KINDRA D3.3

Gaps and trends in groundwater research

Summary

This document Deliverable D3.3 presents the KINDRA project Gaps and Trends Analysis based on data uploaded to the EIGR and structured according to the HRC-SYS approach. From main findings of this analysis, recommendations will be delivered on gaps on groundwater research and knowledge to the European Commission (see D3.4). Main results have been resumed in the executive summary chapter at the beginning of the document

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1 Executive summary

Groundwater quantity and quality needs more attention in order to enable and develop efficient protection policies for this important resource. To support this, KINDRA conducted analyses of European research and knowledge in order to make groundwater and its importance for most of the Horizon 2020 Grand Societal Challenges (in short: Societal Challenges) more visible.

Groundwater delivers drinking water to about 75 % of EU's inhabitants (European Commission, 2018) and it sustains and supports agriculture, industry and important terrestrial and aquatic ecosystems all over Europe. The quantity and quality of groundwater resources is under increasing and severe pressure globally. Climate change will generally aggravate the groundwater related problems and result in water scarcity in some regions, flooding in others or both.

This report analyses metadata on groundwater research and knowledge collected and available in the European Inventory of Groundwater Research (EIGR) developed in the KINDRA project, currently containing more than 2200 records. The fact that nearly 30 % of the records uploaded to EIGR are provided by just one country clearly indicates a huge potential for further development of the database and additional upload of data from other EU countries to serve a broad range of users.

In addition to the data available in EIGR, information on groundwater research publications was added and analysed from (1) the Elseviers Scopus database – the world's largest abstract and citation database of peer-reviewed scientific literature including journals, proceedings and books, and (2) Web of Science (WoS) the first and possibly most widely known and used database globally on citations of papers in scientific journals. On average more than 6.000 groundwater research papers are published annually, and the number is growing significantly each year.

From the analyses conducted on data available in EIGR, Scopus and Web of Science, the **following key findings are highlighted on European groundwater research** in a regional and global context:

(1) The primary added value of the EIGR database is making metadata on reports and research projects and data, which are classified along the main Societal Challenges defined in Horizon 2020, Findable, Accessible, Interoperable and Reusable according to "FAIR" principles of Horizon 2020. This often not peer reviewed, but usually quality assured, data source, providing extensive information is otherwise not available through single point access elsewhere;

(2) The Applicability of the developed and adopted classification of groundwater research and knowledge available from national databases has been demonstrated by classifying and accordingly structuring the content of the metadata uploaded by national experts into the EIGR. Development of future national sections of EIGR is feasible, at least where national association of geologists will support the inventory. Furthermore, comparison of EIGR and Scopus databases clearly indicates that the adopted classification HRC-SYS and related thesaurus of keywords are adequate and representative for classifying groundwater research and knowledge at European level;

(3) The distinction in the adopted classification between research and knowledge highlights the relevance and value of non peer-reviewed (grey) documents for linking the hydrogeological data and knowledge available at primarily regional and national but also international levels;

(4) The "hydrogeological" component of the groundwater knowledge in the EIGR can be readily and easily supplemented by adding information about groundwater research developed in other related research disciplines or be expanded to become a general database on subsurface studies and include information from studies on e.g. geoenergy and raw materials;

(5) The EIGR database contains information relevant for the implementation of (ground)water policies and sustainable management of water resources at national and European scale i.e. mainly the Water Framework Directive, the Groundwater Directive and the Nitrate Directives;

(6) The EIGR and Scopus databases based analyses confirm that most groundwater research is conducted within Societal Challenge 'Climate, environment and resources' with strong overlap to especially Societal Challenge 'Health' and Societal Challenge 'Food and Agriculture' on topics related to either natural elements (arsenic) or pollutants (pharmaceuticals, emerging contaminants, nitrate and pesticides), harmful to both human health and groundwater dependent ecosystems;

(7) The EIGR supported content constitutes a significant additional contribution to the existing knowledge pertaining to groundwater research, especially concerning the more than 50% of the included records belonging to the "grey literature", not considered in scientific databases;

(8) In a global perspective our findings show that European (EU28) groundwater research performs well in comparison with the other major regions (USA, China etc.). A Scopus based analysis showed that Europe had the largest scholarly output and number of scientific (peer reviewed) publications within groundwater research since 2007, when the Groundwater Directive and subsequent related requirements were adopted;

(9) In 2007 Europe and USA both produced nearly 2000 research publications on groundwater, while China around 500. In comparison, in 2016 Europe produced slightly more than 3000 research papers, while USA and China produced slightly more and slightly less than 2000, respectively. Hence, groundwater research is significantly increasing in Europe and China reflecting growing attention to and importance of groundwater issues in Europe as a consequence of the adoption of the Groundwater Directive in 2006.

It is apparent that a significant amount of groundwater research is conducted within all the considered Societal Challenges of Horizon 2020. However, there are large differences between the Societal Challenges ranging from 2600 research papers published within for the Societal Challenge 'transportation' to more than 44.000 research papers for the Societal Challenge 'climate, environment and resources' for the period 1997 – 2016. We draw the following main key findings on gaps in groundwater research, specifically for the three Societal Challenges where groundwater research and knowledge has been found to be particularly relevant:

Societal Challenge 1 'Human health, demographic change and well-being': (a) an increasing amount of new emerging contaminants in groundwater and the rest of the hydrological cycle including e.g. pharmaceuticals and new pesticide degradation products is observed and a rapid increase in papers and citations for papers studying these is observed, but limitedly in most EU countries; (b) Studies on the natural backgrounds of arsenic and nitrate and derivation of groundwater threshold values is highly warranted; (c) Further, groundwater studies are needed on (i) pharmaceuticals, hormones, (ii) degradation products of micro-organics and related cocktail effects, (iii) nanoparticles and microplastics in groundwater and (iv) chemical status of groundwater in relation to human health and the ecological status of ecosystems.

Societal Challenge 2 'Food security, sustainable agriculture and forestry, marine and maritime and inland water research, and the Bioeconomy': (a) relatively low number of publications on biology, geology and mapping indicates a research gap on the topic of finding efficient tools for reducing nitrate (nitrogen) loadings to ecosystems; (b) knowledge gaps exists on (i) linking ecosystems to poor groundwater chemical status; (ii) groundwater threshold values e.g. for protection of ecosystems based on good status objectives of the WFD and GWD, requiring transdisciplinary research between hydrogeology and ecology.

Societal Challenge 5 'Climate action, environment, resource efficiency and raw materials': (a) This Societal Challenge constitutes the highest scholarly output of all considered societal challenges, but climate change (mitigation, impact and adaptation), urban hydrology and the significance of both deep and shallow groundwater, e.g. in connection to nature based and subsurface water solutions and green infrastructure are underrepresented and constitute a gap in research to be quickly filled.

The conclusions related to the considered societal challenges listed above are of value for (i) the further development of EU water policy and research, specifically for **developing new mission-oriented research programmes and targets** and (ii) for supporting the valuable activities of Working Group Groundwater within the Common Implementation Strategy (CIS) of the Water Framework Directive, currently dealing with e.g. common strategies towards developing a groundwater watch list for emerging contaminants, and assessment of groundwater threshold values and trends. In this framework, the data analysis demonstrates that **groundwater directive directly promoted the scientific output in the last decade,** where new research topics and management of emerging challenges have been respectively promoted and tackled by the **fundamental role of CIS Working Group Groundwater, acting as catalizer of modern approaches**. The conducted analyses and the increasing amount of research on the evolution of groundwater quantity and quality clearly demonstrate **the need for expanding and making the importance of groundwater resources, research and knowledge more visible to and apparent for the public and politicians.**

The results of KINDRA clearly demonstrate and underpins the importance of the groundwater resources for the European societies and that groundwater research has relevance for all the societal challenges. Consequently, the following recommendations are delivered to the European Commission.

We promote to continue pursuing and further enhance the following main guiding principle and vision for future mission-oriented groundwater research: **Groundwater management and protection is based on sustainable and geoethical principles that ensure a good quantitative and chemical status of all groundwater bodies** in the EU to the benefit of all EU citizens and ecosystems.

To achieve this goal the EU needs to continuously **strive towards sustainable and integrated management of the subsurface resources as well groundwater and surface water through the continuous support of innovative nature based and subsurface water solutions** that e.g. make use of managed aquifer recharge and re-use of water in a general circular economy. Such solutions **need new efficient tools for environmental monitoring and data management and visualization e.g. via efficient Internet of Things (IoT) solutions**. This is an **important market today for European companies and consultants**, but it needs support to maintain a strong position in competition with especially American and Chinese water technology research and development. Generally, **tools for improved integrated groundwater and surface water management and climate change impact assessment and adaptation need strong support**. European policies towards improving Public-Private-Partnerships, **conditions for competitive water related industry including groundwater and water patents in general need to be continuously adapted, optimised and further developed** to the benefit of European societies.

While EU28 currently performs very well for the scholarly output of groundwater research in comparison with other main regions and countries, globally, Europe has, however, much fewer patents related to groundwater technology in comparison with especially the USA. **Europe has for instance a very low number of patents on new innovative techniques related to new digital developments such as "cloud computing", Information and communication technologies (ICT), internet of things (IoT) and "big data".** While the reasons for this include complex issues related to market mechanisms, legislation, language barriers, data protection rules and economic development, it is recommended to **pursue more research on conditions for innovation and patent applications for groundwater relevant or related technologies** in Europe.

Finally, we conclude that the European Inventory of Groundwater Research was launched successfully and that it with more than 2200 records already contains a significant amount of valuable data on groundwater research and knowledge in Europe. Through discussions with the joint panel of expert and colleagues from other disciplines we also uncovered a significant potential for further improvement and development of EIGR, which include cross-reference with different databases containing information and data on the subsurface such as the knowledge platforms on subsurface water solutions developed in the SubSol project and EIP Water, where preliminary cross-reference is already established, and the GeoERA Information Platform to be developed within the European Geological Data Infrastructure.

2 Introduction

This report presents the gap and trend analysis of groundwater research and knowledge, particularly groundwater research relevant for implementation of the Water Framework Directive and EU water policy in general. To support this a dedicated groundwater research and knowledge classification system was developed to enable population of the new European Inventory of Groundwater Research (EIGR) with **F**indable, **A**ccessible, **I**nter-operable and **R**eusable metadata on groundwater research according to the "FAIR" principles (Wilkinson et al., 2016). The EIGR database was populated with both scientific resources, i.e. peer reviewed literature as well as reports and other resources with little, uncertain or no peer review ("grey literature") according to the developed classification system. The latter category of resources include a large number of data reports, maps and other relevant work published by e.g. authorities, consultants and geological surveys, which contribute substantially to the knowledge pool, but which is often difficult to find (e.g. Lawrence et al, 2015). In order to develop a database system for population with heterogeneous data resources and determine the degree of (peer) review and other types of quality assurance within the KINDRA project, keywords and categories have been identified to allow for an effective and useful classification according to the FAIR principles i.e. with easy access to and reuse of the resources.

In the recent decades research performance and evaluations have developed from using expert judgement to advanced database analyses using a wide range of metrics, preferably the snowball metrics, which are: "robust framework for measuring research performance" (Clements et al., 2017), the value of which can be decisive for individual researchers in pursuing academic careers (Leiden Manifesto, 2015). In 2002, the Web of Science was made available by Thomson Reuters and followed by Elseviers's Scopus in 2004 in addition to these databases, a search engine dedicated to scientific literature: Google Scholar (beta version also in 2004) also emerged. These and other resources provide a fast increasing amount of accessible data on which to perform analyses like bibliometrics, scientometrics and recently altmetrics (Erdt et al, 2016; references to science in social media – see www.altmetric.com), giving many new possibilities for analyses and data visualisations.

The US based National Science Foundation (NSF) uses bibliometric indicators in Science and Engineering Indicators 2016 and 2018 (NSB, 2016; NSB, 2018) based on the Scopus database which is a change from the bibliometric data set used in earlier volumes of Science and Engineering Indicators, which used a subset of Thomson Reuters Science Citation Index (SCI) and Social Science Citation Index (SSCI). This change in data sources is accompanied by several methodological changes intended to simplify the interpretation of the data and increase the cross-field and cross-country comparability of the data.

The use of the Scopus database for Science and Engineering Indicators 2016 represents a substantial increase in the global coverage of bibliometric data compared to prior years. The SCI and SSCI data sets were originally chosen to provide good coverage of a core set of internationally recognized, peer-reviewed scientific journals. The included journals are notable for their high citation rank within their Science and Engineering (S&E) fields and thus can be considered to represent the journals containing the highest-impact articles. For Science and Engineering Indicators 2014, the National Science Foundation (NSF) analyzed 5,087 journals from the SCI and SSCI for 2012. The change to the use of the Scopus database allows NSF to present data on the most highly cited S&E publications as well as on a broader set of publications that provide insight into trends in emerging and developing countries. For Science and Engineering Indicators 2016, approximately 17,000 S&E journals were analyzed.

In addition to expanded global coverage, the Scopus database used for Science and Engineering Indicators 2016 and 2018 includes research output from books and expanded coverage of conference proceedings. Research output from books is particularly important in the social sciences (Hicks 2005; Mingers and Leydesdorff 2015), and conference proceedings are particularly important in computer sciences (Lisée, Larivière, and Archambault 2008; Moed and Visser 2007).

This expansion of global coverage of S&E publications has costs as well as benefits. In particular, the move from SCI and SSCI to Scopus provides greater global coverage at the cost of a somewhat shorter time series of bibliometric data because Scopus data currently begin in 1996. Additionally, Scopus's comprehensive global coverage of journals may include some journals that are not highly cited or have limited international visibility.

Another example is University Office, headquartered in Melbourne with offices in Perth and Sydney, an international leader in research management and administration applications and solutions. They work extensively with the university and research community to deliver solutions tailored for all research-driven institutions. The Scopus database provides the University Office CRIS system IRMA (Integrated Research Management Application) access to data, enabling users to automatically harvest data to populate IRMA (www.universityoffice.com).

The EIGR is an important new tool for mapping and analysis specifically of groundwater research and knowledge that range somewhere between the peer reviewed research tools (Web of Science and Scopus) and other broader databases and tools such as Google Scholar, Mendeley and ResearchGate. The added value of EIGR is to provide direct access to important metadata about available groundwater research and knowledge publications including "grey literature", which has been classified according to a policy relevant classification system based on the grand societal challenges of the EU Horizon 2020 programme.

In addition to the analyses performed on the data available in the developed EIGR database it was decided to evaluate the scholarly output for groundwater and hydrogeology research in Scopus (www.scopus.com) to supplement the EIGR analyses with analyses conducted specifically on peer reviewed research. Scopus contains the largest database for natural science and engineering (Mongeon and Paul-Hus, 2016) including groundwater research with build-in analytical tools, snowball bibliometrics and add-on tools for additional research benchmarking and trend analyses in SciVal. Scopus data were also classified by the classification system and tools developed for EIGR, and "VOSviewer" (Eck and Waltman, 2010) a tool recently developed for bibliometric and science mapping and visualization, and analysis of keyword co-occurrence etc.. All these tools proved to be useful in the assessment of gaps and trends in groundwater research and knowledge.

3 Methods

3.1 Background

This chapter is intended for introducing the methodology employed to map gaps and trends in groundwater research by visualizing and analyzing the most prominent groundwater research categorized after research topics, operational actions related to groundwater management for EC Societal Challenges and active research communities in Europe. This has been done through analysis of groundwater research and knowledge data available from two main sources: uploaded data to the in KINDRA developed European Inventory of Groundwater Research (EIGR) and from Scopus scientific database and search engine in combination with the SciVal tool (see KINDRA D1.1 and 1.2). To establish a common terminology and approach to carry out the analysis presented here, various academic, industrial and research classification schemes have been reviewed to create a hierarchical structure and a selected list of keywords from relevant EU directive documents. Notably, the Water Framework Directive (WFD, European Commission, 2000), its daughter directive the Groundwater Directive (GWD, European Commission, 2006) and the Blueprint to Protect Europe's Water Resources (BWR, European Commission, 2012) as well as scientific literature (KINDRA D1.1 and D1.2).

The analyses performed on data in EIGR and Scopus/SciVal focus on two main analyses identifying the most prominent groundwater research topics in relation to European societal challenges and the most active research communities, respectively. This includes (1) the analysis of the most frequent keywords, popular and emerging research topics and their trends in time and space (varying research interests depending on geographical, climatological and geological settings) ; and (2) the performance of regions, countries, institutions and scientists within groundwater research in general and within the different selected research and knowledge topics and the interactions among them e.g. identification of the strongest research networks on selected specific topics. This is expected to be helpful when selecting research partners on specific topics from different parts of Europe e.g. for EU research programmes.

Emphasis is on (1) developing a better understanding of the contribution of groundwater research and knowledge to meet the European Societal challenges defined in Horizon 2020 and making the importance of groundwater research within each of the challenges more visible. Also, the focus of this report is ultimately to be able to define groundwater research gaps. This is not possible solely by analysing the resources available in the databases of e.g. the EIGR and Scopus and the recent research trends indicated by the analysis of these. These analyses have to be supported by expert judgement and active involvement in ongoing working groups within e.g. the Common Implementation Strategy of the Water Framework Directive, and through discussions with the Joint Panel of Experts.

A list of keywords (listed in Appendix) from EU policy documents, WFD and GWD, and scientific literature has been identified and described in KINDRA deliverables D1.1 and D1.2. The keywords have been assigned to the three main categories in the Hydrological Research Classification System (HRC-SYS): (a) Societal challenges, (b) Operational Actions and (c) Research Topics. The main categories have been defined as follows: (a) Societal Challenges: 1. Health, 2. Food, 3. Energy, 4. Climate-Environment-Resources, 5. Policy-Innovation-Society (in addition 6. Transport was explored, but not part of the overall analyses); (b) Operational Actions: 1. Mapping, 2. Monitoring, 3. Modelling, 4. Water Supply, 5. Assessment & Management; (c) Research Topics: 1. Biology, 2. Chemistry, 3. Geography, 4. Geology, 5. Physics & Mathematics. The 3-D structure of HRC-SYS is shown below in Figure 3.1 (refer to D1.2 for the details).
For the sake of clarity, Societal Challenges were abbreviated in this report as follow.

Full name	Abbreviation
Health, demographic change and wellbeing	Health
Food security, sustainable agriculture and forestry, marine and maritime and inland water research, and the Bioeconomy	Food
Secure, clean and efficient energy	Energy
Climate action, environment, resource efficiency and raw materials	Climate, Environment and Resources
Europe in a changing world - inclusive, innovative and reflective societies	Policy, Innovation and Society

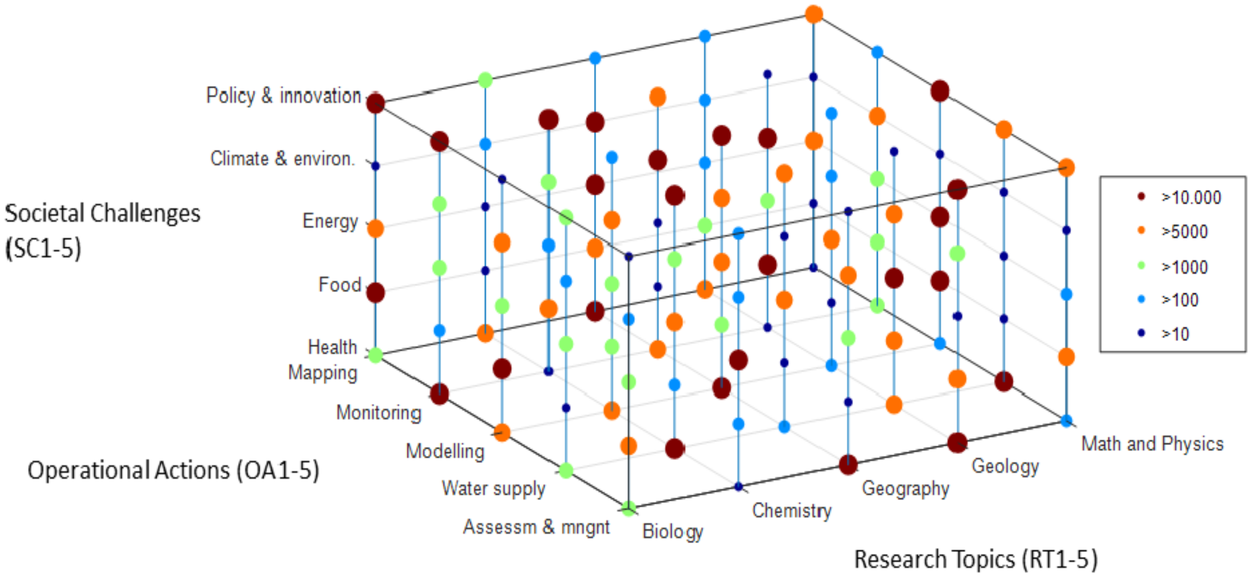


Figure 3.1 . The HRC-SYS classification system for groundwater research (D1.2). The legend indicates the number of resources at each intersection point (as an example)

This classification system (HRC-SYS) constitute the basis for developing a database, European Inventory of Groundwater Research (EIGR), for storing resources (groundwater related research and knowledge: scientific journals, proceedings, book chapters, reports etc). These resources were uploaded by experts in hydrogeology from 20 countries from the member National Associations (EFG Linked Third Parties). EIGR contains metadata, not the resources themselves, and is built on an open source platform (Geonetworks).

EIGR allows population of heterogeneous data, which compared to scientific databases, like Scopus and Web of Science, includes non-peer reviewed resources. The EFG people who uploaded the data have a background in (hydro-) geology on a more applied level. Therefore the EIGR resources are biased towards non-peer reviewed data. The resources uploaded to EIGR were categorized according to four classes (Figure 3.2). The total numbers of records uploaded and published on the EIGR during the project is 2178, updated to 2200 during the final revision phase of the project.

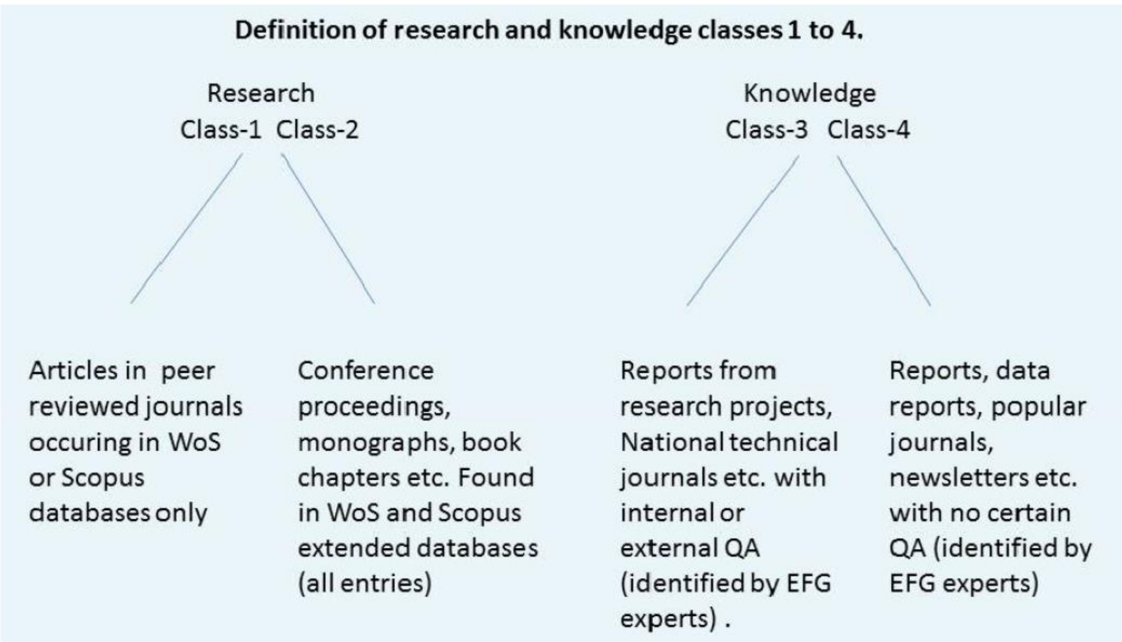


Figure 3.2. Classification of EIGR resources (refer to D1.2)

3.2 Gaps and trends analysis

The gaps and trends analysis is conducted by means of three approaches: (1) HRC-SYS analysis in which for each of the societal challenge (SC) selected in the 3-D HRC-SYS representation (Figure 3.1) coincidences between operational actions and research topics are inspected; (2) Co-occurrence analysis to explore links between and clusters of keywords; and (3) Scopus - SciVal analysis by making use of tools included in Scopus database and the associated SciVal tool suite. These are briefly described in the following.

3.2.1 HRC-SYS analysis

The HRC-SYS three dimensional classification system is explored for resources at intersections for research topics (RT), operational actions (OA) 2-D "slices" (RT, OA). Analyses can be performed in all three directions, i.e. (RT, OA) for each SC, (RT, SC) for each OA and (OA, SC) for each RT, which complement each other (Figure 3.3). As KINDRA is most concerned to explore gaps within societal challenges, the approach of exploring resources at the intersection between research topics and operational actions for societal challenges is adopted for both the EIGR and Scopus databases. As described in D1.1 and 1.2 (Figure 3.2), the EIGR both contains scientific literature (Class 1+2) as well as information which to a lesser degree has been reviewed or otherwise quality assured (Class 3+4). Clearly, the in this project developed EIGR has a population which is much smaller compared to large scientific databases as Scopus (or Web of Science) and also contains mainly Class 3 and 4 information (Figure 3.2). However, inspecting and analysing EIGR data gives insight in research topics and operational action, associated to groundwater management and operation, which is not available in the Scientific Scopus database, i.e. Class 3+4 resources.

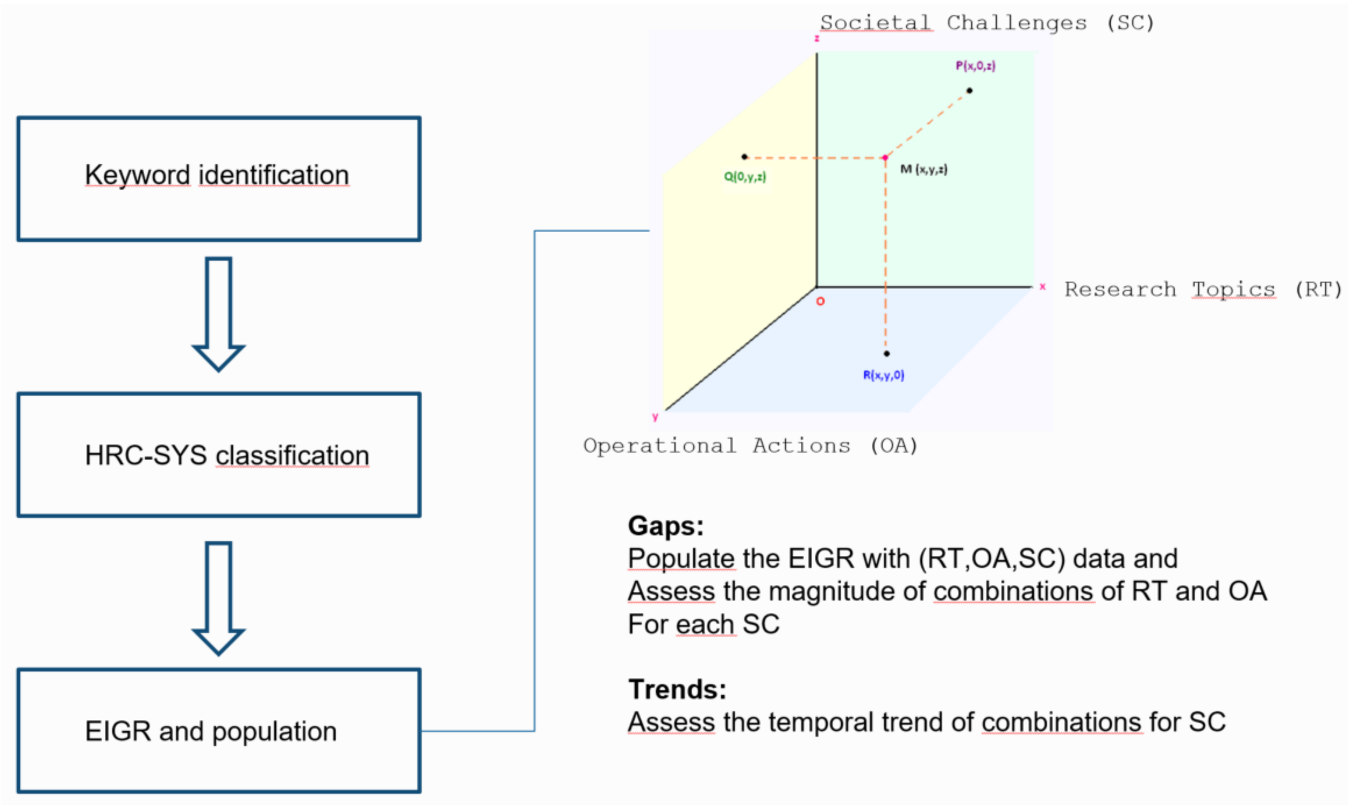


Figure 3.3. The HRC-SYS analysis approach

3.2.2 Co-occurrence analysis

For identification of gaps in groundwater research a co-occurrence analysis and bibliometric mapping approach has been deployed to visualize and map between keywords. For this, the VOSviewer has been deployed, a software tool for creating maps based on network data and for visualizing and exploring these maps (van Eck and Waltman, 2007, 2010, 2017). Bibliometric maps can be graph or distance based, where in the latter employs multidimensional scaling technique (Borg and Groenen, 2005) or VOS mapping technique (van Eck and Waltman, 2007; van Eck et al., 2006). In KINDRA, VOSviewer has been used to construct networks of keywords (called items in VOSviewer) associated to the terminology of the KINDRA HRC-SYS: societal challenges, operational actions and research topic, as earlier explained. For the analysis presented here VOSviewer has been applied to four visualizations of a map: network, density, cluster density and the overlay visualization. Zooming and scrolling functionality allows a map to be explored in full detail, which is essential when working with large maps potentially containing thousands of items. Although VOSviewer is intended primarily for analyzing bibliometric networks, it can in fact be used to create, visualize, and explore maps based on any type of network data (van Eck and Waltman, 2017). For a discussion on other mapping techniques and tools pls. refer to Bornmann et al. (2015) and van Eck & Waltman (2010). The dataflow from EIGR and Scopus to VOSviewer is depicted in the diagram (Figure 3.4) below. In the gaps and trends analysis we are interested in identification of links between the groundwater research related keywords, the frequency of occurrence in the literature and also how keywords cluster as this provides indications for how prominent keywords are and how research areas to which keywords belong are distributed and linked. For example, the frequency of keywords may reveal the intensity of research in an area to which this keyword can be linked and links between keywords and research areas may be to a higher or lesser degree expected (by expert judgement on groundwater research) and give insight in research gaps. How prominence, links and clusters vary over time is crucial for exploring trends.

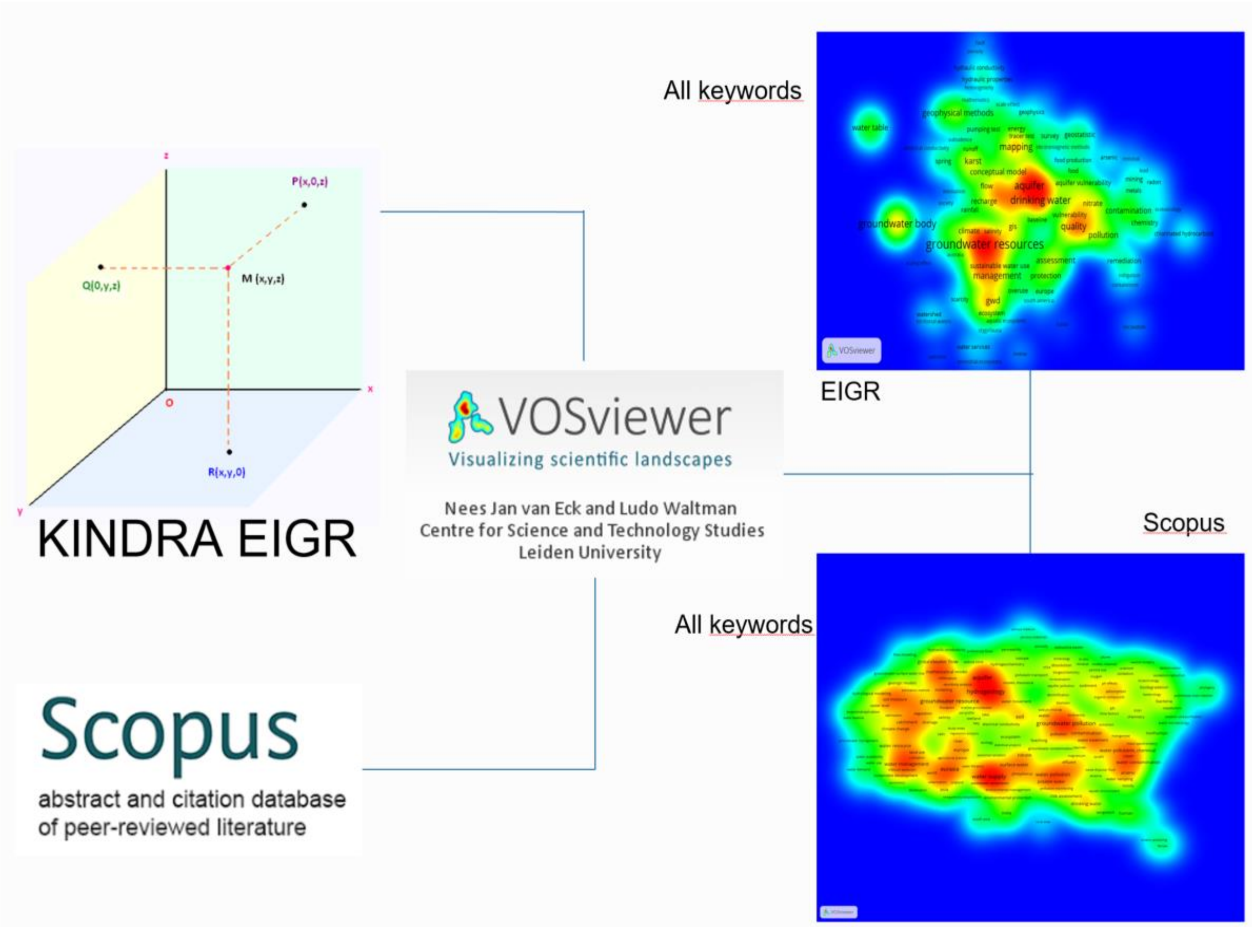


Figure 3.4. Co-occurrence analysis from EIGR and Scopus data by visualizing density maps of items and clustering, exemplified for Societal Challenge Climate, Environment and Resources (SC4)

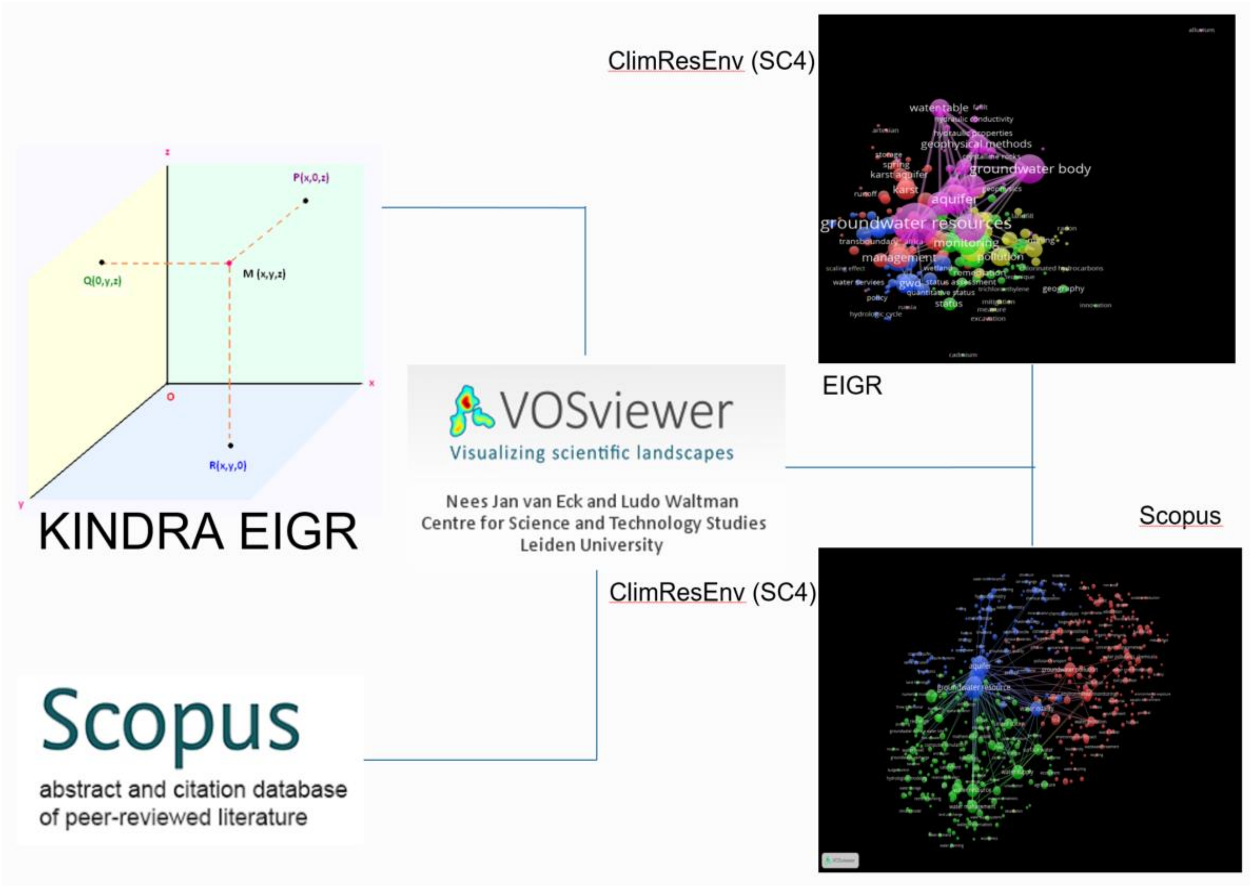


Figure 3.5. Co-occurrence analysis from EIGR and Scopus data by visualizing networks maps of items and clustering exemplified for Societal Challenge Climate, Environment and Resources (SC4)

Thus, the idea is that links between keywords indicate research in which such keywords are related. Missing links, where they are expected, may signify a gap in research. Each link has a strength, represented by a positive numerical value. The higher this value, the stronger the link. The strength of a link may be interpreted as an indication of how keywords are coupled and interact.

In the network visualization, items are represented by their label and by default also by a circle. The size of the label and the circle of an item is determined by the weight of the item (i.e. how many documents the keyword is present in). The higher the weight of an item, the larger the label and the circle of the item. The color of an item is determined by the cluster to which the item belongs. Clusters are determined by an optimization algorithm, that groups items based on association strength (Waltman et al, 2010). Lines between items represent links. The distance between two keywords in the visualization approximately indicates the relatedness of keywords found by searches in EIGR or Scopus. In general, the closer two keywords are located to each other, the stronger their relatedness.

In the item density visualization, items (keywords) are represented by their label in a similar way as in the network visualization and the overlay visualization. Each point in the item density visualization has a color that indicates the density of items at that point. By default, colours range from blue to green to red. The larger the number of items in the neighbourhood of a point and the higher the weights of the neighbouring items, the closer the colour of the point is to red. The other way around, the smaller the number of items in the neighbourhood of a point and the lower the weights of the neighbouring items, the closer the colour of the point is to blue (van Eck and Waltman, 2017).

The cluster density view is similar to the ordinary density view except that the density of items is displayed separately for each cluster of items. The cluster density view is particularly useful to get an overview of the assignment of items to clusters and of the way in which clusters of items are related to each other

3.2.3 Scopus – SciVal

Scopus was launched in 2004 and contains the largest abstract and citation database of peer-reviewed literature, including tools to track, analyze and visualize research (Figure 3.6). With 22,800 titles from more than 5,000 international publishers, Scopus delivers the most comprehensive view of the world's research output in the fields of science, technology, medicine, social science and arts and humanities (elsevier.com/scopus).

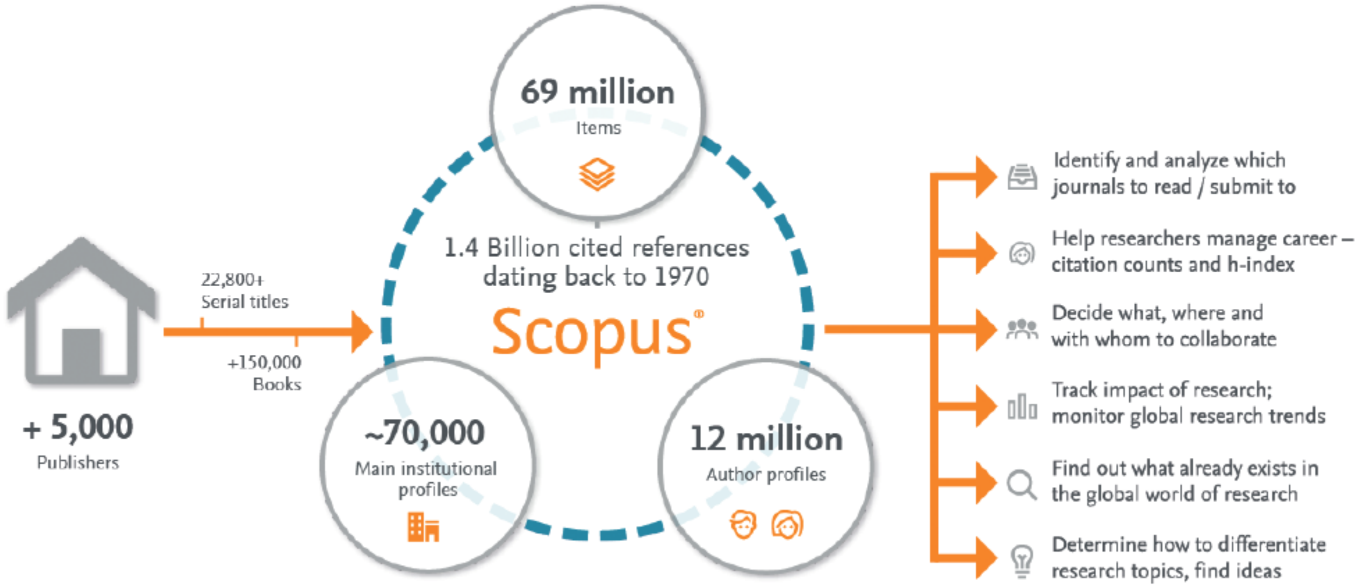


Figure 3.6 Overview of Scopus database (source: elsevier.com/scopus)

In KINDRA both the included tools in Scopus and SciVal are made use of in the gaps and trends analysis, some examples are shown below.

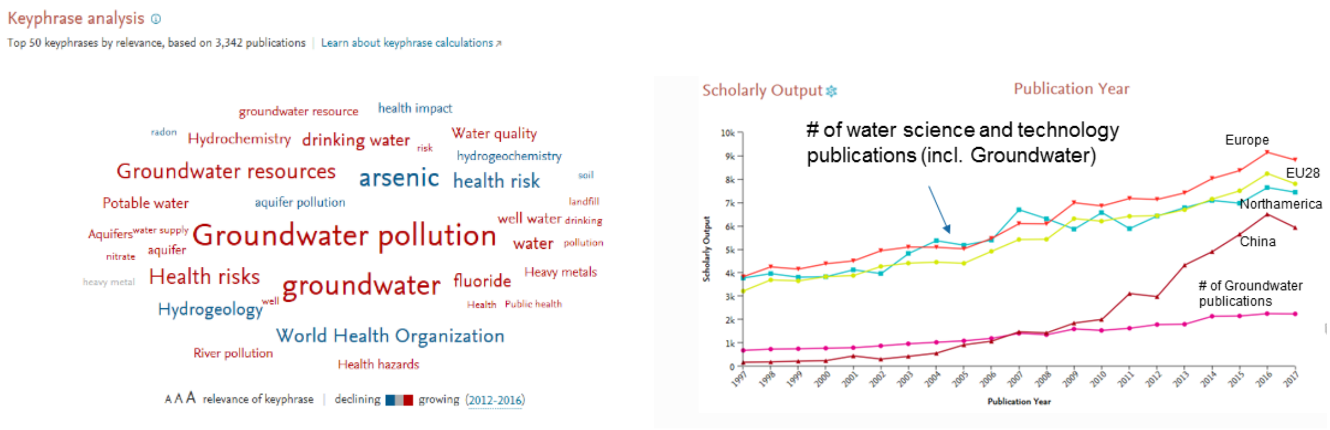


Figure 3.7 SciVal generated word cloud to indicate keyword prominence and trend (left) and publication trends (right)

Scopus database searches were based on search strings with keywords from the KINDRA thesaurus so as to be able to extract groundwater research relevant results. HRC-SYS classified keywords for the three main categories (Societal Challenges, SC; Operational Actions, OA; and Research Topics, RT) and 5 sub-categories, refer to the 3-D HRC-SYS representation in Figure 3.1, in all 15 areas – 298 keywords (see table in appendix) and systematized the keywords into three different groups. The search terms from SC1-5, OA1-5 and RT1-5 were combined into a search string and include the period for the search. This results in a search string like: TITLE-ABS-KEY((Groundwater OR "Ground Water" OR hydrogeolog*) AND <SC terms> AND (OA1 OR OA2 OR

OA3 OR OA4 OR OA5) AND (RT1 OR RT2 OR RT3 OR RT4 OR RT5)) AND PUBYEAR > 1996 AND PUBYEAR < 2017

The KINDRA thesaurus terms of the three main categories (Societal Challenges (SC), Operational actions (OA), and Research Topics (RT)) are included in the search string to assure that every document in the search result will be linked to at least one coordination point in the HRC-SYS classification.

The commands (TITLE-ABS(tract)-KEY(words)) were added as well as the Boolean Operators (AND, OR, NOT)and the defined periods of years (PUBYEAR > or <). Scopus restricts export operations to a maximum of 2,000 documents per search . The files are saved as CSV files and different information is selected from the documents such as the information included in the following categories; Citation information, Bibliographical information, Abstract & Keywords, Funding details and other information.

The CSV-files of each search set were then imported in VOSviewer to perform a co-occurrence analysis on the keywords of the documents. The keyword 'groundwater' was eliminated as it occurs in almost all documents and thus distorts the visualisation, furthermore trivial keywords (e.g. 'article' or 'review') were also filtered out, and the number of keywords were then limited to the strongest 500. The relatedness of items were normalized by association strength (As recommended by Eck & Waltman, 2009), and the resulting image were rotated and if needed flipped, to ease comparison with other search sets.

3.2.4 Illustration of methodology applied in gap analysis

Taking point of departure in the graphical representations of how keyword search data is extracted from either EIGR or Scopus database in Figure 3.4 and 3.5, this process is briefly exemplified to make the user familiar how this is used in the gap analysis and clarify potential and limitations. For this the Societal Challenge 'Climate, Environment and Resources' (SC4) for any selected time period is taken as example.

For SC4 a gap analysis can be based on an intersection (bubble) plot in which the Operational Actions (OA) and Research Topics (RT) intersections are visible as bubbles of varying sizes. Gaps are thus directly visualized as smaller bubbles as compared to larger, more populated, intersections. This is illustrated in Figure 4.38 for EIGR and Scopus. The observations of varying intersection bubble sizes should ideally be subject of further examination by means of e.g. expert judgement to assess whether bubble sizes reflect actual gaps or a lesser need or prioritization. The method by inspecting gaps by means of intersection plots for SC4 is directly derived from the HRC-SYS design and can be further improved on basis of an extended EIGR database which is enabled by dynamically updating by current and future users.

Gaps can also appear from co-occurrence analysis. In this case, gaps within the example of SC4 can be inferred from network and density maps (created in VOSviewer) based on EIGR or Scopus searches and for selected time periods. A network map visualizing links within SC4 for connected keywords, in Figure 4.52, is then used to analyze gaps by inspecting strong and weak links between keywords in this Societal Challenge. For example, weak links between keywords where strong links are expected represent gaps, in this case e.g. between 'groundwater resource' and 'agriculture'. Likewise, density maps show clusters of keywords and other (clusters of) keywords in the chosen example for SC4 may be at varying distance in which larger distances where close proximity is expected represent gaps. The powerful visual representation of clusters of 'groundwater resource', 'aquifer' and 'water quality' (Figure 4.52) shows expected strong interactions. The cluster 'groundwater pollution' is adjacent to the previous cluster, but not part of its which could be further explored. Clearly, as in the intersection plots, data visualizations should be subject to expert judgement for reaching strong conclusions on actual gaps or prioritized needs.

4 Results

4.1 GAPS analyses

Information included in the EIGR have been extracted by following search option tools available in the platform: in detail, searches have been performed by the three main categories (OA, RT, SC) and their 15 overarching categories; additional searches refer to classes 1 to 4, to additional indicators TRL and PRL, and by geographical criteria (mainly for nations included as Linked Third Parties (LTPs), but also for other countries/area). In addition, searches for building VOSviewer maps are based on keyword extractions; only the keyword set included in the KINDRA classification system (KINDRA thesaurus in the EIGR) has been used, if not differently declared along the text.

4.1.1 EIGR analyses

4.1.1.1 EIGR record distributions

Record data inserted into the EIGR comprises inputs from Project Partners as well as European Federation of Geologists Linked Third Parties (20 National Associations) participating in the project.

The total amount of records uploaded during the project on the EIGR, successively validated by the project partners and published (available on-line) is 2178 at the end of 2017. All analyses conducted on the EIGR, illustrated in this report, are based on this number of records (2178). Successively, during the first three months of 2018, some additional records have been inserted and validated, reaching the final number of 2200 published records. Remaining unpublished records inserted in the EIGR are about 130. These records cannot be published because they contain incomplete information and consequently are not useful for the gaps and trends analysis. Actually, it is mandatory when inserting records to specify the category and the overarching group of the classification system HRC-SYS; by this way, all records contain at least this information. Distribution in different sub-categories for the three main categories among published records is shown in Figure 4.1, Figure 4.2 and Figure 4.3

The prevalent type of metadata uploaded to the EIGR are hydrogeology related reports (about 50 %) followed by scientific papers from international and national scientific journals, popular journals, newsletters and quality assured or reviewed papers (about 25 %) and the remaining part contain other publications such as conference proceedings, databases and maps (D2.4). The distribution of uploaded resources for Operational Actions (5 categories Research Topics (5 categories) & Societal Challenges (5 categories). For Operational Actions the distribution is shown in Figure 4.1 below. Clearly, the Assessment and Management category constitutes the main part with well above 50 % of all resources, followed by Modeling (18%); similar occurrences shows the other three groups, Monitoring, Water Supply and Mapping. This distribution confirms that information inserted in EIGR are directly related to real application of groundwater knowledge in societal contexts, offering assessment and management solutions for groundwater use and protection.

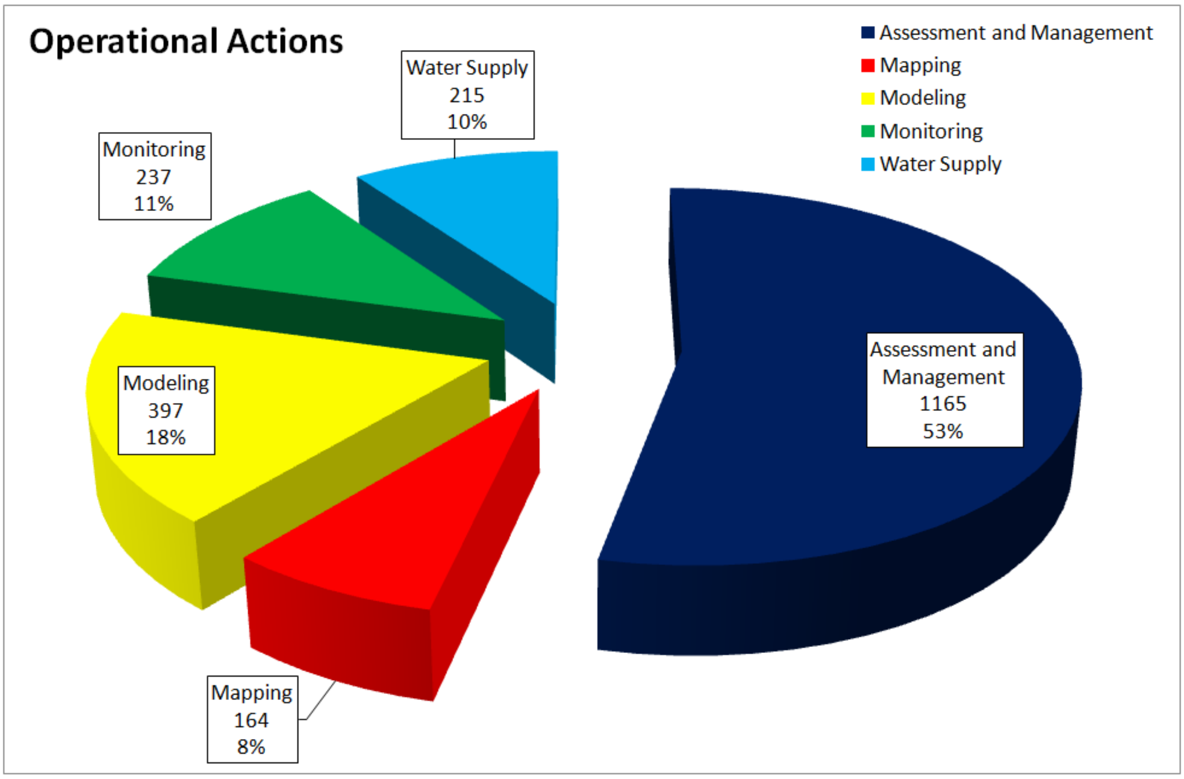


Figure 4.1 EIGR distribution of resources within Operational Actions categories

For the same reason of resources uploaded by European Federation of Geologists LTP, the research topic ‘geology‘ is dominating with over 75 % followed by ‘chemistry’ 12%, related to groundwater quality, whereas the remaining research topics are smaller (Figure 4.2).

The main reason for this unbalance is related to the origin and background of experts (LTP) who inserted data in the EIGR, who are geologists. This bias is a logical result of the project approach, which was originally concerned with hydrogeological issues with respect to more general groundwater issues. Nevertheless, undoubtedly hydrogeology is a fundamental part of the groundwater sciences and its prevalence therefore justified.

However, keywords associated to research topics (and also operational actions) are developing over time and should be added by users to keep the EIGR updated. For example, the biology related keywords when the project was initiated did not, by extension, include the most recent topics and were added later to the analysis. The adding of keywords and quality assurance is a dynamic feature of the EIGR system and included to keep it up-to-date also beyond the lifetime of the projects.

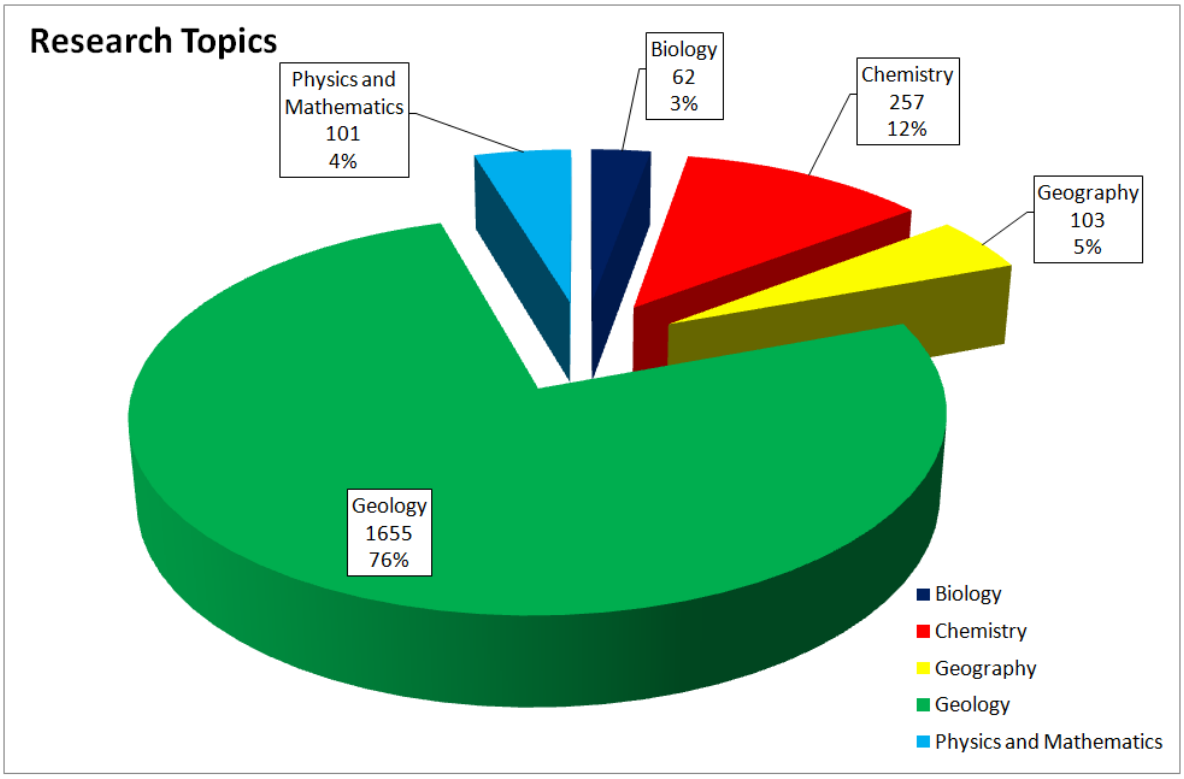


Figure 4.2 EIGR distribution of resources within Research Topics categories

Societal Challenges distribution (Figure 4.3) of EIGR records reveals the largest unbalance among overarching categories: Climate, Environment and Resources covers 87% of the records, confirming the strong influence and relationship of groundwater knowledge on this challenge. Resources as this is the main area of concern for the Linked Third Parties (EFG) partners who mainly populated the EIGR database. For that reason, the gaps and trends analysis focus on this part. A significant percentage of metadata refers to Policy Innovation and Society (7%), which demonstrates that the classification and the EIGR are capable to capture the information related to the application of knowledge in policy actions having societal impacts. Minor percentages are related to Health, Energy and Food sub-categories.

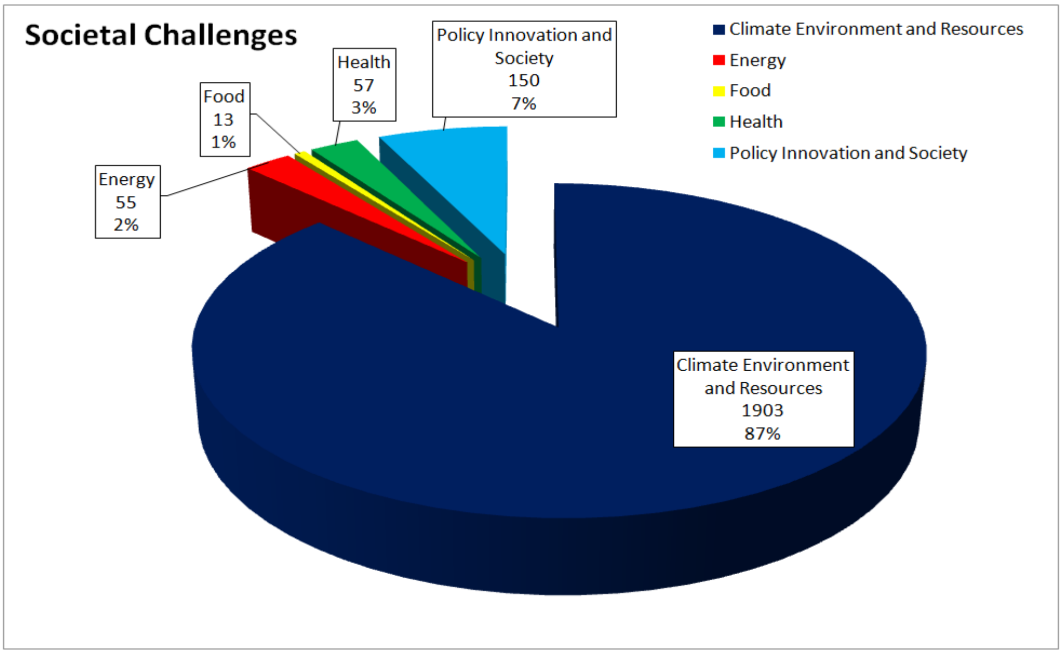


Figure 4.3 EIGR distribution of resources within Societal Challenges categories

The cross relationships of EIGR metadata can be visualized in a 3D diagram (also refer to Figure 3.1), where the 125 intersections among the three axes can be visualized and verified by the occurrence of records. From Figure 4.4 is clear that the records are distributed with a clear dominance for Research Topic 'Geology' and Societal Challenge 4 'Climate Environment Resources' 5 positions; many other positions in the cube (19 of 125) show significant content of records (10-100 metadata), but in several cases the occurrence is limited (less than 10 records for 58 positions), reaching 0 records for 43 positions. Detailed analysis on these data is in chapter 3.1.1.3 and 3.2.1.1.

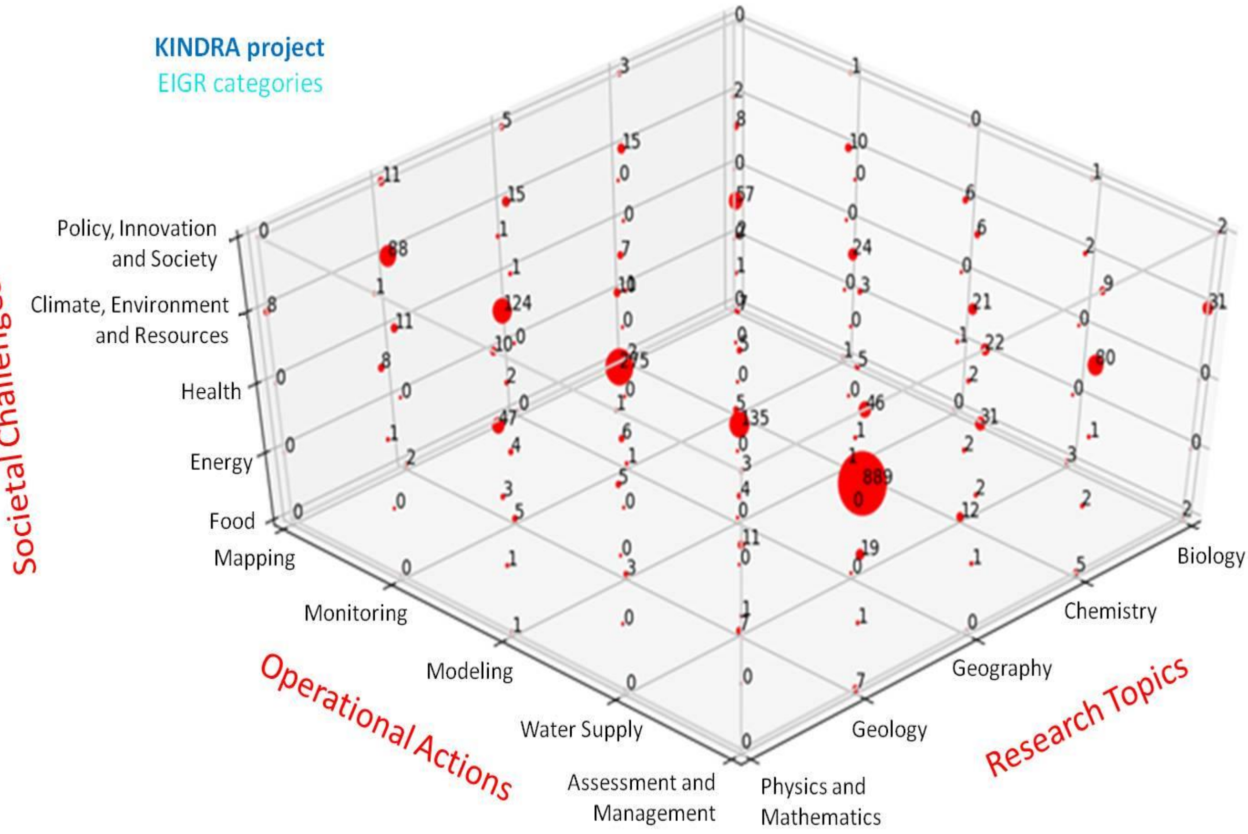


Figure 4.4 Resource occurrence in 3-D HRC-SYS structured EIGR of the main categories and their overarching groups

The EIGR contains four different classes related to research and knowledge, as resumed in Figure 3.2. Classes 1 & 2 represent official research products, classified in international academic databases, and represent about 1/3 of the inserted records (24% for peer-reviewed papers of class 1 and about 9% for proceeding papers), while the majority of the information are related to grey literature (classified in classes 3 and 4 as "knowledge"), with about 24% of records having quality assurance from some degree of review, and about 43% (class 4) are report and information at national scale without quality assurance. The unbalance towards the knowledge classes is in agreement with the aim of the project which wants to reveal also information at various spatial scales published in proceedings, reports with limited quality assurance, e.g. peer review.

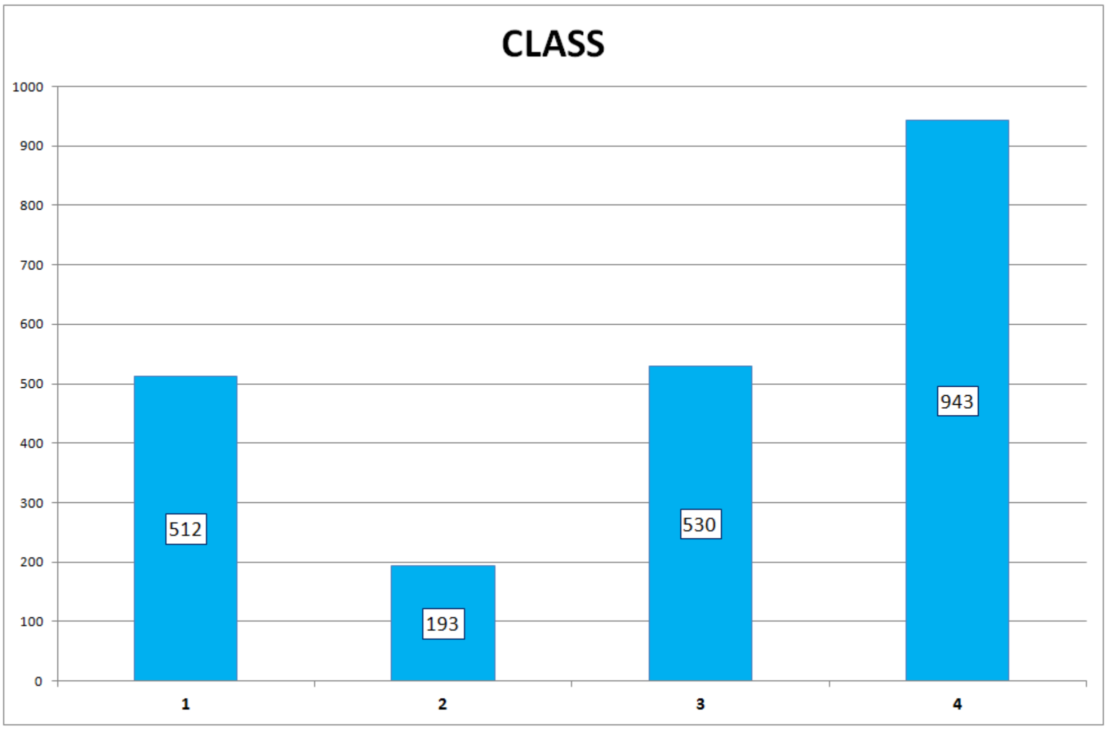


Figure 4.5 Distribution of EIGR records for research and knowledge classes 1-4

The Technology Readiness Level (from TRL1 to TRL9, as classified by the European Community) was included in EIGR as additional indicator for estimating technology maturity of a product/publication. The resource inserted had to be assigned to one of the following levels: TRL 1: Basic principles observed; TRL 2: Technology concept formulated; TRL 3: Experimental proof of concept; TRL 4: Technology validated in lab; TRL 5: Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies); TRL 6: Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies); TRL 7: System prototype demonstration in operational environments; TRL 8: System complete and qualified; and finally TRL 9: Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space).
In addition, the Policy Readiness Level (from PRL1 to PRL4) was included as indicator for estimating the policy maturity of a product/publication. The product/publication inserted had to be assigned to one of the following levels: PRL 1: Not relevant for EU policy implementation; PRL 2: Potentially relevant for EU policy but additional research needed; PRL 3: Relevant for implementation of EU policy, basic research conducted but guidance need to be developed; and PRL 4: Guidance available: ready for implementation of EU.

The distribution of TRL and PRL and also aggregated for TRL 1-4 and 5-9, and PRL 1-2 and 3-4 is shown in the Figure 4.6 below. It is clear that TRL 1-4 and PRL 1-2, requiring more research effort and demonstration before reaching market and policy implementation maturity are dominating. TRL information (Figure 4.6) is available for only 73% of the records and clearly shows a prevalence of lower classes, corresponding to not-technologically advanced information (61% of classes 1 to 4), with a minority of records having mature TRL levels (16%). Looking at the keyword density maps for TRL 1 to 4 and TRL 5 to 9 (Figure 4.6), the former is concentrated on basic knowledge and research information on groundwater issues (as groundwater resources, aquifer, mapping, etc.), while the latter is clearly shifted towards possible solutions for management and assessment, with highest occurrence of keywords as drinking water, contamination, etc.). This different distribution confirms that TRL evaluation by the experts inserting data in the EIGR has been carefully attributed, classifying basic information with lower TRLs and advanced and technological information with higher TRLs.
A similar analysis has been conducted for PRL (Figure 4.6). Also for this case, the prevalence of the records is for lower levels (2/3 having PRL 1 & 2), while minor percentages correspond to higher PRL. Differently from

the TRL case, the EIGR records seem to have a larger attitude with policy actions, and a significant number of data shows the possibility to be implemented in policy actions with limited efforts.

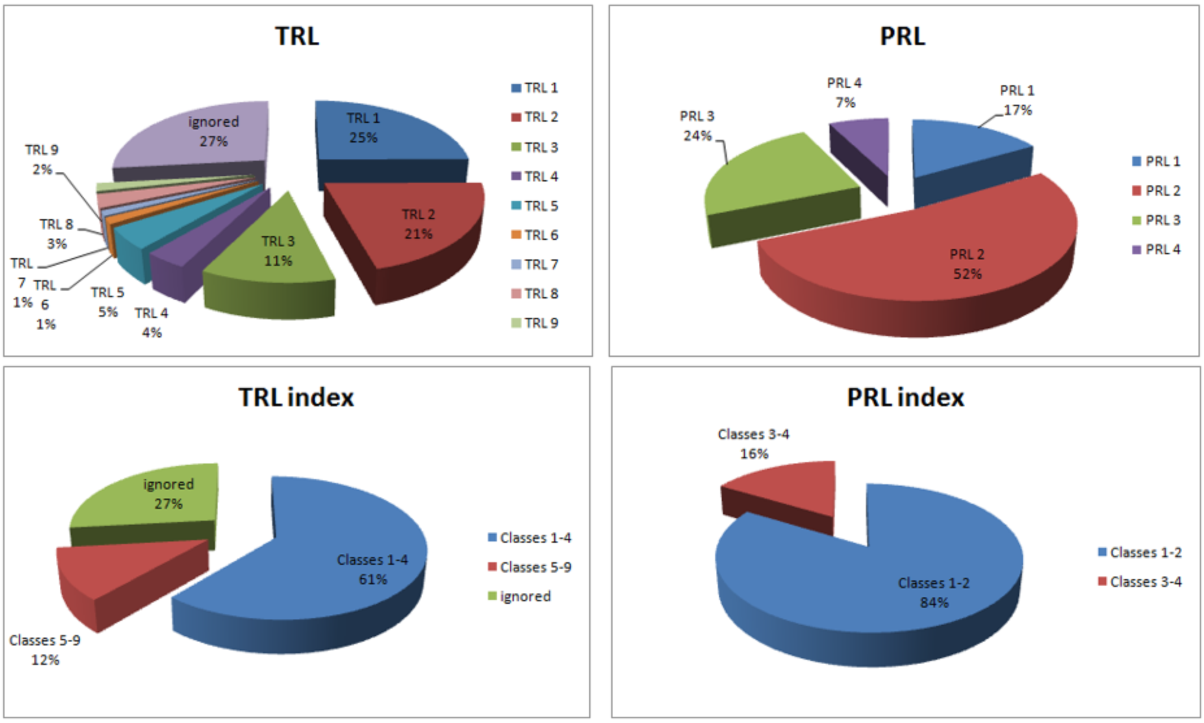


Figure 4.6 EIGR distributions for Technology Readiness Level (TRL), Policy Readiness Level (PRL) and categorised after level 1-4

An analysis of occurrence of records related to main EU research projects having connection with KINDRA has been performed in the EIGR. Results are resumed in the following table. The project focusing on groundwater are represented in the EIGR with a higher number of records (4-6), as BRIDGE, GENESIS, SUBSOL and AQUATERRA.

Pls. refer to ‘Supplementary Material E1’ for more and additional information pertaining to this section.

EU Project	*Number of EIGR records*	*EU Project*	*Number of EIGR records*
GABARDINE	*2*	*BRIDGE*	*6*
GENESIS	*4*	*WATERDISS2.0*	*1*
RISK-BASE	*1*	*SUBSOL*	*4*
WADE	*2*	*DAIAD*	*1*
CIRCE	*1*	*FREEWAT*	*1*
AQUATERRA	*5*	*SmartH2O*	*1*
AQUAREHAB	*1*		

Table 1 Occurrence of previous EU projects in EIGR related to KINDRA

4.1.1.2 Groundwater research derived patents

WIPO is the global forum for intellectual property services, policy, information and cooperation. WIPO is a self-funding agency of the United Nations, with 191 member states, with the mission lead the development of a balanced and effective international intellectual property (IP) system that enables innovation and creativity for the benefit of all. The mandate, governing bodies and procedures are set out in the WIPO Convention, which established WIPO in 1967 (www.wipo.int; WIPO, 2017). While WIPO is not explicitly included in the EIGR the term 'patent' is a keyword included in the EIGR thesaurus and WIPO is in this section used to illustrate the extent of patents in groundwater research

A patent is an exclusive right granted for an invention, which is a product or a process that provides, in general, a new way of doing something, or offers a new technical solution to a problem. To get a patent, technical information about the invention must be disclosed to the public in a patent application

From fig 4.7 and 4.8 it is clear that in the field of groundwater research derived patents (intellectual property) is overwhelmingly dominated by the USA (under USPTO), followed by the European Patent Office and China. One of the reasons for this is that in this field research at the European level is financed by public funding and filing patents on derived products is restricted as compared to products funded in the private market Other reasons for US dominated patents could be related to (1) that there are no language barriers for products developed in the US, English being the dominant language in groundwater research and innovation, and (2) lower data protection rules, e.g. no GDPR data compliance, facilitating the development of tools and subsequent innovations. Clearly, the large volume of groundwater research derived patents for China and India is related to the increasing economic development and available resources for research in general, including groundwater topics (UNESCO Science Report: towards 2030).

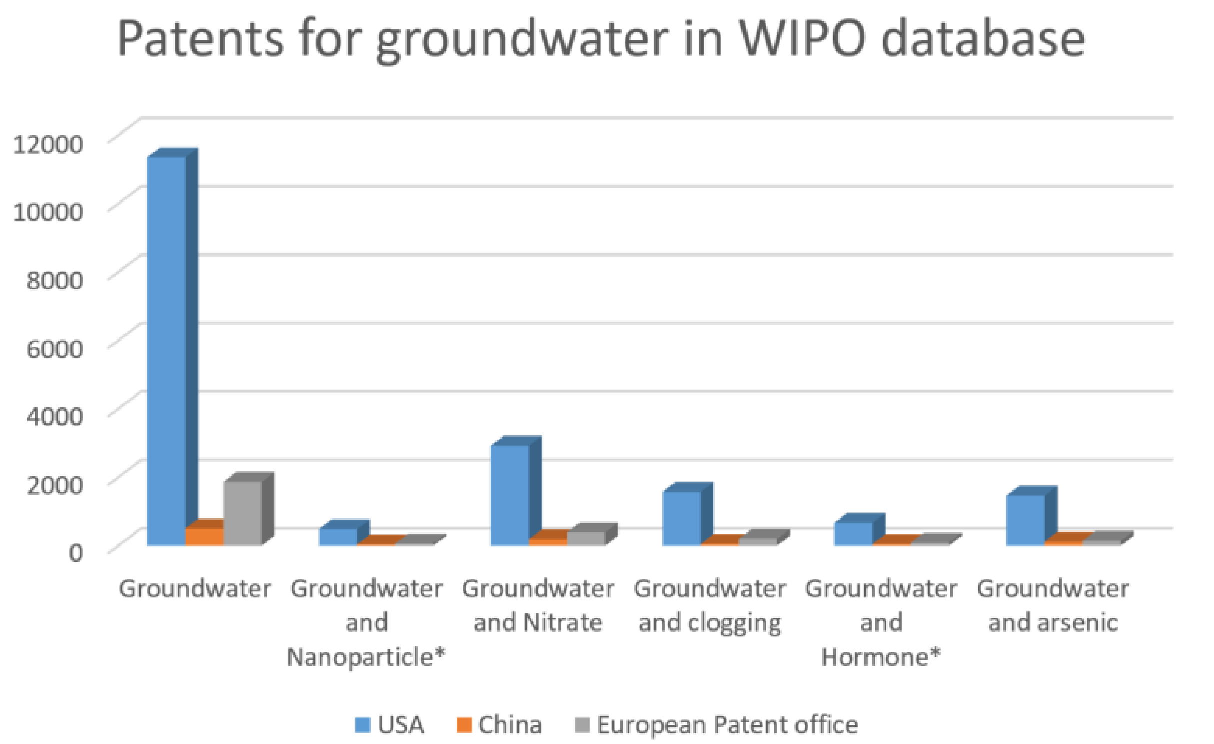


Figure 4.7 Groundwater research derived patents

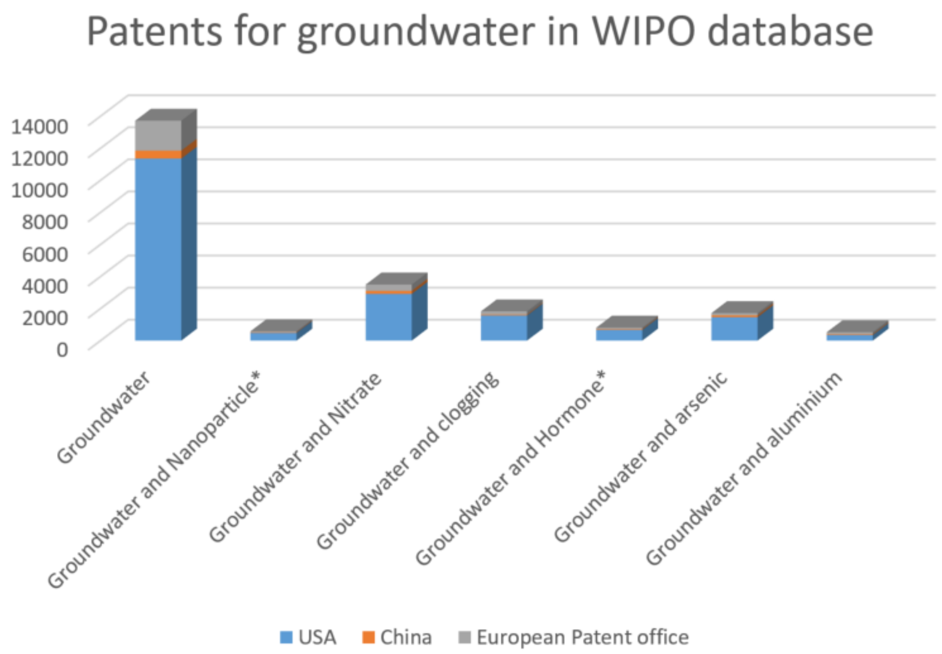


Figure 4.8 Total number of groundwater research derived patents

4.1.1.3 HRC-SYS analyses:

In this section the HRC-SYS three dimensional classification system (refer to Figure 3.1) for the EIGR populated resources is explored for resources at intersections for research topics (RT), operational actions (OA) for each of the 5 societal challenges (SC) and selected for the analysis of gaps and trends. Analyses can be performed in all three directions, i.e. (RT, OA) for each SC, (RT, SC) for each OA and (OA, SC) for each RT, which complement each other. As we are most concerned to explore gaps within societal challenges, the resources at intersections are inspected between research topics and operational actions for each of the societal challenges 'Health', 'Food', 'Energy', 'Climate, Environment and Resources' and 'Policy, Innovation and Society' for the EIGR database. As described in D1.1 and D1.2, the EIGR both contains scientific literature (Class 1+2) as well as information which to a lesser degree has been reviewed or otherwise quality assured (Class 3+4). Clearly, the in this project developed EIGR has a population which is much smaller compared to large scientific databases as Scopus (or Web of Science) and also contains mainly Class 3 and 4 information (Figure 4.6) and gives insight in research topics and operational action, associated to groundwater management and operation, which is not available in the Scientific Scopus database.

In the 3D representation of HRC-SYS, the 125 positions (intersections) above described can be more easily analysed by slicing the cube along each axis, obtaining 15 plots representing the distribution of the 5x5 positions for each overarching group. The most useful analysis for the KINDRA aim (gaps & trends analysis) is related to the five slices for each Societal Challenge. By this way, five plots resuming the occurrence of records for each SC as a function of OA and RT can be derived.

For instance, in Figure 4.9 for societal challenge 'Health' it is seen that the intersection 'Chemistry' and 'Water Supply' is relatively well populated, which is expected and related to the 'Geology' / 'Monitoring' intersection for societal challenge 'Food' when considering the issue of contaminated groundwater for geological layers.

Looking at the SC Health intersection plot (Figure 4.9), counting 57 records, it is clear that population is related mainly to Chemistry and Geology RTs, while OAs connected with Health are clearly 'Assessment and Management', 'Water Supply' and, to a minor extent, Monitoring. In fact, chemical properties and withdrawals for drinking purposes are fields strictly connected with Health. Several zero-records locations appear for Geography, Physics & Mathematics, Modeling and Mapping, which seem to have no apparent relationships with Health.

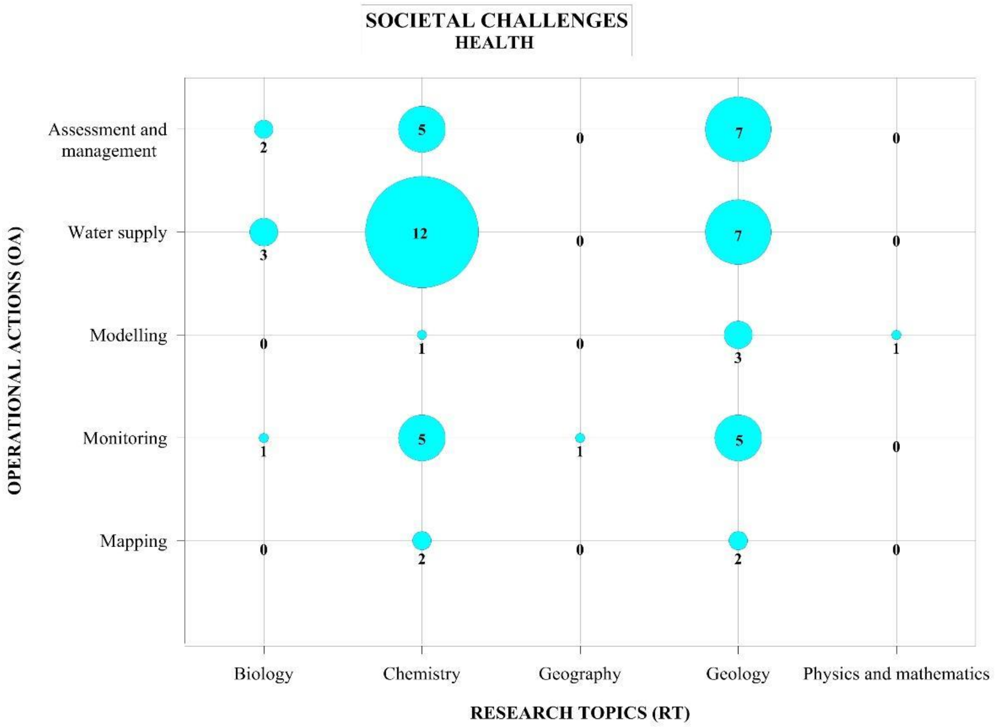


Figure 4.9 EIGR data (RT, OA) plot for SC = Health. The size of the bubbles indicates the relative amount of data at a specific intersection, whereas the number indicates the number of available resources

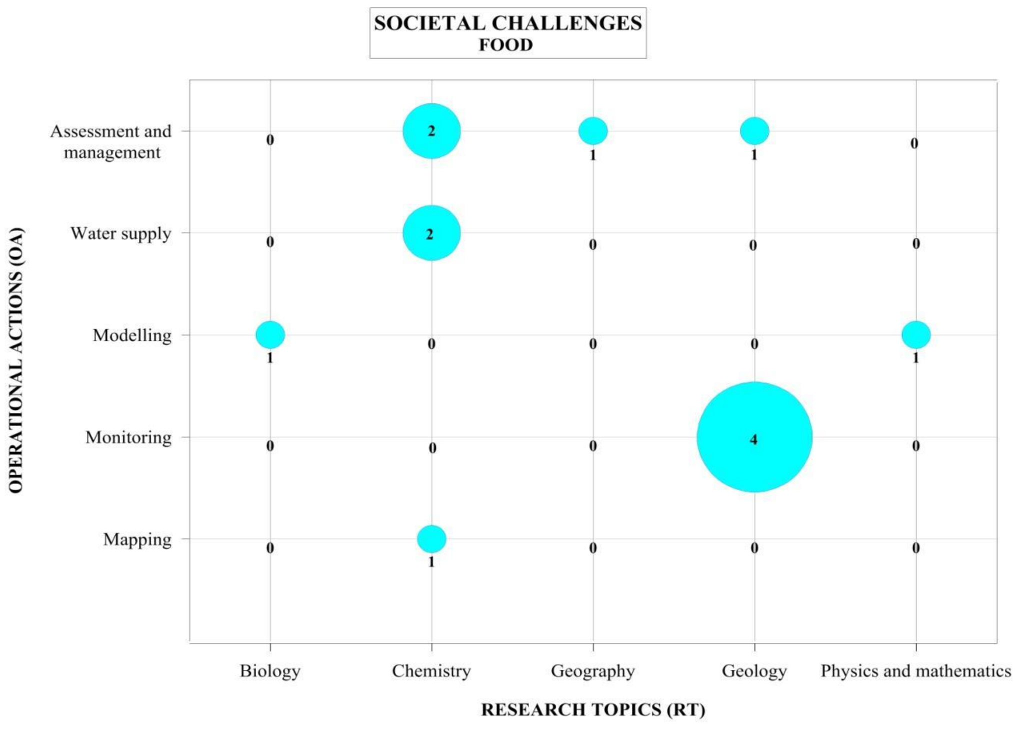


Figure 4.10 EIGR data (RT, OA) plot for SC = Food. The size of the bubbles indicates the relative amount of data at a specific intersection, whereas the number indicates the number of available resources

Concerning the EIGR distribution of resources for the category Food (Figure 4.10.) it appears that there is a very limited number of records, it covers less than 1% (13 data) of the uploaded information. Assessment and management and Water supply are the most relevant concerning the Operational Actions, while for the Research Topics, that is the case for Geology and Chemistry. There is a clear gap in submitted research and knowledge for this Societal Challenges, confirmed by 17 intersections on 25 show zero records. Consequently, no significant correlations can be inferred for this SC.

The Societal Challenge 'Energy' covers 2.5% (Figure 4.11, 55 records) of the uploaded information, it shows correlations mainly with Geology, where 80% of occurrences are located. This is a promising issue demonstrating the link between hydrogeology and energy, while clear gaps appear for all other OAs (no records at all for Biology). Among OAs, 'Assessment & Management' and 'Mapping' contain the majority of records.

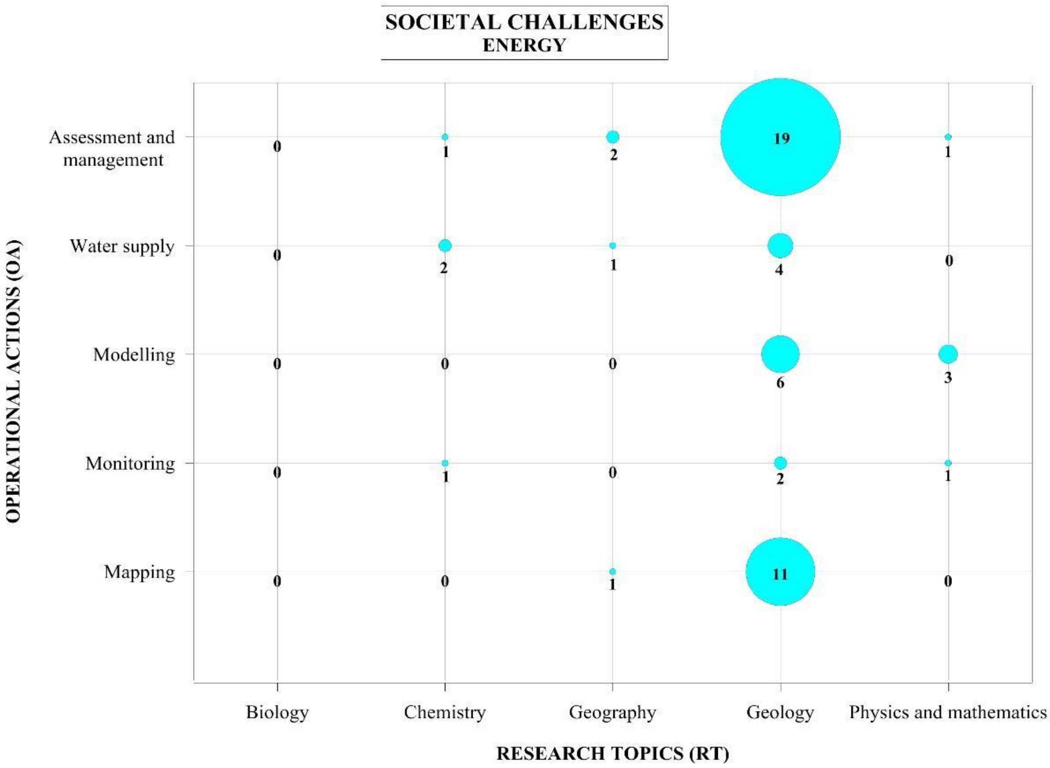


Figure 4.11 EIGR data (RT, OA) plot for SC = Energy. The size of the bubbles indicates the relative amount of data at a specific intersection, whereas the number indicates the number of available resources

The most of the EIGR records are related to SC4, Climate, Environment and Resources (Figure 4.12), where all 25 intersections include some records. The higher occurrence is, as usual, for Geology among RTs and for 'Assessment & Management' for OAs. This fact confirms that EIGR content is oriented towards hydrogeological contributions for management and practical solutions, aimed at solving climatic and environmental critical issues, by using and protecting water resources.

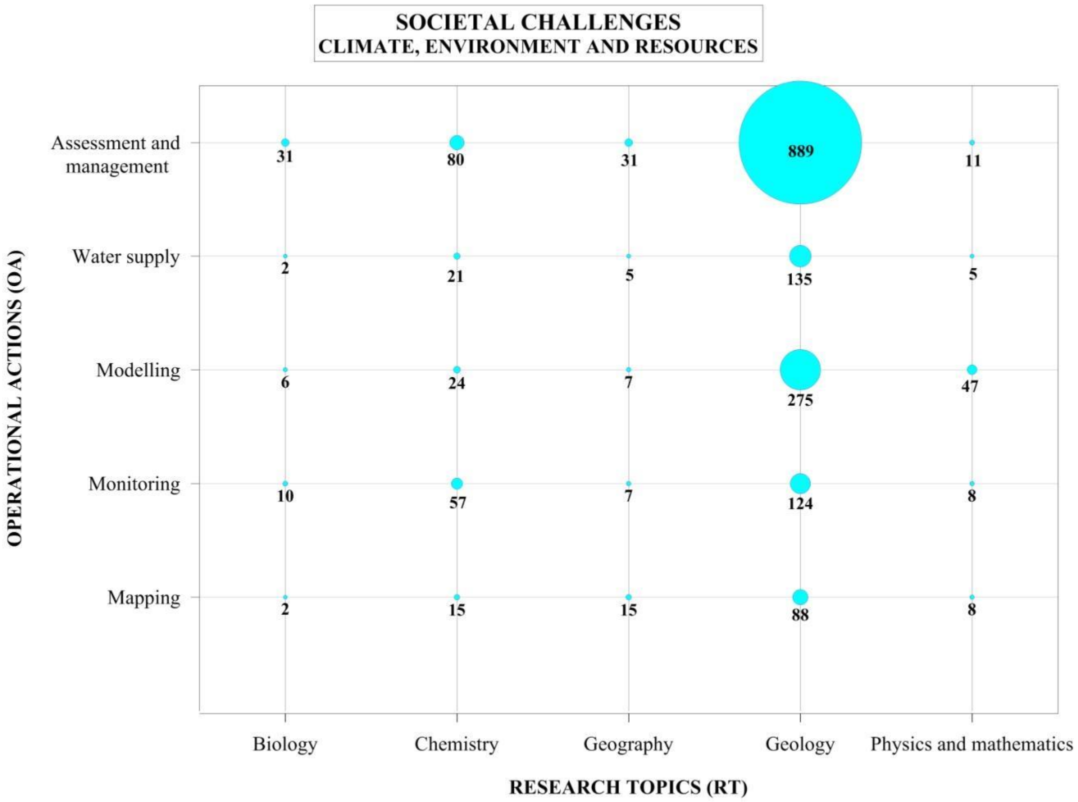


Figure 4.12 EIGR data (RT, OA) plot for SC = Climate, Environment and Resources. The size of the bubbles indicates the relative amount of data at a specific intersection, whereas the number indicates the number of available resources

Finally, a significant number of records deal with SC5 'Policy, Innovation and Society' (Figure 4.13), with 22 intersections containing records. A different distribution among RTs and OAs appears for this SC: beside Geology, Geography becomes prevalent specially for 'Assessment and Management', probably for correlation with Basin Management Plans. Also for OAs, Mapping and Modeling a percentage higher than other SCs, has been observed, revealing the importance of these instruments for policy and society. Conversely, Monitoring has a very limited importance respect with other SCs.

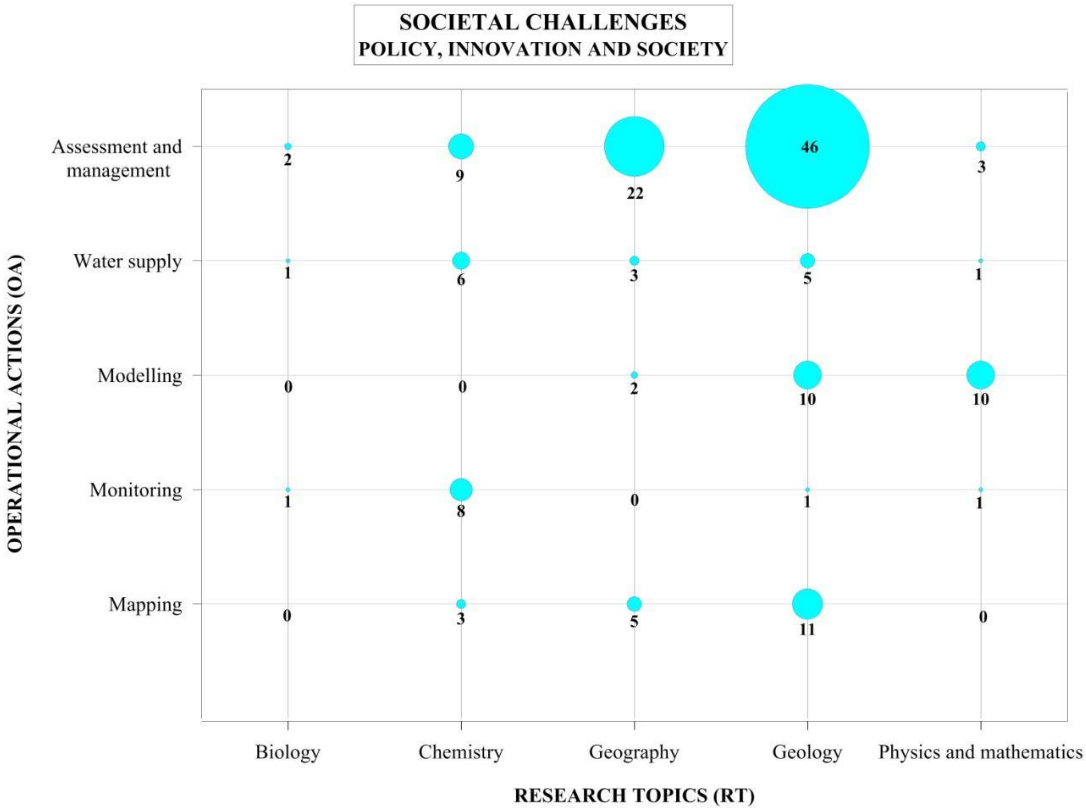


Figure 4.13 EIGR data (RT, OA) plot for SC = Policy, Innovation and Society. The size of the bubbles indicates the relative amount of data at a specific intersection, whereas the number indicates the number of available resources

Slicing the 3D cube along the OA and RT axes is considered less important for gap analysis. Only a resuming plot has been included for OAs and RTs, compacting the occurrence of the other two categories. In the OA resuming plot (Figure 4.14), SC4 and SC5 are the most important, while among RTs, at distance, Geology and Chemistry show the highest occurrence. There is a clear gap for SCs Health, Food and 'Policy, Innovation and Society'.

The other resuming plot for RTs (Figure 4.15) clearly show the concentration of records for SC4 Climate, Environment and Resources and the above cited gap for Food and, to some extent, for Health; among OAs, Assessment and Management is prevalent, but others sub-categories have significant occurrences.

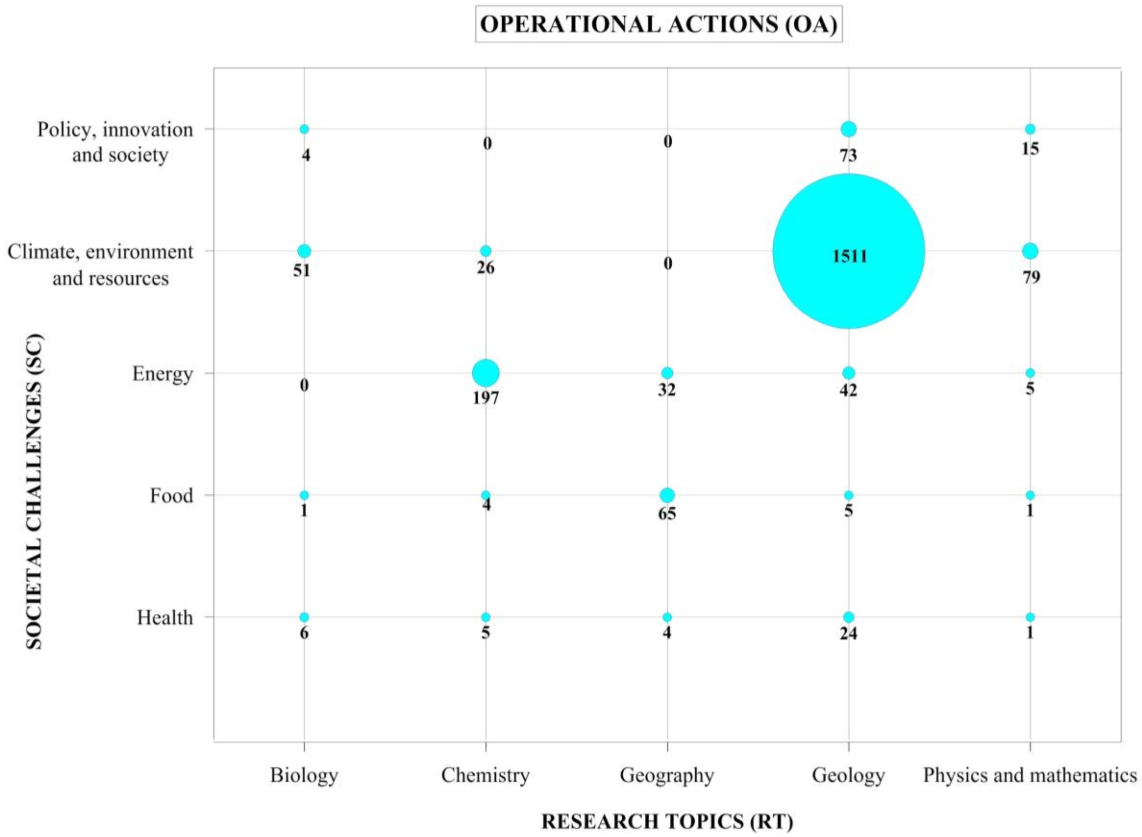


Figure 4.14 Resuming intersection plot of EIGR records for Operational Actions

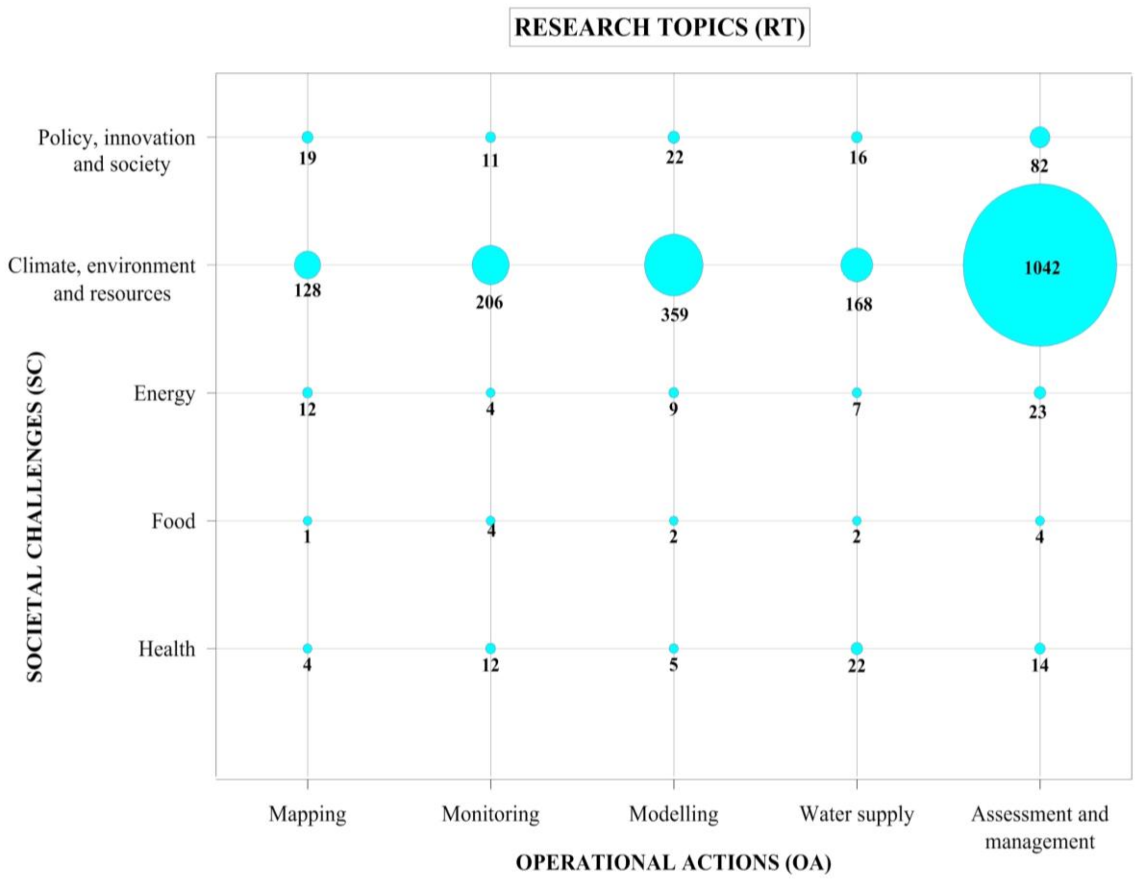


Figure 4.15 Resuming intersection plot of EIGR records for Research Topics

4.1.1.4 Co-occurrence analysis

The co-occurrence analysis for the EIGR system is limited to the Societal Challenge 4 on ‘Climate, Environment and Resources’ for which 1903 records out of a total of 2178 have been inserted. The remaining records for SC1-Food (13), SC2-Health (57), SC3-Energy (55) and SC5-Policy, Innovation and Society (150) contain too few records to make reliable inferences.

Detailed analysis of gaps is based on an in-depth approach, using the keywords of the KINDRA Thesaurus inserted by the EIGR user associated to each record, and analyse them by the VOS viewer tool, which allows to visualize not only the occurrence (frequency) but also the connections (co-occurrence) among keywords (see method chapter).

Keywords are extracted from the EIGR database by selecting all the available records and exporting the selected dataset as a .txt file which can be imported in Excel for further analysis. In each cell, the keywords are separated by "###" characters, for next processing it is necessary to replace them with ", " (comma and space) and saved in a new .txt file, for VOSviewer processing, taking care that each row of the file corresponds to an EIGR record. For further processing in Excel only the KINDRA-EIGR dataset keywords are recognized, generating a suitable string for each record. These new strings contain only the EIGR-KINDRA keywords and can be saved in a .txt file for processing in VOSviewer. If the number of 256 characters is exceeded, some sequences of characters ", , , , , ," need to be deleted. The VOSviewer software does not always correctly recognize the EIGR-KINDRA dataset keywords where even the use of "###" characters leads to errors. Therefore, a specific thesaurus file was developed for creating graphs in VOSviewer which allows to determine which words have to be corrected (and how) or discarded during the VOSviewer processing. For processing in VOSviewer, the “Create a map based on txt data” option is used and accessed by pressing the "Create" button in VOSviewer left menu. The output files contain the statistical information, e.g. the number of occurrences and links, as well as evaluations of their strength.The entire EIGR database has been analysed by different methodologies of the VOSviewer tool: the density map, the cluster map and the cluster density map, which combines the previous two. Some significant examples of these plots have been selected and inserted for evidencing the links and clusters of the EIGR population helping to identify gaps.

In Figure 4.16 the density map of the whole EIGR database is shown. The map is structured in a way that supports the notion that the amount of records uploaded on the EIGR is sufficient for the aim of the project. In fact, different fields of groundwater research are clearly identified, as underlined by the red lines indicating the delineations and identifying main topics of groundwater. Clusters and keyword links can be identified as GroundWater (GW) budget, GW properties, GW quality, GW & Environment and GW use. The identification of keyword delineation and clusters e.g. represented by the keywords Aquifer and Drinking Water, seems to support the notion of representativeness of the EIGR catalogue. Indirectly, this result can be considered a confirmation of the adequacy of the adopted classification (and of the visualization tool) in representing the hydrogeological research and knowledge, because relationships between keywords are reflecting existing correlation in real world.

A similar representation is available by network and cluster map analysis (Figure 4.17). Different colours have a correspondence to main topics identified in previous map, while the dimension of the bubbles is representing their frequency of occurrence. In line with previous results, the management of groundwater resources is linked with the GWD (blue cluster) in which the groundwater body is a prevalent keyword, comparable with the more scientific oriented keyword aquifer and linked with several clusters; GW quality (green cluster) is clearly located, as GW properties (red cluster). GW use (yellow cluster), including management and protection, shows clear links with geographical regions.

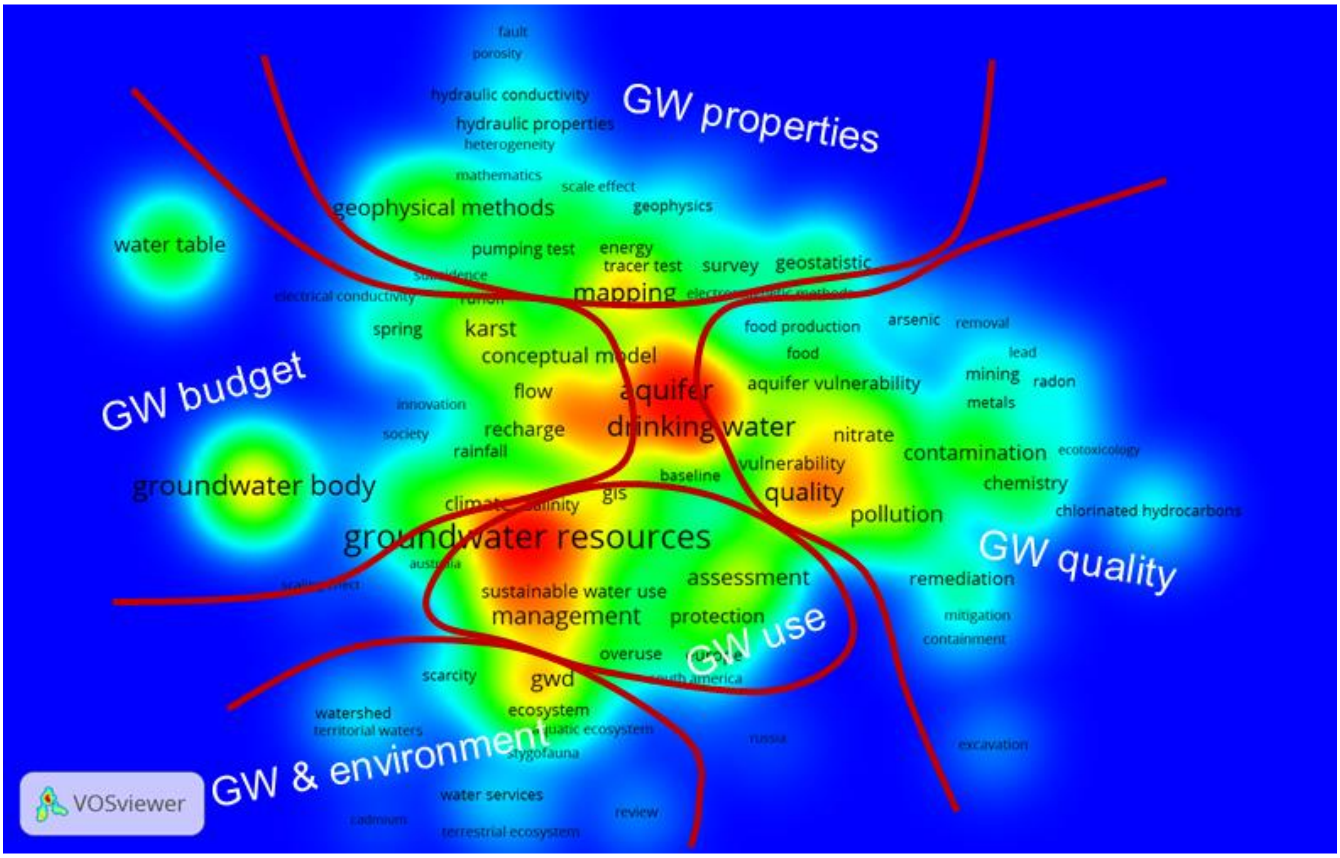


Figure 4.16 Density map of the entire EIGR database (2178 records, 242 keywords used) and delineated into regions

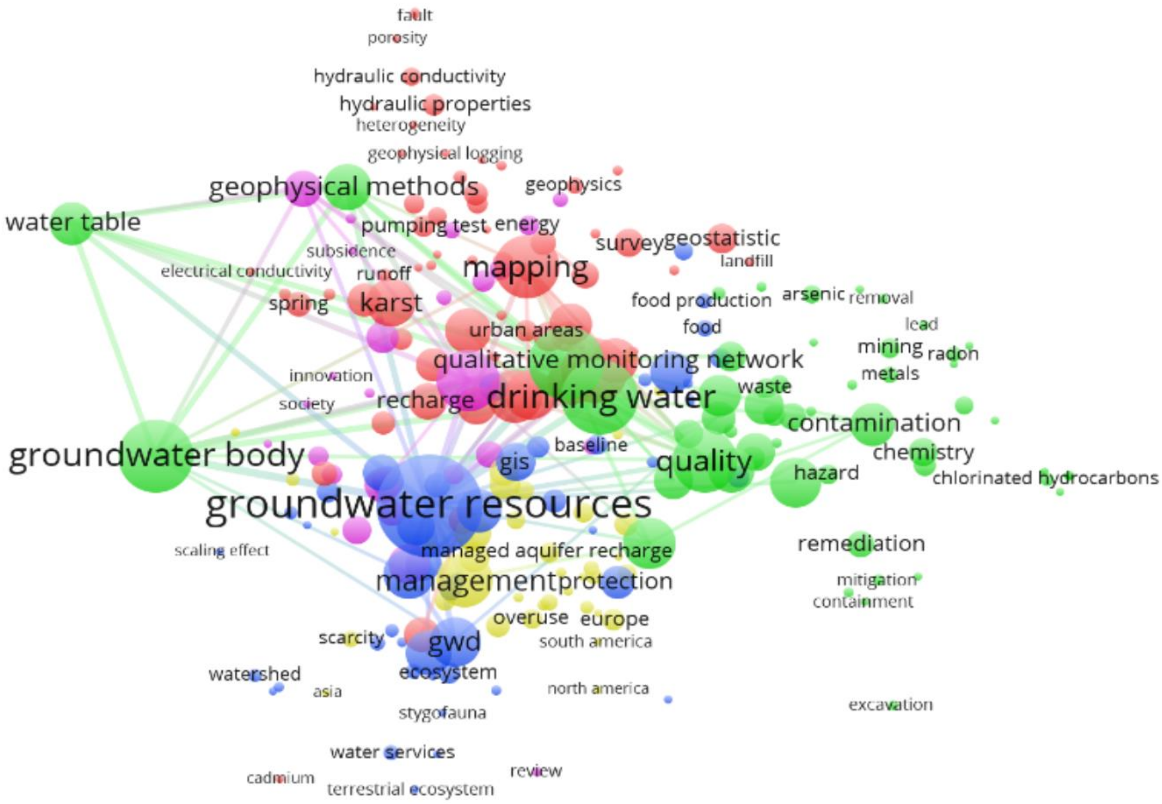


Figure 4.17 EIGR network map of entire EIGR database (2178 items and 242 keywords)

Between the different classes of research & knowledge, some similarities and some differences can be inferred. As expected, Classes 1 & 2 show (Figure 4.18) more typical research keywords, highlighting the academic approach to hydrogeology; in this graph, management and policy keyword families are located far from the core area, as satellites. Conversely, in Classes 3 & 4 network and cluster map (Figure 4.19), the assessment and management keyword group is becoming central, showing higher occurrences and more strict relationships. This fact is a consequence of the application-oriented content of these classes of documents, more aimed at solving practical problems and offering management options rather than scientific explorations.

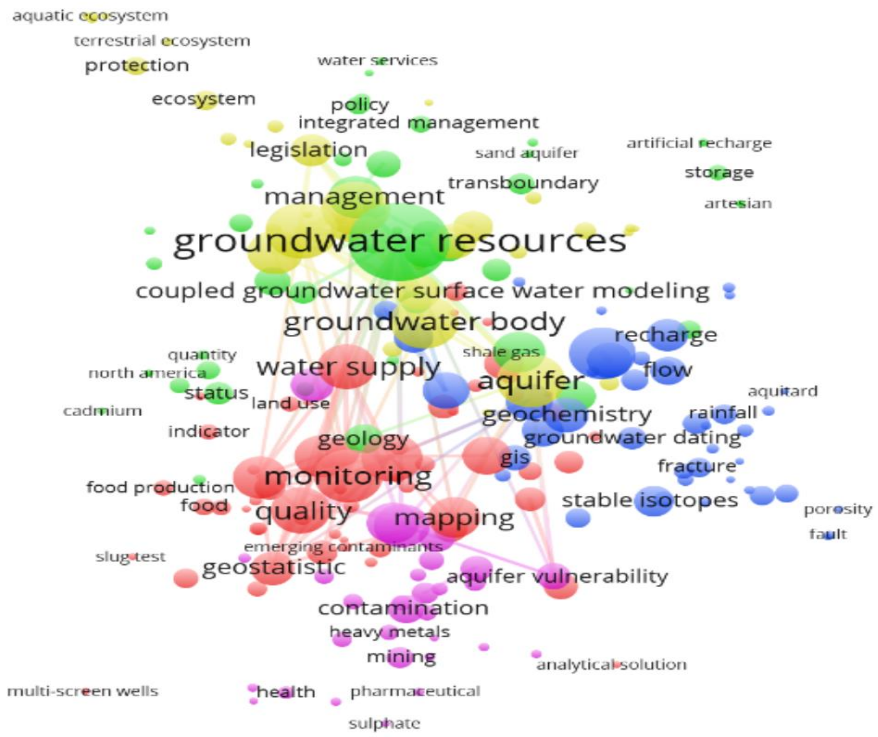


Figure 4.18 Network map of Classes 1 & 2 (705 records)

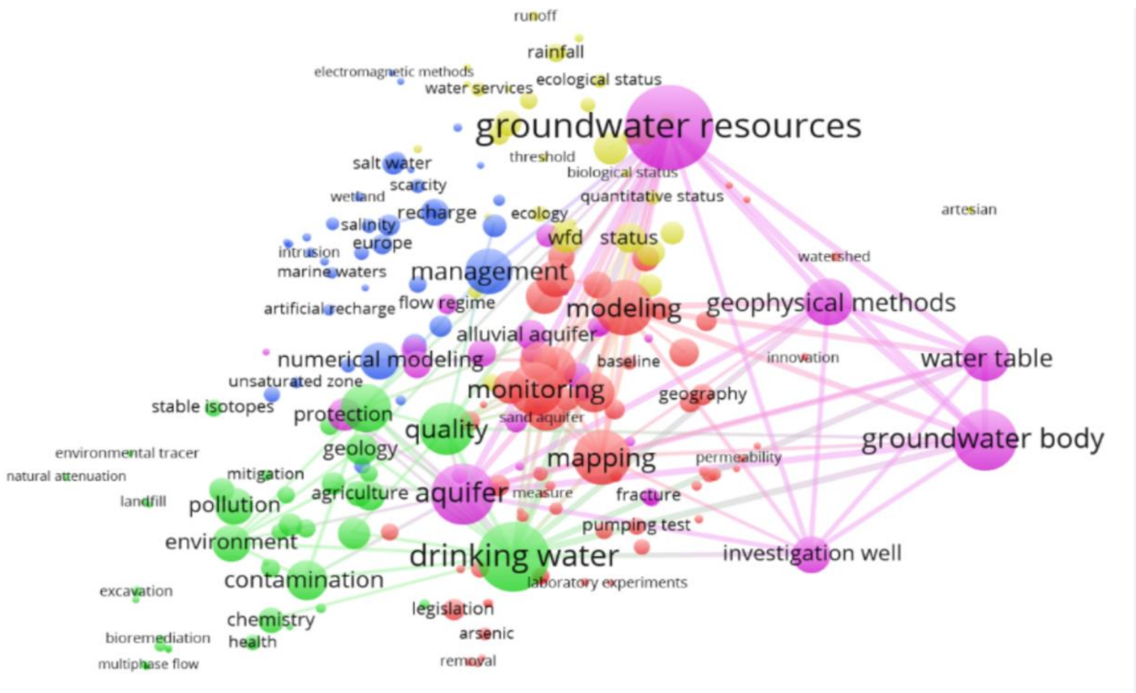


Figure 4.19 Network map of Classes 3 & 4 (1473 records)

Additional analyses have been performed for each overarching category of the three main categories OA, RT and SC. Some significant maps are shown below, for OAs and SCs.

The cluster density network map of OA Mapping (Figure 4.20) is clearly centred on mapping keyword. Several keywords fall in the same cluster (green), but other clusters show direct links with mapping, as the one related to groundwater resources and drinking water (red cluster), while the blue and the yellow clusters, more related to groundwater properties, are far from the centre. The distribution is in agreement with the role of OA mapping in groundwater issues.

A density map for OA monitoring (Figure 4.21) is showing the central location of the main keyword 'monitoring' and the strong links with geochemistry, quality, pollution and characterization keywords, as expected. Very few links exist with important keywords as climate, protection, chemical status, which are far satellites in the map.

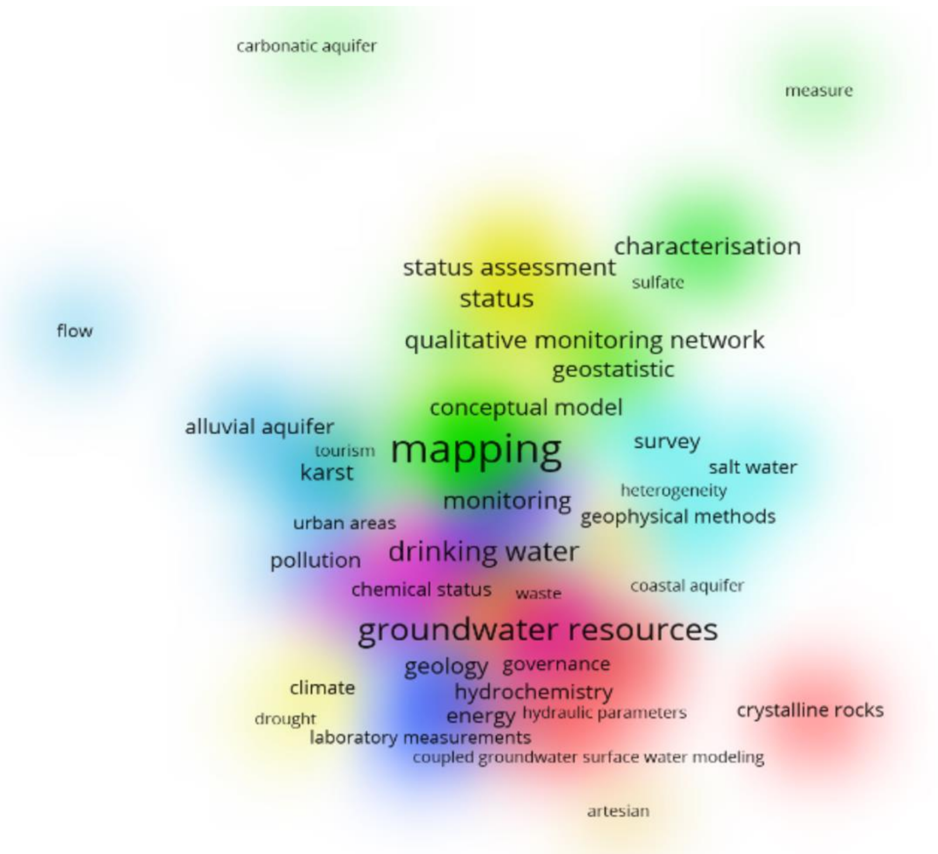


Figure 4.20 Cluster density map of OA Mapping in EIGR (164 records)

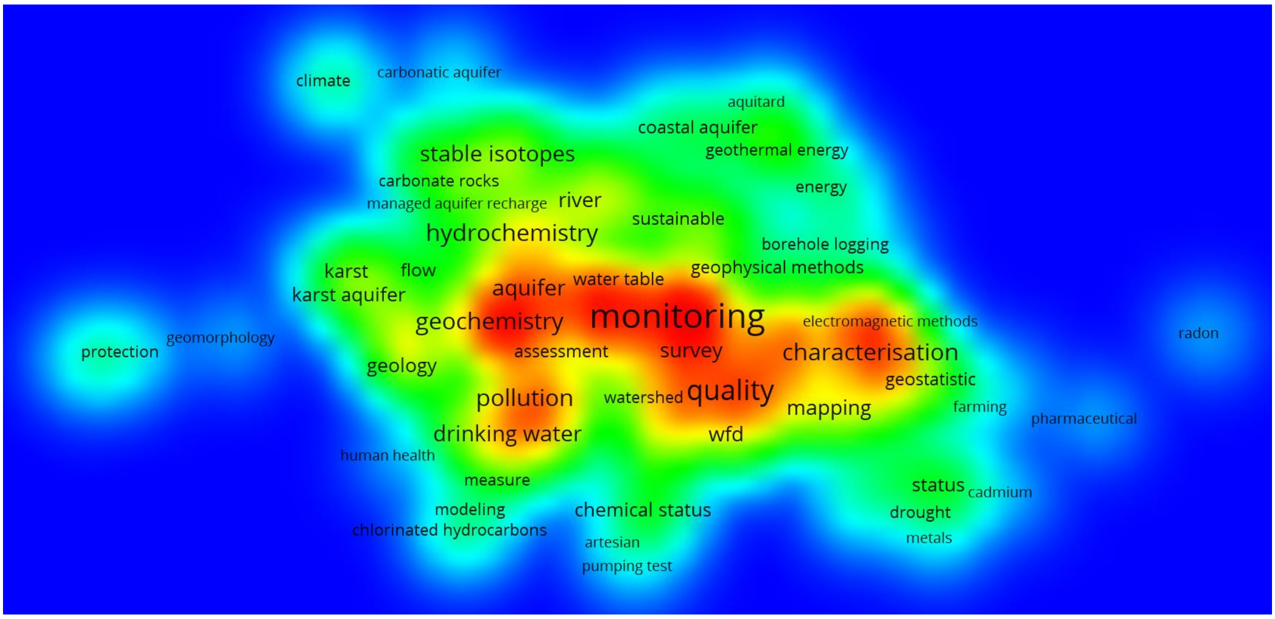


Figure 4.21 Density map of OA Monitoring in EIGR (237 records)

The corresponding density map for OA Modeling (Figure 4.22) is less fragmented. All keywords surround the main Modeling keyword, having links in different directions, as characterization (upper area in the map), properties (lower area) and policy and GWD (left area): this last link is very strong, revealing that modelling is a tool very important for policy applications. On the opposite side (right area), groundwater body, and geophysical methods, keyword has a large occurrence, but is less linked with the core area.

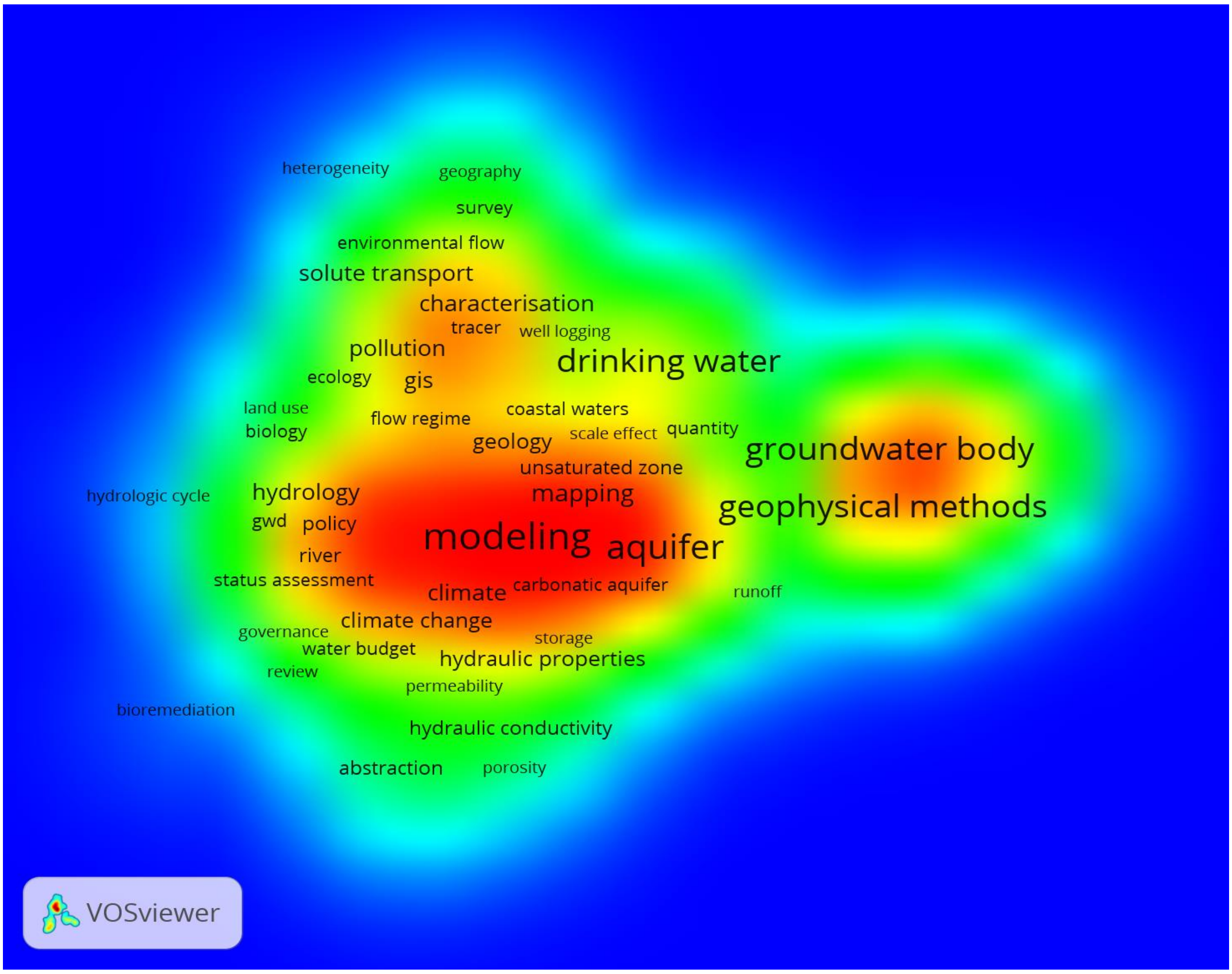


Figure 4.22 Density map of OA Modeling in EIGR (397 records)

For OA Water Supply, the network map has been chosen (Figure 4.23) to illustrate the main links and clusters: the yellow cluster is centered on groundwater resources and include many different keywords related to management; other two important clusters are the red (monitoring and drinking water keywords) and the green (groundwater body-centered). Minor clusters are related to pollution and protection (blue cluster) and to environment and health (pink cluster). The clusters show overlapping which is particularly clear for the dominating ‘groundwater resources’ (yellow) and ‘groundwater body’ (green) which indicates multidisciplinarity, which is useful and needed for complex and multifaceted research areas

Finally, due to the highest (Figure 4.24) number of records, OA ‘Assessment and Management’ has been represented by density cluster map. Groundwater resources is the central keyword, and its green cluster includes the GWD and the ecological keywords, which is important for groundwater dependent ecosystem research. Other clusters as the red (drinking water) and the yellow (contamination and remediation) are well represented, while minor clusters include the pink (GW properties) and the blue, related to the policy and society. The latter cluster illustrates the underrepresentation of policy and society in groundwater resources knowledge for the EIGR data

The analysis of keyword distribution for RTs is difficult, due to the limited number of records for four of these fields. Consequently, only the map based on RT Geology is considered relevant. The density map (Figure 4.25) is centered on groundwater resources, and many main keywords are located in the surrounding area. A gap seems to be epresented by the fact that, the groundwater body keyword is far from the main area, and also the pollution and contamination group is located at some distance from the centre. Some gaps seem to continue to exist between groundwater resources and groundwater body, which has to be tackled for reaching a direct interaction between groundwater use and related policies.

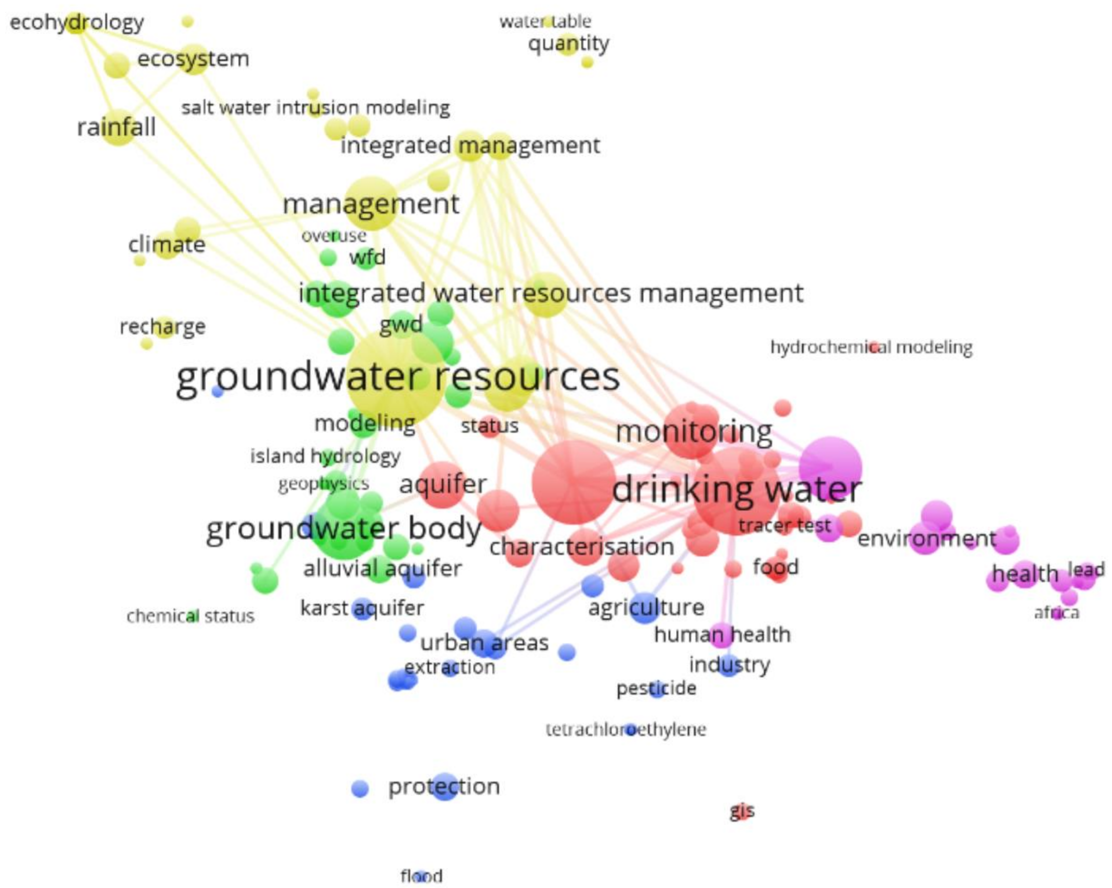


Figure 4.23 Network map of OA Water supply in EIGR (215 records)

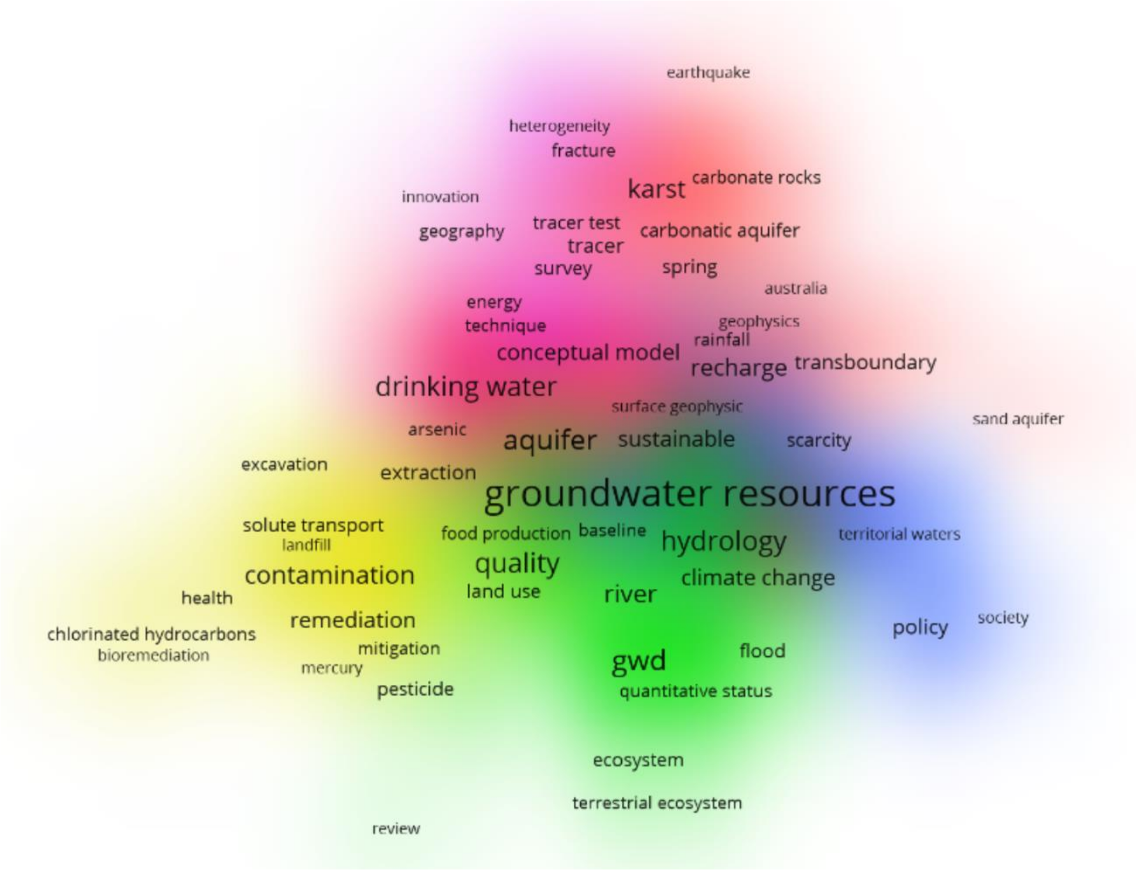


Figure 4.24 Density cluster map of OA Assessment and Management in EIGR (1165 records)

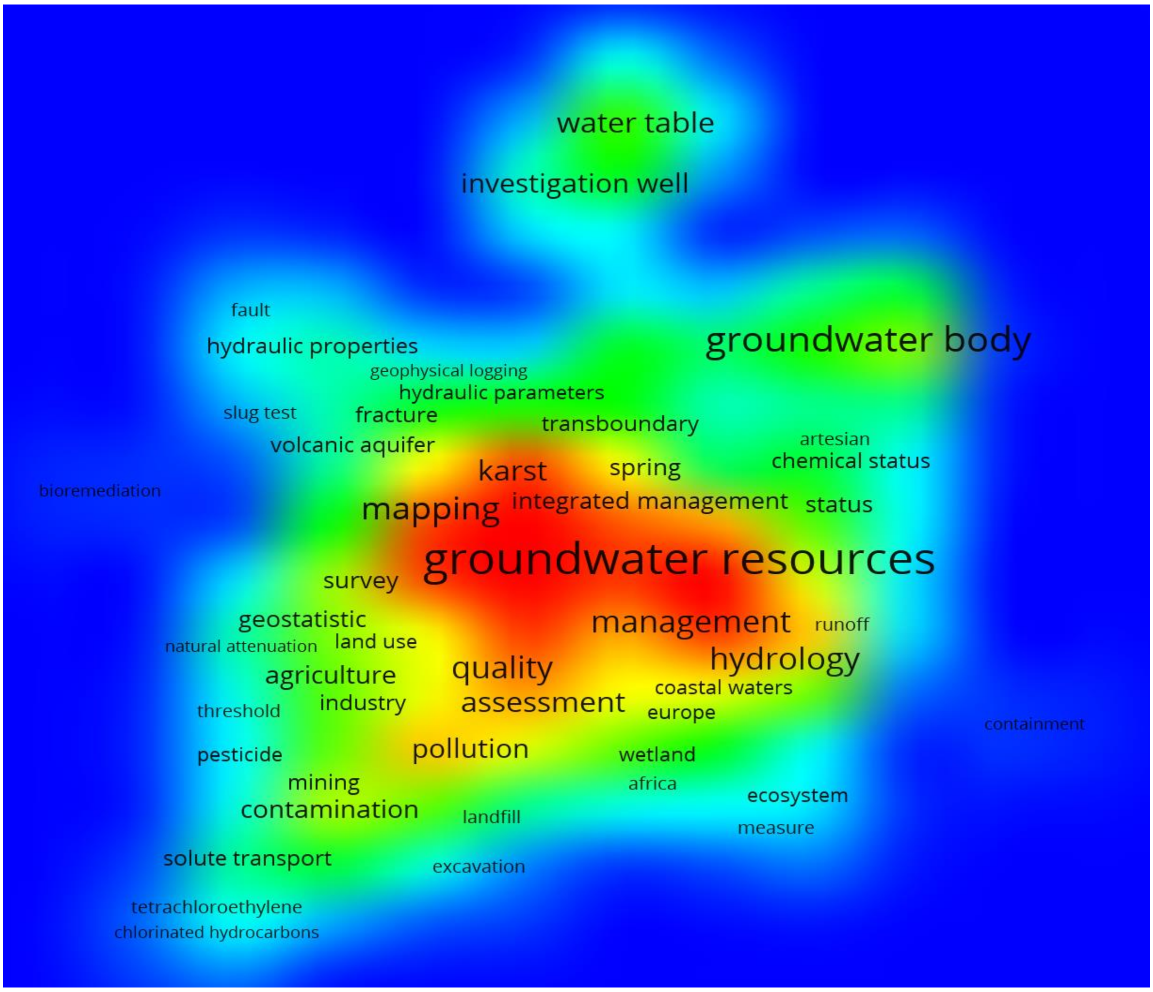


Figure 4.25 Density map of RT Geology in EIGR (1655 records)

Similar analyses have been performed for other SCs, but limiting the presentation of visualization to SC4 and SC5. Analysis of SC1, SC2 and SC3, due to the limited number of records (less than 60 metadata available for each of these SCs) are therefore not included here.

A very structured cluster map (Figure 4.26) has been obtained for SC4 Climate, Environment and Resource, where groundwater resources and groundwater body are in the same (pink) cluster; the other clusters are surrounding the core area, grouping the keywords in management (red), policy (blue), pollution (yellow) and monitoring (green), all of them well connected with the main keywords.

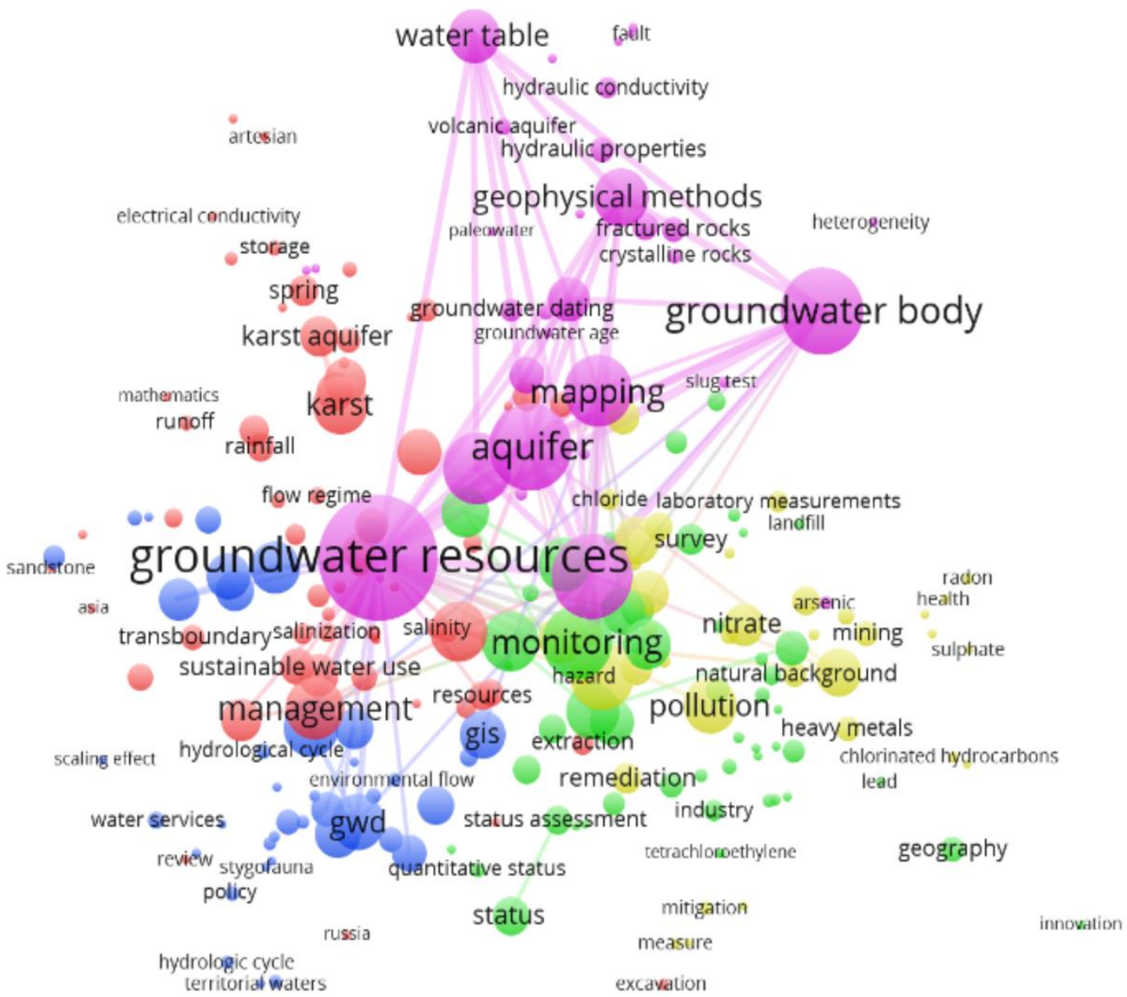


Figure 4.26 Network and cluster map of SC4 Climate, Environment and Resources in EIGR (1903 records, 231 keywords used)

Finally, the network and cluster map for SC5 Policy, Innovation and Society, appears very scattered for many keywords and with overlapping clusters (Figure 4.27). Different satellites on modelling, ecosystems, aquifer recharge, waste and energy are very far from the core area, based on management and integrated management. This map reveals that policy actions are present and significant, but the coordination among them is very limited at the moment; consequently, a real integrated management has not been achieved until now.

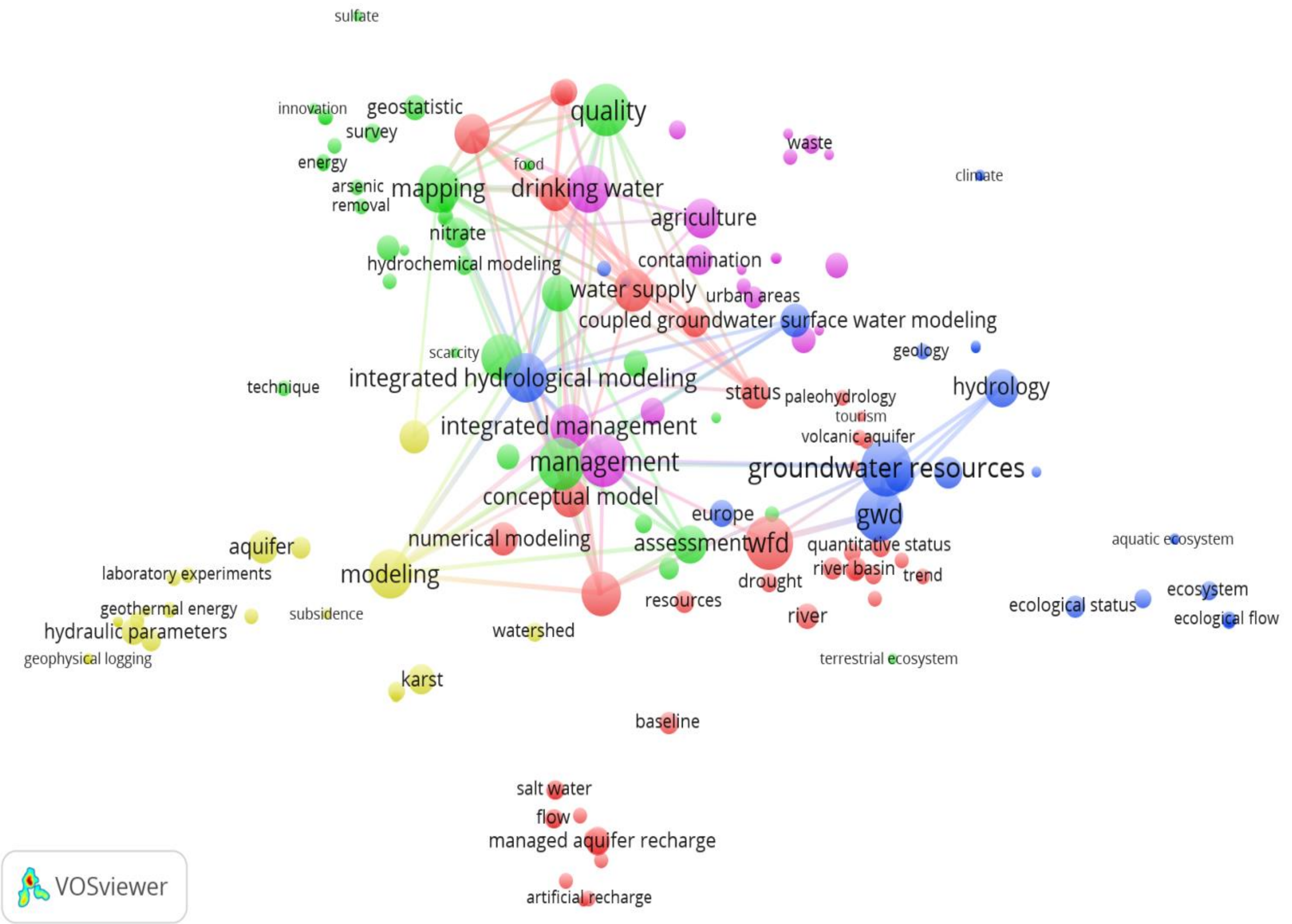


Figure 4.27 Network and cluster map of SC5 Policy, Innovation and Society in EIGR (150 records)

4.1.1.5 Geographical distribution of EIGR categories

From the geographic point of view, EIGR records distribution strongly depends on the activities performed by each single national expert, uploading a different number of metadata. A simple analysis can be conducted for each of the main three categories. In Figure 4.28 the graph for Operational Actions is showing that the high percentage of OA Assessment and Management is influenced by the Czech expert, who uploaded about 600 records mainly classified in this OA, but also by the records inserted by the Consortium. For the other countries, the distribution among the OAs does not show a prevalent action, and records are distributed among them.

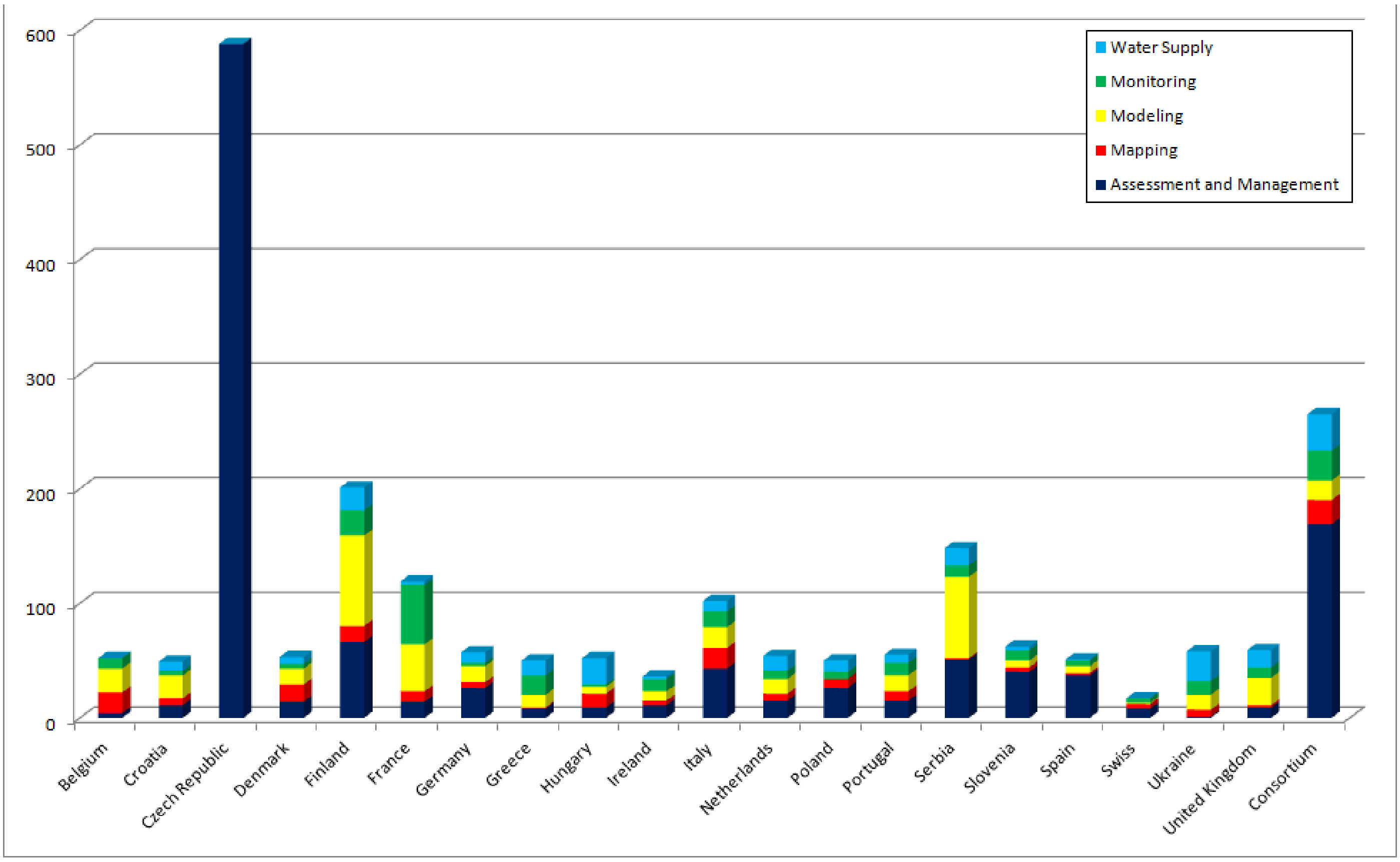


Figure 4.28 Distribution of Operational Actions by nations in EIGR records

Geographic distribution of records for RTs (Figure 4.29) clearly shows the prevalence of Geology, which is only partially balanced by Chemistry, mainly for records uploaded by Denmark, Finland, France, Germany and from the Consortium.

Finally, SCs distribution confirms the absolute prevalence of SC4 Climate, Environment and Resources in all countries, without significant differences per countries for the other SCs (Figure 4.30).

Pls. refer to 'Supplementary Material E1' for more and additional information pertaining to this section.

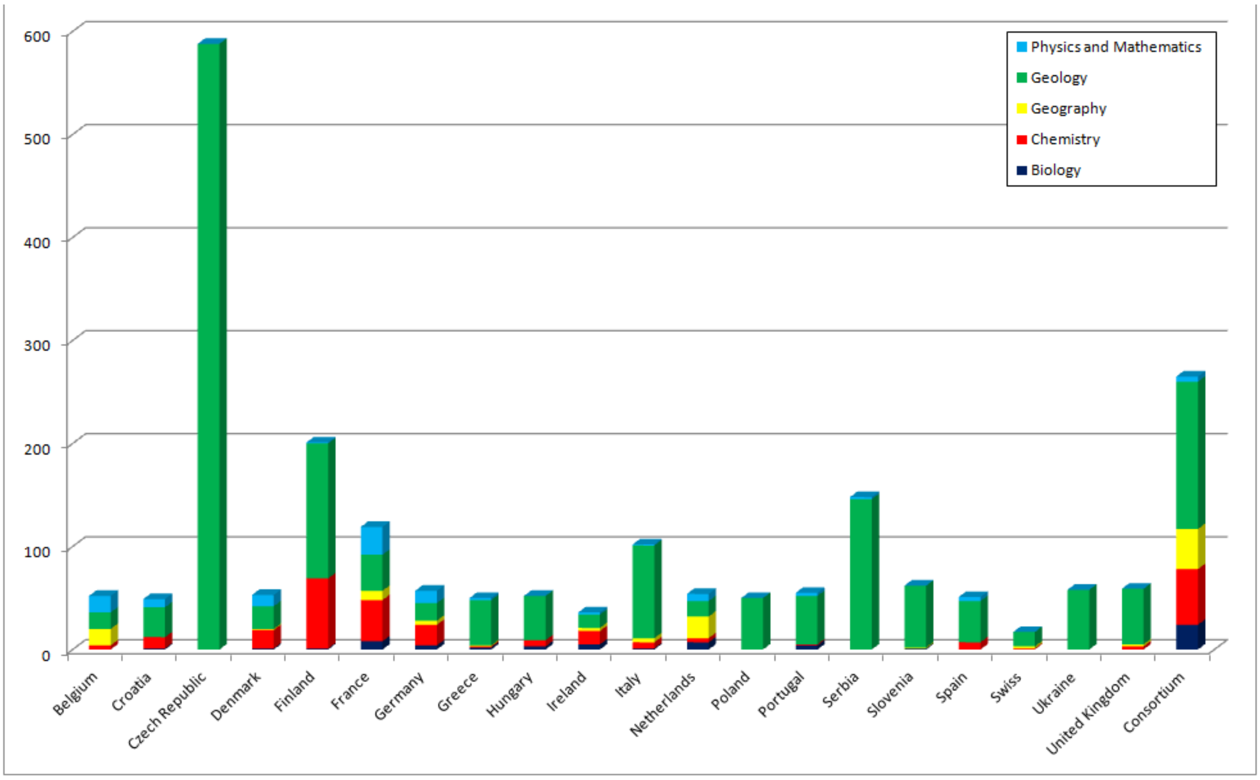


Figure 4.29 Distribution of Research Topics by nations in EIGR records

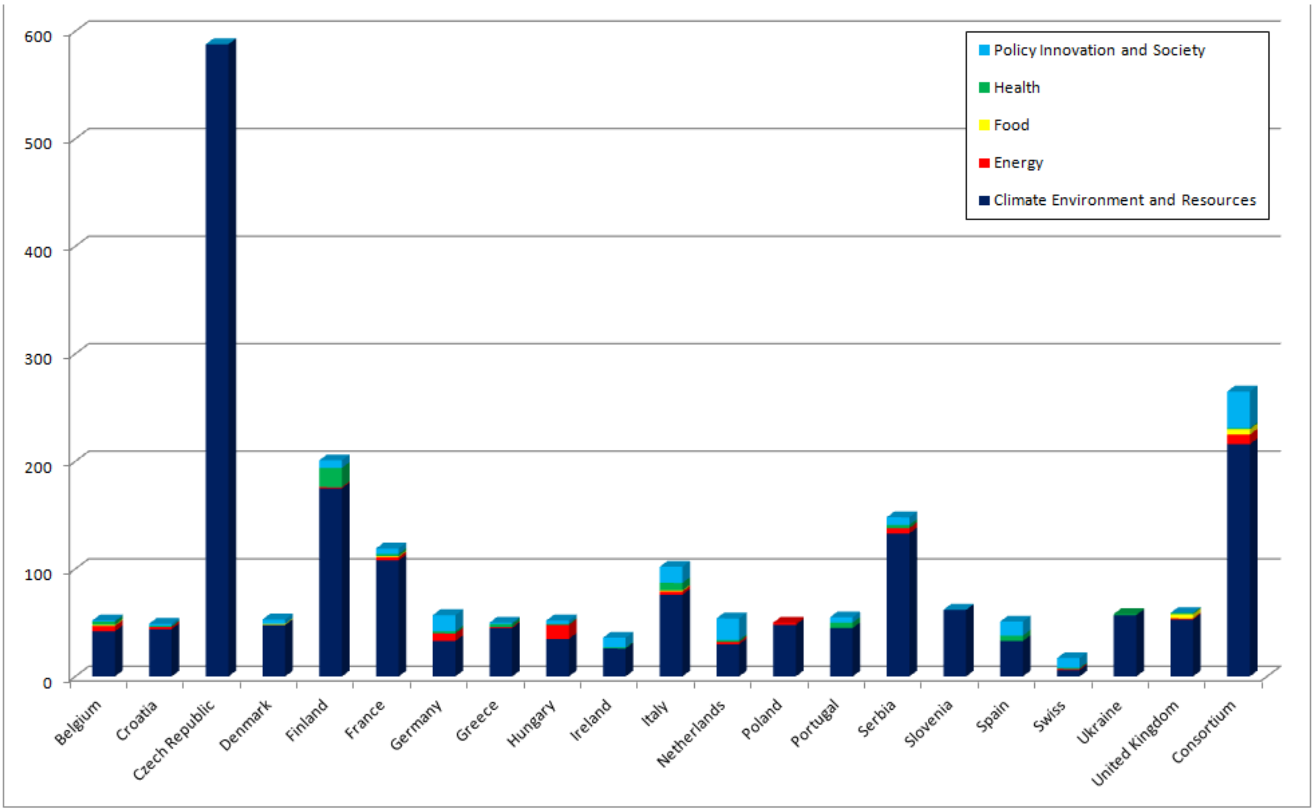


Figure 4.30 Distribution of Societal Challenges by nations in EIGR records

By VOSviewer, additional analyses on contribution by countries have been conducted. A particular series of cluster maps of the keywords has been prepared for each country, where the percentage amount of each keyword can be visualized. A limited number of these maps are shown below, for selected countries where distribution of keywords shows particular trends with respect to the general keyword cluster map for the whole database, shown in Figure 4.31.

4.1.1.6 Co-occurrence network map representations of geographical distribution of keywords

Figure 4.31 below shows the entire EIGR database classified for the percentage keywords from EIGR resources that belong to the time period between 1997-2016. The blue, green, yellow-orange and red colours varying continuously from the blue to red represent percentage resources from 0 to about 15 %.

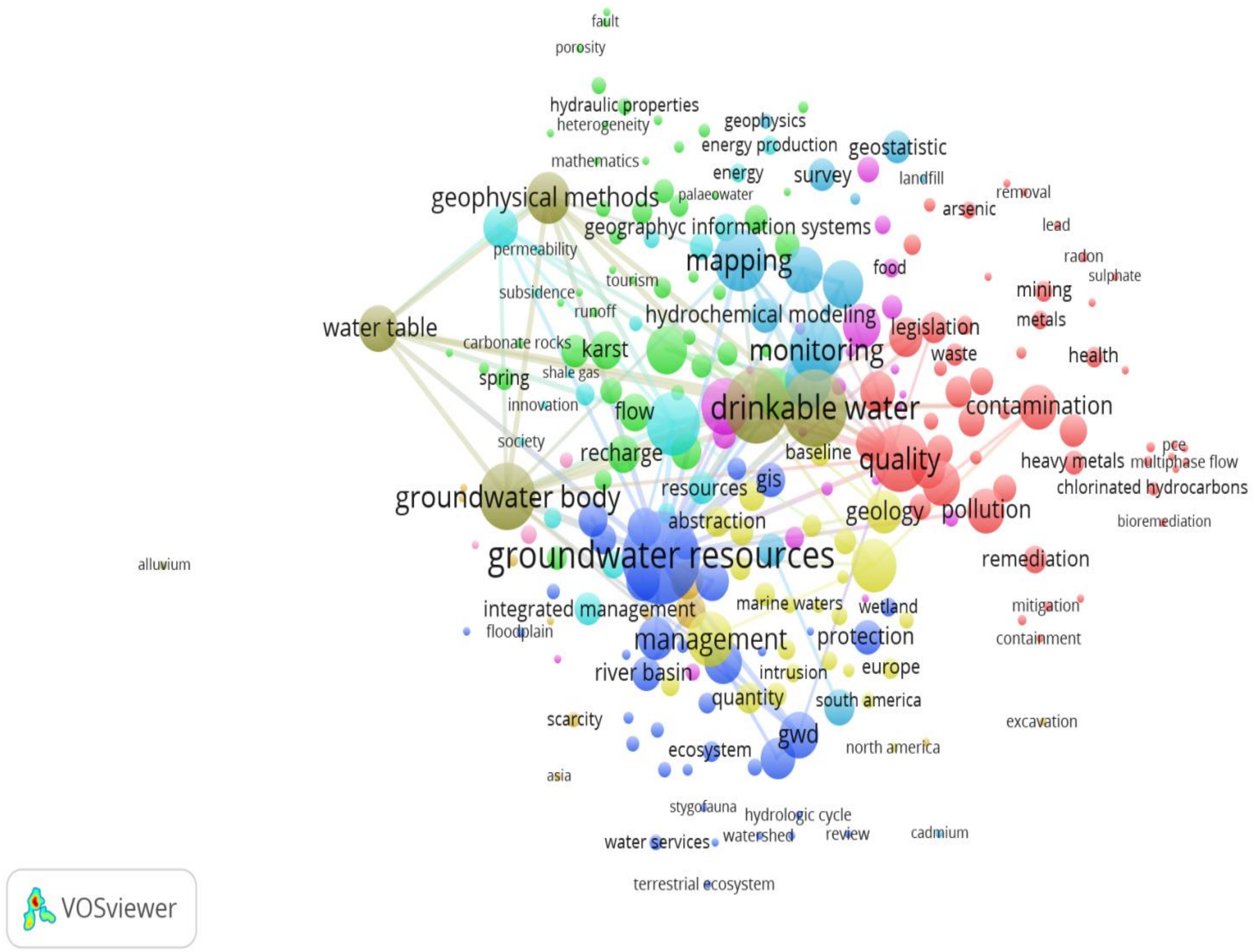


Figure 4.31 EIGR network map for period 1997-2016 and % keywords (note that colour scale in following graphs does not correspond to Figure 4.32 to Figure 4.36) from a nation. All nations

Interestingly, it is now possible to distinguish the distributions of percentage keywords for each individual country with respect to data submitted to EIGR. The use of this is demonstrated for a few countries with sufficient submitted data. It is seen that the keyword ‘mapping’ and ‘contamination’ is among the keywords with high frequency for Belgium, Denmark and Hungary, but less so for Italy and Spain. In principle, these maps can be constructed for shorter or longer time periods and indicate trends in percentage keywords and clusters of keywords on a European regional scale.

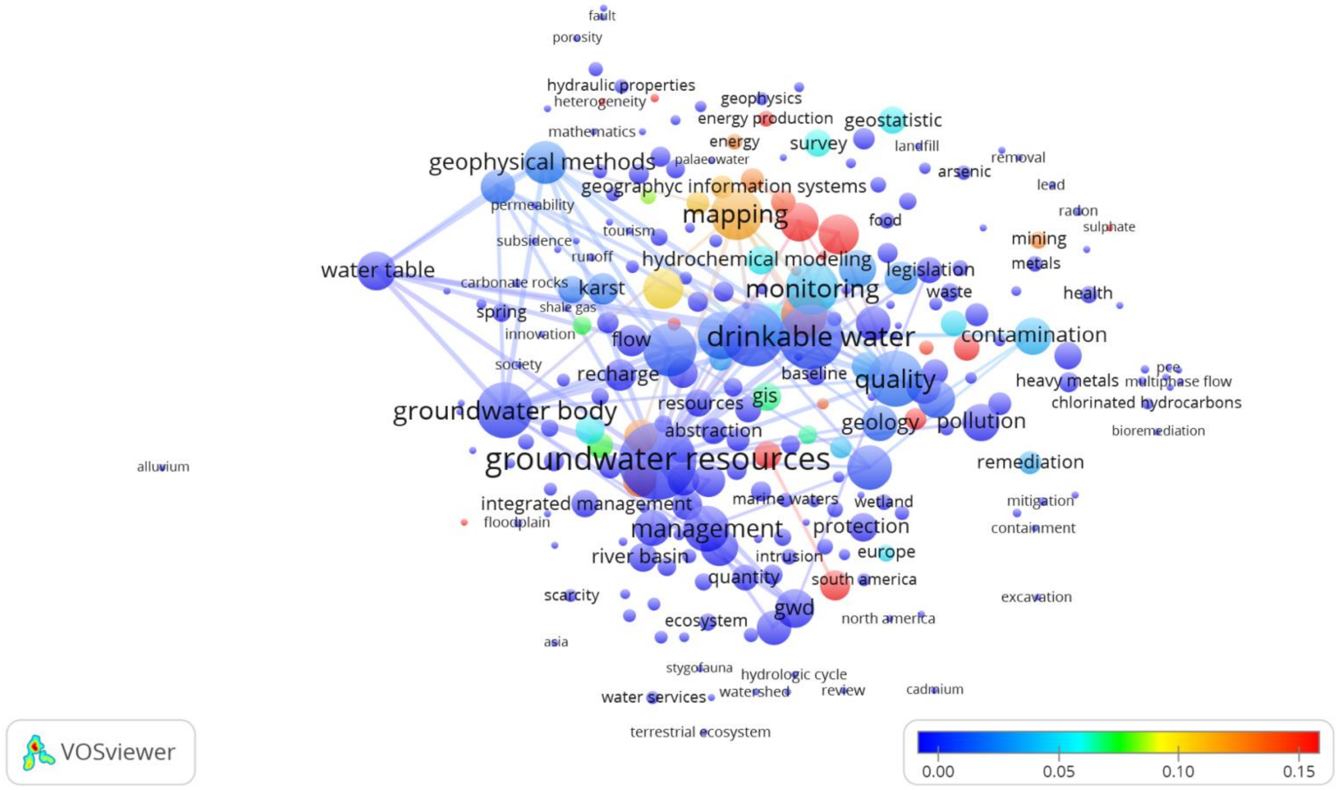


Figure 4.32 EIGR overlay graph for period 1997-2016 and % keywords for Belgium

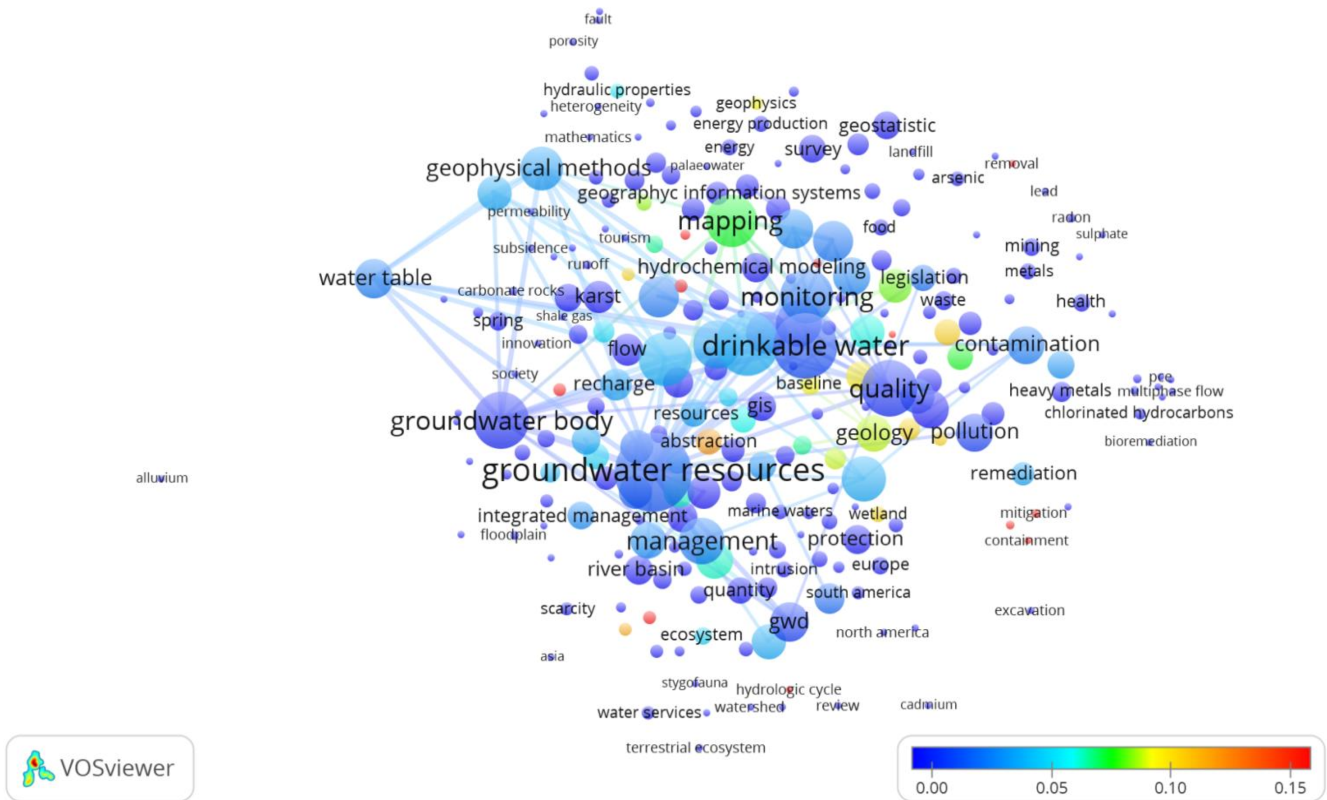


Figure 4.33 EIGR overlay graph for period 1997-2016 and % keywords for Denmark

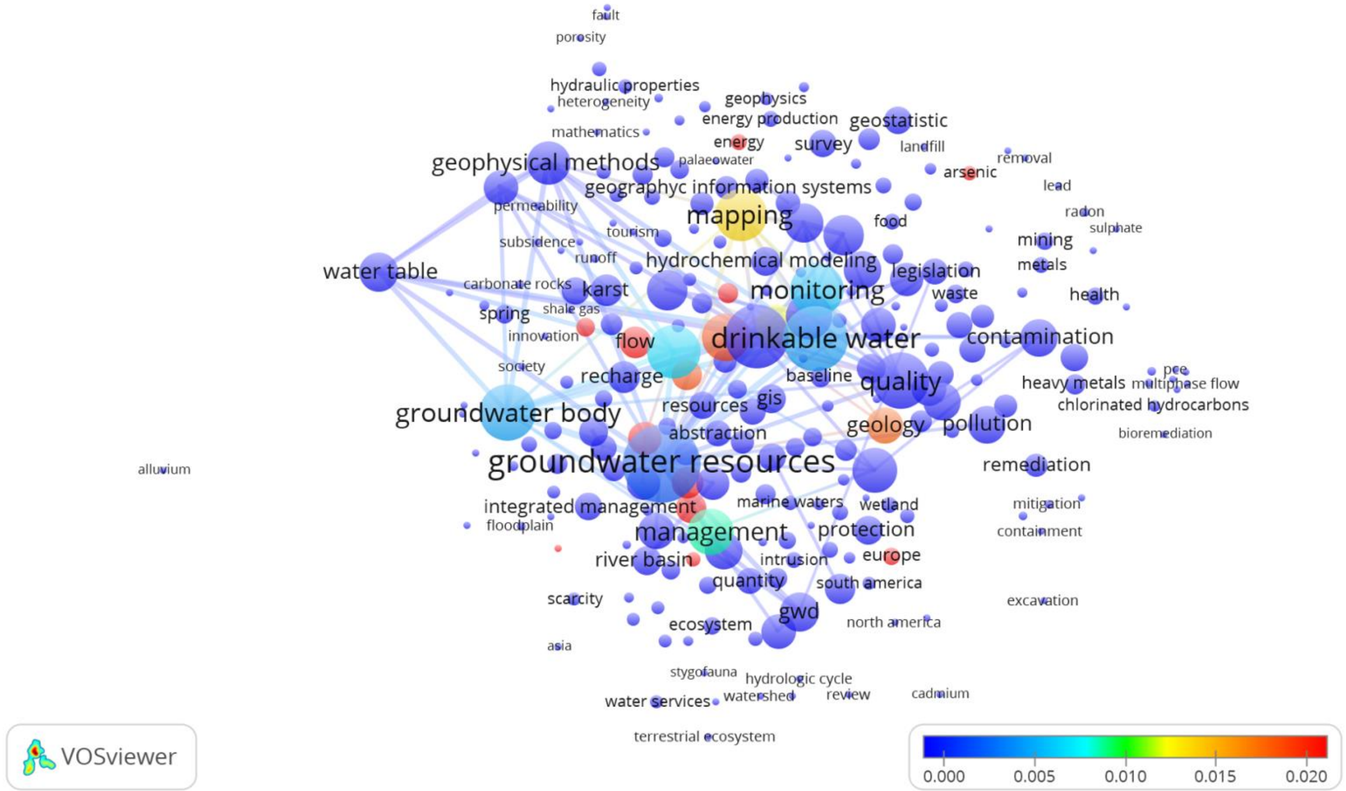


Figure 4.34 EIGR overlay graph for period 1997-2016 and % keywords for Hungary

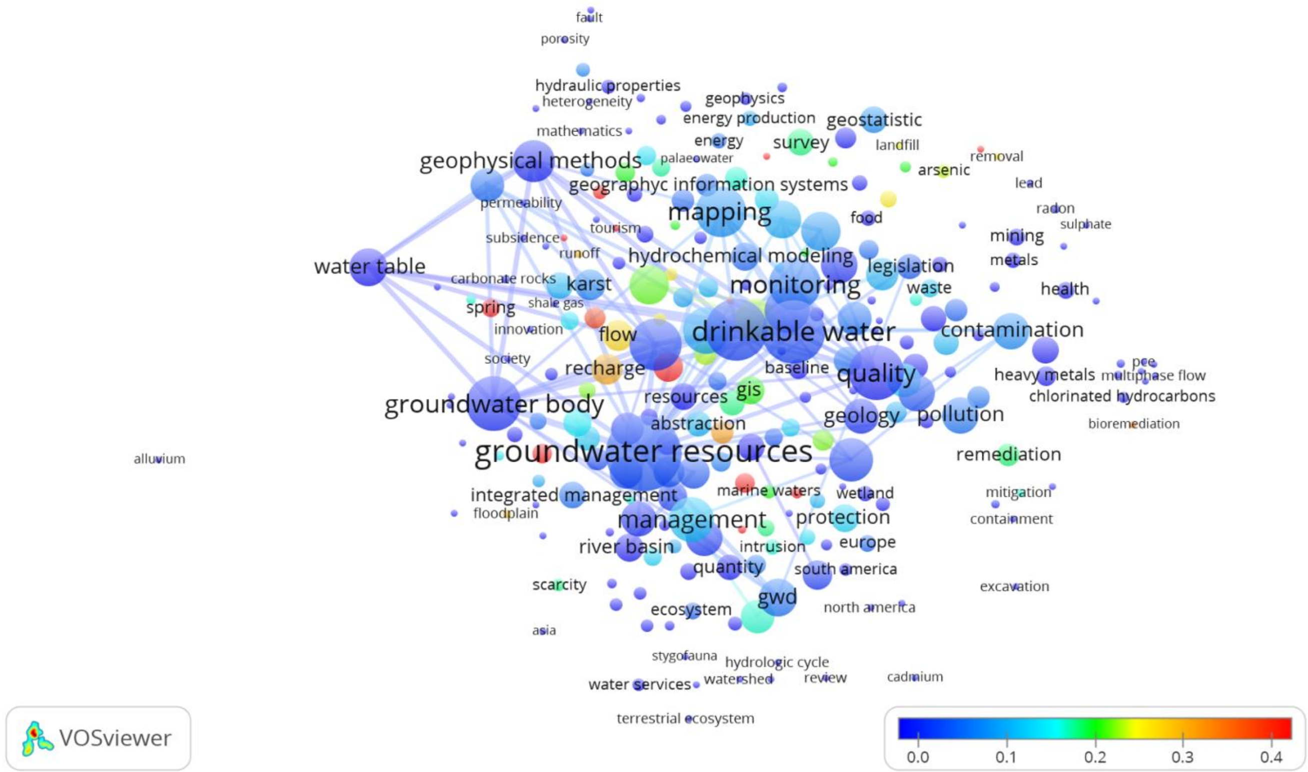


Figure 4.35 EIGR overlay graph for period 1997-2016 and % keywords for Italy

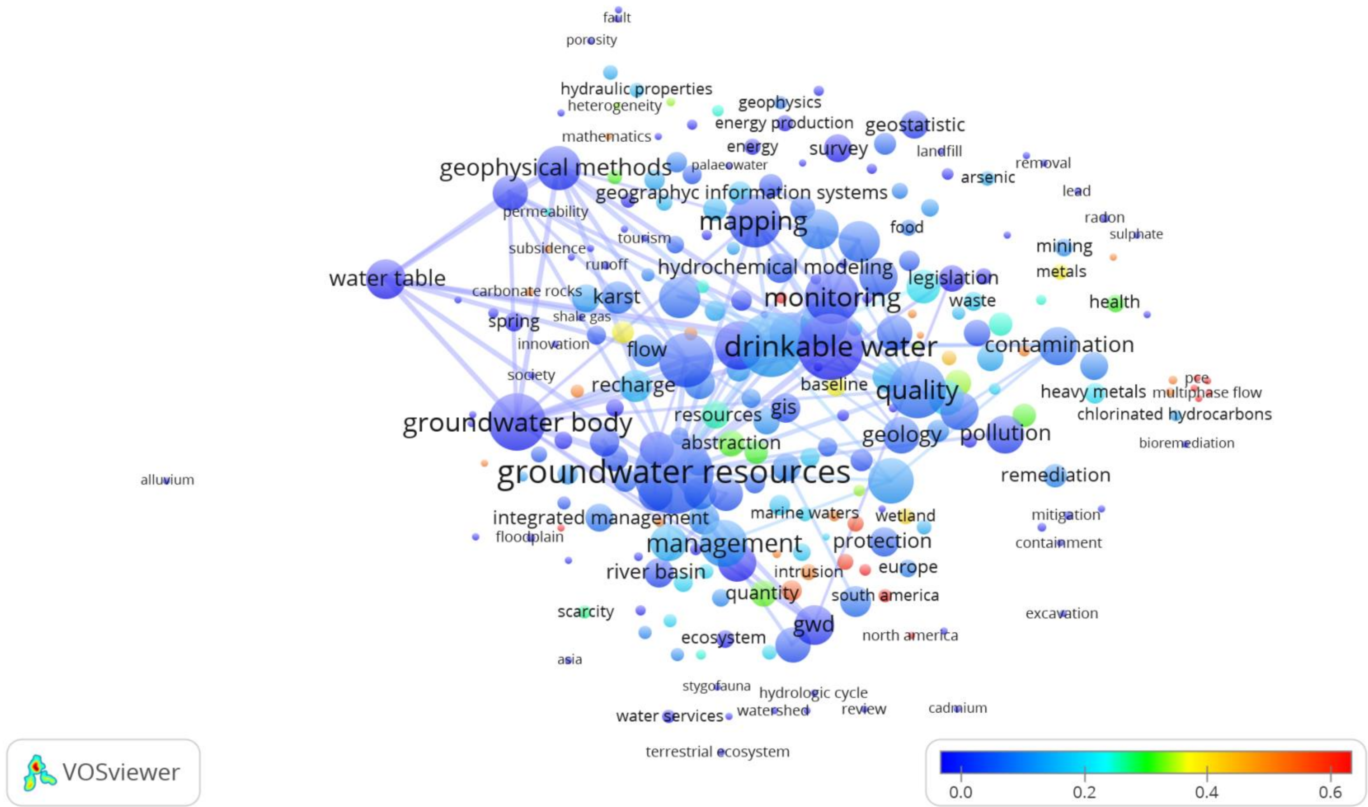


Figure 4.36 EIGR overlay graph for period 1997-2016 and % keywords for Spain

Pls. refer to ‘Supplementary Material E8’ for more and additional information pertaining to this section.

4.1.2 Scopus analyses

In order to enable comparison of popular research areas and research performance for the different research topics and operational actions within each societal challenge between Scopus and EIGR, a subset of the total Scopus database on groundwater research with publications was extracted, which contained at least one keyword from each of the three overall categories (SC, OA and RT). Thus every document in this subset can be placed in at least one of the 125 coordination points in the HRC-SYS classification. Figure 4.37 shows the scholarly output for groundwater and hydrogeology research (number of class 1 and 2 publications) for the period 1997-2016 according to Scopus and Web of Science using the baseline search string (BSS) = Groundwater or “ ground water” or hydrogeology*. For the complete set of search strings for Scopus based co-occurrence map pls. refer to Table 4. The search string that combines the baseline search string with any keyword from all three overall SC, OA and RT categories returns a publication set of about half (63.248) of the total number of groundwater research publications for the period 1997-2016 (125.003). This subset of publications was used to develop intersection plots for comparison with the classified EIGR resources. Figure 4.37 furthermore illustrates that the Scopus database contains over 30.000 research publications (about 30%) more than the WoS database, supporting the conclusion that Scopus has a better coverage of the natural science and engineering research areas than WoS (Mongeon and Paul-Hus, 2016).

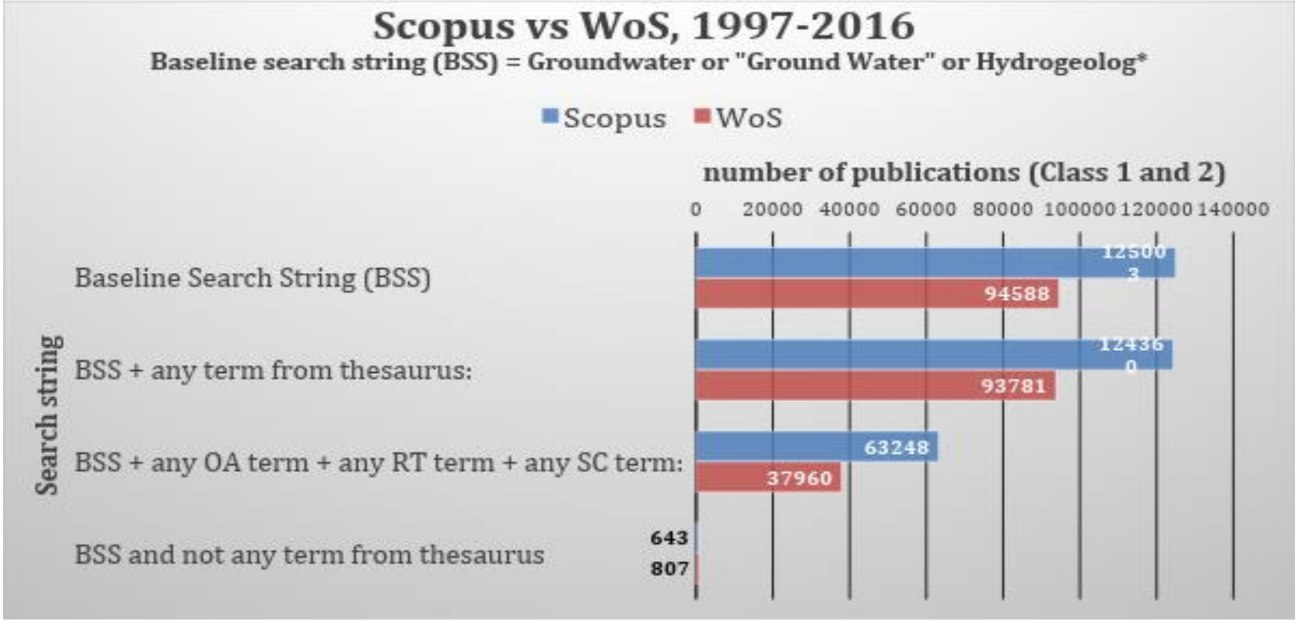


Figure 4.37 Comparison of scholarly output on groundwater and hydrogeology research available in the Scopus and Web of Science databases. The publication set including any terms (keywords) from the OAs, RTs and SCs is used to develop intersection plots in the following

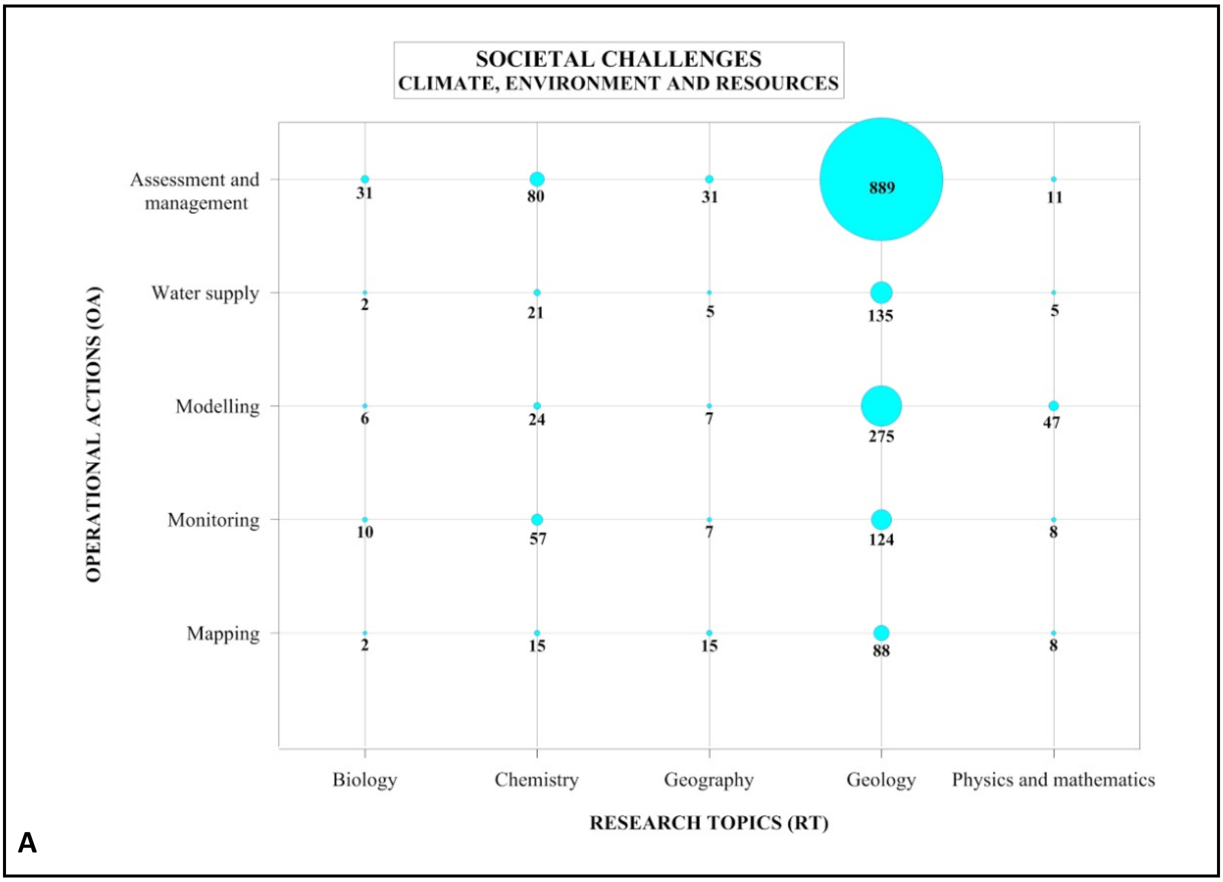
Societal Challenges (refer to section 2.1 on used SC abbreviations)	Publications
SC1 - Health	7.786
SC2 – Food, Agriculture*	15.899
SC3 – Energy	6.324
SC4 – Climate, Environment, Resources	44.465
SC5 – Policy, Innovation, Society	13.217
SC6 – Transport	2606

Table 2 Number of class 1 and 2 groundwater research publications in Scopus for each of the selected SCs for the period 1997-2016 (both years included). Note that documents can be assigned to more than one SC, so the total exceeds the size of the dataset (63248). * SC 'Food and agriculture' are used for searches in Scopus, SC 'Food' in EIGR

Besides the societal challenges used in the HRC-SYS classification system listed in Table 2 we also performed an assessment of groundwater research related to the societal challenge "smart, green and integrated transport". This SC, however, has a significant lower scholarly output than the other SCs, and half of these were already included among the publications related to the other SC. It was therefore decided not to include this as an additional SC. Keyword co-occurrence maps for this societal challenge is provided in Figure 4.55 and Figure 4.56.

4.1.2.1 HRC-SYS analyses:

Groundwater research related to research topic "Geology" (RT4) has been the main focus of data uploaded to EIGR as the project is initiated by the European Federation of Geologists and primarily include work conducted by hydrogeologist (as shown in previous section). This, however, results in a clear bias towards hydrogeological research for the publication information in EIGR compared to searches performed in the Scopus database including all research topics (Figure 4.38), which clearly demonstrate that groundwater research is much more diverse than indicated by the EIGR database. However, the intersection plots of RT4 "Geology" for EIGR and Scopus data Figure 4.39 both demonstrate that most groundwater research is conducted within SC4 “Climate, environment and resources”. In the following, we analyse results from the Scopus database and show examples of groundwater research gaps identified by these analyses one by one for the five societal challenges applied in the EIGR classification.



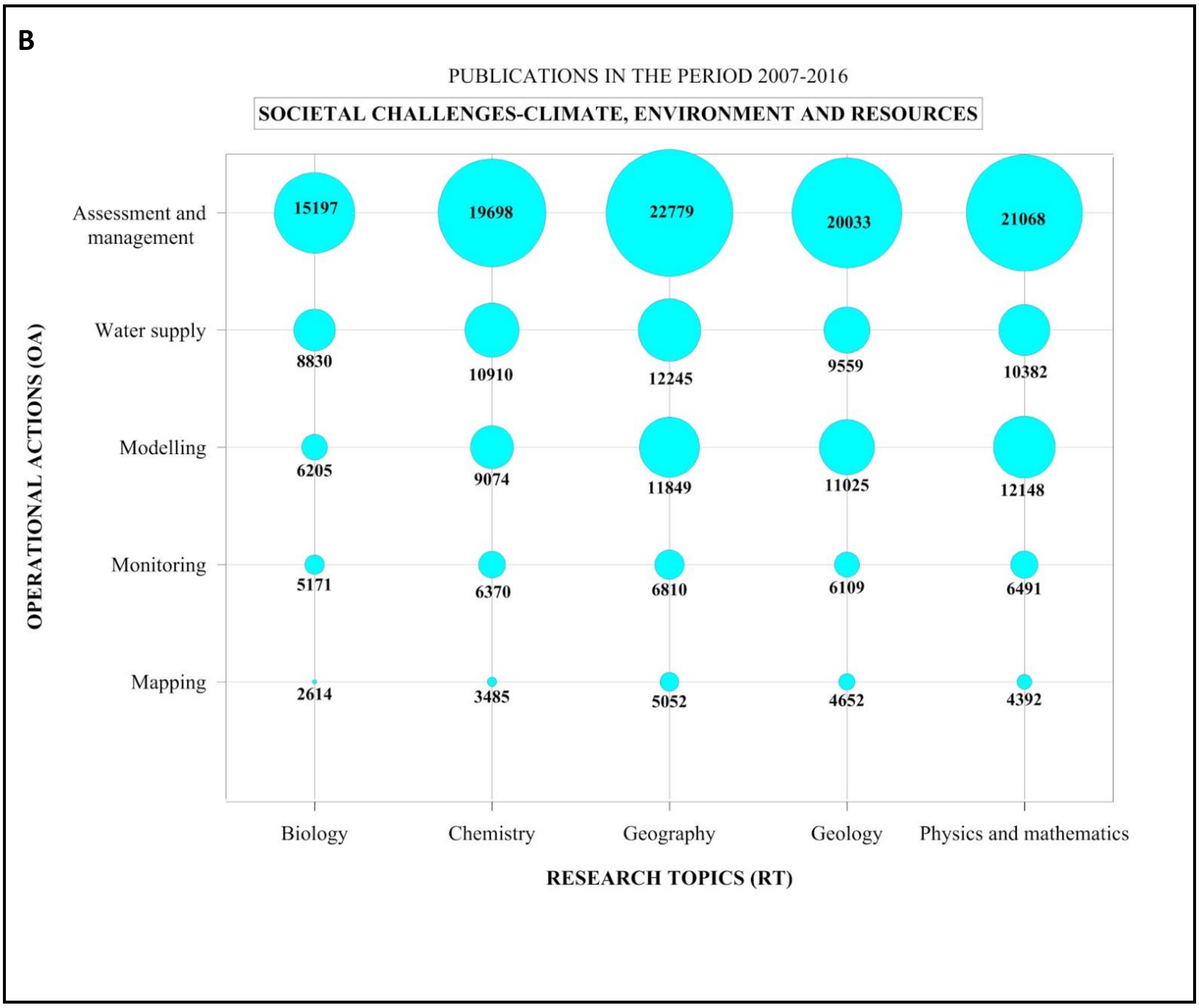


Figure 4.38 Comparison of scholarly output with co-occurrence between keywords of SC4 “Climate, environment and resources”, the five main research topics (x-axis) and the five main operation actions (y-axis) in A) EIGR and B) Scopus for the period 2007-2016

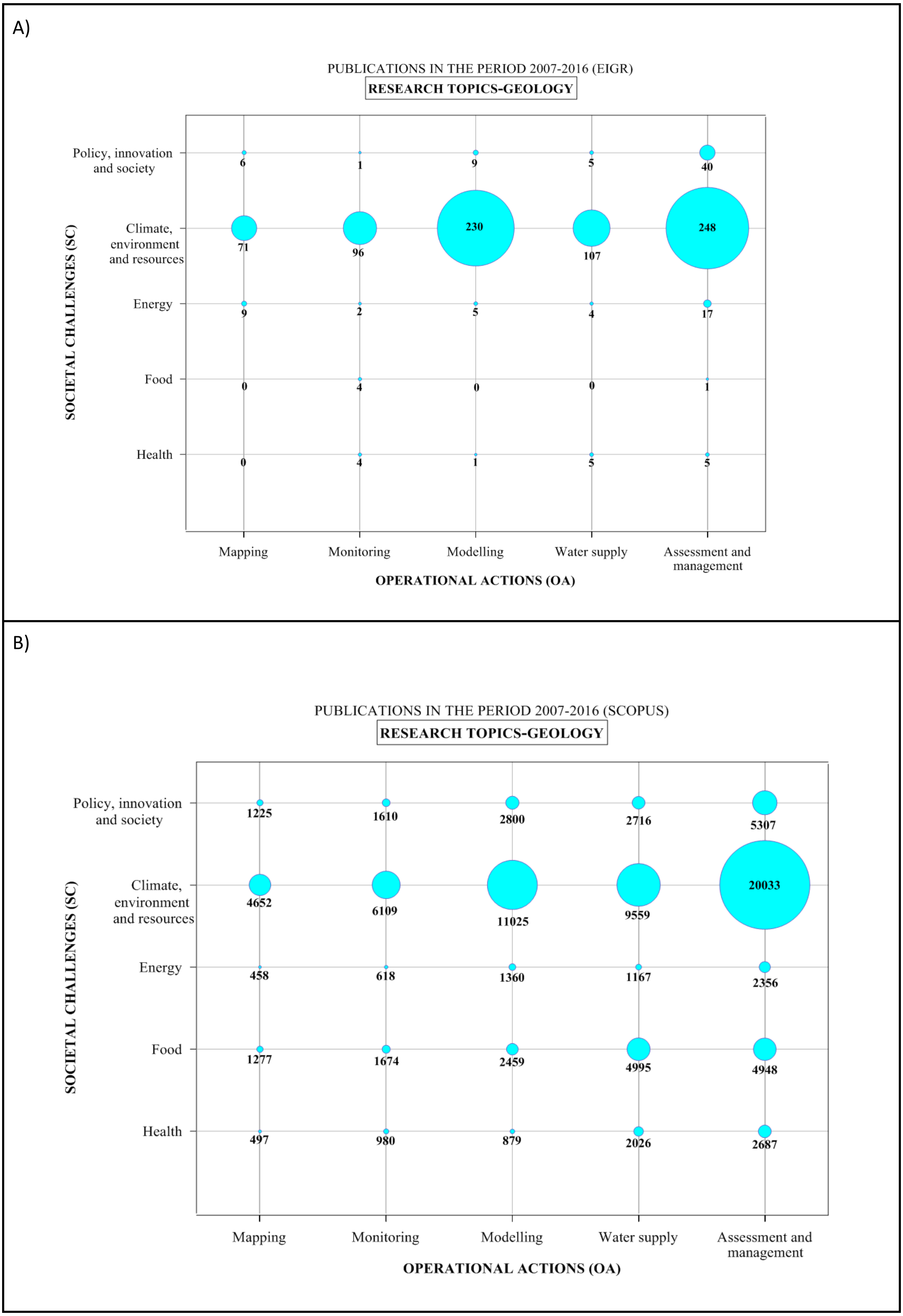


Figure 4.39 Comparison of scholarly output with co-occurrence between keywords of research topic RT4 "Geology", the five main operational actions (x-axis) and main societal challenges (y-axis) in A) EIGR and B) Scopus, for the period 2007-2016

The plot below (Figure 4.40) for SC1 “Health” shows the scholarly output (number of class 1 and 2 publications) of papers containing at least one keyword for each of the OAs and RTs as extracted from Scopus.

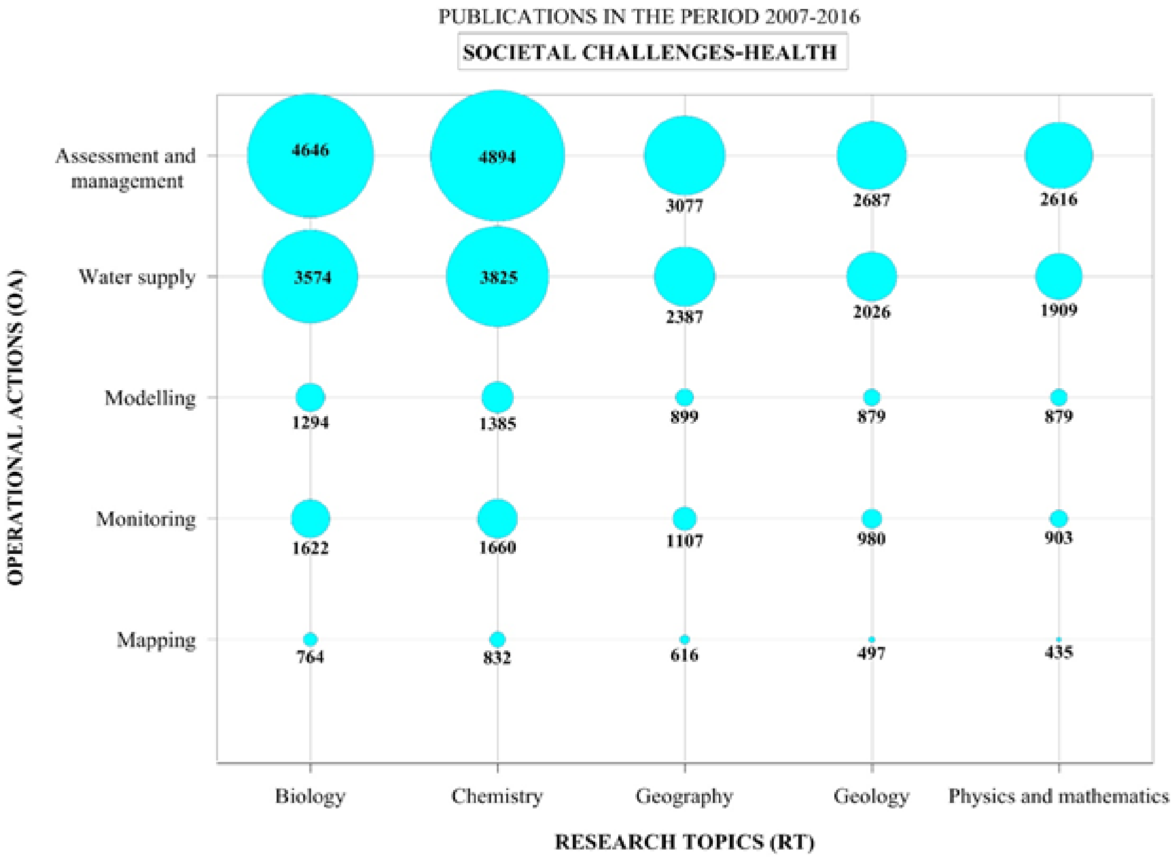


Figure 4.40 Scholarly output for SC1 “Health” of the different combinations of related RTs and OAs

Figure 4.40 illustrates that there is about an order of magnitude difference between the RT and OA combinations with the lowest (Physics and mathematics combined with Mapping) and highest (chemistry combined with assessment and management) number of publications, 435 and 4894, respectively, within research areas related to SC1.

This clearly demonstrates that the dominant research interest is within biology and chemistry, which is logical as they closely relate to health issues controlled by water quality affected by e.g. microbial and chemical pollutants, but it does not reveal whether any of the combination of keywords in the 25 intersection are covered properly. OA1 “mapping” has little research compared to the four other actions. This may reflect that research on human health in relation to the quality of groundwater resources and the geology of aquifers (groundwater bodies) have a relatively little relevance for society. However, recent research and assessments of health issues related to the occurrence of nitrate (Schullehner et al., 2018) and arsenic in groundwater (Wens et al., 2016) indicate that this is a research gap where more research is required.

The intersection plot for SC2 – “Food” is shown in Figure 4.41. The figure illustrates that there is a factor 7 difference in the number of publications between the RT and OA combinations with the lowest (geology and biology combined with Mapping) and highest (Geography combined with water supply) scholarly output, 1615, 1635 and 11401, respectively, within research areas related to SC2.

Considering again the fact that nitrate is the pollutant most frequently causing poor groundwater chemical status in Europe, and that sources of nitrate are often dominated by pollution from agriculture, the relatively low number of publications on biology, geology and mapping may indicate a research gap on this topic. A large number of European coastal waters and ecosystems have poor ecological status (EEA, 2015), but little knowledge exist about where these ecosystems are linked to poor groundwater chemical status etc. This is supported by assessments of recent technical report from Working Group Groundwater within the Common Implementation Strategy for the Water Framework Directive (e.g. European Commission, 2015). The report state that EU member states often argue that they do not have the necessary data and understanding of aquatic ecosystems to be able to derive groundwater threshold values based on good status objectives of the Water Framework and Groundwater directives. Hence, they are not able to assess groundwater chemical status for nitrate for the protection of ecosystems due to a lack of the understanding of ecosystem needs and the link between groundwater chemical status and the ecological status of groundwater associated aquatic ecosystems. The same is the case for many groundwater dependent terrestrial where both poor quantitative and chemical status of groundwater may cause failure to meet the environmental objectives and ensure good ecological status for these ecosystems. This support the call for more transdisciplinary research between hydrogeologists and ecologists as e.g. concluded in technical reports of Working Group Groundwater within the Common Implementation Strategy for the Water Framework Directive (European Commission, 2015).

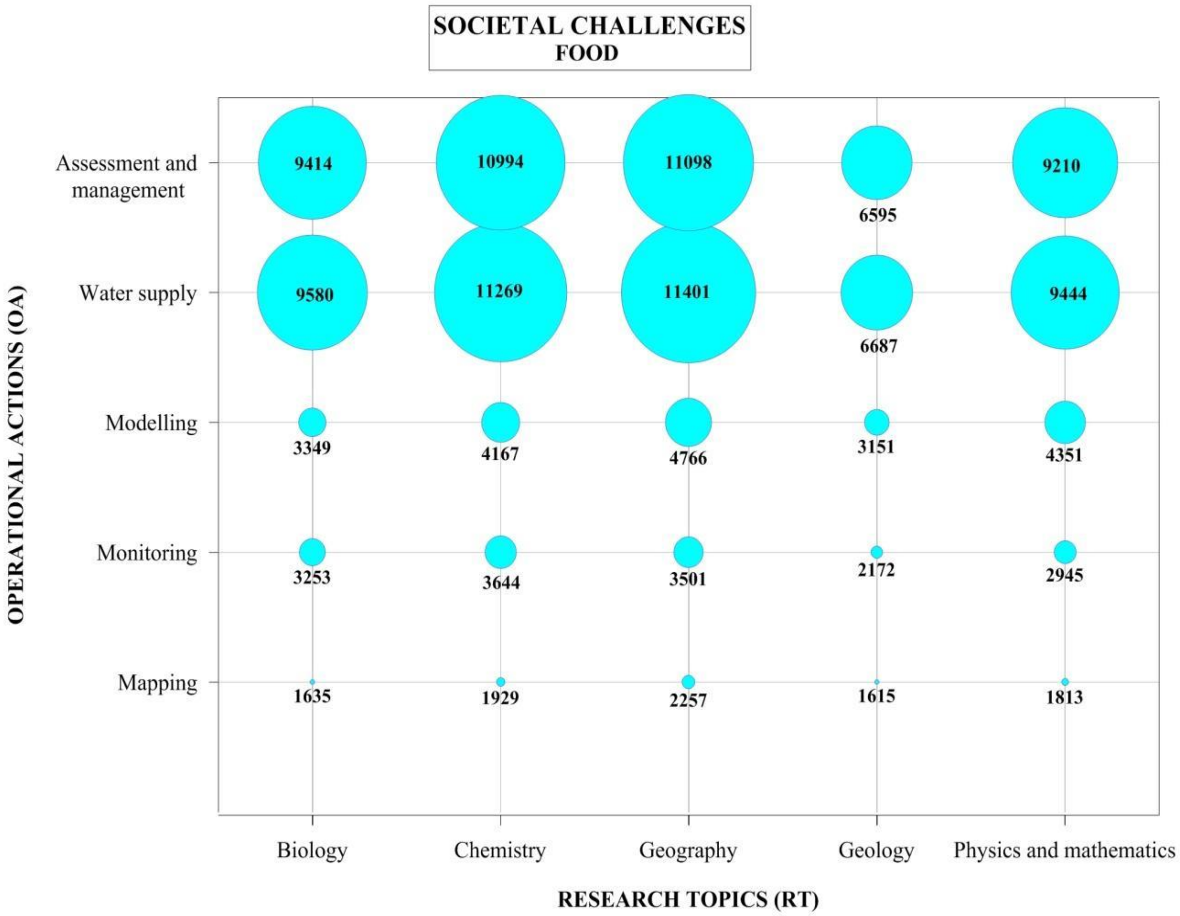


Figure 4.41 Scopus data (RT, OA) plot for SC = Food. The size of the bubbles indicate the relative amount of data at a specific intersection, whereas the number indicates the number of available resources

The intersections for SC3-Energy (Figure 4.42) demonstrates, that the category of Energy covers a substantial amount of the obtained information. The distribution of the data along the Operational Actions and Research Topics is relatively even.

This means that important hits can be found at each cross-section of the the Operational Actions and Research Topics axes. This highlights the importance of the conducted research activity connected to energy issues. A research gap cannot easily be detected in this energy sheet. On one hand, this proves the importance of the energy topic. On the other hand, it also proves that this energy topic is very complex and broad. As it was mentioned earlier, geothermal energy utilization, heat pumps, thermal water resources, underground waste heat storage, conventional and non-conventional hydrocarbon resources are hot issues in the different European countries in order to solve energy related problems. The importance of the Assessment and management topic with 15929 data (28 % of the total uploaded data) is clearly indicated by the obtained Scopus data.

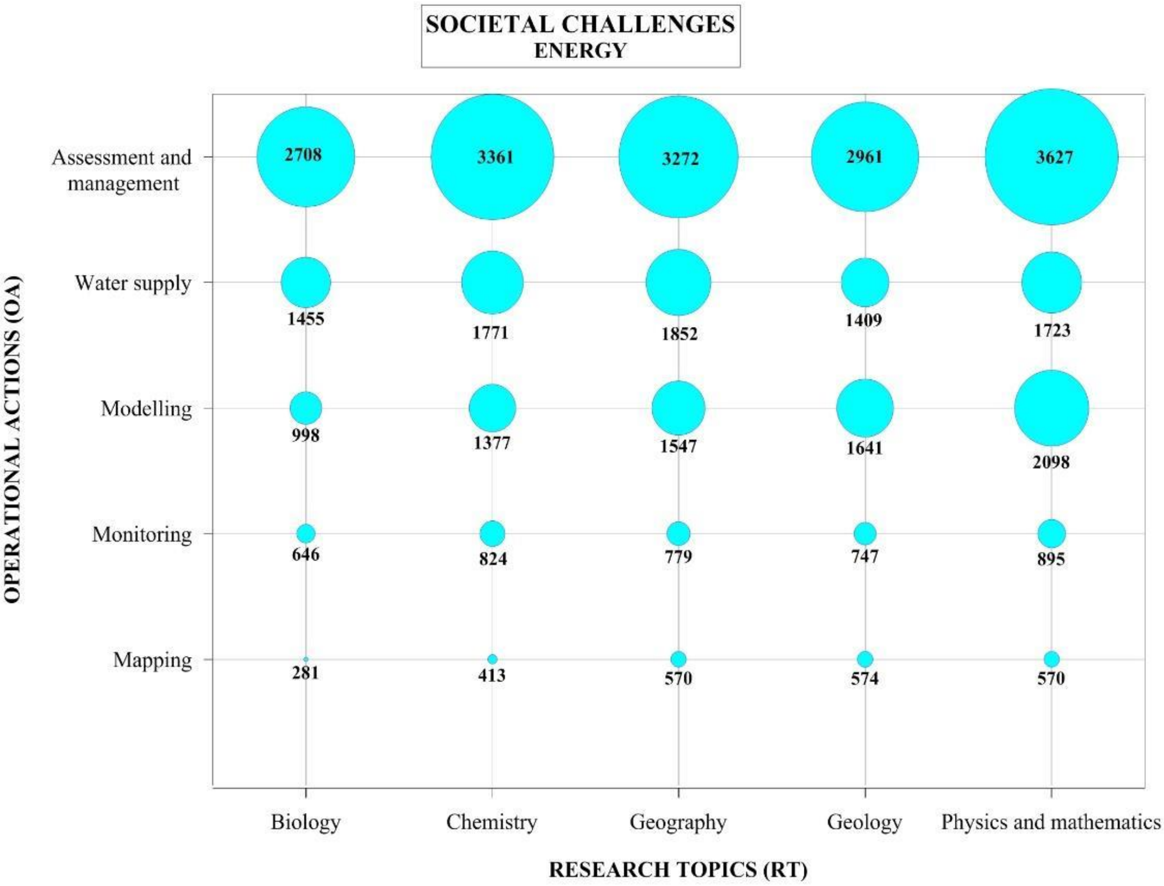


Figure 4.42 Scopus data (RT, OA) plot for SC3 = Energy. The size of the bubbles indicate the relative amount of data at a specific intersection, whereas the number indicates the number of available resources

The intersection plot for the Societal Challenge 4 'Climate, Environment and Resources in Figure 4.43 shows that the OA 'Assessment and Management' is dominating across the 5 Research Topics which also is the case for the EIGR data in Figure 4.38, but where RT4 Geology was clearly very dominant for EIGR, Scopus data displays a more even distribution across all research topics, as expected. Overall, the OA 'Assessment and management' has a broad scope where other operational actions like 'water supply', 'modelling', 'monitoring and 'mapping' are more narrowly defined and in searches conceivably also captured by OA 'Assessment and management'.

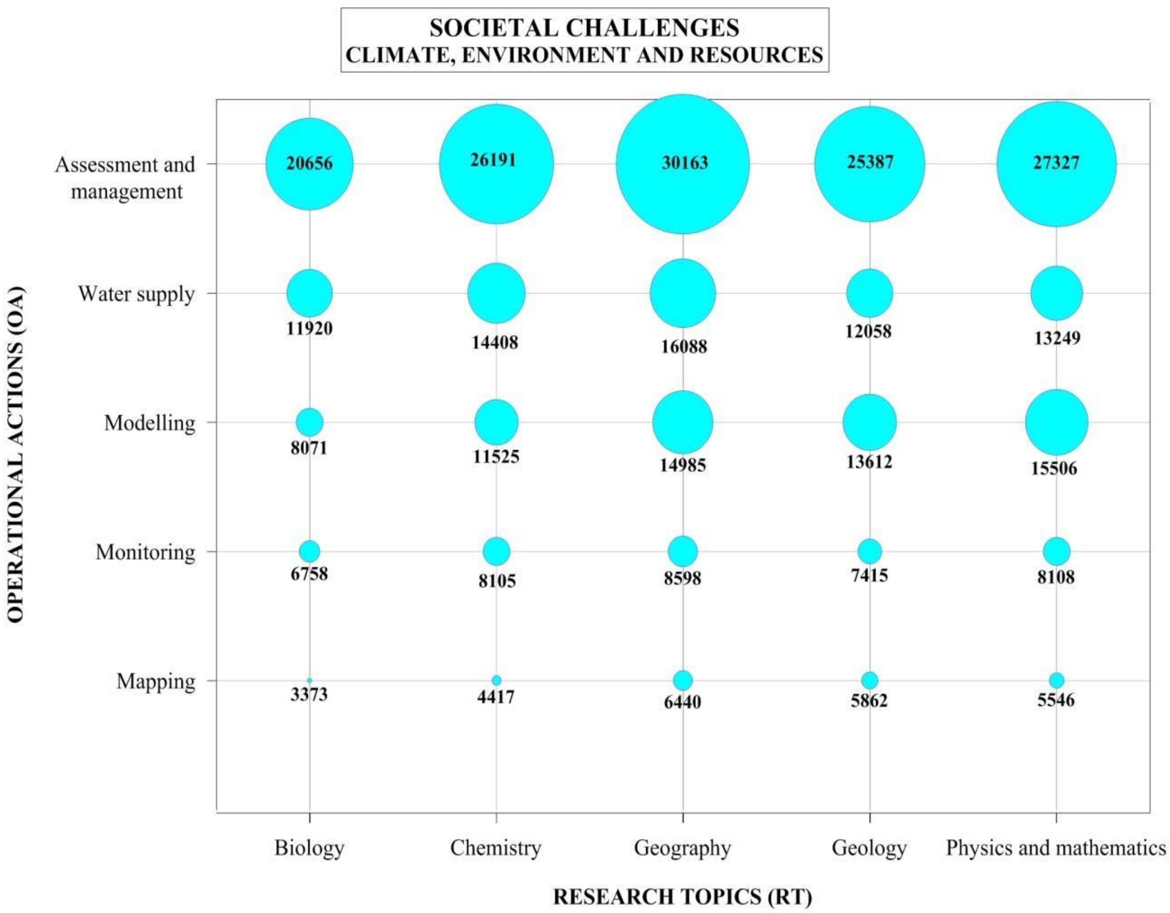


Figure 4.43 Scopus data (RT, OA) plot for SC = Climate, Environment and Resources. The size of the bubbles indicate the relative amount of data at a specific intersection, whereas the number indicates the number of available resources

For SC 'Policy, Innovation and Society' in Figure 4.44 the same trend is visible: the OA-5 'Assessment and management' is dominating, followed by OA-4 'Water supply' with around 40 % less resources. It is expected that OA-5 is more prevalent as this operational action is closely associated to the political and societal sphere of interest, more than the other more specific OA's: water supply, modelling, monitoring and mapping, which typically are part of the broader 'Assessment and management'. When compared to the corresponding EIGR based diagram it again becomes clear that almost all intersections (RT, OA) are underdeveloped and biased towards the EFG submitted resources with focus on geology and OA-5 'Assessment and management'

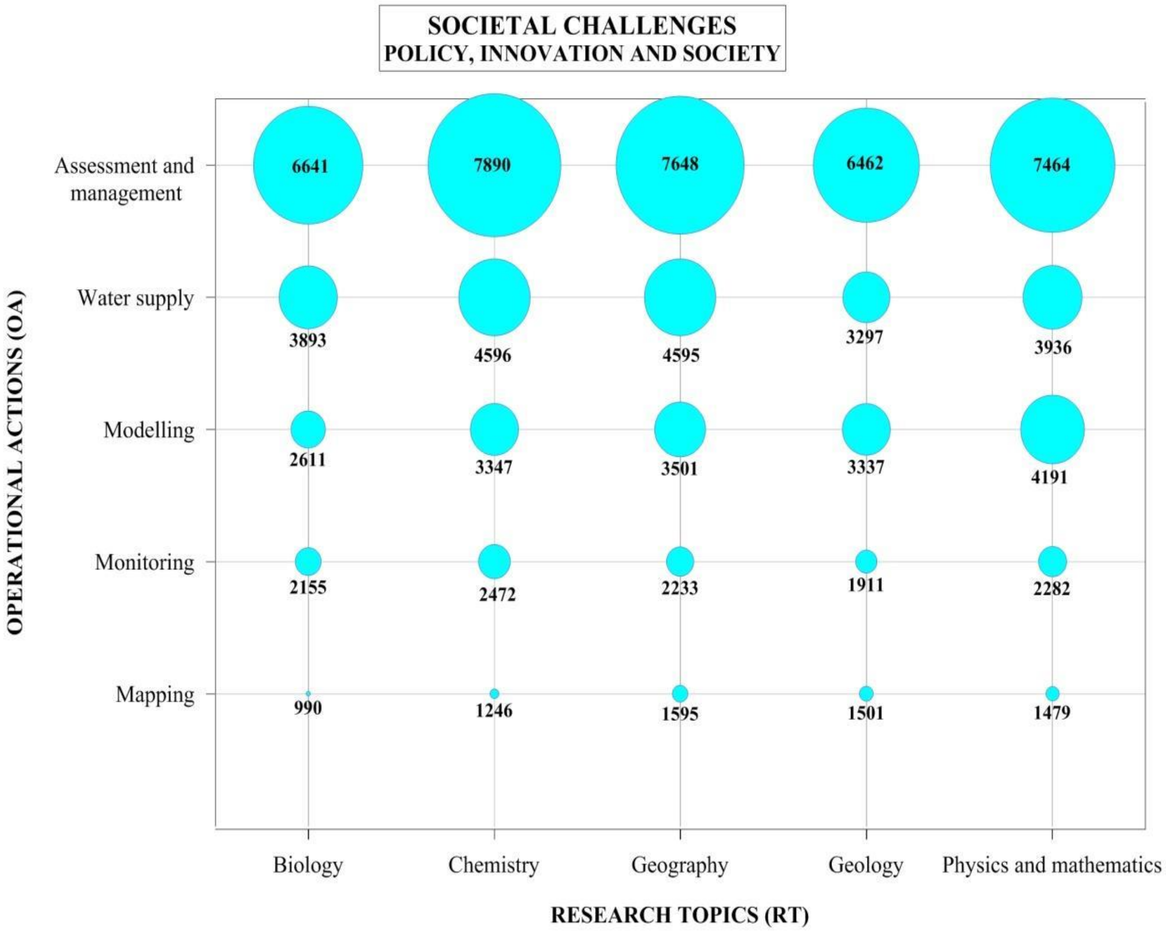


Figure 4.44 Scopus data (RT, OA) plot for SC = Policy, Innovation and Society. The size of the bubbles indicate the relative amount of data at a specific intersection, whereas the number indicates the number of available resources

4.1.2.2 Bibliometric maps and co-occurrence analysis

Resources are extracted from Scopus database using search strings that contain all keywords belonging to each of the categories (5 for each axis in Figure 3.1). For instance, the search string for 'Operational Action: Water Supply' contains the following keywords: Table XX Keywords used in combination with the baseline search string for OA4 "Water Supply"

Water suppl*	Abstract*	Extract*	Energy produc*	Food Produc*	Drinking water
Mining	Industr*	Farm*	Agricultur*	Touris*	

The complete research strings for constructing the VOSviewer co-occurrence maps for each of the figures below is listed in the Appendix Table 4

Therefore a search in Scopus for OA {Water Supply} in the period 1997-2016 is:

```
TITLE-ABS-KEY((Groundwater OR ”Ground Water” OR hydrogeolog*) AND (“water suppl*” OR abstract* OR extract* OR “energy produc*” OR “food produc*” OR “drinking water” OR mining OR industr* OR farm* OR agricultur* OR touris*) AND [any term from SC 1-5] AND [any term from RT 1-5]) AND PUBYEAR > 1996 AND PUBYEAR < 2017
```

Figure 4.45 and Figure 4.46 analyses the relation between and co-occurrence of the most important keywords related to groundwater and human health. The plots clearly indicate and confirm the close relation between groundwater pollution in general, water supply, drinking water, cancer risk, human health as well as the contents of certain elements such as arsenic, radioisotopes and lead, which may occur in groundwater both as a result of natural and anthropogenic impact. The research publications on the occurrence of arsenic and the related health issues are mainly related to Asia (Bangladesh and India) due to high groundwater concentrations of arsenic in these countries, but recent studies in the Netherlands (van der Wens et al., 2016) indicate that this topic should be higher on the agenda in Europe, and that health benefits of reducing arsenic in groundwater should be evaluated at a European scale.

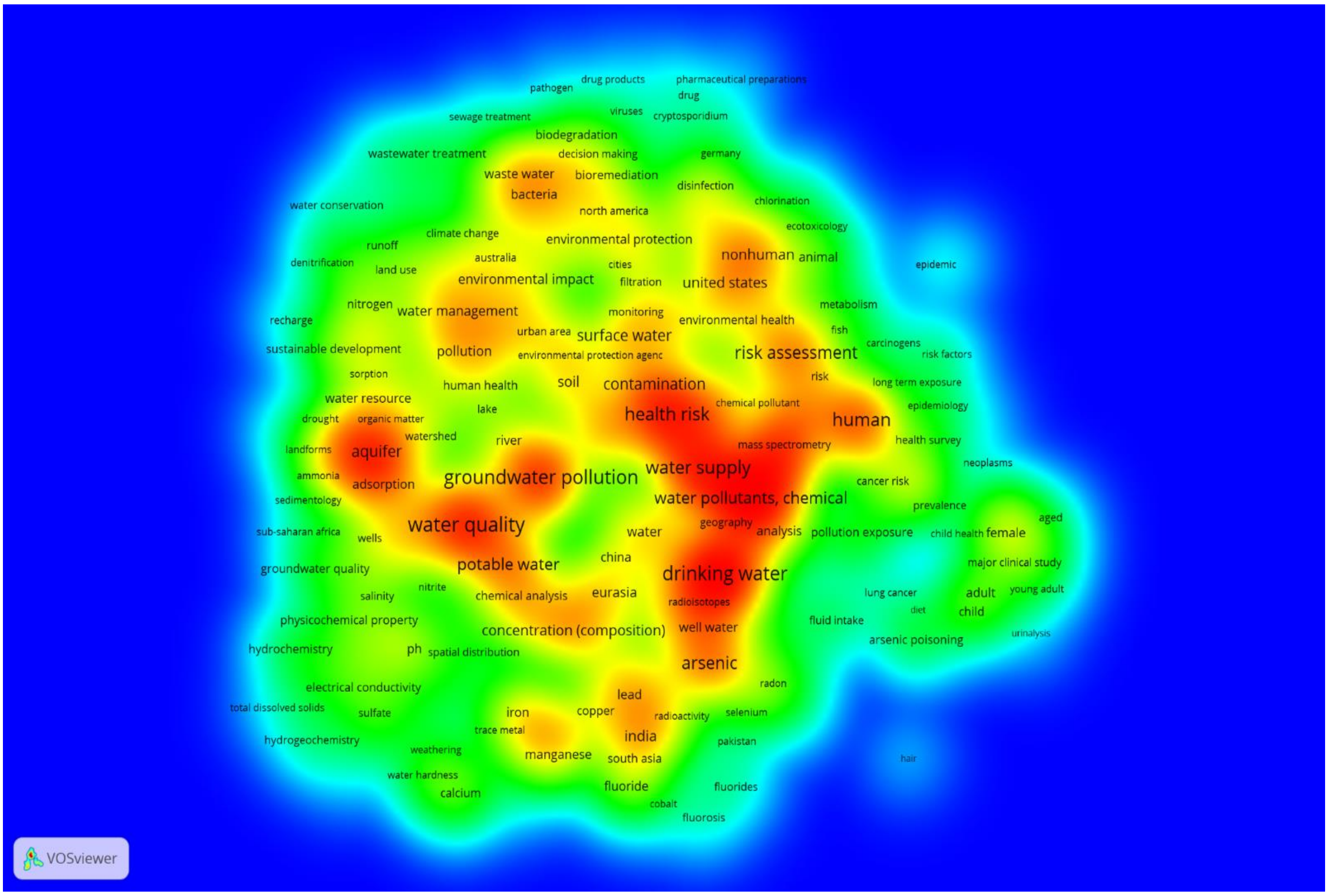


Figure 4.45 VOSviewer density map of most frequent keywords occurring within SC1 – Health

The Dutch study concluded that lowering of the drinking water standard (DWS) for arsenic from 10 µg/l to 1.0 µg/l would reduce the occurrence of cancer and related deaths significantly (van der Wens et al., 2016, 2017). Hence, research assessing the costs and effect of reducing the DWS for As to 1.0 µg/l in Europe in general is highly warranted, and such research requires hydrogeological and hydrochemical assessments of the current groundwater content of arsenic across Europe.

Arsenic has the strongest link to human health issues according to co-occurrence network map (Figure 4.45, below ‘drinking water’), while groundwater pollution in general has a weaker but still significant link to human health.

In the rim of plots in Figure 4.45 and Figure 4.46 one finds e.g. 1) pharmaceuticals, drugs and pathogens in the top/upper periphery of the diagram; 2) fluorides, cobalt, copper, manganese and selenium in the lower, 3) chlorine compounds and ammonia to the left and 4) carcinogens to the right. All these contaminants have no or few links to health-related keywords (human, world health organisation) indicating that gaps may exist in the knowledge and understanding of the effects of these pollutants. That a gap exists at least for some of these pollutants is e.g. indicated by the growing number of highly cited research papers on groundwater and emerging contaminants (e.g. Lapworth et al., 2012).

Nitrate only appears as a minor keyword in the shown plots and hence does not appear to be a prominent research topic in relation to human health at a first glance although nitrate is the pollutant in Europe, which most frequently results in poor chemical status for groundwater bodies and non-compliance with EU directives. Based on a very recent paper on the link between nitrate in groundwater and drinking water and the occurrence of colorectal cancer in Denmark (Schullehner et al., 2018), this appears to be a severe cross-disciplinary research gap, globally.

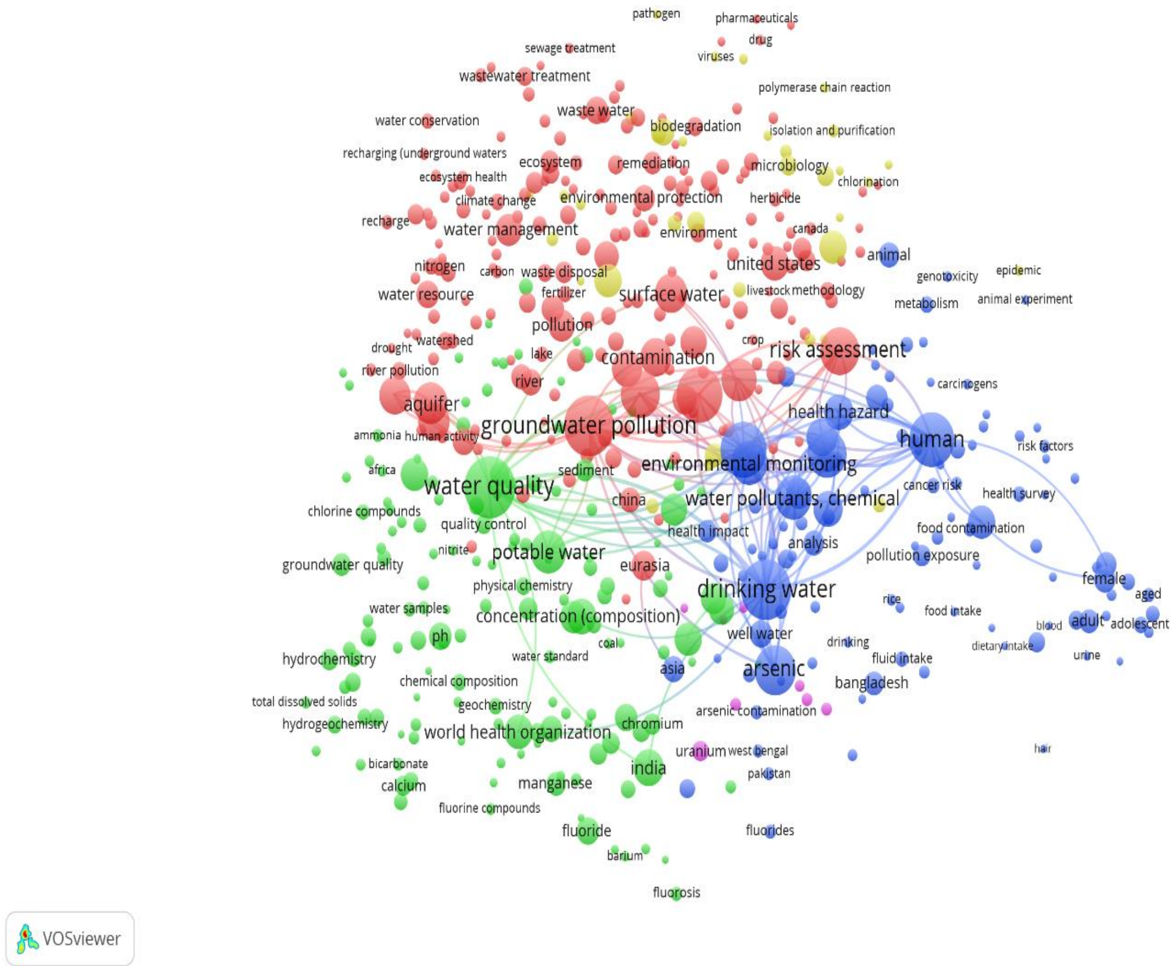


Figure 4.46 VOSviewer network map for SC1-Health showing co-occurrence and links between most important keywords

Figure 4.47 and Figure 4.48 show that the most frequently occurring keywords of SC2 are agriculture, irrigation, water quality, groundwater pollution and nitrate. Showing that both groundwater quantitative and chemical status are important research topics related to food security and sustainable agriculture. Agriculture, nitrate, ecosystem and wetland all occur quite centrally indicating that more research and knowledge in relation to nitrate and ecosystems than indicated by the previous figure may exist. However, nitrate or nutrient loads are not among the most frequent keywords indicating that the link between groundwater chemical status, nitrate and nutrient loads in rivers and further the nutrient loadings to the associated ecosystems in lakes (surface waters), transitional and marine waters are not properly understood and covered. This supports the conclusions of the Technical Report on groundwater associated aquatic ecosystems published by the European Commission (European Commission, 2015) that a gap exists on this research topic.

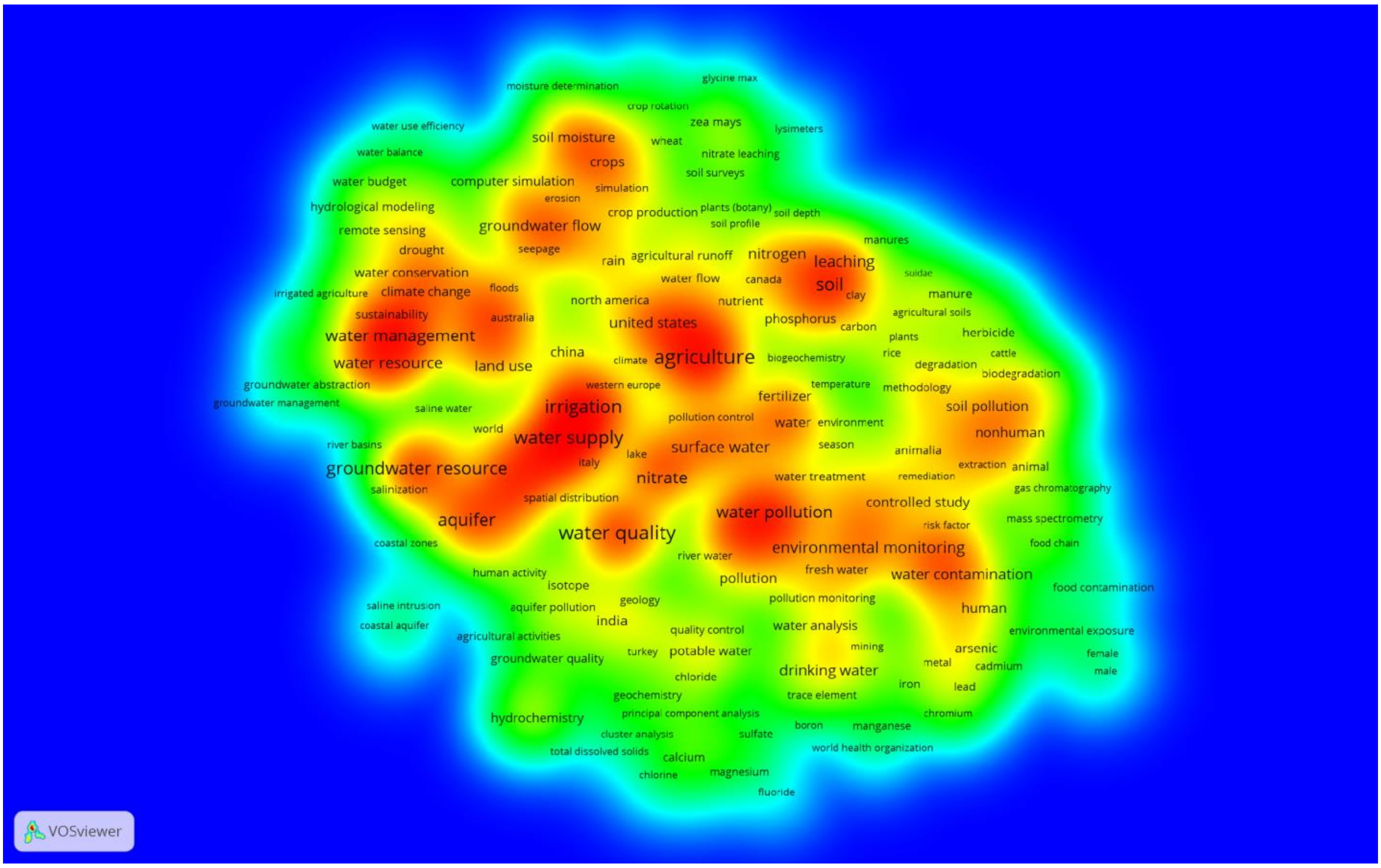


Figure 4.47 VOSviewer density map of most frequent keywords occurring within SC2 – Food

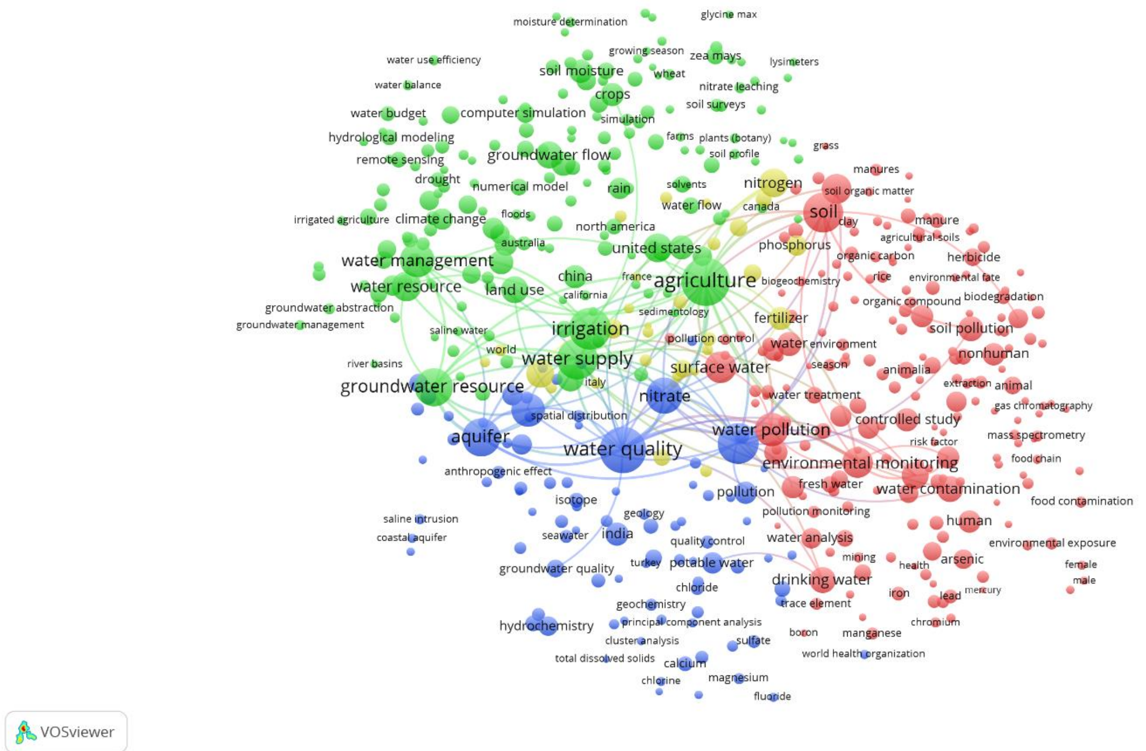


Figure 4.48 VOSviewer network map showing co-occurrence and links between most important keywords within SC2 "Food"

Figure 4.49 and Figure 4.50 indicate that the most frequently occurring keywords of SC3-Energy are hydrogeology, geothermal energy, geothermal flow, geothermal fields, groundwater pollution, groundwater resource, energy resource, water supply, soil, environmental monitoring and carbon dioxide. These keywords clearly reflect the international tendencies of how energy related issues and challenges are connected to groundwater resources. Geothermal energy prospecting and utilization are in close relationship with groundwater resources if renewable energy is cited. There are many regions all over the world where the natural conditions are favorable to produce geothermal energy. Hydrothermal systems cannot be operated in a sustainable manner without the proper knowledge of hydrogeology and reliable monitoring. It is also a well-known fact that energy production can cause environmental pollution in many cases reaching even the subsurface media and groundwater resources. This is the reason why strong connections were revealed among energy and groundwater and soil pollution. There are innovative solutions how groundwater treatment and soil remediation can be effective and reliable. The utilization of thermal water resources, geothermal energy and the increasing number of heat pumps for the heating of houses and buildings can support to reduce the human carbon dioxide emission and the carbon footprint. Although traditional carbon-based energy supply is still very important, that dominance of the research activity has been shifted to the direction of renewable energy resources all over the world. This tendency can be also recognized in the co-occurrence analysis of the keywords connected to the energy.

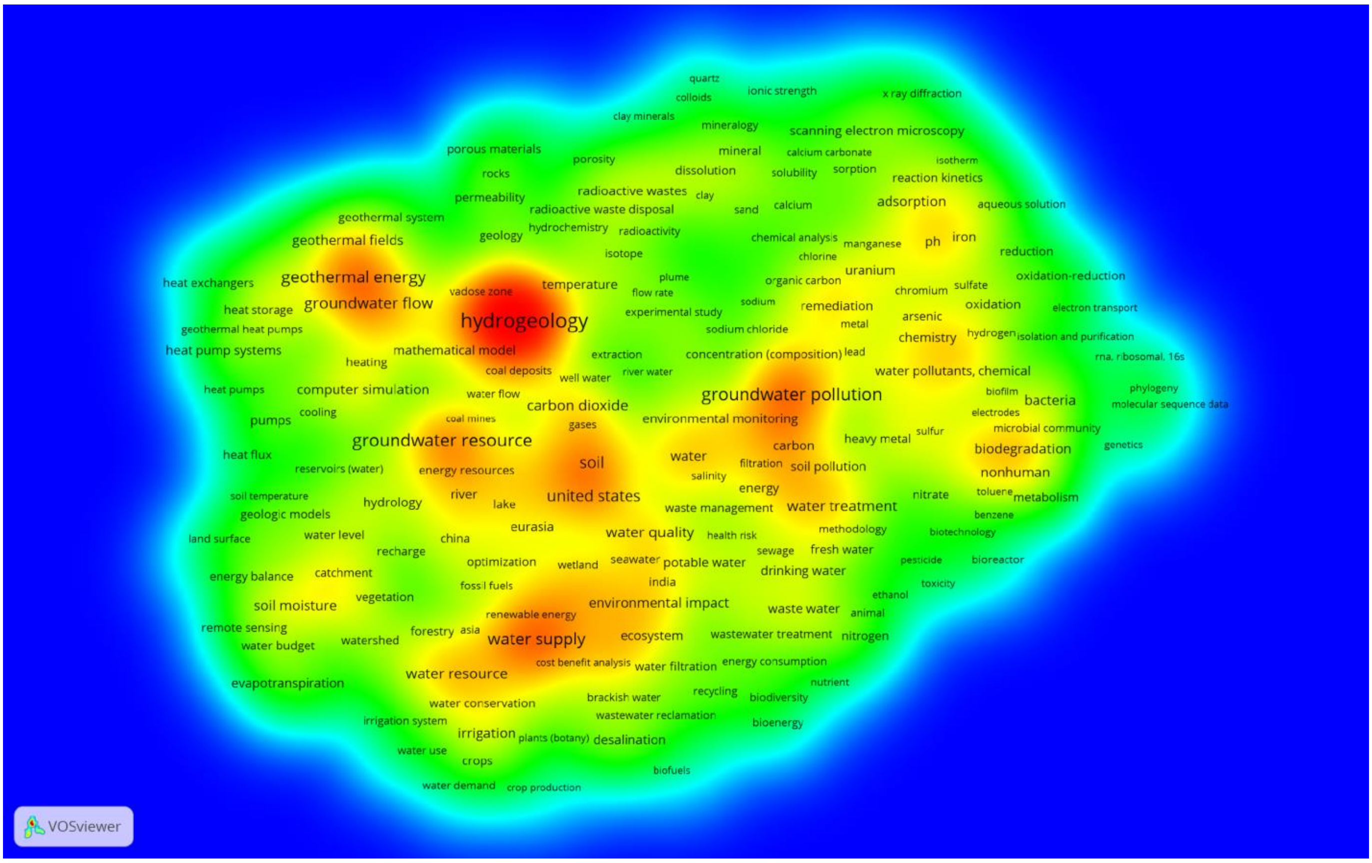


Figure 4.49 VOSviewer density map of most frequent keywords occurring within SC3 – "Energy"

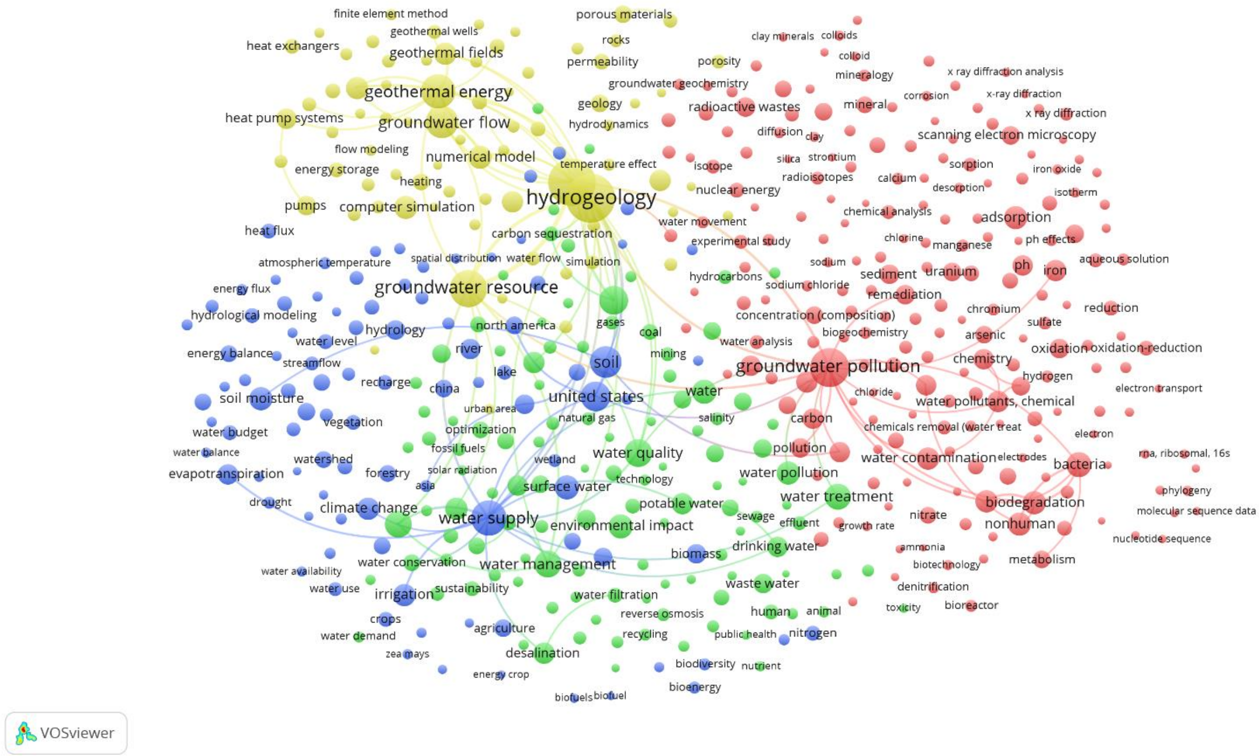


Figure 4.50 VOSviewer network map showing co-occurrence and links between most important keywords within SC3 "Energy"

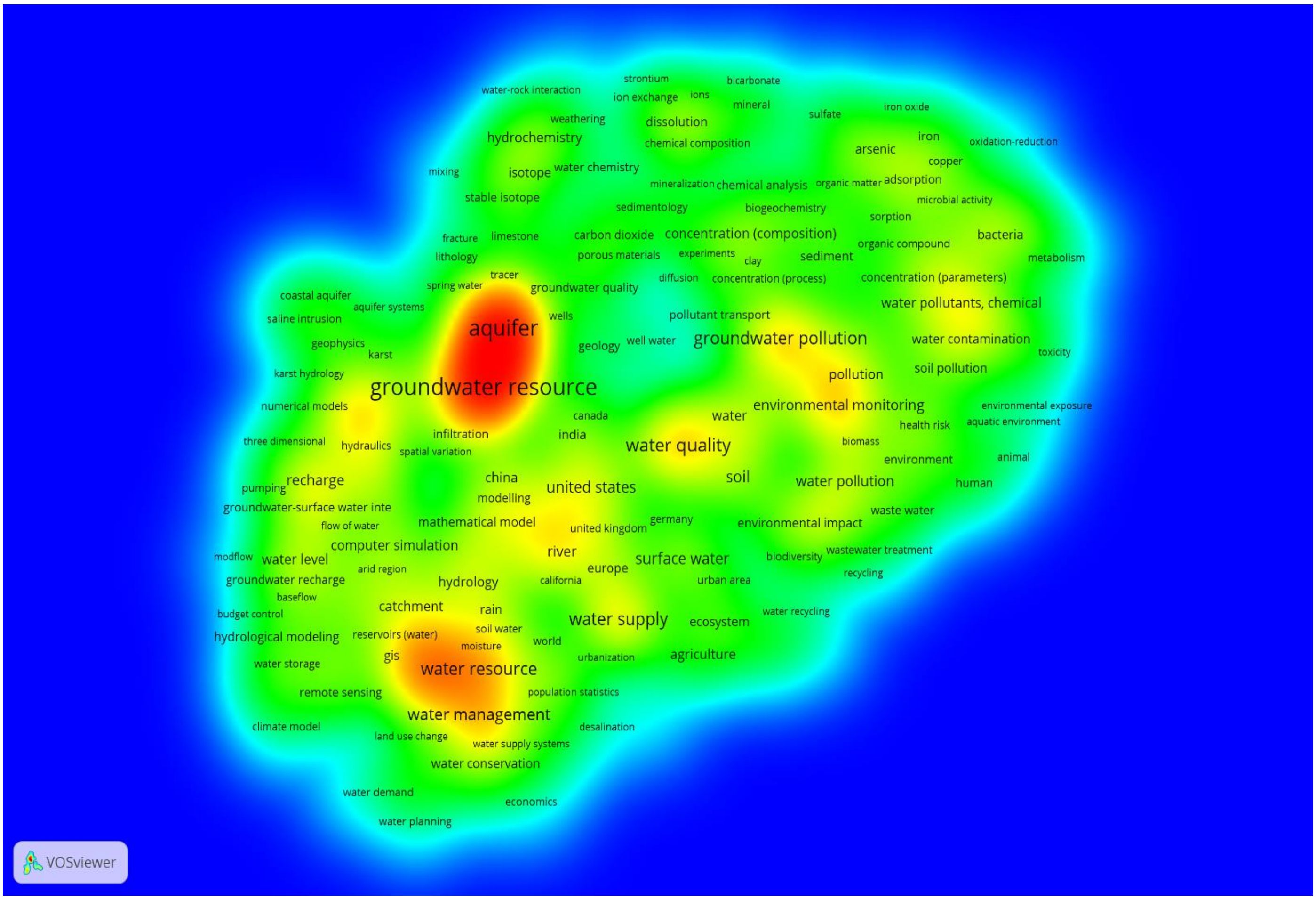


Figure 4.51 Scopus density map for SC4-Climate Environment and Resources, and period 1997-2016

Figure 4.51 displays the density view of SC 4 ‘Climate, Environment and Resources’ in which two clusters are prominent: the cluster around the keywords ‘groundwater resource’ and ‘Aquifer’ (blue cluster in Figure 4.52) and another somewhat less prominent cluster around ‘water resource’ and ‘water management’ (the green cluster in Figure 4.52). Other less visible clusters around keywords on groundwater pollution, water quality are in close proximity to the ‘groundwater resource’ and ‘aquifer’ clusters which is expected. Also, keywords on pollution, specific contaminants, environment and biochemistry cluster around ‘groundwater pollution’, the red cluster in Figure 4.52. Clearly, water (bio)chemistry related keywords include (ad)sorption, organic compounds, bacteria, microbial activity and various chemical compounds, are scattered around clusters on groundwater pollution in the upper part of the density plot. From there the structure seems to suggest that the ‘water quality’ and ‘water supply’ bridge to ‘water resource’ and ‘water management’. This seems logical in the sense that highly specialized topics characterised by geochemical keywords are located and concentrated in the periphery of the density graph and that they gradually evolve towards the more groundwater management related clusters via more general clusters like ‘water quality’ and ‘water supply’. Keywords related to modelling of groundwater and pollutants are located between the dominant ‘water resource’, ‘water management’ and ‘groundwater resource’ and aquifer. Keywords and topics associated to (mathematical) modelling and hydraulics are in the near vicinity: infiltration, tracer, ‘groundwater-surface water interaction’ and ‘computer simulation’. Remarkable for this representation of SC4 ‘Climate, Environment and Resources’ seems to be that the latter two terms are well represented, but the Climate component largely absent, only ‘climate model’ is directly reflecting this. A strongly emerging area in SC4, urban hydrology and the significance of shallow groundwater, e.g. in connection to nature based solutions and green infrastructure (Denjean et al., 2018) is barely represented which like the underrepresented climate keyword constitute a gap in research.

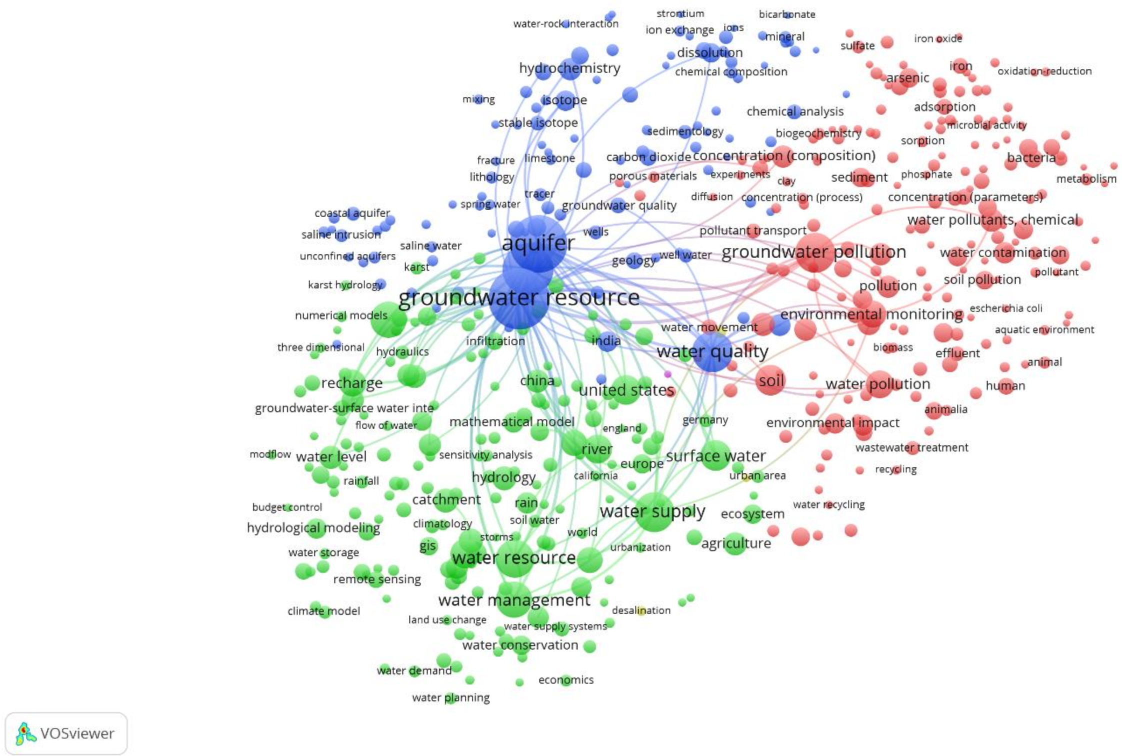


Figure 4.52 Scopus network map for SC4-Climate Environment and Resources, period 1997-2016

The Societal Challenge 5 ‘Policy, Innovation and Society’ keyword structure as shown in the density plot in Figure 4.53 and network plot in Figure 4.54 is characterised by many clusters centered around Aquifer, groundwater pollution, water supply, ‘groundwater resource’ and ‘water pollutants’. As we would expect from a Societal Challenge that embraces a large variety of environmental, policy and societal issues, the clusters while clearly recognizable are entrenched in each other, signifying the multi-faceted topics and research areas. Multi-disciplinarity are clearly visible as compared to the SC4 ‘Climate, Environment and Resources’ in which topics and research areas are less dispersed, even though also in SC4 some degree of multi-disciplinarity is expected and shown in the co-occurrence diagrams. Similar to the SC4 graphs, clustering around Aquifer, groundwater resource, ‘water management’ and ‘groundwater pollution’ can be discerned. The societal aspects are more pronounced with more emphasis on environmental impact and monitoring and the presence of keywords like ‘sustainable development’ and ‘environmental protection’. The data resource for SC4 is about three times larger (Table 2) than for SC5 which needs to be taken into account when interpreting the keyword structure, and also the zooming capabilities of the VOSviewer which enables a more detailed inspection when zooming in when more less pronounced keywords may appear. Nevertheless, SC5 ‘policy, innovation and society’ relevant keywords are clearly mostly related to Operational Action ‘Assessment and management’ and to a lesser degree ‘Water supply’ as also is the case for SC4. Adding subcategory keywords to SC5 most probably would have provided more insight to how groundwater research is interwoven with policy, innovation and society, more than associated keywords to SC1-4 would have done due to the more multidisciplinary character of SC5 as compared to SC1-4.

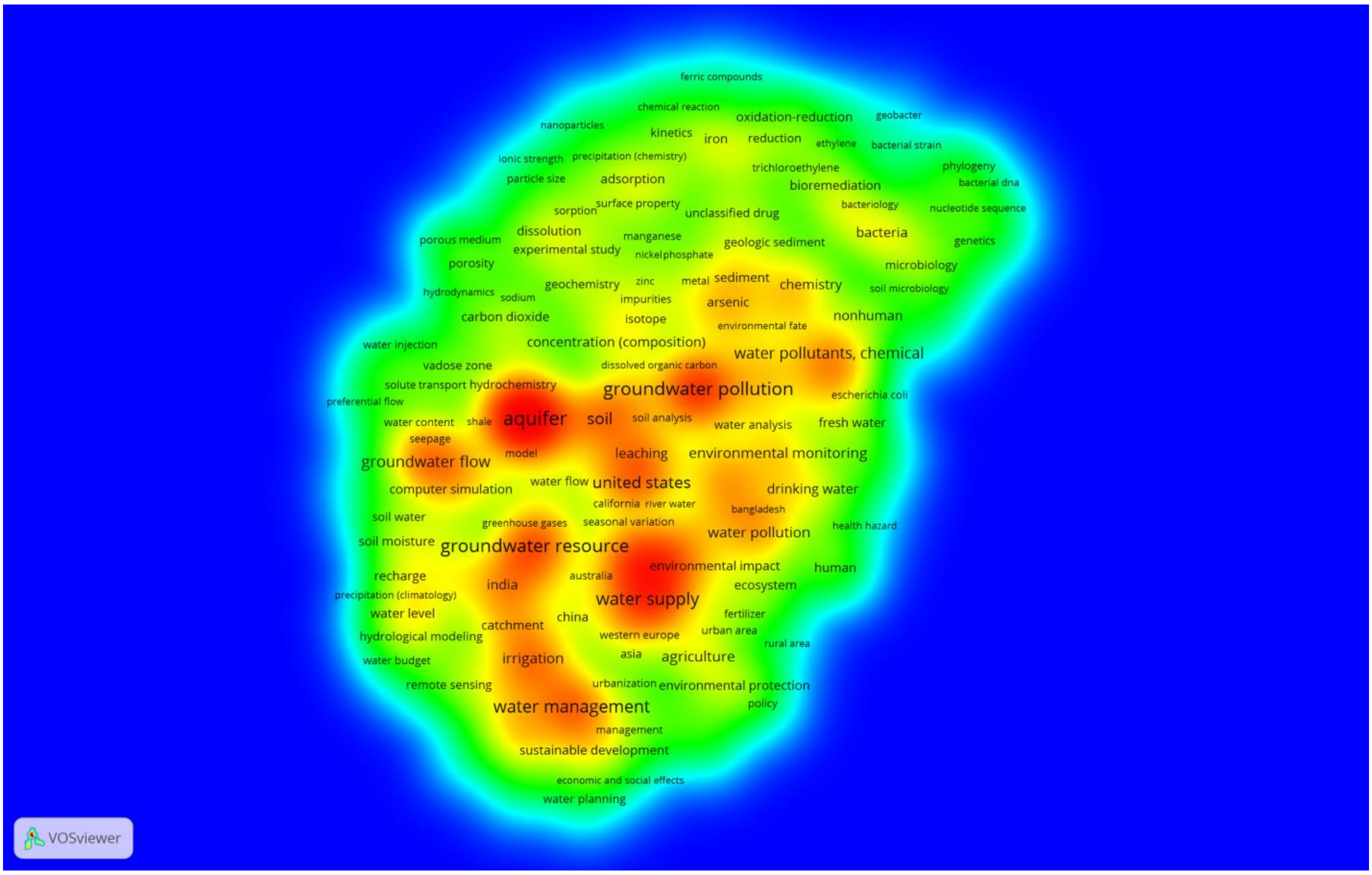


Figure 4.53 Scopus density map for SC5 - ‘Policy, Innovation and Society’, period 1997-2016

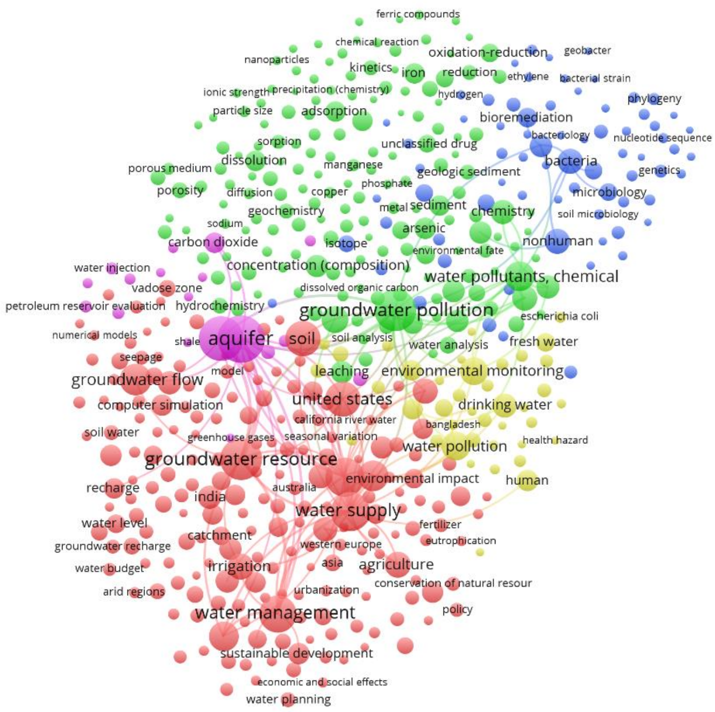


Figure 4.54 Scopus network map for SC5 - 'Policy, Innovation and Society', period 1997-2016

The density graph for SC6 - Transport indicates clearly demarcated clusters around 'roads and streets', hydrogeology, 'groundwater pollution' and a cluster containing several keywords related to infrastructure construction and construction techniques. Groundwater related research on transport and infrastructure is obviously connected to literature on geotechnical topics, like 'slope stability', landslides, and tunnels. Likewise and interestingly, transport and infrastructure alters the soil surface and results in less infiltration (recharge) which again can cause flooding, and this array of topics seems to be well captured in the area close to the 'road and streets' and 'aquifer' clusters including keywords like runoff, storm water and sewers. Also, infrastructure establishment and attracting transport may increase groundwater and soil pollution, like landfills, introducing e.g. heavy metals.

SC6 has the lowest scholarly output of the societal challenges nearly 20 times lower than for SC4 with the highest output. An assessment furthermore showed that about half of the publications returned in a Scopus search are already covered by the publications returned in searches on the other SCs. Important research on both groundwater quality and quantity issues related to transportation including roads, railways, airports and fuel storage is conducted, globally.

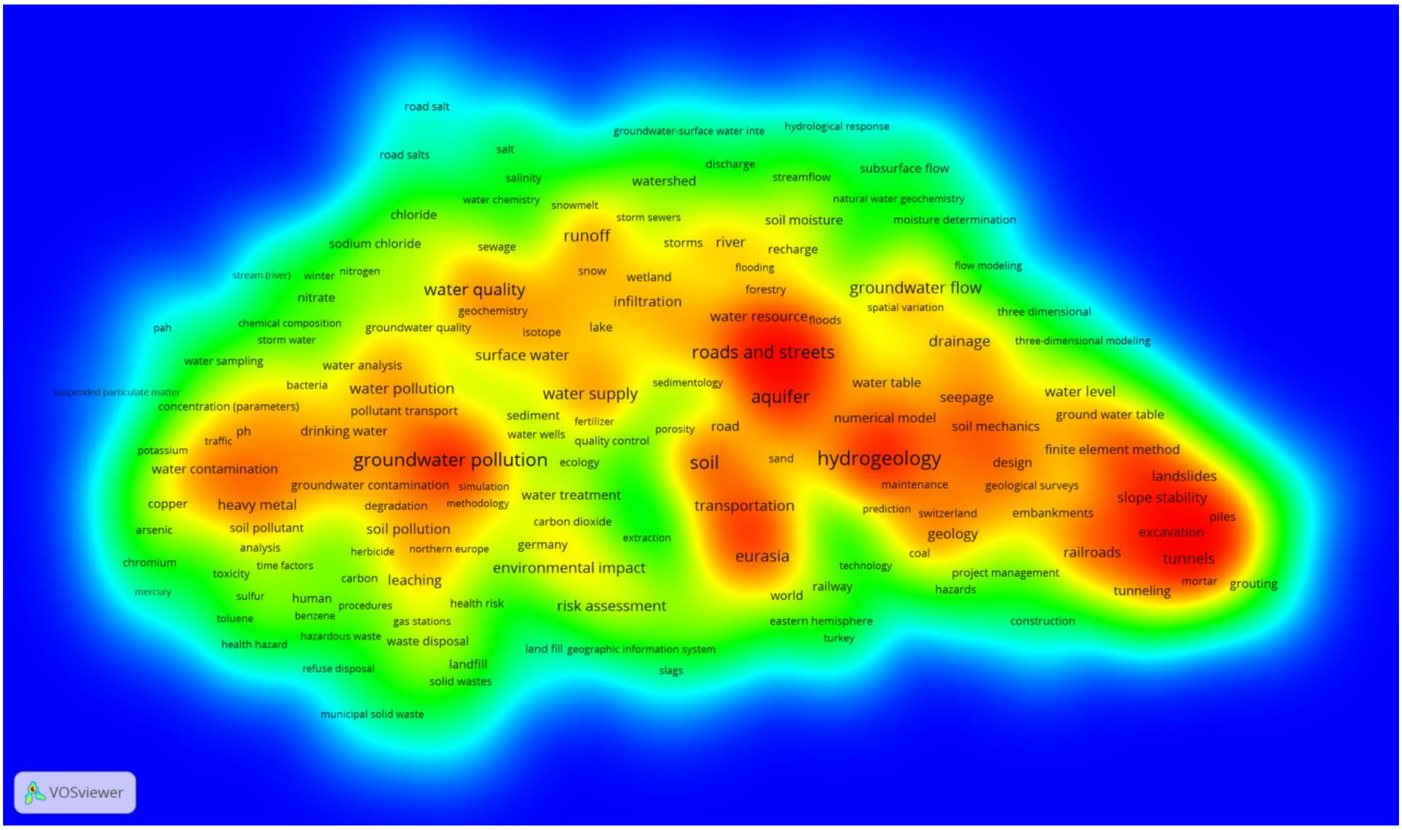


Figure 4.55 Scopus density map for SC6-Transport, period 1997-2016

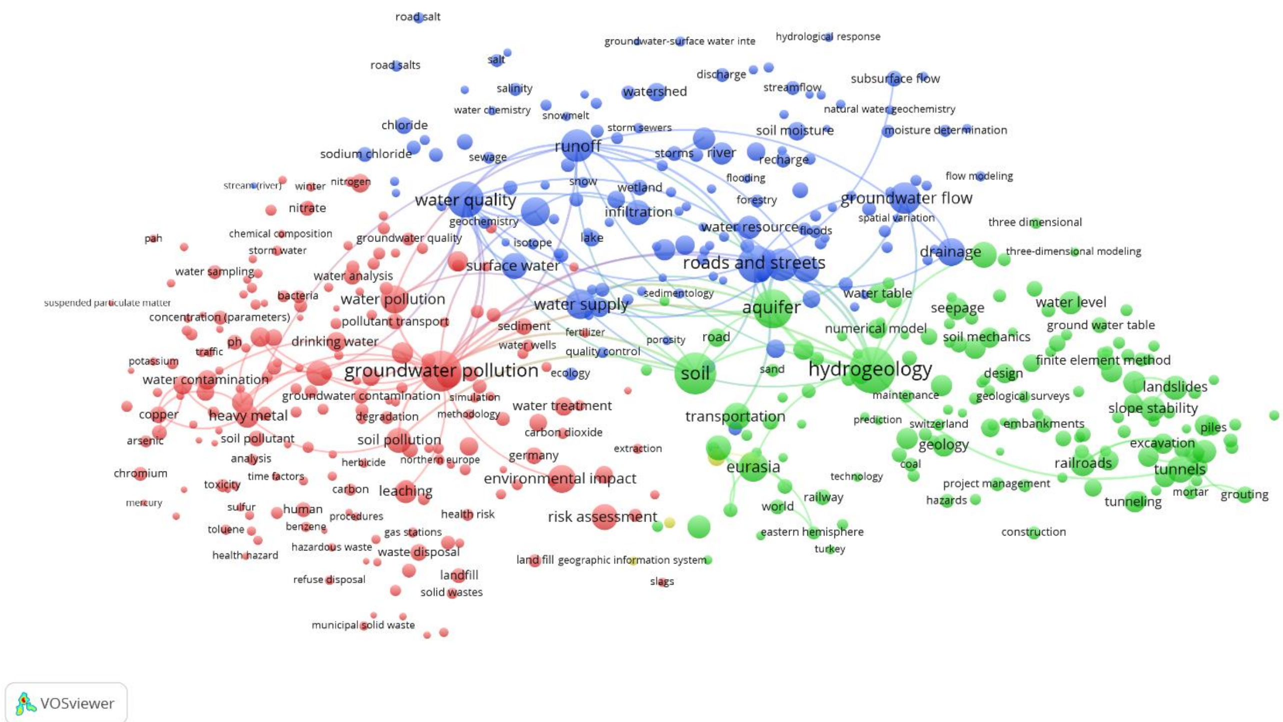


Figure 4.56 Scopus network map for SC6-Transport, period 1997-2016

4.1.3 Scopus and SciVal analyses

The KINDRA partners, current activities of the Working Group Groundwater within the Common Implementation Strategy of the Water Framework Directive, workshops and meeting with third parties, the KINDRA joint panel of experts and invited speakers at the KINDRA final conference identified a list of important contemporary groundwater research topics and keywords, which are relevant to investigate in more detail according to expert judgement. The complete list of these can be found in a table in the Appendix of this report together with scholarly outputs related to these globally and in Europe for the periods > 1996 and > 2006 (i.e. the scholarly output after 1996 and 2006, respectively). The list is not exhaustive, but includes research topics, which are considered important for assessment of future research needs.

The groundwater research topics and keywords with the highest scholarly output related to implementation of EU policies are shown in the Figure 4.57.

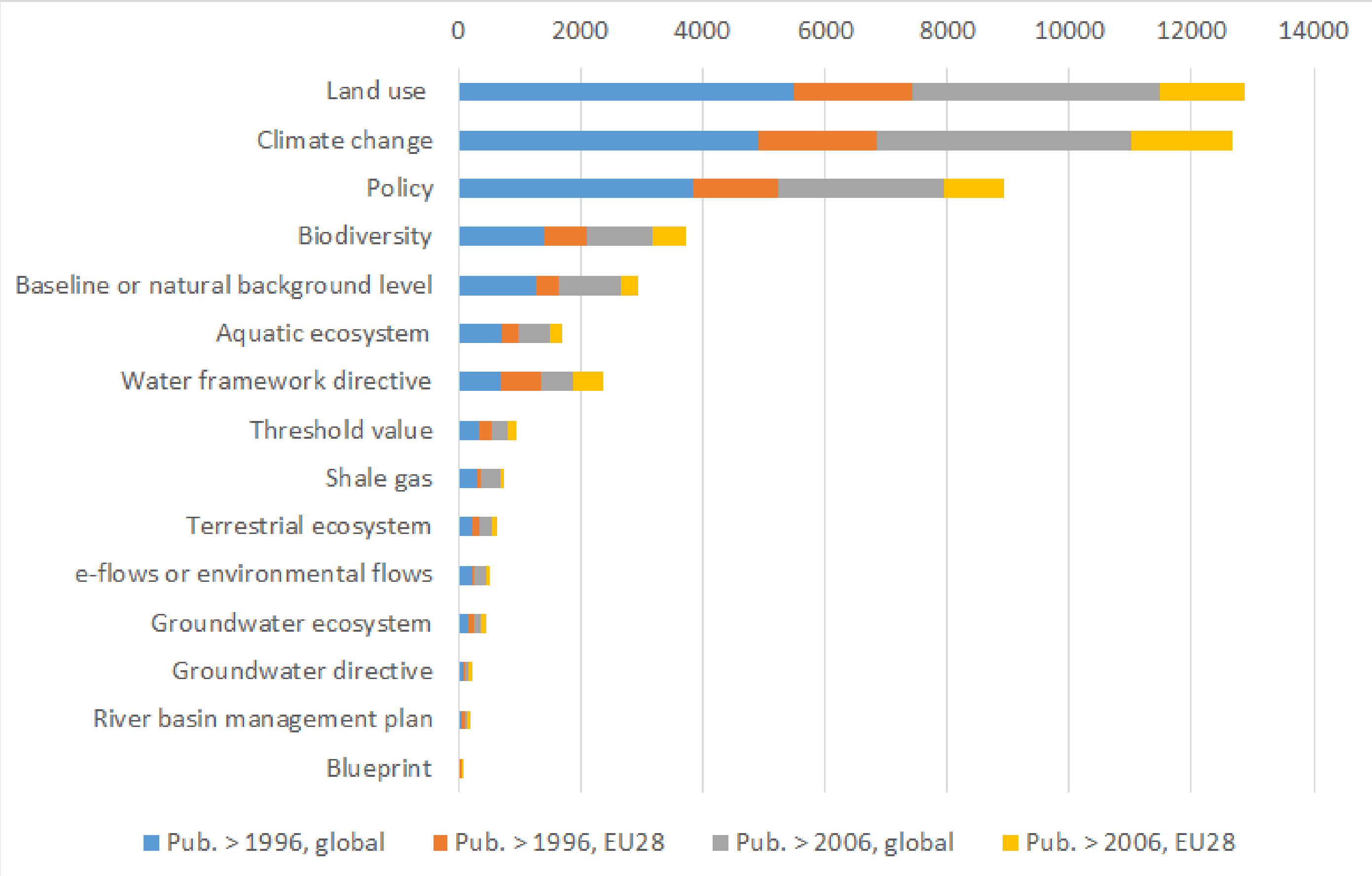


Figure 4.57 Scholarly output for selected groundwater issues relevant for implementation of EU policies e.g. according to the Water Framework and Groundwater directives (Scopus searches performed March 2018

The groundwater research topics and keywords with the highest scholarly output related to groundwater quality are shown in the Figure 4.58.

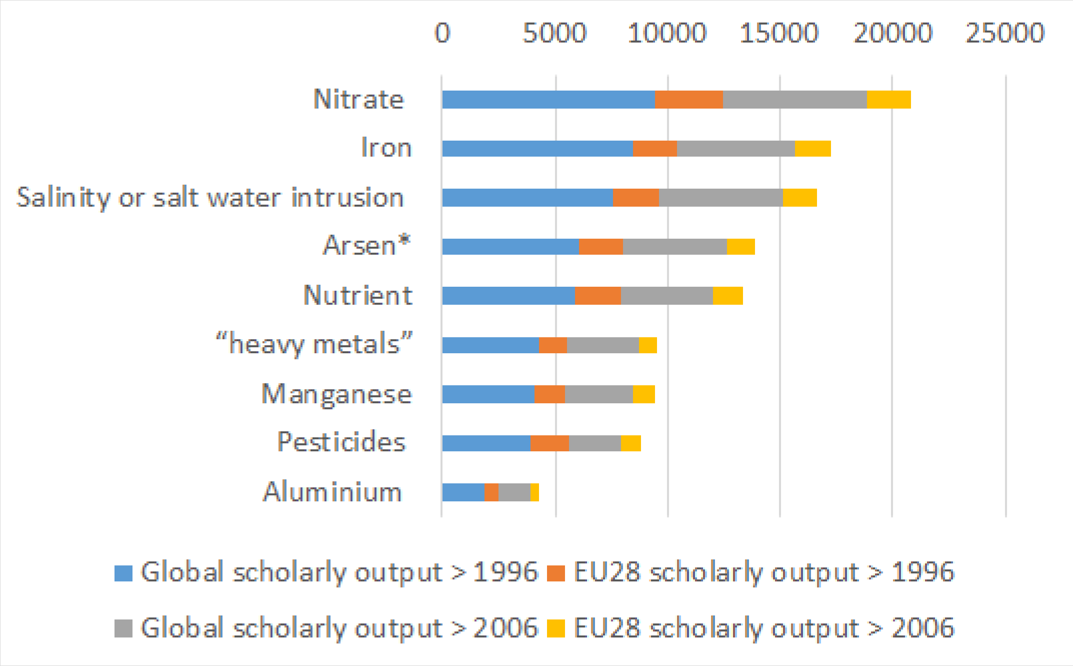


Figure 4.58 Scholarly output for selected groundwater quality indicators most frequently occurring in research papers in Scopus (searches performed March 2018

From the list in the Appendix we identify the following keywords, which represent very recent developing fields for research, as the potentially most important research gaps (**Errore. L'origine riferimento non è stata trovata.**)

Keyword	Global scholarly output 1997-2006	EU28 scholarly output 1997-2006	Global scholarly output > 2006	EU28 scholarly output > 2006
Emerging contaminants, Emerging contamina*	12	4	190	74
Benzapyren* or Benzopyren*	2	1	0	0
Microplastic*	0	0	5	4
Nanoparticle*	76	7	1227	296
Perfluorooctanesulfonic acid or PFOS	6	1	101	30
“cloud computing”	0	0	40	2
“Internet of Things”	0	0	12	1
Nexus	2	0	168	35
“big data”	0	0	28	5
ICT or information and communication technology	4	2	23	3

Table 3 EU and global scholarly output for the periods 1997-2006 and > 2006 (2007-2017)

For the selected types of contaminants of emerging concern Europe seems to conduct a reasonable amount of research compared to the global output. The occurrence of these keywords is strongly raising in the last ten years (see Nanoparticle, PFOS, and Nexus too). Research on microplastics in relation to groundwater seems to be made mainly in Europe within the most recent years.

Errore. L'origine riferimento non è stata trovata. shows that the European scholarly output for keywords r elated to new ICT solutions e.g. "cloud computing", IoT (Internet of Things), "big data" and ICT itself seem to be significantly lower compared to the global output, and that Europe is underperforming in relation to other parts of the world (most probably mainly the USA) for research on these topics. Hence, this probably constitute a research gap in European groundwater research. The table further shows that practically all research on groundwater and ICT, as for the other selected keywords, has been performed during the past 10 years, illustrating an increasing trend for research on this topics, both in the EU and globally.

The analyses on trends in groundwater research continues in the next section of the report.

4.2 TRENDS analyses

4.2.1 EIGR analyses

4.2.1.1 HRC-SYS analyses

Concerning the EIGR distribution of resources within Societal Challenges categories, it can be observed that category Health (SC-1) covers only 2.6 % (57 different data) of the uploaded information. In the period 1997-2006 (Appendix Figure 8.1) only 23 publications can be found in the Health intersections, Water supply (OA-4) is the most relevant concerning the OA's, while in case of the RT's, Chemistry (RT-2) and Geology (RT-4) can be connected to health issues.
It can be identified that the number publications (34 datapoints) was significantly (by 150 %) increasing in the period 2007-2016 (Appendix Figure 8.2). In addition to the Chemistry and Geology research topics, the importance of Biology has increased and in case of the OA's besides the Water supply, the number of publication in the Assessment and management (OA-5) and Modelling (OA-3) categories has increased. There is not any connection in both periods between the Health and Geography (RT-2) and Physics & mathematics (RT-5) categories.

The Societal Challenges Food (SC-2) category includes less than 1% (13 datapoints) of the uploaded publications. In the period 1997-2006 (Appendix Figure 8.3) there can be found 3 publications in the intersections of Food. It can be also realized that the number of data connected to Food was increasing after 2006 (Appendix Figure 8.4). The increase is significant (10 data), but still not adequate. As it was mentioned earlier, this is a general trend concerning increasing number of research publication. Both of the figures demonstrate, that there is not any connection between the EIGR publications with Food issues. It can be identified as a gap in the investigated periods.
Unfortunately, the number of uploaded publications is so low (13) in EIGR, that the real interpretation and conclusions cannot be given to reveal the research trends in this field.

The Societal Challenges Energy (SC-3) shows similar picture as the Food (SC-2) category. The Energy plot includes 2.5 % (55 datapoints) of the uploaded publications. In the period 1997-2006 (Appendix Figure 8.5) there can be found 5 publications in the intersections of Energy. All of the publications belong to the RT Geology (RT-4). In the QA's the Mapping (OA-1), Assessment and management (OA-5) and Modeling (OA-3) has intersections with Energy.
The number of data was increasing after 2007 (Appendix Figure 8.6). The increase is significant (50 data) and the publications are well distributed compared to the previous period. The Geology research topic and the Assessment and management operational action are dominant, their intersections include 17 publications from the 50 datapoints. The researchers gave more focus to the Water supply (OA-4), Mapping (OA-1) and Modelling (OA-3) operational actions in the Energy plain, but the contribution is still insufficient. In Appendix Figure 8.5 it is demonstrated, that there is no connection between the EIGR publications with Energy issues in the period 1997-2006, it can be identified as a gap in the investigated period. The Appendix Figure 8.6 shows, that the importance of Energy has increasing tendency in the last 10 years, but there is not any connection with Biology.

The Societal Challenge Climate, Environment and Resources (SC-4) shows the largest number of records. The category includes 87 % (1903 datapoints) of the uploaded publications. In the period 1997-2006 (Figure 4.59) a large number of records is attributed to Assessment and Management (OA-5) and Geology (RT-4) intersection, while all other fields are very limited represented. Geology (RT-4) is the sole RT sufficiently represented (about 90% of the records for 1997-2006 period).
The number of data was increasing after 2007 (Figure 4.60). The increase is limited to 20% and the publications are well distributed compared to the previous period. The Geology research topic and the Assessment and management operational action is still leading (248 records), but other categories like Modeling and in a minor extent Modelling and the others OAs, show a significant increase. In general, recent publications are better distributed among OAs, while for RTs Geology dominance is less pronounced that in the period 1997-2006, because the increase of 20% can be attributed exclusively to the other RTs except Geology (which confirms the record amount of the previous period).

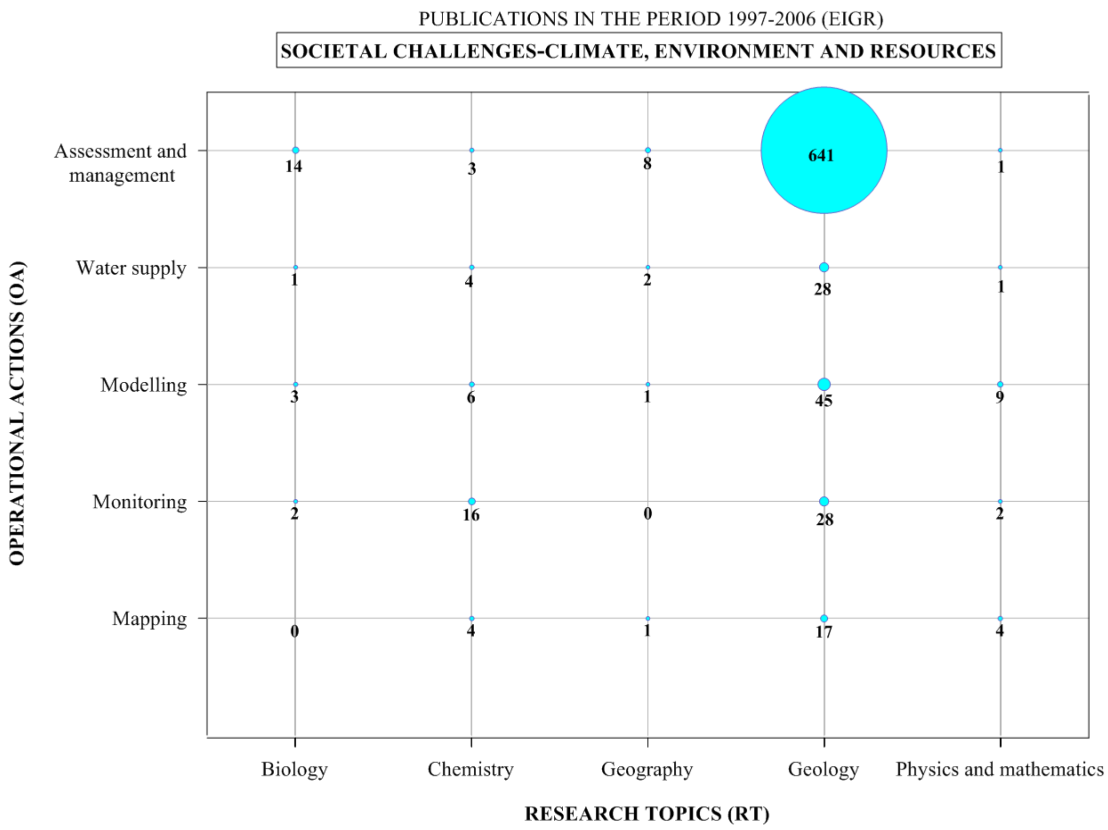


Figure 4.59 SC Climate, Environment and Resources from EIGR: 1997-2006

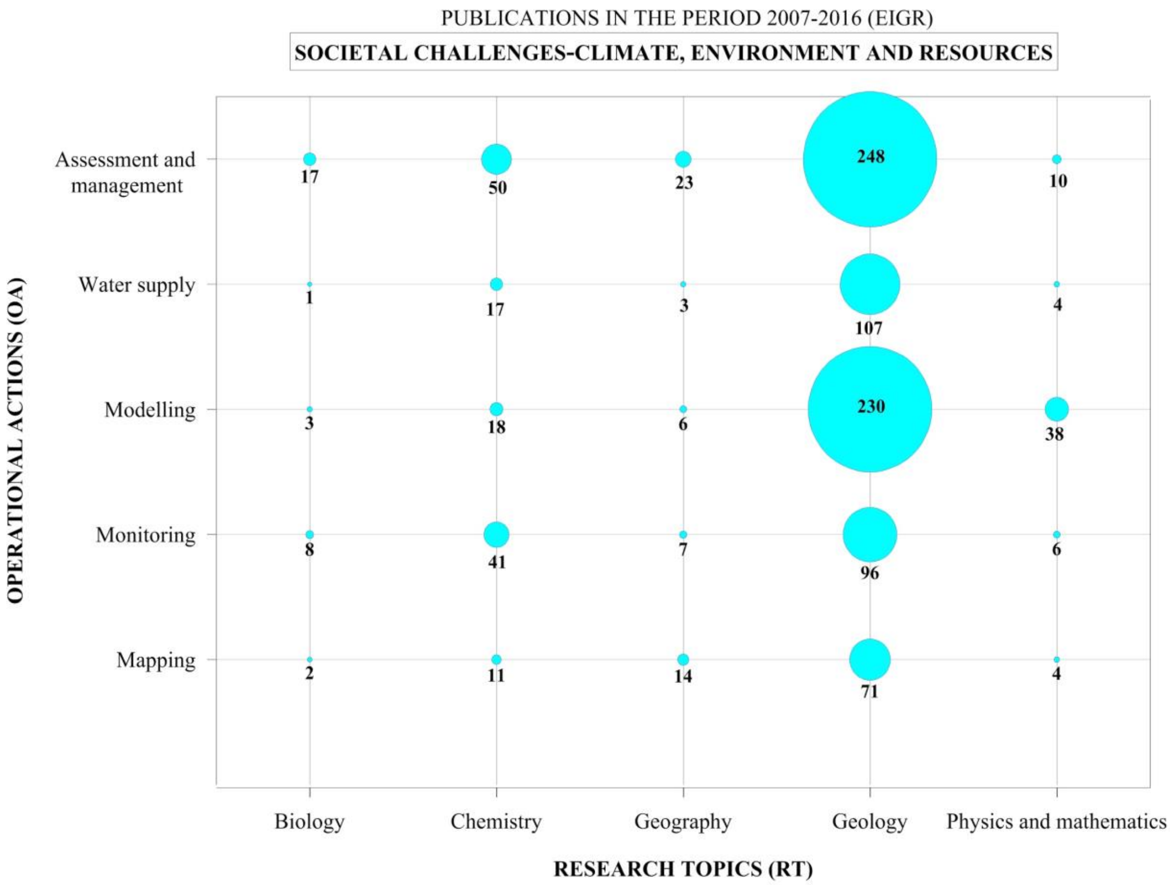


Figure 4.60 SC Climate, Environment and Resources from EIGR: 2007-2016

The Societal Challenge Policy, Innovation and Society (SC-5) includes a limited number of records. The category includes 7% (150 datapoints) of the uploaded publications. In the period 1997-2006 (Appendix Figure 8.9) a very limited number of records are considered (21%), mainly related to Assessment and Management (OA-5), Geology (RT-4) and Chemistry (RT-2), while other intersections are frequently empty (13 intersections and zero contribution for RT Biology).
The number of data was dramatically increasing after 2007 (Appendix Figure 8.10), obviously in relationship with the Groundwater Directive publication. The increase is up to 80% and the publications are concentrated on Geology research topic and the Assessment and management operational action (respectively 57% and 52% of the new records, of which 40 corresponding to the intersection between the two categories). Some empty intersections still remain for RT Biology, RT Mathematics and Physics and several OAs.

The Research Topic Geology (RT-4) includes the largest number of records. The category includes 76% (1655 data) of the uploaded publications. In the period 1997-2006 (Figure 4.61) the 785 records are concentrated in SC4 Climate, Environment and Resources, with very scarce data attributed to the other SCs (only 3% with several empty intersections (9) in SC-2 Food, SC-3 Energy and SC-5 Policy, Innovation and Society. In the following period the records are only moderately increased, reaching 870 metadata. Their distribution is concentrated in SC-4 Climate, Environment and Resources, but it appears more distributed among all OAs and not only on Assessment and Management. Only few empty intersections (3) remain for Food and Health SCs, while records for SC-5 Policy, Innovation and Society increased.

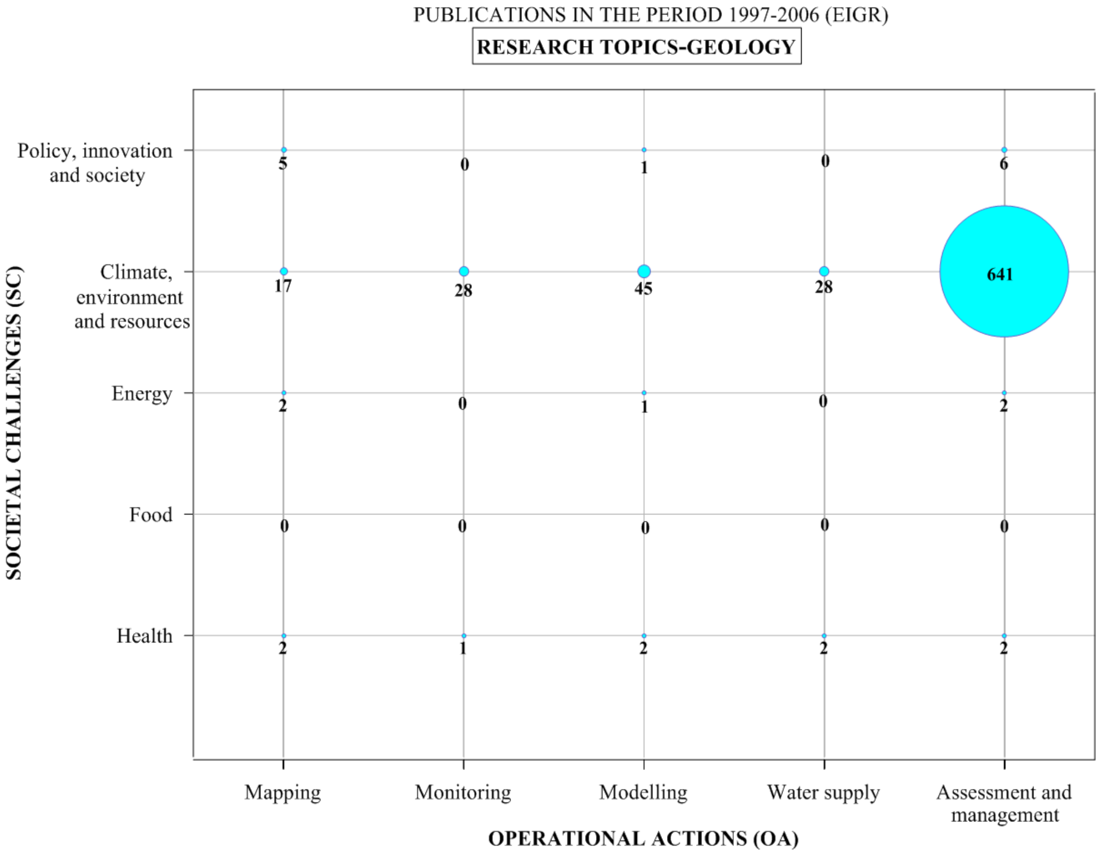


Figure 4.61 RT Geology from EIGR: 1997-2006

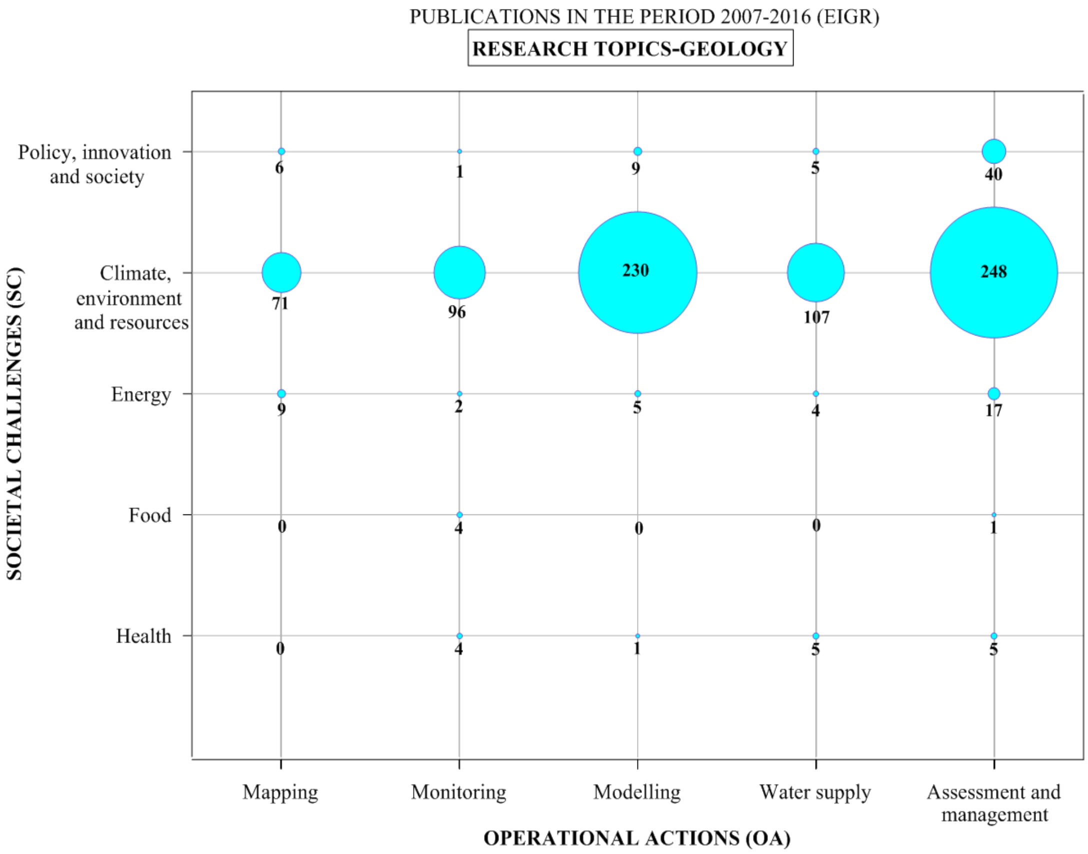


Figure 4.62 RT Geology from EIGR: 2007-2016

4.2.1.2 Co-occurrence analysis

Due to the limited number of records contained in the EIGR, a trend analysis by keywords has been considered only for the entire database (2178 records) and for the Societal Challenge 4, Climate, Environment and Resources (1903 records), which have been splitted in the two selected periods.

Figure 4.63 shows the distribution of keywords of the oldest records, which reveals the prevalence of keywords as “groundwater resources” and the existence of several clusters grouping the keywords in close relationships but with limited co-occurrence.

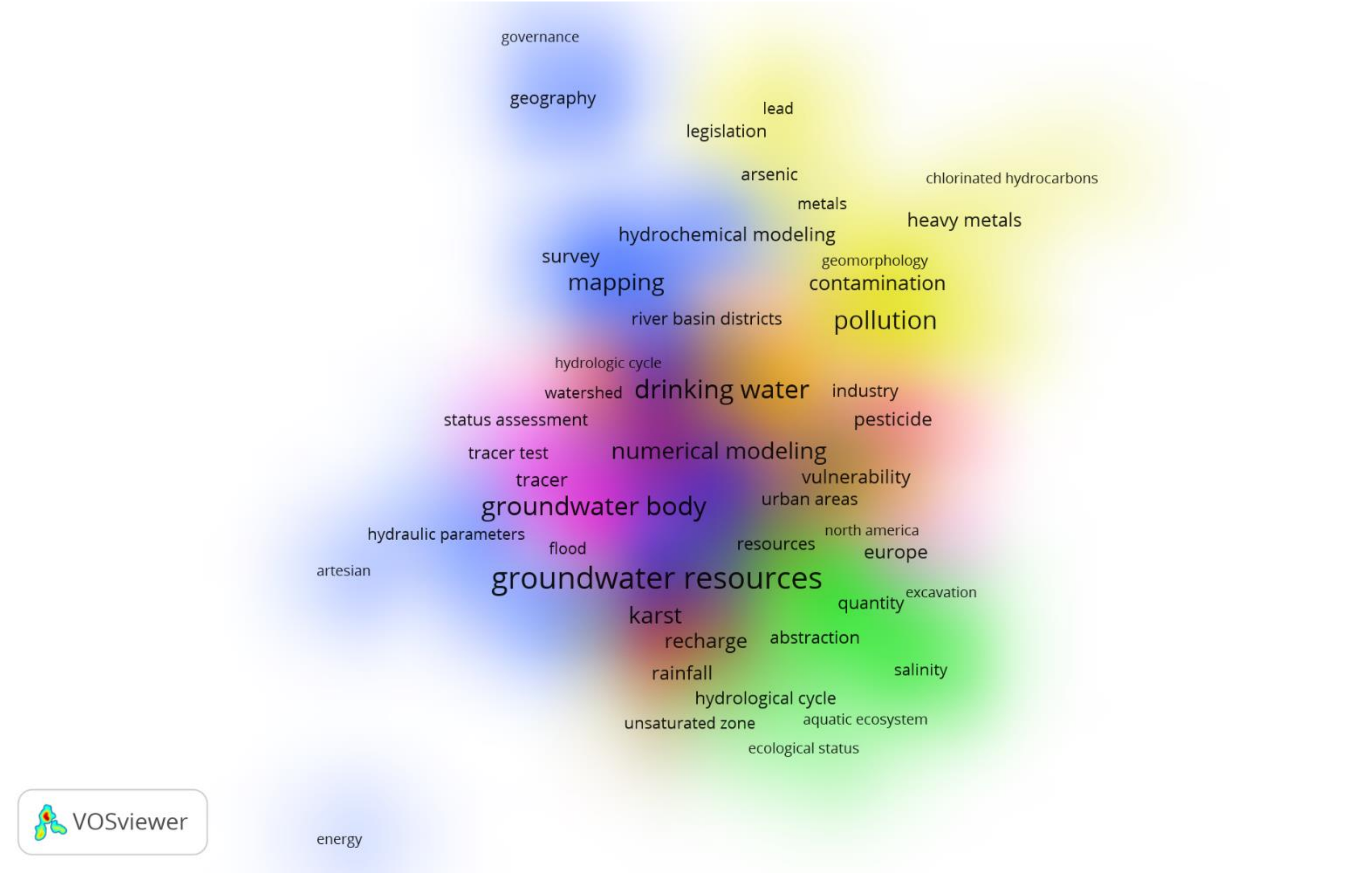


Figure 4.63 Cluster density map of all EIGR records until 2006 (931 records and 194 keywords)

Differently, the cluster density map related to the 2007-2016 period (Figure 4.64), containing more records and more keywords, shows a structure where groundwater resource keyword remains central, but other high-occurrence keywords as groundwater body, aquifer and drinking water are present. Clusters are more pronounced, evidencing a pink cluster related to environment and contamination, a green one based on ecological and river-basin keywords and a blue rather dispersed cluster related to for hydraulic investigation. The higher occurrence of management and environmental issue can be considered as a consequence of the groundwater directive publication, having quick impacts on reports and documents of classes 3 and 4.

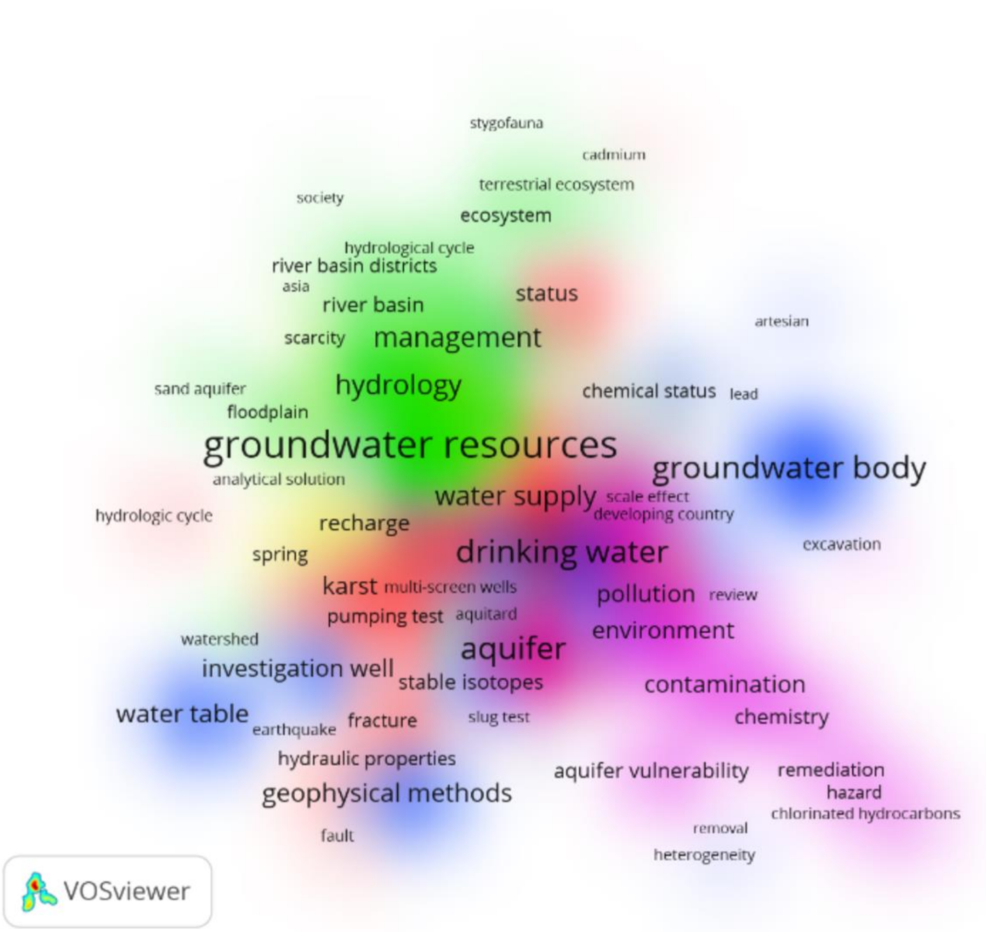


Figure 4.64 Cluster density map of all EIGR records since 2007 (1247 records and 232 keywords)

Similar trends can be inferred analysing the distribution of keywords in the same two periods for the SC4, the sole one having sufficient number of records. The density map related to 1997-2006 (Figure 4.65) period shows the absolute predominance for occurrence and number of links for "groundwater resource" keyword. At the periphery of the map, keywords are grouped for their affinity, not reaching a significant number of links and occurrence.

The density map of the subsequent period 2007-2016 (Figure 4.66) is similarly centered on "groundwater resources", but several keywords have larger occurrence, as drinking water, groundwater body, management, and mapping. This different structure of the map reveals the growing importance of keywords related to the implementation of the WFD and in particular of the GWD.

Pls. refer to 'Supplementary Material E2-E8' for more and additional information pertaining to this section.

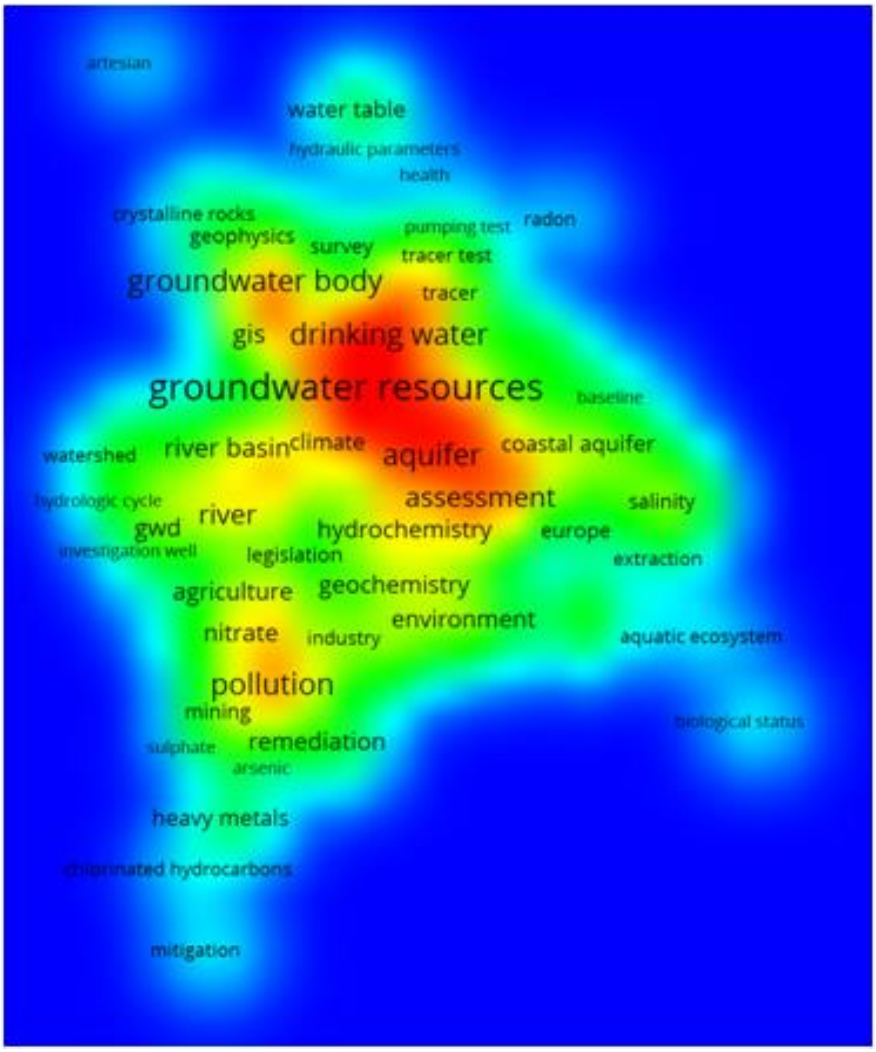


Figure 4.65 Density map of keywords of SC4, 1997-2006 period (279 records, 166 keywords)

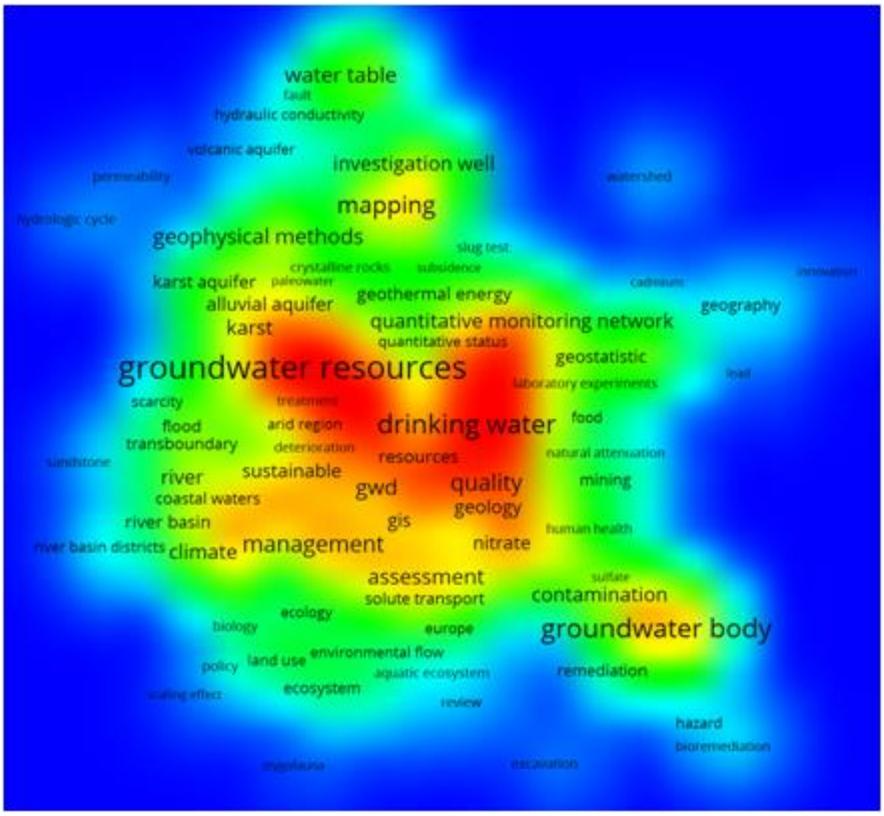


Figure 4.66 Density map of keywords of SC4 for 2007-2016 period (1011 records, 219 keywords)

4.2.2 Scopus and SciVal analyses

Scopus analyses of Figure 4.67 show the trend in the number of groundwater research publications for the period 1997-2017 (both years included) compared to the total number of publications for the Water Science and Technology research area of SciVal (including groundwater) for the three regions producing most water research globally. Europe is leading in scholarly output with a steady increase in the annual number of publications during the whole period and a slightly increasing trend since 2012, while China (incl. Hong Kong) has the largest increase in water research publications especially for the period 2010-2016. The research in North America (USA, Canada and Mexico) seems to have stagnated since 2007. The increase in global groundwater research seems to follow the increase in European research within water science and technology as defined in Scopus / SciVal indicating that the increase in water research in China primarily is driven by research not directly related to groundwater. This is confirmed in Figure 4.68a, which compares the European (EU28) groundwater research performance to the other main contributors of groundwater research, globally.

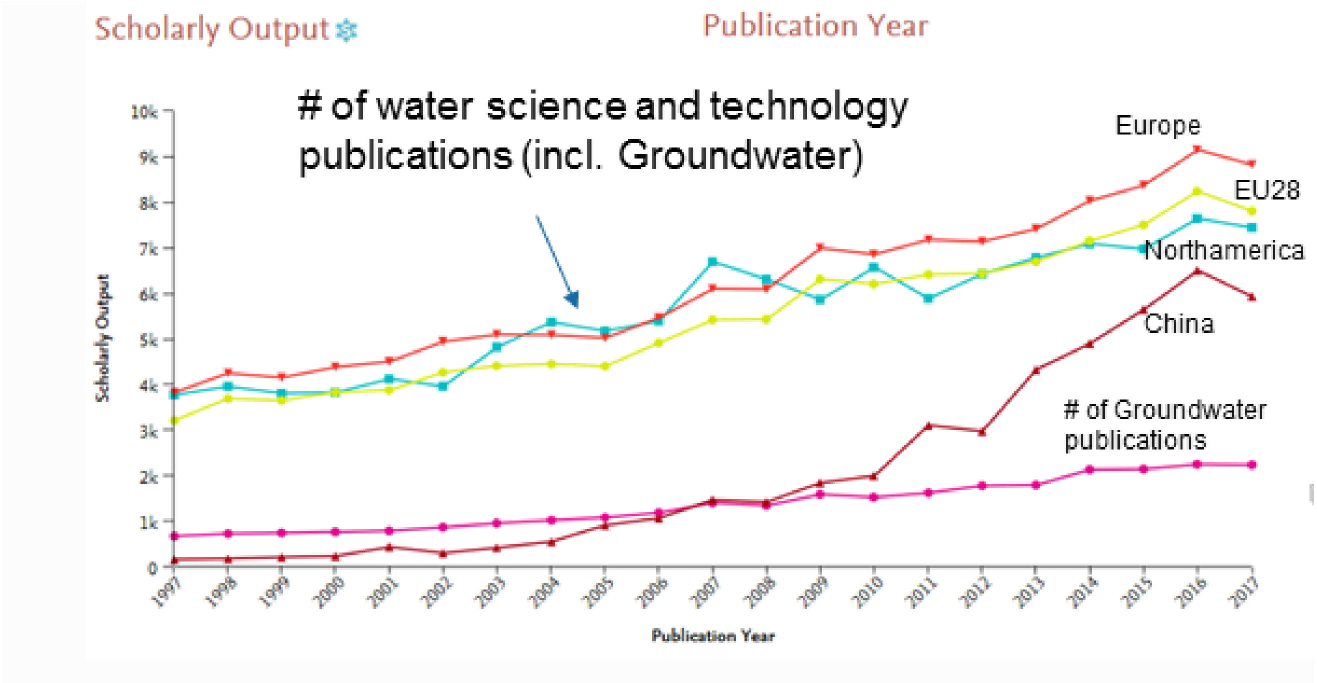


Figure 4.67 Annual scholarly output for the period 1997-2017 for groundwater research compared to scholarly output for the research area water science and technology in the three main water research regions, globally.

Conversely, in Figure 4.68b and Figure 4.69, the trend with time of scientific production of selected countries has been highlighted; in Figure 4.68b the five countries having the highest number of publications are plotted, while Figure 4.69a includes the five EU countries with the more relevant increase of publication; finally, in Figure 4.69b the output for the five KINDRA partner countries is shown.

a)

b)

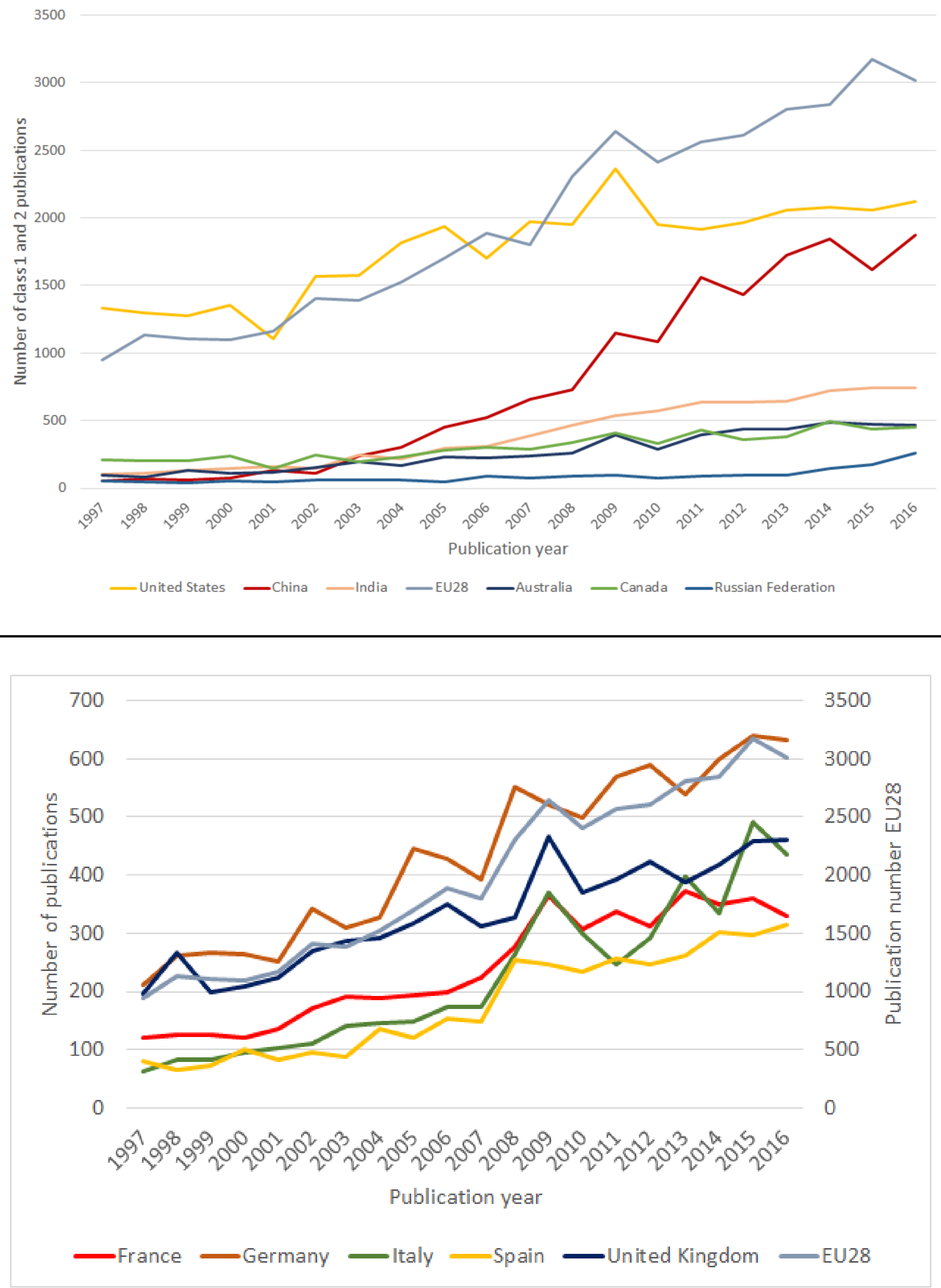


Figure 4.68 Annual scholarly output for EU28 in groundwater research for the period 1997-2016 compared to a) the 6 countries with the highest output in 2016, globally and b) The five EU member states with the highest output in 2016 (Note! EU28 output is on the secondary y-axis).

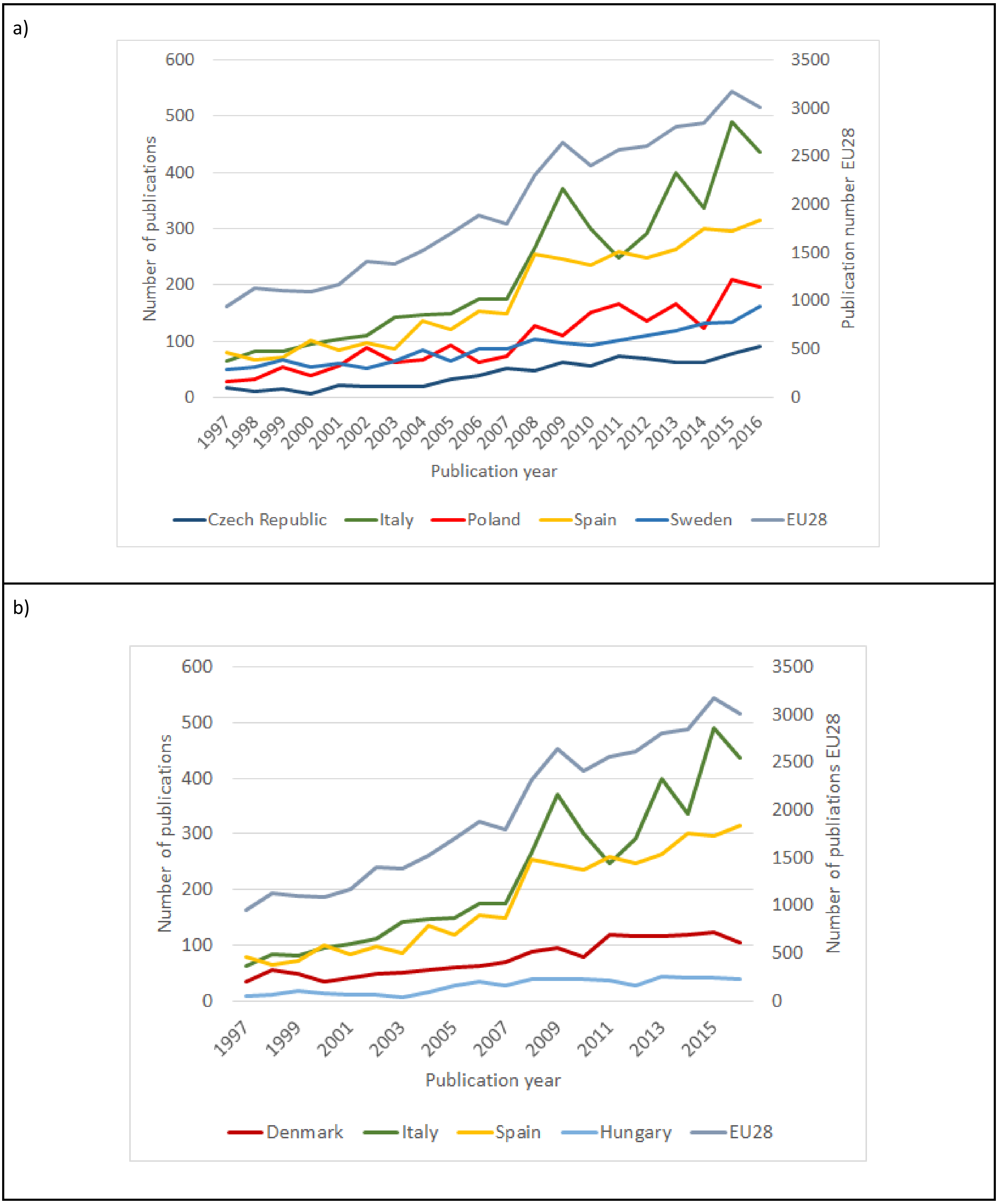
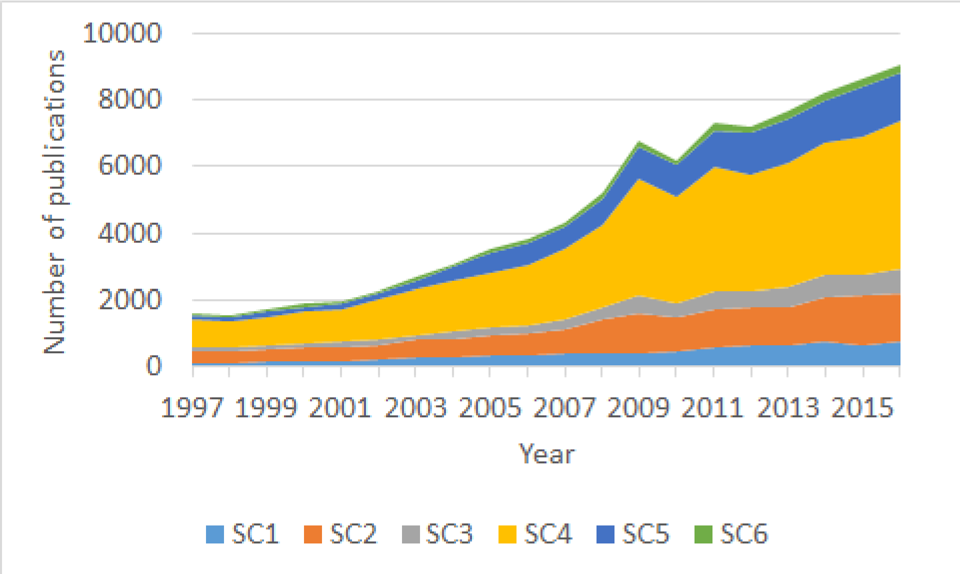


Figure 4.69 Annual scholarly output for EU28 in groundwater research for the period 1997-2016 compared to a) the five EU member states with the highest increase in output from 2006 to 2016 and b) The output from the four KINDRA partners.

Figure 4.70 illustrates that the increase in the number of groundwater research publications primarily occurs within societal challenge 4 “climate, environment and resources” both globally and in Europe (EU28), and that the relative increase in the scholarly output for SC4 is slightly larger in EU28 than for the global output for SC4.

a)



b)

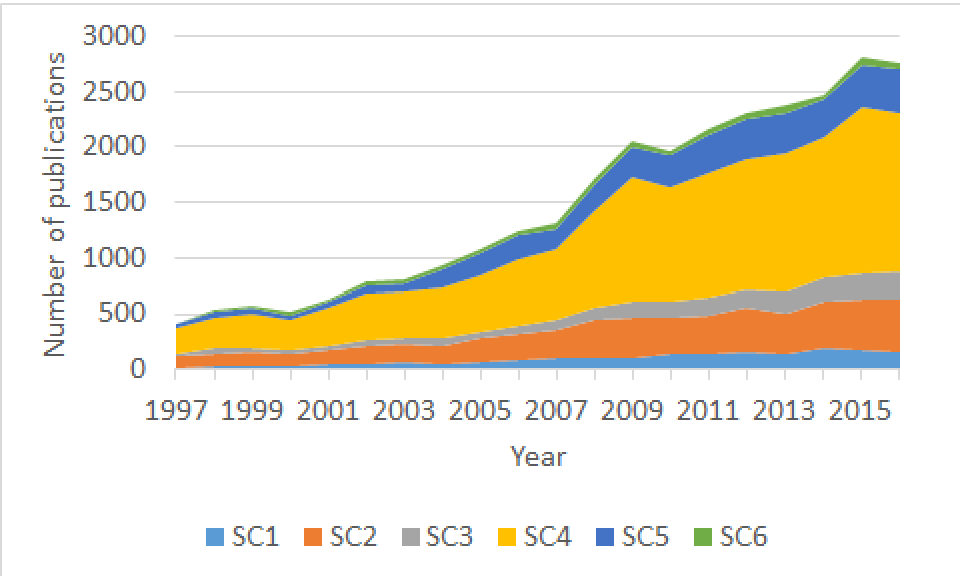


Figure 4.70 Annual scholarly output for groundwater research within the six societal challenges (SC1-6) for the period 1997-2016 for a) Globally b) EU28.

As described above, Figure 4.67 illustrated the general annual increase in groundwater research compared to the overall output for the SciVal research area “Water science and technology”, globally. Conversely, Figure 4.70 shows the increasing trend in groundwater research related to SC4 “climate, environment and resources”, the societal challenge with the highest scholarly output on groundwater research.

However, the scholarly output for all of the societal challenges groundwater research areas seems to increase faster globally than for EU28 (Figure 4.71) since about 2001. This global increase is driven by a very significant increase in groundwater research and scholarly output primarily for China, but also for India (Figure 4.68).

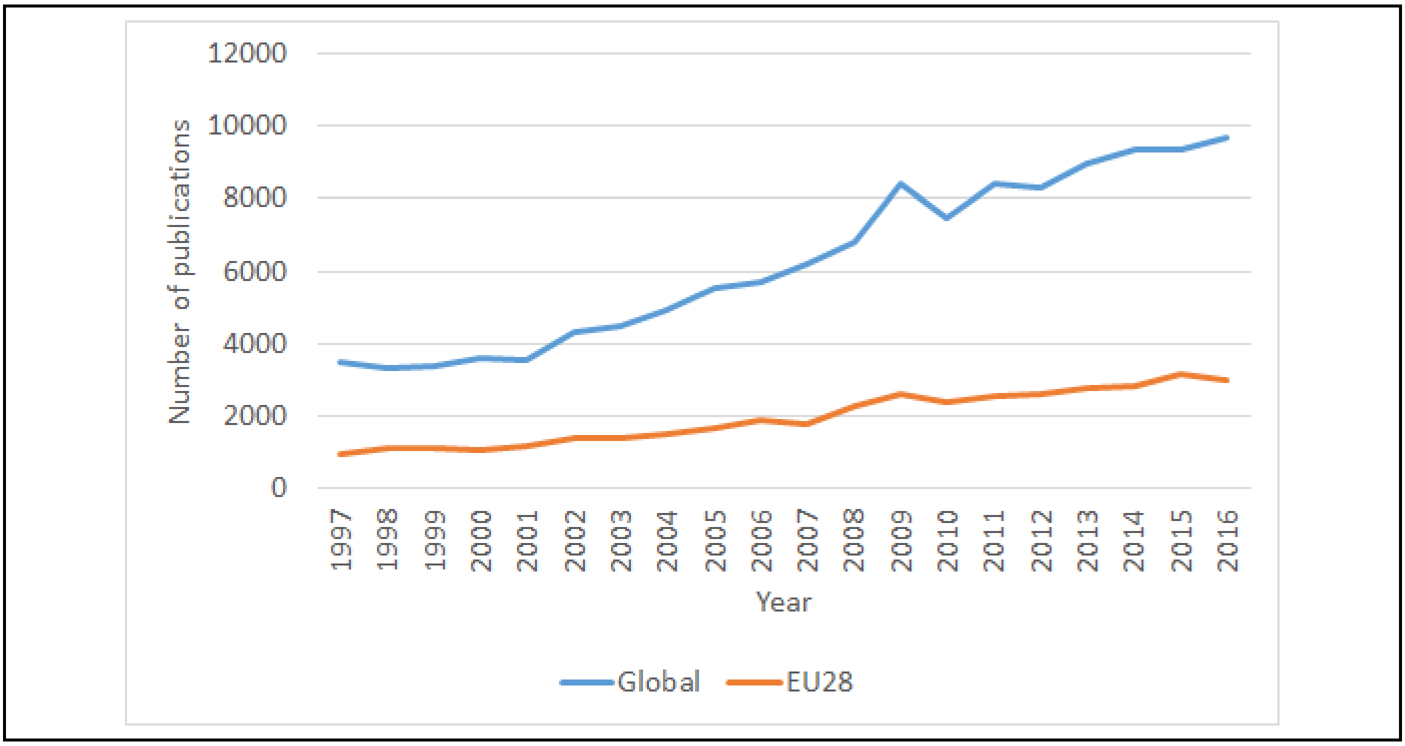


Figure 4.71 Annual scholarly output for all of the six societal challenges (SC1-6) for the period 1997-2016 for a) Globally b) EU28

In the following figures we show the trends in groundwater research illustrated by the most important keywords for each of the five societal challenges.

The most cited papers published after 2014 both globally and in EU28 for SC1 is related to groundwater quality issues: arsenic (Singh et al., 2015), emerging contaminants and pharmaceuticals (Javrilescu et al., 2015, Siu et al., 2015) and the global distribution of modern potentially contaminated groundwater (Gleeson et al., 2015). These publications appear among the five most cited publications in all SCs except for SC3 and SC6 where e.g. publications on solar photocatalysis (Spasiano et al., 2015) and geothermal energy (Horvath et al. 2015) are among the most cited publications for SC3; studies on PFAS e.g. from airports are among the most cited for SC6 (Filipovic et al, 2015). For SC4 a publication on a pan European hydrological model relevant for implementation of the Water Framework Directive and e.g. assessment of nitrate leaching to groundwater (Abbaspour et al., 2015) is also among the five most cited publications after the publications on Solar photocatalysis (Spasiano et al., 2015) and emerging contaminants (Javrilescu et al., 2015).

Arsenic and pharmaceuticals ("emerging contaminants") are not only the most cited research topics during the most recent years for SC1, but they are also the most cited groundwater research topics globally after 1996 in general (Figure 4.72) with >> 1000 citations and field-weighted citation impacts of often more than 10.

The same top five publications as listed above (Figure 4.72) appears for SC4 using the search string "TITLE-ABS-KEY((groundwater or "ground water" or hydrogeolog* and (climate or environment or resources) and 1996<pubyear>2016) indicating that groundwater quality issues of relevance to human health attract the most research attention and funding also within SC4 (Figure 4.73). A search specifically for groundwater and climate change using the search string "TITLE-ABS-KEY((groundwater or "ground water" or hydrogeolog*) and ("climate change")) and pubyear>2012) returns the following top five papers with respect to received citations.

	Document title	Authors	Year	Source	Cited by
1	A review of the source, behaviour and distribution of arsenic in natural waters View abstract KB links Related documents	Smedley, P.L., Kinniburgh, D.G.	2002	Applied Geochemistry 17(5), pp. 517-568	3839
2	Occurrence, fate and effects of pharmaceutical substances in the environment- A review View abstract KB links Related documents	Halling-Sørensen, B., Nors Nielsen, S., Lanzky, P.F., (...), Holten Lützhøft, H.C., Jørgensen, S.E.	1998	Chemosphere 36(2), pp. 357-393	2185
3	Occurrence, fate, and removal of pharmaceutical residues in the aquatic environment: A review of recent research data View abstract KB links Related documents	Heberer, T.	2002	Toxicology Letters 131(1-2), pp. 5-17	1757
4	Arsenic removal from water/wastewater using adsorbents-A critical review View abstract KB links Related documents	Mohan, D., Pittman Jr., C.U.	2007	Journal of Hazardous Materials 142(1-2), pp. 1-53	1725
5	Arsenic round the world: A review	Mandal, B.K., Suzuki, K.T.	2002	Talanta 58(1), pp. 201-235	1719

Figure 4.72 Screen-capture from Scopus showing the 5 most cited groundwater publications published after 1996, search string: TITLE-ABS-KEY(groundwater or "ground water" or hydrogeolog) and pubyear>1996 and pubyear <2016*

	Document title	Authors	Year	Source	Cited by
1	Karst Hydrogeology and Geomorphology (Book) View abstract KB links Related documents	Ford, D., Williams, P.	2013	*Karst Hydrogeology and Geomorphology* pp. 1-562	1034
2	An overview of current status of carbon dioxide capture and storage technologies Open Access View abstract KB links Related documents	Leung, D.Y.C., Caramanna, G., Maroto-Valer, M.M.	2014	Renewable and Sustainable Energy Reviews 39, pp. 426-443	355
3	Ground water and climate change View abstract KB links Related documents	Taylor, R.G., Scanlon, B., Döll, P., (...), Holman, I., Treidel, H.	2013	Nature Climate Change 3(4), pp. 322-329	312
4	The Millennium Drought in southeast Australia (2001-2009): Natural and human causes and implications for water resources, ecosystems, economy, and society View abstract KB links Related documents	Van Dijk, A.I.J.M., Beck, H.E., Crosbie, R.S., (...), Timbal, B., Viney, N.R.	2013	Water Resources Research 49(2), pp. 1040-1057	279
5	Seawater intrusion processes, investigation and management: Recent advances and future challenges View abstract KB links Related documents	Werner, A.D., Bakker, M., Post, V.E.A., (...), Simmons, C.T., Barry, D.A.	2013	Advances in Water Resources 51, pp. 3-26	269

Figure 4.73 Screen-dump from Scopus showing the 5 most cited groundwater publications published after 2012, search string: TITLE-ABS-KEY(groundwater or "ground water" or hydrogeolog and "climate change") and pubyear>2012*

Figure 4.74 illustrates the scholarly output within the 5 year period 2012-2016 as a percentage of the total scholarly out for the period 1997-2016. Between 41 and 47 % or nearly half of the scholarly output for the whole 20 year period has been published within the last five years of the period indicating a general increasing trend and a significant recent increase in groundwater research within SC4 "climate, environment and resources", globally, for all OAs and RTs. Hence, there does not seem to be a significant gap for any of these research areas.

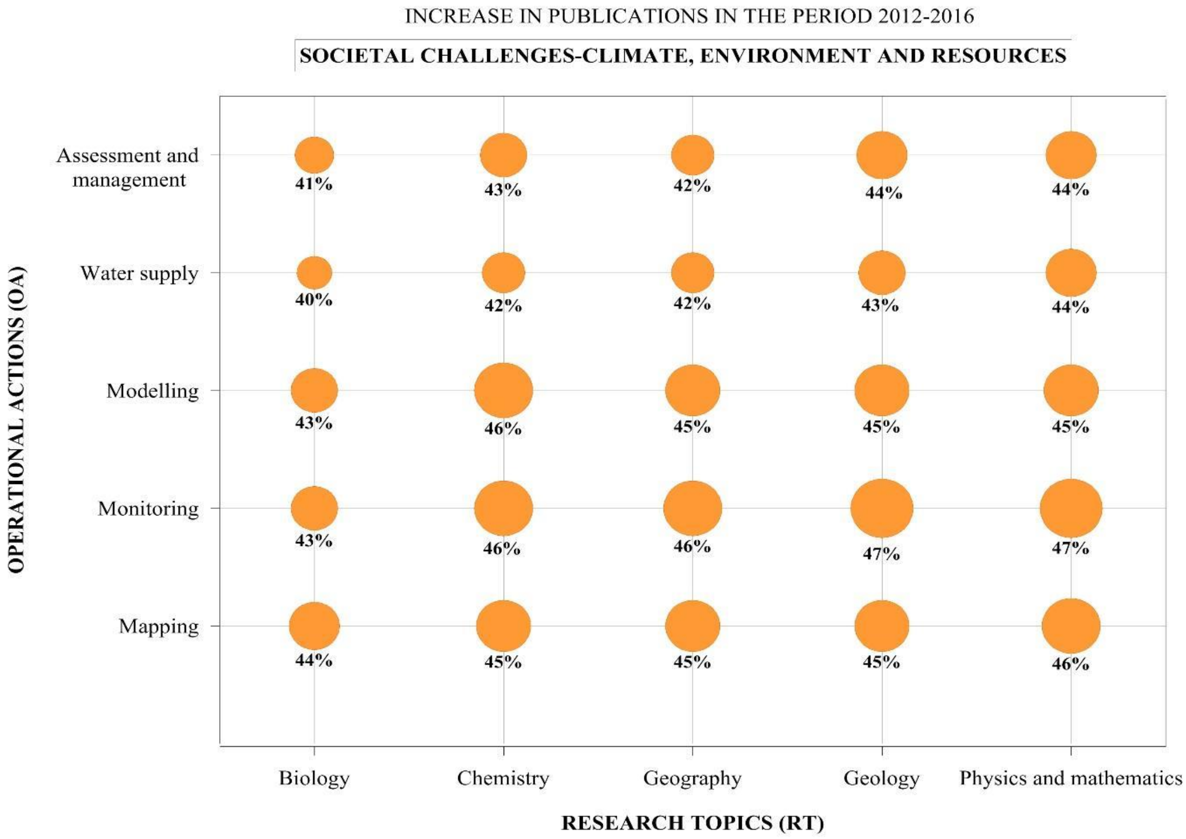


Figure 4.74 Scholarly output within the 5 year period 2012-2016 as a percentage of the total scholarly out for the period 1997-2016 for co-occurrence of keywords within SC4 and all related RTs and OAs

Societal challenge 1 – Health, demographic change and wellbeing

Figure 4.75 shows the increase in the annual number of publications (documents) for groundwater research within SC1 as found in a global search in the Scopus database using the search string: Groundwater OR "Ground Water" OR hydrogeolog*) AND ("human health" OR wellbeing), and the 10 countries with highest scholarly output.

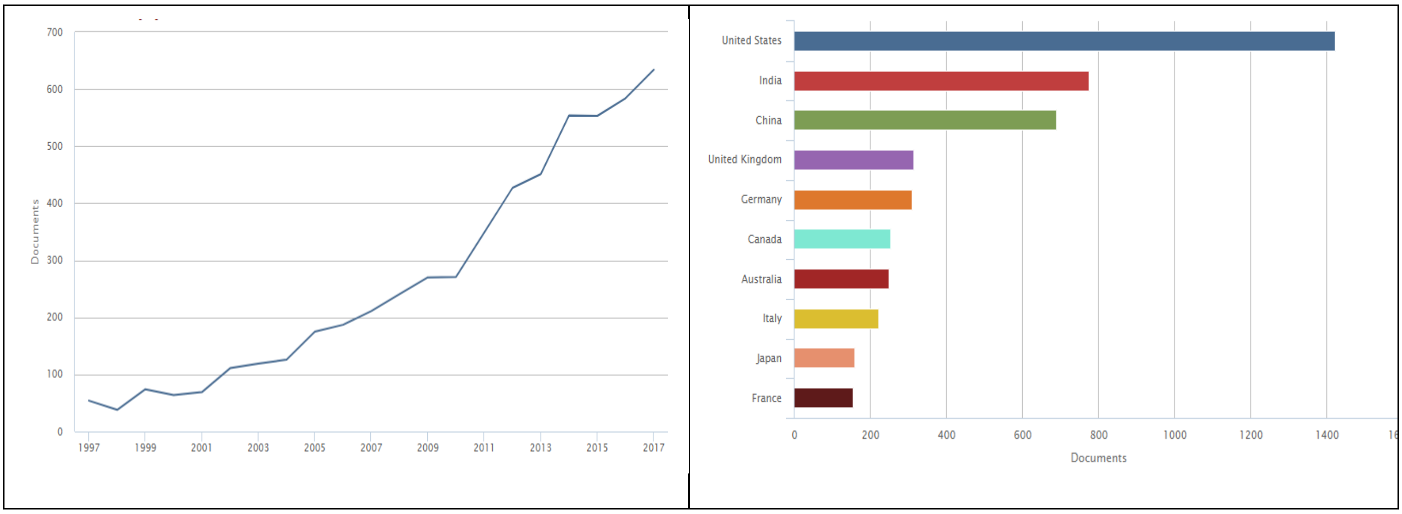


Figure 4.75 Annual increase in the total number of research publications on groundwater and "human health" (left) and the number of publications from the 10 most active countries in this research field (right)

Figure 4.76 shows the trends in groundwater research for the most important keywords within SC1 for the period 2012-2016 as identified by Scopus/SciVal. The figure identifies arsenic, fluoride, nitrate, heavy metals and radon as the elements and substances affecting human health, which has the highest research interest. For the period 2012-2016 the research related to nitrate, heavy metals and fluoride is increasing, while it has been declining for arsenic and radon.

Figure 4.76 SciVal "word cloud" illustrating the most important keywords related to SC1 "Health" and the trend in the scholarly output for each keyword for period 2012-2016. Note red and blue colours show increasing and decreasing trend, respectively

Another way to visualize and analyse trends is by overlay maps in the VosViewer program. Figure 4.77 shows an example for SC1 zoomed in at part of the plot for better readability. The colours indicate the average publication year of documents with that particular keyword. Hence, the documents which include the keywords arsenic, concentration, China, World Health Organisation around 2012, while the keywords Asia, Eurasia, South Asia and e.g. health hazards occur primarily in publications from around 2007. The overlay confirms the rapidly increasing trend for water research in China since 2010 as shown in Figure 4.67.

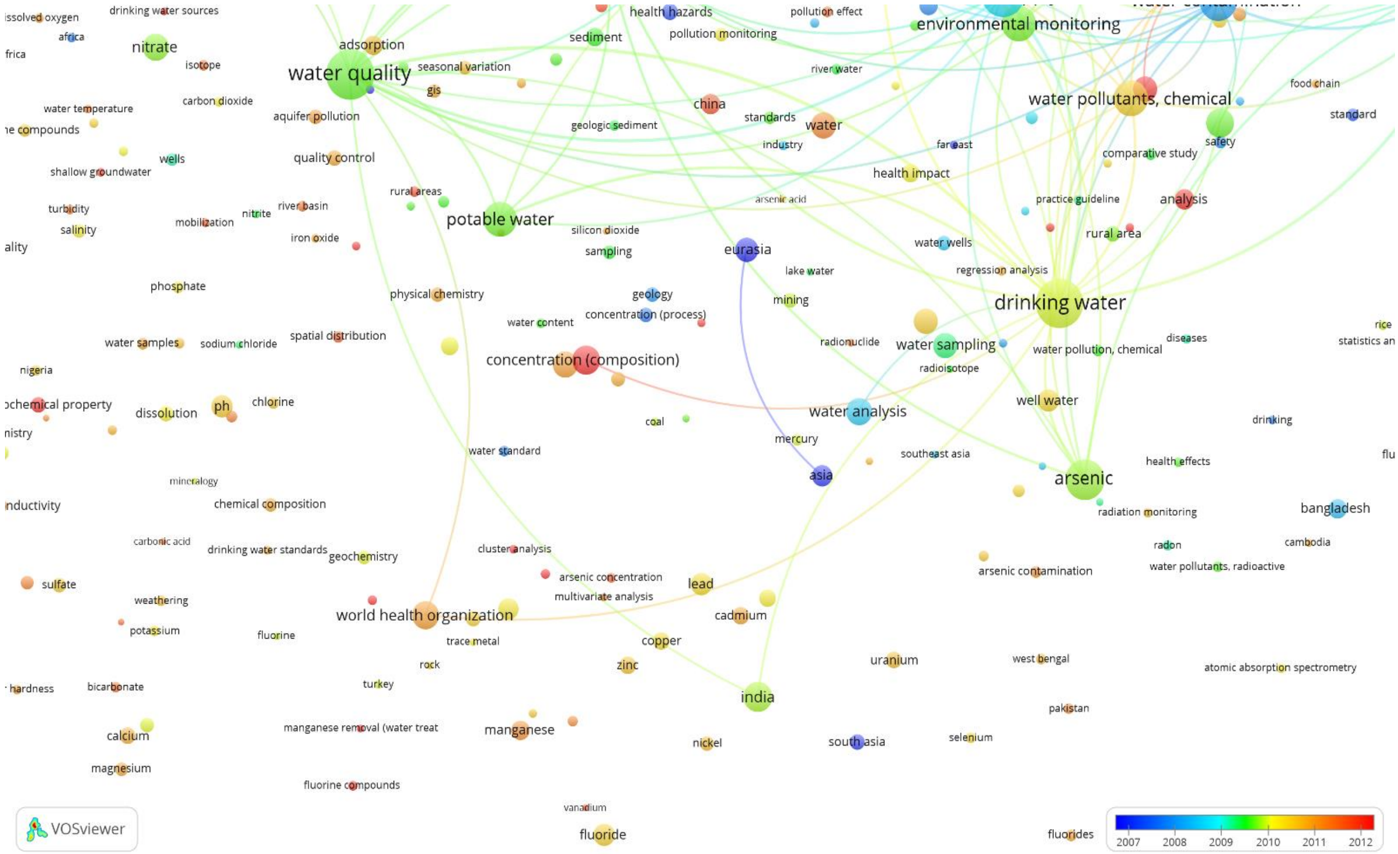


Figure 4.77 VOSviewer overlay map of SC1-Health indicating the average publication year for a specific keyword. Blue colours indicate average publication year around 2007-2009, green/yellow around 2010 and red around 2011-2012.

It seems that the groundwater research in relation to arsenic and human health is stagnating or even declining, however, this conclusion is somewhat premature as shown in Figure 4.78.

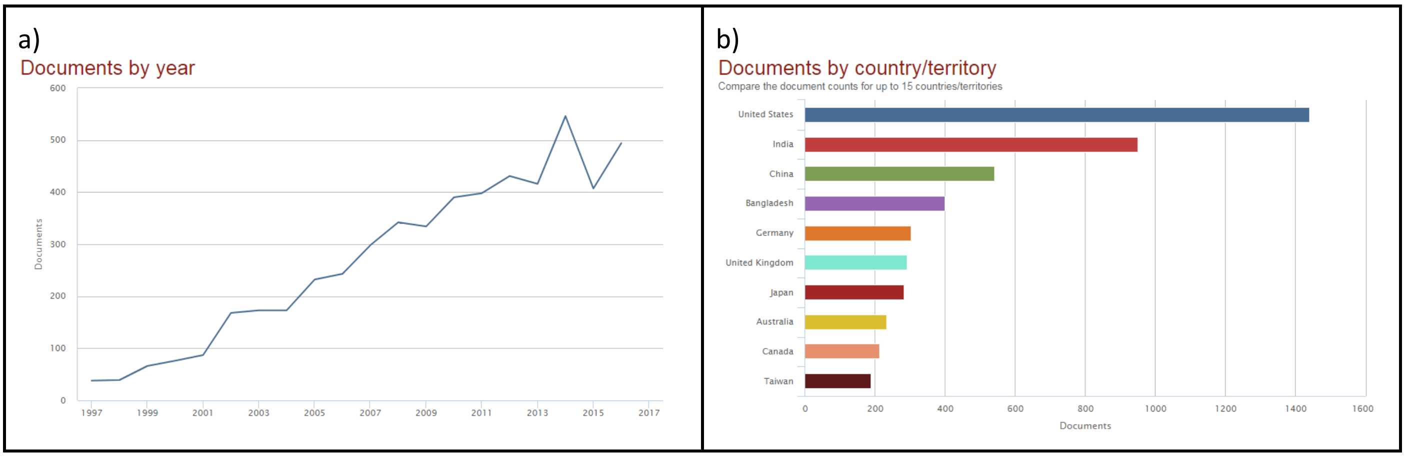


Figure 4.78 a) Number of class 1 and 2 publications for the period 1997-2016 and b) Number of publications from the 10 most active countries within research on "groundwater and arsenic" show that most research is conducted in the USA and in Asia (India, China, Bangladesh), but significant amount of research publications on groundwater and arsenic has also been produced in several EU countries especially Germany and the United Kingdom.

Recent studies in the Netherlands on the toxicity and carcinogenic effects of arsenic clearly demonstrate that further research is required as As concentrations at even very low concentrations have negative health effects and there may not even be a lower limit for these (Wens et al., 2016. 2017). This has recently caused the Dutch water works association to treat groundwater and river water used for drinking water to a content of maximum 1 µg/l of arsenic by own initiative (pers. Comm. Patrick van der Wens, 2018).

Another way of analysing groundwater research trends for Scopus data is to compare keyword co-occurrence for different publication periods e.g. before and after adoption of the Groundwater Directive, i.e. 1997-2006 and 2007-2016 in Figure 4.79 & Figure 4.81 and Figure 4.80 & Figure 4.82 respectively by the use of VOSviewer co-occurrence network and density maps.

Pls. refer to 'Supplementary Material S1-S3' for more and additional information pertaining to this section.

4.2.2.1 Co-occurrence analysis

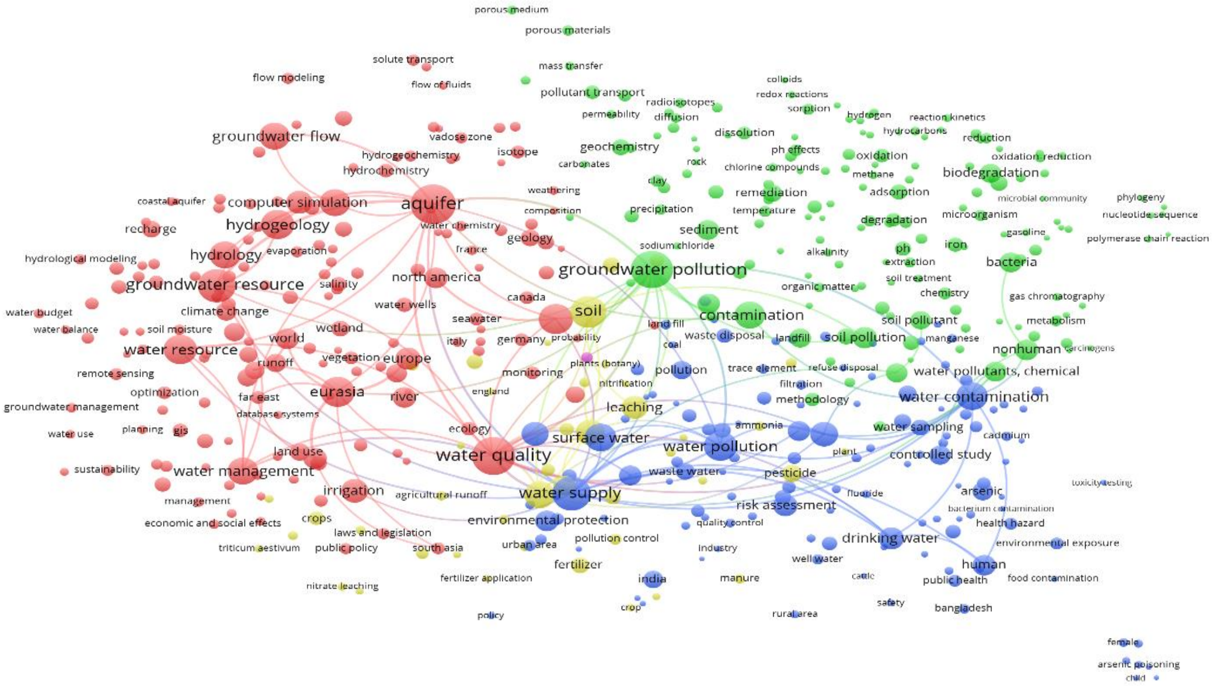


Figure 4.79 VOSviewer network and cluster map of keyword co-occurrence in Scopus for the period 1997-2006

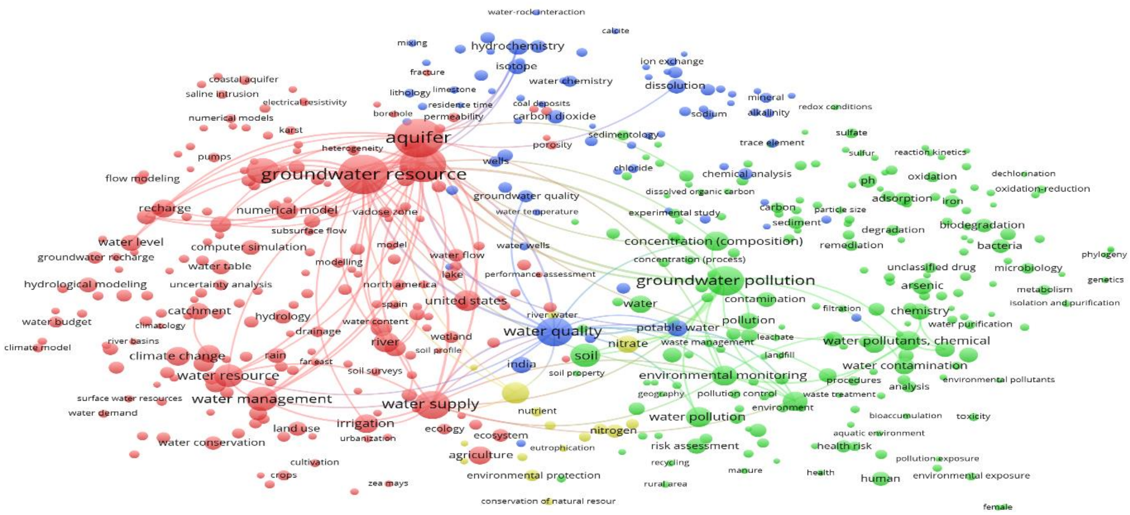


Figure 4.80 VOSviewer network and cluster map of keyword co-occurrence in Scopus for the period 2007-2016

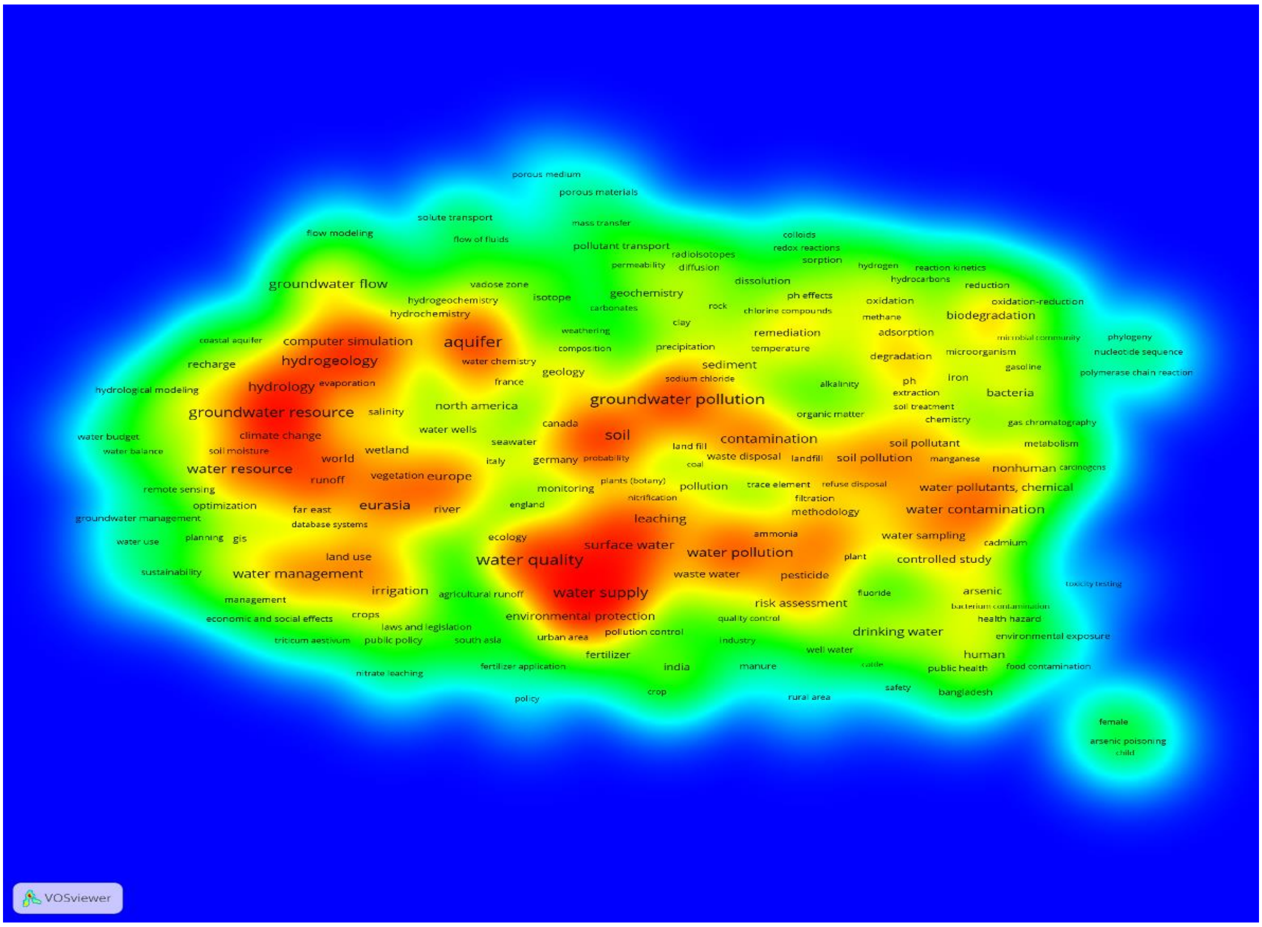


Figure 4.81. VOSviewer density map of keyword co-occurrence for the period 1997-2006

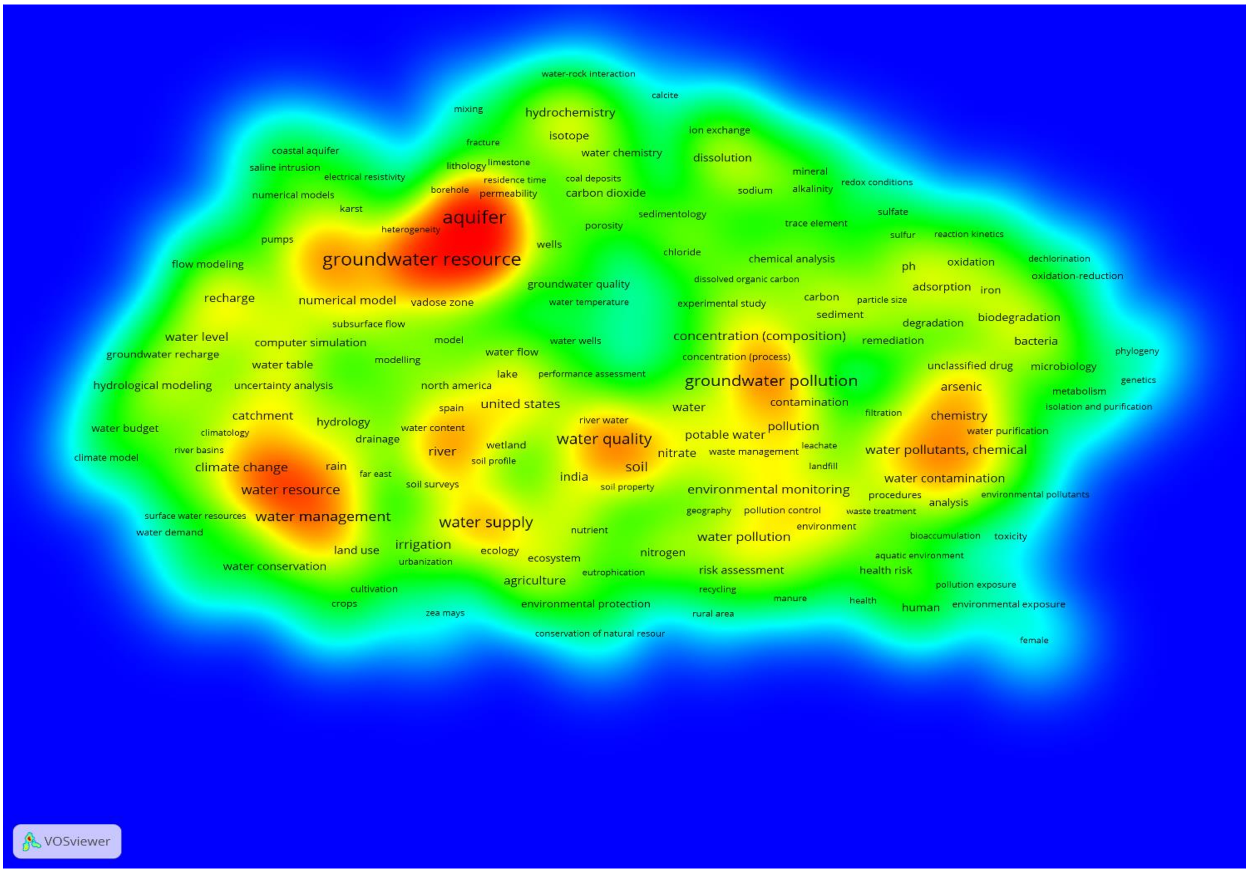


Figure 4.82 VOSviewer density map of keyword co-occurrence for the period 2007-2016

The trends of keywords in the last decade for SC4 and SC5 are represented in Figures 4.83 and 4.84, where the average year of publication is shown for each keyword. Consequently, keywords having blue colour reflect topic which are not so much developed in last years, while keywords with red dots are highlighting very recent development on this topic.

Pls. refer to ‘Supplementary Material S1-S4’ for more and additional information pertaining to this section.

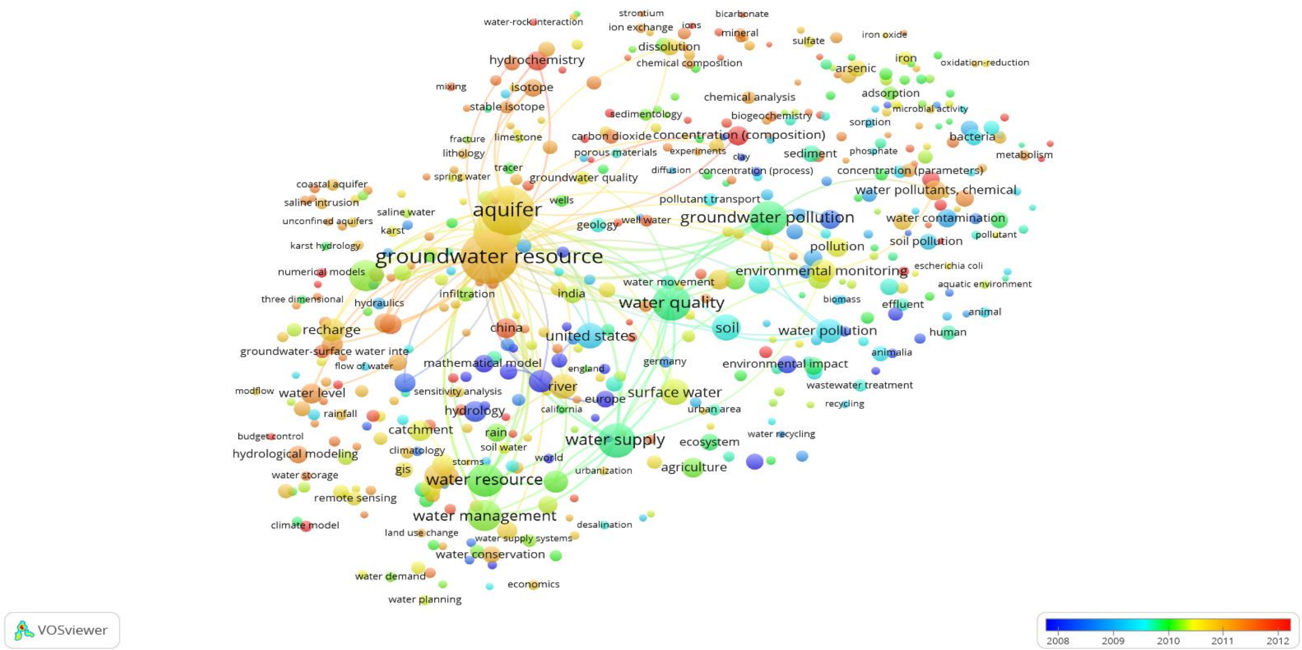


Figure 4.83 Trends for Societal Challenge 4 (Climate, Environment and Resources) in VOSviewer overlay plots in the range from resources published in 2008 until 2012

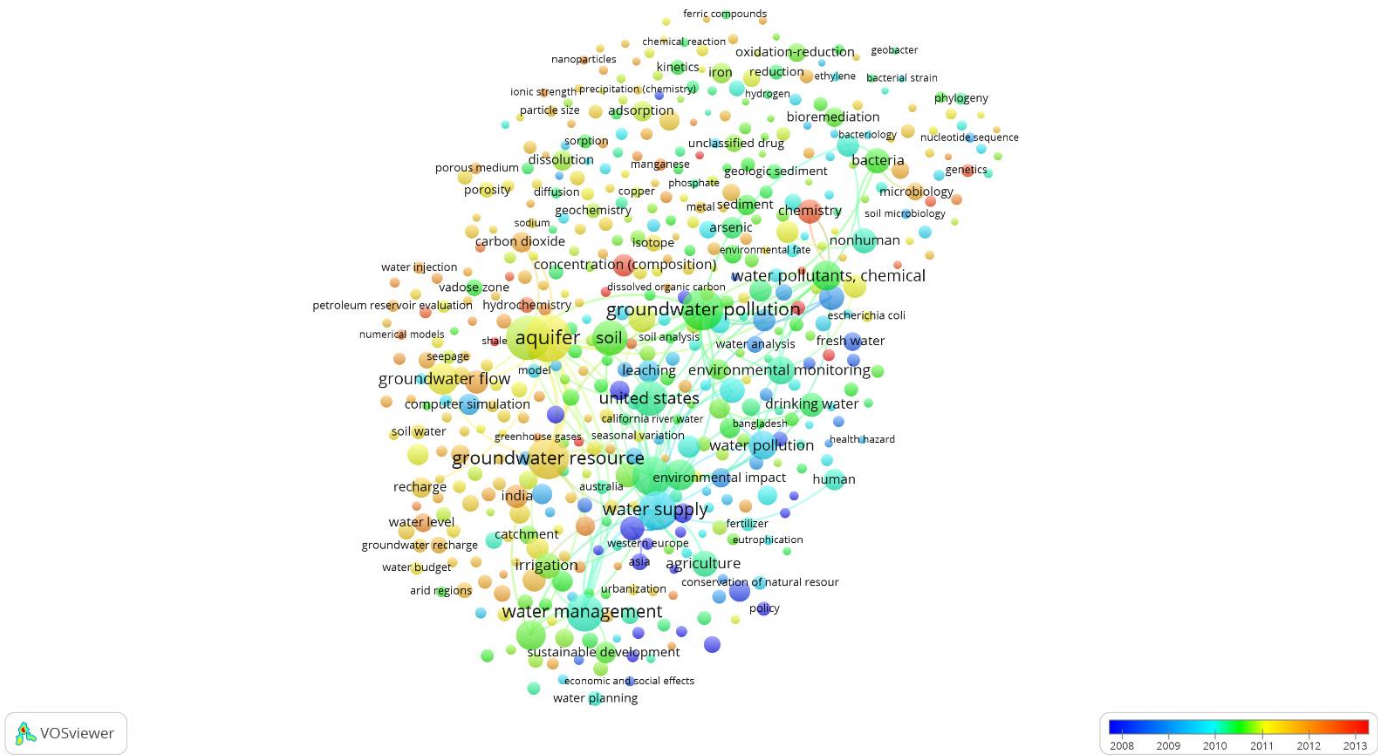


Figure 4.84 Trends for Societal Challenge 5 (Policy, Innovation and Society) in VOSviewer overlay plots in the range from resources published in 2008 until 2012

5 Discussion

Previous sections have focused on groundwater research by visualizing and analyzing data from the European Inventory of Groundwater Research (EIGR) structured according to the HRC-SYS and the largest and most widely used database of peer-reviewed literature, Scopus. The results demonstrate the importance of groundwater research and scholarly output for all societal challenges, research topics and operational actions (the HRC-SYS). This is obtained mainly through the developed diagrams based on the Scopus database as these constitute abundant data with a scholarly output of more than 60.000 publications after 1996 that allows population of all intersections in the intersection plot. The EIGR database has been developed and populated by hydrogeologists as part of the KINDRA project and is yet only partly populated. However, diagrams (i.e. intersection plots) based on both EIGR and Scopus data show that SC4 "climate, environment and resources" currently contains the largest number of publications and hence attracts the largest amount of research interest primarily within the operational action "assessment and management". Data, also show though that many overlaps occur between the SCs and that some publications show up in several or nearly all societal challenges.

In contrast to the diagrams based on EIGR data that show "geology" as the main research topic (discipline), as a result of the biased input by hydrogeologists of the European Federation of Geologists (EFG), the diagrams based on Scopus data show that except for a few cases all the other main research topics (biology, chemistry, geography, mathematics and physics) have a larger scholarly output than geology . This is not surprising as 1) EIGR was populated by hydrogeologists introducing a bias towards geology as mentioned above and 2) the other research topics have much larger research communities than geology/hydrogeology. It is therefore important to have scientists, consultants and practitioners of the other main research disciplines to help populate EIGR with metadata on research and knowledge related to the chemical and quantitative status of the groundwater resources. Nevertheless, this limitation of the KINDRA inventory is highlighting at the same time the central role of geologists in the groundwater topic: undoubtedly, they constitute the primary practitioner group dealing with groundwater evaluation, management and protection. Consequently, results obtained by EIGR analyses are equally significant, also because the inventory contains grey and national literature that is not accounted for in scientific databases as Scopus. The main semantic difference between the two adopted databases can be resumed by the statement that EIGR is primarily dealing with "hydrogeology" and hydrogeological research and knowledge, while Scopus deals with the much larger field of "groundwater" research in general. Scopus contains more than 128.000 peer-reviewed publications with the keyword "groundwater", but just 28.000 peer-reviewed publications with the keyword "hydrogeolog*". In terms of the introduced research and knowledge categories in HRC-SYS, the majority of the documents and resources in the EIGR database is classified as not peer-reviewed publications representing the knowledge classes (3 and 4 of EIGR).

The analyses performed, the keywords included and the results and diagrams presented in this report are by no means exhaustive, and we recommend that an in-depth bibliometric analysis of the groundwater and hydrogeology research topics be conducted to obtain a more complete picture. Generally, comparable studies require analyses applying all of the available research databases (e.g. Scopus, Web of Science, Google Scholar) and additional quantifications using tools, such as altmetrics citation analysis etc. (Cahlik, 2000), which is out of scope of the KINDRA project. However, our analyses show that the selected keywords and performed searches cover more than 99 % of the scholarly output for "groundwater and hydrogeology" available in Scopus. Based on main results of comparative studies including our own comparison between Scopus and Web of Science, we conclude that by selecting Scopus as our most important bibliometrical tool and data source, we cover by far the major part of the class 1 and 2 groundwater research publications produced during the past 20 years in Europe as well as globally. This conclusion is corroborated by other comparative studies, which conclude that Scopus is the most comprehensive scientific database for natural sciences (Harzing & Alakangas, 2016; Mongeon & Paul-Hus, 2016, National Science Board, 2016).

We also find that Scopus and the add-on tool SciVal in combination with other visualization tools such as VOSviewer are able to identify main research trends and gaps within groundwater research and knowledge, although such analyses also require a fair amount of expert judgement. The developed European Inventory of Groundwater Research (EIGR) shows a strong bias towards geological and hydrogeological studies as previously mentioned and the size of the database is much smaller, as EIGR contains about 2100 publications/classified resources while Scopus contains about 63.000. Scopus currently includes more than 124.000 class 1 and 2 research papers published 1997 - 2016. However, only about half of these have co-occurrence of keywords enabling population of the intersection plots in the HRC-SYS classification system. This is though still about 30 times more than the EIGR database, hence the data analyses performed on the Scopus data is generally much more reliable than the analyses performed on the EIGR database for establishing a complete picture of groundwater research.

On the other hand, it has to be considered that attribution of HRC-SYS classification to Scopus content is not unambiguous, and each record may occur within more than one combination of keywords of the overarching categories as many combinations and co-occurrences of keywords searched within the paper title, abstract and keywords exist. In other words, each record in Scopus can be placed simultaneously in more than one position in the KINDRA HRC-SYS classification (e.g. the same arsenic paper occurs within SC1, SC2, SC4 and SC5). This situation cannot occur for EIGR data, as they have been inserted manually, restricting their attribution to only one position i.e. only one SC, one OA and one RT can be defined for each record inserted in the EIGR. This introduces other potential errors as the identification of the proper SCs in EIGR is subjective although based on expert judgements. In any case, the information derived from the EIGR database is certainly relevant within the scope of KINDRA, but it has to be considered from the hydrogeological point of view with respect to the wider topic of groundwater science.

The first result derived from EIGR analysis is that, despite its limited size at the moment, inserted metadata are comparable in distribution among categories with the larger Scopus database. Consequently, the EIGR content, although limited, can be considered representative for the aims of the project and at the same time also significant for correctly describing the state-of-the-art of knowledge in groundwater knowledge and including class 3 and 4 publications in the context of EU policies.

In fact, similar distributions have been observed among the five overarching groups for each main category in both databases. For Societal Challenges, in both databases the majority of records is dealing with SC4, followed by SC5. The remaining SC1-SC2-SC3 represent only 6% of records in EIGR, while they account for 34% of Scopus database. This can be considered the main difference between the databases for the considered Societal Challenges.

Looking at the Operational Action distribution, EIGR evidenced a majority of OA5 Assessment and Management (53%), followed by Modeling (18%) and by the other OAs summing to about 30%. In Scopus, OA5 similarly is the most represented, with about 40% of records, and OA Monitoring, Modeling and Mapping have very similar percentages compared to the EIGR, with difference of less than 1%. The main discrepancy has been observed for OA4 Water Supply, having only 10% of records in the EIGR and reaching the 25% in Scopus. With respect to Research Topics, as mentioned before, the EIGR is clearly unbalanced toward RT Geology (76% of records), while in Scopus all five RTs are equally distributed around 20% each. In general, the distribution of records in both databases shows many similarities.

The main results inferred by the EIGR records, taking into account its limitations (absolute prevalence of RT Geology and limited number of records) but also its strengths (inclusion of non-scientific literature and unambiguous identification of the record by the classification system), can be resumed as follow:

- Societal Challenges 1, 2 and 3 show a very limited number of records and no significant conclusions can be considered at the moment; only several gaps (positions with 0 records) are evidenced, demonstrating the need to enlarge the information base for those SCs;

- For Societal Challenges 4 5, the number of records are considered sufficient for an in-depth evaluation, performed by co-occurrence analysis of keywords; indeed, the unbalance towards RT Geology recommends to consider these results valid mainly for “hydrogeological” issues, more than for “groundwater” in general;
- The density and network maps built with the entire EIGR database show a clear structured relationship among keywords, and different clusters dealing with different hydrogeological topics can be recognized (see Fig. 3.14 and 3.15); so, the record base, also if limited, is significant;
- From comparison of the sub-sections of the EIGR related to classes 1&2 and 3&4 (see Figure 4.18 and Figure 4.19 respectively), many similarities have been inferred; the interpretation is that the two literature groups are representing two faces of the same knowledge system and that consequently the content of the grey literature (class 3 & 4) is dealing with the similar problems of groundwater science;
- Co-occurrence maps related to each OA highlight relationships with keywords, showing similarities but also logical differences among them (see maps from Figure 4.20 to Figure 4.24);
- The absolute majority of records for RT Geology corresponds to a co-occurrence map (Figure 3.25) centered on groundwater resources, with several links to other keywords; this fact testifies the main role of the evaluation, protection and assessment of groundwater resources for the hydrogeologists;
- For Societal Challenge 4, the cluster map (Figure 4.26) highlights different clusters which are balancing the prevalence of the “groundwater resources” keyword, showing how “groundwater body”, “management”, “monitoring”, “pollution” and also “GWD” are relevant for this Societal Challenge;
- In the map of Societal Challenge 5 (Figure 4.27), the keywords are more scattered and less linked than in the previous SC4, revealing that policy actions have now interested many fields of groundwater science, but is seems that a coordination among them has not yet been achieved until now.

The analyses conducted on Scopus data show that Europe (EU28) performs very well in most groundwater related research topics and is currently publishing the largest amount of groundwater research papers annually, globally. While the scholarly output (number of groundwater research documents) in the US has increased only very little since 2007, the scholarly output from EU28 grew significantly from about the same time (at the time of the adoption of the groundwater directive), but even more dramatically in Asia (China and India in combination). If the current trends continue, the scholarly output on groundwater from China will exceed the output from the US before 2020, while it will not exceed the European output as the increase in scholarly output within groundwater research itself is more or less parallel for EU28 and China. China and India combined already surpassed the US in this respect and will surpass Europe within the next few years. .

An assessment of research performed within all 25 combinations of related research topics and operational actions for the societal challenge with the highest scholarly output SC4 “Climate, environment and resources shows that between 41 and 47 % of the total scholarly output of the past 20 years (1997-2016) occured during the last five years of the period (2012-2016) indicating a general significant increase within all combinations of research topics, operational actions and societal challenges related to groundwater quantity and quality aspects during the past decade. Similar trends can be observed for the other societal challenges. In the following we describe and discuss some main issues in relation to the presented data and observations made for each of the investigated societal challenges.

Societal challenge 1 – health, demographic change and wellbeing:

There is growing concern in Europe about the increasing amount of new emerging contaminants (pharmaceuticals, PFOS etc.) in groundwater and the rest of the hydrological cycle and a rapid increase in papers and citations for papers studying these. Recent papers on emerging contaminants are among the most cited papers on groundwater research, globally (e.g. Lapworth et al., 2012; Gavrilescu et al., 2015).

Data and knowledge on the contents in groundwater is, however, very scarce and sporadic and most of the European countries have very limited if any data at all for groundwater. Concentrations are generally rather low, but many different contaminants can be found in both groundwater and surface water and concerns exist for the effect of a cocktail of such contaminants as many of them are difficult to remove by water treatment (Kasprzyk et al., 2009).

The fertility of western men has decreased significantly during the past 40 years (Levine et al., 2017). The relation between environmental pollution (e.g. hormones and other indocrine disruptors), the infertility of both men and women and many other physical and mental health issues are basically unknown, but some relation may exist (Gore et al., 2015). Hence, the relation between the occurrence and concentration levels of indocrine disruptors and other emerging contaminants in groundwater and drinking water seem to be warranted.

The conducted analyses underpin that serious health concerns related to arsenic in groundwater exist mainly in Asian countries, but so far only few studies have been conducted in Europe as As concentrations in Europe is generally much lower than in Asia. Recent studies conducted in the Netherlands, however, show that As is carcinogenic at very low concentrations (Wens et al., 2016). Hence, the Dutch water works have decided to treat groundwater and lower As concentrations to 1 µg/l, as this will save a significant number of human lives annually. It therefore seems that a pan-European study on this topic is highly warranted.

Like for arsenic recent studies on carcinogenic effects of nitrate in groundwater and drinking water show that nitrate is toxic and carcinogenic at much lower concentrations than previously thought (Schullehner et al., 2018). Although nitrate is an important research area, human health concerns are not reflected in the analyses indicating that this is a topic that requires much more attention on a European and global scale.

The above mentioned issues are concerned about the relation between drinking water ("groundwater") and physical health, but groundwater quality has also been linked to mental health issues in several studies in recent years indicating that mental health issues need to be investigated further (Ohgami et al. 2009, Voutchkova et al., 2015, Kessing et al., 2017).

Societal challenge 2 – food security, sustainable agriculture and forestry, marine and inland water etc.

Nitrate is the pollutant most frequently causing poor groundwater chemical status in Europe, and besides probably being a more serious health issue than currently expected (Schullehner et al., 2018), nitrate causes poor ecological status for surface waters all over Europe. As the sources of nitrate are often dominated by pollution from agriculture there is a strong need for finding efficient tools for reducing nitrate (nitrogen) loadings to both marine and inland waters. A relatively low number of publications on biology, geology and mapping may indicate a research gap on this topic.

A large number of European coastal waters and ecosystems have poor ecological status (EEA, 2015), but little knowledge exist about where these ecosystems are linked to poor groundwater chemical status etc. This is supported by assessments of recent technical reports from Working Group Groundwater within the Common Implementation Strategy for the Water Framework Directive (European Commission, 2015a,b). The reports state that EU member states often argue that they do not have the necessary data and understanding of aquatic ecosystems to be able to derive groundwater threshold values based on good status objectives of the Water Framework and Groundwater directives. Hence, they are not able to assess groundwater chemical status for nitrate for the protection of ecosystems due to a lack of the understanding of ecosystem needs and the link between groundwater chemical status and the ecological status of groundwater associated aquatic ecosystems.

The same is the case for many groundwater dependent terrestrial ecosystems where both poor quantitative and chemical status of groundwater may cause failure to meet the environmental objectives and ensure good ecological status for these ecosystems. This supports the call for more transdisciplinary research between hydrogeologists and ecologists as e.g. concluded in technical reports of Working Group Groundwater within the Common Implementation Strategy for the Water Framework Directive (European Commission, 2015). As for SC1 very little research exist on the effect of emerging contaminants on groundwater dependent and associated aquatic ecosystems.

Societal Challenge 3 – Energy:

The most frequently occurring keywords of SC3 are hydrogeology, geothermal energy, geothermal flow, geothermal fields, groundwater pollution, groundwater resource, energy resource, water supply, soil, environmental monitoring and carbon dioxide. These keywords can clearly reflect the international tendencies how energy related issues and challenges are connected to groundwater resources. Geothermal energy prospecting and utilization are in close relationship with groundwater resources if the renewable energy is cited. There are many regions all over the world where the natural conditions are favorable to produce geothermal energy. Hydrothermal systems cannot be operated in a sustainable manner without the proper knowledge of hydrogeology and reliable monitoring.

It is also a well-known fact that energy production can cause environmental pollution in many cases reaching even the subsurface media and groundwater resources. This is the reason why strong connections were revealed among energy and groundwater and soil pollution. There are innovative solutions as to how groundwater treatment and soil remediation can be effective and reliable. The utilization of thermal water resources, geothermal energy and the increasing number of heat pumps can support to reduce the carbon dioxide output and the carbon footprint of the mankind. Although traditional carbon-based energy supply is still very important, that dominance of the research activity has been shifted to the direction of renewable energy resources all over the world. This tendency can also be recognized in the co-occurrence analysis of the keywords connected to the energy.

Societal Challenge 4 – Climate, Environment and Resources

SC4 has the highest scholarly output, which appears from the intersection diagram for this societal challenge where the operational actions 'Assessment and management' and to a lesser degree 'Water supply' are dominating (Figure 3.43). Modelling, monitoring and mapping follow, but are anticipated to be captured by especially 'Assessment and management' as this category is broad and often involves these three disciplines.

Inspection of VOSviewer generated co-occurrence plots based on Scopus data reveals that the prominent research areas (clusters) are 'groundwater resource' and 'Aquifer' and somewhat less prominent 'water resource' and 'water management' (Figure 3.51 and Figure 3.52). Groundwater pollution and water quality are closely linked to the 'groundwater resource' and 'aquifer' clusters which is expected. Pollution of groundwater resources can be linked to specific contaminants, environment and biochemistry.

Groundwater research shows clearly delineated areas on (bio)chemistry, and related specific keywords include (ad)sorption, organic compounds, bacteria, microbial activity and various chemical compounds. Importantly, highly specialized topics characterised by geochemical keywords are clustered, indicating dedicated groundwater research and gradually linked to the more groundwater management related clusters (disciplines) like 'water quality' and 'water supply'.

Modelling of groundwater and pollutants (transport) are distinct research areas linked to the broader 'water resource', 'water management' and 'groundwater resource' topics. Thus dedicated research on (mathematical) modelling and hydraulics include topics on infiltration, tracer, 'groundwater-surface water interaction' and 'computer simulation'.

Remarkable for this representation of SC4 'Climate, Environment and Resources' seems that the climate component is largely absent, which seems to indicate a clear gap in the field of climate related research and groundwater, including topics on climate change. Another strongly emerging area in SC4, urban hydrology and the significance of shallow groundwater, e.g. in connection to nature based solutions and green infrastructure (Denjean et al., 2018) is also clearly underrepresented and constitute a gap in research. This has recently been addressed by several Horizon2020 calls on the topic of nature based solutions (e.g. Denjean et al., 2018).

Societal Challenge 5 – Policy, Innovation and Society

The Societal Challenge 5 'Policy, Innovation and Society' keyword structure (Figure 3.53 and Figure 3.54) demonstrates in the co-occurrence analysis that research areas cluster around topics (keywords) aquifer, groundwater pollution, water supply, 'groundwater resource' and 'water pollutants'. As we would expect from a Societal Challenge that embraces a large variety of environmental, policy and societal issues, the clusters while clearly recognizable are entrenched in each other, signifying the multifaceted topics and research areas.

Multi and trans-disciplinarity are clearly visible as compared to the SC4 'Climate, Environment and Resources' in which topics and research areas are less dispersed. The societal aspects are more pronounced with more emphasis on environmental impact and monitoring and the presence of keywords like 'sustainable development' and 'environmental protection'. The data resource for SC4 is about three times larger than for SC5 which needs to be taken into account when interpreting the keyword structure, and also the zooming capabilities of the VOSviewer which enables a more detailed inspection when zooming in where more less pronounced keywords may appear.

Nevertheless, SC5 'policy, innovation and society' relevant keywords are clearly mostly related to Operational Action 'Assessment and management' and to a lesser degree 'Water supply' as also is the case for SC4. Adding subcategory keywords to SC5 most probably would have provided more insight to how groundwater research is interwoven with policy, innovation and society, more than associated keywords to SC1-4 would have done due to the more multidisciplinary character of SC5 as compared to SC1-4.

Societal challenge 6 – Transportation and infrastructure

SC6 has the lowest scholarly output of the societal challenges nearly 20 times lower than for SC4 with the highest output. An assessment furthermore showed that about half of the publications returned in a Scopus search are already covered by the publications returned in searches on the other SCs. Important research on both groundwater quality and quantity issues related to transportation including roads, railways, airports and fuel storage is conducted, globally. The density and network maps for SC6 - Transportation (figure 3.55 and 3.56 respectively) indicates clearly demarcated clusters around 'roads and streets', hydrogeology, 'groundwater pollution' and a cluster containing several keywords related to infrastructure construction and construction techniques.

Groundwater related research on transport and infrastructure is obviously connected to literature on geotechnical topics, like 'slope stability', landslides, and tunnels. Likewise and interestingly, transport and infrastructure alter the soil surface and result in less infiltration (recharge) which again can cause flooding, and this array of topics seems to be well captured in the area close to the 'road and streets' and 'aquifer' clusters including keywords like runoff, 'storm water' and sewers. Also, infrastructure construction and thereby attracting transport may increase groundwater and soil pollution, like landfills, introducing e.g. heavy metals.

6 Conclusions

Analyses of the content of the EIGR inventory, provide additional and relevant information both about the reliability of the adopted groundwater research classification system HRC-SYS and the focus research areas of the EIGR database compared to the largest natural science research database, Scopus. The added value of EIGR is primarily the provision of metadata on reports and research projects and data, which are not available elsewhere, and the intention of improving and promoting the "FAIR" data principles of Findable, Accessible, Interoperable and Reusable research data of Horizon 2020.

Applicability of the adopted HRC-SYS classification to the groundwater research and knowledge is demonstrated by the content of the metadata uploaded by national experts into the EIGR. Although the insertion of the metadata is time-consuming, the request to clearly individuate for each record the three main categories and at least one of the five overarching groups, has been successful completed by the editors. Considering suggestions received during the project, the keyword list has been implemented and extended, reaching now 284 groundwater related keywords. Consequently, application of the classification can be considered successful and sufficiently tested during the EIGR population. At the same time, distinction between classes 1 & 2 ("research") and 3 & 4 ("knowledge") highlighted the relevance of not-peer reviewed documents for the hydrogeological knowledge at primarily regional and national but also international levels.

The representativeness of the EIGR content is biased by the enhanced contribution on the research topic "geology" due to data upload and database population by hydrogeologists. However, this bias can be tackled in the future by having scientists and consultants from other natural science disciplines populating EIGR with relevant groundwater research information from their disciplines (biology, chemistry etc.). Currently, the inventory primarily represents the "hydrogeological" component of the groundwater knowledge, which historically has been predominant in activities related to water supply and groundwater protection and availability. Consequently, the EIGR content can be considered useful for delivering relevant information for the implementation of groundwater policies at national and European scale.

The analyses using the HRC-SYS classification system and the visualizations of the scholarly output in the developed intersection plots on the Scopus database, using a subset of the Scopus database that contains keywords from all intersections of societal challenges, operational actions and research topics, confirm that most groundwater research is conducted within SC4 "Climate, environment and resources" as indicated in the intersection plots for the EIGR database. However, there is a strong overlap to especially SC1 "Health" and SC2 "Food and Agriculture" as the largest number and most cited papers both within SC4, SC1 and SC2 are related to either natural elements (arsenic) or pollutants (pharmaceuticals, emerging contaminants, nitrate and pesticides), which are harmful to human health and groundwater dependent or associated ecosystems. Consequently, the EIGR content can be considered a significant additional contribution to the existing knowledge on groundwater research especially for the more than 50% of the records belonging to the "grey literature", represented by the classes 3 & 4 of the classification system HRC-SYS, not considered in scientific databases.

Looking at the wider framework, European (EU28) groundwater research performs well in comparison with the other major regions (USA, China etc.), and Europe have had the largest scholarly output and number of classes 1 and 2 publications within groundwater research since 2007, according to Scopus. This reflects increasing attention to and importance of groundwater issues in Europe and possibly new requirements and research needs arising from the adoption of the groundwater directive in 2006. However, the global groundwater research trend primarily driven by China and India increases faster than the European indicating that the scholarly output for groundwater research in Asia will exceed the European in the future. An increasing number of papers published by China and India are also among the most cited, globally.

A significant amount of groundwater research is conducted within all the grand societal challenges of Horizon 2020 with a scholarly output of class 1 (research papers) and 2 (proceeding papers) ranging between approximately 2600 research papers for the societal challenge "transportation" to more than 44.000 research papers for the societal challenge "climate, environment and resources" for the period 1997 – 2016.

While EU28 currently performs very well for the scholarly output of groundwater research in comparison with other main regions and countries, globally, Europe has, however, much fewer patents related to groundwater technology in comparison with especially the USA. Europe has for instance a very low number of patents on new innovative techniques related to new digital developments such as "cloud computing", Information and communication technologies (ICT), internet of things (IoT) and "big data". This may indicate that the conditions for innovation and patent applications for groundwater relevant or related technologies in Europe are less developed as compared to the conditions in the US.

In this report focus has been on analysing gaps and trends from the perspective of societal challenges, which has been discussed in the previous section. From this we can draw the following main conclusions for each societal challenge primarily based on the analyses performed on the Scopus database (EIGR resources too limited to draw firm conclusions).

SC1: (1) increasing amount of new emerging contaminants in groundwater and the rest of the hydrological cycle and a rapid increase in papers and citations for papers studying these. Recent papers on emerging contaminants are among the most cited papers on groundwater research globally; (2) Data and knowledge on the contents in groundwater is scarce and sporadic and most of the European countries have very limited data for groundwater; (3) serious health concerns related to arsenic in groundwater exist mainly in Asian countries, but so far only few studies have been conducted in Europe and new studies in the Netherlands demonstrate negative health effects at very low concentrations of arsenic, and have lowered the drinking water standard by a factor of 10 (to 1 ug/l); (4) recent studies on carcinogenic effects of nitrate in groundwater and drinking water show that nitrate is toxic and carcinogenic at concentrations lower than 5 mg/l or an order of magnitude lower than the existing drinking water standard, (5) Other natural elements (e.g. Li) as well as pollutants such as pharmaceutical and hormones have recently been linked to both physical (cancer, fertility etc.) and mental health (depression, dementia etc.); (6) Very little information exist on the occurrence of degradation products of micro-organics and related cocktail effects as well as nanoparticles and microplastics in groundwater.

Generally, additional research on the chemical status of groundwater in relation to human health effects of e.g. cocktails of emerging contaminants/microorganics, arsenic and nitrate as well as effects of emerging contaminants, heavy metals and nutrients on groundwater dependent terrestrial and associated aquatic ecosystems (SC2 and SC4) is needed.

SC2: (1) nitrate causes poor chemical and ecological status for groundwater and surface waters respectively all over Europe and often it is dominated by pollution from agriculture; (2) a relatively low number of publications on biology, geology and mapping may indicate a research gap on the topic of finding efficient tools for reducing nitrate (nitrogen) loadings; (3) a knowledge gap exists on how ecosystems are linked to poor groundwater chemical status; (4) EU member states argue that they do not have the necessary data and understanding of aquatic ecosystems to be able to derive groundwater threshold values based on good status objectives of the WFD and GWD; (5) more transdisciplinary research is needed between hydrogeologists and ecologists.

SC3: More attention to improved techniques for climate change impact assessment and adaptation and the assessment of uncertainties of projections for groundwater quantity and quality in the future is needed.

SC4: (1) the highest scholarly output; (2) prominent research areas are 'groundwater resource', 'Aquifer', 'water resource' and 'water management'; (3) Groundwater pollution and water quality are closely linked to the 'groundwater resource' and 'aquifer' research areas; (4) Pollution of groundwater resources can be linked to specific contaminants, environment and biochemistry and groundwater research shows clearly delineated areas on (bio)chemistry, and related specific keywords include (ad)sorption, organic compounds, bacteria, microbial activity and various chemical compounds; (5) groundwater research on geochemistry is linked to groundwater management disciplines like ‘water quality’ and ‘water supply’; (6) modelling of groundwater and pollutants (transport) are distinct research areas linked to the broader ‘water resource’, ‘water management’ and ‘groundwater resource’ topics; (7) the climate component is largely absent, which seems to indicate a clear gap in the field of climate related research and groundwater; (8) urban hydrology and the significance of shallow groundwater, e.g. in connection to nature based solutions and green infrastructure is underrepresented and constitute a gap in research;

SC5: (1) co-occurrence analysis show research areas around keywords: aquifer, groundwater pollution, water supply, ‘groundwater resource’ and ‘water pollutants’; (2) a large variety of environmental, policy and societal issues is embraced with entrenched keyword clusters, signifying multi faceted topics and research areas, i.e. multi and trans-disciplinarity; (3) emphasis on environmental impact and monitoring and the presence of keywords like ‘sustainable development’ and ‘environmental protection’; (4) ‘Policy, innovation and society’ relevant keywords are related to Operational Action ‘Assessment and management’ and ‘Water supply’

SC6: (1) Research on both groundwater quality and quantity issues related to transportation including roads, railways, airports and fuel storage is conducted globally; (2) co-occurrence analysis indicates clearly demarcated clusters around ‘roads and streets’, hydrogeology, ‘groundwater pollution’ and a cluster containing several keywords related to infrastructure construction and construction techniques; (3) groundwater related research on transport and infrastructure is connected to geotechnical topics, like ‘slope stability’, landslides, and tunnels; (4) transport and infrastructure alter the soil surface and result in less infiltration (recharge) which may cause flooding, which is well captured in clusters on ‘road and streets’ and ‘aquifer’ clusters, including keywords like runoff, ‘storm water’ and sewers; (5) infrastructure construction and thereby attracting transport may increase groundwater and soil pollution, like landfills, introducing e.g. heavy metals. The most cited publication within this societal challenge is on salt water transport in the subsurface and contamination from airports.

7 References

Abbaspour, K. C., Rouholahnejad, E., Vaghefi, S., Srinivasan, R., Yang, H. & Kløve, B. (2015) A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. J Hydrol 524, 733–752

Bornmann, L. (2015). Alternative metrics in scientometrics: a meta-analysis of research into three altmetrics. Scientometrics (2015) 103:1123–1144, DOI 10.1007/s11192-015-1565-y

Cahlik, T. (2000). Comparison of the maps of science. Scientometrics, 49(3), 373–387.

Clements A, Darroch P, Green J (2017) Snowball Metrics – Providing a Robust Methodology to Inform Research Strategy – but do they help? Procedia Computer Science Sciencedirect, 106: 11–18. doi:10.1016/j.procs.2017.03.003

D1.1 (2015). INITIAL PROPOSAL FOR A HARMONIZED TERMINOLOGY AND METHODOLOGY. KINDRA report. Available from www.kindraproject.eu

D1.2 (2015). HARMONIZED TERMINOLOGY AND METHODOLOGY FOR GROUNDWATER RESEARCH CLASSIFICATION. KINDRA report. Available from www.kindraproject.eu

Denjean, B;Altamirano, M; Graveline, N., Giordano, R.;van der Keur, P.; Moncoulon, D.; Weinberg, J.; Máñez, M.;Kozinc, Z.; Mulligan, M.;Pengal, P; Matthews, J.;van Cauwenbergh, N.; López Gunn, E.;Bresch, D (2017). Natural Assurance Scheme: A level playing field framework for Green-Grey infrastructure development. Environmental Research, Volume 159, November 2017, Pages 24-38. https://doi.org/10.1016/j.envres.2017.07.006

Eck N.J. van & Waltman L. (2017), Accuracy of citation data in Web of Science and Scopus. 16th International Conference of the International Society for Scientometrics and Informetrics, Wuhan. In: Proceedings of the 16th International Conference of the International Society for Scientometrics and Informetrics.. 1087-1092

Eck, N. van & Waltman, L. (2010) Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics 84(2), 523–538. doi:10.1007/s11192-009-0146-3

European Commission (2015a) Technical report on groundwater associated aquatic ecosystems. Technical Report-2015-093, European Commission, Directorate General for the Environment, Unit C1 - Water, Bruxelles.

European Commission (2015b) Threshold values - Initial analysis of 2015 Questionnaire Responses. Directorate General for the Environment, EC CIS Working Group Groundwater, Technical Report

European Commission, 2018. http://ec.europa.eu/environment/water/water-framework/groundwater/resource.htm. Accessed 06.07.2018.

EEA, 2015, The European environment — state and outlook 2015: synthesis report, European

Environment Agency, Copenhagen. Luxembourg: Publications Office of the European Union, 2015

ISBN 978-92-9213-515-7, doi:10.2800/944899

Erdt, M., Nagarajan, A., Sin, S.-C. & Theng, Y.-L. (2016) Altmetrics: an analysis of the state-of-the-art in measuring research impact on social media. Scientometrics 109(2), 1117–1166. doi:10.1007/s11192-016-2077-0

Filipovic, M., Woldegiorgis, A., Norström, K., Bibi, M., Lindberg, M. & Österås, A.-H. (2015) Historical usage of aqueous film forming foam: A case study of the widespread distribution of perfluoroalkyl acids from a military airport to groundwater, lakes, soils and fish. Chemosphere 129, 39–45. doi:10.1016/j.chemosphere.2014.09.005

Gavrilescu, M., Demnerová, K., Aamand, J., Agathos, S., & Fava, F. (2015). Emerging pollutants in the environment: Present and future challenges in biomonitoring, ecological risks and bioremediation. New Biotechnology, 32(1), 147-156. 10.1016/j.nbt.2014.0

Gleeson, T., Befus, K. M., Jasechko, S., Luijendijk, E., & Cardenas, M. B. (2016). The global volume and distribution of modern groundwater. Nature Geoscience, 9(2), 161-164. 10.1038/ngeo2590

Harzing, A.-W., & Alakangas, S. (2016). Google Scholar, Scopus and the Web of Science: a longitudinal and cross-disciplinary comparison. Scientometrics, 106(2), 787–804.

Horváth, F., Musitz, B., Balázs, A., Végh, A., Uhrin, A., Nádor, A., . . . Wórum, G. (2015). Evolution of the pannonian basin and its geothermal resources. Geothermics, 53, 328-352. 10.1016/j.geothermics.2014.07.009

Gore, A., Chappell, V., Fenton, S., Flaws, J., Nadal, A., Prins, G., Toppari, J. and Zoeller, R. 2015. Executive Summary to EDC-2: The Endocrine Society's Second Scientific Statement on Endocrine-Disrupting Chemicals. Endocrine Reviews. 36, 6 (2015), 593–602

Kessing, L., Gerds, T., Knudsen, N., Jørgensen, L., Kristiansen, S., Voutchkova, D., Ernstsen, V., et al. (2017) Association of Lithium in Drinking Water With the Incidence of Dementia. JAMA Psychiatry. doi:10.1001/jamapsychiatry.2017.2362

Lapworth, D. J., Baran, Stuart, M. E. & Ward, R. S. (2012) Emerging organic contaminants in groundwater: A review of sources, fate and occurrence. Environmental Pollution 163, 287–303. doi:10.1016/j.envpol.2011.12.034

Lawrence, M., Thomas, J., Houghton, J. & Weldon, P. (2015) Collecting the Evidence: Improving Access to Grey Literature and Data for Public Policy and Practice, Australian Academic & Research Libraries, 46:4, 229-249, DOI: 10.1080/00048623.2015.1081712

Levine, H., Jørgensen, N., Martino-Andrade, A., Mendiola, J., Weksler-Derri, D., Mindlis, I., Pinotti, R., et al. (2017) Temporal trends in sperm count: a systematic review and meta-regression analysis. Human Reproduction Update 23(6), 646–659. doi:10.1093/humupd/dmx022

Mongeon, P. & Paul-Hus, A. (2016) The journal coverage of Web of Science and Scopus: a comparative analysis. Scientometrics 106(1), 213–228. doi:10.1007/s11192-015-1765-5

National Science Board. 2018. Science and Engineering Indicators 2018. NSB-2018-1. Alexandria, VA: National Science Foundation. Available at https://www.nsf.gov/statistics/indicators/

National Science Board. 2016. Science and Engineering Indicators 2016. Arlington, VA: National Science Foundation, (NSB-2016-1).

Ohgami, H., Terao, T., Shiotsuki, I., Ishii, N. & Iwata, N. (2009) Lithium levels in drinking water and risk of suicide. The British Journal of Psychiatry 194(5), 464–465. doi:10.1192/bjp.bp.108.055798

Schullehner, J., Hansen, B., Thygesen, M., Pedersen, C.B and Sigsgaard, T. (2018). Nitrate in drinking water and colorectal cancer risk: a nationwide population-based cohort study. International journal of cancer, accepted, doi:10.1002/ijc.31306

Singh, R., Singh, S., Parihar, P., Singh, V. P., & Prasad, S. M. (2015). Arsenic contamination, consequences and remediation techniques: A review. Ecotoxicology and Environmental Safety, 112, 247-270. 10.1016/j.ecoenv.2014.10.009

Spasiano, D., Marotta, R., Malato, S., Fernandez-Ibañez, P., & Di Somma, I. (2015). Solar photocatalysis: Materials, reactors, some commercial, and pre-industrialized applications. A comprehensive approach. Applied Catalysis B: Environmental, 170-171, 90-123.

Sui, Q., Cao, X., Lu, S., Zhao, W., Qiu, Z., & Yu, G. (2015). Occurrence, sources and fate of pharmaceuticals and personal care products in the groundwater: A review. Emerging Contaminants, 1(1), 14-24. 10.1016/j.emcon.2015.07.001

Voutchkova, D., Schullehner, J., Knudsen, N., Jørgensen, L., Ersbøll, A., Kristiansen, S. & Hansen, B. (2015) Exposure to Selected Geogenic Trace Elements (I, Li, and Sr) from Drinking Water in Denmark. Geosciences 5(1), 45–66. doi:10.3390/geosciences5010045

Waltman, L. & Eck, N. van (2012) A new methodology for constructing a publication-level classification system of science. J Am Soc Inf Sci Tec 63(12), 2378–2392. doi:10.1002/asi.22748

Waltman, L., Eck, N. van & Noyons, E. (2010) A unified approach to mapping and clustering of bibliometric networks. Journal of Informetrics 4, 629–635.

Wang, Y., Xiang, C., Zhao, P., Mao, G. & Du, H. (2016) A bibliometric analysis for the research on river water quality assessment and simulation during 2000–2014. Scientometrics 108(3), 1333–1346. doi:10.1007/s11192-016-2014-2

Wang, M.-H., Li, J. & Ho, Y.-S. (2012) Research articles published in water resources journals: A bibliometric analysis. Desalin Water Treat 28(1-3), 353–365. doi:10.5004/dwt.2011.2412

Wens, P. van der. Arsenic at low concentrations in Dutch drinking water: assessment of removal costs and health benefits. Keynote presentation at the 6th International Congress on "Arsenic in the Environment" (AS2016) - Arsenic Research and Global Sustainability (As2016), Stockholm, June 19-23, 2016.

Wilkinson M, Dumontier M, Aalbersberg Ij, et al. (2016) The FAIR Guiding Principles for scientific data management and stewardship. Scientific Data 3: sdata201618 – www.nature.com/sdata, doi:10.1038/sdata.2016.18.

Zare, F., Elsawah, S., Iwanaga, T., Jakeman, A. & Pierce, S. (2017) Integrated water assessment and modelling: A bibliometric analysis of trends in the water resource sector. J Hydrol 552, 765–778. doi:10.1016/j.jhydrol.2017.07.031

8 Appendix

KINDRA Thesaurus keywords overview

Societal Challenges			
Level 1	Level 2	Level 3	Level 4
Health			
Food			
Energy			
Climate, environment and resources			
Policy, innovation and society			

Table 4. Societal Challenges

Operational actions			
Level 1	Level 2	Level 3	Level 4
Mapping	Remote sensing		
	Airborne measurements		
	Borehole logging or Well logging OR Geophysical logging		
	Surface geophysic		
	Electromagnetic methods		
	Geophysical methods		
	Cone penetration tests		
	Geographyc information Systems Or GIS		
	Survey		
Monitoring	Qualitative monitoring network	Tracer test	
		Investigation well	
		Multi-screen wells	
	Quantitative monitoring network	Investigation well	
		Multi-screen wells	

Modeling or modelling or Model	Hydrochemical modeling OR Hydrochemical modelling		
	Numerical modeling OR Numerical modelling		
	Integrated hydrological modeling		
	Coupled groundwater surface water modeling		
	Salt water intrusion modeling		
	Solute transport modeling		
	Density dependent modeling		
	Conceptual model		
	Scale effect Or Scaling effect		
Water supply	Energy production	Abstraction	
		Extraction	
	Food Production	Abstraction	
		Extraction	
	Drinking water	Abstraction	
		Extraction	
	Mining	Abstraction	
		Extraction	
	Industry	Abstraction	
		Extraction	
	Farming	Abstraction	
		Extraction	
	Agriculture	Abstraction	
		Extraction	
	Tourism	Abstraction	
		Extraction	
Assessment and Management	Characterisation	Technique	Slug test
			Geostatistic
			Pumping test
			Laboratory experiments
			Laboratory measure-ments
			Analytical solution
	Status	Geophysics	

	assessment	Quality	
		Baseline	
	Review		
	Measure	Remediation	Treatment
			Containment
			Removal
			Bioremedia-tion
			Capping
			Chemical oxidation
			Excavation
			Incineration
			Natural attenuation
			Pump & Treat
			Permeable Reactive Barrier
			Soil Vapor Extraction
		Mitigation	Intrusion
			Salinization
			Artificial recharge Or Managed aquifer Recharge
		Protection	
		Adaptation	Trend
	Legislation	WFD	
		GWD	Overuse Or Over-use
			Groundwater resources
	Governance	Sustainable	Sustainable water use
			Land use
	Organization	Water services	
		Integrated management	
		Integrated water resources management	
	Patent		

Table 5. Operational actions

Research Topics			
Level 1	Level 2	Level 3	Level 4
Biology	Ecosystem	Aquatic ecosystem	Stygofauna
		Terrestrial ecosystem	Wetland
		Dependent ecosystem	Wetland
	Ecology		
	Ecohydrology	e-flow OR ecological flow OR environmental flow	
	Ecotoxicology	Status	Microbial processes
			Biological status
			Chemical status
			Ecological status
			Quantitative status
	Human toxicology	Human health	
	Biodegradation		
	Bioremediation		
	Bacteria		
	Virus		
	Biodiversity		
	Biotransformation		
	Bioavailability		
	Biological treatment		
	Biotreatment		
	Pharmaceuticals		
	Hydrogeotoxicity		
	Antibiotics		
	Pathogens		
	Bacteriophage		
	Forensics		
	Contaminants		
	Pollutants		
	Procaryotes		
	Eucaryotes		
	Micobiology		
	Microbial diversity		
	Degradation		
	Mineralisation		
Chemistry	Geochemistry	Contamination	
		Natural background	Nitrate
			Ammonium

		or Pollution	Arsenic
			Cadmium
			Chloride
			Lead OR Pb
			Radon
			Mercury
			Sulphate or Sulfate
			Metals OR Heavy metals
			Pesticide
			Pharmaceutical
			Emerging contaminants
			Chlorinated Hydrocarbons
			Tetrachloro-ethylene OR Perchloro-ethylene OR PCE
			Trichloroanisole OR TCA
			Trichloro-ethylene Or TCE
			Deterioration
	Hydrochemistry	Multiphase flow	
		Matrix diffusion	
		Synthetic substance	
		Solute transport	
		Threshold	Drinking water
		Indicator	Electrical conductivity
			Salt water or saltwater
			Salinity
	Tracer	Environmen-tal tracer	Groundwater dating
		Stable isotopes	Groundwater dating
		Noble gases	Groundwater dating
Geography	Europe		
	North America		
	South America		
	Asia		
	Russia		

	Australia OR New Zeland		
	Middle East		
	Transboundary	River	River basin districts
			River basin OR Catchment basin OR Watershed
			Surface water interaction
			Ecoregion
		Marine waters	Coastal waters
			Transitional waters
			Territorial waters
			Shale gas
	Climate	Climate Change	
	Hydrology	Island hydrology	
		Water budget	
		Artesian water	
	Hydrological cycle Or Hydrologic cycle	Rainfall OR Rain fall	
		Recharge	
		Runoff	
	Paleohydrology	Paleowater OR Palaeowater	
		Flood	Arid region
		Drought	Scarcity
	Urban areas	Urban groundwater	
		Waste	Landfill OR Land Fill OR Dump site
			Waste disposal
		Developing country	
	Geomorphology	Floodplain	
Geology	Groundwater body	Aquiclude	
		Aquitard	
		Karst	
		Aquifer	Volcanic aquifer
			Karst aquifer
			Carbonatic aquifer
			Sand aquifer
			Alluvium or Alluvial aquifer

			Coastal aquifer
			Artesian
			Carbonate rocks
			Crystalline rocks
			Fractured rocks
			Sandstone
			Unsaturated zone
			Aquifer vulnerability
			Vulnerability
			Heterogeneity
			Saturation
			Physical conditions
			Groundwater age
	Geothermal energy		
	Geohazard	Hazard	
		Earthquake	
Physics and Mathematics	Quantity	Water table	Flow regime
			Flow
		Hydraulic Parameters	Porosity
			Permeability
			Storage
			Yield
			Hydraulic conductivity
		Hydraulic properties	Subsidence
			Compaction
			Fracture
			Fault
			Saturation

Table 6. Research Topics

Search strings for Scopus VOSviewer visualisations and analysis

Figures	Search String
Fig. 3.37	Data extracted by 8 searches in Scopus and Web of Science, the 4 Scopus searches were executed as follows: • [baseline] • [baseline] AND ([any OA term] OR [any RT term] OR TITLE-ABS-KEY(health OR food OR agricultur* OR energy OR climate OR environment OR resource* OR polic* OR innovation OR societ*)) • [baseline] AND [any OA term] AND [any RT term] AND TITLE-ABS-KEY(health OR food OR agricultur* OR energy OR climate OR environment OR resource* OR polic* OR innovation OR societ*) • [baseline] AND NOT ([any OA term] OR [any RT term] OR TITLE-ABS-KEY(health OR food OR agricultur* OR energy OR climate OR environment OR resource* OR polic* OR innovation OR societ*)

Table 2 & Fig. 3.70a	6 searches, example for SC1: [baseline] AND TITLE-ABS-KEY(health) AND [any OA term] AND [any RT term]
Fig. 3.38 – Fig. 3.44	125 searches, example for SC1, OA4, RT5: [baseline] AND TITLE-ABD-KEY((Health) AND ("Water suppl*" OR abstract* OR extract* OR "Energy produc*" OR "Food Produc*" OR "Drinking water" OR mining OR industr* OR farm* OR agricultur* OR touris*) AND (physic* OR mathematic* OR quantity OR "Water table" OR hydraulic OR parameters OR "Hydraulic properties" OR "Flow regime" OR flow OR porosity OR permeability OR storage OR yield OR "Hydraulic conductivity" OR subsidence OR compaction OR fracture OR fault OR saturation)
Fig. 3.45, Fig. 3.46 & Fig. 3.77	[baseline] AND TITLE-ABS-KEY(health) AND [any OA term] AND [any RT term]
Fig. 3.47 & Fig. 3.48	[baseline] AND TITLE-ABS-KEY(food OR agricultur*) AND [any OA term] AND [any RT term]
Fig. 3.49 & Fig. 3.50	[baseline] AND TITLE-ABS-KEY(energy) AND [any OA term] AND [any RT term]
Fig. 3.51, Fig. 3.52 & Fig. 3.83	[baseline] AND TITLE-ABS-KEY(climate OR environment OR resource*) AND [any OA term] AND [any RT term]
Fig. 3.53, Fig. 3.54 & Fig. 3.84	[baseline] AND TITLE-ABS-KEY(polic* OR innovation OR societ*) AND [any OA term] AND [any RT term]
Fig. 3.55 & Fig. 3.56	[baseline] AND TITLE-ABS-KEY(road* OR railway* OR highway* OR airport* OR "gas station*" OR "petrol station*") AND [any OA term] AND [any RT term]
Fig. 3.57 & Fig. 3.58	4 searches for each column, examples for 'Land use': • TITLE-ABS-KEY((groundwater OR "ground water" OR hydrogeolog*) AND "land use") AND PUBYEAR > 1996 • TITLE-ABS-KEY((groundwater OR "ground water" OR hydrogeolog*) AND "land use") AND PUBYEAR > 1996 AND AFFILCOUNTRY(Austria OR Belgium OR Bulgaria OR Croatia OR Cyprus OR "Czech Republic" OR Denmark OR Estonia OR Finland OR France OR Germany OR Greece OR Hungary OR Ireland OR Italy OR Latvia OR Lithuania OR Luxembourg OR Malta OR Netherlands OR Poland OR Portugal OR Romania OR Slovakia OR Slovenia OR Spain OR Sweden OR "United Kingdom") • TITLE-ABS-KEY((groundwater OR "ground water" OR hydrogeolog*) AND ("land use")) AND PUBYEAR > 2006 • TITLE-ABS-KEY((groundwater OR "ground water" OR hydrogeolog*) AND ("land use")) AND PUBYEAR > 2006 AND AFFILCOUNTRY(Austria OR Belgium OR … OR "United Kingdom")
Table 3	As fig. 3.57 and 3.58 but with appropriate change of PUBYEAR values
Fig. 3.68 & Fig. 3.69	[baseline] AND AFFILCOUNTRY(Austria OR Belgium OR … OR "United Kingdom") Limited to one year at the time and divided on countries using 'Analyze Search Result'
3.70b	6 searches, example for SC5: [baseline] AND TITLE-ABS-KEY(polic* OR innovation OR societ*) AND AFFILCOUNTRY(Austria OR Belgium OR … OR "United Kingdom")
3.71	Two searches: • [baseline] • [baseline] AND AFFILCOUNTRY(Austria OR Belgium OR … OR "United Kingdom")
3.74	Searches performed as fig. 3.38-3.44, but comparing two time periods per intersection.
3.78	[baseline] AND TITLE-ABS-KEY(arsen*)
Fig. 3.79 & Fig. 3.81	TITLE-ABS-KEY((groundwater OR "ground water" OR hydrogeolog*) AND (health OR food OR agricultur* OR energy OR climate OR environment OR resource* OR polic* OR innovation OR societ*)) AND PUBYEAR > 1996 AND PUBYEAR < 2007 AND [any OA term] AND [any RT term]
Fig. 3.80 & Fig. 3.82	TITLE-ABS-KEY((groundwater OR "ground water" OR hydrogeolog*) AND (health OR food OR agricultur* OR energy OR climate OR environment OR resource* OR polic* OR innovation OR societ*)) AND PUBYEAR > 2006 AND PUBYEAR < 2017 AND [any OA term] AND [any RT term]

Table 4 Table showing search strings used in Scopus for the various tables and figures

[baseline]

TITLE-ABS-KEY(groundwater OR “ground water” OR hydrogeology*) AND PUBYEAR > 1996 AND PUBYEAR < 2017

[any OA term]

TITLE-ABS-KEY(map* OR "Remote sens*" OR "Airborne measurement*" OR "Borehole log*" OR "Surface geophysic*" OR "Electromagnetic method*" OR "Geophysical method*" OR "Cone penetration test*" OR "Geographic information System*" OR survey OR gis OR "Well log*" OR "Geophysical log*" OR monitor* OR qualitative OR quantitative OR "Tracer test" OR "Investigation well*" OR "Multi-screen well*" OR network OR "Multiscreen well*" OR "Multi screen well*" OR model* OR hydrochemical OR numerical OR "Integrated hydrologic*" OR "groundwater surface water" OR "Salt water intrusion" OR "Solute transport" OR "Density dependent" OR conceptual OR "Scale effect*" OR coupled OR "Scaling effect*" OR "Water suppl*" OR abstract* OR extract* OR "Energy produc*" OR "Food Produc*" OR "Drinking water" OR mining OR industr* OR farm* OR agricultur* OR touris* OR assess* OR manag* OR characteri* OR status OR review OR measur* OR legislati* OR governance OR organization* OR patent* OR technique* OR geophysic* OR remediat* OR mitigat* OR protect* OR adapt* OR wfd OR gwd OR sustainab* OR "Water servic*" OR quality OR baseline OR "Integrated management" OR "Integrated water resource management" OR "Slug test*" OR geostatistic* OR "Pumping test*" OR "Laboratory experiment*" OR "Laboratory measurement*" OR "Analytical solution*" OR treat* OR contain* OR remov* OR bioremediation OR capping OR "Chemical oxidation" OR excavat* OR incinerat* OR "Natural attenuation" OR "Pump & Treat" OR "Permeable Reactive Barrier*" OR "Soil Vapor Extraction" OR intrusion OR salinization OR "Artificial recharge" OR "Managed aquifer Recharge" OR trend OR overus* OR "Groundwater resource*" OR "Sustainable water us*" OR "Land us*" OR over-us* OR organisation* OR "Pump and Treat" OR salinisation OR "Water Framework Directive" OR "Ground Water Directive")

[any RT term]

TITLE-ABS-KEY (ecotoxicolog* OR "Aquatic ecosystem" OR "Terrestrial ecosystem" OR stygofauna OR wetland* OR "Human toxicolog*" OR status OR "ecological flow" OR "environmental flow" OR "Human health" OR "Microbial processes" OR "Biological status" OR "Chemical status" OR "Ecological status" OR "Quantitative status" OR biodegradat* OR bioremediat* OR bacteri* OR virus OR virol* OR biodivers* OR biotransformat* OR bioavailab* OR "Biological Treatment*" OR biotreatment* OR pharmaceutic* OR hydrogeotoxic* OR antibiot* OR pathogen* OR bacteriophag* OR forensic* OR contamina* OR pollut* OR procaryot* OR eucaryot* OR microbi* OR "Microbial divers*" OR degradat* OR minerali* OR chemistry OR geochemistry OR hydrochemistry OR tracer OR contamination OR "Natural background" OR pollution OR "Multiphase flow" OR "Matrix diffusion" OR "Synthetic substance*" OR "Solute transport" OR threshold OR indicator OR "Environmental tracer" OR "Stable isotope*" OR "Noble gases" OR nitrate OR ammonium OR arsenic OR cadmium OR chloride OR lead OR radon OR mercury OR sulphate OR metal* OR pesticide OR pharmaceutic* OR "Emerging contamina*" OR "Chlorinated Hydrocarbon*" OR tetrachloroethylene OR trichloroanisole OR trichloroethylene OR deteriorat* OR pb OR sulfate OR "Heavy metal*" OR perchloroethylene OR "Drinking water" OR "Electrical conductivity" OR "Salt water" OR salinity OR "Groundwater dating" OR tce OR saltwater OR pce OR tca OR geograph* OR europe OR "North America" OR "South America" OR asia OR russia OR australia OR "Middle East" OR transboundary OR "New Zealand" OR climate OR hydrolog* OR "Hydrolog* cycle" OR paleohydrolog* OR "Urban area*" OR geomorphology OR river OR "Marine waters" OR "Palaeowater" OR "Rain fall" OR "Climate Change*" OR "Island hydrology" OR "Water budget" OR "Artesian water" OR rainfall OR recharge OR runoff OR paleowater OR flood OR drought OR "Urban groundwater" OR waste OR "Developing countr*" OR floodplain OR "River basin district*" OR "River basin" OR "Surface water interaction" OR ecoregion OR "Coastal waters" OR "Transitional waters" OR "Territorial waters" OR "Shale gas" OR "Catchment basin" OR watershed OR "Arid region" OR scarcity OR "Land Fill" OR landfill OR "Waste disposal" OR "Dump site*" OR geolog* OR "Groundwater bod*" OR "Geothermal energy" OR geohazard* OR aquiclude OR aquitard OR karst OR "Aquifer*" OR "Hazard*" OR "Earthquake*" OR "Alluvial aquifer*" OR "Volcanic aquifer*" OR "Karst aquifer*" OR "Carbonatic aquifer*" OR "Sand aquifer*" OR alluvium OR "Coastal aquifer*" OR artesian OR "Carbonate rock*" OR "Crystalline rock*" OR "Fractured rock*" OR sandstone OR "Unsaturated zone" OR "Aquifer vulnerability" OR vulnerab* OR heterogeneity OR saturation OR "Physical conditions" OR "Groundwater age" OR hydrogeolog* OR physic* OR mathematic* OR quantity OR "Water table" OR hydraulic OR parameters OR "Hydraulic properties" OR "Flow regime" OR flow OR porosity OR permeability OR storage OR yield OR "Hydraulic conductivity" OR subsidence OR compaction OR fracture OR fault OR saturation)

EIGR trend analysis for Societal Challenges

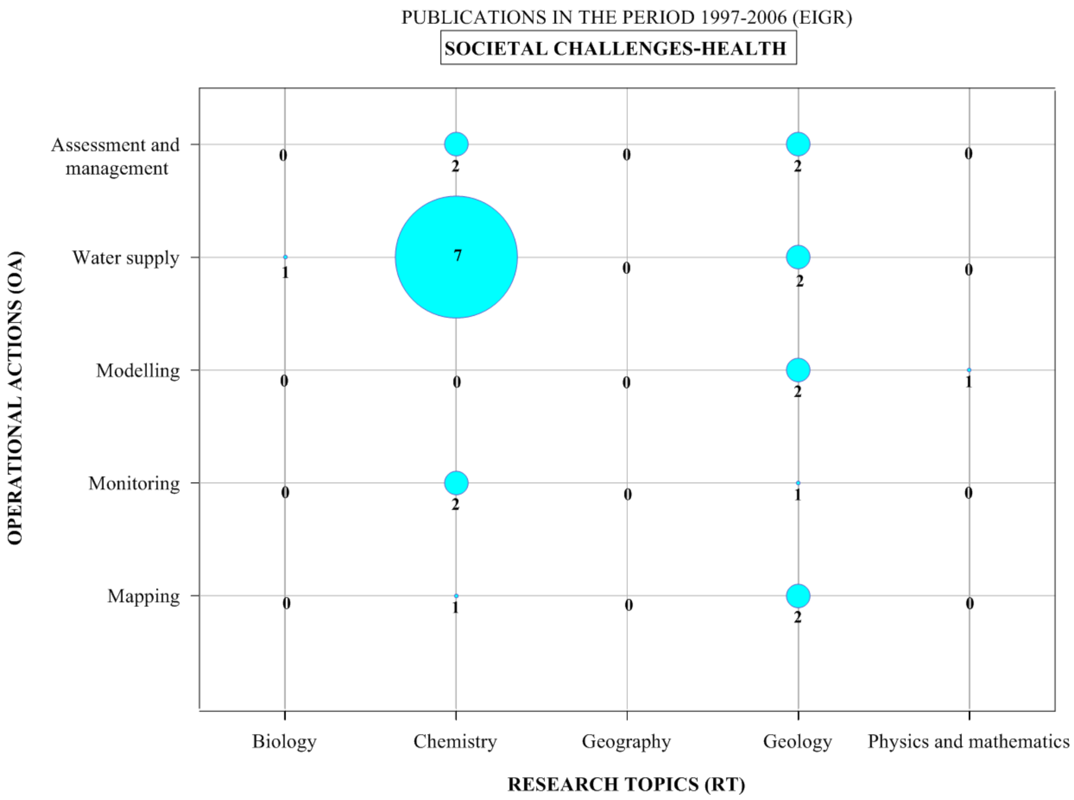


Figure 8.1 SC Health from EIGR: 1997-2006

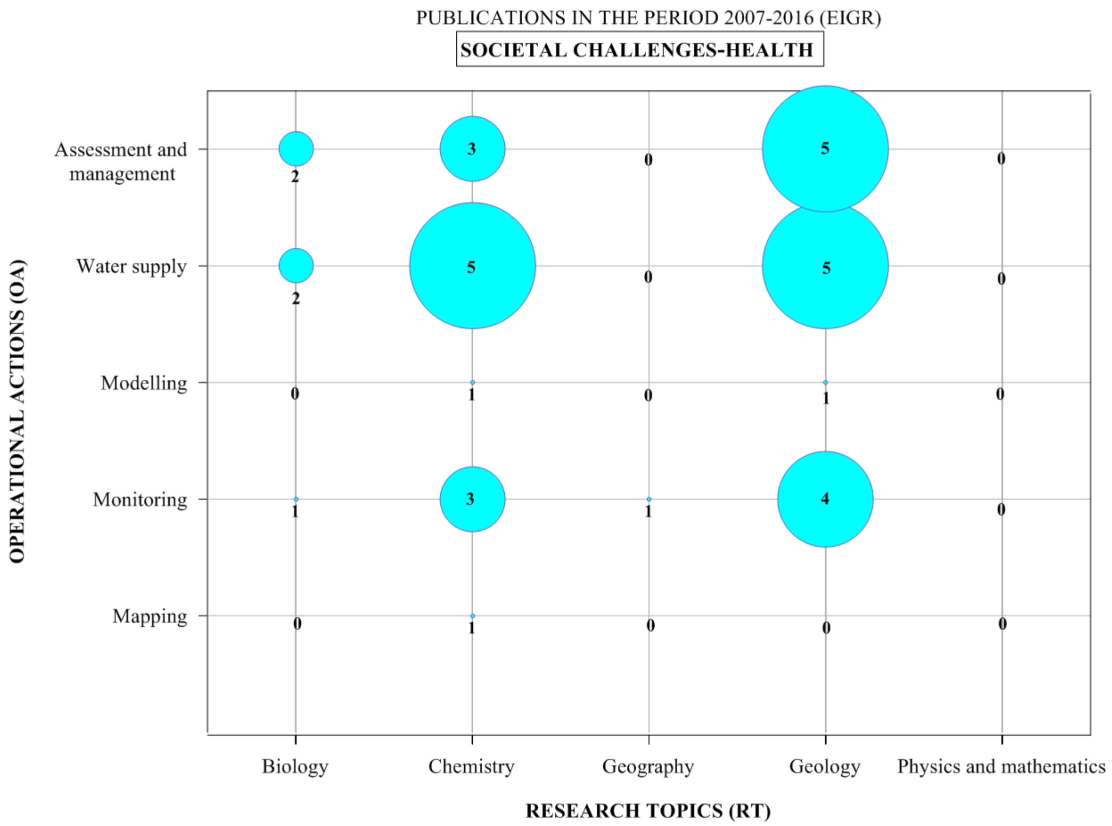


Figure 8.2 SC Health from EIGR: 2007-2016

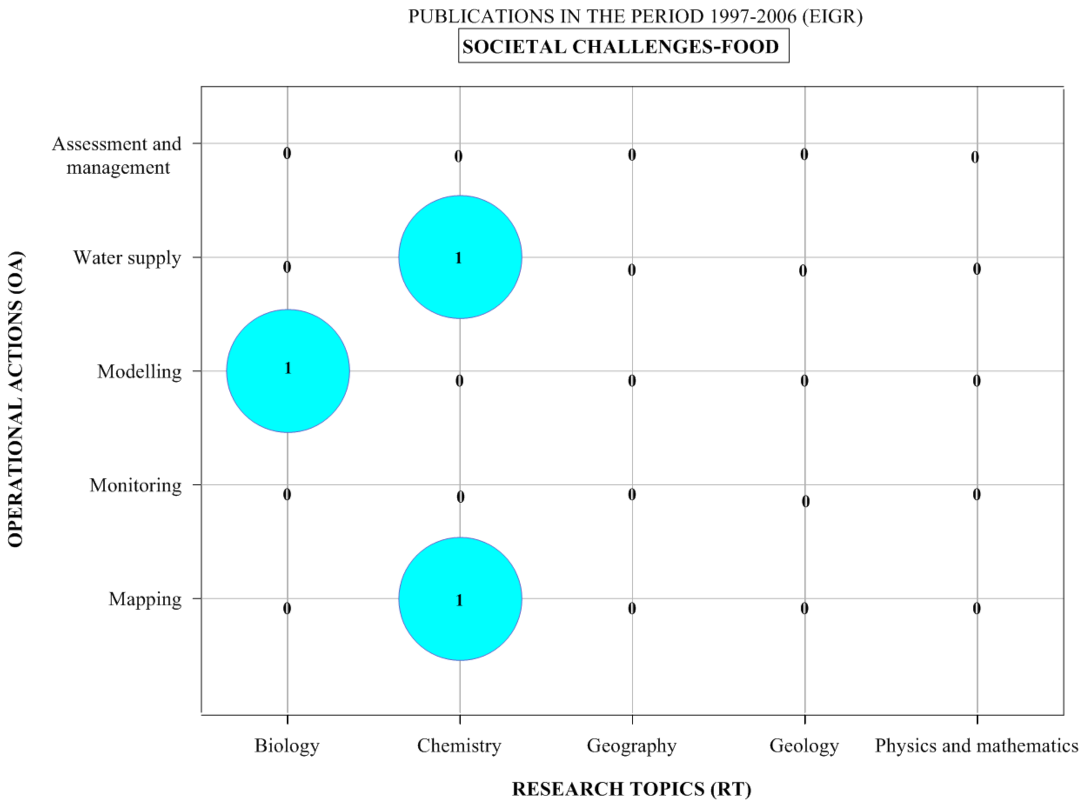


Figure 8.3 SC Food from EIGR: 1997-2006

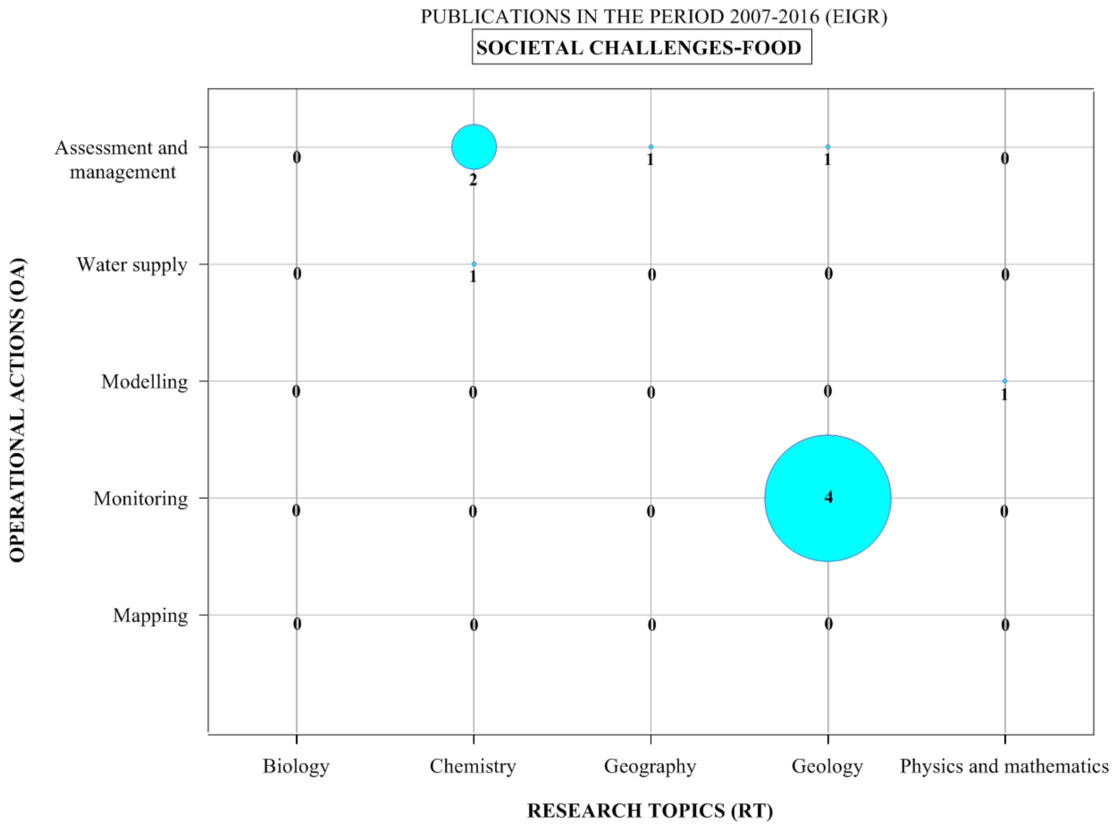


Figure 8.4 SC Food from EIGR: 2007-2016

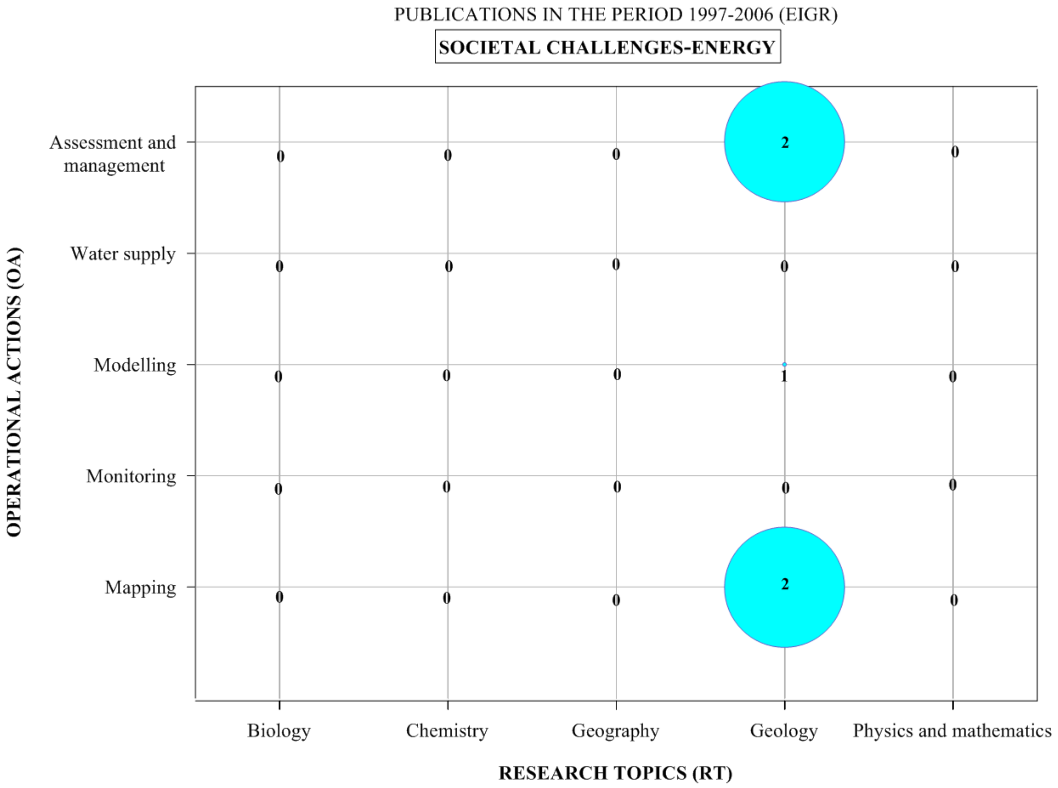


Figure 8.5 SC Energy from EIGR: 1997-2006

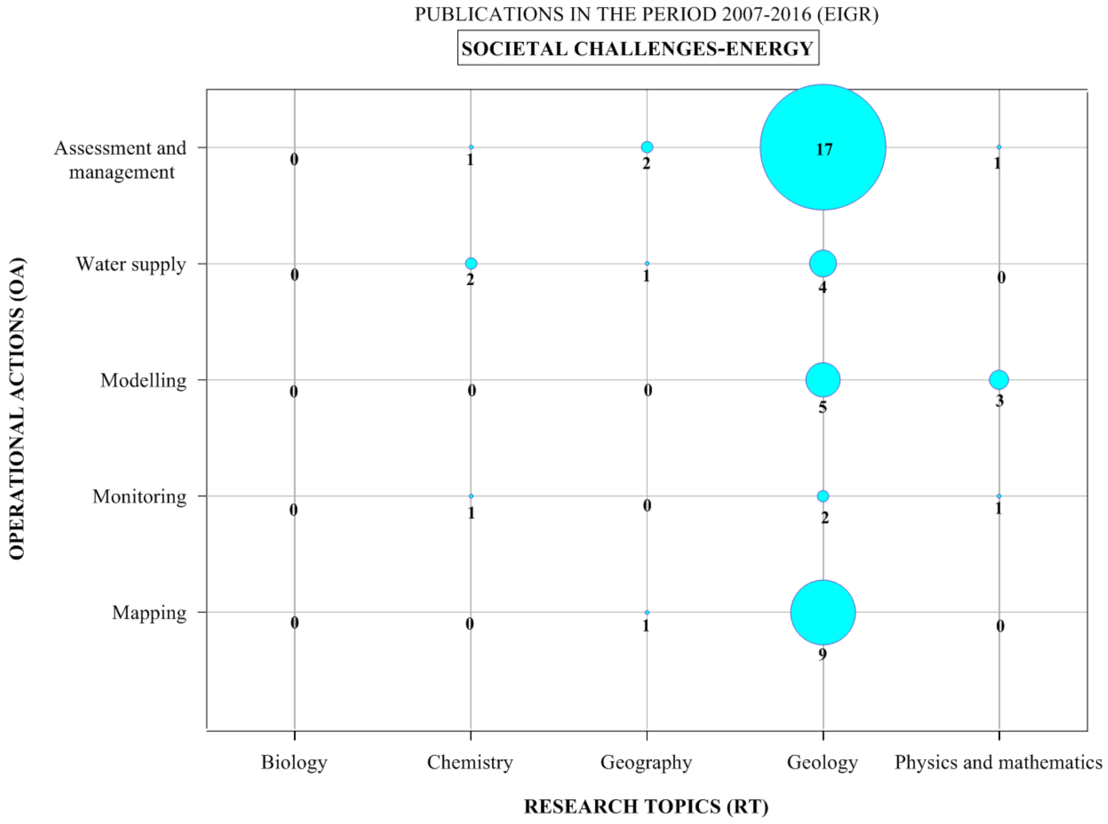


Figure 8.6 SC Energy from EIGR: 2007-2016

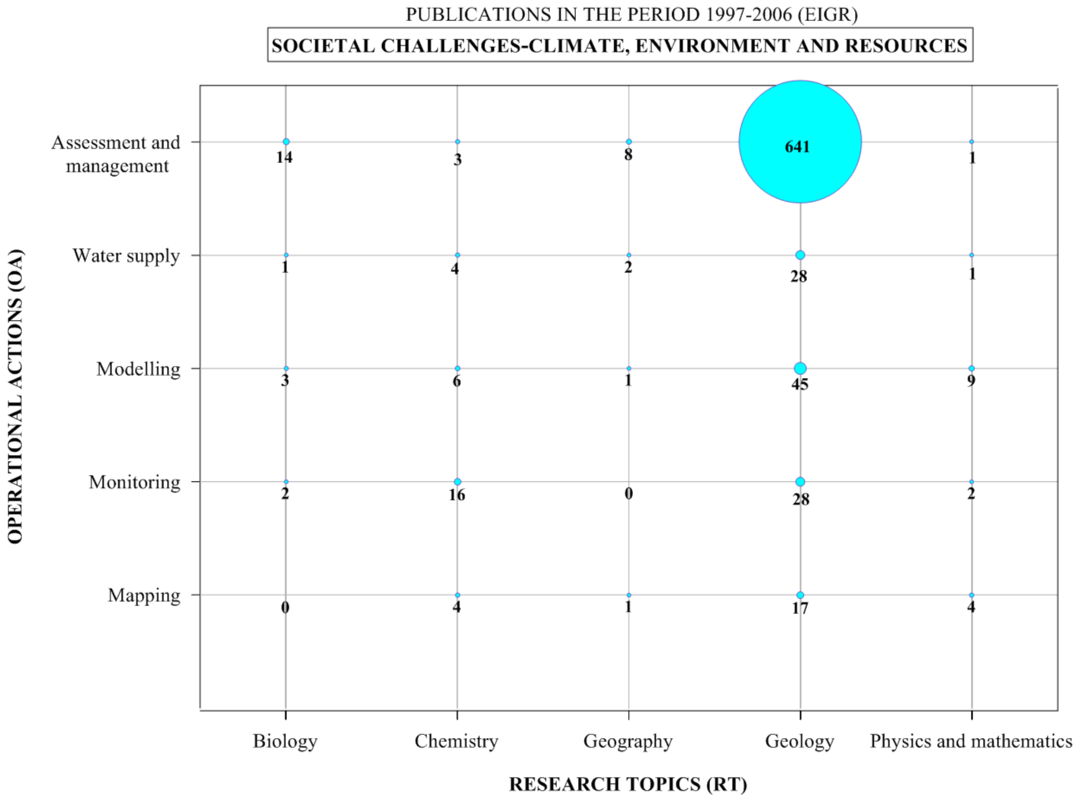


Figure 8.7 SC Climate, Environment and Resources from EIGR: 1997-2006

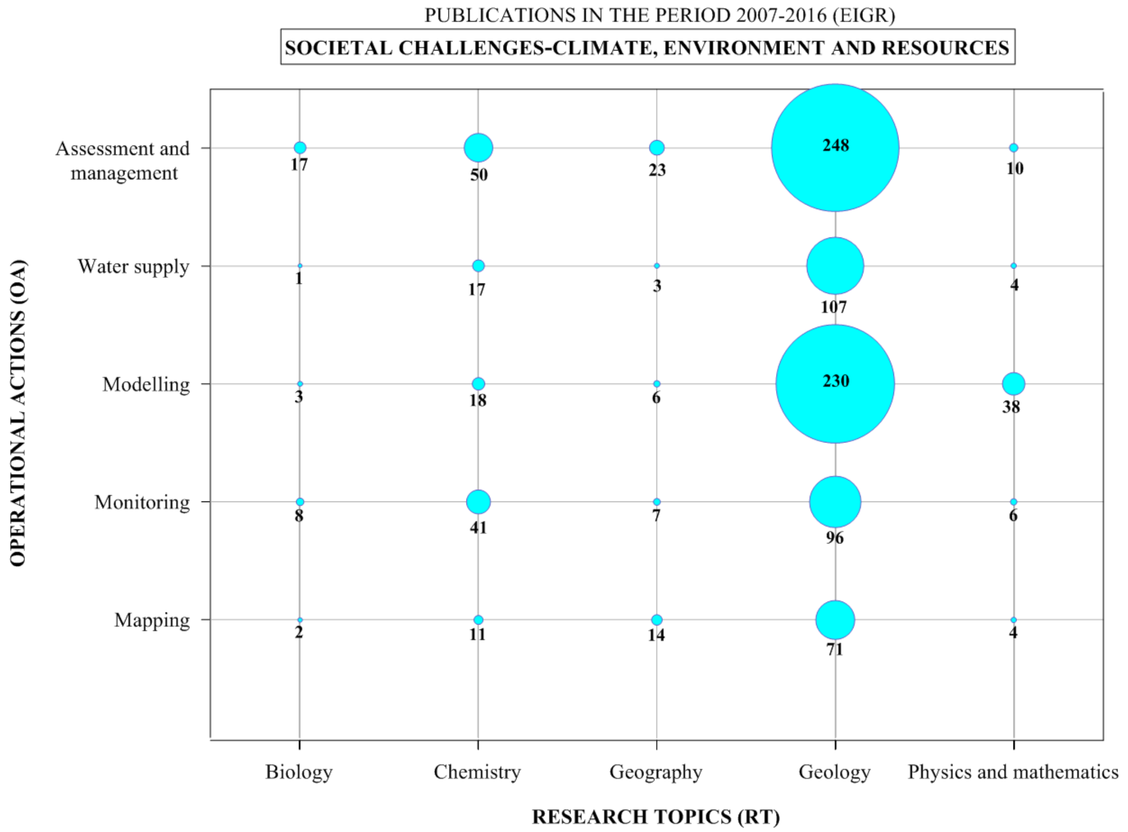


Figure 8.8 SC Climate, Environment and Resources from EIGR: 2007-2016

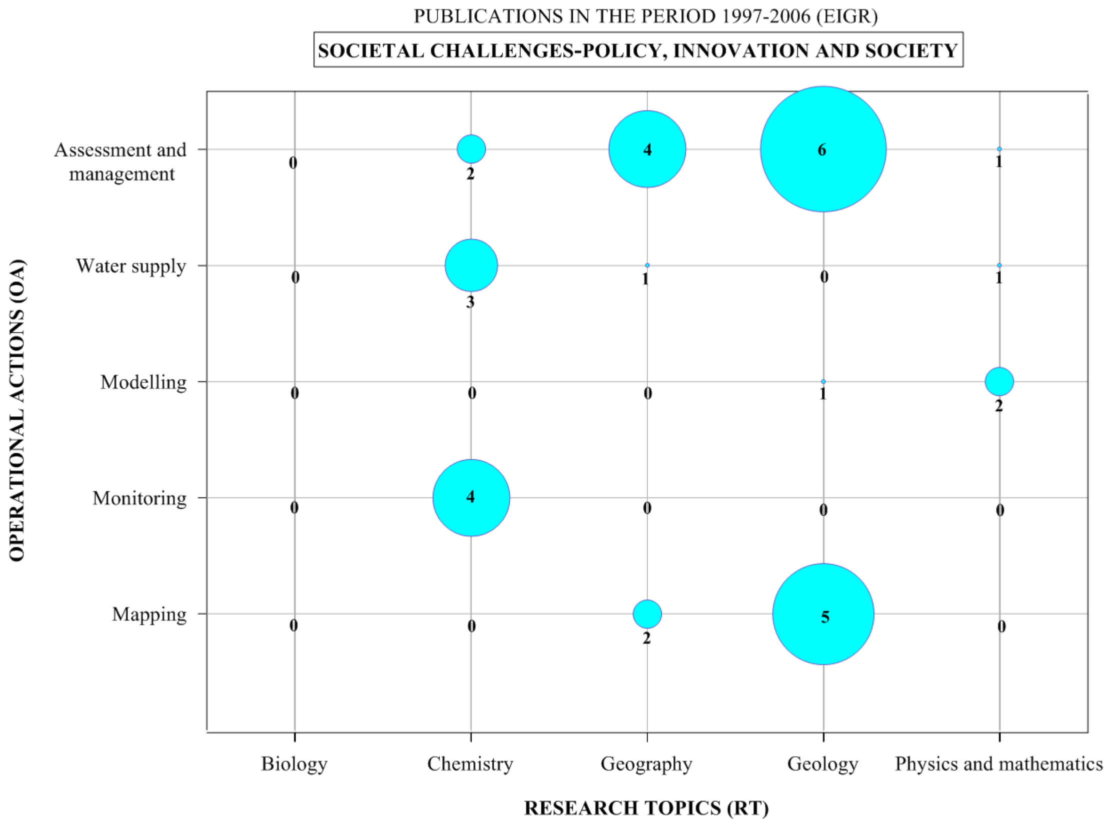


Figure 8.9 SC Policy, Innovation and Society from EIGR: 1997-2006

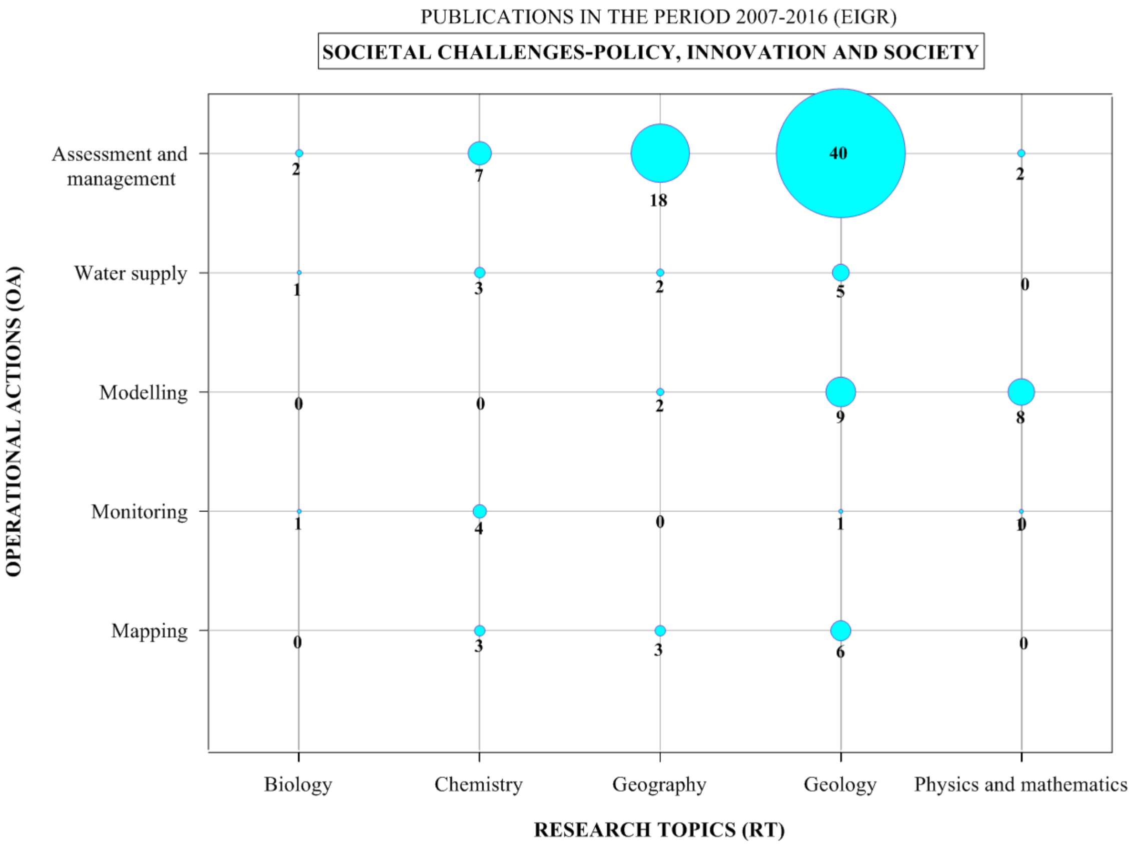


Figure 8.10 SC Policy, Innovation and Society from EIGR: 2007-2016

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