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Integrated water assessment and modelling: A bibliometric analysis of trends in the water resource sector

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ABSTRACT

There are substantial challenges facing humanity in the water and related sectors and purposeful integration of the disciplines, connected sectors and interest groups is now perceived as essential to address them. This article describes and uses bibliometric analysis techniques to provide quantitative insights into the general landscape of Integrated Water Resource Assessment and Modelling (IWAM) research over the last 45 years. Keywords, terms in titles, abstracts and the full texts are used to distinguish the 13,239 IWAM articles in journals and other non-grey literature. We identify the major journals publishing IWAM research, influential authors through citation counts, as well as the distribution and strength of source countries. Fruitfully, we find that the growth in numbers of such publications has continued to accelerate, and attention to both the biophysical and socioeconomic aspects has also been growing. On the other hand, our analysis strongly indicates that the former continue to dominate, partly by embracing integration with other biophysical sectors related to water – environment, groundwater, ecology, climate change and agriculture. In the social sciences the integration is occurring predominantly through economics, with the others, including law, policy and stakeholder participation, much diminished in comparison. We find there has been increasing attention to management and decision support systems, but a much weaker focus on uncertainty, a pervasive concern whose criticalities must be identified and managed for improving decision making. It would seem that interdisciplinary science still has a long way to go before crucial integration with the non-economic social sciences and uncertainty considerations are achieved more routinely.

1. Introduction

There are substantial challenges facing humanity in the water and related sectors and purposeful integration of the disciplines, connected sectors and interest groups is now perceived as essential to address them. This paper deals with integrated assessment (IA) and modelling (IAM) in the water resource sector, conveniently referred to here as Integrated Water Assessment and Modelling (IWAM). IA is a scientific field, sometimes referred to as a meta-discipline, that aims to understand complex problems that arise from the interactions between humans and environmental systems (Parker et al., 2002). According to Rotmans and Van Asselt (1996), "*Integrated Assessment is an interdisciplinary and participatory process of combining, interpreting and communicating knowledge from diverse scientific disciplines to allow a better understanding of complex phenomena.*" Given that the complex nature of these problems defies the capacity of a single scientific field (Rotmans, 1998; Ravetz, 1999), IWAM provides a framework (i.e. theories, methods, tools) for amalgamating, structuring and sharing knowledge about water resource assessment from multiple scientific disciplines (e.g. hydrology, economics, ecology and the social sciences). IWAM is built on the fundamental principles of stakeholder engagement, leveraging the strengths of conceptual and numerical methods, focusing on policy questions, as well as characterization and management of uncertainties (Jakeman and Letcher, 2003).

The number of publications on IA and IAM has grown rapidly since Rotmans (1998) presented one of the earliest discussions and reviews of IA methods. Many authors have since presented reviews focusing on some aspects or methodological approaches within the field of IAM. The review and synthesis papers discussed immediately in the following helped to set the keywords for our analysis. Parker et al. (2002) discussed various definitions of IAM and identified five different types of integration that are needed

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for the effective management of environmental problems, which are integration of issues, models, scales, disciplines and stakeholders. The paper Croke et al. (2006) discussed the various frameworks and methods of IAM, their suitability and unfulfilled potential for these purposes, based on three Australian IA case studies. Pahl-Wostl (2007) articulated IAM as a multi-level learning process (i.e. individual, group, community levels), and described the role of hard and soft systems analysis in achieving the desired learning outcomes. More recently, Kelly et al. (2013) reviewed different IAM papers to identify the most common modelling approaches and introduced a framework to assist modellers and model users in the choice of an appropriate modelling approach for their integrated assessment applications to enable more efficient learning in interdisciplinary settings. Hamilton et al. (2015) reviewed available research on IAM, identified the key dimensions for architecting integration, and mapped how these dimensions can be incorporated into the four main phases of an IAM process: scoping, problem framing and formulation, assessing options, and communicating findings. Such literature review articles as the above address interesting and useful aspects of IWAM, yet none provides an overarching view of the field. At present, the rate of publishing IWAM research results as papers, reports, books and book chapters is accelerating rapidly. Thus, it is timely for a comprehensive, quantitative review of IWAM literature covering its general landscape in order to provide a more structured picture of IWAM topics and generate insights into crucial gaps and potential opportunities.

Moreover, traditional approaches to literature review can identify the knowledge gaps within a problem domain and give an indication of its current status (Maier, 2013), but they are time-consuming and highly subjective. A bibliometric analysis, while potentially more limited in depth, can provide a holistic and objective picture of the structure, topics, and gaps in a field of research. Bibliometric research refers to the study of the quantitative aspects of the production, dissemination, and use of recorded information through the use of quantitative methods and mathematical models for these processes (Broadus, 1987; Tague-Sutcliffe, 1992). As a body of research and methods, bibliometric analysis uses approaches developed in library and information sciences. It evaluates physical units of publication, citations, and surrogate measures from a corpus of literature to discover and describe patterns within publications in a topic, field, journal, institute or even country (Broadus, 1987). The bibliometric approach to literature analysis is valuable in that it can effectively illustrate the stages of development and help researchers navigate through a body of knowledge (Wang et al., 2014), and establish a reproducible workflow for analyses as the field advances over time. In this paper, we focus on IAM publications in the water resource sector as it is a large environmental sector worthy of analysis in itself, and hopefully our analysis will provide guidance for authors intending to study IAM in other sectors.

A very limited number of bibliometric studies have been published in research areas related to environmental assessment and modelling applications. Depending on their objectives, these studies vary according to the analysis focus or the topic under investigation, the level (e.g. field of study, journal) at which the analysis is conducted, the time span and the methods employed for the analysis. For example, Li and Zhao (2015) completed a keyword analysis of 20 years of global Environment Impact Assessment research revealing gradual transitions over time towards research focused on Strategic Environmental Assessment. Niu et al. (2014) used statistical and bibliometric methods to describe the growth in the global groundwater research over the past two decades.

Wang et al. (2010) conducted a keyword frequency analysis, with a focus on publications in "Water Research" journal publications over the period (1967–2008) to elicit the changes in research topics of interest. Through this bibliometric approach, the authors discovered the progression of a topic's development, for example, the increased attention on "drinking water" through the "adsorption" method. Later, Wang et al. (2014) conducted a bibliometric analysis of 3004 papers on climate change vulnerability research. It revealed that the most widely focused research topics in this field include health issues in the socioeconomic system, food security in the field of agricultural systems, and the issue of water resource management.

Most recently, Barthel and Seidl (2017) applied a bibliometric analysis to ascertain to what degree interdisciplinary collaboration has taken place in groundwater research. They covered papers from 1990 to 2014 and used several indicators together with their personal expertise in groundwater and interdisciplinary research, discovering that only a low, single-digit range of papers were really multidisciplinary and a large number of the analyzed papers was authored primarily by an individual researcher, which indicates that they are mono-disciplinary. These studies showcase the contributions and insights that bibliometric analysis can offer for profiling a body of knowledge.

In this article, bibliometric methods are described and used to investigate the landscape of IWAM research through publication. We investigate the nature of the progression of IWAM research to its current status. The aim is to reveal underlying patterns in its scientific outputs. Pertinent results include the number of articles, the main journals for publications, key authors, international spread of first authors, noteworthy trending topics, common keywords and an evaluation of influential publications, in order to provide a comprehensive picture of IWAM research.

2. Research methodology

Similar to any research process, the reliability and robustness of results are determined by the methodology employed. It is essential to have a transparent and reproducible workflow to allow for replication of the study. In this section, we describe the adopted methodology (Section 2.1), and how it has been applied in this study (Sections 2.2 and 2.3).

2.1. Bibliometric analysis steps

We employed a stepwise procedure commonly used in bibliometric studies to complete the analysis in this article (e.g. Morris and Van der Veer Martens, 2009; Börner et al., 2005). The approach adopted consists of eight steps which are illustrated in Fig. 1. These include (1) defining the topic, (2) bounds of the study, selecting sources of data, (3) retrieving and (4) pre-processing data, followed by (5) analysis, (6) quality checking, (7) visualization, and finally (8) evaluation. These steps are further described in the following.

Similar to any type of analysis, the results obtained from the bibliometric analysis are influenced by the decisions that the analyst makes through the process (e.g. keywords selection). To address this, we explicitly report the followed workflow, and the decisions made along the way, and how the results can be interpreted in that context.

Step 1 Topic definition: As with any research problem, the research question and topic of interest must be defined prior to starting a bibliometric analysis. Elements that make up the research question and help bound the problem may include the phenomenon of interest and geographic area. Clearly articulated research questions help refine the boundary of the inquiry and narrow analyses later in the process. This article is focused on examining peer-reviewed publications on Integrated Water Assessment and Modelling (IWAM).

Step 2 Boundary Definition: The main search terms and common synonyms or other forms (noun, verb and adjective) are

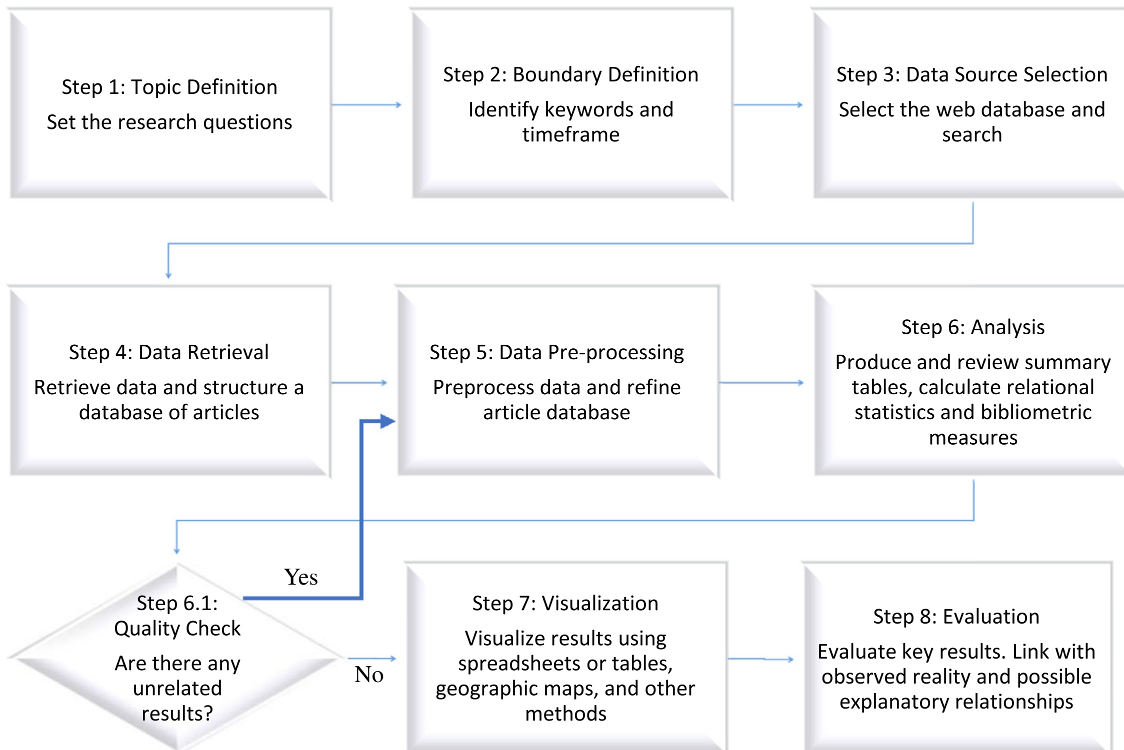

Fig. 1. The stepwise approach to bibliometric analysis applied in this study. Each step is conducted in sequence with a feedback between step 6.1 and 5 occurring if the results are to be checked.

defined within a seed list of terms or keywords. Additionally, the time period for including documents in the corpus is completed in this step (see Section 2.2).

Step 3 Data Source Selection: The corpus of documents or source texts for analysis is critical to determining the outcomes and relevance of results. In this step, a data source, such as an online database must be defined. In the case of peer-reviewed literature, there are different databases for scholarly publications such as Scopus, Google Scholar, and Web of Science. Scopus has been identified as one of the largest abstract and citation based databases of peer-reviewed literature in the form of journals, books and conference proceedings (see Kumar et al., 2015). It provides coverage of the world's research output across various disciplines and, therefore, Scopus was selected as the source database for this study. And Scopus has slightly more coverage on conference articles than WoS, but we expect that results for WoS would show the same trends and proportions; the numbers would obviously be different.

Step 4 Data Retrieval: Having identified keyword terms, timeframes, and source publications, a list of publications must be identified and collected with the primary information about each (e.g. authors, title, keywords, abstract text, cited references, etc.). The final corpus, or publication list, that will be used for analysis is compiled after searching the selected database and downloading selected publications. It is noted here that this step relied heavily on the choice of identified keywords, and their use in the title and abstract text.

Step 5 Data Pre-processing: This is the step in which the initial broad checks are conducted. Checks include filtering out any unrelated journals and duplicate entries, whilst also ensuring publications that are known to be relevant are included in the generated database. We did not use any ranking system to prioritize articles/journals.

Step 6 Analysis: After the search process, one should explore the development track of a topic based on different aspects of the publications like quantity of papers, type of publication, journals and other source types, citation counts, temporal analysis of publications across journals through time, geographic analysis by country, and keyword frequency analysis. Exploring these aspects allows for the identification of noteworthy trends in the topic of research within the field. Many software applications and libraries are available to analyse the large-scale input data from the various data sources such as Scopus, Web of Science and many others (Kumar et al., 2015). A review of available applications from Cobo et al. (2011) documents the use of various science mapping applications to evaluate the corpus and concludes that no single application can complete all possible bibliometric analyses. For this study, we chose BibExcel as the scientometric analysis software with capabilities for completing common bibliometric analyses. Unlike some other software, BibExcel is able to use various data sources beyond search results from common databases, such as Web of Science (Kumar et al., 2015), and the application output file is easily readable by other software.

Step 6.1 Quality Check: After producing the result tables (publications, journals, authors, related tables), one should check if there are any unrelated results; all the results should be in connection with the topic and questions, based on their field and subjects. Generally, this process must be undertaken back and forth several times to lead to a representative database and the result. For example, we started the search with a broad set of keywords with the aim of capturing those dimensions embedded in the notion of integration (e.g. economics, ecology, environment, planning, decision making). With a closer look at the dataset, we were able to make a judgment about the relevance of these keywords to the quality of search results (i.e. relevance to our research problem). Therefore, we refined these keyword sets iteratively until we ended up with the most relevant.

Step 7 Visualization: Arguably, a primary goal of bibliometric and scientometric analysis targets the creation of tables, graphs, charts and maps to illustrate results and make complex information and relationships more understandable. In this study, Excel was used to visualize the target keywords, types of publications, and publishing trend (in the form of tables and graphs). Additional analysis was conducted with the Python programming language, with visualizations created with the Seaborn data visualization package (detailed in Section 3).

Step 8 Evaluation: In this final step, the results are evaluated and reviewed. The results of the previous steps are detailed and explained in Section 3 to give a sense of the progression of advances within the field of IWAM.

2.2. Set the applicable search terms (Steps 1–3)

In this study, we used the conceptual model in Fig. 2, to inform the design and achieve the study objectives, and for best use of the corpus and source database. This study analyzed the bibliometric trends, structure, and topics within the field of integrated water assessment and modelling. Combinations of terminology related to the IWAM field, and their different synonyms, were used as the initial keywords to be searched (12 combinations in total, see Table 1). We used combinations of words as use of a single term was too broadly applicable, resulting in the incorrect identification of publications (over-appraisal), such as those which report studies that are "integrated" or achieve "integration" in some sense, but not in a manner relevant or applicable to IWAM. We also used catchment as a surrogate word for water in the combinations as some articles omitted specific mention of the word water. Use of water, however also captured the word watershed.

On the other hand, studies investigating different aspects of the water system, but which were not described as being "integrated" by the authors were not included. Our assumption is that it is more likely that the study does not belong to IWAM unless integration is explicitly stated. Some of these studies may have been "integrated", such as bio-economic modelling which covers both the bio-physical and economic or groundwater-surface water modelling, but it was not possible to include these studies through this bibliometric approach when the integrated nature of the study is not explicitly acknowledged.

Using the Scopus Database, English-language journals, conference articles, books and book chapters were identified and stored as an Endnote database, with the search dates set to return results up to 2015. All necessary information was downloaded and stored in Research Information System (RIS) file format, including names of authors, contact addresses, title, year of publication, keywords, subject categories, names of journals, times cited in each year, abstract, references and other information.

Table 1
The initial search keywords for IWAM and associated number of published articles.

Keyword category	Number of publications
Integrated + Modelling + Water	9602
Integrated + Model + Water	19,095
Integration + Model + Water	8606
Integration + Modelling + Water	3961
Integrated + Assessment + Water	7959
Integration + Assessment + Water	2550
Integrated + Modelling + Catchment	1437
Integrated + Model + Catchment	1997
Integration + Model + Catchment	591
Integration + Modelling + Catchment	405
Integrated + Assessment + Catchment	935
Integration + Assessment + Catchment	261
Integrated + Model + Basin	3604
Integrated + Modelling + Basin	2193
Integration + Model + Basin	1306
Integration + Modelling + Basin	734
Integrated + Assessment + Basin	1225
Integration + Assessment + Basin	412
Total Publications	66,873

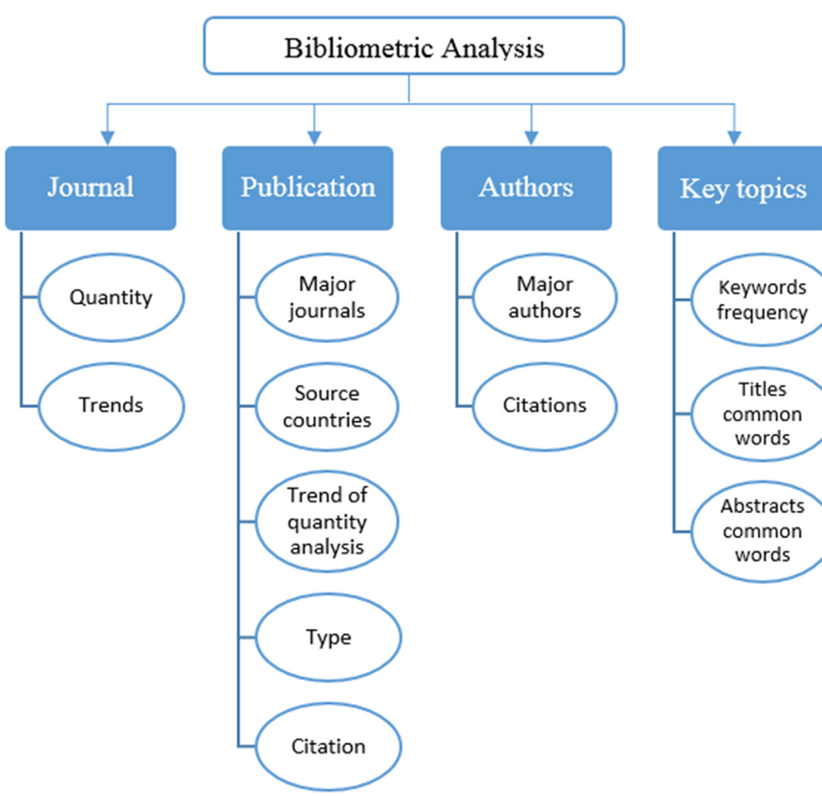

Fig. 2. A concept map of the elements under investigation in the bibliometric analysis.

Initially, journal articles, books and book chapters were the main focus of this study, but articles known to fit the defined criteria were found to be missing in the collated database. In the subsequent process, it was found that Scopus had identified some journal articles as conference papers. Consequently, we also included the conference papers category in the search engine in order to gain a comprehensive database.

2.3. Refinement of the search results (Steps 4–5)

Some of the 66,873 publications in Table 1 belonged to more than one keyword category. After omitting the duplicates using the Endnote automatic analysis, our subsequent database comprised 33,716 publications. Another challenge was that some publications in the downloaded database were not related to the water sector, even though they possessed keywords in Table 1.

The database was therefore filtered of these false matches, removing publications which did not contain any one of the following words in any part of the publication: basin, catchment, watershed, river, lake, groundwater, aquifer, water resources. Then, based on words in the title (such as soil moisture, solar energy, atmosphere, thermal and many others in the database) and/or journals in the database that were apparently unrelated to IWAM, we inspected such articles individually and removed those found to be irrelevant to IWAM.

The missing contents in the database (such as year, name of authors, or journal) were manually added in Endnote. Despite the search period ending in 2015, there were still some papers whose publication year was ascribed to 2016. Checking these, it appears they were available online earlier (mostly 2015) and so these were adjusted to reflect their online publication date. The final database contained 13,239 publications from the year 1970 to2015.

3. Results analysis and discussion (Steps 6–8)

Based on the final database of publications, the bibliometric analysis methods described in Section 2.1 were employed and the results are now presented and analyzed here.

3.1. Types of publications

Table 2 summarises publications by type in the final database. Approximately 72 percent are journal articles, 26 percent are conference papers and the remainder are books or book chapters.

3.2. Quantity of literature and growth trend

The number of publications over time on a research topic is an important indicator of its growth. Fig. 3 shows the trend of IWAM publications over the last 45 years. An increasing trend can be observed over the defined study period, from a single publication in 1970 to 1242 in 2015, with a total of 13,239 publications (mostly journal articles) having been identified in the database.

Early publications in the database were reviewed closely not only to ensure they were relevant to this study but also to appreciate the nature of the early beginnings of the field. The following examples provide a strong indication of IWAM in its infancy. The initial paper in 1970 (Rogers and Smith) determined water balances for a project area and emphasized interactions of a surface water-groundwater system within the economic context of irrigation management. Also, Shun Shih's optimization model (1970) was one of the first integrated models shown up in the reviewed papers, which was designed for river basin planning to water quality management and it considers the economic effects as well (but not any social assessment).

Table 2
Publications by type in IWAM.

Reference Type	Number	Percentage
Journal Article	9541	72.1
Conference Proceedings	3430	25.9
Book	47	0.4
Book chapter	221	1.7
Total	13239	100

Gisser and Mercado (1972) integrated agricultural demand with the hydrological and economic sectors at an aquifer scale. Winn et al. (1972) investigated the application of remote sensing and hydrological simulation models in the development of an integrated program for water resources management; by using the "integration" word, they meant using different hydrological data in one model. Haimes (1973) studied integrated system identification and optimization for conjunctive use of ground and surface water but at that stage it did not pay attention to ecological, economic and social aspects.

De Ridder (1974) studied the use of models in solving agricultural development problems and emphasized that proper planning must relate to the physical, environmental, economic and social factors involved. But he believed at that stage that integration of all these factors encountered some major difficulties, of which insufficient data and lack of an exact and comprehensive methodology were the most serious. Garlauskas (1974) used a systemic and integrated approach for restoring polluted urban watersheds. This publication, in particular, highlights the beginning of IWAM as a field of study. The approach argued the rationale for restoration, and showed watershed delineation of the physical, biological, socio-political, and legal aspects. He emphasized the achievement of any environmental management goal depends on the fully balanced integration of the matrix components. Ryan et al. (1974) made an integrated ecosystem model for a forested river basin which considered the bio-physical sub-system but not socio-economic ones.

The above publications focus largely on the numerical modelling of physical systems and are not as "integrated" as much as occurs these days. There are, however, indications of some consideration of the interactions and processes that may occur in the broader socio-biophysical context. It seems that the USA is the birthplace of IWAM, all the above authors, except the De Ridder (1974), being from that country.

As shown in Fig. 3, the first two decades constitute the early growth of the field. Attention paid to IWAM increased dramatically after the Dublin and Rio de Janeiro conferences in 1992 where the development of Integrated Water Resources Management was particularly recommended in the final statement. In the second phase of integrated water research the number of published papers increased to over 100 in this period when the basic concept was developed. In the third phase, the rapid expansion of scientist attention to IWAM begins from 2004.

The changes in the trend of publications concur with the observation made by Hamilton et al. (2015) who stated that the need for integration in environmental issues was recognized from the end of the 1960s. They divided its history into three phases (Inception, Foundation, and Maturity). The term "maturity" used here and in Hamilton et al. (2015) is not meant to imply that there is little left to explore or achieve, rather that the field is now in a state wherein knowledge has advanced sufficiently to allow further exploration of issues surrounding modelling practices and approaches.

Through the bibliometric approach of this paper, the initial beginnings have been identified as occurring during the period from 1970 to 1990. Rotmans and Van Asselt (1996) described integrated assessment as a growing child on its way to maturity. Following this characterisation, we approximate its birth as being in

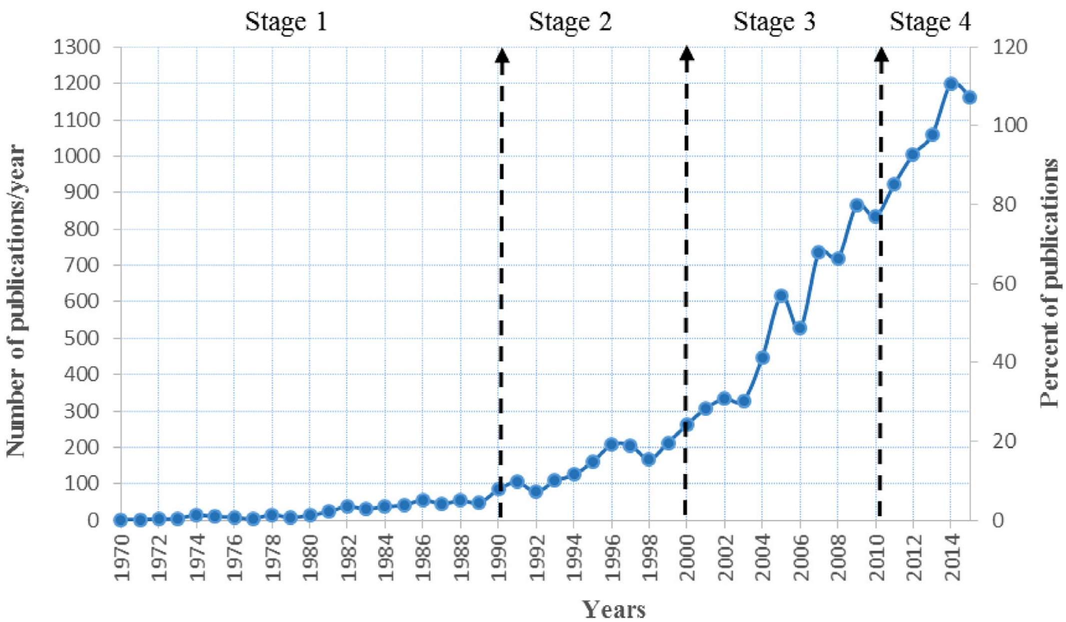

Fig. 3. Publishing trend in the area of integrated water assessment and modelling.

the 1970s, developing through infancy in the 1990s, and adolescence in the 2000s, and suggest that it has now reached a certain maturity. The importance of IWAM was recognized in the 1990s when its application in different fields of study became evident (Hamilton et al., 2015). Subsequent core elements of the IWAM approach such as frameworks, features and principles were developed in the new millennia.

Based on publication trends (Fig. 3) and the observations of Rotmans and Van Asselt (1996) and Hamilton et al. (2015), we posit that the IWAM development process could be categorised into four stages as described in Table 3, occurring during the period from 1970 to 1990. Stage 1 of "Conception" reflects the early establishment of the field which then experienced a slow uptake from 1970 until 1990. In the "Formation" stage, the IWAM concept was defined, and various principles and frameworks suggested and tested. An expansion of applications of water resource related case studies occurred in the "Practice' Stage (in the 2000s) and is represented by an acceleration in the number of publications. The last stage reflects the shift towards rapid development and expansion of the field in the 2010s, having established the concept and frameworks and having examined it in many different cases. The "Maturity" stage reflects that it was time to study more sophisticated (e.g. multisectoral, multidisciplinary) topics and vital considerations such as treating and managing uncertainty.

3.3. Key journals

Table 4 lists the 11 journals from our document analysis that have published more than 100 papers on the IWAM theme and the percentage of their papers compared to all published (13,239). It also shows the number of papers on IWAM normalised by the number of years that each journal has been actively publishing on the theme.

Overall the most productive outlet is *Journal of Hydrology*" with four percent of all publications, followed by "*Water Resources Research*", "*Water Resources Management*" and "*Environment Modelling and Software*". However, when normalising by years actively publishing on IWAM, *Water Resources Research* is overtaken by *Water Resources Management*, *Environmental Modelling and Software*, *Hydrological Processes* and *Hydrology and Earth System Sciences*. Fig. 4 breaks this information down visually by showing the temporal trends of publication on the IWAM topic in the 11 journals. All journals have witnessed a growing trend. Given that journals have different ages, we calculated the average number of publications per each active year as an indicator on the journal's contribution to the field.

3.4. Affiliation analysis

The analysis of publication patterns in all identified articles at the scale of countries also provides interesting information on a research theme or topic. The assumption is that the affiliation of authors gives an indication of research-active countries in a particular topic. To visualize the worldwide distribution of IWAM-related publications among the 115 identified major countries, the numbers according to the location of first author were extracted using BibExcel and then geocoded in a geospatial map, shown in Fig. 5. The size of publication icons is scaled to represent the number of IWAM publications. The United States can be seen as home to the majority of IWAM publications (about 30%),

Table 3
IWAM development phases.

Stage 1	Conception	From 1969	The importance of studying the multi-faceted nature of water management and policy were recognized
Stage 2	Formation	1990s	The concept of "integration" defined and some practical projects were reported, mostly in climate change, energy and economics
Stage 3	Practice	2000s	IWAM frameworks, methodologies, approaches and principles were defined. Case studies were used as testbeds for the approach development and to examine its utility.
Stage 4	Maturity	2010s	Advanced topics such as developing software, uncertainty management, stakeholder involvement and assessing economic and social aspects are investigated.

Table 4
Journals identified with more than 100 publications of IWAM and production statistics (The maximum value of each column is bolded).

Journal	No. Papers	Percentage	Active Years	(No. Papers / Active Years)	Starting year
Journal of Hydrology	**453**	**4.0**	34	13	1963
Water Resources Research	277	2.4	**40**	7	1965
Water Resources Management	248	2.2	22	11	1987
Environmental Modelling and Software	208	1.8	19	11	1997
Hydrological Processes	179	1.6	19	9	1986
Science of the Total Environment	146	1.3	21	6	1972
Hydrology and Earth System Sciences	141	1.2	17	8	1997
Journal of Environmental Management	122	1.1	21	5	1973
Journal of Water Resources Planning and Management	110	1.0	30	4	1983
Environmental Earth Sciences	106	0.9	6	**16**	2009
Environmental Monitoring and Assessment	103	0.9	23	4	1981

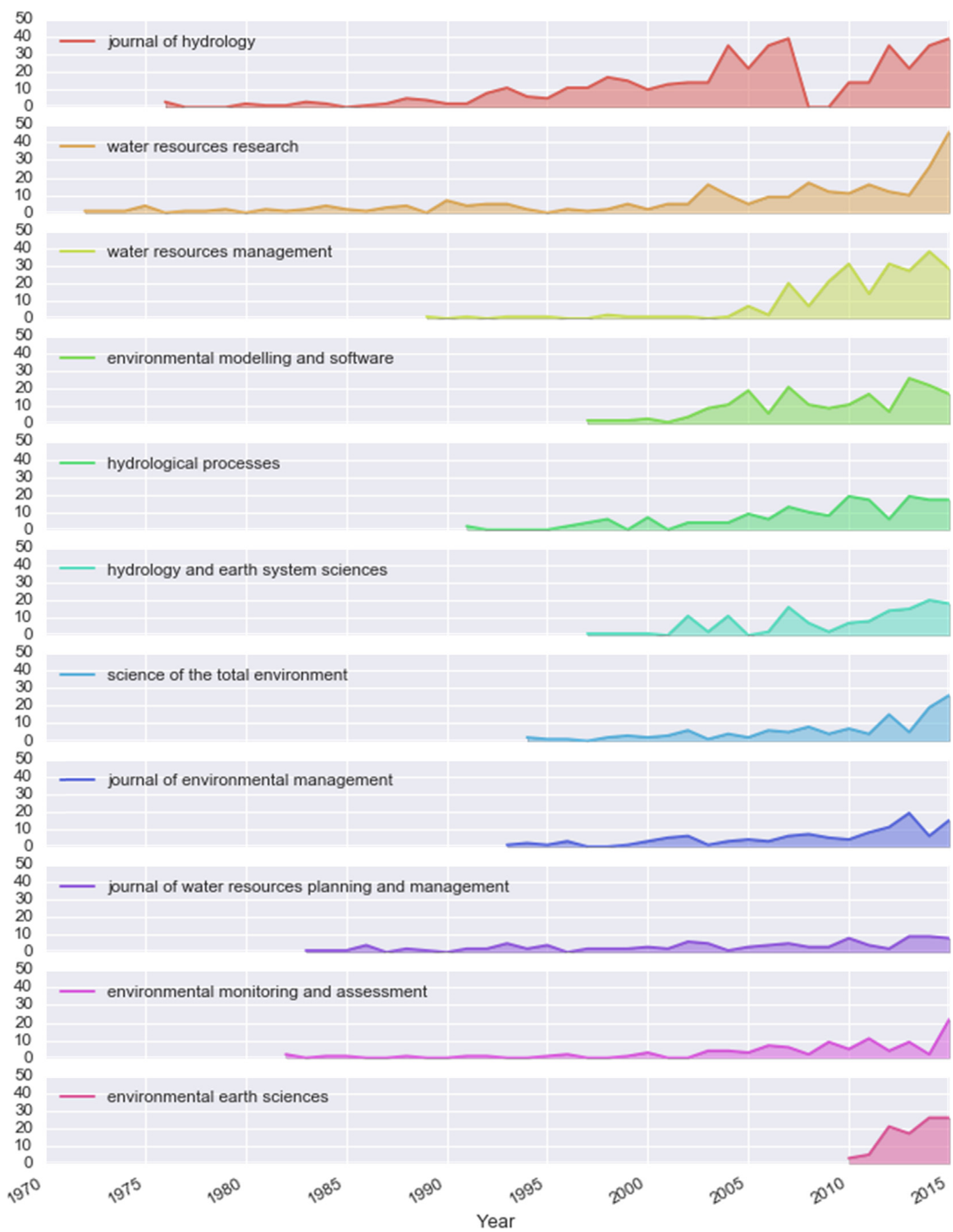

Fig. 4. Comparing publication trends in the 11 identified journals. The year is represented along the x-axis whilst the y-axis indicates the number of publications per year.

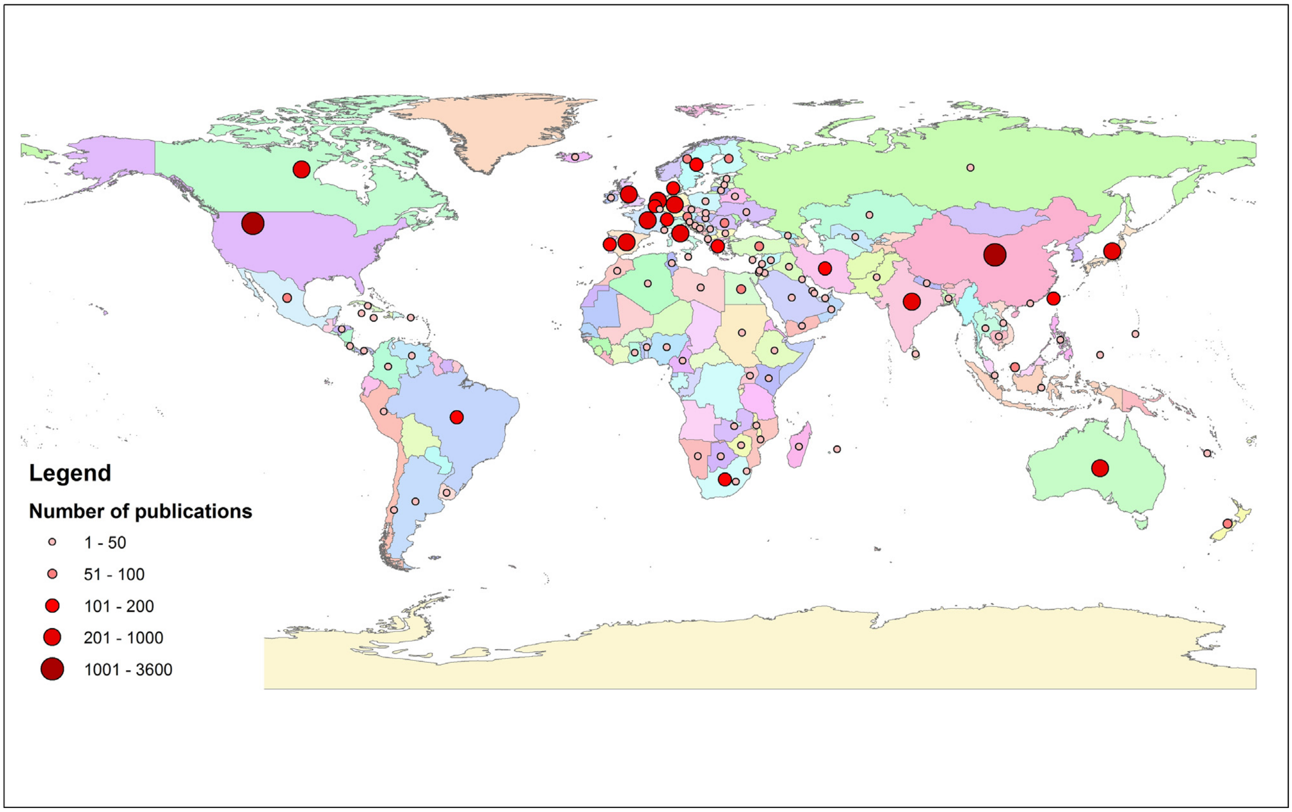

Fig. 5. Map of the distribution of IWAM articles published by country.

followed by China with about 10% of the total. The 22 most research active countries, designated in Fig. 6, include the two North American countries, twelve European countries, six Asian countries, South Africa and Australia. All of the seven major industrialized nations (G7: Canada, France, Germany, Italy, Japan, the UK, and the USA) are among the top 10.

3.5. Citation analysis

We also explored the most cited publications, as an indication of the most influential studies, their authors and, perhaps more importantly, the nature of the integration covered. Table 5 lists the 17 most cited articles, all journal papers with 173 or more citations, on IWAM and categorises them according to their scope (water resources, social, economic, ecology) and focus (modelling focused, management, guidelines). The most frequently cited article with 411 citations was "*Uncertainty in the environmental modelling process – A framework and guidance*" (Refsgaard et al., 2007) which presents the terminology and typology of uncertainty and a framework for the modelling process of IWAM. The papers are predominantly multi-authored (14 out of 17), with the median number of authors being three, indicating the general requirement for multiple contributions for highly cited papers on IWAM. This could be due to the interdisciplinary nature of IWAM research and the prevalence of a focus on modelling (15 of the 17 papers), which is difficult for a single author to cover adequately by oneself.

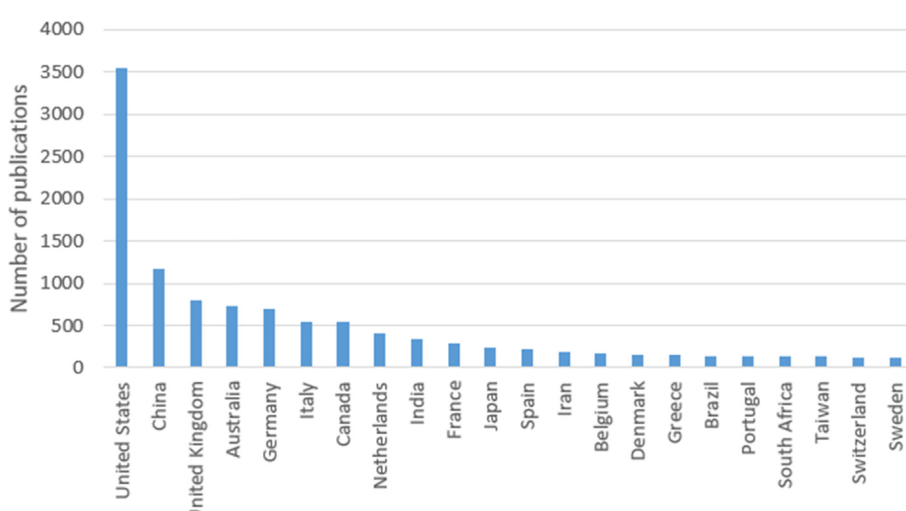

Fig. 6. Number of publications for countries with over 100 journal papers on IWAM.

Table 5
Highly cited papers on the IWAM topic.

Authors	Title	Citation	Year	Water resources	Social	Economic	Ecology	Modelling-focused	Management	Guideline, framework, review
Refsgaard et al.	Uncertainty in the environmental modelling process – A framework and guidance	411	2007	✓	✓	✓	✓	✓		✓
Alcamo et al.	Development and testing of the WaterGAP 2 global model of water use and availability	293	2003	✓				✓		
Lehner et al.	Estimating the impact of global change on flood and drought risks in Europe: A continental, integrated analysis	288	2006	✓				✓		
Castelletti et al.	Integration, participation and optimal control in water resources planning and management	284	2008	✓	✓	✓	✓	✓		✓
Turner et al.	Ecological-economic analysis of wetlands: Scientific integration for management and policy	260	2000	✓	✓	✓	✓		✓	✓
Kollet and Maxwell	Integrated surface-groundwater flow modeling: A free-surface overland flow boundary condition in a parallel groundwater flow model	256	2006	✓				✓		
Madsen	Parameter estimation in distributed hydrological catchment modelling using automatic calibration with multiple objectives	233	2003	✓				✓		
Whitehead et al.	A semi-distributed Integrated Nitrogen model for multiple source assessment in Catchments (INCA): Part I – Model structure and process equations	224	1998	✓			✓	✓		
Jakeman and Letcher	Integrated assessment and modelling: Features, principles and examples for catchment management	228	2003	✓	✓	✓	✓	✓	✓	✓
Bricker et al.	An integrated methodology for assessment of estuarine trophic status	218	2003				✓	✓	✓	
Pahl-Wostl and Hare	Processes of social learning in integrated resources management	217	2004		✓				✓	✓
Pahl-Wostl	Towards sustainability in the water sector – The importance of human actors and processes of social learning	208	2002		✓				✓	✓
Band et al.	Forest ecosystem processes at the watershed scale: incorporating hillslope hydrology	205	1993	✓			✓	✓		
Yates et al.	WEAP21 – A demand-, priority-, and preference-driven water planning model. Part 1: Model characteristics	190	2005	✓			✓	✓		
Bales et al.	Mountain hydrology of the western United States	184	2006	✓			✓	✓		
VanderKwaak and Loague	Hydrologic-response simulations for the R-5 catchment with a comprehensive physics-based model	183	2001	✓				✓		
Pahl-Wostl	The implications of complexity for integrated resources management	176	2007		✓				✓	✓
Ewen et al.	SHETRAN: Distributed river basin flow and transport modeling system	173	2000	✓			✓	✓		
Gregersen et al.	OpenMI: Open modelling interface	173	2007	✓				✓		

The level of discipline and sector coverage, and stakeholder participation, in the table varies. Thus six of the papers are primarily concerned with modelling in the water resources sector, but each of them go far beyond traditional hydrological modelling, examining such issues and methods as the impact of global change at large scales, integrating surface and groundwater modelling, and multi-objective parameter estimation. About half are associated with economic, social and ecological considerations and/or generic methods issues in integrated assessment.

3.6. Key topics

3.6.1. Keywords and title analysis

It is assumed that bibliometric analysis of listed keywords and key terms in the titles of articles can offer insights into overall research emphasis and changing trends and, by omission, into the gaps not being filled. In this subsection and the next we look at the emphasis on IWAM articles over the 45 year period, but then go on in Section 3.6.3 to consider temporal changes.

Fig. 7 shows the most popular keywords in all identified 13,239 publications that have a frequency above 1000. Whilst the figure indicates just one part of speech for each word, the frequency given includes other possible parts of speech for that word. Other issues arose with acronyms, plurals, case sensitivity, and even typos. Such examples include "Geographic Information System" which may be acronymised to "GIS", pluralised ("Systems") or have different casing ("geographic" compared to "Geographic"). As these different forms can be considered to be synonyms of one another, occurrences of these terms were merged together into a single category. In illustration, "decision, decisions, decision making, decision

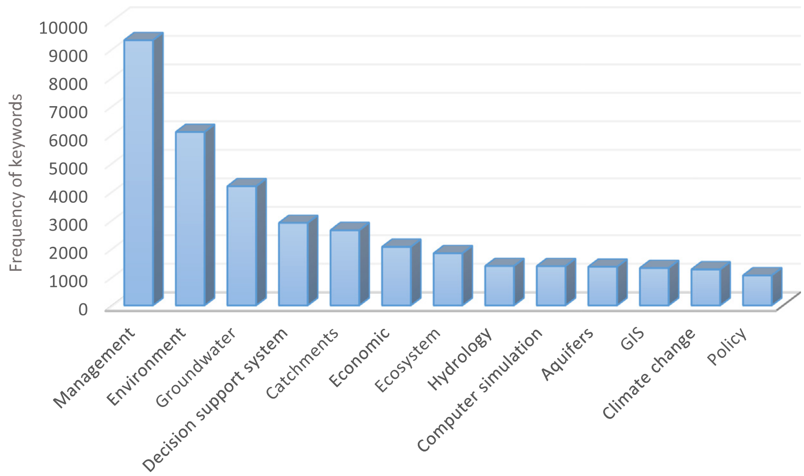

Fig. 7. Frequency of popular keywords listed in IWAM articles.

support, decision criteria, decision analysis, decision support tool, decision support model, decision making method, decision support systems, DSS" and so on framed the decision making category. The words "water", "model", "integrate" and "assessment" were used as keywords in our initial search, so these, and their synonyms, were removed from the final list. However, it is noted that "model" was used about 4 times more than "assessment" and 2.5 times more than "integrate".

The title of an article is one of the first pieces of information presented to readers, so it typically includes key terms and indicates the main focus of an article that the author intends to express and emphasize. While there were in many cases the names of countries, rivers, basins and places in the results, these were all deleted along with some of our original search words like integration, "assessment", "model" and their various non-noun forms. Unsurprisingly, "management" is the most frequent title word, it being a main purpose of modelling and assessment (Fig. 8). Beyond other expected words such as river, basin, catchment, watershed and hydrological, it is interesting to note a strong occurrence of certain biophysical (groundwater, (water) quality, climate, flood) and methodological (simulation, risk and decision support) issues.

3.6.2. Abstract statistics

As an interesting comparison to Fig. 8, Fig. 9 displays the frequency of the most prevalent key terms in abstracts, excluding those initial screening words in Table 1. Management is still the most popular word as was the case with the keyword analysis; and groundwater, environment, quality and climate are common words from both analyses and coincidentally are in the same order of decreasing frequency. The interesting difference is *"uncertainty"* which was not as common in the title or keywords (used 2702 times in abstracts, but just 860 times in keywords and 220 times in titles). It would appear that uncertainty has tended to be a secondary purpose of the research in our identified IWAM articles, although often considered worthy of warranting a mention or being covered to some extent.

The previous three figures represent totals over time and reveal an aggregate lack of emphasis on socio-economic wording. However, these aggregated findings do not convey the overtime changes of the emphasis, and perhaps, changes in research priorities. Thus, we consider the temporal analyses in detail in the next subsection.

3.6.3. Popular keywords as indicators of changing attention in IWAM research

Assuming that keywords collectively indicate the main areas of research attention, we also investigated how these have changed over the years. Here, we explore the trend in frequency of common keywords (and their multiple parts-of-speech forms) in different years (Fig. 10). As before, we omit the keywords in Table 1 as they were used to help select the list of IWAM articles. We also omit

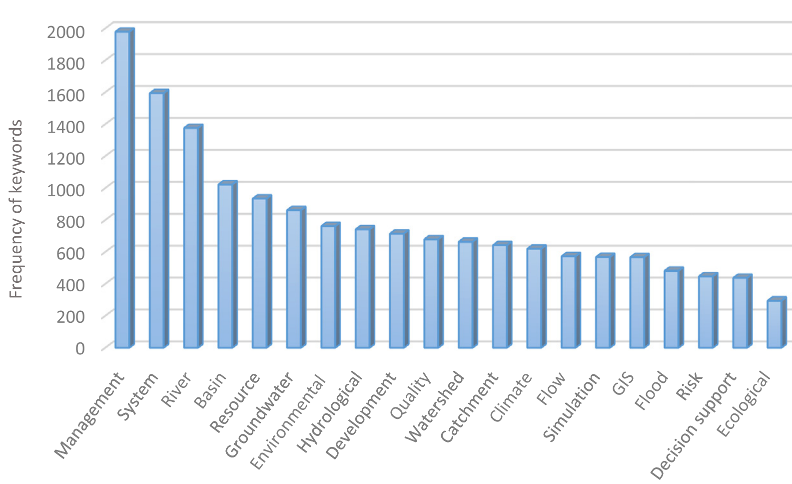

Fig. 8. The most frequent title words in IWAM articles.

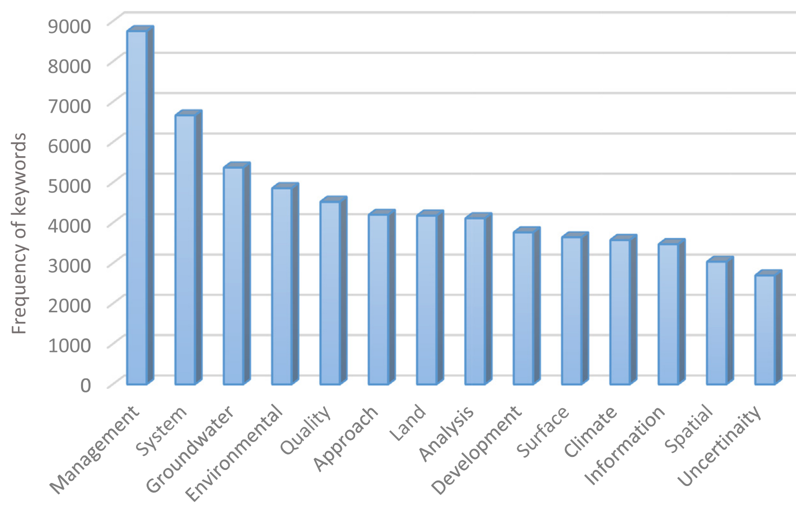

Fig. 9. The most common key terms in IWAM abstracts.

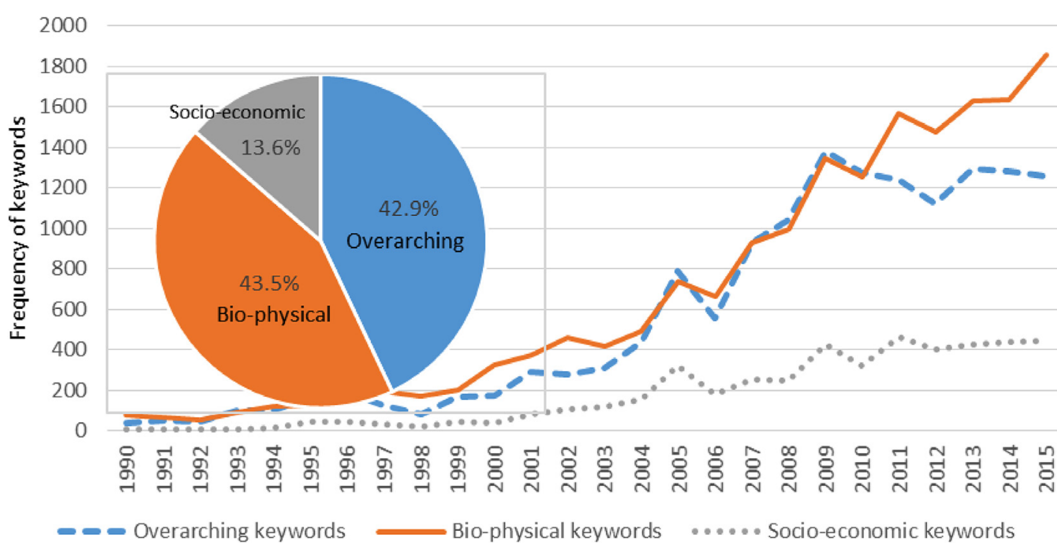

Fig. 10. Keyword category trend and overall percentage.

'computer simulation' as keywords because they are related strongly to modelling. Here, we use some of the insights presented by Hamilton et al. (2015) regarding the dimensions of integration. Bearing in mind that the integration dimensions overlap, we have developed three categories for keywords to highlight which dimensions have received most attention.

Category 1 is intended to represent the natural setting dimension as described in Hamilton et al. (2015). It comprises biophysical keywords, with most frequent to least frequent order being: environment, groundwater and aquifer (combined), ecology (combined with ecosystem and biodiversity), climate change, hydrology, and agriculture. The results for this biophysical category are shown in Fig. 11. For clarity, we only show results from 1990 when trends started to increase more markedly.

Category 2 is intended to represent those dimensions related to the social system: human settings, stakeholders, and governance. It comprises popular socioeconomic keywords, in descending order of frequency being: economic, policy, social, stakeholder, ecosystem services, law, participation, and conflict.

Category 3 is intended to represent overarching concepts and tools, being in descending order: management, decision support systems, GIS, uncertainty, and adapt. These are plotted in Fig. 11 (a, b and c). The common trend in all these keywords, especially if one dismisses the last couple of years, is increasing. Although, this statistical method of keyword aggregation captures the commonly used keywords by IWAM scholars, it might have a drawback. In future studies there is an opportunity to look into related words and synonyms to the keywords found here and thereby undertake a more linguistic analysis.

In Category 1, environment and groundwater/aquifer are the two most prominent with a frequency approaching 600 in 2015, while ecology/ecosystem/biodiversity approaches 300, climate change 200 and both hydrology and agriculture around 100. In a water resource setting it is understandable that these words are biophysically the most popular as they represent the more obvious biophysical links. The lower frequency of hydrology and agriculture may well be that many IWAM publications occur in those types of journals where such keywords are somewhat redundant. The relatively high frequency of groundwater/aquifer can be speculated upon. Concern for the world's depletion and quality deterioration of groundwater is growing (see the data and IWAM type coverage in Jakeman et al. (2016)) and is reflected in that resource being as researched in an integrated modelling sense as environment-related water issues.

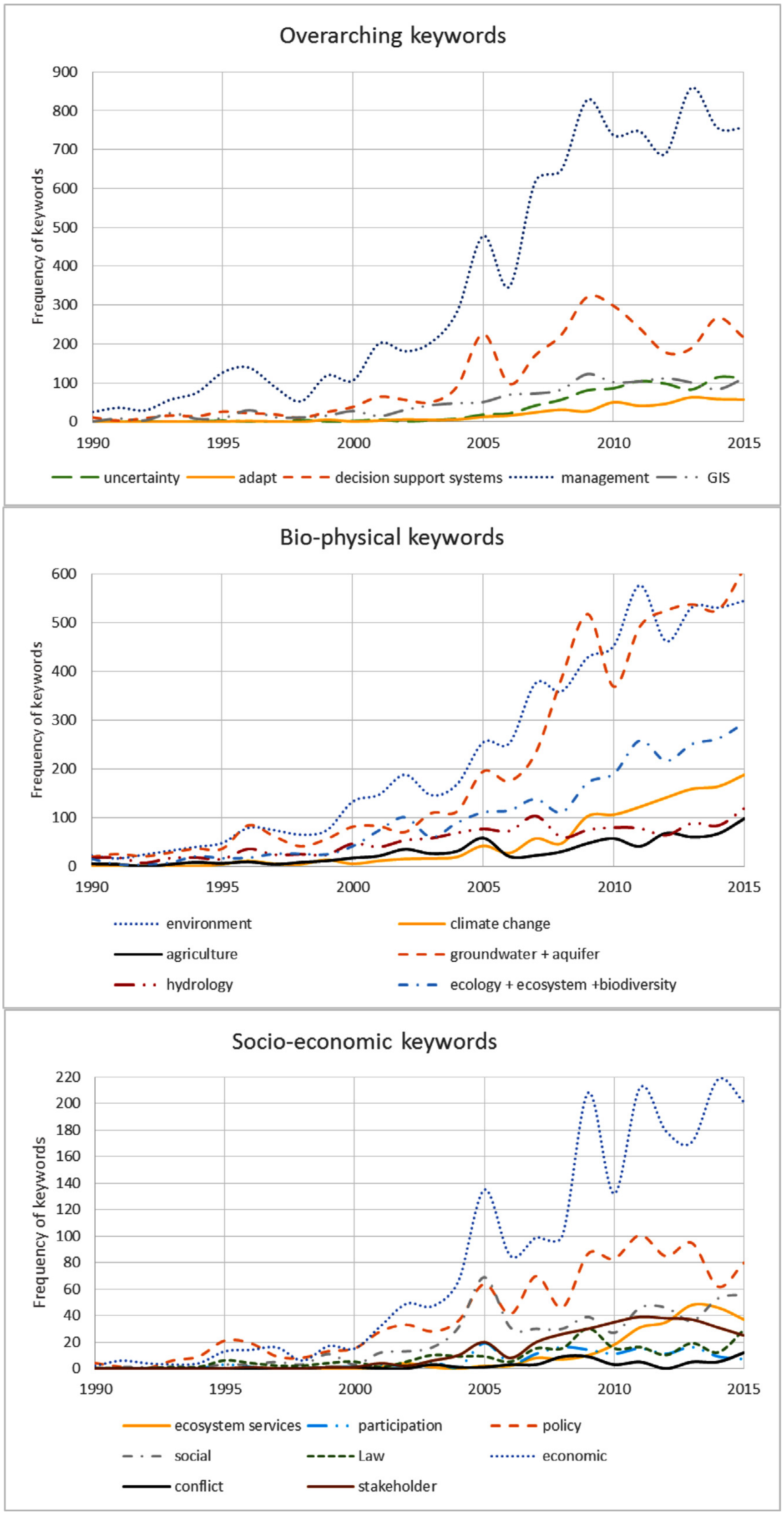

Fig. 11. (a, b, c): Trends of the keywords in the overarching, bio-physical, and socio-economic categories.

In Category 2, economic(s) has a frequency of around 200 by 2015, policy 80, social almost 60 and the others noticeably lower. Thus, there is an emphasis in IWAM more on the economics and policy than on the more human aspects. But even the economic emphasis is lower than in the top three biophysical category keywords.

In Category 3, management is the overarching keyword, having exceeded 800 in frequency in 2009 but apparently flattening from thereon. Likewise decision support systems exceeded 300 and flattened about the same time. The concept of uncertainty and the tool of GIS also seemed to flatten around 2010 at around 100 but the latter may be because it has become a somewhat common tool and is not felt as important to list as a keyword as it once was. While it is heartening to see the frequencies of management and decision support at the levels they are, it would seem that there is a gap to be filled in the uncertainty area. Uncertainty is rife in issues requiring IWAM treatment and in the authors' opinion one would hope that it received routine recognition and substantial attention in IWAM research publications. Hamilton et al. (2015) viewed uncertainty as important enough to be included as one of 10 dimensions of integration in environmental assessment.

In Fig. 10, we try to capture the temporal trends in, and differences between, the three categories. In each category the keywords have been added each year. Noticeable is the ongoing increase in biophysical and socioeconomic keywords, but with the former at a faster rate than the latter and with absolute numbers more than fourfold by 2015. The pie chart captures the relative differences among the three categories over the 45 year period, again showing biophysical dominating the socioeconomic according to frequency of keywords in IWAM articles over the 45 Year period. Assessing these categories in the first four journals (Table 4) and comparing with Fig. 10, the overarching keywords category varies from 29 to 35 percent in these first journals while they received 42.9 overall; the bio-physical category attained 41–57 percent of journal keywords and 43.5 overall; but socio-economic keywords were used less than the other two categories, in these first four journals its percentage varies from 14 to 24 and overall is just 13.6 percent.

As far back as (2003) Jakeman and Letcher noted that in many cases the management of water resources has concentrated on the physical control of water with not enough focus given to the economic, environmental, and social aspects. Fig. 10 illustrates these aspects within IWAM research. Attention towards environmental and economic issues has increased, but the social aspects of IWAM appear to receive far less attention. While the incorporation of social aspects emerges in 2000, the amount and rate of year-on-year increase in publications is lower than those that involve the economic aspects, which started some years earlier. The progress of using interdisciplinary approaches and integration has been slow, despite the claims by Pahl-Wostl et al. (2013). Barthel and Seidl (2017) came to similar conclusions in their review into the current state of interdisciplinary groundwater research. The review, which applied a bibliometric approach, found just 5 out of 203 papers analyzed (published between 1990 and 2014) that were multidisciplinary in nature.

4. Conclusions

Research questions are determined largely through literature reviews and the subjective opinions of researchers in the area. Whilst this expert opinion will always remain valuable, the rapid advances in "big data" analytics can be used adjunctively to provide the evidence to support the charting of open research topics. With the advances in science and other fields of study being documented through the publications of subject matter experts and maintained within bibliometric archives, these sources of information provide a rich text-based dataset for undertaking systematic analyses about the state of knowledge within a field of study (Broadus, 1987). This paper documents an approach to bibliometric analysis and attempts to portray the types of decisions made in each step of the analysis.

The dynamic nature of any field of study will demonstrate shifts and changes over time, location, and topic. Based on the Scopus database, this paper has undertaken a bibliometric analysis of integration in water modelling and assessment over the past 45 years. Developments in the field of IWAM exhibit four stages from 1970 to 2015 "Conception, Formation, Practice and Maturity". *Journal of Hydrology* has published the largest number of IWAM papers. But if one considers the average number of publications per active years of publishing on the topic of IWAM, then *Environmental Earth Sciences* has enjoyed a most promising start followed by *Journal of Hydrology, Water Resources Management, Environmental Modelling and Software, Hydrological Processes and Hydrology and Earth System Sciences.*

Highly cited publications are noted in the paper and represent one starting point for researchers stepping into the area. Looking into the trends of keywords used in publications, there has been a growth in the integration that covers social-economic-hydrological aspects since 2004, but it is concerning that this linking of integration with the social sciences, especially the non-economic ones, remains modest.

Another emerging trend is the slow but growing attention towards uncertainty aspects since 2000. This observation illuminates the open opportunities for future research that recognizes the importance of human drivers and uncertainty treatment in water issues (Hamilton et al., 2015).

The analyses in this paper are based on the Scopus database (Table 1) which does not contain the entire literature of this field. But with more than 11,000 articles identified, our analysis is felt to provide a reliable indication of emphasis and trends in IWAM. Furthermore this bibliometric analysis focused on modelling and assessment (based on our selected keywords Table 1) so expanding to specific journals and keywords used by social and economic scientists and a wide variety of other keywords could result in a more exhaustive review of the field. A useful starting point is to perform bibliometric analysis for a predominantly interdisciplinary journal from those identified in this paper (e.g. Environmental Modelling and Software) to help inform the selection of most relevant keywords. Elsawah, Jakeman and Pierce are leaders of a related project with the Socio-Environmental Synthesis Center, which motivated this review.

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