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Recent Developments of Water Footprint Methodology

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Pressure humanity is facing from environment-related problems has been increasing in the past decades. A comprehensive and effective approach for environment protection management has been the top priority. Water footprint (WF) provides a good methodology to assess the environment related problem and address the challenges. In the last several years the Web of Science has witnessed that WF-related publications have significantly increased. The research in WF has become mature and linked with a growing number of topics. The “WF-Energy”, “WF-Carbon Emissions (CE)” (mainly CO_2) and “WF-Nitrogen Emissions (NE)” (mainly NOx) were selected and proposed as recent hot topics. This paper analyses current and future development trends in WF.

1. Introduction

The freshwater resources have become an increasingly important global resource, driven by growing international trade in goods and services (Egan, 2011). There is no more than 0.007 % of all water on Earth which can be immediately consumed by human beings. It dropped more than 50 %, from 13,000 m^3 to 6,000 m^3, regarding the per capita water availability per year, from 1975 to 2005 (Loucks and Van Beek, 2017). This drop is influenced by many factors like climate change, increasing water pollution. Until 2016, almost 4×10^9 people in the world lived at least one-month facing severe water scarcity each year. 0.5×10^9 people are facing severe water scarcity all year round (Mekonnen and Hoekstra, 2016).
WF, introduced in 2002 (Hoekstra and Huang, 2002), was proposed as life cycle assessment (LCA) quantifiers to evaluate water resources utilisation relative to human consumption. WF is an indicator of freshwater use that looks at both direct and indirect water use of a consumer or producer. WF has been one of the key indicators to deal with water resources management and governance (Zhang et al., 2017b), especially on the background of increasing water scarcity and imbalance of total WF of humanity. Figure 1 shows the annual average WF of humanity between 1996 – 2005 (Hoekstra and Mekonnen, 2012). Over the past decade, WF has been recognised as a globally hot topic, developing into blue water footprint, green water footprint and grey water footprint, and into main implementation fields, such as industrial water footprint, agriculture water footprint, regional water footprint or product water footprint. The reviews have been developed by several authors, such as Čuček et al. (2012), covering and comparing a wide range of various footprints. Related research has been important in supporting the sustainable use of water. A global study on national water footprints was carried out by Hoekstra and Huang (2002). Another global assessment of nations WF was carried out by Chapagain and Hoekstra (2008), proposing that the interdependencies of global water will grow drove with increasing globalisation of worldwide trade (Liu et al., 2017). Mekonnen and Hoekstra (2011) conducted a global nations’ WF assessment, estimating and mapping the nations’ WF in terms of production and consumption.
WF has been promoted by the Water Use in Life Cycle Assessment since 2007. An important WF assessment method based on LCA was proposed by Ridoutt and Pfister (2010). Water Footprint Assessment Manual was released in 2012 and started to standardize the WF methodology (Hoekstra et al., 2012). In 2014, the International Organization for Standardization released the ISO 14046, which defined the criteria and standards for WF assessment as an environmental impact indicator. A solution to the real-life challenges by linking WF with other concepts has been paid more and more attention. Three topics were selected - energy, CE (CO_2),

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and NE (NO_x). The publications covered in Web of Science were analysed. Current and future research trends stressing the most recent period up to 2018 were considered as a priority.

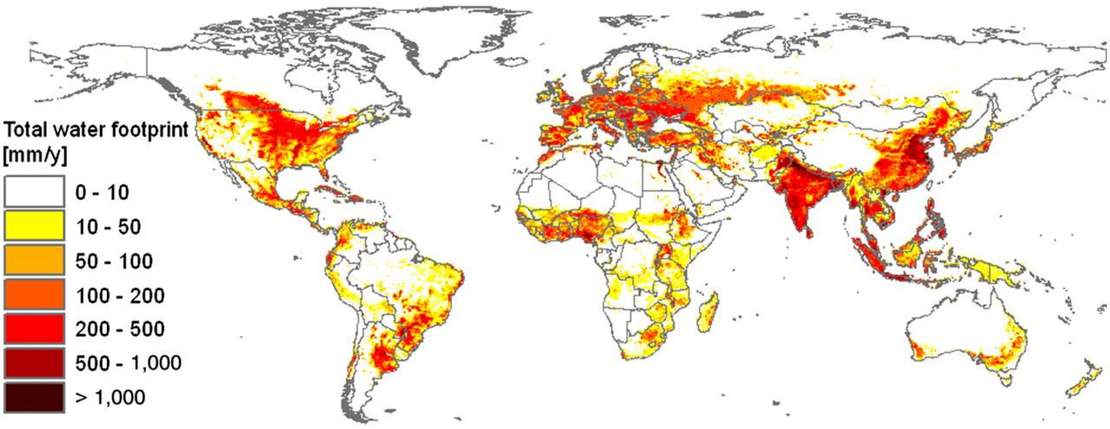


Figure 1: WF of humanity in the period 1996–2005. Data are shown in mm/y on a 5’ × 5’ grid (Hoekstra and Mekonnen, 2012).

2. Overview of WF

From 2008 to 2017, 4,479 publications on the topic of WF were retrieved from Web of Science database. Out of them, 80 % is published articles and others include reviews, book chapters and so on. As shown in Figure 2, the number of WF publications was increasing steadily from 144 in 2008 to 838 in 2017. The WF publications from the top five regions also demonstrated the increasing trend. The USA and China are leaders. The increasing number of publications obviously reflected the rising occurrence as well as the concern for water-related issues.

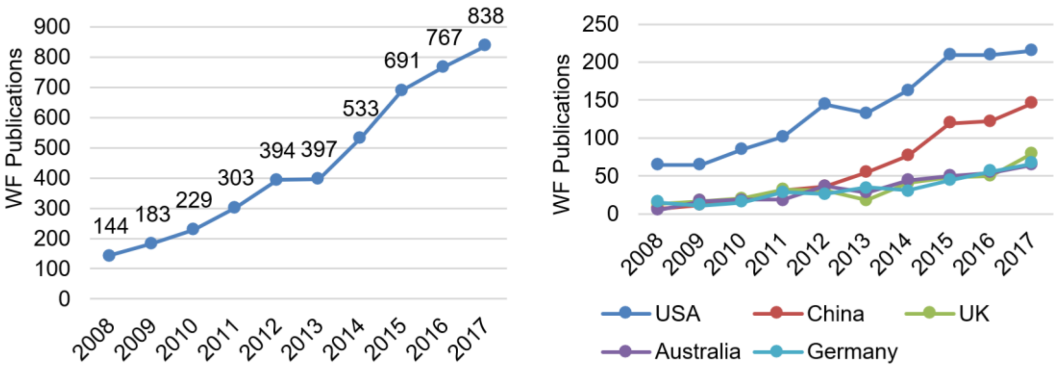


Figure 2: The number of publications on the topic of WF and Top 5 Publication Regions, from 2008 to 2017.

Regarding the regions of these publications, the USA and China were the largest two sources. Nearly 45 % publications belong to these two countries, followed by the UK, Australia, Germany, Netherland, Canada, Italy, Spain and France. From 2012 to 2013, there was a decrease in WF publications from the USA (144 to 133), the UK (31 to 18) and Australia (37 to 28). The same situation applies to Germany (35 to 31) from 2013 to 2014. This maybe a consequence of the economic crisis, which had no influence on China. Figure 3 shows the top ten regions of WF Publications, from 2008 to 2017. The map (Figure 1) reflects the rising WF issues in these countries. Although it does not reflect the WF per person, it highlights the high total WF of some regions. These regions had high water demand and consumption, along with the pursuit of more improved WF research and management. The booming economy of China brought growing pressures on water resources (Zhang and Anadon, 2014). The multi-regional input-output virtual water (VW) analysis and regional water footprint assessment in China was made by Zhang and Anadon (2014). Results show that the VW of big cities in China, like Beijing, Tianjin, Shanghai, significantly depend on the inflow from other regions of China. Hoekstra and Mekonnen (2012) also found that several countries significantly rely on a water resources inflow from other countries. It is urgent to build the water-trade nexus and to improve water-use efficiency for addressing the water scarcity pressure (Liu et al, 2017).

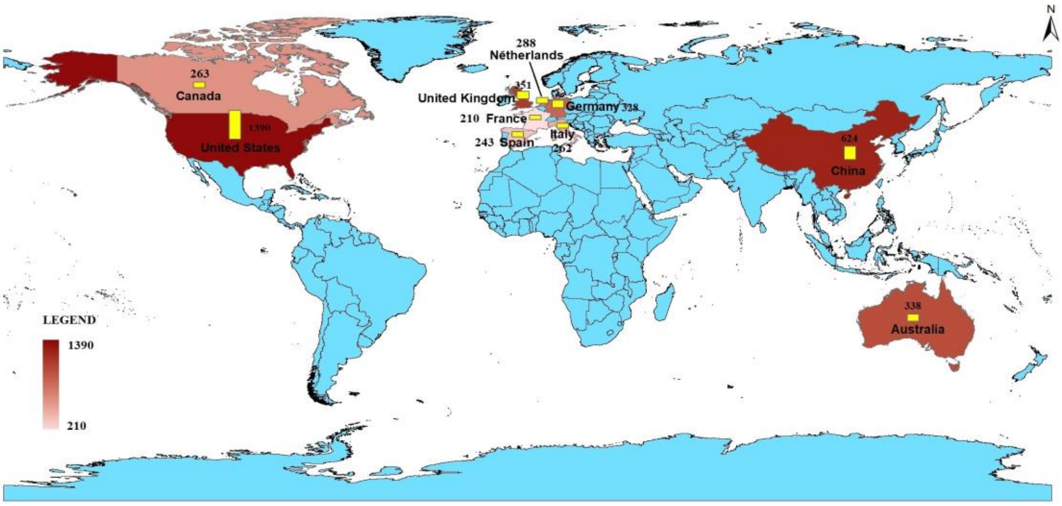


Figure 3: Top 10 Regions of WF Topic Publications, from 2008 to 2017.

The contribution of different institutions to study the WF was analysed according to authors' affiliations. The top 30 affiliations of WF publications are shown in Figure 4. They are consistent with the Figure 2 and Figure 3. 16 (53 %) of these affiliations belong to the USA, five (17 %) to China and the remaining eight (30 %) to other countries. However, regarding the top five affiliations, three of them belong to China, including the first one. China's WF publications are concentrated in the hands of a few institutions.

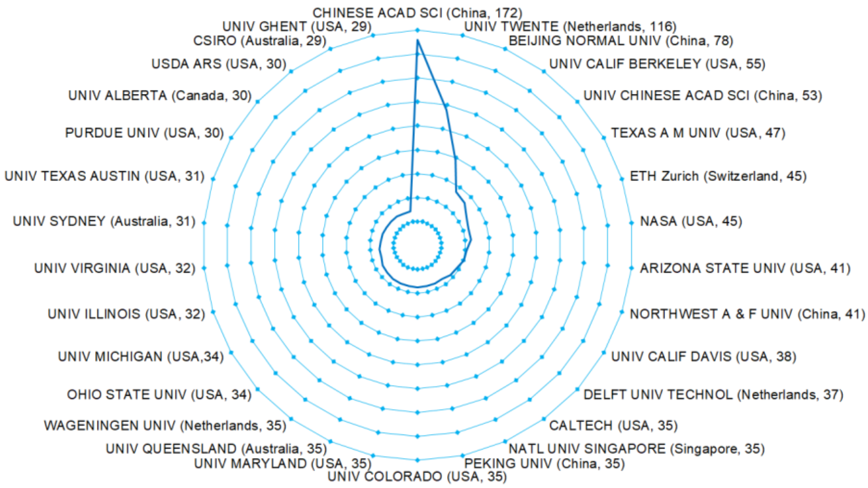


Figure 4: Top 30 Affiliations of WF Publications, from 2008 to 2017.

Following to the source titles of these publications, Figure 5 shows the distributions of output in key journals from 2008 to 2017. The Journal of Cleaner Production (269, 6 %) has a lead compared with other journals, like Environmental Science & Technology (87, 2 %), Science of The Total Environment (81, 1.8 %), Ecological Indicators (75, 1.7 %). However, besides the Journal of Cleaner Production, the percentage of other journals is not high. This indicates that the range of article distribution as well as the broad interest in WF, are from various research perspectives (Zhang et al, 2017b). The ranking and impact factor (IF) in 2016 of each journal were also shown in the brackets of Figure 5, which can possible reflect the journals' influence on the topic.

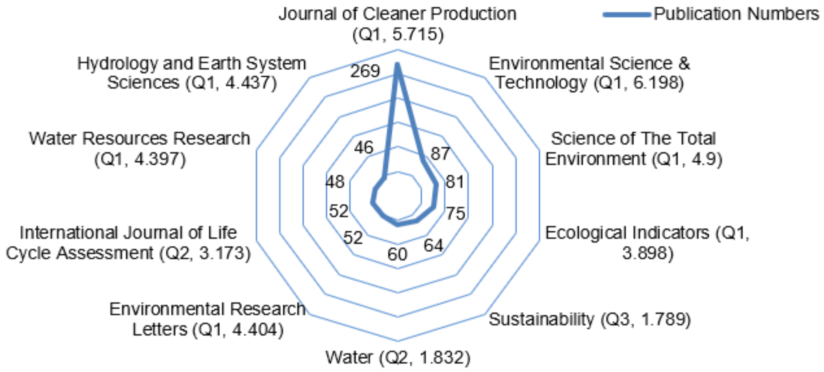
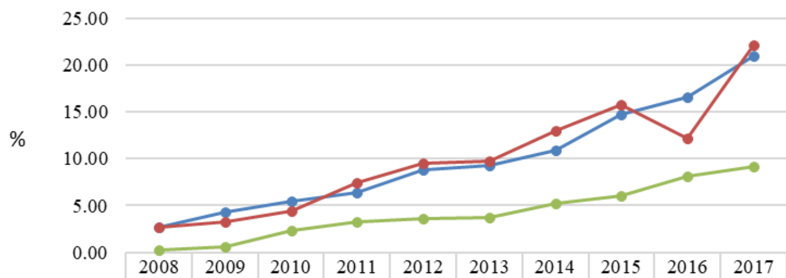


Figure 5: Top 10 Journals of WF Topic Publications, from 2008 to 2017.

3. The nexus between WF and other topics

WF has become an important and dynamic field of environmental research. The interest in WF has been steadily increasing over the past years. Research on WF has included a wide number of topics. On this basis, worldwide research trends and opportunities have also been appearing from various fields of science and technology. WF has been increasingly linked with other topics, like energy, CE (mainly CO_2), NE (mainly NO_x) and effluents etc. The CE account for about more than 2/3 of the GHG, which also include CH_4, NO_x and fluorinated gases (IPCC, 2014). This study focusses on the main component of GHG – CO_2. From 2008 to 2017, the publication percentage under the topics of “WF and Energy”, “WF and CE” and “WF and NE” increased significantly (Figure 6). The publications of these topics (3,468) account for more than 77 % of total publications (4479) of WF. “WF and Energy” account for more than 37 %, “WF and CE” for 33 % and “WF and NE” for 7 %. A conclusion can be drawn that research on the nexus between WF and these topics has been the main trend of this domain. This research of nexus between WF and other topics can provide us with a clearer and more comprehensive perspective to support the regional or worldwide sustainable development.



	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
WF & Energy	2.64	4.26	5.52	6.36	8.82	9.24	10.92	14.70	16.62	20.94
WF & Carbon Emissions	2.66	3.23	4.45	7.39	9.48	9.76	12.99	15.79	12.13	22.11
WF & Nitrogen Emissions	0.27	0.55	2.33	3.29	3.56	3.70	5.21	6.03	8.08	9.18

Figure 6: Percentage of Publications under Topics of “WF and Energy”, “WF and CE” and “WF and NE” from Overall WF Publications Each Year, from 2008 to 2017.

3.1 WF-Energy Nexus

Water and energy have always been two pillars of environmental and ecological systems. The demands for comprehensive approaches to managing these pillars have been significant. The trade-offs among water consumption, energy generation/consumption and the reduction of environmental impact of water and energy flow have been the focus. The WF represent an innovative evaluation approach to this topic. Gerbens-Leenes et al (2008) studied the WF of biomass energy.

Pacetti et al (2015) analysed the environmental impact of bio-energy from virous crops by integrating the WF and LCA. The integration of WF and LCA provides a comprehensive and useful perspective for insight and assessing the bioenergy and water resources. Zhang et al (2017a) assessed the water footprint of energy supply with a regional input-output analysis for Shanghai. Water feasibility for energy production was analysed from a consumption-based perspective and a strategy for energy self-sufficiency for the city was also proposed, suggesting that it is significant to comprehensively manage the water resources to guarantee the future energy security. Besides that, the research into WF and energy was recently carried out by Miglietta et al (2018), assessing the WF and economic water productivity during electricity production.

3.2 WF-CE Nexus

Human environmental impact cannot be comprehensively monitored by a single indicator. Multi indicators should be joined and integrated. Several attempts have been made to improve the methodology for assessing the productive and consumptive impacts on the environment to reduce and possibly minimise the environmental pressure. For example, the virtual footprints like the CE footprint (CEF), especially more comprehensive GHG Footprint, and WF are considered for achieving the goal (Liu et al., 2017). Galli et al (2012) analysed the rationale, methodology and research questions of WF and carbon footprint (CF), highlighting the interaction and complementarity of these two indicators. The "Footprint Family" is becoming a set of indicators which, if properly used, can track the human activities and reduce the environmental pressure. Steen-Olsen et al (2012) quantified the total environmental pressures caused by consumption in the EU mainly by integrating the indicators of CEF or more comprehensive GHG or WF. They found that the EU got a much higher GHG emission and blue water consumption than global averages, displacing all these environmental pressures to the rest of the world through international trade. Liu et al (2017) also reviewed the CE and water flow embodied in the international trade, resulting in a conclusion that consumers and producers of different regions correspond to the different CE. The EU and USA have high absolute net CO_2 imports. The research combining WF and CE were also carried out by Yousefi et al (2017). It assessed the CF and WF of sunflower production. Ali (2017) assessed the WF and CE accounts of Italy. The integration of WF and CEF, as well as other indicators, has been and will be pivotal approach to comprehensively monitor environmentally sustainable development.

3.3 WF-NE Nexus

The increasing use of nitrogen has both the pros and cons (Mekonnen and Hoekstra, 2015). It can increase the yield of crops and reduce the part of world population suffering from hunger. In contrast to that, the rising use or even overuse of nitrogen compounds may bring about the pollution of freshwater system and degradation of the water quality. The later one is a growing important social concern. An appropriate trade-off between WF and nitrogen-application has become important, especially for the domain of agriculture and surface and groundwater. Chukalla et al (2018) analysed the trade-off between the WF and nitrogen-applications based on crop production practices. The nitrogen pollutants also contributte to the water eutrophication than other factors like phosphorus pollutants(Bai, 2017). It is a high requirement for us to decrease nitrogen-application influence on water and minimise the environmental impact, which will be a long-term goal of the future.

4. Conclusions

The current and the future developments trends of WF have been briefly analysed in this paper. The WF publications ignificantly increased, from 144 in 2008 to 838 in 2017. The USA and China leads the top countries list. The situation is the same with the affiliations belonging to USA and China. The topics of "WF and energy", "WF and CE" and "WF and NE" were selected and proposed as recent hot topics according to the increasing attention they got. Publications (3,468) in these three topics account for more than 77 % (37 %, 33 % and 7 % separately) of total publications (4,479) of the topic of WF.

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