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A Review on Water Footprint Research of Materials Industry

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Abstract. The scarcity of water resource has become one of major issues that constrain economic development and urbanization process in China. The water footprint is a comprehensive indicator used to measure water consumption and pollution that is widely used in global or regional studies. The previous practices showed that water footprint analysis was an effective tool to achieve sustainable utilization of water resources by guiding the development of water-saving technology and product. This paper reviewed the progress of water footprint research in materials industry including related theory, method and application. Firstly, the basic concept of water footprint was introduced. Secondly, the current accounting and assessment methods of water footprint and their applicable fields were summarized. Thirdly, the case studies on the water footprint of metallic materials, nonmetallic materials and chemical materials were reviewed to analyze its guidance significance on the sustainable development of water resources. At last, some suggestions for future research on the water footprint of materials were proposed.

Introduction

70% of the earth's surface is covered by water, and the water storage is as high as 13.86 billion km^3, but the available fresh water resources only account for 0.77% of the total water [1]. At the same time, global freshwater resources are not only in shortage, but the regional distribution is extremely unbalance. China's fresh water resources per capita only account for a quarter of the world's average, and the lack of water resources has become one of the "bottlenecks" that seriously restrict China's social economic development. It was predicted that China's total water demand will reach 7000-8000 billion m^3/a by 2030, which is close to the total amount of available water (8000-9500 billion m^3) [2]. The regional distribution of China's water resources is also very unbalance. The north of the Yangtze River Basin, with 63.5% of the country's total land area, which only account for 19% of the country's water resources [3]. Fig. 1 shows the amount of water resources per capita of main countries in the world in 2017 and the amount of water resources in different regions of China.

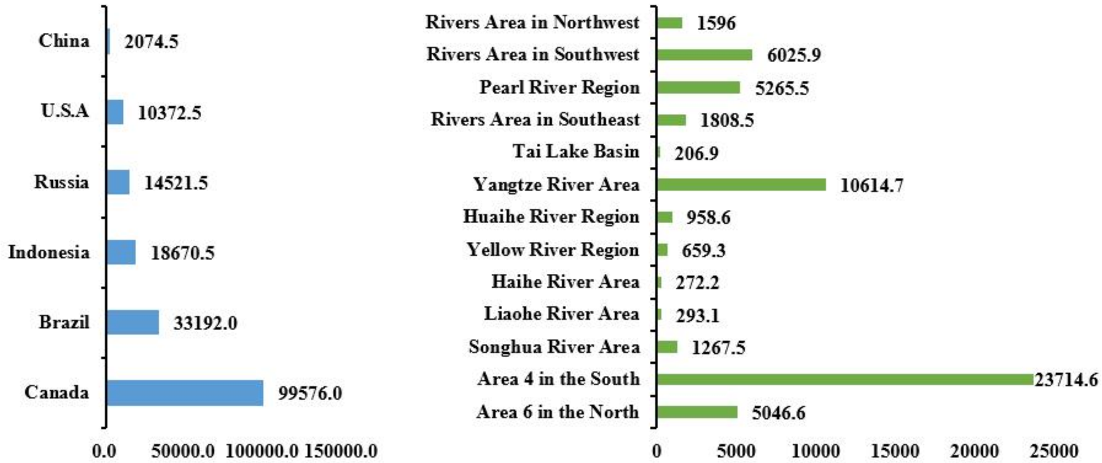

Fig. 1 The amount of water resources per capita in main countries and different regions in China (Unit: m^3/per capita; billion m^3)

Industry is the pillar industry of national economy and social materials production. However, the large-scale industrial production process not only consumes a large amount of water resources, but also discharges a large amount of production wastewater, thereby causes serious water environment pollution and intensifies water shortage in countries or regions. Industrial economy in China has developed rapidly, and the scale of industrial production dominated by manufacturing has been continuously expanding, which has brought increasing pressure on China's water resources and environment. Since 21st century, industrial water consumption has increased continuously, and its proportion has increased from 20.7% in 2000 to 24.0% in 2017. Discharge amount of industrial wastewater reached 181.6 billion tons in 2017 [4]. Fig. 2 shows the condition of water use and wastewater discharge in China in 2017.

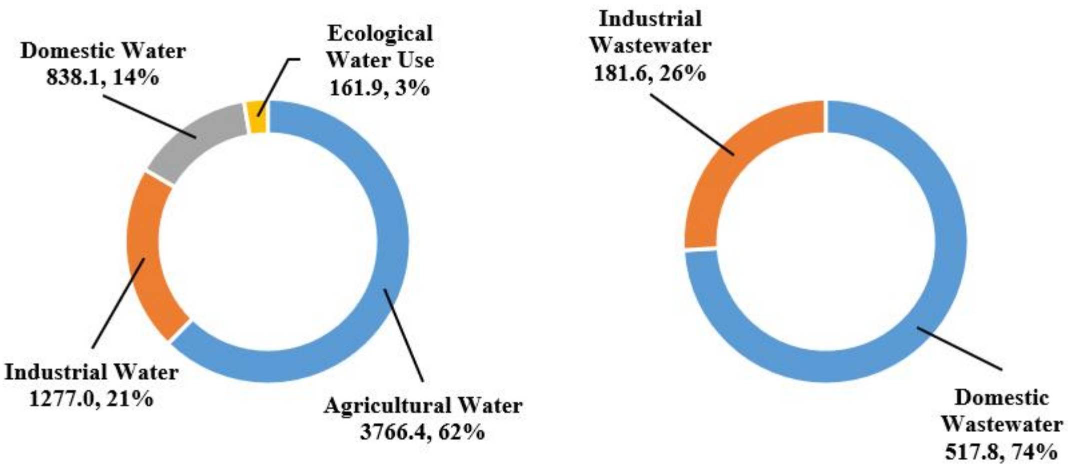

Fig. 2 The condition of water use and wastewater discharge in China (Unit: billion m^3; billion tons)

In the early scientific research and practice of water resources management, it is believed that the total amount of water consumption and pollution is the sum of various independent water demand and pollution activities. Only a few people realize that water consumption and pollution are profoundly affected by the organization way and characteristics of production and supply chain, and associated with the product of final consumption. In order to solve this important problem, Dutch scholar *Hoekstra* proposed a new water resources occupation assessment indicator (water footprint) in 2002 [5]. It is used to study how to reduce water resources consumption and pollution to achieve sustainable utilization of water resources. This paper reviewed the progress of water footprint research in materials industry including related theory, method and application, Firstly, the basic concept of water footprint was introduced, and then the current accounting and assessment methods of water footprint and their applicable fields were summarized. Finally, on the basis of systematically combed the research progress of water footprint at home and abroad, the paper put forward suggestions and prospects for water footprint research.

Definition of Water Footprint

Water footprint is a water use indicator related to consumer goods. Its concept uses the thought of ecological footprint to describe the demand for freshwater resources by human activities through the intervention of virtual water concept [6]. Since the introduction of the water footprint, different scholars and research institutions have proposed the definition of water footprint from different angles [7-10].

Although different scholars do not define the water footprint exactly the same, the core content all for the total amount of freshwater resources consumed by products and services that is consumed by any known population (individual, regional, national or global) for a certain period. The products and services referred to here and include the food, daily necessities, domestic and environmental water necessary for people's lives, and the invisible water they consume in the production process (that is "virtual water"). Until *the International Organization for Standardization* released the *ISO 14046* standard in 2014, and unified the concept of water footprint. The standard defined the water footprint as an indicator for quantifying the potential environmental impact associated with water, which is embodied in the comprehensive environmental impact of changes in water quantity and quality [11]. China converted the standard equally into *GB/T 33859-2017* in 2017.

Accounting Methods of Water Footprint

The water footprint accounting object can not only be the water footprint of a particular process in the production chain, or the water footprint of the final product, but also be the water footprint of consumers, products or an economic sector. In addition, the water footprint in the study area of different spatial scales, such as a basin, city-region, province, country or globe, can still be analyzed from a geographical perspective. At present, the internationally accepted accounting methods of water footprint can be divided into the "top-down" and the "bottom-up" method [12].

(1) The top-down method is based on the theory of consumption balance, which calculates the water footprint from the angle of product production, that is equal to the internal water footprint plus imported virtual water, and then subtract exported virtual water. The calculation results can reflect the dependent degree of the study area on external water resources, but detailed import and export trade volume data is needed. Despite the trade volume data is difficult to obtain, it can be estimated by the multi-regional input-output method (MRIO). The MRIO method can comprehensively reflect the virtual water input-output situation between economic sectors in the region, and also distinguish the virtual water intensity of the same product in different sources, to be able to improve the accuracy of estimation. Moreover, without the need for inter-regional product flow data of sub-regional and sub-sector, the impact of production technology and trade patterns on virtual water can also be distinguished [13].

(2) The bottom-up method is a calculation method based on the water footprint of consumer group, which calculates the water footprint from the angle of product consumption. It can decompose the water footprint into direct water footprint (use solid water) and indirect water footprint (use virtual water), whereas the indirect water footprint is equal to the consumption of a certain consumer goods multiplied by the virtual water content of the unit product. The calculation results can reflect the impact of the consumption structure on the water footprint, but detailed consumption data is needed. Meanwhile, there are virtual water flows between different regions in the actual calculation process, which makes the difference between the accounting results and actual water resources of the bottom-up method [14].

To sum up, the top-down method is suitable for the water footprint accounting of large-scale or import-export trade administrative units of the region, the country and the world, yet the bottom-up method is applicable to the water footprint research of products and industries that have difficulty in obtaining trade data. However, due to China lack of long-term serial trade and consumption data from different products by regions, both methods have been restricted to some extent in practical applications.

Assessment Methods of Water Footprint

Water footprint assessment is based on water footprint accounting, the key links leading to the shortage and pollution impact of water resources are identified by the analysis of indicators such as water use impact, which provides a scientific reference for promoting the sustainable utilization and management of water resources. At present, there are two main methods for assessing water footprint.

(1) The assessment method of "The Water Footprint Assessment Manual" issued by *the Water Footprint Network Organization* (WFN) [9]. The manual stipulates the assessment methods and steps for blue, green and grey water footprint.

- The blue water footprint refers to consumption of blue water resources (surface and groundwater) along the supply chain of a product.
- The green water footprint refers to consumption of green water resources (rainwater insofar as it does not become run-off).
- The grey water footprint refers to pollution and is defined as the volume of freshwater that is required to assimilate the load of pollutants given natural background concentrations and existing ambient water quality standards.

The main idea of WFN sustainability assessment is to compare the results of water footprint accounting with the amount of available freshwater resources, and then judge the sustainability of water resources. When diving into this issue, however, one will discover that there are many different sorts of questions that one can pose and that there are many complexities involved. Sustainability, for instance, has different dimensions (environmental, social, economic, etc.), impacts can be formulated at different levels (primary, secondary impacts) and the water footprint has different colors (green, blue, grey). Many scholars have paid more and more attention to this issue. *Hoekstra* [15] made for the first time explicit mentioning of the need for a "sustainability assessment" phase after the accounting phase, although at that time it was called "impact assessment". Comparing water footprints to actual water availability and identifying hotspots of scarcity was done for the first time by *Van Oel et al.* [16], *Kampman et al.* [17] and *Chapagain et al.* [8]. The main indicators of WFN sustainability assessment are blue water scarcity (WS_{blue}) and water pollution level (WPL). Here, the WS_{blue} and WPL can be calculated by Eq. (1) and Eq. (2), respectively.

$$WS_{blue} = \frac{\sum WF_{blue}}{WA_{blue}} \quad [-] \tag{1}$$

$$WPL = \frac{\sum WF_{grey}}{R_{act}} \quad [-] \tag{2}$$

where $\sum WF_{blue}$ is the total of blue water footprints in the catchment (volume/time), WA_{blue} is the blue water availability in the catchment (volume/time), $\sum WF_{blue}$ is the total of grey water footprints in the catchment (volume/time), and R_{act} is the actual run-off in the catchment (volume/time).

(2) The assessment method of the international standard *ISO 14046* "Environmental Management-Water Footprint-Principles, Requirements and Guidelines" issued by *the International Organization for Standardization* (ISO) in August 2014 [11]. The standard stipulates the principles, requirements and guidelines for water footprint assessment of product, process or organization based on the view of life cycle assessment (LCA). The method is first divided into two major impact categories based on the water footprint list results: water scarcity (caused by change in water quantity) and water deterioration (caused by change in water quality); then characterize the list

substances to obtain quantitative assessment indicators. *ISO 14046* only stipulates the general process and requirements for water footprint assessment, and does not give a specific characterization calculation method of each class water footprint. The models and methods currently available for assessing water scarcity footprint include user deprivation potential, water scarcity indicator, and water stress indicator. No matter which model and method, it is necessary to clearly calculate the consumption of fresh water. This value can be the fresh water consumption calculated from the water balance diagram, and also the fresh water intake measured on site. However, the fresh water consumption has more uncertainty in the actual calculation process, and most of them are approximate values. Therefore, researchers prefer to use the WFN assessment method for water footprint assessment.

On the whole, the water footprint based on WFN focuses on the "quantity" of water resources use, while the water footprint based on *ISO 14046* pays more attention to the "impact" of water resources use. Although the two assessment methods differ in emphasis and results expression form, since the WFN assessment method only considers the pollutants directly discharged into the water while does not consider the pollutants that affect water quality by discharged into the air or soil, thereby its corresponding grey water footprint is equivalent to part of the water deterioration footprint in ISO. Therefore, there is still a relationship between the two.

Application of Water Footprint

Water Footprint Application Research of Energy Products. *Gu* [18] calculated and assessed the blue and gray water footprint of coal, thermal power and coal-based fuel. The results showed that the water footprint of secondary energy such as thermal power is much higher than the water footprint of primary energy such as coal. The blue and grey water footprint of coal-based fuel per unit energy were 2 to 3 times and 4 to 6 times of that of gasoline/diesel respectively.

Hu et al. [19] calculated the carbon, water and ecological footprint of sodium ion, polysilicon solar and lithium air batteries by means environmental assessment software *Simapro*. It was found that the polysilicon solar battery produced the most environmental pollution during the preparation process, and its footprint value was the highest. The lithium-air battery has the least environmental pollution, and its footprint value has obvious magnitude difference with the other two types of batteries.

Ma et al. [20] assessed the water footprint of coal-based electricity generation in China from 2006 to 2015. The results showed that the national total gray water footprint increased significantly and an opposite trend was observed for blue water footprint from 2006 to 2015. The direct freshwater consumption contributed 63.6% to blue water footprint, whereas indirect water footprint contributed 84% to grey water footprint.

He et al. [21] performed the water footprint calculation method from the perspective of the whole life cycle and calculated the total water footprint and the water purification footprint of *the Xiluodu Hydropower Station*. The analysis found that the largest proportion of the total water footprint is the water consumption during the operation period. The largest proportion of the water purification footprint was the increment in operating water consumption, while the largest proportion of the water footprint in the construction period was the processing water for sandstone aggregate.

Overall, the water footprint accounting of energy products is one of the important contents of water footprint research field in recent years. At present, focusing on the water footprint accounting of energy products such as coal and its derivatives, thermal power, hydropower and solar cells, which can reflect the difference between the whole level for water consumption and industrial wastewater discharge from energy development and product process with other industries, and also warn management department or decision maker to limit and regulate the industries development of high water consumption and pollutants discharge, thereby reducing environmental cost in the process of national or regional economic development. According to the measure principle of water footprint, the quantification of water footprint for energy products is to calculate the water consumption in the whole production process from top to bottom along the production chain and supply chain, and can reflect the characteristics such as product categories, processes and production conditions. However, due to the wide variety of energy products and the complicated production processes, it is difficult to construct an accounting framework for their water footprint, and largely lack of relevant data support also increases the difficulty of accounting. In addition, the process, technology and management of the energy product production process are relatively strong in artificial control, and the potential for water resource saving and pollution reduction is huge. It has great potential and significance for targeted regulation and optimization of water resources utilization and remission of water resources contradiction.

Water Footprint Application Research of Materials Products—Metallic Materials. *Peña et al.* [22] quantified the consumption of blue water footprint in the mining process of copper sulfide and copper oxide ore in the Atacama Desert of northern Chile. The results showed that the blue water footprint of the sulfide ore refining process is 2.4 times higher than that of the oxide ore refining process. In the oxide ore process, the main user of water is the heap-leaching process, with 45% of blue water footprint, and most of the water consumed in the oxide ore process was lost to evaporation.

Gu et al. [23] assessed the water footprint of an iron factory in Eastern China from a life cycle assessment perspective. It was found that the iron factory has a water consumption (blue water) footprint of 2.24×10^7 m^3, including virtual water, and a theoretical water pollution (gray water) footprint of 6.5×10^8 m^3 in 2011.

Ma et al. [24] assessed a life cycle water footprint of China's crude steel production based on the methodology prescribed in the ISO 14046 standard, and discussed the main factors causing the environmental burden. The results showed that the grey water footprint generated during the crude steel production was higher than blue water footprint, and the environmental degradation caused by it mainly came from metal depletion, fossil depletion, respiratory inorganics, global warming, freshwater ecotoxicity, and non-carcinogens. Furthermore, COD, Cr (VI), phosphate, BOD5, Hg, As, nitrogen oxides, particulates, and sulfur dioxide were the key substances for environmental improvements.

Water Footprint Application Research of Materials Products—Nonmetallic Materials. *Hosseinian et al.* [25] proposed a comprehensive model for assessing water footprint of cement production based on the type of energy consumption, transportation and human effects, and analyzed the water footprint of a cement plant located on western Iran. The research showed that the total water footprint in the cement plant accounted for 3.614 million m^3 with 2.126 m^3 water consumption intensity and 0.2 m^3 direct water consumption intensity in 2016, of which virtual water consumption contributed to the 90 percent of the total water footprint value, while the virtual water in fossil energy used in the production process was 9.3 times more than the direct water consumption.

Skouteris et al. [26] based on based on water footprint principles and water pinch analysis techniques, quantified the water footprint of the brick-manufacturing processes and analyzed the water reduction efficiency of the two water recovery schemes, i.e. direct re-use/recycle and water regeneration. The results showed the total water consumption footprint of a brick was determined as 2.02 L, of which blue water was identified as 1.71 L (84.8%) and green water as 0.31 L (15.2%), while the theoretical grey water footprint of a brick was found to be 1.3 L. Furthermore, the analysis found that direct re-use/recycle scheme reduced water consumption by only 15.6%, whereas water regeneration scheme improved the current value by 56.4%.

Gerbens-Leenes et al. [27] assessed blue and grey water footprints of five construction materials: chromium-nickel alloyed steel, unalloyed steel, Portland cement (CEM I), Portland composite cement (CEM II/B) and soda-lime glass. It was found that steel, cement and glass have water footprints dominated by grey water footprints, that were 20–220 times larger than the blue water footprints. For steel, critical pollutants were cadmium, copper and mercury; for cement, these were mercury or cadmium; for glass, suspended solids. Moreover, blue water footprints of steel, cement and glass were mostly related to electricity use.

Water Footprint Application Research of Materials Products—Chemical Materials. *You* [28] conducted accounting and sustainability assessment of the product water footprint in the chlor-alkali product chain. It was found that the caustic soda and PVC in the chlor-alkali product chain have the largest water footprint, and the unsustainable ratio of the two water footprints exceeds 80%. Therefore, in view of the water use process of caustic soda and PVC, a water-saving plan was proposed to improve water resource utilization and management.

Li [29] used the water footprint pinch analysis method to analyze the water-saving process of coal-to-methanol. The research found that when the company was in a water-poor area, the water saving target was higher throughout the life cycle, while when it was in a water-rich area, the water saving goal of the whole process was lower. Furthermore, the step by step linear programming method was used to optimize the water network of the methanol production process. The optimized water network consumed 87 t/h of fresh water and saved 52.2% of fresh water.

Gong et al. [30] assessed the carbon, water and ecological footprint of three typical lithium ion batteries, i.e. $LiFePO_4$/C, $LiFe_{0.98}Mn_{0.02}PO_4$/C and $FeF_3(H_2O)_3$/C, and calculated and analyzed the footprint values of lithium-ion batteries from the elemental and compound levels. The results showed that under the unified functional unit, $LiFe_{0.98}Mn_{0.02}PO_4$/C has the largest footprint values and the largest environmental impact, while the footprint values of $FeF_3(H_2O)_3$/C were the smallest and the greenest among the three batteries.

To sum up, the water footprint research on materials products has increased in recent years. Through the comparative analysis of the water footprint accounting values of different materials products, quantitatively excavated the key factors threatening water resources security, and provided scientific basis for making feasible water resources strategies for water resources security issues such as solving water shortage and water pollution. In addition, by assessing the historical dynamics of water footprint and virtual water trade in different materials product sectors, characterizing the configuration path and consumption condition of water resources, it is helpful to discover the use of water resources hidden behind product consumption, and to clarify the relationship between the water resources use link and real water resources occupation. Although the water footprint research in the materials industry increases day by day, most water footprint accounting studies simplify the accounting methods to different degrees, making the comparability of assessment results of different materials products not strong. At the same time, the scale and structure of product water footprint accounting are significantly affected by raw materials of different production, and the virtual water content of same product from different materials is quite different, while the water footprint accounting of materials industry starts late, and rarely the empirical study on the reference and practice of accounting results. Therefore, it is necessary to carry out systematic accounting of the product water footprint in the materials industry to improve the scientific and accuracy of accounting, thereby lay a solid foundation for the further development of water footprint comprehensive research in the materials industry in China.

Conclusions and Suggestions

The analysis of water footprints not only provides a scientific basis for reducing water use, improving water use efficiency, comprehensively assessing the sustainability, effectiveness, fairness and safety of water resources, and making water resources strategies, but also indicates direction for the planning of industry, regional and national water use policies. Based on the continuous improvement of the research results of water footprint accounting evaluation methods, more and more scholars have begun to pay attention to the research of macro water footprints in industries, regions and countries, and on this basis, put forward new sustainable development strategies for water-saving and water supply. Although water footprint analysis is a scientific and reasonable analytical tool for assessing water use, it still has certain limitations. For example, water footprint research does not take into account economic and social benefits. It only measures the impact of human activities on water resources and water-related environmental impacts, and does not adequately describe the full potential environmental impacts of products and processes, more not a decisive indicator for assessing the pros and cons of the product and the rationality of the process. The accounting method for water footprint inventory analysis is not complete and accurate, and it is difficult to use for small-scale research. In the process of environmental impact assessment, there is no uniform recognized standard for the selection of impact types and characterization models. It is difficult to compare the gray water footprint between countries and it is easy to ignore the pollutants characteristic and the self-purification ability of natural ecosystem, and so on. Combined with the research on water footprint in this paper, the following suggestions and prospects are put forward in order to promote the further research of water footprint.

(1) Studying the comprehensive analysis method of water footprint, based on the further improvement and perfection of the water footprint accounting method, comprehensive contrast analysis with other indicators of relevant environmental impacts, and widely developing research on small-scale areas. It will be a hotspot in water footprint research for a period of the future.

(2) Making full use of the relevant research results of virtual water or water footprint of agricultural and livestock products. On this basis, carry out method research and application promotion on industrial water footprint of high-water consumption products such as building materials, steel, chemical and other materials processing, and strengthen the water footprint assessment and management of these key products to enrich the basic database and application tools for industrial water footprint assessment.

(3) Quantitatively identifying the production and transmission path of uncertainty in the process of water footprint assessment, clarifying the sensitive factors affecting the uncertainty and its regulation pathway, and then improving the reliability and accuracy of the water footprint accounting results, thereby to propose more effective measures of water-saving and emissions-reducing.

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