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Monthly blue water footprint caps in a river basin to achieve sustainable water consumption: The role of reservoirs

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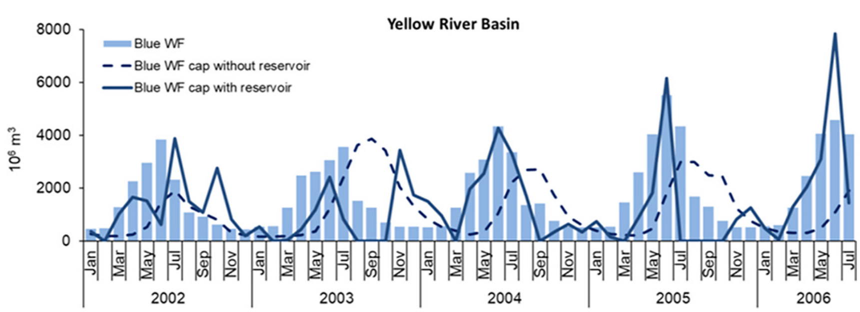
HIGHLIGHTS

- A water footprint cap sets a sustainable upper limit to human water consumption.
- The effects of reservoirs on water footprint caps and water scarcity are shown.
- The effect of reservoirs on increasing dry-season WF caps is largest in dry years.
- Reservoir storage increases blue water scarcity in wet months.

GRAPHICAL ABSTRACT



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ABSTRACT

The blue water footprint (WF) measures the consumption of runoff in a river basin. In order to ensure sustainable water consumption, setting a monthly blue WF cap, that is an upper-limit to the blue WF in a river basin each month, can be a suitable policy instrument. The blue WF cap in a river basin depends on the precipitation that becomes runoff and the need to maintain a minimum flow for sustaining ecosystems and livelihoods. Reservoirs along the river generally smooth runoff variability and thus raise the WF cap and reduce blue water scarcity during the dry season. Previous water scarcity studies, considering the ratio of actual blue WF to the blue WF cap under natural background conditions, have not studied this effect of reservoir storages. Here we assess how water reservoirs influence blue WF caps over time and how they affect the variability of blue water scarcity in a river basin. We take the Yellow River Basin over the period January 2002–July 2006 as case study and consider data on observed storage changes in five large reservoirs along the main stream. Results indicate that reservoirs redistribute the blue WF cap and blue water scarcity levels over time. Monthly blue WF caps were generally lowered by reservoir storage during the flood season (July–October) and raised by reservoir releases over the period of highest crop demand (March–June). However, with water storage exceeding 20% of natural runoff in most rainy months, reservoirs contribute to "scarcity in the wet months", which is to be understood as a situation in which environmental flow requirements related to the occurrence of natural peak flows are no longer met.

1. Introduction

Freshwater consumption in a certain place and time is limited by the available supply. Water availability often hugely fluctuates between dry

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and wet periods of the year and differs across river basins depending on climate (Postel et al., 1996; Oki and Kanae, 2006). Water consumption varies in time and space as well, often countercyclical, with water consumption being highest when water availability is lowest (Hoekstra et al., 2012). Water scarcity, the ratio of water consumption to availability, is thus both river basin and time dependent. It has been estimated that, worldwide, 1.8 to 2.9 billion people live in areas that experience severe water scarcity for at least 4 to 6 months per year, while half a billion people live in places that have severe water scarcity all year round (Mekonnen and Hoekstra, 2016).

From the perspective of sustainability, the blue water footprint (WF) in a river basin, i.e. the consumptive use of the runoff flow, cannot exceed the rate of replenishment, and a substantial part of the natural flow needs to be maintained to support ecosystems and livelihoods. Hoekstra (2013a, 2013b) has proposed that river basin authorities agree on a certain sustainable upper limit to the water consumption. This could be done by formulating a "WF cap" that shows the maximum volume of water consumption specified over time in the year. The blue WF measures water consumption of renewable blue water resources, i.e. the volume of water withdrawn from renewable groundwater and surface water minus the volume of water that is returned (Hoekstra et al., 2011). Practically, the blue WF cap in a river basin can be defined as total natural runoff minus the environmental flow requirement (Hoekstra, 2013a, 2013b). Since both natural runoff and environmental flow requirement vary seasonally, the blue WF cap is also time-dependent.

Blue water scarcity in a river basin can be defined on a monthly basis as the ratio of the blue WF in the month to the maximum sustainable blue WF or the blue WF cap for that month (Hoekstra et al., 2012). There are a few global studies that have quantified blue water scarcity on a monthly basis, either per watershed or river basin (Hoekstra et al., 2012; Brauman et al., 2016; Degefu et al., 2018) or on a 30 arc minute grid level (Wada et al., 2011; Mekonnen and Hoekstra, 2016). There are various monthly water scarcity studies for specific river basins as well: in Morocco (Schyns and Hoekstra, 2014), South Africa (Pahlow et al., 2015), Latin America (Mekonnen et al., 2015) and China (Zeng et al., 2012; Liu et al., 2015; Zhuo et al., 2016). None of the available studies, however, shows the effect of reservoirs on water scarcity mitigation. To some degree, water scarcity in the dry periods of the year can be mitigated by storing water in artificial reservoirs in the wet period and releasing it in the dry period. In the presence of reservoirs, the blue WF cap can thus be raised in dry months. The cap is lowered in the wet months (when water is being stored), but this doesn't need to be a problem as long as there is sufficient water for meeting both human water demands and environmental flow requirements in these months.

Over half of the large river systems on the planet are regulated by human beings. More than 45,000 dams and reservoirs, holding back one seventh of global total annual river runoff, have been constructed to store river water for irrigation, urban water supply, hydroelectricity generation, flood control and smoothing runoff variability (Nilsson et al., 2005; Jaramillo and Destouni, 2015). Most of the reservoirs built in water-abundant river basins are for hydroelectric generation, while the majority of the reservoirs located in water-scarce areas are meant for collecting water in the wet season to secure adequate supply of water for irrigation, households and industries in the dry season (Bakken et al., 2015; Hogeboom et al., 2018). Reservoirs are water consumers themselves: total evaporation from all reservoirs in the world has been estimated to be equivalent to 25% of global consumptive water use in irrigation and industrial and municipal purposes (Hogeboom et al., 2018; Mekonnen and Hoekstra, 2012). The growth in global storage capacity in large and medium-sized reservoirs has been levelling off in the past century and will be insufficient to satisfy future increasing water demands from expanding populations and economies under different climate change scenarios (Yoshikawa et al., 2014; Veldkamp et al., 2017). Various earlier studies have analysed the effects of reservoir operations on runoff (Vörösmarty et al., 1997; Haddeland et al., 2006; Jaramillo and Destouni, 2015). Hanasaki et al. (2006) simulated global river discharge accounting for 452 reservoirs and found that reservoir operations could alter monthly discharge for individual basins by >20%. The annual global discharge had decreased by 0.8–2.1% due to reservoir operations and irrigation extractions, which seems relatively small, but the impacts manifest themselves in specific river basins in the dry periods of the year (Biemans et al., 2011; Döll et al., 2009). All these studies focused on the effects of reservoirs on runoff and have not addressed the next question, i.e. how reservoirs affect the water availability regime over time when accounting for environmental flow requirements (EFRs) and thus how reservoirs could influence the blue WF cap over time.

Earlier water scarcity studies either exclude the effect of reservoirs, or when they include it, they don't show the difference between water scarcity with and without reservoirs. Meigh et al. (1999), for example, estimated blue water scarcity for eastern and southern Africa with a distributed rainfall-runoff model incorporating reservoirs, but not explicitly showing their effect. Wada et al. (2011) assessed current monthly blue water scarcity at global scale using the PCR-GLOBWB model and Hanasaki et al. (2013) estimated future blue water scarcity under alternative climate scenarios based on the H08 model. Recent global studies that analyse runoff, water availability and water scarcity with and without dams include Haddeland et al. (2014) and Veldkamp et al. (2017), but these studies also consider the effect of water withdrawals, land use changes and climate change and do not present the effect of reservoirs separately. Until date there is no study that explicitly addresses the effect of reservoir storage on the redistribution of water availability and scarcity over time. Another gap left by earlier studies is that reservoir operations are usually simulated based on simple rules in hydrological models, which are calibrated based on observed downstream discharges rather than following real-time monitoring in reservoir storages (Wada et al., 2017).

The current study aims to investigate the role of reservoir storage in defining the blue WF cap in a river basin over time and in reducing blue water scarcity in a river basin during the months of relatively low water availability. This is done in a case study for the Yellow River Basin in China, making use of available observations in reservoir storage operations over the period from January 2002 to July 2006. This study provides information on how reservoir storage operations in practice affect the environmental health and the associated sustainability of human water consumption.

2. Methods and data

2.1. Case study description

The Yellow River Basin (YRB) is the second largest river basin of China, with a drainage area of 795×10^3 km^2, feeding 9% of the national population, and contributing 13% of the national grain production, with only 2% of the national water resources (YRCC, 2013). According to previous studies, the YRB faces moderate to severe blue water scarcity during seven months a year (Hoekstra et al., 2012; Zhuo et al., 2016), but these studies don't include the redistributing effect of reservoirs on blue water availability. By the end of 2014, there were 29 large and 174 medium-sized reservoirs in the YRB (YRCC, 2015). The total storage capacity of all registered reservoirs was about 72×10^9 m^3, which is equivalent to 1.2 times the mean annual natural runoff (Ran and Lu, 2012). Almost all the large and medium reservoirs have been constructed in the upper and middle reaches of the basin (Ran and Lu, 2012). In the current study, we consider actual blue WFs, maximum sustainable blue WFs and blue water scarcity at basin and sub-reach level, on a monthly basis, by considering five large reservoirs: Longyangxia and Liujiaxia in the upper reach, and Wanjiazhai, Sanmenxia and Xiaolangdi in the middle reach (Table 1). All reservoirs are located on the river's main stream (Fig. 1). The total storage capacity