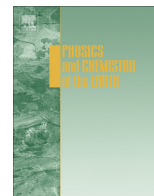




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A new approach to assessing the water footprint of hydroelectric power based on allocation of water footprints among reservoir ecosystem services

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ABSTRACT

Hydroelectric power is an important energy source to meet the growing demand for energy, and large amounts of water are consumed to generate this energy. Previous studies often assumed that the water footprint of hydroelectric power equaled the reservoir's water footprint, but failed to allocate the reservoir water footprint among the many beneficiaries; dealing with this allocation remains a challenge. In this study, we developed a new approach to quantify the water footprint of hydroelectric power (WF_h) by separating it from the reservoir water footprint (WF) using an allocation coefficient (η_h) based on the ratio of the benefits from hydroelectric power to the total ecosystem service benefits. We used this approach in a case study of the Three Gorges Reservoir, the world's largest reservoir, which provides multiple ecosystem services. We found large differences between the WF_h and the water footprint of per unit of hydroelectric production (PWF_h) calculated using η_h and those calculated without this factor. From 2003 to 2012, η_h decreased sharply (from 0.76 in 2005 to 0.41 in 2012), which was due to the fact that large increases in the value of non-energy ecosystem services, and particularly flood control. In 2009, flood control replaced hydroelectricity as the largest ecosystem service of water from the Three Gorges Reservoir. Using our approach, WF_h and PWF_h averaged $331.0 \times 10^6 \text{ m}^3$ and $1.5 \text{ m}^3 \text{ GJ}^{-1}$, respectively. However, these values would almost double without allocating water footprints among different reservoir ecosystem services. Thus, previous studies have overestimated the WF_h and PWF_h of reservoirs, especially for reservoirs that serve multiple purposes. Thus, the allocation coefficient should not be ignored when calculating the WF of a product or service.

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1. Introduction

Water and energy are critical natural resources that sustain modern civilization. As one of the planet's most valuable resources, freshwater is an essential life-sustaining element that cannot be replaced (Koehler, 2008). During socioeconomic development, humans consume increasing amounts of water and energy. As a result, it is a growing challenge to meet humanity's water and energy security needs. Currently, 1.1 billion people lack adequate access to water (UNEP, 2006) and 1.5 billion lack access to electricity (IEA, 2009). About one-third of the world's population suffers from a water scarcity, and this may increase to two-thirds by the end of the 21st century in the worst-case scenario (Vörösmarty et al., 2010; Oki and Kanae, 2006). Global energy demand is projected to grow by 40% between now and 2030. Almost all of

the growth will come from countries that do not belong to the Organization for Economic Co-operation and Development, and China, India, and the Middle East are expected to double their primary energy demand (IEA, 2009). Electricity is the fastest growing form of energy, and is projected to grow by 87% by 2035 (UNEP, 2011a), with almost one-third of that growth coming from China alone (IEA, 2009). According to China's Energy Policy 2012 (Information Office of the State Council, 2012), China's goal is to increase consumption of non-fossil energy to 15% of the total energy consumption by 2020, with more than half of this total coming from hydroelectric power (The National Development and Reform Committee, 2008).

As one of the most popular forms of renewable energy, hydroelectricity is often regarded as a clean and environmentally friendly energy source. However, reservoirs create many problems; in the context of the present paper, the most significant problem is that hydroelectricity generation consumes water resources. Storage of water behind hydroelectric power dams leads to a large

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amount of consumptive water use through evaporation from the open water surface. Hydropower provides about 21% of global electricity consumption and 86% of the global renewable energy consumption (IEA, 2010). Water consumption caused by hydroelectricity generation may exacerbate regional water scarcity problems (Fthenakis and Kim, 2010; Gerbens-Leenes et al., 2009; Gleick, 1993). Hence, it is urgently necessary to accurately assess the water consumption of hydroelectric power.

The water footprint (WF) concept was proposed by Hoekstra (2003). The WF of a product can be defined as the amount of water used to produce the product, including all consumption throughout the supply chain (Hoekstra et al., 2011). By identifying the impacts of human production and consumption behavior on water consumption and pollution generation, WF can be used to measure the effect of humans on the available water resource and on the environment. WF provides a rational and holistic perspective on the relationship between consumers and producers and the water system that sustains them (Hoekstra et al., 2011).

In recent years, three approaches have been applied to assess the water consumption of a reservoir: in the gross water consumption method (Gleick, 1992; Mekonnen and Hoekstra, 2012), the gross water evaporation from different water sources is accounted for except for treated wastewater. In the net water consumption method, the above gross evaporation is subtracted by the land surface evaporation that was used before the reservoir was built (Herath et al., 2011). In the water balance method, the reservoir is regarded as closed watershed, and both outputs (e.g., evaporation, river flow) and inputs (e.g., rainfall, release of treated wastewater) are accounted for. The difference between annual water outputs and inputs is used to represent the total amount of water consumed by a reservoir (Herath et al., 2011; Yesuf, 2012; Arnøy, 2012). Gross water consumption has been used in most studies (Gerbens-Leenes et al., 2009; Mekonnen and Hoekstra, 2012; Pasqualetti and Kelley, 2008; Torcellini et al., 2003), and it is the dominant method for estimating water consumption by hydroelectric power plants. The WF of hydroelectric power plants in different regions ranges from only $0.01 \text{ m}^3 \text{ GJ}^{-1}$ (Gleick, 1992) to $846 \text{ m}^3 \text{ GJ}^{-1}$ (Mekonnen and Hoekstra, 2012). However, research on the WF of hydroelectric power remains in its infancy (Arnøy, 2012; Demeke et al., 2013; Gerbens-Leenes et al., 2009; Gleick, 1994, 1993, 1992; Herath et al., 2011; Mekonnen and Hoekstra, 2012; Pasqualetti and Kelley, 2008; Tefferi, 2012; Torcellini et al., 2003; Yesuf, 2012).

The WF of a reservoir in previous studies was assumed to equal the WF of hydroelectric power. This is problematic because it allocates all water consumption by a multi-purpose reservoir to hydroelectric power, even if the reservoir provides many other services. As a result, this approach overestimates the WF of hydroelectric power (Herath et al., 2011; Mekonnen and Hoekstra, 2012). In the present study, we used a new approach to quantify the water footprint of hydroelectric power (WF_h) by developing an allocation coefficient (η) that estimates the ratio of the ecosystem services value of hydroelectricity to the total ecosystem services value of a reservoir. We applied this approach to the Three Gorges Reservoir, the world's biggest reservoir, to demonstrate the insights provided by the new method.

2. Methods and data sources

Hoekstra et al. (2011) defined WF with three components: the green water WF (i.e., consumptive use of soil water), the blue water WF (i.e., consumptive use of ground or surface water), and the grey water WF (i.e., the volume of polluted water). Reservoirs consume mainly surface water (blue water) through the process of evaporation, but consume little or no soil water (green water) and

produce little or no grey water (Mekonnen and Hoekstra, 2012). Thus, our analysis focuses on blue water consumption arising from evaporation from the artificial reservoirs that develop behind hydroelectric dams.

2.1. A new approach to assess the water footprint of hydroelectric power based on an allocation coefficient

In previous studies, the WF of reservoirs was used to represent the WF_h . However, this is only suitable for reservoirs whose only or primary purpose is to generate hydroelectricity, and is inappropriate for reservoirs that provide multiple ecosystem services (e.g., flood control, irrigation). Approximately 25% of the world's reservoirs with a dam higher than 15 m are multi-purpose reservoirs (ICOLD, 2013). Some reservoirs provide many ecosystem services, including hydroelectricity, flood control, navigation, water supply, and fisheries (Ministry of Water Resources, 2012). The traditional gross water consumption method will therefore overestimate WF_h because it does not allocate the overall WF among all services. Hence, for reservoirs that provide multiple ecosystem services, it is necessary to allocate the total WF among the ecosystem services. We used the following approach to accomplish this:

$$WF_r = \sum_{i=1}^n WF_i = \sum_{i=1}^n (\eta_i \times WF_r) \quad (1)$$

where WF_r is the total water footprint of the reservoir, WF_i is the water footprint of ecosystem service i , and η_i is the allocation coefficient for ecosystem service i , and $\eta_1 + \eta_2 + \dots + \eta_n = 1$.

In this new approach, it is necessary to accurately determine the allocation coefficients, since this will determine the accuracy of the estimated footprint of each service. We defined the allocation coefficient (η_h) as the ratio of the benefit obtained from hydroelectricity to the total benefits provided by a reservoir. The detailed procedure is as follows:

1. Assess the total economic value of all ecosystem services provided by the reservoir.
2. Calculate the ratio of the economic value of hydroelectricity to the total economic value of all ecosystem services. This ratio is the allocation coefficient (η_h).
3. Calculate WF_h by multiplying the gross water footprint of the reservoir (WF_r) by the allocation coefficient (η_h).

WF_r ($\text{m}^3 \text{ yr}^{-1}$) equals the annual total amount of water that evaporates from the reservoir, which is estimated by multiplying the annual water evaporation by the surface area of the reservoir:

$$WF_r = 10 \times E \times A \quad (2)$$

where E is the annual evaporation (mm yr^{-1}), A is the surface area of reservoir (ha), and 10 is a constant used to convert mm into $\text{m}^3 \text{ ha}^{-1}$.

The water footprint of hydroelectric power is calculated as follows:

$$\eta_h = R_h / R \quad (3)$$

$$WF_h = WF_r \times \eta_h \quad (4)$$

where R_h is the economic value of hydroelectricity ($\times 10^9$ CNY), R is the total economic value of all ecosystem services ($\times 10^9$ CNY), and WF_h is the WF of hydroelectric power.

The product water footprint of hydroelectric power (PWF_h , $\text{m}^3 \text{ GJ}^{-1}$), which represents the water footprint per unit of production, is calculated by dividing WF_h by the amount of energy generated (EG , GJ yr^{-1}).

$$PWF_h = \frac{WF_h}{EG} \quad (5)$$

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