Mapping Science Through Bibliometric Triangulation: An Experimental Approach Applied to Water Research

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The idea of constructing science maps based on bibliographic data has intrigued researchers for decades, and various techniques have been developed to map the structure of research disciplines. Most science mapping studies use a single method. However, as research fields have various properties, a valid map of a field should actually be composed of a set of maps derived from a series of investigations using different methods. That leads to the question of what can be learned from a combination—triangulation—of these different science maps. In this paper we propose a method for triangulation, using the example of water science. We combine three different mapping approaches: journal–journal citation relations (JJCR), shared author keywords (SAK), and title word-cited reference co-occurrence (TWRC). Our results demonstrate that triangulation of JJCR, SAK, and TWRC produces a more comprehensive picture than each method applied individually. The outcomes from the three different approaches can be associated with each other and systematically interpreted to provide insights into the complex multidisciplinary structure of the field of water research.

Received August 17, 2014; revised November 13, 2015; accepted November 16, 2015

• Published online 3 August 2016 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/asi.23696

Introduction

Bibliometrics provides a set of methods to describe quantitatively various attributes of a corpus of literature, such as patterns in journal, paper, or author relations. In this way, bibliometrics provide insight into knowledge dynamics: the development of knowledge in a given area in relation to a larger knowledge landscape. A variety of techniques have been developed to map the structure and dynamics of disciplines and its research fronts. Coword analysis and citation analysis are the most commonly used bibliometric mapping methods based on the content of and the relations between publications in a field. Comparing word-based and citation-based maps leads to different clustering outcomes, suggesting that one most likely needs multiple maps showing different insights (Börner, Chen, & Boyack, 2003).

In the past decade, attention to science maps has increased, and different kinds of science maps have been proposed to reveal relations among, for example, authors, documents, journals, or keywords, and they are usually constructed based on citation, cocitation, bibliographic coupling, or co-occurrence of words in documents. These mapping methods may be broadly grouped according to different levels of scope based on their targeted units of analysis, for example, analysis of journal citations may present the broadest scope at the journal level; coauthorship or title word co-occurrence analyses may present a highly condensed summary content level; and keyword, abstract, or content words co-occurrence analyses may represent more detailed content levels. Many of these methods have been successfully applied to various scientific fields. Most of the empirical studies map science using a single method, depending on the purpose of the study (for an overview, see Morris & Van der Veer Martens, 2008). Apart from the analytical tools, the recent decade also has shown an increased emphasis on the visualization of the results. Also, mapping studies have started to compare the cluster solutions resulting from various similarity approaches or classification algorithms (Ahlgren & Colliander, 2009; Börner et al., 2003; Janssens, Zhang, Moor, & Glänzel, 2009; Jarneving, 2005; Lu & Wolfram, 2012; Shibata, Kajikawa, Takeda, & Matsushima, 2009) to find "the most accurate representation" (Boyack et al., 2011; Boyack & Klavans, 2010).

However, as is the case with geographical maps, different maps highlight different aspects of the phenomenon under study. For science maps to be reliable and useful, they should be based on a combination—a "triangulation"—of mapping approaches using a variety of data. In social science, *triangulation* is defined as the mixing of data or methods so that diverse viewpoints cast light upon a topic (Olsen, 2004). Cohen and Manion (2000, p. 254) viewed triangulation as an "attempt to map out, or explain more fully, the richness and complexity of human behavior by studying it from more than one standpoint." Altrichter, Posch, and Somekh (1993, p. 117) contended that triangulation "gives a more detailed and balanced picture of the situation."

Although scholars have started realizing that using multiple maps provides a broader picture of a scientific field (Börner et al., 2003), it is not yet common practice. One reason is that even mapping outcomes from individual approaches are already often complex to interpret. Another reason is that we lack systematic methods for comparing maps. The key challenge in this paper is developing such a systematic "triangulation" method for linking multiple mapping approaches and interpreting them in a meaningful manner. To do this, we first select three often-used approaches for mapping scientific fields. In addition, we propose a method for cross-tabulation of clusters revealed by the science maps.

As a proof of concept, we apply this bibliometric triangulation method to water research. This field was selected because the scope and volume of water research are growing rapidly, making it increasingly difficult to understand the complex relationships between the involved scientific specialties. This poses challenges for effective research planning in this important societal field of science (and technology). Consequently, there is a need to better characterize, define, and understand the field of water research.

This paper contributes to the development of bibliometric metrics that helps to formulate a (practical, relevant) theory of knowledge dynamics. We explore how different approaches to mapping a scientific field provide different insights, and how they can be related. We demonstrate how triangulation results, in conjunction with visualization, can lead to a better understanding of the (disciplinary or interdisciplinary) structure of scientific fields.

The paper is organized in five sections. The Research Framework and Related Work section introduces a triangulation model based on a multimethod approach used to delineate knowledge domains and identify research specialties, including a brief review of the related bibliometric techniques. The Data and Methods section details data collection and the application of our model. In the Results section, we show the cognitive maps derived from each individual methodology for delineating the field of water research. In the Triangulation section, we combine the three methods and illustrate the added value of triangulation. Finally, we draw conclusions and end with a general discussion.

Research Framework and Related Work

In this section, we discuss several commonly used bibliometric methods and provide the reasoning behind our triangulation framework. Boyack et al. (2005, p. 352) stated that a correctly constructed science map can help to understand the inputs, associations, flows, and outputs of science and technology: "Just like in a physical world, maps help us to understand our environment—where we are, what is around us, and the relationships between neighboring things." The issue in this paper is not so much whether the map is "correct," but what different insights come from differently constructed maps. Morris and Yen (2004) have identified a variety of entities that can be the object of mapping exercises, such as papers, authors, references, journals, and terms (e.g., keywords). These basic entities of science are interlinked through papers. For example, papers are written by authors, published in journals, characterized by title words and keywords, and linked to other literature through cited references.

Papers contain new knowledge in detail as well as changes in the interests and concerns of the discipline or the author constituencies. They embody the evolution and dynamic of science over time. They are one of the most common units used to map a knowledge domain (Börner et al., 2003). We can construct maps by clustering papers based on title words, keywords, references, journals, or combinations thereof. The clusters of (in one or another way similar) papers are the entities the map consists of. A *keyword* is an index term representing the core of a documents' *content*, such as the method and the specific objects. Authors as well as editors assign keywords to papers. We use the author keywords because that can be considered a careful positioning of the paper (Whittaker, 1989). If papers share more author keywords, they have a more

DOI: 10.1002/asi

similar technical content. *Title words* have a different role. Although they may lead to similar maps in small and homogeneous fields, in larger fields title words refer more to the newness and the topic of the study (Whittaker, 1989). By selecting references, authors link their work to previous work. This better represents the disciplinary (or multidisciplinary) identity of the work than the technical content or the topic. The emergence of field-specific academic journals is a sign of the growth and maturity of a discipline. Journals are scholarly media, normally long lived, and journals belonging to the same field have similar aggregated citation patterns. Delineating a journal communication network may offer more definitions of disciplines and specializations. Journal maps can also provide the relative relationships between major disciplines at a macro view of science (Börner et al., 2003). This makes it possible to define how different fields of knowledge interact and provides effective ways of evaluating research performance and predicting interdisciplinary impact (Garfield, 1972; Van den Besselaar & Leydesdorff, 1996).

The two entities (papers and journals) and the three attributes (keywords, title words, and references) can be analyzed using different bibliometric procedures, leading to different maps, each of which may clarify specific aspects of a field. We want to study whether triangulating (combining) these methods tells more about a field than the different maps together. We start with three different analytical procedures (analyzing journal structures using references; analyzing papers structures using keywords; analyzing papers structures using title words and references). The resulting maps give a first analysis of the field. As journal clusters can also be handled as clusters of papers, we have three paper-cluster structures. Cross-tabulation of the three paper-cluster structures provides interesting additional information about the field (in this paper, water research).

Journal Networks Based on Journal–Journal Citation

In most disciplines, journals are the dominant channel of scholarly communication. Journals provide entries into topical specializations (research fronts) within a field or a discipline, and they provide researchers with means to find relevant information. Journals belonging to a field are expected to have a shared knowledge base, which forms a major source for references in papers published in those field specific journals. Consequently, journals belonging to a (sub)field are expected to have similar aggregated citation patterns. Analyzing patterns of citation between journals allows us to delineate scientific fields, as well as to determine knowledge flows between fields. Journal–journal citation analysis has been widely accepted as a powerful method for mapping the intellectual structure and dynamics of science at the macro level, and for the analysis of scientific specialties and the disciplinary organization of the sciences in terms of networks of journals (Van den Besselaar & Leydesdorff, 1996). Delineating research fields on the higher aggregation level is an essential step to investigate the (inter)disciplinary identity of research fields (Van den Besselaar, 2000; Van den Besselaar & Heimeriks, 2001; Vugteveen, Lenders, & Van den Besselaar, 2014). Journal–journal citation analysis enables us to delineate knowledge domains and to sketch out the boundaries between research specialties.

Publication Networks Based on Keywords

Coword analysis, introduced by Callon, Courtial, Turner, and Bauin (1983) and Callon, Law, and Rip (1986), makes use of the patterns of co-occurrence of words or phrases in a corpus of texts to cluster the texts thematically. For the most part, it is based on title words, abstract words, or keywords, although increasingly full text is used. Coword analysis has been used to map the cognitive structure and the development of research fields (Bauin, 1986; He, 1999) and of science as a whole (Boyack & Klavans, 2014). Quite a few researchers have used cokeyword analysis to reveal patterns and trends in a specific discipline. Some examples concern technology foresight (Su & Lee, 2010), research policy (Lee & Su, 2010), ethics and dementia (Baldwin, Hughes, Hope, Jacoby, & Ziebland, 2003), library and information science (Åström, 2002), and information retrieval (Ding, Chowdhury, & Foo, 2001).

Whittaker (1989) mapped the structure of scientific fields by using coword analysis of both the keywords and the titles of a set of papers. His study suggested that the keyword-derived results provide substantially greater detail than title or abstract words because as the former tends to show the relationship with other papers, whereas the latter often emphasizes the supposed originality of a paper. In this paper, we use papers, rather than words, as the units of analysis to compare the resultant network with the other paper network. We use the author keywords-based approach drawing upon Whittaker's argument that authors choose technical terms carefully to constitute an adequate description of the content in terms of problem/method combinations. Consequently, the more co-occurring keywords two papers share, the more similar they are. This creates a paper network that provides a good entry point for understanding the set of problems and related methods structure of a scientific field.

Publication Networks Based on Word-Reference Combinations

Science maps of articles are not only based on keywords, as in the previous section, but also on title words and citation relations (cocitation analysis or bibliographic coupling). In all of these cases, only one attribute is used. An increasing set of "hybrid" approaches at article level has been developed using combinations of attributes of papers (Zitt, 2015). For instance, Braam, Moed, and Van Raan (1991) investigated the structural and dynamical aspects of science maps based on a sequential combination of author cocitation and coword analysis. Åström (2002) constructed maps for delineating library and information science using the co-occurrence of keywords and cited authors. Zitt and Bassecoulard (2006) developed hybrid approaches associating lexical and citation-based analysis that they believe can be

TABLE 1. Initially selected search terms.

Initial search terms PY = 2008–2009 (October 2010)	No. of hits	No. of unique hits	% of unique hits	Impact on initial data set, %
TS = water treat*	28,991	17,133	60	48
TS = water quality	15,545	9,703	62	26
TS = drinking water	6,836	3,239	47	11
TS = (waste water OR wastewater)	16,919	9,098	54	28
TS = desalinat*	1,029	637	62	2
TS = hydrolog*	7,555	6,465	86	13
Sum	76,375	46,275		128
Combination (total number of documents)	60,162		77	

*Indicates that we retrieved all words using the indicated word stem.

efficiently applied for clustering and mapping research specialties. Boyack and Klavans (2010) tested the accuracy of cluster solutions resulting from different similarity approaches, including a hybrid text-citation approach—and suggest that the hybrid approach has more potential.

Our analysis is based on shared co-occurring title word-cited reference combinations (Van den Besselaar & Heimeriks, 2006). Word-reference analysis differs from the well-known concept of bibliographic coupling because it includes not only references but also title words for the coupling of texts. The idea behind this hybrid approach is that title words point at the topic of research, whereas cited references represent the relations of the paper with previous research, indicating the paradigmatic identity of a paper. Scholars select title words to describe the supposed originality of their research and cite specific literature to indicate the tradition to which their work is related. Title word-cited reference combinations measure these dimensions simultaneously, providing a fine-grained topical structure of a scientific field or specialization. Other advantages exist too, such as avoiding threshold (and through this coverage) problems (Van den Besselaar & Heimeriks, 2006).

Data and Methods

There are many ways to collect the bibliographic data and map the scientific fields, either globally (those based on the entire bibliometric databases such as the Web of Science [WoS] or Scopus) or locally (those based on a subset of data). In this study, we focus on water-related science and technology for which the related bibliographic data represent only a subset of the entire database. The mapping solution from this subset is also expected to be different from a global solution using the entire database. To achieve a solution that is specific and fitting the targeted water domain, we consulted content experts to judge if our selected sets of publications and the resultant clusters make sense rather than relying on parameters from unsupervised algorithms. Furthermore, the idea of triangulation is to address the complex interrelationships between clustering solutions at three distinct levels of scope, that is, journal level, content level, and paper level. Therefore, we chose some of the established analytical methods at each level, that is, journal mapping (Leydesdorff & Cozzens, 1993; Van den Besselaar & Leydesdorff, 1996), coword (here keyword) mapping (Callon, 1986; Klavans & Boyak, 2006), and hybrid citation/lexical mapping (Van den Besselaar & Heimeriks, 2006).

We avoid discussions of what constitutes the "best method" for doing journal citation-based mapping, hybrid mapping (Boyack and Klavans, 2010), or for coword analysis-based mapping (Boyack et al., 2011). First, because the "best" is in our view often not the issue—different mapping methods result in maps offering different perspectives of the field under study—and second because we focus in this paper on how those differences can be used productively.

We use the following analytical steps.

1. Selecting an appropriate data set using relevant search terms. This leads to the delineation of a corpus of relevant papers—in interaction with field experts.
2. Organizing the data relating to a unit of analysis, that is, constructing title word-cited reference combinations, a list of shared keywords, and journal–journal citations counts.
3. Calculating correlations or similarities for each unit of analysis (papers and journals), applying a clustering algorithm to identify research communities, and visualizing the structure of the data using social network analysis software.
4. Assigning higher-level denominations to the communities identified in each map in order to interpret the three structures—in interaction with field experts. This leads to a conclusion about what the different maps show.
5. Triangulation: "cross-tabulation" of the three maps to deepen the understanding of the structure of the field.

Data Acquisition and Preparation

The analysis is based on 2010 publications downloaded from the five citation databases of Thompson Reuters WoS in April 2013.[1] We used "topic search," which retrieves documents based on the appearance of selected search terms in the title, the abstract, or the keywords. We restricted the search to citable items: articles, reviews, proceedings papers, notes, and letters. For processing and analyzing the bibliographic data we used the Science Assessment

[1]We used the five citation databases of Thomson Reuters Web of Science: *Science Citation Index Expanded, Social Sciences Citation Index, Arts & Humanities Citation Index, Conference Proceedings Citation Index-Science,* and *Conference Proceedings Citation Index-Social Science & Humanities.*

DOI: 10.1002/asi

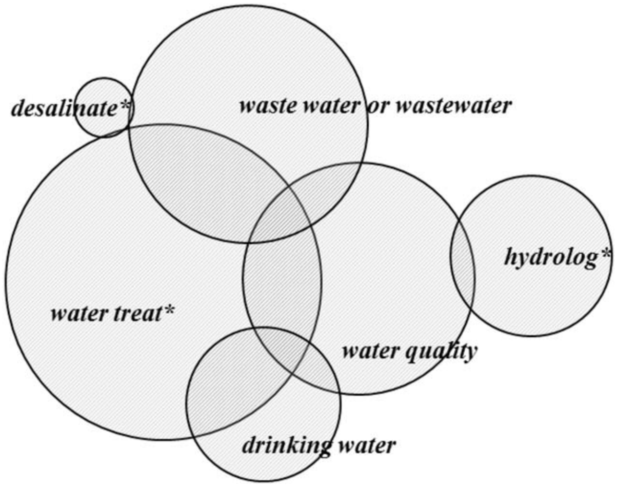

FIG. 1. The extent of disjunction of the initial search terms.

Integrated Network Toolkit (SAINT; Somers, Gurney, Horlings, & Van Den Besselaar, 2009).[2]

The first exploratory task is to define a set of search terms that properly delineates the field of water (related to the production, distribution, and use of drinking water, wastewater treatment, hydrology, etc.). A set of search terms is considered perfect if all resultant papers belong to the water field (precision) and, simultaneously, if all of the papers belonging to the water field are found by this set of search terms (recall). To achieve this goal, the identification of search terms was done through an iterative process of asking experts, retrieving papers, and validating the retrieved set with the experts, then updating the search terms and starting the next cycle. After the experts validated the cognitive maps, a sound balance between recall and precision was reached, and the process was stopped (Van Den Besselaar & Gurney, 2009). The experts involved covered the following water research fields: hydrology, wastewater treatment, waster reuse, drinking water and desalination, and so on, and most of them were employed at a water cycle research institute.

An initial experiment was done with a nonrestricted set of search terms: water treat*, water quality, drinking water, waste water OR wastewater, desalinate* and hydrolog* using topic search in WoS. For the period 2008–2009, there were 60,162 documents in total (Table 1).

The sum of individual search term searches was 76,375, while the sum of unique hits of each individual search term was 46,275. This implies that 77% of the documents were found using only one search term. In the document set, the initial search terms turned out to be rather disjunctive (Figure 1).

The initial document set was used to sketch out preliminary cognitive maps based on keywords, journals, and papers. These maps provided an overview of research communities and their interrelationships. The results were complemented and validated with expert insights. Experts from KWR Watercycle Research Institute[3] were asked to reflect on the obtained set of publications. Their suggestions were included by adding a number of additional search terms, such as "water re-use OR water reuse," "water cycle*," "fluid dynamics," "water system*," "water management," "sewer* OR sewage," "water distribution," "water suppl*," "water safety," "water sanitation," "water resource*," "water quantity," "water demand," "water policy," "water sustainab*," "climate change," "global warming," and "water energy."

Is the selection of search terms correct? There is a tradeoff between precision and recall: The more precise we try to be, the higher the risk that relevant papers are excluded, and the better recall we try to get, the lower the precision generally is. We assessed the list suggested by experts in terms of recall and precision. Adding search terms such as "fluid dynamics," "water safety," and "water energy" increases recall. For instance, 98% of the papers found with the search term "fluid dynamics," 76% with "water energy," and 59% with "water safety" were not included in the initial data set. However, the precision of the data set decreases because these words contain a high proportion of papers belonging to nonrelevant research topics. This becomes clear when we take a closer look at what is behind the unique hits. For example, "fluid dynamics" has a wide range of applications focused much more on mechanical engineering than on water issues. Conversely, search terms such as "water safety," "water energy," and "water re-use OR water reuse" are eliminated from the list because they do not bring in new relevant documents. With the updated search terms, the document set (Table 2) was improved in terms of recall without seriously compromising precision.

We applied the new set of search terms to the WoS 2010 corpus, resulting in 23,406 documents (among which 22,929 are articles, reviews, proceedings papers, notes, and letters). The sum of the results of all individual search terms is 31,685. The sum of the unique hits of each search term is 17,271, which means that 74% of the papers are found through only one search term.

Relationship Matrices

For each of the three approaches we constructed a relationship matrix. The cells of the journal–journal matrix represent the citation frequency, and the cells in the two paper–paper matrices represent the number of shared keywords and the number of shared word-reference combinations. The constructed matrices provide the strength of the relation between the entities (journals, publications). Applying clustering techniques, groups of similar entities (papers, journals) were identified.

Journal–journal citation analysis. From our data set we calculated the number of papers that were published in

[2] SAINT Toolkit is a set of data-processing tools for bibliometric research (Somers et al., 2009).

[3] KWR Watercycle Research Institute (http://www.kwrwater.nl/) is a private R&D firm whose shareholders are publicly owned Dutch drinking water companies.

DOI: 10.1002/asi

TABLE 2. Selected search term combinations for extracting the final data set.

Revised search terms PY = 2010 (April 2013)	No. of hits	No. of unique hits	% of unique hit	Impact on initial data set, %
"water treat*"	2,279	694	30	10
"water quality"	3,235	1,766	55	14
"drinking water"	3,202	1,901	59	14
("waste water" OR wastewater)	7,163	4,560	64	31
desalinat*	608	414	68	3
hydrolog*	3,868	2,682	69	17
"water cycle*"	241	115	47	1
"water system*"	954	671	70	4
"water management"	1,003	446	44	4
(sewer* OR sewage)	2,493	1,147	46	11
"water distribution"	491	249	51	2
"water suppl*"	1,352	532	39	6
"water sanitation"	19	10	55	0
"water resource*"	1,741	615	35	7
"water quantity"	106	20	19	0
"water demand"	256	65	25	1
"water policy"	87	25	29	0
"water sustainab*"	20	4	18	0
("climate change" AND water)	2,217	1,205	54	9
("global warming" AND water)	350	150	43	1
Sum	31,685	17,271		135
Combination	23,406		74	

*Indicates that we retrieved all words using the indicated word stem.

each journal. The distribution of a total of 3,317 journals in the data set is very skewed, and the top 150 journals cover 50% of all papers. Core journals were selected using two criteria: they include more than 1% of total papers in our data set (meaning that the journal is important for the field), or a journals' papers in the data set account for more than 20% of all papers published in that journal (meaning that the journal is enough focused on the field and that water science and technology [S&T] is not a marginal topic in the journal). A total of 24 core journals satisfied these criteria, which accounted for about 25% of all papers in our data set. These 24 journals were used as seeds to further select their interciting journals to construct a journal–journal citation environment. A citing or cited journal was selected if it covers more than 0.6% of all cites from one of the seed journals. The threshold of 0.6% was chosen due to our computational capacity, and it restricts the journal network to 254 journals. The journal–journal citation information was obtained from the *Journal Citation Reports* of the *Science Citation Index*, published by Thomson Reuters. The final relationship matrix with journal citing and cited counts contained 254 inter-citing journals (including the 24 seed journals, covering 11,598 papers in our database) as rows (i) and columns (j), in which the cell (i,j) represents the total number of times journal i is being cited by journal j. This (nonsymmetrical) relationship matrix was normalized using cosine as the similarity measure (Leydesdorff & Probst, 2009).The cosine value was calculated based on the cited dimension, which was used as the input for the subsequent clustering analysis.

Shared keyword analysis. We extracted m ($m = 43{,}745$) keywords from n ($n = 18{,}816$) papers with at least one keyword available. For each pair from the n papers, we counted the number of shared keywords pairs, resulting in a large, symmetric, and pairwise $n*n$ shared keywords matrix. We only considered publications ($n = 9{,}410$) that share two or more keywords with at least one other publication to construct a shared author keyword (SAK) matrix as input for the subsequent clustering analysis.

Word-reference analysis. Consider a paper with a title of x meaningful[4] title words and with y cited references. This paper is characterized by $x*y$ title word-cited references combinations (TWCR). For each pair of retrieved papers n ($n = 20{,}890$), we count the number of shared TWCR combinations. The degree of similarity between each pair of papers is represented by a Jaccard coefficient, which is equal to the intersection of two papers divided by the union of two papers (the sum minus the intersection). This results in an $n*n$ symmetric relationship matrix that was used as input for subsequent clustering analysis.

Clustering Algorithms

The three methods that we compared in this paper share one significant property: They organize the data in the form of large and complex networks. Studying such networks demands efficient methods to retrieve comprehensive information about their structure. We applied clustering algorithms to classify bibliometric units into mutually exclusive communities with high homogeneity within clusters and low similarity between clusters. Furthermore, for identifying and characterizing the important concepts of a scientific field,

[4]Stop words were removed.

DOI: 10.1002/asi

TABLE 3. The number of papers studied by the three bibliometric methods and the overlap.

Method			Covered by JJCR (28 clusters)	Covered by SAK (765 clusters)	Covered by TWCR (192 clusters)
JJCR	Covered	10,864	-	4,856	10,457
	Not covered	12,065	-	4,284	10,433
AWKC	Covered	9,140	4,856	-	8,772
	Not covered	13,789	6,008	-	12,118
TWCR	Covered	20,890	10,457	8,772	-
	Not covered	2,039	407	368	-
Total		22,929	10,864	9,140	20,890

we label the clusters of these research interests in a structured content-map according to the detailed information extracted from each cluster.

Two clustering techniques were applied in our study to find communities of similar papers: Blondel et al.'s method (2008) and factor analysis. The clustering algorithm of Blondel et al. is used to identify coherent clusters in the keyword-based paper network and in the word-reference-based publication network. The method is a heuristic method based on the modularity optimization of the partition as an objective function, which is highly suited to find structure in our data set, because the number of keyword pairs and title word-cited reference combinations can be extremely large.

The combined citation environments of the selected journals were consolidated. The resulting journal–journal citation matrix was factor-analyzed, not using the Pearson correlations between the variables but using the cosine. The processed journals are the independent variables. Factor analysis enables multivariate exploration for either variable reduction or structure detection. It results in clusters of journals with similar citation patterns—which is different from strongly citing each other. When applied to the main journals in our data set, the resulting map shows the different fields and disciplines that constitute water research, as well as fields that provide relevant knowledge to these fields and disciplines (Van den Besselaar & Leydesdorff, 1996).

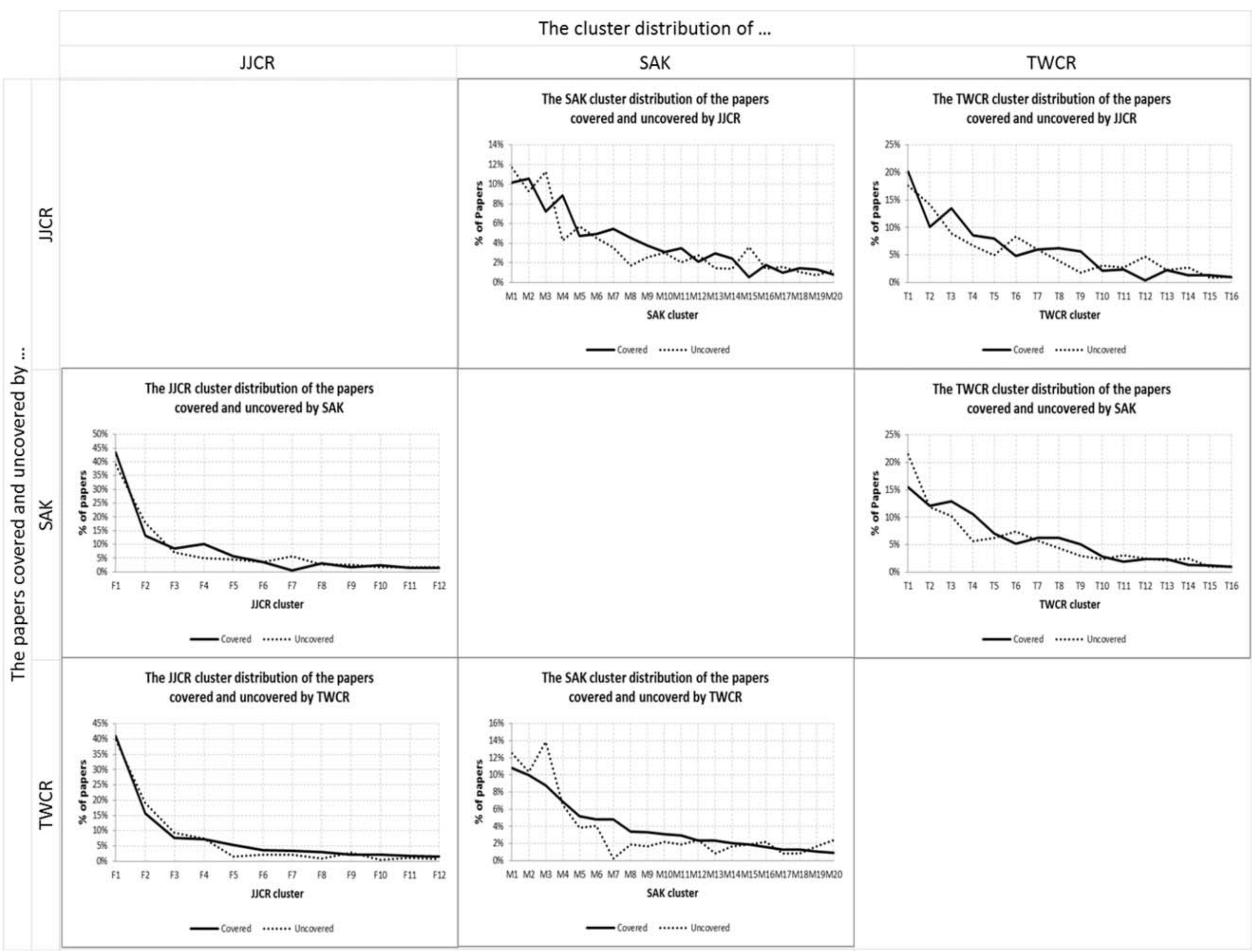

FIG. 2. Cluster distribution of covered and uncovered papers.

DOI: 10.1002/asi

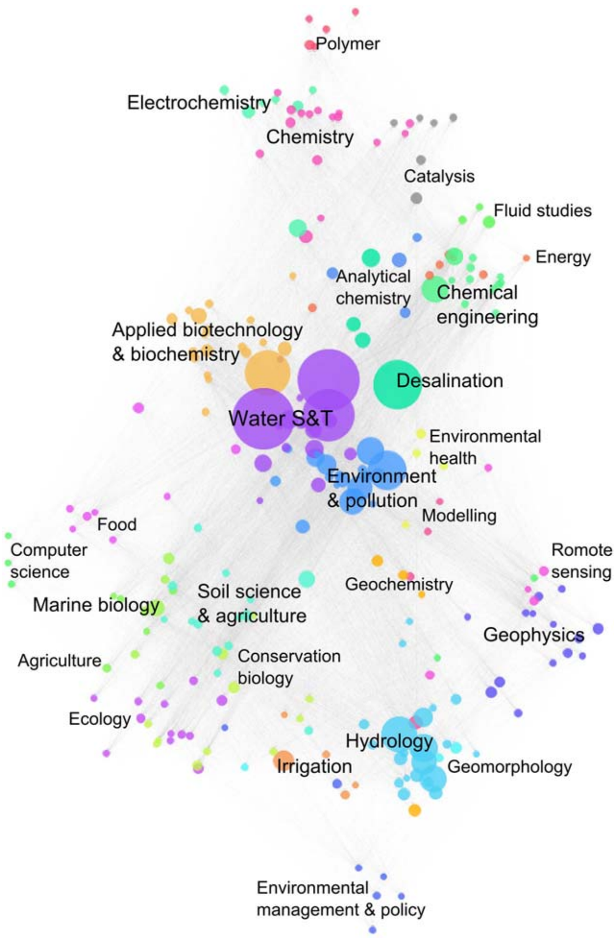

FIG. 3. Journal citation network for water research. The journal citation network contains citing and cited journals in the environment of entrance journals accounting for a minimum of 0.6% of the total environment. The nodes are journals and their size is proportional to the number of publications (N = 10,864) in our data set. The edges between the nodes denote the strength of the correlation between their citation patterns, not the actual citations. Factor analysis suggests that the journals are clustered into 28 clusters. The color of the nodes indicates to which cluster they belong. The clusters have been named according to the aims and scope of the journals belonging to it. The layout was created using the OpenOrd algorithm in Gephi. [Color figure can be viewed at wileyonlinelibrary.com]

Visualization

Similarity, occurrence, and correlation between publications, keywords or journals can be expressed in the form of network data. The networks were visualized in Gephi (Bastian, Heymann, & Jacomy, 2009), a software tool for large network analysis, using the OpenOrd layout algorithm (Martin, Brown, Klavans, & Boyack, 2011).

Triangulation Through Cross-Tabulation

As explained previously, we mapped the field of water research using three different approaches: as journal clusters (JJCR), as publications clusters through shared author keywords (SAK), and as publications clusters through shared word-reference combinations (TWCR). Each approach provides its own insight into the structure of a field, which can be visualized in the form of a network. The objective of triangulation is to relate the results of the different bibliometric approaches. We analyze the results using three cross-table comparisons.

Each of the clustering methods assigns a paper to a set: a journal set representing a field; a paper set representing a topic and a paper set representing a problem/method combination. We now can do the following cross-tabulations:

i. Topics by field. This shows how topics are embedded in one of more fields—and informs us about the disciplinarity of the topics. If most of the papers of a topic belong to only one field, the topic is clearly monodisciplinary, if the papers are in more fields, the topic is multidisciplinary. As there are always some papers of a topic in any field, we only count those fields that cover at least 5% of the papers of the topic. The number (N) of fields is similar to the variety (Porter & Rafols, 2009). Not only is the number of fields (N) per topic relevant but also the distribution of the papers of a topic over the fields. If a topic is mostly in one field and only slightly in others, it is less multidisciplinary than in the case the papers of a topic are evenly distributed over fields. We use the coefficient of variation (CoV) for this: the ratio of the standard deviation and the mean, and this is similar to *balance* as defined by Porter and Rafols (2009). The lower the CoV is, the more evenly the papers are distributed over the involved fields, the higher the level of multidisciplinarity.
ii. Methods by field. This shows the relation between the methods and the fields: what methods are used in the water research fields, and in what other fields are they developed and used. Here again, there may be a 1-to-1 relation between method and field, or a method may be used in more fields. In the same way as with the topics we can define the multidisciplinarity of the methods: the higher the N and the lower the CoV, the more multidisciplinary the method is.
iii. Topics by methods. We can describe the use of methods in the various topics, and calculate the degree of "multimethod" of the topics. And we obtain insight into which topics are covered by similar methods—and which methods.

Coverage

Table 3 summarizes the coverage of the papers clustered by these three methods. In total, there were 1,823 of 22,929 papers that were not covered by any of these three methods.

We compared the papers covered by a method with the papers uncovered by that method. This was done by looking at how these papers were clustered through the two other methods, that is, if the covered and uncovered papers in one method show different clustering solutions in another method. Figure 2 shows that the covered and uncovered papers by one method followed roughly the same distribution

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through other clustering methods, and therefore the included papers seem a reasonable sample from the complete papers set, with only a few exceptions—exceptions that may need further exploration in follow-up studies. This indicates that although a substantial proportion of papers were excluded by our filtering criteria, it is unlikely that it led to a biased figure about the interrelationships between the clustering results from different methods.

Results

In this section, we apply each individual method to delineate the field of water research. The results are described in the following subsections.

Clustering Using Journal Citation Relations

What are the dominant journals and citation environment in water research and technology? From the document set, we selected the most frequently occurring 24 journals.[5] These journals were used as entrance (or seed) journals for building the citation environment of water research. The citation environment contains 254 journals. Factor analysis was used to cluster these journals according to similarities in the way they cite other journals in the environment, resulting in 28 factors, each representing a different research field. Figure 3 illustrates the structure of the journal citation environment. In the center of the map we find two factors (clusters): "water science & technology" and "environmental science." These two factors contain a large part of the entrance journals (25% each) and therefore form the core of water research. Next to it, we have a third smaller cluster belonging to water research, which is desalination. Also, this contains several (8%) entrance journals, but these form half of the desalination factor. The fourth water research-related cluster is hydrology, which contains 21% entrance journals. The distance in the map between hydrology and the three other clusters indicates that water research in our definition may consist of two weakly linked parts.

The network furthermore shows the relative position of different scientific fields that are related to water research, and some may be a knowledge source for water research, and others may use water research results. For example, close to "water science and technology" we find "biotechnology," suggesting that in water research some biotechnology knowledge and methods may be used.

[5]*Water Science and Technology, Journal of Hazardous Materials, Water Research, Desalination, Bioresource Technology, Environmental Science & Technology, Journal of Hydrology, Water Resources Research, Chemosphere, Hydrological Processes, Chemical Engineering Journal, Environmental Monitoring and Assessment, Water Resources Management, Science of the Total Environment, Agricultural Water Management, Water Air and Soil Pollution, Hydrology and Earth System Sciences, Water Environment Research, Fresenius Environmental Bulletin, Journal of Environmental Sciences-China, Journal of Membrane Science, Industrial & Engineering Chemistry Research, International Journal of Hydrogen Energy, and Ecological Engineering.*

The value of the journal map is that it shows some main characteristics of water research, and it shows the relative positions of different scientific fields that are related to water research. That clarifies some aspects of the nature of water research, but leaves unknown other crucial characteristics, such as the research fronts and their methodological and (multi) disciplinary nature. As discussed later, for that one needs, the combination of maps.

Clustering Using Author Keywords

The SAK method clusters 9,410 papers into 765 clusters. We only include the top 20 communities in the analysis (those containing at least 1% of total publications), which account for 82% of the total or 7,717 publications. The keyword communities appear to reflect various methods used in the water research field in relation to the specific research aim or problem, such as filtering (the method) for organic matter removal (the problem to be solved). The keyword network offers a content map. Figure 4 presents the resulting map and reveals the relationships among publications in terms of shared keywords.

The dominant community in the map is "modeling the relationship between land use and water quality," with about 10.5% of the papers. The map reveals a dichotomy between the models used in water management on the left side of the map and the techniques used in water treatment on the right side.

The advantage of the keyword-based map is that we show what method/problem combinations dominate water research. But the map at the same time only reveals partial insight, as the relationship between these methods and the dominant research fields and the main research topics remains unclear.

Clustering Using Title-Words/Cited-Reference Combinations

The TWCR method clusters 20,890 publications into 192 communities (Figure 5). Community names have been assigned on the basis of author keywords, assigned keywords, title word combinations, journal titles, journal categories, most cited articles, and authors. To do so, we also examined subcommunities in each community (communities aggregated at a lower level). The results provide insight into the cognitive structure of water research topics—the focus of this paper. The largest community is "influence of climate change on hydrology cycle and water resource management" with about 19.0% of the papers. Quite a few other research topics relate to wastewater treatment in different ways. Also, this map reveals a dichotomy—here between water management on the left side of the map and water science and technology on the right side.

One of the questions that immediately comes up here—but cannot be answered with this map alone—is about the disciplinary nature of the research topics. Also, here we assume that triangulation may help.

DOI: 10.1002/asi

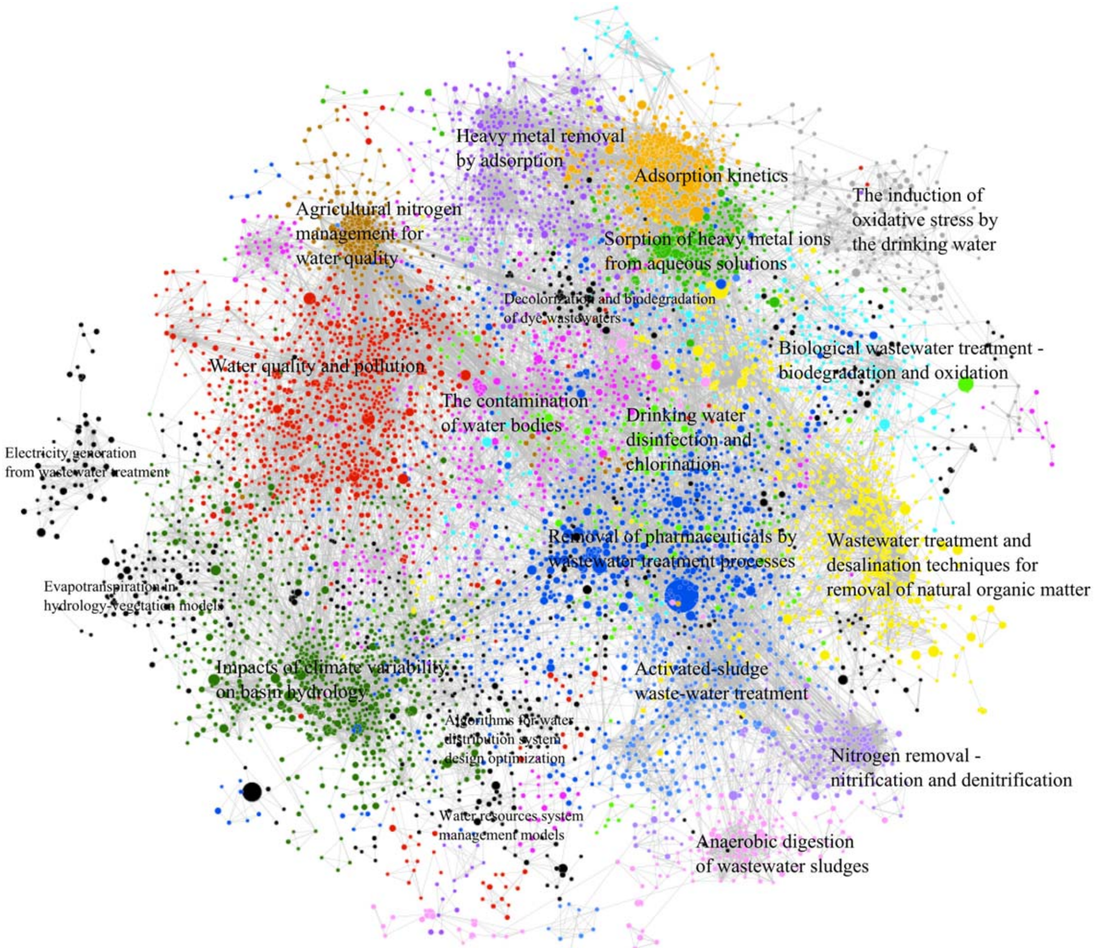

FIG. 4. Publication map of water research based on shared keywords. Each node is a publication. The size of nodes indicates the number of times the publication was cited. The edges indicate the shared keywords in each pair of publications. Of the total of 18,816 publications containing keywords, the figure only contains 9,410 publications that share at least one pair of keywords. The publications in the top 20 clusters ($N = 7,717$, 82% of 9,410 publications) are colored according to the cluster to which they belong. The rest of the publications in black are not in the core of the water research community based on keyword co-occurrences. The layout was created using the OpenOrd algorithm in Gephi. [Color figure can be viewed at wileyonlinelibrary.com]

Triangulation

We used three bibliometric approaches for studying the cognitive structure of scientific fields using the water research field as an example. The clustering results from these approaches (Figures 3–5) obviously highlight different perspectives. The analysis of the journal citation networks shows the disciplinary environment of water research. For example, JJCR analysis shows that “environmental science” and “water science & technology” are the central disciplines of the field (Figure 3). The SAK focuses more on the content in terms of approaches, methodologies, and techniques used to solve specific problems. For example, various modeling techniques are used to support management of water quality and nutrient pollution, as shown in the largest cluster (Figure 4). On the other hand, the TWCR outcomes shed light on the dominant research topics. For example, some research addresses challenges related to climate change and water resource management, as well as to wastewater treatment (Figure 5). Although the three bibliometric approaches are all valuable, they also lead to rather different maps, each providing only a partial image of the complex structure of the field. Understanding the relations and differences between the three clustering outcomes may therefore provide a more comprehensive picture. In the next section we will answer the question of how the three maps can be combined, using cross tabulation.

Cross-Tabular Analysis

The main clusters derived from three different mapping approaches, that is, the 12 largest JJCR clusters (J1–12; see Appendix A3), the 20 largest SAK clusters (C1–20; see Appendix A2), and the 16 largest TWCR clusters (T1–16; see Appendix A1), were cross-tabulated in a pairwise manner (Tables 4–6). The shading of the cells represents the distribution of a topic across fields (Table 4), of a method across fields (Table 5), and of a topic across methods (Table 6).

DOI: 10.1002/asi

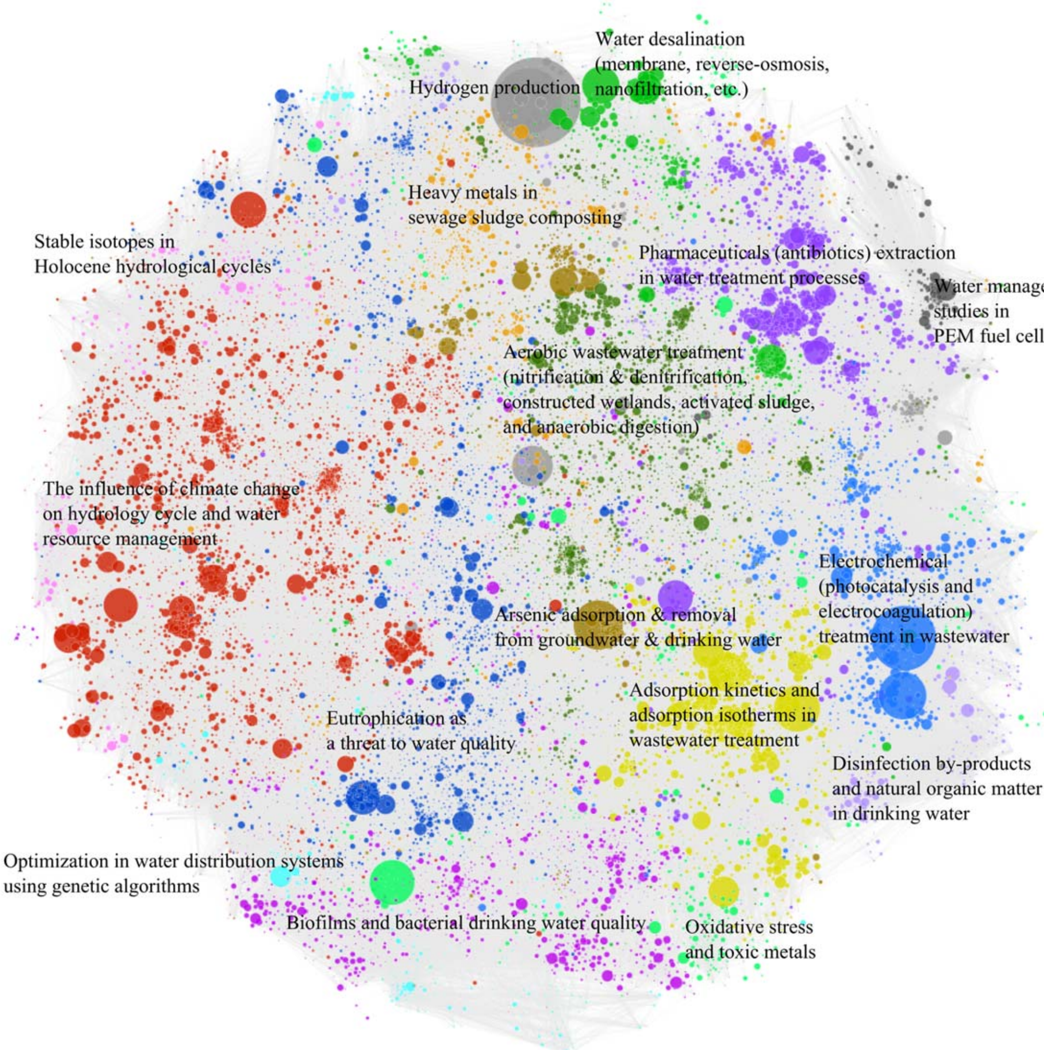

FIG. 5. Publication map of water research based on shared title words–cited reference combinations. Each node is a publication. The size of nodes indicates the number of times the publication was cited. The edges indicate the degree of similarity between each pair of papers. The map contains only publications in the top 16 clusters, each of which accounts for at least 1% of the total (i.e., 19,165 or 92% of a total of 20,890 publications). The colors of the nodes indicate the cluster to which they belong. The layout was created using the OpenOrd algorithm in Gephi. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 4. Topics by field.

	T1	T2	T3	T4	T5	T6	TT	T8	T9	T10	T11	T12	T13	T14	T15	T16	N
Marine biology		0.2															1
Electrochemistry								0.1							0.5	0.9	3
Chemistry				0.1													1
Irrigation	0.1																1
Soil agriculture							0.2							0.1			2
Geophysics	0.2													0.3			2
Chemical engineering				0.1				0.1	0.1				0.1				4
Applied biotechnology/biochemistry			0.3	0.1		0.2	0.1	0.1	0.1	0.1		0.1			0.4		9
Desalination				0.2				0.1	0.5	0.1			0.1				5
Hydrology	0.6	0.1				0.1				0.1	0.6			0.6			6
Environmental pollution	0.1	0.3	0.1	0.1	0.5	0.3	0.4	0.2		0.3	0.1	0.6	0.3				12
Water Science & Technology	0.1	0.2	0.5	0.4	0.3	0.4	0.2	0.4	0.3	0.4	0.2	0.3	0.4		0.1		14
Coefficient of Variation = balance	1.16	0.40	0.68	0.65	0.41	0.47	0.57	0.77	0.93	0.85	0.99	0.87	0.80	0.85	0.51	n.a.	
N(umber of fields) = variety	5	4	3	6	2	4	4	6	4	5	3	3	4	3	3	1	

Values below 5% were omitted—the rest are rounded-up decimals.

DOI: 10.1002/asi

TABLE 5. Methods by field.

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	N
Marine biology	0.1									0.1											2
Electrochemistry														0.2				0.1			2
Chemistry							0.1		0.1												2
Irrigation	0.1		0.2													0.1	0.2			0.1	5
Soil agriculture																	0.1				1
Geophysics																	0.1				1
Chemical engineering							0.1	0.1	0.1		0.1		0.1					0.1	0.1		7
Desalination		0.1		0.4	0.1	0.1	0.2	0.1	0.1		0.1				0.1				0.1		10
Appl biotech/biochemi		0.1		0.1	0.1		0.1	0.2	0.1	0.1	0.3	0.1	0.2	0.3	0.2			0.3	0.2		14
Hydrology	0.2		0.6			0.2				0.1			0.1			0.6	0.4			0.7	8
Environmental pollution	0.3	0.3	0.1	0.1	0.3	0.3	0.1	0.1	0.1	0.3	0.2	0.3	0.1	0.1	0.3	0.2	0.1	0.1	0.3	0.1	20
Water S&T	0.2	0.4	0.1	0.3	0.3	0.4	0.5	0.5	0.4	0.3	0.3	0.5	0.6	0.3	0.5	0.1	0.1	0.3	0.4		19
Coeff of Variation = balance	0.56	0.76	1.04	0.85	0.52	0.59	0.91	0.85	0.87	0.76	0.57	0.74	1.14	0.47	0.67	0.97	0.82	0.68	0.70	1.21	
N(umber of fields) = variety	5	4	4	4	4	4	6	5	6	5	5	3	5	4	4	4	6	5	5	3	

The darker the cell, the more papers are in it. The number of fields (*N*) per topic shows the variety of the fields a topic is embedded in. The same holds for the number of methods by field. The lower the variety (*N*), the more disciplinary a topic is. The CoV shows whether the topics are evenly distributed over the fields: a high or low balance (Porter & Rafols, 2009).

TABLE 6. Topics by method.

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	N
Water resources system management models											0.1					1
Decolorization and biodegradation of dye wastewaters								0.1								1
Electricity generation from wastewater								0.1								1
Hydrological and vegetation modeling	0.1															1
Optimization models concerning system uncertainty											0.5					2
Antioxidants against metal toxicity										0.2		0.6				2
Anaerobic digestion of wastewater sludges			0.1				0.1								0.6	3
Nitrification and denitrification for nitrogen removal			0.2													1
Drinking water disinfection and chlorination process						0.2							0.2			3
Degradation by oxidation kinetics			0.1		0.1		0.1	0.2							0.1	5
Nitrogen management to uphold water quality		0.1	0.1				0.1									4
Adsorption to remove heavy metal ions from aqueous solutions				0.2				0.1							0.1	3
Activated-sludge process			0.2						0.2						0.1	4
Activated carbon adsorption (biosorption) to remove heavy metal ions from aqueous solutions				0.4						0.1						2
Adsorption for contaminants in drinking water	0.1	0.1				0.1		0.1		0.4	0.1	0.1	0.1	0.2		9
Adsorption for removal of heavy metal				0.1		0.1	0.4			0.2		0.1				5
Filtration/ultrafiltration/microfiltration for removal of natural organic matter			0.1	0.1	0.1	0.1		0.1	0.6				0.2	0.1	0.1	10
Modeling the impact of climate variability and climate change in water management	0.5	0.1				0.1	0.1				0.1			0.4		6
Advanced oxidation technologies (solid-phase extraction, tandem mass-spectrometry, TiO2, etc.) for removal of pharmaceuticals		0.1	0.1	0.1	0.5	0.2	0.1	0.4			0.1		0.1	0.1	0.1	11
The management of water quality and nutrient pollution (modeling the relationship between land use and water quality)	0.2	0.5	0.1			0.1	0.1			0.1	0.1		0.1	0.2		9
Coefficient of Variation = balance	0.99	1.1	0.41	0.81	1.26	0.47	0.89	0.98	0.74	0.69	1.02	0.98	0.51	0.84	1.35	1.22
N(umber of fields) = variety	4	5	8	5	3	7	7	7	2	5	6	3	5	5	6	5

DOI: 10.1002/asi

A topic is less multidisciplinary if the CoV is high: then one or two fields are dominant, and the role of the other fields is small. When the CoV is low, the papers of a topic are evenly distributed over the relevant fields, indicating a high balance and therefore a higher level of multidisciplinarity. In other words, these two indicators can be used to measure the level of multidisciplinary of a topic. High variety (High N) and high balance (low CoV) suggest a high level of multidisciplinary.

Apart from these more formal indicators of multidisciplinarity, the three matrices also give substantive insight into the nature of the field. More specifically, triangulation by cross-tabulation shows in what fields the core topics are embedded, and what methods are deployed in these fields and topics, and additionally what fields these methods come from. Together with the findings of the three mapping methods, this cross-tabulation provides a detailed and multiperspective set of maps of the field of water S&T. A few examples may illustrate the specific benefits of the triangulation through cross-tabulation.

i. Topics by fields: most topics in the water research field are highly multidisciplinary, as they are embedded within the fields of water S&T, environmental science, and in some cases also in hydrology or desalination. The multidisciplinary topic of "eutrophication as a threat to water quality" (Topic 2, $n = 4$, CoV = 0.40, Table 4) is more or less equally distributed across four research fields including "environmental pollution," "water S&T," "marine biology," and "hydrology." Moderate multidisciplinary topics are water desalination (Topic 9, $n = 4$, CoV = 0.93), which is mainly in the field of "desalination," and less strongly within "water S&T," and "stable isotopes in Holocene hydrological cycles" (Topic 14, $n = 3$, CoV = 0.85), which is in hydrology and geophysics. Another moderate to weak multidisciplinary topic is "the influence of climate change on hydrology cycle and water resource management" (Topic 1, $n = 5$, CoV = 1.16, Table 4). This topic is mainly but not completely concentrated within the discipline of "hydrology," next to four other marginally involved fields. At the other extreme we find the monodisciplinary topic "Water management aspects of PEM fuel cells" (Topic 16, $n = 1$, CoV = 0, Table 4), which is almost completely within the electrochemistry field
ii. Methods by fields: The cross-tabulation shows what methods are used were, but also the disciplinary background of methods. "Anaerobic digestion of wastewater sludges" (Method 11, $n = 5$, CoV = 0.57, Table 5) is one of the broader deployed methods, as it is used by three water research fields ("water S&T," "environment and pollution," "desalination"), with a firm basis in "applied biotechnology/biochemistry" and "chemical engineering." On the other hand, "water resource system management models" (Method 20, $n = 3$, CoV = 1.2, Table 5) shows a monodisciplinary pattern, as it is mainly used in hydrology research.
iii. Methods used in topics. Also, a different pattern can be identified. The topic of "aerobic wastewater treatment" (Topic 3, $n = 8$, CoV = 0.41, Table 6) involves a most diverse set of methods, such as "nitrification and denitrification for nitrogen removal," "activated-sludge process," "anaerobic digestion of wastewater sludges," "advanced oxidation technologies for removal of pharmaceuticals," "nitrogen management to uphold water quality," "degradation by oxidation kinetics," "filtration/ultrafiltration/microfiltration for removal of natural organic matter," and "modeling for the management of water quality and nutrient pollution." In the same way, the triangulation shows the multimethod nature of some of the other topics. Conversely, "advanced oxidation technologies" is mainly deployed in the topic of "pharmaceuticals (antibiotics) extraction in water treatment processes" (Topic 5, $n = 3$, CoV = 1.26, Table 6).

Summing up, our triangulation approach reveals the multidisciplinary and complex web of fields, methods/problems, and the topical focus of water research.

Conclusion and Discussion

In this paper we presented a triangulation approach to mapping research fields. In contrast to other methods, we do not restrict the map to show the structure of a field at various levels of granularity or its degree of interdisciplinarity. Our mapping exercise also shows the content of the field and the methods and approaches selected. Furthermore, the method indicates the complex relations between fields, topics, and methods and therefore the measurement of multidisciplinarity remains not only a formal characteristic ("the level of multidisciplinarity"), but it gets substantial meaning.

- Using Web of Science data, we mapped the field of water research using three commonly used bibliometric methods: journal clustering through journal–journal citation relations (JJCR), paper clustering using shared author keyword (SAK), and paper clustering through shared title word-cited reference combinations (TWCR). We showed that the three resulting networks represent different phenomena at different levels. Journals are channels of scholarly communication and show the disciplinary environment of water research. JJCR networks map the range of disciplines involved in and relevant for a scientific field. Paper maps based on keyword similarity show the methods, techniques, and materials used in research. Paper networks based on TWCR closely represent the topics that researchers actually study.
- In both paper-based maps, we found a distinction between water management and water technology "regions," with specific research fronts and specific method-problem clusters within each of the two regions.
- By translating the journal map into a paper map, we could identify the three-dimensional overlap of the papers clusters. This underlies the proposed triangulation approach. The three mapping approaches and their integration tell us various interesting properties of the field of water science and technology: (a) In which field water S&T is embedded as well as neighboring fields of the knowledge sources for water S&T, that is, the journal map; (b) what topics are studied within water S&T—the TWCR map, showing the divide between water management and waste water treatment; (c) the dominant methods—the SAK map, which shows the

DOI: 10.1002/asi

dominance of modeling and a large amount of water-cleaning techniques; (d) which topics are multidisciplinary which are not, and more important, what disciplines they are embedded in (topics by field cross table); (e) what methods are deployed in the various topics (the methods by topic cross-table); and finally (f) from which fields the methods are imported (the methods by field cross-table). Here we see the dominant role of biotech and several chemistry fields.
- In this paper we used the method to develop a three-dimensional map of water science and technology at one moment in time. However, as shown elsewhere (Vugteveen et al., 2014), it would be relevant to add a dynamic perspective by relating the journal, keyword, and paper networks at moment T to the same networks at moment T-1. Within the dynamics of science, the convergence and divergence over time of keywords can be used as indicators of scientific specialization. A changing topic structure gives another perspective on the dynamics of research fronts. Finally, changing journal clusters indicate the changing disciplinary structure of science. Then we may be able to investigate how dynamics at the three levels influence dynamics at the other levels. From this perspective, the current paper not only offers a method for making multidimensional static maps of research fields, but it may also contribute to the study of knowledge dynamics.

Overall, our triangulation method successfully integrated the results from multiple maps and enabled a meaningful interpretation that adds to the findings from the individual maps at the different levels. The proposed triangulation method results in a better understanding of the complicated network of water research.

Acknowledgments

The authors thank the ASIS&T SIIGMET student paper contest 2011 committee, and the three anonymous reviewers for their constructive feedback on earlier versions. The authors are also grateful to Professor Wim van Vierssen (KWR Water Research Institute and Delft University) for valuable discussions and advice and to the researchers who participated in the expert meeting at KWR Water Research Institute.

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Appendix A1: Method clusters (SAK)

M1 Modeling for the management of water quality and nutrient pollution
M2 Advanced Oxidation Technologies for removal of pharmaceuticals
M3 Modeling the impact of climate variability and climate change in water management
M4 Filtration/Ultrafiltration/Microfiltration for removal of natural organic matter
M5 Adsorption for removal of heavy metal
M6 Adsorption for contaminants in drinking water
M7 Activated carbon adsorption/biosorption to remove heavy metal ions
M8 Activated-sludge process
M9 Adsorption to remove heavy metal ions from aqueous solutions
M10 Nitrogen management to uphold water quality
M11 Degradation by oxidation kinetics
M12 Drinking water disinfection and chlorination process
M13 Nitrification and denitrification for nitrogen removal
M14 Anaerobic digestion of wastewater sludges
M15 Antioxidants against metal toxicity
M16 Optimization models concerning system uncertainty
M17 Hydrological and vegetation modelling
M18 Electricity generation from wastewater
M19 Decolorization and biodegradation of dye wastewaters
M20 Water resources system management models

Appendix A2: Topic clusters (TWCR)

T1 The influence of climate change on hydrology cycle and water resource management
T2 Eutrophication as a threat to water quality
T3 Aerobic wastewater treatment (nitrification & denitrification, constructed wetlands, activated sludge, and anaerobic digestion)
T4 Adsorption kinetics and adsorption isotherms in wastewater treatment
T5 Pharmaceuticals (antibiotics) extraction in water treatment processes
T6 Biofilms and bacterial drinking water quality
T7 Heavy metals in sewage sludge composting
T8 Electrochemical (photocatalysis and electrocoagulation) treatment in wastewater
T9 Water desalination (membrane, reverse-osmosis, nanofiltration, etc.)
T10 Arsenic adsorption & removal from groundwater & drinking water
T11 Optimization in water distribution systems using genetic algorithms
T12 Oxidative stress and toxic metals
T13 Disinfection by-products and natural organic matter in drinking water
T14 Stable isotopes in Holocene hydrological cycles
T15 Hydrogen production
T16 Water management studies in PEM fuel cells

Appendix A3: Journal clusters (JJCR)

F1 Water science and technology
F2 Environment and pollution
F3 Hydrology
F4 Desalination
F5 Applied biotechnology & biochemistry
F6 Chemical engineering
F7 Geophysics
F8 Soil science & agriculture
F9 Irrigation
F10 Chemistry
F11 Electrochemistry
F12 Marine biology

DOI: 10.1002/asi