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Calculation of water footprint of the iron and steel industry: a case study in Eastern China

Yifan Gu [a], Jin Xu [a], Arturo A. Keller [b], Dazhi Yuan [c], Yi Li [a], Bei Zhang [a], Qianting Weng [a], Xiaolei Zhang [d], Ping Deng [e], Hongtao Wang [f, a, *], Fengting Li [a, f]

[a] College of Environmental Science and Engineering, State Key Laboratory of Pollution Control and Resource Reuse, Tongji University, Shanghai 200092, China
[b] Bren School of Environmental Science and Management, University of California, Santa Barbara, CA 93106, United States
[c] Department of Chemistry, Tongji University, Shanghai 200092, China
[d] BaoSteel Engineering and Technology Group Co., Ltd., Shanghai 201900, China
[e] Ningbo Iron and Steel Co., Ltd., Zhejiang 315800, China
[f] Key Laboratory of Yangtze River Water Environment, Ministry of Education, Shanghai 200092, China

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ABSTRACT

China is the largest producer of iron and steel in the world. This heavy industry is characterized by significant water consumption and numerous water-related hazards. In this study, we propose the use of water footprint instead of conventional indicators (fresh water consumption (FWC) per tonne of steel or water consumption (WC) per tonne of steel) for the iron and steel industry. Using an iron factory in Eastern China as an example, we develop a water footprint calculation model that includes direct and virtual water footprints. A system boundary analysis method is then proposed to develop a common and feasible industrial water footprint assessment methodology. Specifically, we analyze the characteristics of the iron and steel industry from a life cycle assessment perspective. A water risk assessment was performed based on the results of the water footprint calculations. The selected 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, indicating that the enterprise poses a serious risk to the water environment. The blue water and gray water footprints are calculated separately to provide more detailed water risk information, instead of adding these two indicators, which has less environmental significance.

1. Introduction

Water and energy are crucial components of steel production (Wolters et al., 2008). China is a major producer of iron and thus contributes to the development of the international iron and steel industry. Table 1 illustrates steel production from 2008 to 2010 (China Industry Economy Yearbook, 2012) for key countries. In 2004, the water consumption (WC) of the iron and steel industry in China was 4×10^9 m^3, which accounted for 10% of the annual industrial WC (Hao, 2004). The iron and steel industry can significantly affect local water environments via wastewater discharge. This wastewater can contain a wide range of toxic pollutants, such as dissolved metals including Cd, petroleum-derived products, volatile phenol, arsenic, etc. (Mortier et al., 2007). Therefore, the iron and steel industry significant impacts local, regional and global water resources and faces high water risk. Currently, the iron and steel industry uses *fresh water consumption (FWC) per tonne of steel*, *WC per tonne of steel*, and other indicators. FWC per tonne of steel denotes the fresh water used in the production of 1 tonne of iron and steel. The term "fresh water" is used to refer to fresh tap water, groundwater, or surface water added to the water system of an iron and steel factory, excluding the circulating water for cooling. *WC per tonne of steel* denotes all the water used in the production of 1 tonne of iron and steel, including recycled and reclaimed water.

Abbreviations: WF, water footprint; FWC, fresh water consumption; WC, water consumption; LCA, life cycle assessment; COD, chemical oxygen demand; BOD, biochemical oxygen demand; TN, total nitrogen; GB, Chinese national standard.

* Corresponding author. Key Laboratory of Yangtze River Water Environment, Ministry of Education. College of Environmental Science and Engineering, State Key Laboratory of Pollution Control and Resource Reuse, Tongji University, Shanghai 200092, China. Tel.: +86 21 65980567.
E-mail address: hongtao@tongji.edu.cn (H. Wang).

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Table 1
Global steel production from 2008 to 2010 (unit: 10^6 tonne).

Year	First	Second	Third	Fourth	Fifth
2008	China	Japan	America	Russia	India
	512.3	118.7	91.3	68.5	55.1
2009	China	Japan	Russia	America	India
	567.8	87.5	59.9	58.1	56.6
2010	China	Japan	America	Russia	India
	626.7	109.6	80.6	67.0	66.9

(Chinese Bureau of Statistics Industrial Division, 2012).

FWC and WC are relatively simple and practical. However, they only reflect the direct WC of the iron and steel industry and ignore virtual WC and wastewater pollution. The concept of virtual water was introduced by Allan (1998), and refers to the water needed to produce the inputs for the current process (Verma et al., 2009). For example, the water needed to generate electricity for the steel mill would be considered virtual water for this enterprise. Gao et al. (2011) applied substance flow analysis to establish an evaluation index for the water use systems of steel enterprises. The index system includes WC per tonne of steel, FWC per tonne of steel, recycled WC per tonne of steel, and water losses per tonne of steel. This index is used to evaluate the water use status of large steel enterprises in China and to identify the problems in current WC. However, this method does not consider the influence of virtual water on energy expenditures and other production expenditures (from the supply chain) and disregards the environmental influences generated by wastewater discharge. Thus, a comprehensive indicator must be established to assess the pressure on the water resources and water risk of the iron and steel industry.

Hoekstra (2002) proposed the water footprint concept, which refers to the sum of WC and the net virtual water inputs, which can be evaluated at various scales, from a single process, a factory, an industrial sector, national and regional. In Hoekstra's study, the water footprint concept was proposed as a measure of the global water resource appropriation of various regions. Water footprint is important in underpinning strategies and activities aimed at reducing pressure on water resources because this measure can more accurately reflect the impact of human activities on regional water resources. Ridoutt and Pfister (2010) proposed the reduction of human water footprint to relieve pressure on water resources. With the progression of water footprint methodology research, the water footprint method can now be implemented for the analysis of production processes and services. Water footprint includes blue water footprint, green water footprint, and gray water footprint (Gerbens-Leenes et al., 2009a,b). Green water footprint refers to rainwater that has been consumed directly on the landscape, for example by agricultural production. Blue water footprint refers to surface water and groundwater that are withdrawn from the environment for human uses. Gray water footprint refers to the theoretical amount of water required to dilute pollutants that have been discharged into the natural water system such that the quality of ambient water remains above the relevant water quality objectives (e.g. standards). In many cases, wastewater treatment can significantly reduce the actual water needed to meet the objectives. Gray water footprint is used as an indicator of water quality.

In contrast to WC, the total water footprint includes direct WC and virtual water, as well as its influence on water quality. With the development of water footprint methodologies by the life cycle assessment (LCA) community, an LCA-based water footprint can be utilized to assess the effects of products or businesses on aquatic environments during the product life cycle (Boulay et al., 2013; Jeswani and Azapagic, 2011).

Currently, most studies focus on regional and agricultural water footprints (Chiu and Wu, 2012; Feng et al., 2012; Ge et al., 2011; Liu et al., 2012; Mekonnen and Hoekstra, 2012; Zhang et al., 2012), while the calculation of industrial product water footprint is still in its early stages (Berger et al., 2012; Shao and Chen, 2013). Water footprint methodologies exhibit some drawbacks that impede industrial water footprint assessments (Gu et al., 2014a). The simple numerical sum of gray, blue (direct and virtual), and green water is not environmentally informative for manufacturers (Gu et al., 2014b; Pfister and Ridoutt, 2014). Green water cannot be generally used by industrial facilities unless they implement a rainwater harvesting system. Virtual water may be consumed far away from the industrial facility, with no direct impact on local water resources. Thus, adding these footprints generates values that don't have a clear environmental impact.

Energy and water sustainability are inextricably intertwined in the industry. Thus, the nexus between energy and water has generated great research interest in recent years (Chiu et al., 2009; Gerbens-Leenes et al., 2009a; Herath et al., 2011; Scown et al., 2011). However, the water footprint of energy consumption in the production process is still difficult to calculate because the amount of water resources used varies according to different areas and different energy-producing methods. In addition, LCA-based water footprints, which consider WC and water pollution in the whole product life cycle, are difficult to calculate because of limited data availability. In the present work, we aim to develop a common and feasible industry water footprint assessment methodology for water management and cleaner production.

This study uses an iron and steel factory in Eastern China as an example of a water footprint analysis of the iron and steel industry. The analysis includes the validation of the footprint method and model, the assessment of the virtual WC for energy, and the consideration of water footprint and industry water risks (risk of limitations in water supply quantity and risk of water contamination). As opposed to FWC per tonne of steel or WC per tonne of steel, the water footprints are proposed as indicators of water impact for the iron and steel industry because they comprehensively evaluate water risk factors and are much better indicators for attaining a cleaner and sustainable production. In terms of methodology, we build a feasible system boundary for research based on the LCA perspective. The blue water and gray water footprints are calculated separately to show the detailed water risk information instead of their simple numerical sum. Thus far, only a few cases of water footprint assessment have been conducted in China, especially in the heavy industry (Hoekstra et al., 2012). The present work is expected to contribute to the development of industrial water footprint assessment methodologies.

2. Materials and methods

2.1. Overall system analysis

Two methods can be used to calculate water footprint: the chain summation approach and the stepwise accumulative approach (Herath et al., 2011; WWF-UK, 2009). The chain summation approach is primarily used for production systems with only one product output. The water footprint associated with the various steps in the production system can be entirely attributed to the product that results from a system. The stepwise accumulative approach is a general water footprint calculation method based on the water footprint of the final steps in the production of final and necessary products and on the water footprint calculation in the processing steps. The production chain of the iron and steel industry is complex and includes ore smelting refining, continuous casting, rolling, and other processes carried out in numerous workshops with extensive water and energy consumption in every link. Fig. 1 shows the iron and steel production processes. The water