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Review

Outcomes of the hydromorphology integration in the Water Framework Directive: A review based on science mapping

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A R T I C L E I N F O

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A B S T R A C T

The goal of our review was to evaluate scientific outcomes connected to hydromorphology and Water Framework Directive by synthesizing the main themes based on keywords, research domains, and the spatial coverage of high visibility publications. These data were integrated into a social network analysis to understand the structure of science related to our topic. Thus, we investigated 183 articles and conference proceedings from the Web of Science Core Collection. Among the 505 authors keywords, the central ones in our network were *Water Framework Directive*, *hydromorphology*, *macroinvertebrates*, *ecological status*, *water quality*, *reference conditions*, and *river*. The characteristics of the network of keywords indicated that information developed around a few key-concepts linked to numerous peripheral keywords, which highlighted some main themes of research. *Hydromorphology* appeared mostly in articles with *macroinvertebrates* and *river restoration*, suggesting the acceptance of environmental-based paradigm in water bodies' management. Consequently, we expected to count the majority of publications in *Environmental Sciences & Ecology* research domain. Issues related to the society (e.g. public participation, stakeholders) didn't appear in our analysis. Publications covered especially European Union member states, the network being dominated by Germany, Italy, and UK in terms of both study area and authorship. Besides traditional scientific relations between Western and Northern European states, we also noticed numerous comparisons between Danube countries. To comment the position of these publications in the scientific world, we used the Article Influence Score, which was below the average for the main research domain of *Environmental Sciences & Ecology*, probably as a consequence of the regional cover and concern of the Water Framework Directive. Further, we recommend more connections between environmental and social sciences, as well as between countries and we encourage funding for open access publications in order to increase the visibility and influence of the topic of hydromorphology and Water Framework Directive both bibliometrically and for decision and policy makers.

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1. Introduction

The integration of the concept "hydromorphology" in the Water Framework Directive 2000/60/EC was an element of novelty (Large and Newson, 2005), which transformed into legislation some previous scientific concerns. As example, for rivers, the hydromorphology referred to hydrological regime, continuity and morphological features (European Commission, 2000). These conditions, alongside with the water physico-chemical quality, were described as support for the biological components, which is a proof of ecosystem approach (Solimini et al., 2009; Voulvoulis et al., 2017). Hydromorphological, water physico-chemical, and biological elements were part of defining a river's ecological status. Methods were developed for the monitoring and assessment of a river's ecological status, by taking into account objective indicators demonstrative for hydromorphological, water physico-chemical, and biological elements (Feio et al., 2016; Carré et al., 2017). As main principle, the ecological status was defined in relation to human pressures (Solimini et al., 2009). Consequently, a good ecological status was conditioned by minimal anthropogenic impact (Acreman and Ferguson, 2010). Numerous questions were raised about the definition of reference conditions (Pardo et al., 2012; Voulvoulis et al., 2017). Moreover, the Water Framework Directive ambitiously required the achievement of a good ecological status for all river bodies by measures of river reconstruction, rehabilitation or restoration (Muhar et al., 2016). The entire administrative process at river basin district scale (i.e. methods with indicators, monitoring, assessment, and Programme of Measures) was attributed to River Basin Management Plans (RBMPs) (Hering et al., 2010). All management issues must include public participation (Cabezas, 2012). All other decisions related to water should respect Integrated Water Resources Management principles and the Water Framework Directive (De Stefano et al., 2010; Tsakiris, 2015). European Union (EU) member states made efforts in implementing these new concepts presented in the Water Framework Directive (Jager et al., 2016).

So far, we miss a synthesis on how scientists responded to this challenge of integrating hydromorphology in the Water Framework Directive until the recent application of the second cycle of the RBMPs in 2016. Numerous efforts were certainly made by scientists to draw expertise from different areas and communicate by publications, while employing EU instruments to fund their projects (Vaughan et al., 2009). Introducing a new concept associated to a European directive determines a scientific effervescence and a development in transdisciplinary knowledge. Such a review that exceeds the limits of a certain research domain is important, because, in the context of the Water Framework Directive, hydromorphology is seen as component of aquatic ecosystems. Moreover, such a review may find research opportunities and drawbacks in order to further inform and prepare the next cycle of the Water Framework Directive.

To fill the gap of lacking an overall image on scientific outcomes arisen from the introduction of "hydromorphology" in the Water Framework Directive, the goal of our work was to analyze the conceptual structure of science developed around this topic. We followed the flow model of Popescu et al. (2014), which analyzed the development of knowledge around another concept connected to European environmental legislation (i.e. for Natura 2000 concept and Habitats and Birds directives). By investigating high visibility publications, Popescu et al. (2014) found main axis of advancement in scientific knowledge linked to an EU concept. Around a new concept with an EU cover of implementation, indicators and methodologies were created; some research domains were more active than others; management questions were raised; new knowledge was unevenly acquired in EU member states. Popescu et al. (2014) proved also that analyzing publications as a network is an adequate method to give an overview on the scientific knowledge originating from a concept, as well as understanding directions and limitations of existing approaches. Network analysis of publications builds maps of science that describe how a topic is conceptually structured (Leydesdorff, 2007; Cobo et al., 2011; Nardi et al., 2016; Xiang et al., 2017).

Therefore, our paper provides a broad perspective on research connected to hydromorphology in the context of the Water Framework Directive, encompassing the full breadth of scientific fields. Our review of previous publications builds maps of scientific knowledge on this topic. More precisely, the specific objectives were: (i) to synthesize the main themes of scientific publications by using their keywords, (ii) to summarize main scientific findings as research domain by analyzing journals' profiles publishing these researches, and (iii) to analyze the spatial coverage of these publications. The analysis is objectively constructed, but all interpretations and commentaries are made from a fluvial geomorphologist viewpoint.

2. Material and methods

We investigated the English-written scientific literature (articles and conference proceedings) that addressed hydromorphology in the context of the Water Framework Directive between 2000 and April 2017. We searched Web of Science Core Collection by topic (i.e. titles, abstracts, and keywords) using simultaneously the terms *hydromorphology* (or *hydromorphological*, or *hydromorphologic*) and *Water Framework Directive*. We found a sample of 183 articles and conference proceedings responding to these criteria (Supplementary material 1). For each article, we extracted as data to be used: authors keywords, research domain per journal, and study area and authorship per country (Fig. 1).

These data were mainly analyzed as a network, connecting one publication to another. In the network, our data were nodes connected by edges (Newman, 2010). Data from one publication (e.g. keywords) were paired using an undirected edge. If the same pair appeared in another publication, the weight of the edge was increased by one step. The process was repeated for all publications, resulting an undirected, weighted network (Newman, 2010). To characterize nodes and edges, we used metrics specific to social network analysis such as: for nodes, degree centrality and betweenness centrality; for edges, weight; for overall network, density, average geodesic distance, and average clustering coefficient. Definitions and equations of these metrics were put in Supplementary materiel 2.

Furthermore, the analysis was organized to respond in parallel to the three aims of the paper: finding main themes of research around the concept of hydromorphology and within the context of

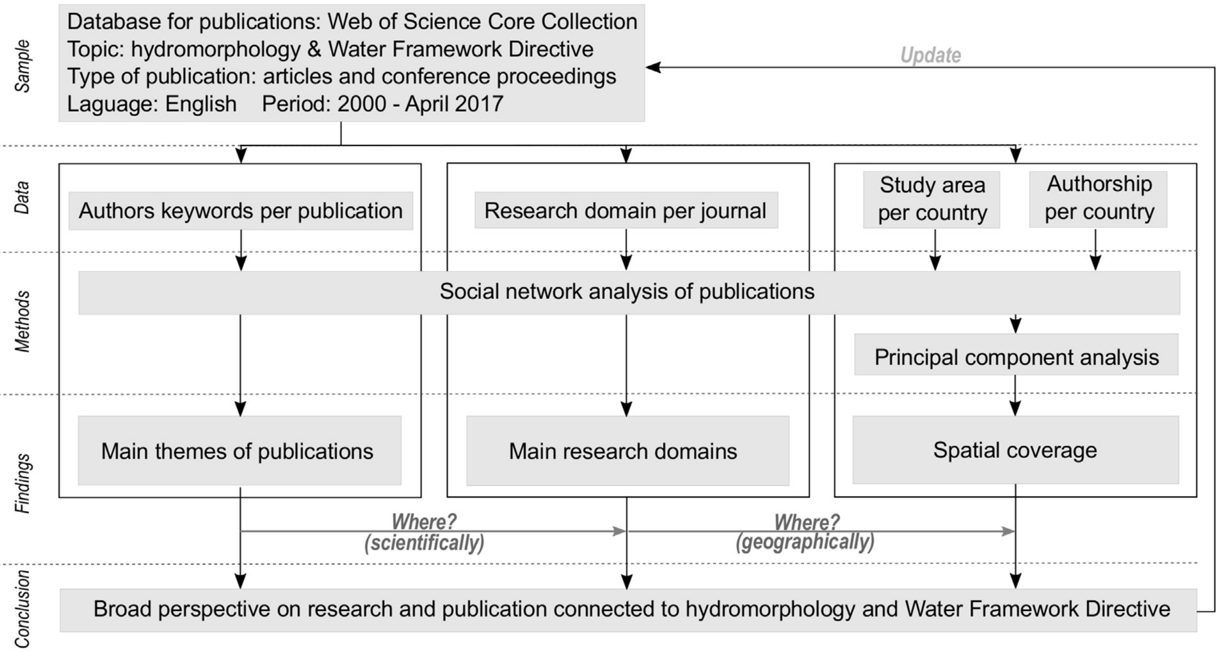

Fig. 1. Flowchart of methodological protocol of this study; metrics used in the social network analysis are described in Supplementary material 2.

the Water Framework Directive based on authors keywords; identifying main research domains interested to publish on this subject based on research domain of journals; and pointing out countries researching and publishing on this topic by using data on study area and authorship. Consequently, four networks were created and analyzed: for keywords, research domain, study area, and authorship.

First, we aimed at finding the most important themes in research and publications on hydromorphology and Water Framework Directive. Therefore, we examined authors keywords. The keywords were extracted, then standardized: using singular instead of plural (e.g. *river* instead of *rivers*), using all caps or small caps (e.g. *Habitats Directive, Czech Republic*), choosing the abbreviated or unabbreviated form (e.g. *RHS* instead of *River Habitat Survey*, *LHS* instead of *Lake Habitat Survey*, *BQE* instead of *Biological Quality Element, HMWB* instead of *Heavily Modified Water Body*), as well as unifying synonyms (e.g. *alien species* to *invasive species*, *macrophytes* to *aquatic plants*, *reference conditions* to *reference state*). We created a network where keywords were nodes and a pair of every two keywords from the same article formed an edge. For every keyword as node, we estimated the degree centrality and betweenness centrality. A high degree of a keyword suggested a popular concept, with more connections then other keywords. A high betweenness of a keyword hinted a critical term, connecting otherwise disparate keywords. For every edge, we calculated the weight, a high value revealing a repetition of the pair of keywords in several articles. Based on edges, we estimated also other metrics to characterize the strongness of interrelations between keywords of the network: average geodesic distance (high value – disconnected keywords), density (high value – interconnected keywords), and clustering coefficient (high value – strong neighbors).

Second, to summarize previous scientific findings, we searched for research domains of journals which published our sample of articles, as they were indexed on the Web of Science. We separated journals which had attributed a single research domain from journals with several research domains. Based on the last ones, we built a network, where research domains were nodes and a pair of every two research domains associated to a journal formed an edge. For every research domain as node, we computed the degree centrality and betweenness centrality. A high degree indicated a popular research domain for our topic. A high betweenness indicated an influent research domain for our topic. For every edge, we calculated the weight, a high value revealing a repetition of the pair of research domains associated to several journals, thus a strong relation between the two of them. We computed also the average geodesic distance, density and clustering coefficient for the network of research domains.

Finally, we explored the spatial coverage of the articles aiming to show the particularities per country in the flux of publications on hydromorphology and Water Framework Directive. Therefore, we examined countries as study area to reveal comparisons and as authorship to reveal collaborations. We separated single-country from multiple-country study area and authorship. Afterwards, we transformed multiple-country study area and multiple-country authorship, respectively, into networks. In one network, a node represented a country and a pair of two countries analyzed as study area in an article formed an edge. In the other network, the edge was formed by two countries being co-authors of an article. Similar to previous analysis, we calculated the degree centrality and betweenness centrality of countries as nodes, as well as the weight of the edges between countries and the network's average geodesic distance, density and clustering coefficient. A high degree indicated countries with numerous connections through respectively comparisons and collaborations. A high betweenness showed countries with more control over the network, as more information pass through them. A great weight of an edge means strong links between two countries as comparison subjects or collaboration partners. At last, to find each country profile, we integrated the above parameters calculated per country into a principal component analysis. Within the principal component analysis, countries were characterized by eight variables (V): number of articles as single-country case study (V1); number of articles as across-country case study (comparisons) (V2); number of other countries used for comparison (degree) (V3); betweenness among other countries used for comparison (V4); number of articles as single-country authorship (V5); number of articles as multiple-country authorship (collaboration) (V6); number of other countries implicated in collaborations (degree) (V7); betweenness among other countries implicated in collaborations (V8).

3. Results

3.1. Analysis of the keywords

Among the 183 articles, 174 had authors keywords. The 174 articles contained 505 keywords. The average number of authors keywords per article was 5.6. Among the analyzed keywords, 99 were used in several articles, while 406 were present in a single article. The keywords formed 2465 edges, of which 1993 were unique, with an average weight of an edge between two keywords of approximately 1.

The network formed by these keywords characterized by a low density (0.017), a relatively high average geodesic distance (2.555), and by a high average clustering coefficient per node (0.880).

The keywords with a high degree and betweenness were less represented, while the ones with a low degree and betweenness were numerous. The average normalized degree of the keywords was 0.017 (median = 0.010; standard deviation = 0.034) and the average normalized betweenness was 0.003 (median = 0; standard deviation = 0.029) (Supplementary material 3). Only 10% of the keywords had simultaneously the degree and betweenness above the average.

The most important keywords in our network, in terms of both high degree and high betweenness, were *Water Framework Directive*, *hydromorphology*, *macroinvertebrates, ecological status*, *water quality*, *reference conditions*, and *river* (Fig. 2, Table 1). Other central nodes with high degree were *monitoring*, *macrophytes*, and *assessment*. Critical nodes in the network, with high betweenness, were also *eutrophication*, *ecological potential*, and *biodiversity*. The strongest relations were between *Water Framework Directive* and *hydromorphology* (24 articles) as expected, followed by *Water Framework Directive* and *macroinvertebrates* (23 articles), and *Water Framework Directive* and *ecological status* (16 articles).

Focusing on specific fluvial hydromorphology issues, we noticed some particularities in the network. Among the methods used for physical habitat and hydromorphological assessment, *River Habitat Survey* and *EcoRivHab* occupied the best positions, with degree and betweenness above the average; the methods *LAWA-OS*, *LAWA-Von-Ort*, *SEQ-MP*, *CARAVAGGIO* and *IDRAIM* came later in the classification, with a betweenness below the average. The fluvial hydromorphology elements and associated indicators were mostly peripheral keywords in the network, with less favorable positions, respectively low degree and low betweenness. Only *hydromorphological conditions*, *sediments*, *connectivity,* and *riparian zone* had a degree higher than the average. Meanwhile, the *continuity*, *channel changes*, *channel form*, *channel geometry*, *channel pattern*, *channel profile*, *flow regime*, *pools and riffles*, *channel dynamics*, *channel morphology*, *evolutionary trajectory*, *hydrological regime, geomorphic units,* and *riverbank structure* were keywords in a single article, therefore peripheral terms in the network. Overall, keywords such as *fluvial geomorphology* and *hydromorphological status* or *quality* were also located in the second part of the list.

In terms of management, the position of the relevant keywords in the network indicated an emergent concern for this issue. Keywords such as *river restoration*, *restoration*, *stream restoration*, *rehabilitation,* and *river basin management* had a degree higher than the average. The *Programme of Measures* was identified as a peripheral keyword. Among the EU legal norms, *Habitats Directive*,

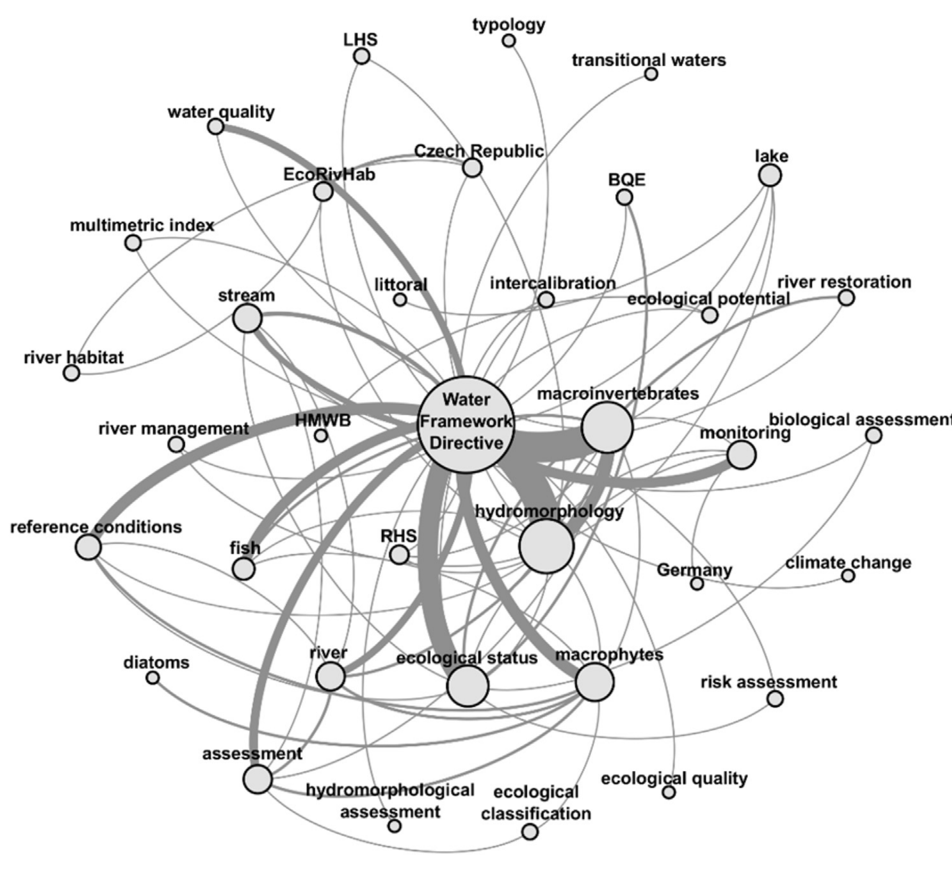

Fig. 2. Core of the network of keywords: selection of the most important 10% keywords as degree connected by edges with weight >2.

Table 1
Top ten list of the most important keywords in the network, with high degree (left) and high betweenness (right).

Rank	Keyword	Normalized degree	Rank	Keyword	Normalized betweenness
1	**Water Framework Directive**	0.615	1	**Water Framework Directive**	0.620
2	**hydromorphology**	0.271	2	**hydromorphology**	0.156
3	**macroinvertebrates**	0.244	3	**macroinvertebrates**	0.104
4	**ecological status**	0.162	4	**ecological status**	0.066
5	**water quality**	0.121	5	**water quality**	0.043
6	**reference conditions**	0.113	6	**reference conditions**	0.025
7	**river**	0.093	7	eutrophication	0.022
8	monitoring	0.093	8	ecological potential	0.021
9	macrophytes	0.093	9	biodiversity	0.021
10	assessment	0.081	10	**river**	0.021

Keywords in bold are on both lists.

Barcelona and *Helsinki* conventions occupied intermediary positions while *Floods Directive* and *Marine Strategy Framework Directive* had a degree lower than the average.

3.2. Analysis of journals' research domains

We counted 88 journals publishing our sample of articles, with an average number of articles per journal of 2.1 (median = 1; standard deviation = 2.5). The journal *Hydrobiologia* reached the top position as number of articles published (Tables S4–1 in Supplementary material 4). Other journals highly interested by our topic were *Limnologica*, *Science of the Total Environment*, and *Ecological Indicators*. Out of 88 journals, 59 published a single paper on our topic.

For 88 selected journals in our sample, we found 22 research domains (Fig. 3a). Among these journals, 41 had single affiliation and the balance of 47 were affiliated to multiple research domains. The most numerous articles belonged to *Environmental Sciences & Ecology*. Other domains standing out, with a high number of articles were *Marine & Freshwater Biology* and *Water Resources*.

For multiple affiliation journals, major part of research domains were connected to each other (18 out of 22), forming a network. In the core of the network, we found *Environmental Sciences & Ecology*, with the highest values of degree and betweenness (Table S4-2 in Supplementary material 4). *Environmental Sciences & Ecology* was strongly connected to *Water Resources*, *Marine & Freshwater Biology*, and *Geology* (Fig. 3b).

3.3. Analysis of the spatial coverage

We conducted an analysis per country in terms of study area and authorship. As expected, more than 90% of our results were focused on EU member states.

The 183 articles analyzed case studies (172) or were theoretical approaches (11). The articles on case studies investigated 38 countries. The average number of articles per country was 7.9 (median = 4.5; standard deviation = 8.9). As example, the most numerous studies were conducted on Germany (46) (Fig. 4a). Among these articles, 151 focused on one country and only 21 presented cross-country comparisons. In the group of 151 articles, we found 27 countries as single study areas, with an average value of 5.6 articles per country (median = 2; standard deviation = 7). In this list of single countries as study area, Germany occupied the first position with a number of 32 articles. In the group of the other 21

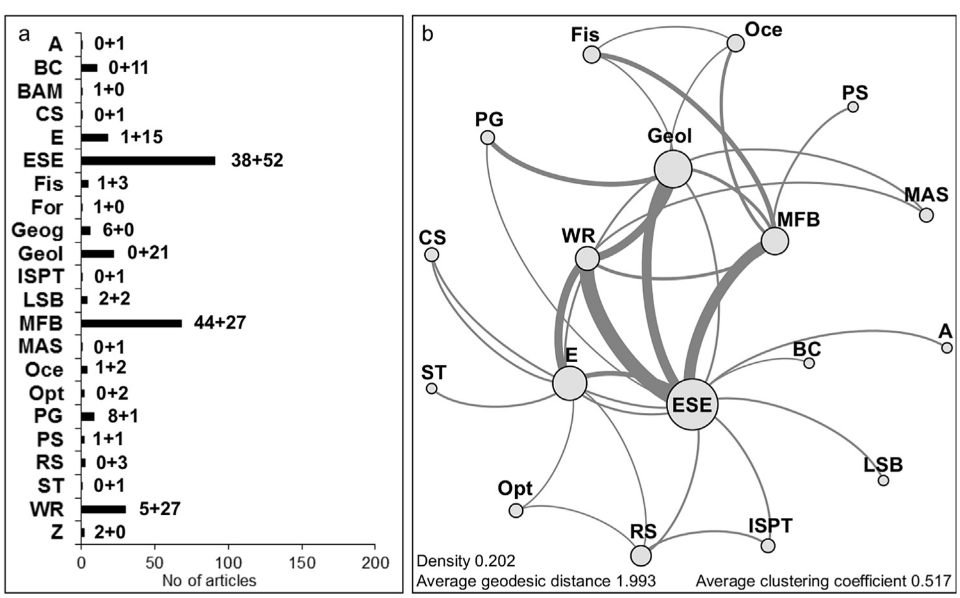

Fig. 3. Characteristics of research domains in our study: a) number of articles per research domain (in single affiliation journals + in multiple affiliation journals); b) network of research domains for journals with multiple affiliation. Acronyms of research domains: A – Agriculture; BC – Biodiversity & Conservation; BAM – Biotechnology & Applied Microbiology; CS – Computer Science; E – Engineering; ESE – Environmental Sciences & Ecology; Fis – Fisheries; For – Forestry; Geog – Geography; Geol – Geology; ISPT – Imaging Science & Photographic Technology; LSB – Life Sciences & Biomedicine; MFB – Marine & Freshwater Biology; MAS – Meteorology & Atmospheric Sciences; Oce – Oceanography; Opt – Optics; PG – Physical Geography; PS – Plant Sciences; RS – Remote Sensing; ST – Science & Technology; WR – Water Resources; Z – Zoology.

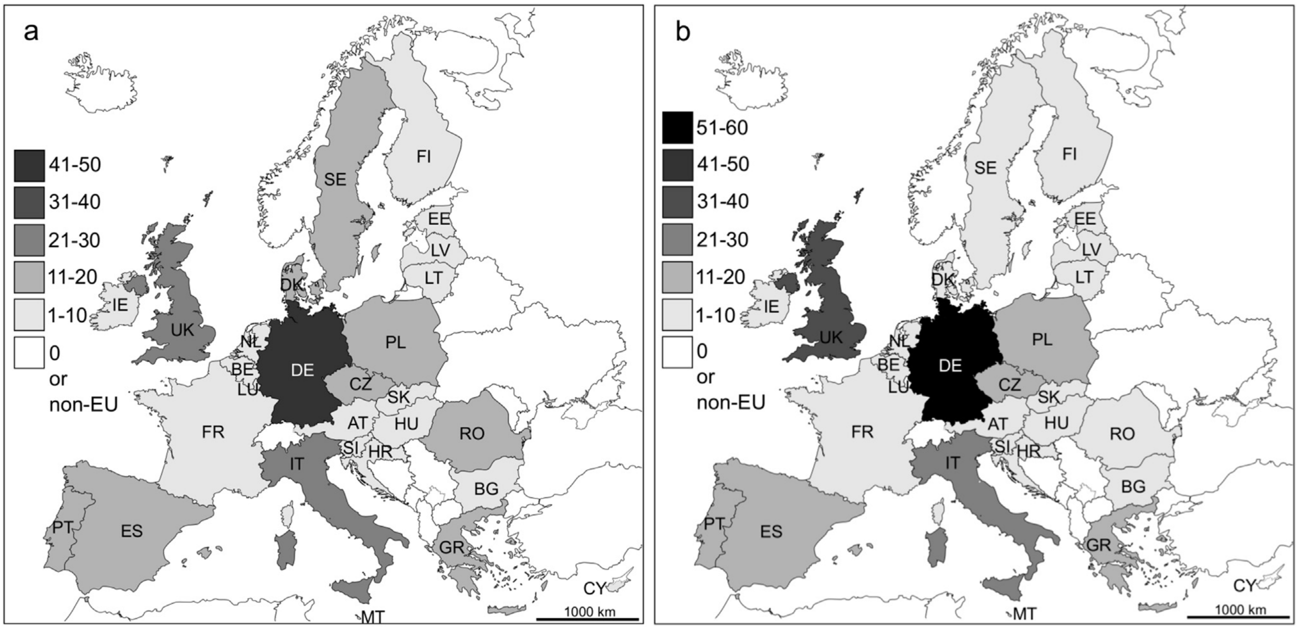

Fig. 4. EU spatial coverage of articles as study area per country (a) and authorship per country (b). Acronyms of countries: AT – Austria; BE – Belgium; BG – Bulgaria; CY – Cyprus; CZ – Czech Republic; DE – Germany; DK – Denmark; EE – Estonia; ES – Spain; FI – Finland; FR – France; GR – Greece; HR – Croatia; HU – Hungary; IE – Ireland; IT – Italy; LT – Lithuania; LU – Luxembourg; LV – Latvia; MT – Malta; NL – Netherlands; PL – Poland; PT – Portugal; RO – Romania; SE – Sweden; SI – Slovenia; SK – Slovakia; UK – United Kingdom.

articles, we found 32 countries as comparative study areas, with an average number of 4.6 articles per country (median = 4.5; standard deviation = 3.2). Again, Germany had the most numerous articles (14). As example, Germany was compared to 29 other countries and the most frequent analogies were conducted between Germany and, respectively, Austria and United Kingdom (7 articles) (Fig. 5a).

In terms of authorship, 36 countries were identified. The average number of articles per country was 7.5 (median = 4; standard deviation = 10.2), with the maximum number of articles having German authorship (51) (Fig. 4b). The number of single country publications (143 articles) overpassed the one of cross-country collaborations (40 articles). Among the 143 articles, we found 26 countries, with an average number of articles per country of 5.5 (median = 3; standard deviation = 6.4). Germany was on top of the list with 30 articles as single author. The other 40 articles had authors from 30 countries with an average value of 4.3 articles per

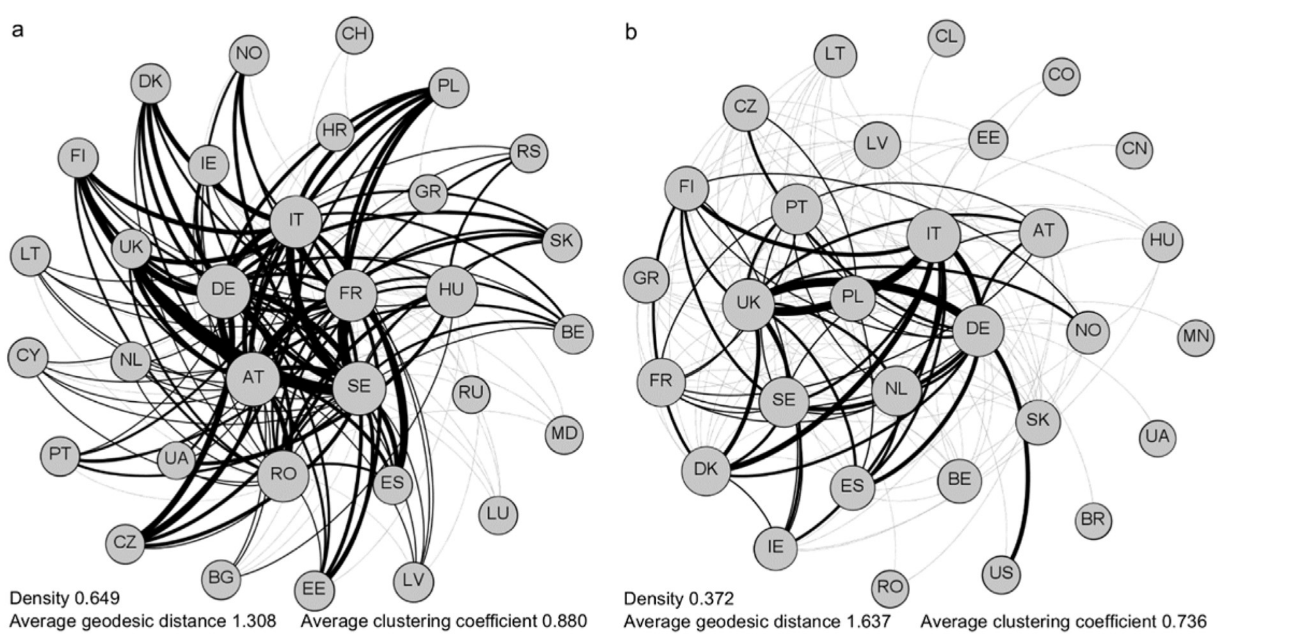

Fig. 5. Connections between countries as study area comparison (a) and authorship collaboration (b). Acronyms of countries: AT – Austria; BE – Belgium; BG – Bulgaria; BR – Brazil; CH – Switzerland; CL – Chile; CN – China; CO – Colombia; CY – Cyprus; CZ – Czech Republic; DE – Germany; DK – Denmark; EE – Estonia; ES – Spain; FI – Finland; FR – France; GR – Greece; HR – Croatia; HU – Hungary; IE – Ireland; IT – Italy; LT – Lithuania; LU – Luxembourg; LV – Latvia; MD – Moldova; MN – Mongolia; NL – Netherlands; NO – Norway; PL – Poland; PT – Portugal; RO – Romania; RS – Serbia; RU – Russia; SE – Sweden; SK – Slovakia; UA – Ukraine; UK – United Kingdom; US – United States.

country (median = 2.5; standard deviation = 4.8). Similarly, Germany had the most numerous publications in collaboration (21), with 21 different countries. The strongest collaborations were between Germany and United Kingdom, respectively Italy and United Kingdom, with 7 common articles (Fig. 5b).

Overall, the spatial coverage of publications on hydromorphology and Water Framework Directive characterized by disparities between EU member states; while some countries were over-represented, others didn't appear on the list (Fig. 4). Comparisons and collaborations were less numerous compared to single country study area and single authorship. The network of comparative study areas was denser, with a lower geodesic distance and a higher clustering coefficient than the one of collaborative articles, indicating that regional studies were not necessarily conducted in collaboration between the implicated countries. The top countries (with high degree) described in comparative studies were Austria, Germany, Romania, and Sweden; in this network, Hungary had the greatest betweenness. The top countries (with high degree and high betweenness) in collaborative studies were Italy, United Kingdom, and Germany. While Romania was in the center of the comparison network of countries, it had a peripheral position in the collaboration network of countries (Fig. 5). Croatia had a peripheral position in the comparison network of countries and it was missing from the collaboration network of countries.

The overall particularities of each country publishing on hydromorphology and Water Framework Directive result from Fig. 6, supported by Supplementary material 5. We found that Germany, Italy and UK had distinct positions, because they published numerous papers on this topic as single country study area/author (V1, V5) or in comparative/collaborative studies (V2, V6); due to their collaborations, they had also a high influence in the network of author countries, with a high betweenness (V8). Hungary had a lower number of articles as single country study area/author or in collaborative studies (V1, V5, V6); numerous comparisons with other countries (V3, V4) gave Hungary a particular position in the analysis. Austria, Slovakia and Romania had similar profiles, with numerous comparisons in terms of study area (V3, V4). Croatia, Slovenia, and Serbia had a low number of publications as single study area/author (V1, V5); all the three countries lacked of collaborations (V6-8).

4. Discussion

To call into question the relevance of this review of publications on hydromorphology and Water Framework Directive, three issues can be addressed. First, the identified keywords were demonstrative for themes of research and publication that were encouraged at European level. Second, certain research domains were more active than others. Finally, the disparities in the EU spatial coverage of these publications were discussed in relation to countries' membership status.

4.1. Indicators, methods, and management issues

We identified the main concepts of the Water Framework Directive in our network of keywords, which shows that scientists responded to the EU challenge of introducing hydromorphology as element of a water body's quality. In the core of our analysis, we found key-concepts such as *ecological status* and *reference conditions*. We found also the notion *monitoring*, demonstrative for efforts to bring new data into the system of environmental resources management. We found researches on methodological issues for status *assessment*, with a preference for *multicriteria index* approach. Among elements and indicators, the biological ones had the best position in the network (i.e. *macroinvertebrates*, *macrophytes*, and *fish*). Water physico-chemical indicators were represented in the central part of the network by *nutrients* and *pollution*. Hydromorphological elements and indicators were present mostly in the peripheral part of the network. The keyword *hydromorphology* connected strongly with *macroinvertebrates* and *river restoration*, which confirms that hydromorphology is also scientifically treated as a support for the biological elements (Elosegi et al., 2010). Among water bodies, rivers were found in the core of our analysis to the detriment of lakes and coastal waters.

Concerning management issues, we concluded on a variety of themes more or less analyzed by our sample of articles. As examples, *river restoration* and *measures* were in the core of our network of keywords, suggesting efforts to achieve a river's good status. However, surprisingly, there was no mention of RBMPs as keyword in the network of publications despite the role of main instrument for the implementation of the Water Framework Directive. Terms such as public participation and stakeholders lacked also from the

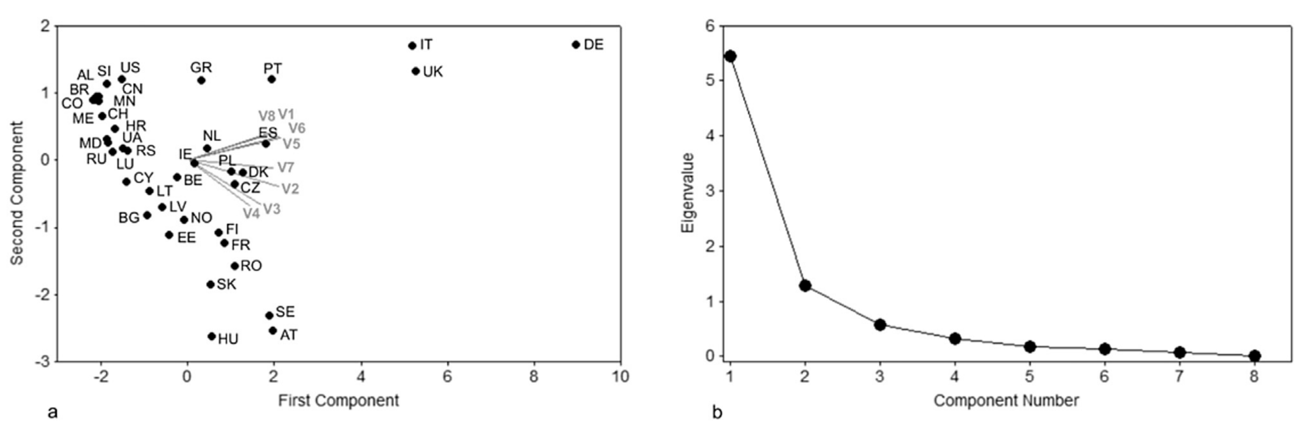

Fig. 6. Characteristics of countries based on the flow of publications on hydromorphology and Water Framework Directive: a) biplot of the principal component analysis; b) scree plot of the principal component analysis. Variables: V1 = number of articles as single-country case study; V2 = number of articles as across-country case study (comparisons); V3 = number of other countries used for comparison (degree); V4 = betweenness among other countries used for comparison; V5 = number of articles as single-country authorship; V6 = number of articles as multiple-country authorship (collaboration); V7 = number of other countries implicated in collaborations (degree); V8 = betweenness among other countries implicated in collaborations. Acronyms of countries: AL – Albania; AT – Austria; BE – Belgium; BG – Bulgaria; BR – Brazil; CH – Switzerland; CL – Chile; CN – China; CO – Colombia; CY – Cyprus; CZ – Czech Republic; DE – Germany; DK – Denmark; EE – Estonia; ES – Spain; FI – Finland; FR – France; GR – Greece; HR – Croatia; HU – Hungary; IE – Ireland; IT – Italy; LT – Lithuania; LU – Luxembourg; LV – Latvia; MD – Moldova; ME – Montenegro; MN – Mongolia; NL – Netherlands; NO – Norway; PL – Poland; PT – Portugal; RO – Romania; RS – Serbia; RU – Russia; SE – Sweden; SI – Slovenia; SK – Slovakia; UA – Ukraine; UK – United Kingdom; US – United States.

network. Moreover, we found that connections to other policy frameworks were weak.

Overall, the characteristics of our network of keywords suggested that information was concentrated around a few themes of research. We found some key-concepts around which peripheral keywords were grouped in clusters, with a low density of links over the network. This finding appears to be characteristic for the development of knowledge, as it was already showed for other domains by Popescu et al. (2014).

The results of our keywords analysis need to be considered with some caution. Electing keywords when publishing a paper could be related to certain journals' requirements (e.g. number of keywords, eluding words used in title). We noticed also that certain articles are missing from the Web of Science Core Collection by error (e.g. Rinaldi et al., 2016). Moreover, we worked only on a sample of articles chosen based on their topic in order to objectively conduct the review. Hence, we found other publications on hydromorphological themes analyzed in the context of the Water Framework Directive, without these concepts named as topic (e.g. González del Tánago et al., 2016; García de Jalón et al., 2017). Therefore, our results must be interpreted as mostly reflecting concerns in environmental and earth sciences inside the Water Framework Directive's wide subject matter rather than a review of studies on hydromorphology.

4.2. Scientific coverage

We identified *Environmental Sciences & Ecology* as main research domain with publications on hydromorphology and Water Framework Directive: largest number of articles in our sample, central position in the network of research domains of selected journals, and strong relations with other research domains on water and geology. This finding confirms previous studies, highlighting that the Water Framework Directive put aquatic ecology at the base of water management decisions (Hering et al., 2010; Cabezas, 2012). More focused, this finding re-demonstrates that the field of ecology occupies a central position in river research, which signals the acceptance of the ecosystem-based paradigm in river management, replacing the traditional engineering paradigm (Vugteveen et al., 2014). We conclude that the environmental friendly ideal is the main gain of studies on hydromorphology and Water Framework Directive, demonstrative for an ecosystem approach although not explicitly mentioned in legislation (Vlachopoulou et al., 2014).

Several other research domains had publications on hydromorphology and Water Framework Directive, but lacked of strong connections with each other: almost half of the journals were focused on a single research domain, therefore almost a fifth of research domains were missing from the network of publications. As examples, research domains related to social sciences, management, economics, and education were missing from our inventory, domains which are considered to be under-represented on the Web of Science (Waltman, 2016). Consequently, as deficiencies of scientific research on our topic, we recall those on some management issues: planning and management of a river basin (Boeuf and Fritsch, 2016), in-depth involvement of social aspects in river research (Vugteveen et al., 2014), and institutional integration of EU policies on environmental management of water resources including potential conflicts between policies' goals (Fliervoet et al., 2015; Janauer et al., 2015).

When compared to the study of Popescu et al. (2014), which served as a model for our analysis, we found some similarities with regard to the introduction of new concepts in European legal frameworks. Both studies found that knowledge developed around some main themes of research. Ecological concepts had a better position than concepts related to management and social sciences. These findings indicate numerous efforts to better understand processes in natural sciences. Societal matters concerning the implementation of European legal frameworks seem to be marginal for now. Despite the European integrated concern for environmental issues, researchers from various domains don't collaborate enough to each other.

Our sample of articles had a low influence position in the scientific world of publications, with a mean Article Influence Score of 0.548 and 0.660 for *Environmental Sciences & Ecology*, thus below the average of 1 (Walters, 2014). The issue of hydromorphology and Water Framework Directive is mostly regional, with a focus on the EU member states, which automatically attracts a lower number of citations than the ones with a world-wide spatial cover or concern. Moreover, this finding could be explained by scientists' interest to publish in traditional and prestigious journals with a precise focus on aquatic sciences (e.g. *Hydrobiologia* is available since 1948) and not necessarily in multidisciplinary journals. Hence, traditional journals were bibliometrically outrun recently by the multidisciplinary and open access ones (Leydesdorff and de Nooy, 2016; Wang and Waltman, 2016). Additionally, it is well known that citations depends on the research domain, network of co-authors, and other random factors (Wallace et al., 2012; Waltman and van Eck, 2013; Walters, 2014; Waltman, 2016). Therefore, the low influence position of our sample of articles in the scientific world is understandable. Publishing in multidisciplinary journals and open access ones could boost the scientometrics of our topic. Moreover, the choice of open access could make the findings more accessible to decision makers at regional and local scale and to the great public. Therefore, we recommend to encourage funding for open access publication in research projects.

4.3. Disparities in the EU geographical coverage

We found that most publications on the topics of hydromorphology and Water Framework Directive focused on EU member states, in terms of both study area and authorship, which was expected due to the EU coverage of the Directive. The flow of publications was dominated by Germany, Italy and UK in terms of both study area and authorship. United Kingdom and Germany are known as well-researched countries on the Water Framework Directive, "hot-spots" of scientific publications in the EU, with good ranks in terms of citations (Bornmann and Waltman, 2011; Aksnes et al., 2012; Boeuf and Fritsch, 2016). The top position of Italy in our analysis is probably related to numerous publications on fluvial geomorphology in the Italian Alps conducted in this framework (Scott, 2010).

Overall, our analysis showed also the dominance of single-country publications to the disadvantage of comparative and collaborative works, which seems to be a generalized issue of publications on EU environmental policy (Popescu et al., 2014). Traditional relations between Western and Northern European countries, as long-term members of the EU, were the strongest ones. We also noticed numerous comparisons between the Danube's countries, especially Austria, Hungary and Romania, due to common research efforts in the field of water management despite the tumultuous times of political and economic transformations (Feldbacher et al., 2016). Member states joining EU after 2004 made efforts to publish, but had a low number of collaborations (e.g. Poland – 8 articles as single author versus 3 articles in collaboration; Romania – 8 articles as single author and 1 collaboration; Bulgaria – 1 article as single author and no collaborations), therefore, being under-represented in our network. Small countries such as Cyprus and Luxembourg had the lowest number of publications on this topic, while Malta lacked from the list. Among the countries aspiring to join EU, Albania, Montenegro and Serbia shyly made their appearance, with a very low number of articles, while Macedonia had no publications in high visibility journals on these topics. These disparities are certainly due to different strategies and phases of the ongoing process of implementation of the Water Framework Directive (Bourblanc et al., 2013; Nielsen et al., 2013). The discrepancy in the number of publications might also be related to socio-economic aspects, such as the number of inhabitants and population income (Dragos and Dragos, 2013). Additionally, the access to funds for research and therefore the publication in high visibility journals differ from one country to another (Auranen and Nieminen, 2010).

Even if this discrepancy between the intensity of publication flux in EU member states is understandable, it only slows down the implementation process of the Water Framework Directive concerning hydromorphology and more largely. Therefore, taking a closer look at candidate states (Boeuf and Fritsch, 2016), implementing twinning projects in order to set European models for candidate countries (Bürgin, 2014), and setting up joint education programs, co-ordinated research infrastructure and pan-European research programs (Irvine et al., 2016) could only be helpful to develop scientific knowledge, publish in international teams, and further align the scientific advancement with water policies. The project REFORM (REstoring rivers FOR effective catchment Management), financed by the 7th Framework Programme of the EU, is an example of good practice due to collaboration between 15 countries, with over 100 publications (REFORM, 2015).

Outside EU, we found little collaboration. As example, US had only 6 collaborations with EU countries. Hence, US had great experience with the topic of naturalness of aquatic ecosystems conditions (i.e. restore and maintain the chemical, physical, and biological integrity of waters) derived from the 1972 Clean Water Act (Stoddard et al., 2006). Consequently, US developed numerous methods similar to a hydromorphological assessment (Langhans et al., 2013; Belletti et al., 2015) and implemented a great deal of river restoration projects (Castillo et al., 2016). Therefore, gaining experience from lessons learned by US collaborators and obtaining comparable results for water bodies' assessment might accelerate gaining know-how and further implement public policies to the advantage of environment protection.

5. Conclusions

Was the introduction of "hydromorphology" in the Water Framework Directive followed by its integration into the scientific concerns? In the network of keywords selected from high visibility articles on this topic, *hydromorphology* was a key-concept well connected to other key-concepts such as *macroinvertebrates* and *river restoration*. Yet, hydromorphological elements were mostly peripheral keywords in our network. This confirms that hydromorphology is scientifically considered as a support for biological elements. Hydromorphology appears to be occasionally the main subject of research inside the Water Framework Directive even if a healthy environment should also contain a diversity of hydrological phenomena and fluvial processes. Issues related to *reference conditions*, *ecological status monitoring* and *assessment* were other central outcomes of our topic. Therefore, we expected to found the research domain of *Environmental Sciences & Ecology* as a star in our analysis. Issues related to hydromorphology and society, such as *stakeholders* or *public participation* in decision making lacked from our analysis. Despite obvious efforts to research and publish on our topic, the main research domain had a relatively low bibliometric influence in the scientific world. This finding might be explained by the regional (EU) geographical coverage of the topic of hydromorphology and Water Framework Directive, with great disparities per member state. We conclude that hydromorphology was integrated especially in environmental sciences when working for the implementation of the Water Framework Directive. The majority of EU member and aspirant states showed preoccupation for the topic of hydromorphology and Water Framework Directive.

Our review used the network analysis to give an overview of the main outcomes of hydromorphology integration into the Water Framework Directive, which covered a wide area of scientific domains at the detriment of depth. While this could be interpreted as a potential weak point, the study showed main scientific concerns, as well as limitation of current researches and publications. Deeper insight into certain themes could be gained by systematic reviews. As example, subjectively choosing and analyzing publications on a river's hydromorphology could show main themes of research preferred by fluvial geomorphologists.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2017.11.078.

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