Journal of Cleaner Production xxx (2017) 1–9

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Optimal water utilization and allocation in industrial sectors based on water footprint accounting in Dalian City, China

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ARTICLE INFO

Article history:
Received 31 December 2016
Received in revised form
23 March 2017
Accepted 25 November 2017
Available online xxx

Keywords:
Sustainable water utilization
Optimal water allocation
Blue water footprint
Gray water footprint
Water footprint intensity

ABSTRACT

The problem of fresh water scarcity is one of the major constraints for regional development. Rapid urbanization and rising economic prosperity has further exacerbated problems with not only water quantity, but also water quality. Hence, sustainable utilization of water resources should be a priority, especially in water stressed areas. However, most current studies on optimal water allocation models are based on physical water, which cannot fully reveal the water flows embedded in imported and exported raw materials and products throughout all production processes. Thus, they fail to achieve sustainability goals. Therefore, the objective of this study was to set up an optimal water allocation model for industrial sectors based on water footprint accounting. In this paper, first the internal and external blue and gray water footprints were evaluated. The results indicated that the external water footprint was the major contributor to Dalian's water footprint, which shared around 72.58% of the total. Among all the industrial sectors, the chemical industry and chemical production sector had the highest total WF. Second, analyses of water productivity intensity of the WF and physical water for the industrial sectors were conducted. The comparison of the results revealed that physical water productivity intensity failed to explain the embedded water inflows in the production processes among the regions and sectors. Third, an optimization model based on the water footprint accounting results was thus set up. The optimal consequences indicated that a water allocation plan could meet both the water requirements for the blue and gray water footprints of the industrial sectors, and their target output goals as well. Therefore, this optimal allocation model is both rational and applicable for sustainable water utilization in future water management strategy formulations.

1. Introduction

The increasing demand for fresh water is the main challenge to sustainable water utilization all over the world (Zhuo et al., 2016), but is especially severe for developing countries like China. As a country with rapid population growth and economic development, China's total water use has dramatically increased in recent decades (Yang et al., 2016). Consequently, the growth in water consumption not only worsens the shortage in water quantity, but also contributes to severe degradation of the water quality in this country. The poor water quality caused by pollution further exacerbates the lack of water availability, especially in the water-scarce areas of China (Jiang, 2009). This severe water shortage combined with the poor water quality pose a large obstacle to sustainable utilization of water resources in China.

Facts show that one of the fundamental causes of the current water crisis is the increasing scale and intensity of industrial production activities. Therefore, study on the water consumption for industrial activities and products is a significant field of research, which could scientifically reveal the multiple impacts on freshwater resources caused by industrial processes, and improve the sustainable and equitable use of water for industrial activities and products. In addition, understanding the industrial water utilization structure of the economic sectors, in relation to water resource

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https://doi.org/10.1016/j.jclepro.2017.11.203

Please cite this article in press as: Xu, M., et al., Optimal water utilization and allocation in industrial sectors based on water footprint accounting in Dalian City, China, Journal of Cleaner Production (2017), https://doi.org/10.1016/j.jclepro.2017.11.203

flows from production to household consumption, is essential for solving the problems of water availability (White et al., 2015). However, in current studies on regional, sustainable water resources, analyses are predominantly focused on direct water consumption; whereas, attention to intermediate water consumption is lacking. Thus, the relevant previous research is not conducive to the establishment of a scientific, efficient water utilization structure.

Moreover, for the regions that lack adequate water resources, it is difficult to achieve the sustainable utilization using only the regional water supplies. Thus, imported water resources, both physical and virtual water, should be taken into consideration. Virtual water, as proposed by Tony Allan in 1993 (Allan, 2003), refers to the volume of embedded water required to produce a product or service (Deng et al., 2016). In the early 2000s, this concept was extended to a “water footprint” by Hoekstra (Chapagain and Hoekstra, 2007; Hoekstra and Chapagain, 2007; Hoekstra and Hung, 2005; Ma et al., 2006). The water footprint is an indicator of freshwater use that identifies not only the direct water use of a consumer or producer, but also the indirect water use (Ercin et al., 2013). It can be regarded as a comprehensive multidimensional indicator of freshwater consumption volume by source, and polluted volume by type of pollution. The water footprint is typically further analyzed in three parts: the blue, green, and gray water footprints. 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 is the consumption of green water resources (rainwater insofar as it does not become run-off). The gray water footprint 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 (Hoekstra et al., 2011).

The direct and indirect water consumptions for the industrial sectors can be accounted through the water footprint assessment (WFA) methods. The methods adopted mainly fall into two categories: the bottom-up method and the top-down method (Deng et al., 2016). The bottom-up approach is developed via a Life Cycle Assessment (LCA) by implementing water use-related impact categories and inventory methods within LCA studies (Manzardo et al., 2016). This method has been widely applied in the accounting of the virtual water content of industrial production (Bakken et al., 2016; Chang et al., 2016; Han et al., 2016; Kondash and Vengosh, 2015; Lu et al., 2016; Manzardo et al., 2014; Scheepers and Jordaan, 2016; Semmens et al., 2014; Shao and Chen, 2016; Zhang et al., 2014b). The top-down method is based on input-output analysis. This method generally applies input-output tables and water uses to account for both the direct and the intermediate water inputs and outputs for each industrial sector in a region (Bogra et al., 2016; Cazcarro et al., 2013; Deng et al., 2016; Feng et al., 2014; Hoekstra et al., 2016; Konar and Caylor, 2013; Llop, 2013; Loch, 2016; Wang et al., 2013; White et al., 2015; Yang et al., 2016). The former approach is mainly used for the water footprint evaluation of an industrial product or production process. The latter is predominately applied for the water footprint accounting of industrial sectors. Therefore, it is more applicable to use the top-down method for regional water resource allocation when industrial sectors are the main concerns.

In recent years, many studies have been conducted on the assessment of the blue and gray water footprints of regional industry via input-output analysis (Chapagain and Hoekstra, 2007, 2008; Chapagain et al., 2006; Chouchane et al., 2015; de Miguel et al., 2015; Hoekstra and Chapagain, 2007; Mekonnen and Hoekstra, 2011, 2015; Yan et al., 2013; Zhao et al., 2010; Zhi et al., 2015). The follow-up research has primarily been focused on three aspects. First is the spatial or temporal water footprint variation analyses (Cazcarro et al., 2013; Deng et al., 2016; Duan et al., 2016; Gu et al., 2014; Zeng et al., 2012; Zhuo et al., 2016). Second is a regional water scarcity evaluation derived from the water stress index, which is defined as the ratio of the total WF to the total water availability in the local area (Ma et al., 2015; Metulini et al., 2016; Zhao et al., 2015). The third aspect is decomposition analysis of the factors contributing to water footprint changes via a structure decomposition model (Yang et al., 2016; Zhang et al., 2014a; Zhi et al., 2014). Evidently, most of the studies are based on the water footprint accounting methods, and the analytic methods on the accounting results; whereas, further study on water resource allocation based on water footprint accounting is lacking. It should be pointed out that quantification of WF does not provide for supervision of water resource flow in different sectors, consistent with a sustainable water allocation strategy. Only with the assistance of rational and scientific planning of water resource allocation among the various industrial sectors, could the sustainable utilization of water resources be achieved. Thus, the accounting results of the water footprints need to be further utilized in an optimization model to provide water resources planning among the industrial sectors.

Therefore, the objectives for this work were: a) to quantify the blue and gray water footprints in various industrial sectors in the study area; b) to analyze the water productivity intensity for the industrial sectors using water footprint intensity and physical water intensity; and c) to set up an optimization model for water resource allocation planning in various industrial sectors based on the water footprint results. The research outcomes can consequently guide scientific planning of water resource utilization and allocation, thereby helping to relieve the water scarcity in these regions and create a set of water allocation strategy instructions for the study areas.

2. Methodology and material

2.1. Study area

Dalian City (Liaoning Province) is located at the southern tip of Liaodong Peninsula (Fig. 1). It is an important port and tourist city in the north of China, and one of the 14 earliest coastal cities in China

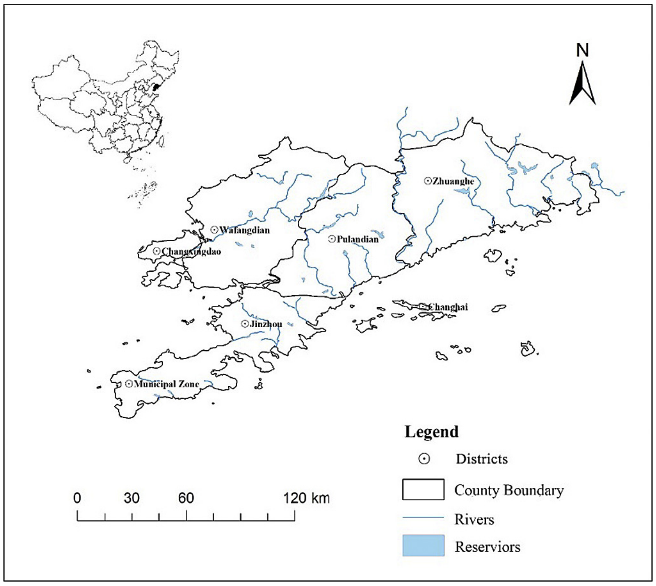

Fig. 1. Location of Dalian city in China.

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