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Original Article

Comparing volumetric and impact-oriented water footprint indicators: Case study of agricultural production in Lake Dianchi Basin, China

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ABSTRACT

Water Footprint (WF) assessment provides a basis for quantitative description and evaluation of water consumption and degradation related to human activities. Several different WF methods have been developed, which can be broadly divided into volumetric and impact-oriented approaches. The former, coming from the discipline of water resources management, has mainly focused on water resource consumption. The latter, coming from the discipline of life cycle assessment, has generally considered a wider range of environmental impacts associated with water use, including water degradation. The purpose of this paper was to investigate water use in agricultural production in the environmentally sensitive Lake Dianchi Basin. It was found that WF results had different tendencies depending on the WF assessment method chosen. From 2001–2012, volumetric WF results (20570 ~ 75838 L kg^{-1}) showed an upward tendency, whereas impact-oriented WF results (1069 ~ 1453 L H_2O-eq kg^{-1}) declined modestly over this period. In the Lake Dianchi Basin, the agricultural water degradation footprint (1047.2 ~ 1410.9 L H_2O-eq kg^{-1}) far outweighed the water scarcity footprint (21.8 ~ 45.6 L H_2O-eq kg^{-1}). There has been a history of agricultural production placing a heavy burden on the quality of catchment water resources. In particular, fertilizers applied to wheat crops contribute to aquatic eutrophication. Wheat cultivation contributed most to the agricultural WF in the Lake Dianchi Basin, followed by tobacco, pulses, and then other cereals. Reductions, over time, in the impact-oriented agricultural WF were explained by reductions in total fertilizer application in the basin, despite increased use of irrigation in some years. These results highlight the importance of considering both water consumption and degradation in a complete WF assessment. Further improvements in fertilizer use efficiency and waste water treatment are identified as priorities in the Lake Dianchi Basin to safeguard water resources.

1. Introduction

As water is an increasingly scarce resource, effective environmental indicators have become a requirement to support sustainable water resource management and governance. Water Footprint (WF) assessment provides a basis for quantitative description and evaluation of water consumption and degradation related to human activities (Hoekstra and Chapagain, 2007). Several different WF methods have been developed to support decision-making (Bayart et al., 2010; Milà Canals et al., 2009; Pfister et al., 2009; Ridoutt and Pfister, 2010), which can be broadly divided into volumetric and impact-oriented approaches (Berger and Finkbeiner, 2013). The former has focused on evaluation of global freshwater consumption related to products and virtual water transfers related to trade, while the latter has given greater emphasis to the assessment of impacts resulting from water consumption and contamination (Berger and Finkbeiner, 2013).

Based on the concept of virtual water (VW), the volumetric WF refers to the total volume of direct and indirect freshwater used, typically including the green water footprint (WF_{green}, rainwater that does not run-off or recharge the groundwater), blue water footprint (WF_{blue}, water withdrawn from ground- or surface water) and grey water footprint (WF_{grey}, the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards) (Chapagain and Hoekstra, 2011). Bottom-up and top-down approaches have both been employed in volumetric WF accounting (Fang et al., 2014; Hoekstra, 2009), and a formal elaboration of the methodology has been developed by the Water Footprint Network (WFN) (Hoekstra et al., 2011).

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A large number of studies have been conducted using the volumetric WF assessment to analyze water use on a variety of temporal and spatial scales. As for agricultural water use, research on the coupling relationship between agricultural production/consumption and water sustainability (Hu et al., 2015; Zhuo et al., 2016) has become a major topic, and the results can be obtained in the range of global scale (Mekonnen and Hoekstra, 2014), national scale (Zhuo et al., 2016), provincial scale (Xu et al., 2015), as well as river-basin scale (Pellicer-Martínez and Martínez-Paz, 2016). Exploring the driving mechanism of WF variation is another significant part (Zhang et al., 2017), such as climate change (Zhao et al., 2014), land use change (Miguel Ayala et al., 2016), irrigation technology (Miguel Ayala et al., 2016), conditions of agricultural production and consumption (Liu et al., 2012) etc. While the component parts of the volumetric WF can provide useful information, the single WF value with the sum of green, blue and grey water has been a cause for concern as it cannot accurately reflect the potential impact of agricultural water use on the environment, and therefore may be misleading and result in mistaken decisions by producers or consumers (Berger and Finkbeiner, 2013).

Based on Life Cycle Assessment (LCA) method, the impact-oriented WF assessment provides a new insight into water resources management. To assess the freshwater use impacts in LCA, inventory analysis and impact assessment are systematically combined (Milà Canals et al., 2010; Milà Canals et al., 2009). This approach is now formalized in an international standard published by the International Organization for Standardization (ISO 14046:2014) (Fang et al., 2014). A comprehensive WF assessment usually includes several indicators, each with their own specific units. However, it is also possible to express both the water scarcity footprint (WSF) and water degradation footprint (WDF) in the reference unit H_2Oe (Pfister et al., 2009; Ridoutt and Pfister, 2013), enabling combination into a single indicator to compare the WF of different agricultural products from different places or the same product in different production stages.

Applications of the impact-oriented WF approach through various case studies are now many (e.g. (Pfister and Bayer, 2014), and consideration has also been given to method consistency, reliability, and limitations for decision making (Boulay et al., 2015a; Boulay et al., 2015b). Meanwhile, inventory analysis and impact assessment procedures continue to be refined and improved (Kounina et al., 2013) with the aim of providing more accurate data support for strategic decisions in agricultural water management and other research fields (Hoekstra, 2016; Pfister et al., 2017).

As applications of the volumetric and impact-oriented WF assessment methods continue, a limited number of case studies have been published comparing the differences between these two methods (Berger and Finkbeiner, 2013). Huang et al. (2014) quantitatively analyzed the WF of cereals and vegetables for the Beijing market, and compared the WF of the same crop from different watersheds. Conclusions were drawn that the impact-oriented WF assessment is more instructive to identify locally relevant solutions. Jefferies et al. (2012) conducted case studies on tea and margarine and concluded that the two WF approaches have much in common and that there would be benefit from further collaboration and joint development. Comparing different food packaging alternatives, Manzardo et al. (2015) found that the two methodologies could give consistent results in terms of hotspot analysis and decision-making related to consumptive water use, but not to degradative water use. However, the number of the case studies contrasting the different approaches is limited so far. More exploration and comparison of these two approaches are needed on different temporal and spatial scales. To address this research gap, this study focused on the two WF indicators of various agricultural production on a longer time scale and watershed scale. Methodological development and its applications were also discussed on lake-basin water management during decision-making processes.

The objectives of this paper were to (a) compare the similarities and differences between the volumetric and impact-oriented WF evaluation methods; (b) use the two approaches to evaluate water use in agricultural production in the environmentally sensitive Lake Dianchi Basin over the period 2001–2012; and (c) explore the application of WF as an indicator to inform policy development and decision making with reference to agricultural water management at the watershed scale.

2. Methodology

2.1. Study area

Lake Dianchi Basin is located in Yunnan Province, in the southwest of China (N 24°29 ' to 25°28′, E 102°29′ to 103°01′), and consists of Wuhua, Guandu, Panlong, Xishan, and Chenggong Districts, as well as Jinning and Songming Counties. This is an environmentally sensitive basin that has experienced serious water availability and water quality problems (Shi and Li, 2012). With a watershed area of 2920 km^2, the perennial water resources availability in Lake Dianchi Basin is about $1.0 \times 10^9\ m^3$, meaning that the per capita water resource is barely 300 m^3 per year (only 13% of national average) (Li et al., 2012). Meanwhile, the pollution loads of nitrogen and phosphorus from farmland runoff have become the primary pollution source, contributing to the aquatic eutrophication in Lake Dianchi (Cheng et al., 2008; Hu et al., 2015). As the total amount of the water consumption progressively increases, the catchment is facing a double burden of limited water availability and poor water quality. Thus, it is necessary to investigate the water utilization structure and its environmental impacts in the study area, to direct improvements in water use efficiency and agricultural adaption management in crop production processes.

2.2. Volumetric WF assessment

Based on the VW concept, the volumetric WF evaluation included WF_{green}, WF_{blue} and WF_{grey} components. WF_{green} and WF_{blue} of crop production depend on the agricultural water utilization and the crop yields, calculated as follows (Hoekstra and Chapagain, 2007):

$$WF_{green} = CWU_{green}/Y = 10 \times ET_{green}/Y \tag{2-1}$$

$$WF_{blue} = CWU_{blue}/Y = 10 \times ET_{blue}/Y \tag{2-2}$$

where CWU_{green} and CWU_{blue} represent the green and blue water components in the total crop water consumption ($m^3\ ha^{-1}$); the factor 10 converts the water depth (mm) into the water volume per area ($m^3\ ha^{-1}$); ET_{green} and ET_{blue} refer to the green and blue water evapotranspiration (mm); and Y is the crop yield per unit area ($kg\ ha^{-1}$).

WF_{grey} of crop production is defined as the volume of water demanded in the whole production process to dilute pollutants to such an extent that the quality of ambient water remains above water quality standards. Given the impact of fertilizer application and other material inputs on the agricultural water environment, WF_{grey} can be computed as follow (Chapagain and Hoekstra, 2011):

$$WF_{grey} = (\alpha \times AR)/(c_{max} - c_{nat})/Y \tag{2-3}$$

where AR refers to the rate of chemical application to the field per hectare ($kg\ ha^{-1}$); α represents the leaching-runoff fraction, c_{max} means the maximum acceptable concentration ($kg\ m^{-3}$); and c_{nat} means the natural concentration for the pollutant considered ($kg\ m^{-3}$).

The total volumetric WF of agricultural production can be calculated by summing the three WF components:

$$WF = WF_{green} + WF_{blue} + WF_{grey} \tag{2-4}$$

2.3. Impact-Oriented WF assessment

Based on the LCA method, the impact-oriented WF evaluation includes the calculation of WSF and WDF in the reference unit H_2Oe