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Inter- and intra-annual variation of water footprint of crops and blue water scarcity in the Yellow River basin (1961–2009)

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ABSTRACT

The Yellow River Basin (YRB), the second largest river basin of China, has experienced a booming agriculture over the past decades. But data on variability of and trends in water consumption, pollution and scarcity in the YRB are lacking. We estimate, for the first time, the inter- and intra-annual water footprint (WF) of crop production in the YRB for the period 1961–2009 and the variation of monthly scarcity of blue water (ground and surface water) for 1978–2009, by comparing the blue WF of agriculture, industry and households in the basin to the maximum sustainable level. Results show that the average overall green (from rainfall) and blue (from irrigation) WFs of crops in the period 2001–2009 were 14% and 37% larger, respectively, than in the period 1961–1970. The annual nitrogen- and phosphorus-related grey WFs (water required to assimilate pollutants) of crop production grew by factors of 24 and 36, respectively. The green–blue WF per ton of crop reduced significantly due to improved crop yields, while the grey WF increased because of the growing application of fertilizers. The ratio of blue to green WF increased during the study period resulting from the expansion of irrigated agriculture. In the period 1978–2009, the annual total blue WFs related to agriculture, industry and households varied between 19% and 52% of the basin's natural runoff. The blue WF in the YRB generally peaks around May–July, two months earlier than natural peak runoff. On average, the YRB faced moderate to severe blue water scarcity during seven months (January–July) per year. Even in the wettest month in a wet year, about half of the area of the YRB still suffered severe blue water scarcity, especially in the basin's northern part.

1. Introduction

The increasing demand for fresh water by humanity is challenging the sustainable water use in many river basins around the world [30,67,69]. The Yellow River Basin (YRB, or "Huang He"), the second largest river basin of China, with a drainage area of 795×10^3 km^2 [76], is well known as one of the world's basins facing severe water scarcity. The YRB is now responsible for producing 13% of national grain production with only 2% of the national water resources [76]. In the last half century, with a booming agriculture and burgeoning population, the total consumption of blue water (ground and surface water) by agriculture, industry and households in the YRB increased from 17.8×10^9 m^3 in the 1960s [11] to 39.3×10^9 m^3 in 2009 [75]. Agriculture is by far the largest water user in the basin, accounting for 77% of the total blue water consumption, of which 91% is used for field irrigation (2009) [75]. In 2009, the total annual water withdrawal in the YRB for agriculture, industry and households reached 76.5% of the renewable water resources in the basin [75]. In recent years, competition among the different sectors over the limited water resources has intensified [78]. Meanwhile, when comparing the 1960s to 2000s, precipitation and evaporation showed downward trends in most areas within the YRB [40,72]. The yearly natural runoff of the YRB decreased constantly in the 1990s [71] and reached its lowest value in 2002 ($\sim30.0\times10^9$ m^3), after which it increased again and remained fluctuating (at an average level of $\sim57.5\times10^9$ m^3) [75]. As a result of climatic variability, the inter-annual variability of natural water availability and water demand in the YRB are large, whereby demand in agriculture is typically high when availability is low.

Unfortunately, data on variability of and trends in water consumption, pollution and scarcity in the YRB are lacking. Another problem is that traditional statistics like 'annual gross water abstraction' per sector and 'irrigation efficiency' in the agricultural sector do not provide a comprehensive picture of water use and water scarcity. For understanding water scarcity at catchment or river basin level, we need to measure net water abstraction (consumptive water use) rather than gross water abstraction, because return flows can be reused and thus do not contribute to water scarcity [29]. A similar shortcoming exists with the indicator of irrigation efficiency, which measures

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losses between gross water abstraction and the volume of water that reaches the crop. Only a part of this so-called loss, namely the part that evaporates, is really lost to the catchment and will thus contribute to scarcity; a large part of the so-called loss refers to water that percolates and thus adds to the groundwater and remains available in the catchment [47]. Another gap in traditional statistics is the focus on the use of blue water resources (ground and surface water), which is insufficient, given the fact that agriculture heavily relies on green water resources (rainwater) [17]. Besides, water pollution and water scarcity are intricately linked, because the effect of pollutants becomes worse if groundwater and river flows get depleted. Finally, usual statistics on water use and scarcity are annual, while the key to understanding water use and scarcity is the recognition of intra-annual variability [55]. The water footprint (WF) – introduced by Hoekstra [27] – is a comprehensive measure of human freshwater appropriation that addresses these shortcomings.

The WF is a multi-dimensional indicator that measures consumptive water use of both rainfall and ground-surface water (the green and blue WF, respectively) and the water required to assimilate anthropogenic loads of pollutants to freshwater bodies (the grey WF) [29]. In geographic applications, several soil-water-balance models have been applied in order to map WFs at high spatial resolution levels so that one can see where they are located [25,38,41,54,57]. Rost et al. [54] estimated, using the LPJmL model at 30 arc min resolution level, total green and blue WFs in global crop production for 1971–2000. Hanasaki et al. [25] evaluated, employing the H08 model at 30 arc min resolution level, global total green and blue WFs of major crops for 1985–1999. Liu and Yang [38] estimated, based on the GEPIC model at 30 arc min resolution level, global total green and blue WFs of crop production for the year 2000. Siebert and Doll [57] computed, with the GCWM model at 5 arc min resolution level, global total green and blue WFs of major crops worldwide for 1998–2002. Mekonnen and Hoekstra [41] estimated, applying the Cropwat model at 5 arc min resolution level, the green, blue and grey WFs of crop production worldwide for 1996–2005. Cai et al. [10] and Feng et al. [22] applied an input–output model to evaluate the WF and regional virtual water trade for the YRB from a consumptive perspective for 2002 and 2007, respectively. Hoekstra et al. [30] estimated blue water scarcity for the major river basins in the world over the period 1996–2005, by taking, per basin, the ratio of blue WF to the maximum sustainable blue WF. Mekonnen and Hoekstra [43] estimated, at 5 arc min grid level, the global grey WF related to nitrogen for the period of 2002–2010. These studies show that the blue WF in the YRB is relatively large during several months per year [25,30,54,57] and has the highest blue water proportion in total consumptive (green + blue) use among river basins around the world [38]. Meanwhile, there is net virtual water export from the YRB [10,22]. The YRB faces severe blue water scarcity for four months per year, as a long-term average, mostly in spring time when runoff is still low while water consumption for irrigation starts to increase [30]. The nitrogen-related grey WF in the YRB has been estimated to be about eight times the annual runoff, which implies a very high water pollution level [43].

Although temporal and spatial variations in WFs are keys in understanding water scarcity, most existing geographic WF assessment studies consider one specific year or the average for a period of five to ten years. There are a few studies focusing on the long-term variability of green and blue WFs, for example, Zhuo et al. [80] and Tuninetti et al. [64] estimated WFs of four major crops in the YRB and globally, respectively, at 5 arc min grid level inter-annually over 1996–2005; Sun et al. [63] calculated WFs for grain production in the Hetao irrigation district over 1960–2008. But there are no water scarcity studies at a high temporal and spatial resolution for a series of years.

The current study aims at investigating (i) the temporal and spatial variability of green, blue and grey WFs of crop production in the YRB for the period of 1961–2009; and (ii) the temporal and spatial variability of blue water scarcity in the YRB for 1978–2009. The YRB is usually divided into three reaches: the upper reach (upstream of Hekouzhen, Inner Mongolia), the middle reach (upstream of Taohuayu, Henan Province) and the lower reach (draining into the Bohai Sea) [76]. This is the first river basin study that combines a high temporal resolution (WF estimated per day; blue water scarcity estimated per month), a high spatial resolution (5×5 arc min), and a multi-year record including both dry and wet years. In addition, the study is innovative in applying a combined soil-water-balance and crop-growth model in estimating the green and blue WFs in crop production. Most of earlier WF studies (e.g. [38,41,57,80]) applied a soil-water-balance model in combination with an assumed simple linear relationship between yield and evapotranspiration [16]. We applied, for the first time, the FAO crop water productivity model AquaCrop [31,49,61] to estimate crop WF. AquaCrop separately simulates crop transpiration (Tr) and soil evaporation (E) and the daily Tr is used to derive the daily biomass gain via the normalized biomass water productivity of the crop [61]. Compared to other crop growth models, AquaCrop has a significantly smaller number of parameters and better balances between simplicity, accuracy and robustness [60]. The model performance regarding crop water use and yield simulation has been widely tested for a number of crops under diverse environments and types of water management [1,3,21,24,34,35,62,77]. This is the first time that the AquaCrop model is applied to simulate crop water use and yields for a whole river basin, by running the model per crop for each grid cell. Besides, we added a module that separates green and blue water evapotranspiration in order to be able to calculate green and blue WFs of crops.

2. Method and data

2.1. Estimating green and blue water footprints in crop production

The WFs related to the production of seventeen major crops (listed in Table 1) in the YRB during the period 1961–2009 were estimated year by year with a daily time step at a 5×5 arc min grid (∼7.4 km × 9.3 km at the latitude of the YRB) following the accounting framework of Hoekstra et al. [29]. The crops considered account for about 87% of the harvested area and 93% of crop production in 2009 [46]. Per crop, the green WF of producing a crop within a grid cell (in $m^3\ y^{-1}$) was estimated by multiplying the green water evapotranspiration (ET, $m^3\ ha^{-1}$) over the growing period by the harvested area for the crop (in ha y^{-1}). Similarly, the blue WF was estimated by multiplying the blue ET by the harvested area. The green or blue WF per unit of a crop (in $m^3\ t^{-1}$) was calculated per grid cell by dividing the green or blue ET over the growing period by the crop yield (Y, t ha^{-1}). The AquaCrop was used to simulate ET and Y for each type of crop per year per grid cell. Simulated Y per crop per year per grid cell was calibrated at provincial level, by scaling the model outputs in order to fit provincial crop yield statistics [46]. AquaCrop is a water-driven crop water productivity model with a dynamic daily soil water balance:

$$S_{[t]} = S_{[t-1]} + PR_{[t]} + IRR_{[t]} + CR_{[t]} - ET_{[t]} - RO_{[t]} - DP_{[t]} \qquad (1)$$

where $S_{[t]}$ (mm) refers to the soil water content at the end of day t, $PR_{[t]}$ (mm) the precipitation on day t, $IRR_{[t]}$ (mm) the irrigation water applied on day t, $CR_{[t]}$ (mm) the capillary rise from groundwater, $ET_{[t]}$ (mm) actual evapotranspiration, $RO_{[t]}$ (mm) daily surface runoff and $DP_{[t]}$ (mm) deep percolation. $RO_{[t]}$ is estimated through the Soil Conservation Service curve-number equation [51]:

$$RO_{[t]} = \frac{\left(PR_{[t]} - 0.2 \times S\right)^2}{PR_{[t]} + S - 0.2 \times S} \qquad (2)$$

where S (mm) refers to potential maximum storage, which is a function of the soil curve number. $DP_{[t]}$ is defined by the drainage ability ($m^3\ m^{-3}\ day^{-1}$) given the actual soil water content between