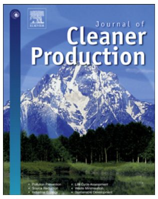
Journal of Cleaner Production 68 (2014) 7–15

Contents lists available at ScienceDirect

Journal of Cleaner Production

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



Virtual water accounting for building: case study for E-town, Beijing

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ARTICLE INFO

Article history:
Received 11 June 2013
Received in revised form
7 November 2013
Accepted 18 December 2013
Available online 28 December 2013

Keywords:
Green building
Virtual water
Hybrid method
Water consumption

ABSTRACT

Virtual water as the overall water consumption of a building includes not only the on-site water use for constructing and operating, but also the off-site water used to supply the necessary manpower, material and equipment inputs required by the building. This paper advances a systematic virtual water accounting framework for building by employing a hybrid method as the combination of both process and input–output analysis. Based on the raw project data in the Bill of Quantities, a detailed case study is performed for the structure engineering of six landmark buildings in E-town, Beijing, supported by the virtual water intensity database for the Chinese economy in 2007. The total virtual water of the case buildings is quantified as 1.25E+06 m^3, corresponding to an intensity of 20.83 m^3 per square meter floor area. On-site tap-water supply, material inputs and manpower inputs contribute to 43.55%, 50.05% and 6.31% of the virtual water, respectively, indicating the fact that off-site water use plays a critical role in balancing the overall water budget of a building.

1. Introduction

With escalating water consumption instigated by the rapidly growing economy as well as increasing population, water scarcity in many regions has become a widely recognized problem and attracts more and more attention in recent years. From the point of urban development, building industry is deemed as a major consumer of water resource (Bardhan, 2011). According to United Nations Environment Program (2006), the building industry induces 30% of fresh water consumption at a global average. As water scarcity seems to expand considerably and Chinese construction industry is growing at an astounding rate of about 2.0 billion square meters per year (Tu, 2013), the concept of green building has been prevailing in recent years. Besides, the core of green building is resource conservation and environmental protection, with water saving as a crucial aspect (MNC, 2006).

Most previous efforts to reduce water consumption and improve water efficiency have continually laid emphasis on direct water use, such as the promotion and adoption of more water-efficient appliances as well as wastewater treatment and recycling. However, the direct water consumption within buildings merely takes a share of about 12% of the total water demand (Green Building Council of Australia, 2008). Water is also required in the processing and manufacture of building materials and equipment, and even the manpower input to support these processes, which is known as indirect water consumption. Studies have revealed that the total of direct water and indirect water associated with building construction is significant (Crawford and Treloar, 2005; Crawford and Pullen, 2011). Thus, the virtual water (Allan, 1993) as an indicator of fresh water consumption revealing both direct and indirect water uses of building construction is proposed to be accounted, which is of significant necessity for water management of building.

Internationally, most existing studies on building water consumption just focus on direct water use during the operation of buildings (Balaras et al., 2002; Li, 2008; Proença and Ghisi, 2010; Qi and Shen, 2008; Wong and Mui, 2008), only a very limited number of researches have evaluated the virtual water consumption of buildings. Water consumption associated with the Australian commercial building construction has been assessed, which is found to take up a significant proportion in building's life cycle (Crawford and Treloar, 2005; McCormack et al., 2007). Similarly,

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http://dx.doi.org/10.1016/j.jclepro.2013.12.045

assessment of water consumption in residential building construction in India has been conducted by Bardhan (2011), suggesting that water consumption at material production stage has to be paid more attention. Crawford and Pullen (2011) also performed a life cycle water analysis of a residential building and its occupants over a 50-year period, analyzing both the direct water and indirect water consumption. They concluded that water embodied in materials of the dwelling was more than direct water consumption, to operate the house policies and minimizing water consumption should address more than just saving direct water usage. Results of those studies confirm that water embodied in the construction period plays a crucial role in building's life cycle water balance. However, for building construction, the existing studies only evaluated the water embodied in raw materials, excluding the water embodied in other goods and services essential to support the process, such as manpower input and equipment input. In addition, suffering from the rough raw materials' inventories and embodied water coefficient (Bardhan, 2011), it is difficult for aforementioned research to accurately identify water consumption sources of building construction.

Under these circumstances, a systematic evaluation supported by detailed raw project data in the Bill of Quantities is performed in this paper. It also gives detailed accounting procedures to cover total water consumption of various individual inputs such as manpower, material, tap-water and equipment. Besides, a hybrid method, combining the accuracy of process analysis and the completeness of input–output method, is employed in this study. The prime aim of this paper is to provide an explicit accounting procedure to calculate virtual water of building construction, and to identify the most potential part for conserving water from building construction by performing a case study. The systemic analysis can provide an insight into the virtual water consumption profile in typical office buildings in China and could be used as a reference to help reduce water consumption of building construction. Meanwhile, the framework provided in this study can be applied to other virtual water studies in the future.

2. Method and procedure

2.1. Virtual water

The concept of virtual water was first introduced by Allan (1993) in context of the water scarcity in the Middle East to indicate water required for the agricultural product, and then widely employed to stand for the volume of water used in the production of a commodity or service (Chapagain and Hoekstra, 2008; Ridoutt et al., 2012; Wang et al., 2013). Virtual water is the water embodied in the supply chain of a product, not merely in a physical sense. It is also termed as "embodied water", and closely related to the concept of water footprint (Chapagain and Hoekstra, 2003; Chapagain and Orr, 2009). Extensive research on virtual water have been conducted in recent years, varying from global scale to specific products (Chen and Chen, 2010, 2012; Chen et al., 2012; Yu et al., 2010; Wang et al., 2013; Zhou et al., 2010). For example, the virtual water content of tea, wastewater treatment, rice and hydroelectricity have been explored (Chapagain and Hoekstra, 2007; Herath et al., 2011; Hoekstra, 2012; Shao and Chen, 2013).

However, virtual water is still a "young" academic concept in the field of building construction. Virtual water for building refers to the water needed through all stages of production, containing both direct and indirect paths for all inputs required by the building construction engineering. The direct and indirect water requirements are included simultaneously by combining the boundary information and the processes information. System boundary of the virtual water assessment for a building is shown in Fig. 1, figuring the inputs related to the process of building construction which are classified as four categories, i.e., manpower, materials, tap-water and equipment. Then the overall water consumption of all inputs can be well traced by averaged sectoral intensities provided by proper input–output analysis of the economy.

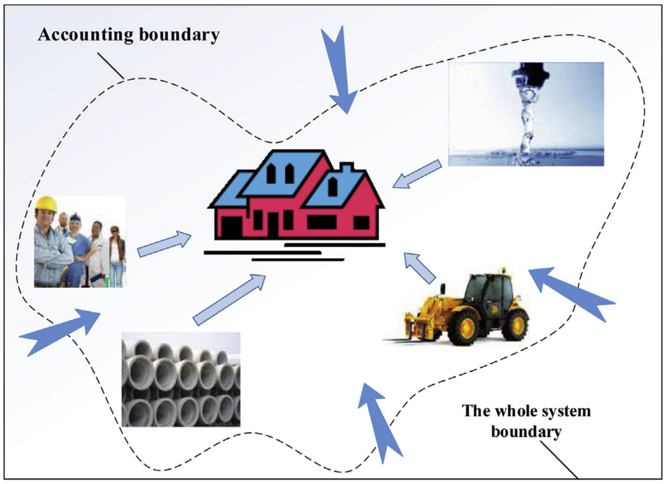

Fig. 1. Diagram for virtual water accounting for a building.

2.2. Hybrid method

Among the increasing studies emerged these years, there are two widely accepted methods to assess the virtual water, i.e., process analysis and input–output method. As a bottom-up method, process analysis is generally employed to calculate the virtual water by tracing major indirect water consumption caused by some key inputs (Chapagain et al., 2006; Chapagain and Orr, 2009; Ridoutt et al., 2009; Solís-Guzmán et al., 2013). Nevertheless, the process analysis method inevitably has some deviations with actual results deriving from the neglect of some inputs and scattered water intensity data support (Chapagain and Hoekstra, 2003; Ridoutt et al., 2012).

Meanwhile, a lot of researchers tried to investigate the virtual water on the basis of input–output analysis (Chapagain and Hoekstra, 2007; Herath et al., 2011; Velázquez, 2006; Wang et al., 2013; Zhao et al., 2009, 2010). The top-down approach offers a complete modeling of the economy and avoids the truncation error rooted in process analysis. Nevertheless, stemming from the level of aggregation at which goods and services are defined, input–output analysis is subject to limited accuracies (Ronald and Peter, 2009). Consequently, it can only be used to calculate the macro systems, such as overall virtual water consumption of the construction sector or the average intensity of all buildings (Ridoutt et al., 2012; Shao et al., 2013).

To combine the strengths as well as to reduce the weaknesses of both methods, Bullard et al. (1978) proposed a hybrid method to calculate the energy required directly and indirectly by a target product. The hybrid method has been applied by Chen and his collaborators to devise a general formulation to assess the carbon emissions or embodied energy of many typical projects, such as an individual building (Chen et al., 2010a; Chen et al., 2011b), a constructed wetland wastewater treatment system (Chen et al., 2011a), a wind power plant (Yang et al., 2011a,b), or even a city (Li and Chen, 2013; Li et al., 2013, 2014). Given its comprehensibility and adaptability, the method has been chosen to account virtual water of a target product which could similarly be beneficial in terms of water-use impact reduction.