge number of photos was submitted by the deadline for participation and a vote determined the 12 most popular photos, which are shown in a travelling exhibition that visits several EAGE and EFG events throughout Europe. The Top 12 are also included in a standing flip-over desk calendar. You may purchase the calendar via the EAGE bookshop at ***http://bookshop.eage.org***

Erosional Act by Nature
• ABHIMANYU MAITRA
• JUNE 2011
• SARCHU, HIMACHAL PRADESH, INDIA

From the Volcano to the Sunset
• DARIO CHISARI
• APRIL 2014
• STROMBOLI (AEOLIAN ISLANDS), ITALY

Trusting in Trusting
• CHRISTIAN RAMBOUSEK
• 25 AUGUST 2012
• PETRA, JORDAN

Book review:

A Geochemical Atlas of the Portuguese Mineral Waters

José Martins Carvalho, School of Engineering (ISEP), Polytechnic of Porto, Porto, Portugal

A Geochemical Atlas of the Portuguese Mineral Waters
by H. G. M Eggenkamp, J. M. Marques and O. Neves
Onderzoek en Beleving, Bussum, The Netherlands, 53 pp, 2015
ISBN 978-90-816059-6-0

Mineral water is any groundwater clearly distinguished by a physical and/or chemical characteristic from "common waters" in a given area. This is a hydrogeological approach not to be confused with thermal, mineromedicinal or medicinal waters used in balneology or balneotherapy under the umbrella of the medical hydrology. Inside the European Union in the normative point of view, some of those waters used in thermal spas or in the bottled water industry are designated as natural mineral water.

In this book the studied area (page 4) is mainland Portugal (89 000 km^2) and 606 samples were obtained in the selected bibliography, with no specific field investigation, as emphasised by the authors. The main sources for the sample data (page 6) are several references dating from 1952 till 2008. All references (particularly, *"Le Portugal hydrominéral"* from L.M. Acciaiuoli, 1952/1953), *"Inventário Hidrológico de Portugal"* from A. de Almeida & J.D. de Almeida, 1970/1988 and *"O Novo Aquilégio"* from C. Bastos *et al.*, 2008) are inventories of natural groundwater used for balneological purposes or other therapeutic uses in thermal baths or in an informal way by the local people. Some of the sites are no longer accessible.

Based on the above data, and using a kriging gridding method, 15 geochemical maps in scale 1/3 850 000 were produced (maps 2 to 16) representing the distribution of chemical elements in thermal and mineral waters, namely total dissolved solids (TDS), pH, Sodium, Chloride, Calcium, Magnesium, Sulphate, (Bi)carbonate, Silica, Nitrate, Aluminium, Iron, Bisulphide, Fluoride and Lithium. To the reader the absence of geographical indications in these maps makes it difficult to correlate the ionic distribution with the geological and hydrogeological features described in the text. Map 1 gives a simplified geologic map of the Portuguese mainland in a 1/3 125 000 scale.

The authors conclude (page 42) that the approach used gives a good representation of the deeper geochemistry of the mapped area, as opposed to more conventional sediment and stream water mapping. This is only partially true, as most of the sample population is constituted by groundwater from shallow aquifers.

The selected references (page 44) are questionable. Some are almost irrelevant and several Master and PhD theses or key papers are missing.

This book is a nice start for beginners interested in the chemistry of mainland Portuguese groundwater but the title is misleading for two major reasons: (i) the sample points were selected by former researchers from a medical hydrology perspective (only some of them are true mineral water), and, (ii) the book does not include the Portuguese volcanic islands of Azores, with a plethora of mineral and thermal waters in several balneological and balneotherapeutic locations as well as outside of them. In conclusion, it is recommended that in a revised edition the book title should be changed to comply better with the geographical location and the subject studied.

Sacavém, 27 October 2015
jmc

Submission of articles to European Geologist journal

Notes for contributors

The Editorial Board of the European Geologist journal welcomes article proposals in line with the specific topic agreed on by the EFG Council. The call for articles is published twice a year in December and June along with the publication of the previous issue.
The European Geologist journal publishes feature articles covering all branches of geosciences. EGJ furthermore publishes book reviews, interviews carried out with geoscientists for the section 'Professional profiles' and news relevant to the geological profession. The articles are peer reviewed and also reviewed by a native English speaker.
All articles for publication in the journal should be submitted electronically to the EFG Office at ***info.efg@eurogeologists*** according to the following deadlines:

- Deadlines for submitting article proposals (title and content in a few sentences) to the EFG Office (***info.efg@eurogeologists.eu***) are respectively 15 July and 15 January. The proposals are then evaluated by the Editorial Board and notification is given shortly to successful contributors.
- Deadlines for receipt of full articles are 15 March and 15 September.

Formal requirements

Layout

- Title followed by the author(s) name(s), place of work and email address,
- Abstract in English, French and Spanish,
- Main text without figures,
- Acknowledgements (optional),
- References.

Abstract

- Translation of the abstracts to French and Spanish can be provided by EFG.
- The abstract should summarise the essential information provided by the article in not more than 120 words.
- It should be intelligible without reference to the article and should include information on scope and objectives of the work described, methodology, results obtained and conclusions.

Main text

- The main text should be no longer than 2500 words, provided in doc or docx format.
- Figures should be referred in the text in italic.
- Citation of references in the main text should be as follows: 'Vidas and Cooper (2009) calculated…' or 'Possible reservoirs include depleted oil and gas fields… (Holloway *et al.*, 2005)'. When reference is made to a work by three or more authors, the first name followed by '*et al.*' should be used.
- Please limit the use of footnotes and number them in the text via superscripts. Instead of using footnotes, it is preferable to suggest further reading.

Figure captions

- Figure captions should be sent in a separate doc or docx file.

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- References should be listed alphabetically at the end of the manuscript and must be laid out in the following manner:
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- Measurements and units
- Measurements and units: Geoscientists use Système International (SI) units. If the measurement (for example, if it was taken in 1850) was not in SI, please convert it (in parentheses). If the industry standard is not SI, exceptions are permitted.

Illustrations

- Figures should be submitted as separate files in JPEG or TIFF format with at least 300dpi.
- Authors are invited to suggest optimum positions for figures and tables even though lay-out considerations may require some changes.

Correspondence

All correspondence regarding publication should be addressed to:
EFG Office
Rue Jenner 13, B-1000 Brussels, Belgium.
E-mail: ***info.efg@eurogeologists.eu***

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- EFG website, *www.eurogeologists.eu*
- GeoNews, a monthly newsletter with information relevant to the geosciences community.
- European Geologist, EFG's biannual journal. Since 2010, the European Geologist journal is published online and distributed electronically. Some copies are printed for our members associations and the EFG Office which distributes them to the EU Institutions and companies.

By means of these tools, EFG reaches approximately 50,000 European geologists as well as the international geology community.

With a view to improving the collaboration with companies, EFG proposes different advertisement options. For the individual prices of these different advertisement options please refer to the table.

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