Scientometrics (2014) 100:73–96
DOI 10.1007/s11192-014-1286-7

The dynamics of interdisciplinary research fields: the case of river research

Pim Vugteveen · Rob Lenders · Peter Van den Besselaar

Received: 4 July 2013 / Published online: 1 April 2014

Abstract Interdisciplinarity results from dynamics at two levels. Firstly, research questions are approached using inputs from a variety of disciplinary fields. Secondly, the results of this multidisciplinary research feed back into the various research fields. This may either contribute to the further development of these fields, or may lead to disciplinary reconfiguration. If the latter is the case, a new interdisciplinary field may emerge. Following this perspective, the scientific landscape of river research and river science is mapped to assess to which current river research is a multi-disciplinary endeavor, and to which extent it results in a new emerging (inter)disciplinary field of river science. The paper suggests that this two level approach is a useful method to study interdisciplinary research and, more generally, disciplinary dynamics. With respect to river research, we show that it is mainly performed in several fields (limnology, fisheries & fish research, hydrology & water resources, and geomorphology) that hardly exchange knowledge. The different river research topics are multidisciplinary in nature, as they are shared by different fields. However, river science does not emerge as an interdisciplinary field, and often-mentioned new interdisciplinary fields such as hydroecology or hydromorphology are not (yet) visible. There is hardly any involvement of social within river research. Finally, the field of ecology occupies a central position within river research, whereas an expected engineering field is shown absent. This together may signal the acceptance of the ecosystem-based paradigm in river management, replacing the traditional engineering paradigm.

Electronic supplementary material The online version of this article (doi:10.1007/s11192-014-1286-7) contains supplementary material, which is available to authorized users.

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Keywords Cognitive change · Knowledge dynamics · Interdisciplinarity · Multidisciplinarity · River science

Introduction

Recognition of system complexities and societal demands have challenged the science system to move away from traditional discipline-driven research towards a socially relevant and problem-driven mode of research that connects research activity across scholarly and societal boundaries (e.g. Kates et al. 2001; Gallopin et al. 2001). Understanding complex societal problems does challenge vertical boundaries between experts, policy-makers, practitioners, and the public, and horizontal boundaries between disciplines (Van Kerkhoff 2005; Klein 2004; Nowotny et al. 2003), and asks for cross-disciplinary research (CDR). For example, environmental issues typically are complex problems due to the interplay of phenomena at different temporal and spatial scales in social, economic and ecological dimensions. However, social and policy relevant research approaches do not emerge easily from existing disciplinary research. Despite its encouragement by research funders and science policy makers, the nature, status, and prestige of CDR remain unclear (Buter et al. 2011).

In this study, we test a novel approach to CDR (Van den Besselaar forthcoming) by applying it to river research, a heterogeneous and societal relevant research domain. Doing so, we contribute to (a) better understanding of concepts of cross-disciplinarity, (b) better understanding of the dynamics of disciplinary change, and (c) the understanding of research domains that focus on results relevant for societal challenges—such as river science.

Approaches to cross-disciplinary research

Cross-disciplinary research is attracting a lot of attention, as it is expected to produce more often societal relevant and scholarly innovative outcomes. Despite this, the meaning of the concept (and related concepts), and the indicators for identifying it, are still disputed. At the same time, in order to understand the claims about cross-disciplinarity, we need to understand its nature.

The terminology is still not stabilized, and concepts like multidisciplinary, interdisciplinary, and transdisciplinary are used in different ways by different authors. Furthermore, the terms *multi/inter/trans/disciplinary* are used in many different contexts, and seem to refer to many things, such as researchers, research groups or departments, individual papers and sets of papers, individual journals and sets of journals, research topics and scientific fields. So, one may talk about an interdisciplinary department, defined in terms of the disciplinary background of the members of the department, or in terms of the fields covered by the research of the department. And one may then ask whether the degree of interdisciplinarity of the department correlates with e.g., scholarly performance, or with interdisciplinary output, or with societal relevance of the research done by the group. Here we approach cross-disciplinarity from the perspective of the *development of research fields*.

We use cross-disciplinary as the generic term, and the other three in more specific ways, as will be argued in the paper (Van den Besselaar & Heimeriks 2001; Merkx and Van den Besselaar 2008; Tress et al. 2005).

Quite some work has been done over the years to develop concepts and indicators for cross-disciplinarity. Basically, two approaches can be distinguished. Many authors have defined cross-disciplinarity of a research field in terms of the share of references to other fields, i.e. in terms of the size of knowledge flows (Van Raan and van Leeuwen 2002; Rinia et al. 2002). In this approach, the topology of the fields is generally based on top-down defined (Web of Science) subject categories, but sometimes bottom-up generated using some kind of similarity measure for papers or journals. In the latter case, only a part of the scientific landscape is generated, and therefore only a part of the knowledge flows can be taken into account. This approach focuses on the *input* for research, and on the integration of heterogeneous sources into CDR output (Porter et al. 2006).

Others have defined cross disciplinarity as the change of the disciplinary landscape (Van den Besselaar and Heimeriks 2001). This approach is based on mapping the disciplinary landscape bottom up, based on journal similarity measures (Van den Besselaar and Leydesdorff 1996). By comparing the disciplinary landscape between years, changes in research fields (growth, decline, merging, splitting, emerging, disappearing) become visible. The emergence of new fields can be read as an *second order effect* of CDR. The focus is on what could be called the these second order effects of CDR on the knowledge landscape through the development of new interdisciplinary fields.

We do not intend to discuss the whole CDR literature here (for reviews see e.g., Morillo et al. 2003; Bordons et al. 2004; Zitt 2005; Wagner et al. 2011), but contrast our approach with the recent work of Rafols and colleagues, which plays a central role in the current debate about CDR. They extended and generalized the first approach (e.g., Rafols et al. 2012; Liu et al. 2012), and focus on interdisciplinarity as knowledge integration (Porter et al. 2006). Their aim is to develop set of generic measures for interdisciplinarity, which has been applied on, for example, individual papers or sets of papers (Rafols and Meyer 2010) and on research groups (Rafols et al. 2012). The approach deploys two (composite) indicators for the level of knowledge integration: *diversity* of knowledge inputs (which consists of variety, balance and disparity of the knowledge inputs) and *coherence* of knowledge inputs. A third indicator, *betweenness centrality* (now called *intermediation*), is used for measuring research that does not fit within existing fields—and therefore seems to adopt the topological approach. Although this work offers an interesting perspective on cross-disciplinarity, the approach has the following drawbacks:

(i) The diversity and coherence indicators depend on boundaries between fields, and for this one generally deploys the top-down fixed (WoS subject) categories. This implies that the dynamics of the disciplinary landscape is not taken into account, when calculating diversity and coherence. However, what is observed as variety, balance, disparity and coherence of, or intermediation between knowledge sources in terms of a fixed categorization of disciplines, may disappear if measured against a new and updated classification. In other words, for an adequate identification of CDR, it is necessary to have a full bottom-up (and therefore dynamic) definition of disciplinary stability and change.

(ii) The focus is on integration of knowledge sources used in CDR, so on *inputs*. However, disciplinary change as a possible *effect* of CDR activities is not taken into account. The results of CDR may get integrated in one of the disciplinary fields it is based on, or it may contribute to the development of emerging cross-disciplinary fields. So understanding of cross-disciplinarity not only needs to take into account the inputs, but also the uptake of the outputs at its effects.

(iii) The indicators for variety, balance, disparity and coherence measure the *degree* of cross-disciplinarity, but it is not so clear what that means—especially as the indicators should be updated in terms of disciplinary change.

(iv) Last but not least, the adoption of betweenness centrality (Leydesdorff 2007), or intermediation (Rafols et al. 2012) confuses the topological perspective with the relational. As well known, betweenness centrality measures "the extent to which a vertex lies on the path between other vertices" (e.g., Newman 2010, p185), which is *not* a topological characteristic. However, Leydesdorff calculates betweenness centrality through (i) setting a threshold, (ii) removing all similarities below the threshold, and (iii) calculating *betweenness centrality for non-valued graphs* on the resulting 'truncated' valued graph. This results in a kind of similarity measure—for which better alternatives are available (Van den Besselaar and Leydesdorff 1996, 2001). By using *relational* terminology for the *position* of the (cross-disciplinary) journal(s) between established fields, one suggests that the (cross-disciplinary) journal(s) function as broker (controlling the information exchange between the two fields) or as mediator (bringing the two fields together). And this is in fact generally not the case.[1]

Based on these considerations, we take a different approach. Cross-disciplinarity is here considered as disciplinary change, resulting from the interaction between two levels: the level of research where new knowledge is produced, and the level of knowledge communication where new knowledge claims are accepted and integrated into (sometimes changing) disciplinary frameworks (Van den Besselaar forthcoming).

At the level of disciplines, theoretical and methodological frameworks ("paradigms") are developing gradually, and sometimes radically, influenced by the outcomes of research. At the same time, these paradigms provide the researcher with a framework that structures the research activities. Normal science is the further development of the discipline through disciplinary research. However, researchers also explore new ways of answering questions—often drawing from methods and ideas from other disciplines. Research questions are then approached in a *multidisciplinary* way using a diversity of *inputs* from a variety of disciplinary fields. The result of this multidisciplinary research feeds back into various research fields: through publications that are being cited (Fujigaki 2000). This may either contribute to the further development of the disciplinary fields the research is based on, or may lead to new developments outside those existing fields. Multidisciplinary research may sometimes generate a new-weak but identifiable–communication network. This takes the form of an initially small and not yet very coherent communication network consisting of a few journals for the new research. These journals are positioned between the disciplinary fields the new development is emerging from. In an earlier study we defined this as *early stage interdisciplinarity*, which may develop into more mature stages (e.g., artificial intelligence, neural networks, robotics)—or may disappear again (e.g., cognitive science). We showed that the structure of the communication network of mature interdisciplinary fields becomes identical to those of the traditional disciplines (Van den Besselaar and

[1] An instructive example of the resulting confusion is a study by Goldstone & Leydesdorff (2006) of cognitive science. Using betweenness centrality to measure the position of the journal *Cognitive Science* between computer science and cognitive psychology makes them conclude that the *Cognitive Science* functions as a broker between the two research fields, and that the knowledge flows between the two fields go through the journal *Cognitive Science*. However, the large majority of citations between the two fields are direct citations between journals in the two fields.

Heimeriks 2001). In other words, interdisciplinarity is a temporary stage of *disciplinary reconfiguration*, as the further a new interdisciplinary field develops, the more disciplinary it becomes. Of course, these changes can only be observed if one avoids working with predefined fields. Definitions of research fronts and of fields and disciplines have to be dynamically based on similarities between journals and between papers.

In previous studies we focused on the development of the disciplinary landscape, operationalized as changing sets of *journals*[2] with the same position in the global journal citation network (Van den Besselaar and Leydesdorff 1996; Van den Besselaar and Heimeriks 2001). Here we combine this approach with an analysis of the development of CDR at the research front level, operationalized as communities of similar *papers* (Van den Besselaar and Heimeriks 2006). A comparison of the paper network and the journal network will lead to an understanding of cross-disciplinarity as a two-level process of change.

The case: river research

There is widespread recognition amongst scholars in environmental science that cross-disciplinary efforts are necessary to increase our understanding of complex environmental issues (Brierley and Fryirs 2008; Thorp et al. 2007; Wear 1999; Naiman 1999; Benda et al. 2002; Palmer and Bernhardt 2006; McCulloch 2007). Especially in the research and management of water systems, the bridging of disciplinary perspectives figures prominently on the agenda's, as evidenced by the promotion of fields like hydroecology, eco-hydrology, eco-hydromorphology and eco-geomorphology. It has been suggested that these fields extend beyond ecology, geomorphology and hydrology into other contributing fields such as civil engineering, economics and social sciences (Vaughan et al. 2009; Hannah et al. 2004; Bond 2003; Thoms and Parsons 2002). These claims have been noted for coastal research (Merkx and Van den Besselaar 2008) as well as for river research (Van Hemert and Van der Meulen 2011).

However, when considering water research, interdisciplinary integration is still relatively uncommon (Hillman 2009). This has been attributed to the "turbulent" boundaries among different disciplines, a qualification that refers to mutual misunderstandings between disciplinary cultures, and to a lack of effective communication (Boulton et al. 2008). Interdisciplinary efforts tend to be perceived as being more complex for participants than traditional intra-disciplinary collaborations because participants have different paradigms and approaches (Cullen 1990; Benda et al. 2002; Petts et al. 2006).

In this paper we take the case of river research to study the dynamics of cross-disciplinarity. River research is a suitable case, as especially water-related issues call for the development of cross-disciplinary approaches to understand the systemic nature of the riverine landscape with its ecological, social, political, economic and cultural dimensions (Thorp et al. 2007; Lenders and Knippenberg 2005; Vugteveen et al. 2006). Following the approach outlined in the previous section, the landscape of river research is mapped using a combination of methods.

[2] It has been argued that in the current phase of scholarly publishing, the paper, more than the journals is the relevant unit. With direct (on line) access to articles, the journals would lose their central role in scholarly communication. If this would be the case, one would expect that journal citation networks are becoming less coherent over time. We tested this, and that does not seem to be the case. We will publish these results separately.

Firstly, we map the disciplinary landscape in which river science is embedded, based on the citation relations between the relevant journals. We test whether river science is developing into an interdisciplinary field, indicated by an emerging set of river research journals with similar referencing patterns.

Secondly, the citation links (the knowledge flows) between the relevant research fields are mapped, in order to measure the cross-disciplinary inputs for river research

Thirdly, we map the topical structure of the research front in river research at the paper level using similarity in terms of title words and references. Clusters of papers representing specific river research topics may be published within single disciplines, indicating a mono-disciplinary approach, or published within different disciplines, indicating a multi-disciplinary approach to those topics.

Fourthly, the disciplinary environment and the topical structure of river research will be compared, and that leads to conclusions about the development of cross-disciplinarity in river research, and about its meaning for integrated river management.

Methods and data

Document set

Science can be viewed as a communication network. Journals as well as the scientific publications in journals allow us to map these communication systems. Journals are used for mapping the more global scientific landscape in terms of research fields around river research, whereas papers are used for mapping the research fronts, i.e. leading research topics. A variety of bibliometric techniques are available for this and will be used in this study. Fig. 1 presents a flowchart of the methodological steps, which are briefly outlined below.

In order to map current river research we started by using *river** as a search term in order to retrieve all papers indexed in the Web of Knowledge with river* in title, keywords or abstract (step 1 in Fig. 1).[3] The search was restricted to so-called citable items: articles, reviews, and proceedings papers (we use the commonly used term 'papers' to refer to all these document types for the remainder of the article). We searched multiple years (2007–2009) to avoid incidental citation relations. By using the simple generic search term river* we aimed for a high recall (but consequently a lower precision) of papers.

The resulting document set ($N = 31{,}869$) was used to identify the core river science journals by considering those journals with the highest shares of river related papers. Table 1 shows a listing of the journals in the set that are the most strongly focusing on rivers. Core journals are defined as (i) having more than 35 % of their total paper output in the 2007–2009 period belonging to the river* document set and (ii) having an absolute number of at least 100 papers in the document set. This selection was done because of pragmatic reasons, as we want to keep the journal maps readable. So we leave out a large number of less central and marginal journals. However, many of the journals that were

[3] The use of river* may lead to a bias towards large, non-wadeable river systems and may partly exclude literature on the wadeable parts of the river system more commonly associated with terms such as 'streams'. To test, deploying 'stream*' as search terms resulted in a set documents that hardly overlapped (some 10 %) with the river* set. This is to a large extent because the term stream* has a much wider meaning. When restricting the stream* papers to the relevant subject areas (e.g., Environmental Sciences, Ecology, Water Resources, Marine Freshwater Biology, Oceanography, Biodiversity, Conservation, Physical Geography), the overlap increases to about 50 % of the papers.

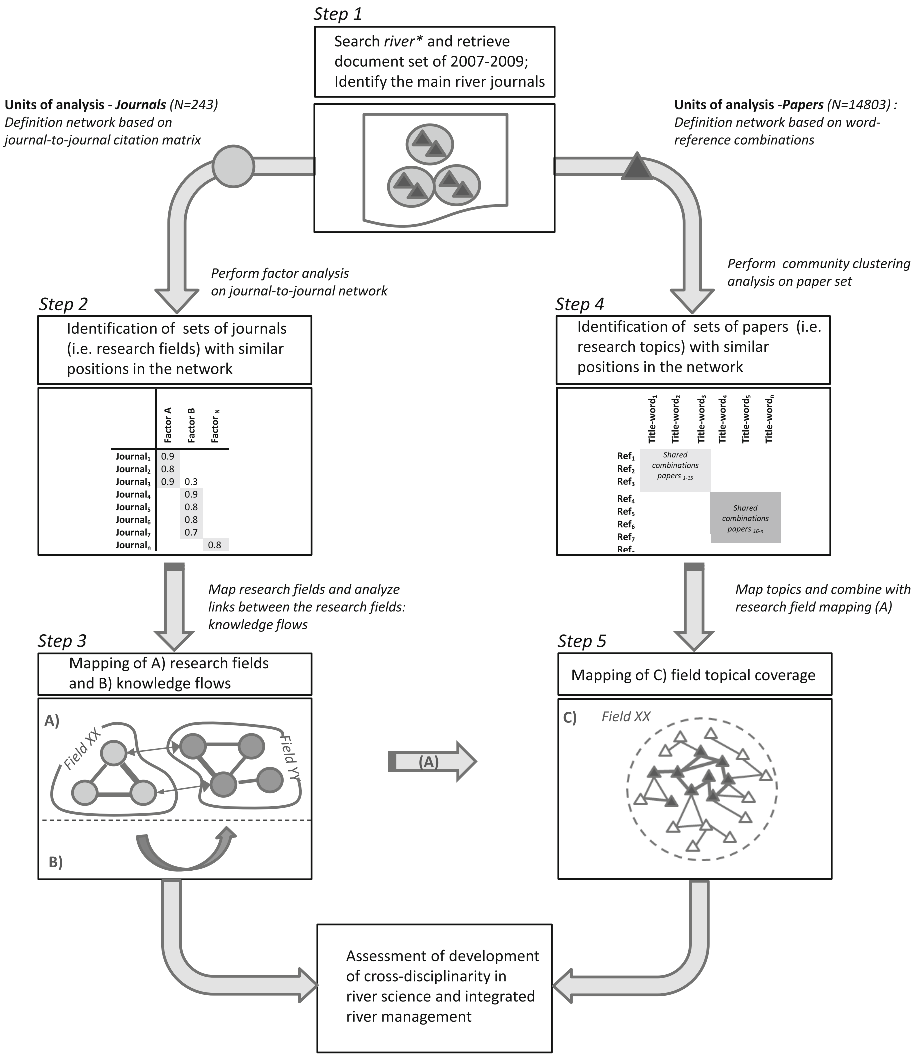

Fig. 1 Flowchart of methodological steps in this study: **a** Mapping of research fields (Fig 2); **b** Analyzing knowledge flows between fields (Fig 3); **c** Mapping of topical coverage (Fig 4)

excluded through the two criteria are still included in the analysis, as they do belong to the citation network of the core journals (see below).

Mapping research fields

Journal citation networks are used for mapping research fields that are relevant for international river research (step 2 in Fig. 1). The approach is based on the notion that researchers in a field share a set of research questions and methodologies and refer to a largely overlapping core literature. The use of a common knowledge base is reflected in the references. Consequently, journals belonging to the same research field exhibit similar

Table 1 Entrance journals for the citation analysis with river research papers (2007–2009)

S. No.	Source title	River papers in document set		
		Share (%)	# Papers	Mass (%)
1.	River research and applications	96	246	0.8
2.	Ecology of freshwater fish	59	108	0.3
3.	Transactions of the American fisheries society	48	206	0.6
4.	Journal of the american water resources association	48	168	0.5
5.	North American journal of fisheries management	44	192	0.6
6.	Hydrological sciences journal	42	105	0.3
7.	Geomorphology	41	379	1.2
8.	Estuaries and coasts	41	119	0.4
9.	Earth surface processes and landforms	41	187	0.6
10.	Hydrological processes	40	411	1.3
11.	Hydrology and earth system sciences	39	163	0.5
12.	Water resources management	38	155	0.5
13.	Freshwater biology	37	211	0.7
14.	Journal of hydrology	35	474	1.5
15.	Continental shelf research	35	191	0.6

For each journal the table presents (i) the share (%) of river papers across all published papers in the journal concerned (ii) the total number of papers and (iii) the mass (%) of the journal output across the total document set

aggregated citation patterns. The identity of the field can subsequently derived from the journal titles in the delineated cluster, and when needed with the help of field specialists (Van den Besselaar and Leydesdorff 1996; Van den Besselaar and Heimeriks 2001). Using these citation-based communication patterns, we can retrieve the position of river science within the overall scientific landscape.

The analysis is based on the journal network of the 15 journals with the most river research papers (Table 1). We used the 2008 CD-Rom version of the Journal Citation Reports to compile the network. The network was constructed with all journals citing or being cited by the core 15 journals of Table 1. Since we were interested in structure and not in incidental citations, we removed the "noise" by discarding those journals that contributed <0.5 % to the citations over 2008. Many of the journals that were not selected as core journal reappear in the analysis, as they belong to the (above threshold) citation environment of one or more of the 15 core journals. Factor analysis is a proven approach to find the main structure of a network (Hanneman and Riddle 2005) and for a journal network this represents the underlying landscape of research fields. Factor analyzing the matrix of 243 $\times$ 243 journals resulted in 23 factors,[4] each representing a research field. The analytical question we pose is whether one of the factors represents river science, and the other factors do represent fields that are relevant for river science, or whether the core river science journals are distributed over a variety of fields. In other words, is river science

[4] Though appearing in the factor analysis as a separate field we exclude *Science Magazine*, *Nature* and the *Proceedings of the National Academies of Science* from most of the further analysis of river science. These three journals have an explicit broad multi-disciplinary scope and are heavily cited by all fields, and that puts them together in a factor. However, they cannot be considered as representing a distinct research field.

a (emerging) single field or is river research cross-disciplinary and distributed across a set of distinct research fields?

Mapping knowledge flows

The next question is how the research fields that are relevant for river research are mutually related (step 3b in Fig. 1). Do these fields depend on each other, and how strongly? Numbers of citations between the different research fields (as represented by the factors) were calculated using the same journal–journal citation matrix. These citation relations are an indicator for knowledge flows and cross-disciplinary knowledge exchange, which can be analyzed in terms of their direction, their magnitude, and network configuration. For example, the more substantively a field is citing a range of heterogeneous other fields, the more cross-disciplinary it is considered to be.

Mapping research topics

To map the research topics within river science we selected from the initial 3-year document set only those documents ($N = 14{,}803$) that were published in the 243 journals included in the factor analysis. Researchers simultaneously select (title) words to describe their research subject and references to relate to the tradition in which they work. These title words acquire their specific meaning within the context of the cited references. We used word-reference similarities between papers (Van den Besselaar and Heimeriks 2006) to map and analyze the topical structure of river research (step 4 in Fig. 1). The more combinations of title words and cited references are shared between papers, the more similar they are. Title words were reduced to their stem, which increased the accuracy of the clustering.[5] For such a large set of papers, factor analysis cannot be used to cluster similar papers. Therefore we used the Saint tool (Somers et al. 2009) and a fast community detection algorithm (Blondel et al. 2008) to reveal 1340 clusters of topical similar papers, of which 108 have a reasonable size (defined as at least 15 papers over three years). For research topics with a social science nature we set a minimum of 5 papers.[6] In total, slightly more than 10,000 papers (out of 14.803) are included in these 108 clusters.

In the final step the disciplinary structure and the topical structure of river science were compared by a superposition of the topics map on the field map (step 5 in Fig. 1). This shows the level of cross-disciplinarity of the research topics.

Results

Mapping the relevant river science fields

The 15 entrance journals have overlapping citation environments and together span a network of 243 journals. The factor analysis of the journal citation network reveals 23

[5] The nodes of the network are papers and the ties between papers are based on shared word-reference combinations: Title word A, B to N are combined with cited reference 1, 2 to x to form A1, A2, …. Ax, B1, B2, ….., Bx… Nx. Similarity between papers depends on the number of shared combinations.

[6] For a more detailed explanation of clustering algorithms in general, see Palla et al (2005). For a comparative analysis of Blondel et al's algorithm versus others' see Lancichinetti and Fortunato (2009).

factors, representing research fields that constitute river science as well as several related research fields that provide knowledge input for river research (see for the result of the factor analysis: Online Resource 1). The factors are labeled according to the focus of the journals loading on that factor. This was done through inspecting the titles, which was then checked by field specialists (two of the authors).

The journal network consists of fields belonging to biology, geochemistry, environmental science (including environmental management), hydrology, and water resources research. Generally, journals load on one factor and have only a very low loading on other factors, indicating their mono-disciplinary nature. Journals that show a relatively high loading on different factors are cross-disciplinary, filling the space between the disciplines (Van den Besselaar and Heimeriks 2001). For example, Global Planet Change loads 0.46 on oceanography, 0.34 on general environmental ecology, 0.47 on quaternary science, and 0.46 on climatology. Also River Research and Applications shows a typical multidisciplinary behavior, as it loads moderately on more factors: 0.61 on limnology and 0.40 on fisheries & fish research. On the other hand, the ecology journals and the hydrology & water resource journals hardly load on a second factor, indicating that these research fields have a strong disciplinary identity.

The fifteen major river science journals (Table 1) are not concentrated in one factor but are distributed across multiple fields. Hydrology and water resources contains six of the entrance journals, fisheries and fish research three, limnology and geomorphology each contain two, and marine and estuarine biology and oceanography each include one. The citation analysis thus shows that river science does not constitute a separate discipline but is a multidisciplinary endeavor. Based on their share of river related papers, i.e. the degree to which the research fields contribute to river science, the first four of these five fields can indeed be considered as core fields for river science (Table 2). Based on absolute numbers of papers, hydrology and water resources ranks, as expected, highest as a major contributor to river science. Environmental pollution is also a significant field as it has a large contribution to the document set in absolute terms. River systems may be a major object, but are not core object of research in environmental pollution, which is reflected in the relatively low amount of river papers compared to its total output. Limnology and fisheries and fish research are also among the major contributors as well as marine and estuarine ecology, the latter adding significantly to the number of river related publications.

Figure 2 presents a visualization of the results of the factor analysis, and shows the way the research fields are positioned in and around river science.[7] The nodes represent journals while the thickness of the links is a measure of the degree of similarity in citation behavior between the two nodes. Research fields are represented by (factor analysis-based) groups of journals within the larger network. The denser the network is (and the thicker the lines), the stronger the disciplinary orientation of a research field. Figure 2 reveals which fields are similar to each other in terms of citation patterns. These so called meta-fields are:

(i) Ecological sciences, situated on the right side of the map. Ecology is in the middle, surrounded by different river science fields: limnology, marine and estuaries biology, with fisheries and fish research and aquacultures clustering at the far right. Also general environmental ecology, and evolutionary ecology are in this part of the map;

[7] Please note that this is a two dimensional map of a multidimensional space. The projection influences the distances between the fields on the map.

Table 2 Core fields in river science 2007–2009

Rank	Label	Share (%)	# River papers	Mass (%)
1.	Limnology	37.6	1,493	10.1
2.	Fisheries and fish research	27.6	1,456	9.8
3.	Hydrology and water resources	27.1	2,532	17.1
4.	Geomorphology	26.2	850	5.7
5.	Sediment geology	19.6	210	1.4
6.	Geochemistry	16.4	813	5.5
7.	Quaternary science	14.2	538	3.6
8.	Environment pollution	13.7	1,676	11.3
9.	Marine and estuarine biology	12.1	1,112	7.5
10.	Environmental management	10.8	232	1.6
11.	Water science and technology	10.5	550	3.7
12.	Soil science and agricultural water	9.6	388	2.6
13.	Geology	7.8	313	2.1
14.	Oceanography	7.8	733	4.9
15.	General environmental ecology	7.3	62	0.4
16.	Ecology	7.0	860	5.8
17.	Aquaculture	7.0	248	1.7
18.	Climatology	6.8	221	1.5
19.	Evolutionary ecology	5.9	193	1.3
20.	Remote sensing	4.2	158	1.1
21.	Microbiology	3.3	126	0.9
22.	Behavioral ecology	0.7	39	0.3
		Sum	14.803	100

Document set 2007 – 2009 from journals drawn in the factor analysis. For each field the share (%) and absolute number of river papers across all published papers in the subsequent field journals is presented, as well as the mass (%) of the field across the river science document set

(ii) Geosciences, at the left of the map, including geology, sedimentology, quaternary sciences and climatology;
(iii) Environmental pollution and Water science and technology, in the left-bottom corner;
(iv) Hydrology and water resources, center bottom the map. The map shows that this field has a strong own citation identity; separated from the other fields and having a dense network structure.

Several other fields that are relevant for river science can be found on the map. Geochemistry is in the center of the map, between geosciences and hydrology. At the edges we find Microbiology, and Behavioral ecology. In the right top, close to the Geosciences, we find Remote sensing. Finally, Environmental management is in the lower middle of the map.

Concluding, river science has not developed into an early or mature interdisciplinary field, but consists of a few fields in which river research has an important position. River research and main journals publishing about it are distributed across hydrology (six journals), the various ecology fields (seven journals), and geosciences (two journals).

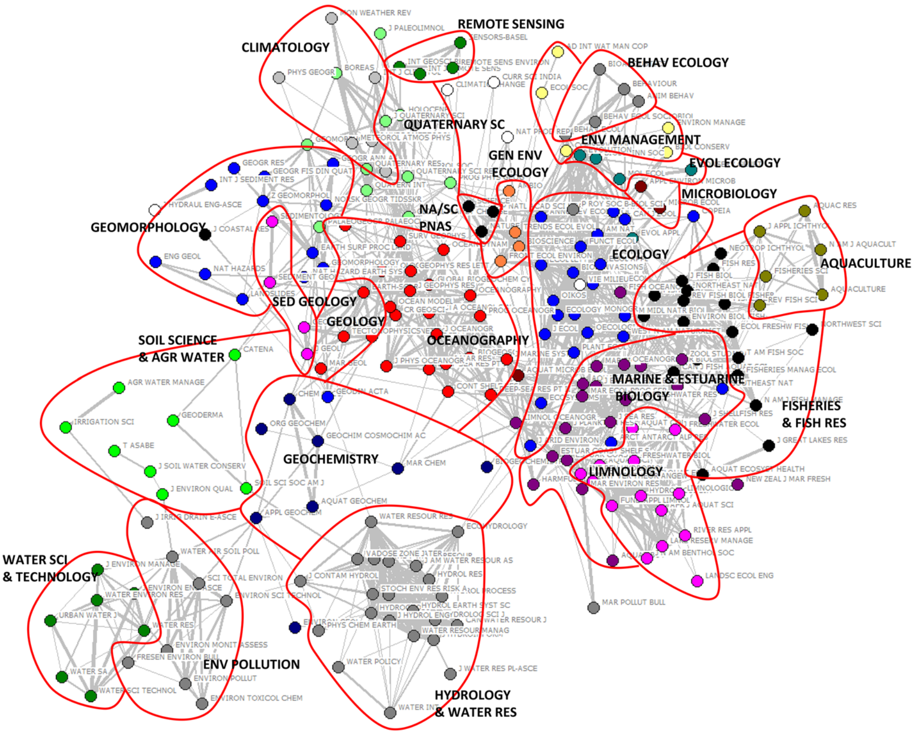

Fig. 2 River science 2008 journal network (The nodes represent journals. *Dense areas* and *thick links* between nodes represent high similarity in citing behavior)

Mapping of knowledge flows between the fields

The various research fields have mutual citation relations whereby the more field A cites field B, C, D etc., the more it depends on these other research fields. The observed meta-fields that compose river science present themselves clearly when considering the knowledge flows (citation relations) between the fields. Figure 3 presents a visual representation of these relations, and Online Resource 2 supplies the underlying data.

The eco-sciences meta-field includes ecology and more specialized fields such as human environmental ecology, ecological genetics, evolutionary- and behavioral ecology. Environmental management has the strongest citing relations with ecology. The meta-field further includes aquatic ecology and biology fields such as limnology and marine and estuarine biology, and fisheries and fish research and aquaculture. Within the eco-sciences the field of ecology is central and presents a so-called reference field for other eco-fields as it is being cited substantively, as well being cited by other fields throughout the whole network. Furthermore there is an environmental pollution and water science and technology grouping consisting of hydrology and soil science and agricultural water research, and also a geoscience meta-field including a subgrouping of oceanography and climatology. The geoscience meta-field is quite separate from the eco-science meta-field in which oceanography and geology present reference fields. Finally, we found hydrology and soil water as a fourth meta-field.

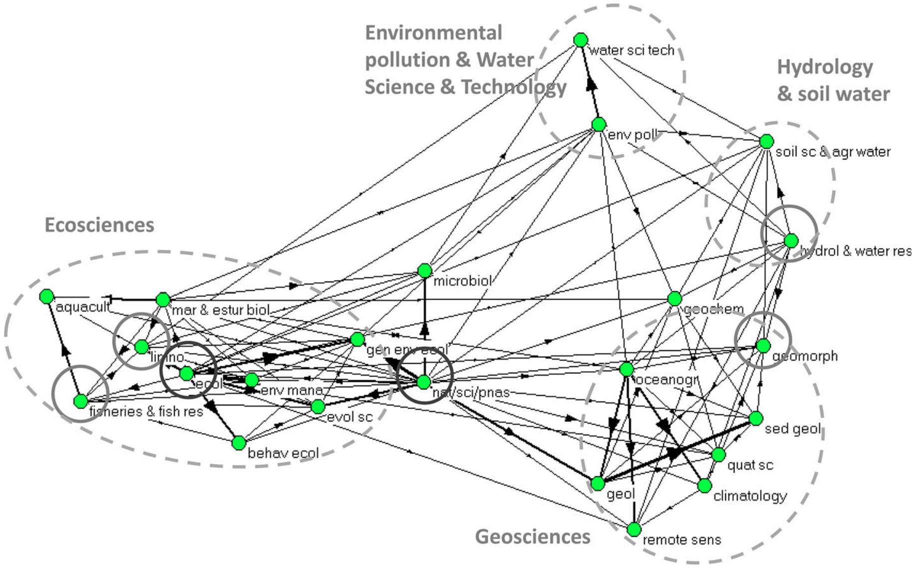

Fig. 3 Knowledge flows between research fields (The *nodes* represent the fields. The *dashed circles* indicate meta-fields. Thickness of the *arrowhead* and distance between fields express the strength of the flows. The closer together, the stronger the mutual knowledge flows. The *light gray circles* indicate the four fields that include the core of river science. The *dark grey circle* in the center of the map indicates Science Magazine, Nature, and the Proceedings of the National Academies of Science. As expected, these journals are cited by (almost) all other fields, and therefore get a position in the center of the map. The *second dark circle* is the ecology field, a center field in the eco-sciences.)

One may classify a field as cross-disciplinary when it is substantively citing a range of other fields belonging to different meta-fields. From inspecting the knowledge flows across these meta-fields it appears however that the citation relations within the four meta-fields are rather tight, whereas the cross-disciplinary exchange between the four meta-fields is much more limited. For example the environmental pollution and water science & technology meta-field does show citation relations to the eco- and geosciences meta-fields but to a very limited extent.

We have identified river science as a multidisciplinary activity within hydrology & water resources, limnology, fisheries and fish research and geomorphology. When we consider these core fields (light grey circles in Fig. 3), hydrology and water resources presents a distinct research field that is mainly self-citing (60 %) and has links to both the environmental pollution meta-field as well as the meta-field of geosciences. The most substantial mutual citing relation is shown with soil science and agricultural water. The citation relations with the other three mentioned core river science fields are small or absent. Limnology and fisheries and fish research belong to the same grouping—but hardly cite hydrology and water resources and geomorphology. Finally, geomorphology heavily cites hydrology and water resources (and not the other way around) but does not cite fisheries and fish research and limnology (see Online Resource 2 for further details). In other words, the different river research fields are not strongly connected in terms of knowledge exchange.

Table 3 Major river science research topics having at least 50 papers. Per topic the contributions (%) of metafields and single fields to the topical paper set (third column) is presented

Nr.	Topics	Nr. of papers	Meta-field[a] (%)				Most contributing field	Share (%)	All contributing fields[b]
			Ecol Science	Geoscience	Hydr & Soil	WST & Poll			
1	Fish assemblages-habitat effects	1436	**83**	3	6	8	Limnology	37.7	5; 7; 9; 13; 14; 15
2	Hydrol modeling-climate change	1349	5	21	**67**	7	Hydrology & water res	61.8	3; 13; 21
3	River flow-fish and vegetation effects	714	**64**	15	16	5	Limnology	29.6	5; 9; 11; 13; 14
4	Salmon trout-population genetics	474	**98**	1	0	1	Fisheries and fish res	31.9	1; 5; 8; 9; 14; 15
5	Holocene river evolution	464	5	**91**	5	0	Quaternary science	43.3	4; 11; 18; 20
6	River sediments	318	14	**70**	11	5	Oceanography	24.8	4; 11; 13; 15; 17; 18; 20
7	Heavy metal pollution	263	6	28	9	**57**	Env pollution	51.7	7; 10; 21
8	Dissolved organic carbon	246	29	29	15	27	Env pollution	20.7	7; 10; 13; 14; 15; 17; 22
9	Estuarine phytoplankton-nutrient dynamics	227	**71**	14	2	14	Mar and est biol	49.3	7; 14; 15; 17
10	River basin weathering	200	3	**77**	14	7	Geochemistry	47.5	4; 7; 10; 13; 17
11	River sediments–organic matter	186	19	**69**	2	9	Geochemistry	32.3	7; 10; 15; 17
12	Groundwater-surface water interactions	186	20	9	**64**	7	Hydrology and water res	61.3	7; 13; 14
13	River bed–transport	168	4	**57**	38	2	Geomorphology	44.6	11; 13; 20
14	Mercury contamination	166	16	17	3	**64**	Env pollution	62.0	7; 10
15	estuarine plume modeling	152	23	**67**	7	4	Oceanography	58.6	13; 15; 17
16	Flow modeling-artificial neural network	148	7	4	**80**	8	Hydrology and water res	78.4	13
17	Nitrogen phosphorus effects	142	**40**	19	33	8	Soil science	16.9	5; 7; 10; 13; 14; 15; 16; 21
18	Polycyclic aromatics and hydrocarbons distr.	127	9	8	3	**80**	Env pollution	74.8	7; 15; 22
19	Food web-trophic levels isotopes	105	**87**	4	0	10	Mar and est biol	45.7	5; 7; 9; 14; 15
20	Nutrients-agricultural loading	105	16	12	**47**	25	Soil science	23.8	7; 10; 13; 14; 17; 21; 22
21	Groundwater–isotopes	100	7	**49**	42	2	Hydrology and water res	42.0	10; 13; 18

Table 3 continued

Nr.	Topics	Nr. of papers	Meta-field[a] (%)				Most contributing field	Share (%)	All contributing fields[b]
			Ecol Science	Geoscience	Hydr & Soil	WST & Poll			
22	Salmon trout–habitat	96	**97**	2	0	1	Fisheries and fish res	59.4	5; 9; 14
23	Wastewater treatment-pharm occurrence	81	2	0	5	**93**	Env pollution	65.4	7; 22
24	Sturgeon, green-habitat use	79	**97**	0	0	3	Fisheries and fish res	54.4	1; 9
25	Eel migration	76	**97**	1	0	1	Fisheries and fish res	55.3	9; 14; 15
26	Water quality assessment–pollution	75	4	5	25	**65**	Env pollution	44.0	7; 10; 13; 22
27	Salmon trout, atlantic-migration & survival	74	**97**	0	0	3	Fisheries and fish res	64.9	1; 9; 14; 15
28	River sediments–transport	72	6	33	**51**	10	Hydrology and water res	43.1	7; 11; 13; 21
29	Salmon, pacific-migration & spawning	70	**97**	1	1	0	Fisheries and fish res	45.7	5; 6; 8; 9
30	Mekong delta-arsenic pollution	65	0	**62**	14	25	Geochemistry	56.9	7; 10; 13
31	Wastewater treatment–hormones	58	3	0	3	**93**	Env pollution	81.0	7; 22
32	River-estuary interaction-tidal circulation	56	30	**59**	2	9	Marine and estuarine biology	50.0	13; 15; 17
33	Carbon fluxes	56	**50**	41	7	2	Oceanography	35.7	7; 10; 15; 17
34	Fish otolith chemical composition	54	**96**	2	0	2	Fisheries and fish res	55.6	9; 15
35	Integrated water management-social learning	53	25	0	**58**	17	Hydrology and water res	56.6	6; 13; 22
36	Leaf-litter decomposition	53	**91**	0	0	9	Limnology	66.0	5; 7; 14; 15; 16
37	Polychlorinated and brominated substance distr.	50	0	0	2	**98**	Env pollution	98.0	7
38	Pesticides distribution	50	4	0	6	**90**	Env pollution	84.0	7; 21; 22

[a] Meta-field definition follows from identified factors (Fig. 2) and knowledge flows (Fig. 3). The meta-field with the highest share is shown in bold

[b] Fields contributing more than 5 % to the topic paper set are presented as well as the most contributing field and its respective share. Identification of contributing fields, i.e. research field representation, is based on the journal affiliations of topic papers and their respective identified factorial research fields. *1* Aquaculture, *2* behavioral ecology, *3* climatology, *4* geology, *5* ecology, *6* environmental management, *7* environmental pollution, *8* evolutionary ecology, *9* fisheries and fish research, *10* geochemistry, *11* geomorphology, *12* general environmental ecology, *13* hydrology and water research, *14* limnology, *15* marine and estuarine biology, *16* microbiology, *17* oceanography, *18* quaternary science, *19* remote sensing, *20* sediment geology, *21* soil science, *22* water science and technology

Table 4 Major social issues research topics having at least 5 papers. Per topic the contributions (%) of metafields and single fields to the topical paper set (third column) is presented

Nr.	Topic	Nr. of papers	Meta-field[a] (%)				Most contributing field	Share (%)	All contributing fields[b]
			Ecol Science	Geoscience	Hydr & Soil	WST & Poll			
1	Integrated water management-social learning	53	25	0	**58**	17	Hydrol and water res	57	6; 7; 13; 21; 22
2	Integrated water management–allocation	24	4	0	**88**	8	Hydrol and water res	83	6; 13; 21; 22
3	Conservation planning	19	**84**	0	5	11	Env mana	58	5; 6; 14; 21; 22
4	Integrated water management–governance	14	0	0	**86**	14	Hydrol and water res	86	13; 22
5	Coping with floods	10	10	**70**	10	10	Geomorph	70	6; 11; 13; 22
6	Water sharing-disputes and cooperation	10	0	0	**100**	0	Hydrol and water res	100	13
7	Water resources–economics	8	25	0	**50**	25	Hydrol and water res	50	5; 13; 22
8	Virtual water trade	7	0	0	**71**	29	Hydrol and water res	71	13; 22
9	Stakeholder water demands	7	14	0	29	**57**	Water sci tech	57	13; 14; 22
10	Integrated urban management: systems approach	7	0	14	29	**57**	Water sci tech	57	3; 13; 22
11	Planning under uncertainty	7	0	0	**86**	14	Hydrol and water res	71	13; 21; 22
12	Balancing water needs	7	14	14	**57**	14	Hydrol and water res	57	10; 12; 13; 22
13	EU water framework directive	6	17	33	17	33	Geochem	33	6; 7; 10; 13; 22
14	Trading discharge permits	6	17	0	**50**	33	Hydrol and water res	50	6; 7; 13; 22
15	Water markets	6	0	0	**100**	0	Hydrol and water res	83	13; 21
16	Recreation management	5	**80**	0	0	20	Env mana	40	1; 6; 9; 22
17	Flood vulnerability: informing policy	5	0	20	20	**60**	Water sci tech	60	3; 13; 22

[a] Meta-field definition follows from identified factors (Fig. 2) and knowledge flows (Fig. 3). The meta-field with the highest share is shown in bold. Social topics were identified based on "socially-relevant" title words

[b] See legend of Table 3

Mapping of river research topics

So far we mapped river science on a high level of aggregation: as a network of research fields, based on the relevant journals. Using the published papers as unit for mapping we now proceed by producing a more detailed map of river research. Clustering papers through title word-cited reference similarity we derived the main research topics in river science over the last few years, i.e. the research front. Table 3 gives an overview of the 38 largest topics out of 108 main research topics we identified in the document set.

The research topics cover fish, climate, river evolution and pollution issues. Specifically, the distribution and diversity of fish assemblages in relation to habitat changes presents a large topic in the set, followed by hydrological modeling in the context of climate change. Table 4 also shows that many major topics in river science are focusing on different forms of environmental pollution. Furthermore, topics focuses on fish migration, sediments multiple topics address systemic relations, specifically ecological and geomorphological cycles as well as hydrological interactions and dynamics.

Table 3 shows which research fields contribute to the various topics. It can be seen that most of the topics are the research domain of multiple fields indicating CDR endeavors. Some topics are explicitly the object of study for a single field, for example in environmental pollution (e.g. Nos. 7, 14), hydrology and water resources (e.g. Nos. 2, 12) and fisheries and fish research (e.g. Nos. 22, 24). Above, we observed that fields like hydrology and water resources and environmental pollution show high self-citing behavior suggesting mono-disciplinarity. But also the topics that have cross-disciplinary orientation remain within a single meta-field. These findings suggest that cross-disciplinary interaction across broader scientific meta-fields is limited. This is in line with the analysis of knowledge flows presented above.

Despite the discussions on the relevance of social research (such as planning, management, economics) for river research and management, the fields map (Fig. 2) only included one such field: environmental management. The topics list (Table 3) does not show any social science topics. By investigating the presence and nature of 'societal' research topics in river scientific output in detail, more insight is gained in the position of social science within river research. Using a title word search,[8] a total of 38 different topics were identified of which Table 4 shows the major ones. These topics relate to integrated water management, planning, system approaches, water sharing & trade, and user/stakeholder perspectives. The focus is on (integrated) water management and related topics, with clear policy relevance. Over half of the social topics are related to the field of hydrology and water resources and are published in the more general water resource (management) oriented journals such as Water Resources Management and Water Policy. Other societal topics are within environmental management and in water science and technology. Interestingly, although societal issues are being discussed in the river research literature, there is no significant reference to social science literature as no factor with social science journals was found.

Tables 3 and 4 show that some topics predominantly belong to a single research field whereas most topics are researched by a variety of fields. Differences and similarities in topical relations of research fields are further visualized in Fig. 4 representing a topics map

[8] We used an automated search on the following search terms and derivatives (based on an inspection of the title words frequency distribution): agencies, cost, decision, development, economic, institution, learning, management, participant, place, planning, policy, public, social, socio, stakeholder, strategy, sustainability, user. The remaining topics were manually and visually checked.

based on similarities in terms of word-reference combinations. This means that papers of similar topical scope are clustered. Related topics are close to each other, whereas unrelated topics are farther apart. A so-called ‘spring model’ algorithm fitted all articles into a 2D visualization, using the BibTechMon visualization tool (Kopcsa and Schiebel 1998).

On this topics map a field map was superimposed. For clarity reasons we partitioned the mapping and produced separate maps for each research field. For each field (= a set of journals) all papers belonging to the field are colored. This way of presenting and visualizing allows for comparisons between fields and it reveals that the topical scopes of research fields differ in range and structure. In some field maps, papers are concentrated indicating a more homogeneous topical structure of the field. This is true for smaller fields like evolutionary ecology and climatology. Other fields show a more heterogeneous topical structure like ecology and environmental pollution. Multi-disciplinary topics (Table 3) are indicated where colored areas in field maps show overlap. For example limnology and marine & estuaries biology partly cover the same topics.

Overviewing the complete field-configuration of the topics mapping, the previously observed division in meta-fields is recognizable again; the upper half of the mapping presents the ecological sciences with aquatic ecological science positioned at the edge and general ecology lying more to the center. Hydrology and water resources is concentrated at center-bottom and the geosciences are found at the lower left. Environmental pollution is more spread out across the ecological sciences region. Core fields like limnology and fisheries and fish research cover a large part of the topics map of river science, along with marine and estuarine biology. Ecology itself is more heterogeneous and spread out, indicating a wide topical scope. Water science and technology and soil science are heterogeneous fields as well. Soil science and hydrology and water resources have shared topics. The link between these fields is also apparent from their mutual citation streams (Fig. 3). The core field hydrology & water resources field covers a broad topical scope of research issues. Part of this field shows shared topical interest with ecology and environmental management, and with geomorphology. This latter field overlaps with ecology as well. Furthermore, Fig. 4 makes clear that the fields of oceanography and geochemistry have considerable topical overlap. This concerns fluxes and loading of organic carbon and nutrients from river basins into oceanic systems as can be derived from the main topics in which both fields are involved (see also Table 4). Finally, the societal topics are presented in a separate visualization and it can be seen that they cluster quite strongly in a specific part of the hydrology and water research meta-field.

Discussion and conclusions

In this study the scholarly output of river research was analyzed using bibliometric techniques with the aim to investigate claims and calls for CDR endeavors (Palmer and Bernhardt 2006; McCulloch 2007). Such a quantitative evaluation of river research seems timely, given the growing body of literature expressing the need for research crossing traditional academic boundaries in support of understanding and managing the social-ecological complexity of rivers (Hillman et al. 2008; Vugteveen et al. 2006; Brierley and Fryirs 2008; Surridge and Harris 2007).

The availability of extensive publication databases makes river science amenable to bibliometric indicators, and enables to investigate its dynamics. That leads to a study based only on research output published in peer reviewed scientific journals. Differences exist in publication traditions between scientific disciplines. In the social sciences and humanities,

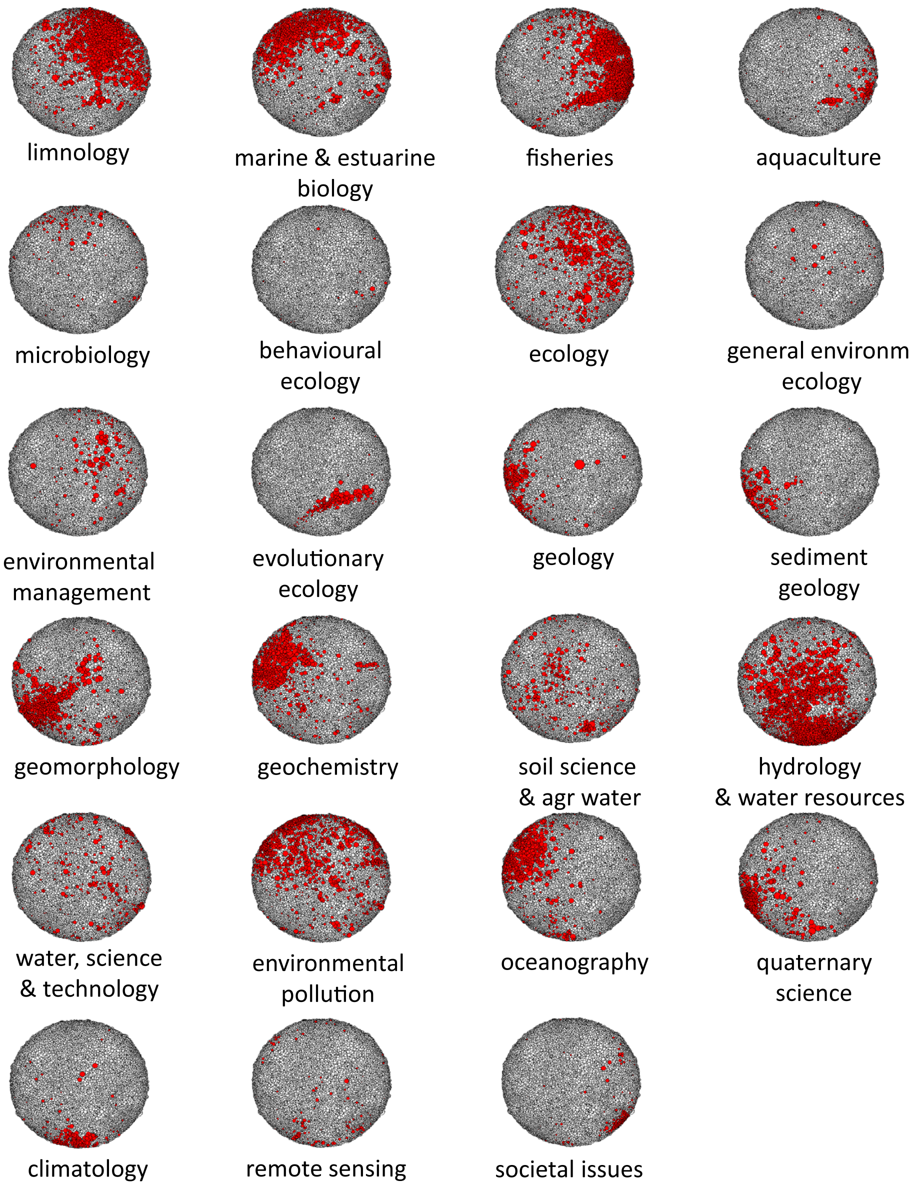

Fig. 4 Topical scope of all river research fields (including societal issues). (Nodes in the figures represent papers whereby the relations between articles are based on similarity in terms of word-reference combinations. The mapping has been partitioned and colored in separate 'layers' according to the research field affiliation of the individual papers.)

also books provide an important publication format whereas technical fields intensively use conference proceedings. In water related research this is about 25 % (Van den Besselaar and Horlings 2010), which means that journals are the dominant form of communicating research in river science. Therefore, our analysis results in a valid representation of the field. However, including other publication types such as reports may add the applied (transdisciplinary) part of river science in a more detailed way. This we may address in a next study. We will now first discuss the findings about cross-disciplinarity in river science, and then draw conclusions about our approach and method to study cross-disciplinarity.

(i) We started our study mapping river research within the disciplinary landscape and found that river science has not (yet) emerged as an interdisciplinary research field but is performed in four core disciplinary fields: limnology, fisheries and fish research, hydrology and water resources, and geomorphology. Overall this structure confirms what other authors identified as the main components of a scientific framework for studying the biophysical functioning of rivers, i.e. river ecology, hydrology and fluvial geomorphology (Poole 2002; Dollar et al. 2007; Thoms and Parsons 2002; Mika et al. 2008). As discussed above, cross-disciplinarity is related to the evolution of the disciplinary landscape. Therefore we also made a map of river science in 1998. We factor-analyzed the 1998 journal citation network in a similar way as presented for 2008. We observed growth of the relevant fields in terms of the number of journals, but overall there appear to be no meaningful changes between 1998 and 2008 with respect to the position of river research in the scientific landscape.

Closer examination of disciplinary orientations and cross-disciplinary patterns showed a division of river science in distinct clusters of fields, i.e. meta-fields broadly covering biological and ecological sciences, environmental sciences, the geo- and geochemical sciences and the hydrological sciences (Fig. 1; Table 3). The knowledge flows were shown to be much stronger within than between these meta-fields, although even within the meta-fields, cross-field citations are relatively scarce. This suggests that traditional disciplinary divisions between the biological, environmental and physical dimensions of river system research are still prominent.

Ecology was identified as a primary research field in the river science citation network and is found to be the most cited across all fields (Table 4). This suggests that the field of ecology has become an authoritative knowledge reference underlying river research. This finding fits with an observed shift in river (management) approaches away from an engineering-based to an ecosystem-based water management paradigm (Brierley and Fryirs 2008), and is also supported by the fact that hydraulic engineering did not show up as a separate field in our mapping. Based on a quick scan, the citation environment of hydraulic engineering journals constitutes a network adjacent to what defines river science in this paper.

Despite calls for cross-disciplinary fields such as eco-geomorphology, hydroecology or hydromorphology (Vaughan et al. 2009; Hannah et al. 2004; Thoms and Parsons 2002) the map of river science does not show the arrival of these fields. Nor do we observe a connection with relevant social science research.

These findings are in line with observations by Porter and Rafols (2009) who examined the degree of interdisciplinarity in mathematics, physics, biology, engineering, medicine and neurosciences. They concluded that science is becoming more interdisciplinary, but in small steps—drawing mainly from direct neighboring fields and only modestly increasing the connections to distant cognitive areas, like social scientific fields in the case of river science.

(ii) In the next step research topics were analyzed in order to provide deeper understanding of the cross-disciplinary nature of river research fronts. This demonstrated that although river science operates in a ‘traditional’ disciplinary mode as indicated by the field mapping, various research topics represent a combined contribution of disciplinary research, which implies multi-disciplinary research efforts at the operational research level (Tress et al. 2005). Major topics address the interface of hydrology and water resources, geomorphology and ecology (Poole 2002; Dollar et al. 2007; Thoms and Parsons 2002) and concern the study of systemic cycles, interactions and dynamics at the interface of these disciplines (see Table 5).

The complex societal context of riverine management issues not only demands understanding from the natural sciences but also from the social sciences including psychology, sociology, geography, political science, economics and policy studies (Vugteveen et al. 2006; Pahl-Wostl et al. 2007; Hillman 2009; Lenders and Knippenberg 2005; Brierley and Fryirs 2008; Surridge and Harris 2007). Thorp et al. (2007) in their presentation of the International Society for River Science (ISRS) - mention social science, economics, management and policy as relevant to river science next to hydrology and water resources, geomorphology, ecology and chemistry. We analyzed whether current multidisciplinary river research includes research beyond natural science. We did find planning and management issues to be part of river science research, evidenced by the presence of an environmental management field, and by several management related research topics mainly within the hydrology and water resources field (Table 5). The cross-disciplinary orientation of this latter field can be attributed mainly to the water resource journals, which have a broader scope than the hydrology research journals, and which consider water resources in their societal context. However, river research literature does hardly cite social science literature, suggesting that one is reinventing the wheel instead of using what is available. This is in line with Botey et al. (2012), who found that studies related to ecosystem management are dominated by the philosophical, ontological, and epistemological preferences of natural science.

(iii) Our analysis did not confirm that research on river issues in their societal context produces the type of knowledge referred to by Hillman (2009) as *phronesis*; i.e. contextual and place-dependent knowledge derived from practical experience and values at the local level and applied in a particular socio-political setting. This type of *transdisciplinary* knowledge is considered necessary to advance river management next to *techne* or applied "know-how", as in art, craft or technology and *episteme* or "know-why", scientific knowledge that is universally applicable. Our results thus support Hillman's observation that claims for a paradigm shift based on the full inclusion of the three mentioned knowledge types in river management must be treated with considerable caution (Hillman 2009). Qualitative approaches to the development of river science (Van Hemert 2008; Van Hemert and Van der Meulen 2011), based on interviews and document analysis, often sketch a picture where wishes and aims dominate, and not so much the *de facto* trends in a research field. The advantage of the quantitative approach in this study is to deliver the latter.

(iv) The local and practical (transdisciplinary) integration of river science in everyday engineering and social interventions may not proceed through paper-based communication of research results, as we noted earlier. Other forms of interaction may be relevant here as well, such as co-researching and collaboration between researchers and river professionals and policy makers. Future research on these collaborative relations may reveal this in more detail.

(v) Finally, we introduced an approach to cross-disciplinarity based on a two level analysis of disciplinary change and research front dynamics. The application of the approach on the river research case suggests its usefulness. At the level of the research front, most topics combine contributions from multiple research fields. This signals emerging multi-disciplinary research activities in river science. By combining this with an analysis of the topological structure of the disciplinary environment of river research, it becomes clear that the multidisciplinary research feeds back into the constituent individual disciplines, without any (early) signs interdisciplinary integration at the field research level. No new clustered research activities outside the boundaries of the established disciplines are visible yet. Actually, despite all the multidisciplinary activities within river research, the 2008 map suggests a firm stability of the disciplinary landscape. For the time being, claims about interdisciplinary river science remain presumptions.

Acknowledgments This study has been partly financed by the Interdepartmental Institute Science and Society of the Radboud University Nijmegen (grant W&S 2004-04), and by the Kennis voor Klimaat (Knowledge for Climate) program. Thanks to Mieke van Hemert for providing input when discussing the set up of the project, to André Somers for assistance with the SAINT Toolbox, to Jan Hendriks, Rob Leuven and two anonymous reviewers for providing valuable comments on earlier drafts.

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