Journal of Cleaner Production 149 (2017) 70–79

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

Mapping of water footprint research: A bibliometric analysis during 2006–2015

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ARTICLE INFO

Article history:
Received 31 May 2016
Received in revised form
5 January 2017
Accepted 9 February 2017
Available online 23 February 2017

Keywords:
Bibliometric
SCI-Expanded
Water footprint
Co-word analysis
Social network analysis

ABSTRACT

A bibliometric analysis of the research in the field of Water Footprint (WF) during 2006–2015 was presented with the information related to countries, institutions, journals, categories, top cited publications, keywords, hot issues and research trends. Researches on WF have increased sharply over the past decade. The United States (24.1%), China (19.2%) and Netherlands (16.0%) had high productivity in total publications. Based on co-word and social network analysis (SNA), the USA-China has been most closely correlated in the cooperative web system. University of Twente took the leading position of institutions in total articles and also conducted the most independent, collaborative, first authored, and corresponding authored articles. *Journal of Cleaner Production*, *Environmental Science & Technology* and *Ecological Indicators* are the top three journals with the most publications in this field. A summary of the most frequently used keywords obtained from title, author keywords and keywords plus analysis provided the clues to discover the current research emphases. The mainstream research related to WF was its accounting methodologies and application in water resource management. Water-food-energy nexus, driving mechanism of WF variation, environmental impact of water use and integration of footprint indicators strongly promoted the development of WF research and are getting popular in recent years. Findings provide a better understanding of characteristics of WF research which serves as a useful reference for future studies.

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http://dx.doi.org/10.1016/j.jclepro.2017.02.067
0959-6526/

1. Introduction

Population growth and rapid economic development place a heavy burden on water resources through growing demand for agricultural products, industrial goods and household consumption (Launiainen et al., 2014). As water is an increasingly scarce resource, effective sustainability indicators have become a cause for concern in water resource management and governance. Water footprint (WF) was proposed as an indicator to evaluate water resources utilization relative to human consumption (Hoekstra and Hung, 2002). From the perspective of water consumption and pollution, WF evaluation is becoming one of the priorities for water sustainability (Čuček et al., 2015) and provides decision-making support for water resources management (Hoekstra and Chapagain, 2007).

WF analysis can be mainly applied for a particular product (or goods and services), for any well-defined group of consumers (individual/region/basin/district/nation/globe, etc.) or producers (public organization/private enterprise/industrial sector, etc.) (Chapagain and Hoekstra, 2008; Galli et al., 2012; Hoekstra and Chapagain, 2007). WF of a nation is defined as the volume of water required for the production of the goods and services consumed by the inhabitants of the country (Hoekstra and Chapagain, 2007). WF of a product is regarded as the volume of freshwater used to produce the certain product, measured at the place where the product was virtually produced (Hoekstra and Aldaya, 2010). It refers to the total volume of direct and indirect fresh water used, consumed, and/or polluted. WF usually consists of green WF (rainwater that does not run-off or recharge the groundwater), blue WF (irrigation water withdrawn from ground- or surface water) and grey WF (the volume of freshwater that is required to assimilate the load of pollutants) (Chapagain and Hoekstra, 2011). The bottom-up and top-down approaches are two principal methods applied to WF accounting (Fang et al., 2014; Hoekstra, 2009). The international WF standards are simultaneously in the process of being developed by the Water Footprint Network (WFN) (Hoekstra et al., 2011) and the International Organization for Standardization (ISO 14046) (Fang et al., 2014).

The last decade witnessed a rapid development of the WF research due to the growing public awareness of water conservation and a widespread acceptance of sustainable utilization. The purpose of this study is to investigate the characteristics and implications of the WF research from 2006 to 2015 by using bibliometric technique. A general profile of authorships, mainstream journals, Web of Science categories, leading countries and institutions was recognized by the bibliographic statistics. A summary of the most frequently used keywords obtained from title, author keywords and keywords plus analysis provided the clues to discover the current research emphases. Findings will provide a better understanding of characteristics of WF research which serves as a useful reference for future studies.

2. Methodology

2.1. Data description

For bibliometric analysis, the Science Citation Index Expanded (SCI-Expanded) database of the Web of Science from Thomson Reuters has been widely adopted due to its comprehensiveness and high-quality records (Gao and Guo, 2014). According to the Journal Citation Report (JCR), it indexes 8659 journals across 176 Web of Science subject categories in 2014. "Water footprint" (or "virtual water" AND footprint) was used to search titles, abstracts and keywords (author keywords and keywords plus) of the documents published between 2006 and 2015 in the database of the SCI-Expanded. Although WF concept was proposed in 2002, few publications were found during 2002–2006, so we selected 2006–2015 as the study period. Altogether, 636 original publications were downloaded in Web of Science format for further analysis. The downloaded information included authors, title, publication year, page numbers, contact address, author keywords, keywords plus, countries/territories, institutions, journals, citations, Web of Science categories etc. Publications originating from England, Scotland, Wales and Northern Ireland were reclassified as from the United Kingdom (UK). The term "single country/institution publication" was assigned if the researchers' addresses were from the same country/institutions. And the term "international/inter-institutionally collaborative publication" was assigned if the authors were from multiple countries/institutions (Wang et al., 2014).

2.2. Methods

Performance analysis and science mapping are two main procedures in a bibliometric analysis (Noyons et al., 1999). Performance analysis was conducted in this paper to evaluate the characteristics of publication outputs, such as authors, journals, countries and citations, resulting in hotspots or variation trends of WF research. Science mapping was employed in this paper to display the structural aspects in the field of WF research. Co-word analysis, as one of the most commonly used methods in developing a science map (Hou et al., 2015), was used to evaluate the interaction of countries/territories and institutions in this study. Social network analysis (SNA) was employed in this study to quantitatively assess the collaborative relationship among the top 30 productive countries/territories and institutions.

The analysis was conducted using BibExcel 1.0.0.0, Pajek 1.0.0.1 and Office Excel 2010. BibExcel is a free bibliometric toolbox developed by Olle Persson (Persson et al., 2009), which is particularly useful for most types of bibliometric analysis, including frequency analysis, citation analysis, co-occurrence analysis, etc., and allows easy interaction with Pajek and Office Excel. Pajek was adopted as a tool to assist making cooperation networks of productive countries/territories and institutions in this study.

3. Results and discussion

3.1. Document types and records

As a result, 636 records were obtained from 2006 to 2015. The publications were downloaded in the bibliographic style of Web of Science with information in title, authors, country, language, journal, subjects, citations, keywords, references etc. These 636 records related to WF from the databases over the past decade were categorized into 8 types. Among them, articles (562) accounted for

88.36% of total number of publications, followed far behind by reviews (37, 5.82%), editorial materials (12, 1.89%), proceeding papers (11, 1.73%) and letters (10, 1.57%). The other three categories represented <0.5% in each item. Considering the representativeness and impact of publications, 632 records from the document types of articles, reviews, editorial materials, proceeding papers and letters were selected as data for further analysis in this study.

3.2. Characteristics of publication outputs

To obtain an overview of WF research, the characteristics of publications during 2006–2015 were displayed in Table 1. The number of WF publications increased from 5 in 2006 to 181 in 2015, with the total publications reaching 632. The number of publications per year has increased steadily since approximately 2009, with an abrupt growth in 2014, which reveals that research in the field of WF are attracting more increasing attention. And the average article lengths fluctuated slightly, with an overall average of 10.6 pages. Additionally, 39.4 references were cited per article in 2006, comparing to 51.9 references per article in 2015, with slight increases during the last 10 years. A rising number of authors carrying out research on WF from 16 in 2006 to 677 in 2015, the average number of authors of a single article was 3.0. The progressive rise in publications and references indicates a growth trend in the field of WF research over the past decade.

3.3. Contribution of the countries/territories and institutions

The contribution of different countries/territories and institutions was analyzed according to the addresses and affiliations of authors. There were 2 articles without any author address information and 630 records were used to analyze the distribution of countries/territories and institutions. Of all the publications with author address, 429 (68.1%) were single country articles and 201 (31.9%) were internationally collaborative articles.

Table 2 demonstrates the top 20 countries/territories ranked by the number of total publications with additional information: the number and percentage of single country publications and internationally collaborated publications, as well as first author and corresponding author publications. As is shown in Table 2, the USA (152, 24.1%) is the most productive country with the largest number of publications during the whole period. China (121, 19.2%) and Netherlands (101, 16.0%) also showed great counts of total publications, followed distantly by other countries.

The cooperative relationships among the top 30 productive countries/territories in the field of WF research were further analyzed by using the SNA (Fig. 1). The circles represent the frequency of international cooperation, the larger the circle is, the more frequent it is. The lines represent the cooperative relationships among productive countries/territories, the thicker the line is, the closer the cooperative relationship is. As is vividly shown in Fig. 1, the USA and China, playing the vital roles in WF research, has been most closely correlated in the network. It is also worth noting that Netherlands, Switzerland, Australia, the UK and Germany have acted as significant countries in global communication in the cooperative web system. As virtual water trade and water resource management have become crucial issues all over the world, regionalization and globalization will be a significant trend in WF research.

Table 1
Characteristics by year of publication outputs from 2006 to 2015.

PY	TP	AU	AU/TP	PG	PG/TP	NR	NR/TP
2006	5	16	3.2	56	11.2	197	39.4
2007	6	9	1.5	63	10.5	240	40.0
2008	4	16	4.0	46	11.5	124	31.0
2009	27	64	2.4	209	7.7	1110	41.1
2010	30	78	2.6	306	10.2	1263	42.1
2011	52	162	3.1	622	12.0	2470	47.5
2012	78	232	3.0	774	9.9	3570	45.8
2013	92	288	3.1	940	10.2	4365	47.4
2014	157	462	2.9	1656	10.5	7111	45.3
2015	181	677	3.7	2252	12.4	9388	51.9

PY: published year; TP: total publications; AU: author number; AU/TP: author number per paper; PG: page count; PG/TP: page count per paper; NR: cited reference count; NR/TP: cited reference count per paper.

Table 2
Contribution of the top 20 productive countries/territories during 2006–2015.

Country	TP (%)	SP R (%)	CP R (%)	FP R (%)	RP R (%)
USA	152 (24.1)	1 (14.1)	1 (10.0)	1 (18.7)	1 (17.5)
China	121 (19.2)	2 (10.5)	2 (8.7)	2 (16.5)	2 (16.7)
Netherlands	101 (16.0)	3 (8.7)	3 (7.3)	3 (11.0)	3 (10.8)
Australia	49 (7.8)	6 (2.7)	5 (5.1)	5 (4.9)	5 (4.6)
UK	45 (7.1)	8 (2.2)	6 (4.9)	7 (3.8)	6 (4.1)
Germany	43 (6.8)	8 (2.2)	7 (4.6)	8 (3.7)	7 (3.8)
Switzerland	43 (6.8)	18 (0.8)	4 (6.0)	11 (2.5)	10 (2.5)
Italy	40 (6.3)	4 (4.0)	10 (2.4)	4 (5.4)	4 (5.4)
Spain	38 (6.0)	5 (3.0)	9 (3.0)	6 (4.1)	8 (3.7)
Canada	25 (4.0)	18 (0.8)	8 (3.2)	11 (2.5)	11 (2.1)
France	19 (3.0)	13 (1.1)	11 (1.9)	15 (1.4)	12 (1.9)
Brazil	19 (3.0)	8 (2.2)	21 (0.8)	9 (2.7)	12 (1.9)
Sweden	15 (2.4)	21 (0.6)	12 (1.7)	21 (1.0)	21 (1.0)
India	15 (2.4)	15 (1.0)	14 (1.4)	16 (1.3)	16 (1.3)
New Zealand	13 (2.1)	11 (1.6)	28 (0.5)	13 (1.9)	14 (1.6)
Japan	13 (2.1)	32 (0.3)	12 (1.7)	21 (1.0)	25 (0.8)
Austria	12 (1.9)	15 (1.0)	19 (1.0)	18 (1.1)	18 (1.1)
Belgium	12 (1.9)	26 (0.5)	14 (1.4)	16 (1.3)	15 (1.4)
South Africa	11 (1.7)	12 (1.4)	33 (0.3)	14 (1.6)	16 (1.3)
Norway	10 (1.6)	32 (0.3)	16 (1.3)	31 (0.5)	32 (0.5)

TP: Total publications; SPR: Single country publication rank; CPR: International collaborative publication rank; FPR: First author publication rank; RPR: Corresponding author publication rank.

The contribution of different institutions was estimated by the institute of the authors' affiliation. Among all the publications with author address, 60.2% of them involved international collaborations. Table 3 displays the most productive institutions in research in the field of WF during 2006–2015. Among them, University of Twente (Netherlands) ranked the first with 70 (11.1%) publications, followed by the Chinese Academy of Sciences (China, 32, 5.1%) and the Commonwealth Scientific and Industrial Research Organization (CSIRO, Australia, 29, 4.6%). Remarkably, University of Twente also published the most independent, collaborative, first authored, and corresponding authored articles over the past decade. In this study, the data of all sub-institutes was merged into the Chinese Academy of Sciences (China), similarly, the records of all campuses were also merged into University of California (USA). That's the reason why these two institutions ranked at the head of the list.

The corresponding cooperation network diagram of the top 20 productive institutions is depicted in Fig. 2. As shown, the Chinese Academy of Sciences and Northwest Agriculture & Forestry University in China were in strong connection. University of Twente, CSIRO, ETH and University of California have acted as significant institutions in institutional communication in the network. It is noticeable that only 16 productive institutions appeared in Fig. 2, indicating that although involving international cooperation with other countries, some institutions didn't cooperate with rest of the top 20 productive institutions, such as Univ Zaragoza, Univ Virginia etc.

3.4. Distribution of output in subject categories and journals

In total, 632 records on WF research were published in a wide

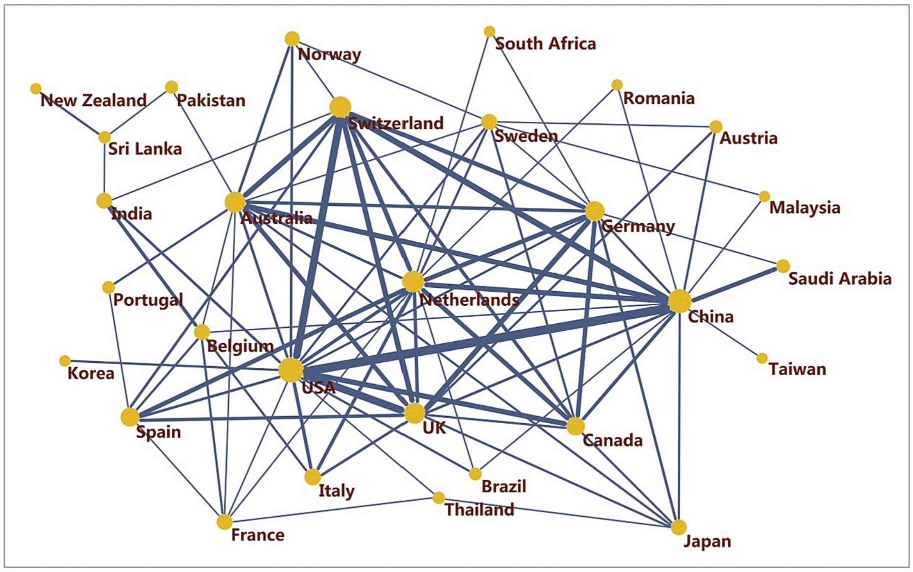

Fig. 1. The cooperation network of the top 30 productive countries/territories.

Table 3
Most productive institutions in research in the field of WF during 2006–2015.

Institution	TP (%)	SP R (%)	CP R (%)	FP R (%)	RP R (%)
Univ Twente, Netherlands	70 (11.1)	1 (6.2)	1 (4.9)	1 (8.1)	1 (7.9)
Chinese Acad Sci, China	32 (5.1)	5 (0.6)	2 (4.4)	2 (2.8)	2 (3.5)
CSIRO, Australia	29 (4.6)	5 (0.6)	3 (4.0)	6 (1.9)	4 (2.1)
Univ Calif, USA	25 (4.0)	4 (0.8)	4 (3.2)	3 (2.5)	4 (2.1)
Northwest A&F Univ, China	21 (3.3)	5 (0.6)	5 (2.7)	3 (2.5)	6 (1.7)
Beijing Normal Univ, China	20 (3.2)	2 (1.4)	7 (1.7)	5 (2.4)	3 (2.4)
ETH, Switzerland	16 (2.5)	10 (0.5)	6 (2.1)	14 (0.8)	19 (0.8)
Beijing Forestry Univ, China	12 (1.9)	38 (0.2)	7 (1.7)	7 (1.4)	7 (1.4)
Peking Univ, China	10 (1.6)	18 (0.3)	10 (1.3)	8 (1.1)	12 (1.1)
European Commiss, Joint Res Ctr, Italy	9 (1.4)	5 (0.6)	32 (0.8)	8 (1.1)	12 (1.1)
Wageningen Univ, Netherlands	9 (1.4)	18 (0.3)	13 (1.1)	18 (0.6)	8 (1.2)
Univ Zaragoza, Spain	8 (1.2)	5 (0.6)	48 (0.6)	14 (0.8)	8 (1.2)
Arizona State Univ, USA	8 (1.2)	10 (0.5)	33 (0.8)	14 (0.8)	15 (0.9)
Univ Virginia, USA	8 (1.2)	10 (0.5)	33 (0.8)	18 (0.6)	8 (1.2)
Univ Utrecht, Netherlands	8 (1.2)	10 (0.5)	33 (0.8)	29 (0.5)	19 (0.8)
Tech Univ Berlin, Germany	8 (1.2)	38 (0.2)	13 (1.1)	18 (0.6)	8 (1.2)
Purdue Univ, USA	8 (1.2)	38 (0.2)	13 (1.1)	18 (0.6)	12 (1.1)
WWF, UK	8 (1.2)	38 (0.2)	13 (1.1)	18 (0.6)	15 (0.9)
Norwegian Univ Sci & Technol, Norway	8 (1.2)	38 (0.2)	13 (1.1)	29 (0.5)	8 (1.2)

TP: Total publications; SPR: Single institute publication rank; CPR: Inter-institutionally collaborative publication rank; FPR: First author publication rank; RPR: Corresponding author publication rank.

range of 38 subject categories. Among these subjects, 25 (65.8%) subjects contained less than 10 publications. Fig. 3 shows the top 12 productive subjects, accounting for approximately 96.3% of the publications. The top three subjects in terms of the number of publications are Environmental Sciences & Ecology (347, 30.6%), Engineering (245, 21.6%) and Water Resources (139, 12.3%). Additionally, Fig. 3 also depicts the annual publications on the 12 most frequent subject categories in WF research. The number of publications in the subject categories of Environmental Sciences & Ecology and Engineering soared rapidly since approximately 2010. And the number of publications in the subject categories of Water Resources and Agriculture also grew obviously since roughly 2008. The three most productive categories have been taking the lead, and it seems unlikely to be exceeded by other categories in the foreseeable future, which mainly take focus on the water resources management and environmental or ecological sustainable development.

Table 4 shows the distributions of output in key journals on WF research from 2006 to 2015. The total of 632 records were published in 193 journals. *Journal of Cleaner Production* (58, 9.2%), *Environmental Science & Technology* (32, 5.1%) and *Ecological Indicators* (28, 4.4%) are the top three journals with the most publications of research on WF, which account for only 18.7% of all the publications. The percentage of the top three productive journals was not high, which indicates the breadth of article distribution as well as the broad interest in WF from various research perspectives. The impact factor (IF) in 2015 of each journal was shown in Table 4, whereas it cannot be said that the journals are very influential on this topic based on journal IF. Therefore, top cited publications in WF research were discovered as follows.

3.5. Top cited publications in the field of WF research

Table 5 lists the top cited publications in the field of WF research with additional information: authors, journal's title, the total citations, and the country/institutions of origin during 2006–2015. As

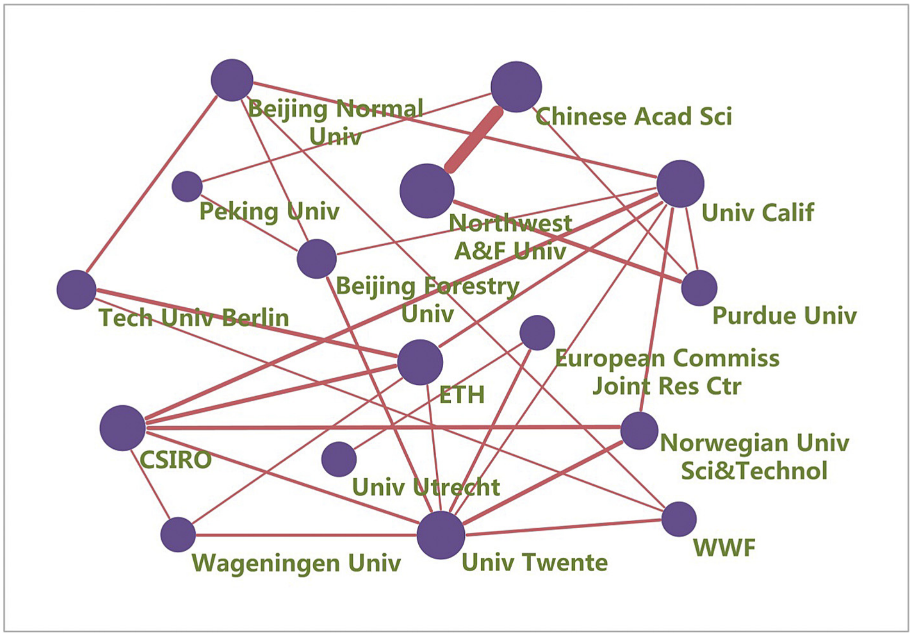

Fig. 2. The cooperation network of the top 20 productive institutions.

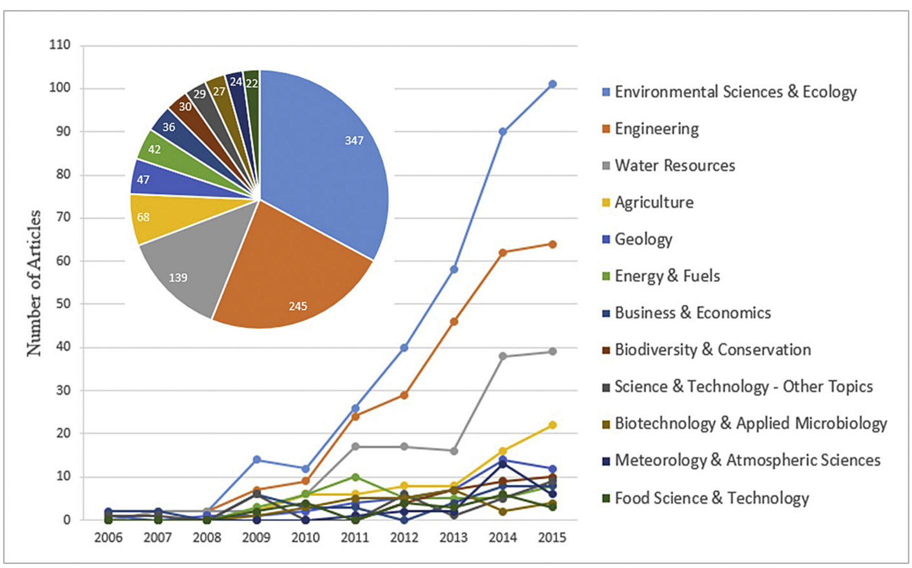

Fig. 3. Publications of the top 12 productive Web of Science categories during 2006–2015.

Table 4
Distributions of output in key journals from 2006 to 2015.

Journal	TP	R (%)	IF 2015
Journal of Cleaner Production	58	1 (9.2)	4.959
Environmental Science & Technology	32	2 (5.1)	5.393
Ecological Indicators	28	3 (4.4)	3.190
Ecological Economics	27	4 (4.3)	3.227
Water Resources Management	27	4 (4.3)	2.437
Sustainability	21	6 (3.3)	1.343
International Journal of Life Cycle Assessment	19	7 (3.0)	3.324
Science of the Total Environment	18	8 (2.8)	3.976
Hydrology and Earth System Sciences	17	9 (2.7)	3.990
Environmental Research Letters	16	10 (2.5)	4.134

TP: Total publications; R(%): Rank and the percentage of total publications; IF: Impact factor (2015).

is shown in Table 5, the most highly cited article is entitled “Water footprints of nations: Water use by people as a function of their consumption pattern”, authored by Hoekstra and Chapagain, and published in *Water Resources Management* in 2007, with totally 395 citations. Based on a calculation of the WF for each nation of the world, their study found out four major direct factors that determine the WF of a country, including volume of consumption, consumption pattern, climate and agricultural practice (Hoekstra and Chapagain, 2007). A large number of further researches cited its data or results to discover the impacts of these four factors on WF in temporal and spatial scales, which have become the main topics in WF research over the past decade.

“The water footprint of humanity (2012)” and “The water footprint of bioenergy (2009)” published by *Proceedings of the National Academy of Sciences of the United States of America* ranked as the

Table 5
Top 30 cited publications in the field of WF research during 2006–2015.

No.	Author	Journal	Country/Institute	Citations
1	Hoekstra and Chapagain (2007)	Water Resour Manag	Netherlands/Univ Twente	395
2	Hoekstra and Mekonnen (2012)	P Natl Acad Sci USA	Netherlands/Univ Twente	256
3	Gerbens-Leenes et al. (2009a)	P Natl Acad Sci USA	Netherlands/Univ Twente	244
4	Yang et al. (2011)	Bioresource Technol	USA/Georgia Inst Technol	233
5	Mekonnen and Hoekstra (2011)	Hydrol Earth Syst Sc	Netherlands/Univ Twente	207
6	Chapagain et al. (2006)	Ecol Econ	UK/WWF	196
7	Ridoutt and Pfister (2010)	Global Environ Chang	Australia/CSIRO; Switzerland/ETH	164
8	Dominguez-Faus et al. (2009)	Environ Sci Technol	USA/Rice Univ	155
9	Gleeson et al. (2012)	Nature	Canada/McGill Univ	139
10	Galli et al. (2012)	Ecol Indic	USA/Global Footprint Network	129
11	Hoekstra et al. (2012)	PLoS One	Netherlands/Univ Twente	123
12	Gerbens-Leenes et al. (2009b)	Ecol Econ	Netherlands/Univ Twente	119
13	Chapagain and Hoekstra (2008)	Water Int	UK/WWF; Netherlands/Univ Twente	118
14	Mekonnen and Hoekstra (2012)	Ecosystems	Netherlands/Univ Twente	114
15	Hubacek et al. (2009)	J Clean Prod	UK/Univ Leeds	99
16	Zhao et al. (2009)	Ecol Model	China/Beijing Normal Univ	95
17	Mila i Canals et al. (2009)	Int J Life Cycle Ass	UK/Unilever Safety & Environm Assurance Ctr	91
18	Ma et al. (2006)	Philos T R Soc B	China/China Inst Water Resources & Hydropower Res	91
19	Chapagain and Hoekstra (2011)	Ecol Econ	UK/WWF; Netherlands/Univ Twente	89
20	Chapagain and Hoekstra (2007)	Ecol Econ	UK/WWF; Netherlands/Univ Twente	87
21	Hoekstra (2009)	Ecol Econ	Netherlands/Univ Twente	83
22	Chapagain and Orr (2009)	J Environ Manage	UK/WWF	81
23	Hoekstra and Wiedmann (2014)	Science	Netherlands/Univ Twente; Australia/Univ Sydney	77
24	Steen-Olsen et al. (2012)	Environ Sci Technol	Norway/Norwegian Univ Sci & Technol NTNU; Switzerland/Global Footprint Network; Netherlands/Univ Twente	77
25	Mekonnen and Hoekstra (2010)	Hydrol Earth Syst Sc	Netherlands/Univ Twente; UK/WWF	75
26	Pfister et al. (2011)	Environ Sci Technol	Switzerland/ETH	75
27	Yang et al. (2009)	Energ Policy	Switzerland/Eawag, Swiss Fed Inst Aquat Sci & Technol; China/Beijing Forestry Univ	67
28	Zhao et al. (2010)	Environ Sci Technol	China/Beijing Normal Univ; Switzerland/Eawag, Swiss Fed Inst Aquat Sci & Technol	66
29	Yu et al. (2010)	Ecol Econ	England/Univ Leeds/Univ Sheffield/ Univ Cambridge; USA/Univ Maryland	66
30	Zhang et al. (2011)	Ecol Econ	Switzerland/Swiss Fed Inst Aquat Sci & Technol Eawag; China/Chinese Acad Sci	65

The citations were counted by October 2016.

second and third most highly cited article, with respectively 256 and 244 citations. The former illustrated the global dimension of water consumption and pollution (Hoekstra and Mekonnen, 2012), the latter served as a reference to select agricultural production and countries that produce bioenergy in the most water-efficient way (Gerbens-Leenes et al., 2009a). The 4th article entitled “Life-cycle analysis on biodiesel production from microalgae: Water footprint and nutrients balance (2011)” was from Georgia Institute of Technology, with 233 citations. The results reflect microalgae biofuel development in the US and highlight the necessity of water recycling (Yang et al., 2011). Relevant publications usually cite their methods or results to assess WF from both a production and consumption perspective. The high number of citations of these three articles indicates that much more attention has been drawn in the field of virtual water trades/flows, agricultural/biodiesel production, sustainable consumption and water pollution in the last ten years.

3.6. Hot issues and research trends

3.6.1. Keywords analysis and hotspots

To capture the hot issues and identify the research trends, bibliometric method through keywords analysis has been developed in many previous studies (Fu et al., 2013; Gao et al., 2015; Wang et al., 2014). Title words, author keywords and keywords plus are often selected to reveal the hotspots and discover the emerging trends in scientific research. Among 632 publications, 538 articles (85.1%) had record information of author keywords, while 567 articles (89.7%) with keywords plus information were analyzed. Totally, 3865 title words, 3511 author words and 3951 keywords plus were found in this study, and the rankings of these kinds of words according to their frequency were performed. Table 6 shows the top 25 most frequently used keywords appeared in WF research during 2006–2015, with combination of their plural forms, abbreviations, and other transformations. Apart from the search words we have used before, the most frequent keywords were “energy”, “consumption”, “resource”, “life cycle assessment”, “trade”, “model”, “input-output”, “management” and “impact”, implying that the WF research is mainly focused on WF accounting methodologies, water energy nexus and impacts of water use, etc.

Other than the searching keyword “water footprint”, the most frequently used author keyword was “energy”, which also ranked 4th both in title words and keywords plus; “resource” ranked 2nd in keywords plus, 5th in author keywords and 8th in title words list; simultaneously, “consumption” ranked at the head of all three lists. It indicates that great importance has been attached to water energy nexus and resource consumption in the field of WF research over the past decade, taking bioenergy (biomass, bioelectricity, biodiesel, biofuel etc.) (Nunez et al., 2013; Pacetti et al., 2015; Subhadra, 2011) and water resource consumption (Ono et al., 2015; Zhang and Yang, 2014) as examples. Meanwhile, the word “consumption” refers in many papers to not only water consumption/consumptive water use, but also food consumption. Since “food (security)” and “diet” were mentioned in top 25 frequency of keywords, the researches on the WF of different diets and food losses/waste (Vanham et al., 2013a,b; 2015; Kummu et al., 2012)

Table 6
Top 25 frequency of title words, author keywords and keywords plus used during 2006–2015.

Rank	Title words	Author keywords	Keywords plus
1	production	energy	consumption
2	impact	consumption	resource
3	China	life cycle assessment	impact
4	energy	trade	energy
5	crop	resource	life cycle assessment
6	consumption	model	trade
7	trade	scarcity	system
8	resource	input-output	model
9	system	management	carbon
10	evaluation	sustainability	management
11	model	irrigation	flow
12	nation	agriculture	emission
13	carbon	carbon	China
14	sustainability	ecology	crop
15	irrigation	China	production
16	management	efficiency	green
17	life cycle assessment	flow	nation
18	green	climate change	river-basin
19	input-output	food security	biofuel
20	biofuel	impact	input-output
21	emission	evapotranspiration	climate change
22	land use	productivity	sustainability
23	food	nation	indicator
24	quality	diet	food
25	framework	quality	ecology

All keywords related to filters, such as "water" and "footprint" are not included in this table.

have been very hot issues.

In addition, "life cycle assessment" ranked 3rd in author keywords and 5th in keywords plus, as one of the useful methods in environmental impact assessment in the field of water resource sustainability (Berger and Finkbeiner, 2013; Huang et al., 2015; Pfister and Bayer, 2014). With respect to author keywords, "input-output" (ranking 8th) and "model" (ranking 6th), played an important role in evaluating the WF and virtual water trade, especially in China (ranking 3rd in title words and 13th in keywords plus) (Wang et al., 2013, 2016; Zhao et al., 2015). Similarly, much concern was attracted by "agriculture", coupled with "crop" (ranking 5th in title words and 14th in keywords plus) and "production" (taking first place in title words). It indicates that WF of a certain crop production (Sun et al., 2012) and irrigation water use efficiency (Zhang et al., 2015) were of wide concern in agricultural adaption management.

To discover the research patterns by nation, the top 20 productive countries were selected as the primary contributors to the literature and represent various social and economic conditions. As is depicted in Fig. 4, of the 25 frequent keywords, energy, carbon, LCA, scarcity, impact, trade, resource, model, sustainability, climate change, land use and production were among the most common in no fewer than 13 countries. The remaining 13 keywords were shared among 12 countries or fewer. Among the top 20 productive countries, the USA (24), China (23), Netherlands (22) and Australia (21) shared the most, followed by Spain (19), the UK (17), Switzerland (17), Italy (17), Germany (17) and France (17). Apart from the 25 common keywords among different countries, each country has its own specific keywords. For the USA, food security (Gephart et al., 2014) received most of the attention among WF research. For China, more emphasis was placed on key regions, such as Beijing (Huang et al., 2012; Xu et al., 2015), important irrigation districts (Feng et al., 2012; Liu et al., 2014) and lake basins (Hu et al., 2016), where water scarcity is a threat to ecological and economic sustainable development. For Netherlands, water pollution (Liu et al., 2012; Schyns et al., 2015) and planetary boundaries (Fang et al., 2014) were listed as high frequency terms in addition to the shared terms. For Australia, livestock in agriculture (Ridoutt et al., 2012) and environmental labelling (Ridoutt and Pfister, 2013) were its featured keywords.

3.6.2. *Research trends*

Results based on keywords analysis provided the clues for the potential future of WF research. In the meantime, further studies are required to explore the WF research and its applications for water resource management at all geographical levels. Research trends in WF research can be consisted of the facets as follows:

3.6.2.1. Water-food-energy nexus. Water, food and energy are crucial resources for socioeconomic development and are inextricably and reciprocally linked (Okadera et al., 2015; Vanham, 2016). Given the water resources availability to produce energy and food from both production and consumption perspectives, it is very likely that water-food-energy nexus will remain a hot topic of WF research in the coming years. Vanham (2016) has begun to investigate the components included in WF accounting to address the water-food-energy-ecosystem nexus. By evaluating WF of energy or food supply and introducing indicators to assess water-food-energy nexus, researchers will provide greater visibility and

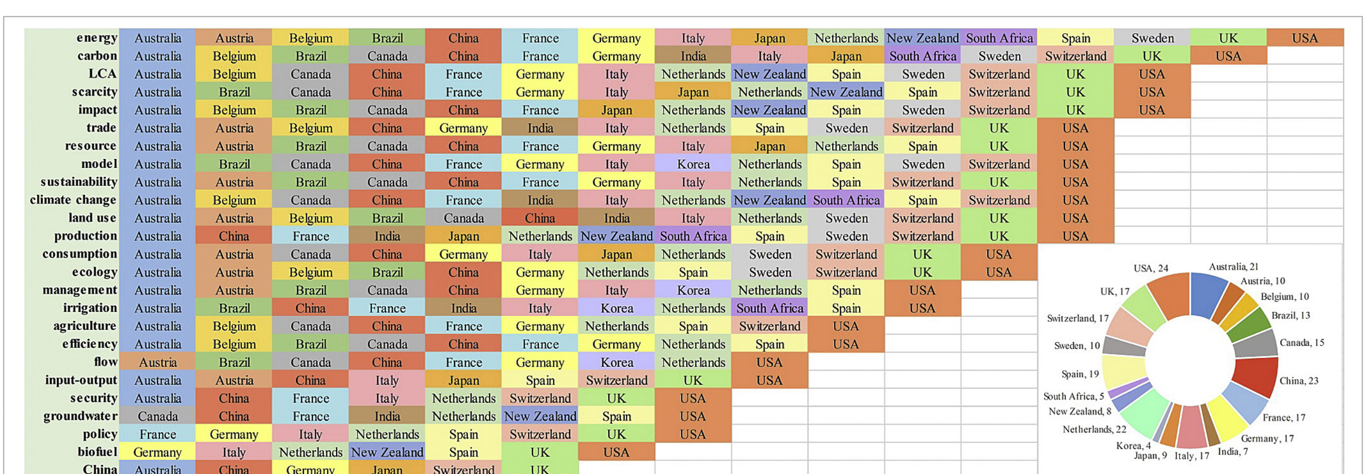

Fig. 4. Co-occurrence of author keywords among countries.

insight into the water/food/energy security and the water consumption of energy/food production on different temporal and spatial scales (Spang et al., 2014).

3.6.2.2. Driving mechanism of WF variation. Exploring the driving mechanism of WF variation is a significant step to facilitate the future water policies and sustainable economic development. 1) Climate change. Given the uncertainty of climate expectations and natural hazards, the anticipated impact of climate change on WF cannot be omitted. Climate change projections in WF studies is of great significance to adapt integrated water resources management and sustainable water uses (Bocchiola et al., 2013; Zhang et al., 2015). 2) Human activities. Previous studies have attempted to uncover the underlying causal drivers of WF changes by placing emphasis on both productive process and consumptive patterns. Future studies are worthy to be carried out to investigate the comprehensive effects caused by virtual water trade, water-saving techniques and socioeconomic development, etc. (Sun et al., 2013; Wang et al., 2013).

3.6.2.3. Environmental impacts of water use. In an attempt to provide WF methods with an improved competence to quantify environmental impacts, studies have been done proposing various ways to integrate WF with LCA methodologies (Berger and Finkbeiner, 2013; Mila i Canals et al., 2009; Chenoweth et al., 2014). The LCA has demonstrated its advantage by standardizing the quantification of environmental impacts on water resources and evaluating the supply chains to account for the full life of individual products and commodities in the systems concerned (Paterson et al., 2015). Concerning both consumptive and degradative water use, hybrid approaches combining the WSI index and impact assessment models (e.g. Eco-indicator-99 LCIA method (Pfister et al., 2009), ReCiPe impact assessment methodology (Ridoutt and Pfister, 2013), etc.) have incorporated best practice in life cycle impact assessment (LCIA). Promising methodological development can enable accurate accounting and impact assessment of water utilization in the future (Berger and Finkbeiner, 2010).

3.6.2.4. Integration of footprint indicators. With the aim to establish an evaluation index system of environmental impacts of production and consumption, some researchers have begun to consider integrating WF and other footprint indicators. Footprint Family is this kind of comprehensive indicators. Footprint Family has a wide range of research and policy applications as it could be adopted at scales ranging from a single production, a process, up to individuals, cities, nations, and the whole world (Galli et al., 2012). According to the definition of Footprint Family, the ecological, energy, carbon and water footprints have been employed as selected indicators. A deeper understanding of the connections and interactions between these different footprints is required to develop a multi-criteria decision making process and provide environmental impact mitigation strategies (Čuček et al., 2015; Fang et al., 2014). Representing the environmental consequences of human activities, the ecological, energy, carbon and water footprints need to be regarded as complementary in the sustainability debate (Fang et al., 2013; Galli et al., 2012) and it will become a new trend in footprint research.

4. Conclusion

An overview of the research on WF was presented with the information related to countries, institutions, journals, categories, top cited publications, keywords, hot issues and research trends. Researches on WF have increased sharply over the past decade. The United States (24.1%), China (19.2%) and Netherlands (16.0%) had high productivity in total publications. Based on co-word analysis and SNA, the USA-China has been most closely correlated in the cooperative web system. University of Twente took the leading position of institutions in total articles and also published the most independent, collaborative, first authored, and corresponding authored articles. More than half of the studies in the subject categories of Environmental Sciences & Ecology, Engineering and Water Resources have been taken to explore the water resources management and environmental or ecological sustainable development. *Journal of Cleaner Production*, *Environmental Science & Technology* and *Ecological Indicators* are the top three journals with the most publications of research on WF. Keywords analysis has been proved to be an effective approach for discovering hotspots and research trends. It reveals that previous studies were mainly focused on WF accounting methodologies and its application in water resource management. Water-food-energy nexus, driving mechanism of WF variation, environmental impact of water use and integration of footprint indicators strongly promoted the development of WF research and are getting popular in recent years.

Acknowledgements

This research was supported by National Natural Science Foundation of China (41301636, 51474033) and Beijing Natural Science Foundation (9172012).

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