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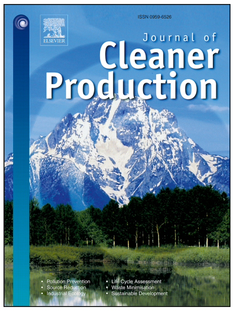

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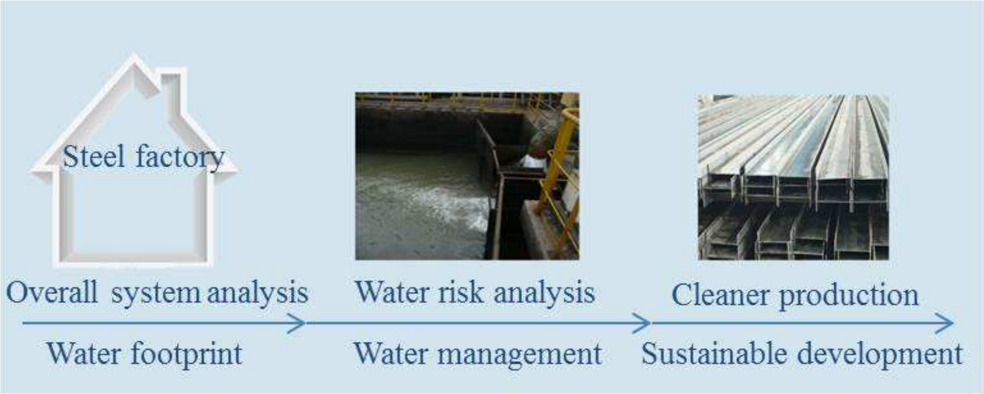
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Calculation of water footprint of the iron and steel industry: A case study in Eastern China

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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

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.

Keywords: Water footprint assessment, Iron and steel industry, Life cycle assessment, Water risk, Cleaner production

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 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. 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.

Table 1. Global steel production from 2008 to 2010.

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., 2009). 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 rain water 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., 2012b). 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. Figure 1 shows the iron and steel production processes. The water discharged by each workshop undergoes substantial recovery or flows into other production workshops. Most large iron and steel factories have their own wastewater treatment facilities. Both footprinting methods require detailed information and an extensive amount of supporting data, which may be confidential, especially in the heavy industry. This makes it difficult to calculate the industry's water footprint and promote better water management practices.

In this work, an overall system analysis is performed to assess water footprint. In the process of calculating the water footprint, we consider direct WC, energy consumption, and local water environmental effects, to better understand the effects of the iron and steel industry on water resources. This method is mainly focused on the water footprint of the production process in the selected factory and therefore does not require long-term analysis and an extensive amount of data. Given these features, the proposed method can be applied in other industries.

FIGURE 1. Iron and steel production processes.

2.1. Research range and determination of system boundary

The life cycle of the iron and steel industry includes raw material extraction (mainly iron ore and coal), iron and steel production processes, steel product consumption, recycling, and transportation. Thus, life cycle-based water footprints can be utilized to assess the effects of products or businesses on aquatic environments during the whole product or business life cycle. However, the water footprints of some inputs (e.g., raw materials and supply chain) upstream of steel production are difficult to obtain for enterprises. In addition, the extraction and transportation of raw materials can be very different depending on the sources and are typically not well documented, and the consumption of iron and steel products varies dramatically depending on the end use (e.g. buildings, pipes, automobiles, and appliances). Finally, the water used in the installation and decommissioning of the steel mill is not typically tracked, so there is no data available for this aspect. Given the multi-decade life of most steel mills, this is likely a small fraction of the overall water footprint, and thus it is not considered here. Figure 2 illustrates the research boundary (the object of the study is in solid lines). The production processes are utilized as the main body, which is the most important part that manufacturers should consider when they decide to alleviate water risk, in industrial water footprint assessments. Thus, we focus on the water footprint assessment in the production process of a steel enterprise.

FIGURE 2. System boundary of the research on the calculation of water footprint of the iron and steel industry.

2.3. Research model

From the water footprint calculation model, the following formula is obtained:

$$WCF = DWF + VWF, \tag{1}$$

where WCF is the water consumption footprint, DWF is the direct water footprint, and VWF is the virtual water footprint. Here,

$$DWF = WF_{obtained} - WF_{D\text{-}discharge} - WF_{loss}, \tag{2}$$

where $WF_{obtained}$ is the amount of water obtained, $WF_{D\text{-}discharge}$ is the amount of direct water discharge, and WF_{loss} is the water loss caused by evaporation, infiltration, and by-products.

The virtual water footprint calculation for a steel mill is complex because it requires knowledge and accounting of water used in production of inputs, domestic (i.e. staff) WC, internal electric power consumption, transportation energy, and chemicals (mainly for the treatment of circulating cooling water corrosion, scale inhibitors, flocculent for sludge dewatering, etc.). By referring to steelworks investigations, the WC for production and domestic use is relatively easy to obtain. First-hand data on power consumption, coal consumption, and oil consumption are collected to calculate power consumption for steelworks. The virtual water embodied in electricity generation in China is based on Zhang et al. (Zhang and Anadon, 2013). They studied the life cycle water withdrawals, consumptive water use, and wastewater discharge of China's regional energy sectors by using a mixed-unit multiregional input-output (MRIO) model. All of these parameters have a considerable amount of variability, depending on the specific technologies and processes, the source of the primary energy carrier, and even temporal considerations.

Another important aspect is the gray water footprint, which refers to the theoretical volume of freshwater required to assimilate the load of pollutants to natural background concentrations or existing ambient water quality standards. The gray water footprint includes domestic sewage management and industrial sewage management. In the calculation of the water footprint of domestic sewage, chemical oxygen demand (COD) and other indexes are measured, and the amount of diluted water is calculated based on the *Environmental Quality Standards for Surface Water* (*GB3838-2002*) (Ministry of Environmental Protection of the People's Republic of China, 2002) or the *Seawater Quality Standard* (*GB3097-1997*) (Ministry of Environmental Protection of the People's

Republic of China, 1997). In the calculation of the gray water footprint of industrial sewage, sewage from different workshops is collected and treated before being discharged. The amount of dilution water needed (Y_i) is based on meeting the *Environmental Quality Standards for Surface Water* (*GB3838-2002*) (Ministry of Environmental Protection of the People's Republic of China, 2002)or the *Seawater Quality Standard* (*GB3097-1997*) (Ministry of Environmental Protection of the People's Republic of China, 1997). Y_i is calculated using Eq. (4).

$$Y_i = \frac{X_i}{Q_i}. \tag{4}$$

where Q_i is the water quality standard of the wastewater discharge for pollutant *i*, and X_i is the measured average value of pollutant concentration of the sewage samples. MAX [Y_i] is the final gray water footprint. Eqs. (1)–(4) are used to calculate the water footprint of steelworks.

2.4 *Water risk assessment based on water footprint*

Enterprise water risk contains physical risk, regulatory risk and reputation risk (Stuart Orr, 2009; Stuart Orr, 2011). Among the three risks, physical risk is closer to water footprint. Physical risk is the direct risk of water resources. When there are water shortages or water is seriously polluted, enterprises may face physical risk, which consists of water quantity risk and water quality risk. In water risk assessment, water footprint is a useful tool, and three major parts are involved: water footprint calculation, water risk assessment and water risk management. Analyzing the water footprint of the whole enterprise and every production process can provide all the information for effective and more sustainable water resources management. Furthermore, enterprises can take management actions based on the results of water risk assessment

3. Results and discussion

3.1. Water footprint of an iron and steel factory

A steelworks enterprise in Eastern China was used as an example in this study. This enterprise offers a complete raw material production process for iron making, steel making, continuous casting, steel rolling and other processes using advanced equipment. In 2011, the enterprise produced 4.46×10^6 tonnes of steel. According to the overall system analysis method, the DWF of the enterprise in 2011 was 1.46×10^6 m^3 within 5% error, considering a 10% water loss as estimated by the engineer in this factory. This means 90% if the water is consumed in the enterprise.

The production process of the selected enterprise is complex. Up to 20 different chemicals, such as corrosion and scale inhibitors, are incorporated into various processes. The enterprise annually uses 4.82×10^7 tonnes of chemicals. 90% are solid with no direct water footprint; the water used in the process for the other chemical was considered in the DWF. The virtual water of these chemicals could not be assessed due to limited data availability, but is likely to be much smaller than DWF.

Table 2 shows the energy consumption and water footprint of the various sources of energy in 2011, for the case study factory. The water footprint of electricity was 1.98×10^7 m^3 in 2011. During the same year, the water footprints of coal and hard coke were 78.3×10^4 m^3 and 191.4×10^4 m^3, respectively. Therefore, the total virtual WC for energy was 2.25×10^7 m^3 in 2011, which is more than an order of magnitude greater than the DWF.

Table 2. Energy consumption and energy water footprint of the case factory

The applicable water quality standard for the selected enterprise is the *Integrated Wastewater Discharge Standard* (*GB 8978-1996*) (Ministry of Environmental Protection of the People's Republic of China, 1996) Class II. Table 3 presents the measured water quality in the discharge and the corresponding dilution factors. The amount of domestic water discharged by the staff that live in this factory is 4.35×10^4 m^3. As shown in Table 3, the maximum dilution factor of is 50. The gray water footprint of domestic water prior to wastewater treatment use is 2.17×10^6 m^3.

Table 3. Average case steelmaker effluent concentrations, water quality standard of integrated wastewater discharge and dilution ratio needed.

The sewage from the steelworks is sent to the regional sewage treatment plant, and the treated effluent is discharged to the East China Sea. The East China Sea is regulated according to the fourth level marine water quality standard. Based on the *Seawater Quality Standard* (*GB 3079-1997*) (Ministry of Environmental Protection of the People's Republic of China, 1997) and water quality of the sewage treatment plant effluent, the maximum dilution factor is calculated to be 106. In 2011, the amount of treated effluent discharged by the selected steelwork enterprise was 6.10×10^6 m^3. During this period, the gray water footprints of industrial sewage were 6.46×10^8 m^3. Thus, the total gray water footprint is 6.5×10^8 m^3.

Table 4. Average treated effluent concentrations in case study steelmaker region, seawater quality standard and dilution ratio needed.

Figure 3 shows the various elements of the total water footprint of this steelmaker. In most studies, the results of the water footprint assessment of a product or a business are usually shown as the total water footprint determined by the sum of the green water footprint, blue water footprint, and gray water footprint. However, the combination of a hypothetical "pollution volume" (gray water) with WC volumes (blue water) for total water footprint is considered to have no environmental meaning. In this study, the total WC footprint (blue water footprint) and water pollution footprint (gray water footprint) are calculated separately to show the detailed water risk information instead of the sum. For the selected steelworks enterprise, the total WC (blue water) footprint is 2.44×10^7 m^3 and total water pollution (gray water) footprint is 6.5×10^8 m^3. The high power consumption of the steelworks enterprise results in large virtual WC. The high gray water footprint indicates that the enterprise poses a serious risk to the water environment.

FIGURE 3. Total water footprint of steelworks enterprise in 2011.

Generalizing the results of this study, it is estimated that the water footprint of iron and steel industry in China was approximately 4×10^9 m^3 in 2010, considering China's steel production in 2010. Ge et al. (2011) estimated that the total water footprint of China is 860×10^9 m^3 and the per capita water footprint was 650 m^3/year in 2007. It means that the iron and steel industry sector accounts for about 0.4% of the total water footprint. It appears that the water footprint intensity of iron and steel industry is significant compared with other water related industries. It confirms the necessity of this study to calculate the water footprint of a specific iron and steel industry treatment plant.

In addition, iron and steel are very important as raw materials for the manufacturing industry. Berger et al. (Berger et al., 2012) showed that steel and iron materials contribute almost 35−40% to the total water consumption of Volkswagen's Golf car models. Thus, reducing water footprint of the iron and steel industry will greatly reduce the industrial water footprint of many products in China and around the world.

The iron and steel industry not only has a significant water consumption, but also poses significant water-related hazards. The gray water footprint of the selected steelworks enterprise is nearly 27 times total WC (blue water) footprint. In contrast, for the global animal production the gray water footprint is only 1.06

times blue water footprint (87.2% green water footprint, 6.2% blue water footprint and 6.6% grey water footprint) (Mekonnen and Hoekstra, 2012). The reason attributed to the disparity of ratios of gray water footprint to blue water footprint is the high-concentration of specific industrial wastewater discharged from the steelworks enterprise.

3.2. Comparison of the three indicators of water consumption

Large amounts of water are used for steel production processes. The quality of wastewater discharged by the iron and steel enterprise in Table 3 shows that its wastewater can have a negative impact on the local water environment if it is not treated adequately. Thus, the iron and steel industry poses risks of decreased water supply and water contamination. Other inputs (raw materials from the supply chain and energy) are also extensively consumed.

Compared to FWC and WC, the water footprint estimate has more uncertainties. The total water footprint not only considers the water footprint of the enterprise itself but also takes into account the water footprint of the external supply chain. As shown in this case study, the virtual water footprint can be much greater than DWF. While it is challenging to assess the virtual water footprint, it is important to consider the most relevant input and their water footprint, such as energy in this case. As more information becomes available on the water footprint of the supply chain, better estimates of overall blue water footprint (=DWF + virtual water of energy + virtual water of other inputs) will lead to enhanced decision making and water risk management.

FIGURE 4. From water footprint to water risk analysis.

Figure 4 shows the relationship between water footprint and water risk analysis. Virtual water footprint of the supply chain, including extraction and transport of iron ores, reflects the water risk of the supply chain and is thus significant for the sustainable development of the iron and steel industry. The virtual water footprint of energy consumption can reflect the risk of energy consumption. Based on the virtual water footprint of the supply chain, the iron and steel industry can choose suppliers of chemicals, energy and other major inputs that are proven to be committed to sustainable development and to the protection of the environment by reducing their blue and gray water footprints.

Wastewater from the iron and steel industry is difficult to treat. Although most factories have their own wastewater treatment systems, the effluent discharged into the local water environment can have negative impacts. The total water pollution footprint (gray water footprint) of the selected steelworks enterprise is nearly 27 times of the total WC footprint (blue water footprint), thus showing the significant impact on the local water environment. It is imperative to upgrade the enterprise's internal wastewater treatment to reduce the gray water footprint or even to achieve zero-discharge. The gray water footprint of the iron and steel industry can reflect the risk of water pollution that otherwise cannot be revealed by FWC and WC.

Unlike FWC and WC, water footprint can comprehensively evaluate the water risk of the iron and steel industry and is helpful for water resource management. Analyzing the water footprint can provide managers a better knowledge of the enterprise water resources use, and thus reduce risks. Through this analysis, enterprise can take actions for better water resources management, such as green production design, water system management, supply chain management and wastewater management. The purpose of all these analyses is to reduce the water footprints of the enterprise, to eventually reach sustainable development.

The water supply risk for the industry could be evaluated considering the magnitude of overall water supply in the region around the steelmaker, and then determining the fraction that the steelmaker requires. It's reported that the amount of blue water (surface water and groundwater) in the city where the iron and steel enterprise used in this study is located is 61×10^{8} m^{3} in 2011 (Zhejiang Provincial Water Resources Bureau, 2011). Thus, the direct blue water footprint of case factory only accounts for 0.02% of local blue water footprint, indicating that the water supply risk of this factory is not very high considering the locally abundant water resources. The pollution risk considers the amount of water needed for dilution compared to the mean low flow rate in the region. It's reported that the surface flow in the city is 59×10^{8} m^{3} in 2011(Zhejiang Provincial Water Resources Bureau, 2011). The gray water footprint of the case study factory accounts for 11% of total surface flow in the region, indicating a very high pollution risk. Therefore, the case factory must take more action to reduce its gray water footprint.

3.3. Recommendations

Water resources can limit the development of the iron and steel industry, among other factors. Iron and steel industry enterprises in China should consider their reputation when consuming water resources. From the case study, it is clear that reducing the virtual water footprint is key to reducing the blue water footprint, particularly from electricity consumption. Emphasis should be placed on energy efficiency measures, as well as source energy from more water-efficient suppliers. In addition, using new energy resources such as wind power to reduce the energy costs of water footprints is recommended.

Although the enterprises' discharge of sewage is within the national requirements, it still does not satisfy the *Sea Water Quality Standard* (*GB3097-1997*) (Ministry of Environmental Protection of the People's Republic of China, 1997). Sewage discharge that contains high concentrations of pollutants is not considered part of the direct water footprint of an enterprise. However, this type of sewage discharge requires large amounts of water to be diluted to natural water. Gray water footprint accounts for a large portion of the total water footprint. Therefore, the potential threat of gray water footprint cannot be disregarded. If enterprises can improve sewage treatment efficiency, their gray water footprint can be reduced significantly. A detailed analysis of the factors that increase the gray water footprint (e.g NH_3-N and TN in this case study) can lead to optimize the wastewater treatment or industrial processes. The steel makers may invest in internal wastewater treatment to reduce the very large gray water footprint.

Chemicals with small water footprints should be chosen for obvious reasons. For example, some corrosion scale inhibitors with phosphorus used will cause phosphates. Reducing gray water footprint requires the use of environment-friendly chemicals. For water treatment, factories can choose green agents such as corrosion scale inhibitors without phosphorus.

To reduce direct WC, the iron and steel industry should improve the efficiency of their production processes such as internal recycling and treatment of cooling water or using more advanced equipment. Rainwater harvesting and utilization are also recommended for other factories. Water system management needs to be improved to reduce the freshwater use.

Water footprint may be a more reliable and efficient indicator than FWC per tonne of steel or WC per tonne of steel for the iron and steel industry because of its comprehensiveness. Considering the fact that China is facing a critical water crisis, the water footprint evaluation of its iron and steel industry is useful in conserving scarce water resources. Water footprint assessment is in accordance with water risk assessment, and the proper management of water footprint can reduce water-related hazards. To reduce wastewater discharge and gray water footprint in the iron and steel industry, enterprises and supply chain manufacturers should conduct advanced wastewater treatment and promote reuse.

4. Uncertainty analysis

Uncertainties result from the assumptions to establish the research range and system boundary. Calculating the water footprint extraction and transport processes of raw materials is complicated by lack of data and multitude of sources. The consumption of iron and steel products also varies remarkably. In this study, we focus our calculation of the water footprint on iron and steel production processes and disregard the water footprints of raw materials and product consumption processes. Although efforts have been made to provide high-quality direct and virtual water consumption data, limitations occur due to the lack of reliable data. In this study, the primary data on the water intake, wastewater discharge, and energy consumption of the selected enterprise are accurately obtained from the company's statistical data, within 5%.

There are uncertainties from the calculation of the energy water footprint. The energy sector is the second largest water user in the world in terms of withdrawals, following irrigation (Hightower and Pierce, 2008). There is a large variability in the water needed even for the same primary energy, depending on the specific technologies and processes, the source of the primary energy carrier, and even temporal considerations (Fthenakis and Kim, 2010; Keller et al., 2010). In the calculation of the energy water footprint, the conversion coefficients are cited from related research (Zhang and Anadon, 2013) in China, considering the water footprint of energy consumption varies according to different areas. That study assesses the water use in energy production section on province and national scale in China. The data sets can be used for water footprint calculations but may underrepresent the real virtual water consumption embodied in energy in this factory. Thus, uncertainties exist in the final results. Herein, the range of uncertainties of energy water footprint is qualified in Table 2. The water footprints of electricity, coal, and hard coke are in the ranges of 82-7,700×10^4 m^3, 0-220×10^4 m^3, and 0-420×10^4 m^3, respectively, based on Zhang et al. (Zhang and Anadon, 2013).

5. Sensitivity analysis

A sensitivity analysis was conducted to understand how parameter variability affect the results and to identify parameters that are critical for quantifying the water footprint of the iron and steel industry. The water footprint for energy consumption accounts for a large portion of the total WC footprint (92 %). The parameters used in the energy water footprint analysis include electric power, coal, and hard coke. Electric power is the most sensitive factor because it is consumed by the selected enterprise in large amounts. Thus, having high quality information on the water footprint of local or regional electricity generators will significantly reduce the uncertainty in virtual water footprint estimates.

For the gray water footprint assessment, the discharged water quality is the most sensitive factor because gray water footprint is classified as the 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 established water quality standards. It is important for the enterprise to collect accurate water quality data and discharge flows to better estimate the gray water footprint.

6. Conclusion

For the selected iron and steel factory the blue water (total WC) footprint was 2.44×10^7 m^3 and the gray water footprint was 6.5×10^8 m^3 in 2011. As opposed to FWC per tonne of steel or WC per tonne of steel, water footprint should be promoted as an indicator for the iron and steel industry because it can reflect the industry's actual WC and water risks. In this way, water efficiency can be improved. Reduction in the water footprint of the iron and steel industry can result in cleaner production.

The system boundary analysis method is proposed in this work to develop a common and feasible industry water footprint assessment methodology. The blue water (total WC) footprint and the gray water (water pollution) footprint are calculated separately to better understand the different water risks instead of the simple numerical sum of the two footprints. This leads to specific recommendations for reducing the risks. This work is expected to contribute to the development of industrial water footprint assessment methodologies.

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LIST OF TABLE

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. China industry economy yearbook (Ed.). China financial economic publishing house. (in Chinese))

Table 2. Energy consumption and energy water footprint of the case factory

Energy type	Energy consumption	Direct water withdrawal intensity at provincial level[a]	National average direct water withdrawal intensity[a]	Energy water footprint range (10^4 m^3)	Average energy water footprint (10^4 m^3)
electricity	1275 GWh	0.64-60.14 m^3/MWh	15.50 m^3/MWh	82-7668	1976
Coal	206.1×10^4 tonne	0-1.07 m^3/tonne	0.38 m^3/tonne	0-221	78
Coke	185.8×10^4 tonne	0-2.24 m^3/tonne	1.03 m^3/tonne	0-416	191
total	-		-		2246

[a] Zhang, C., Anadon, L.D., 2013. Life Cycle Water Use of Energy Production and Its Environmental Impacts in China. Environmental Science & Technology 47, 14459-14467

Table 3. Average case steelmaker effluent concentrations, water quality standard of integrated wastewater discharge and dilution ratio needed

Indicator	Average concentration (mg/L)[a]	Sea water quality standard (GB3079-1997)[b] Class IV (mg/L)	Dilution ratio
COD	150	5	30
Petroleum	10	0.50	20
Volatile phenol	0.5	0.05	10
NH_3-N	25	0.5	50
Chloride	0.5	0.2	2.5
Zn	5.0	0.5	10
Cr^{6+}	0.5	0.5	1
Cd	0.1	0.01	10
As	0.5	0.5	1
Pb	1.0	0.5	2

COD: chemical oxygen demand. GB: Chinese national standard.

[a] Ministry of Environmental Protection of the People's Republic of China., 1996. Integrated wastewater discharge Standard (GB 8978 -1996). (in Chinese)

[b] Ministry of Environmental Protection of the People's Republic of China, 1997. Sea water quality standard (GB3097-1997) . (in Chinese)

Table 4. Average treated effluent concentrations in case study steelmaker region, seawater quality standard and dilution ratio needed

Indicator	Average concentration (mg/L)	Seawater Quality Standard (GB3079-1997)[a] Class IV (mg/L)	Dilution ratio
COD	323	5	65
BOD_5	182	5	36
TN	52.9	0.5	106

COD: chemical oxygen demand; BOD: biochemical oxygen demand; TN: total nitrogen.

[a] Ministry of Environmental Protection of the People's Republic of China, 1997. Sea water quality standard (GB3097-1997) . (in Chinese)

LIST OF FIGURES

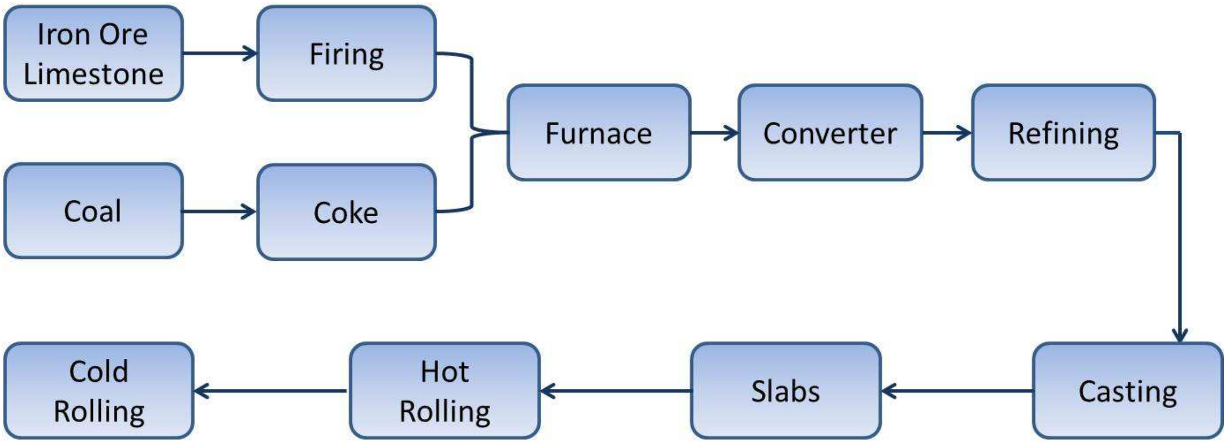

FIGURE 1. Iron and steel production processes.

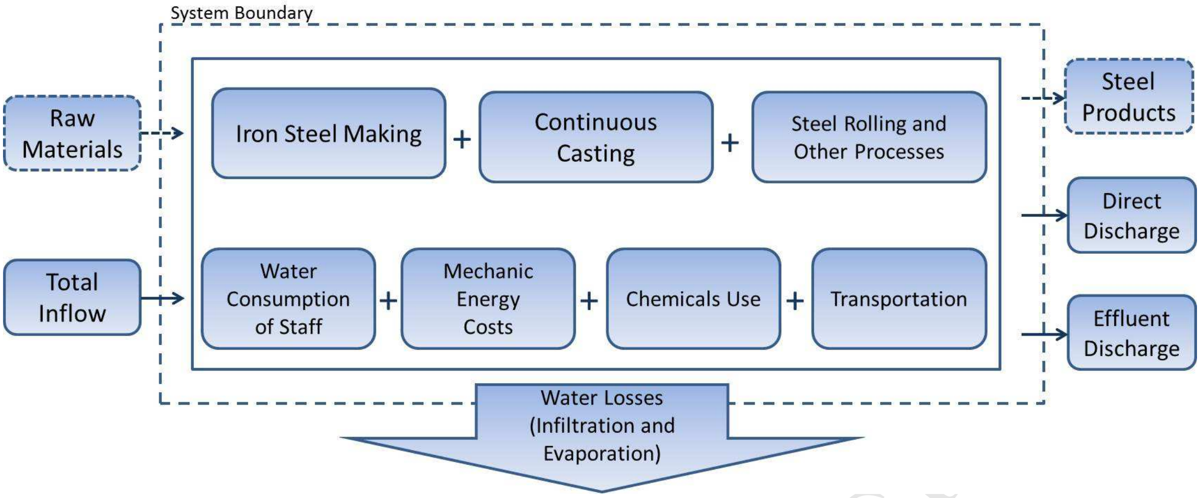

FIGURE 2. System boundary of research on the water footprint calculation of the iron and steel industry.

(Object of study in solid lines)

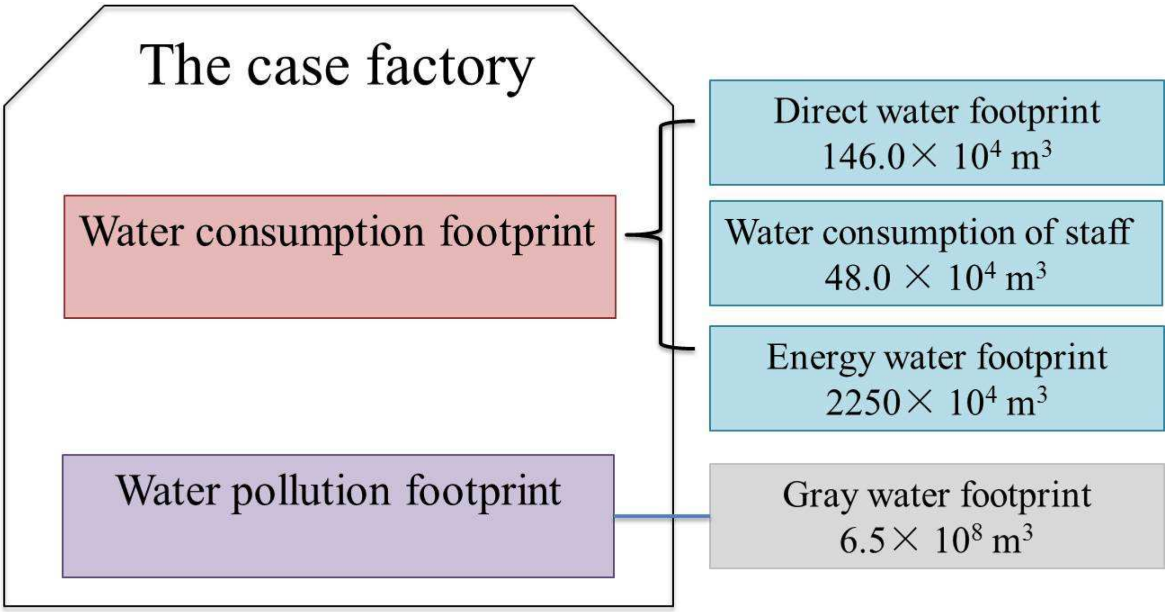

FIGURE 3. Water footprint of steelworks in 2011.

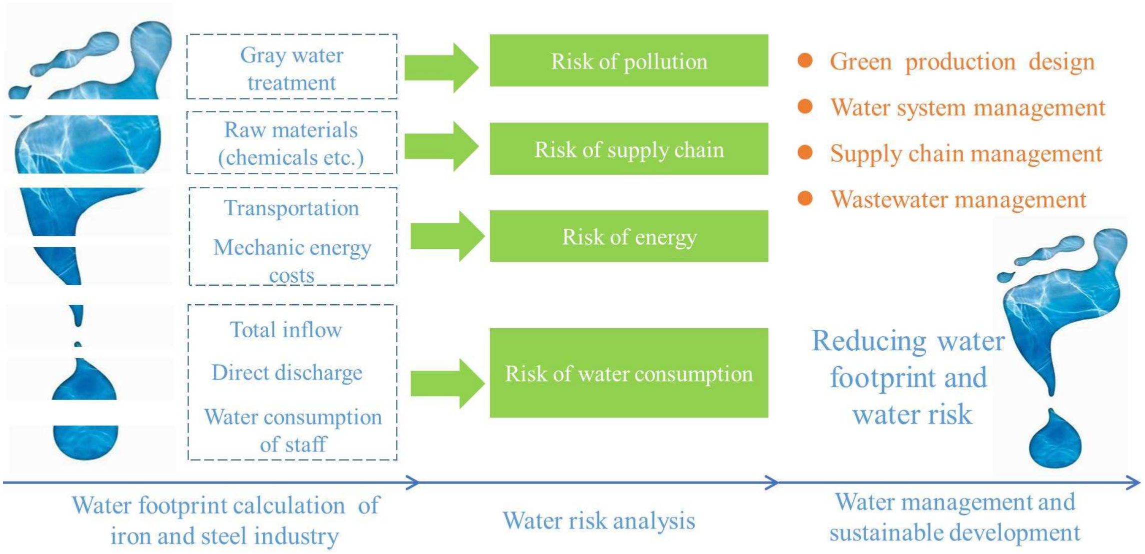

FIGURE 4: From water footprint to water risk analysis.

- We developed an overall system analysis model to evaluate industry water footprint.
- We used a Chinese iron factory as case study and made life cycle assessment.
- We calculated water consumption footprint and water pollution footprint separately.
- Water footprint is more comprehensive than the current indicators of steel industry.
- Water footprint can evaluate the water risk of the iron and steel industry.