Research papers

Volume versus value of crop-related water footprints and virtual water flows: A case study for the Yellow River Basin

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ABSTRACT

Blue water (irrigation water) and green water (rainwater) constitute the indispensable inputs in crop production, and they virtually flow through crop trade. The valuation of water for crops is becoming essential for providing not only guidance in measuring both the biophysical and economic sustainability of agricultural water resources but also crucial information for investors and authorities engaged in water allocations. However, valuation of green water has been severely disregarded. Here, taking the Yellow River Basin as the study case, we show the feasibility of estimating the value of green water for crop production considering the costs in production processes in addition to blue water valuation. Thus, the volume versus value of blue and green water consumed in crop production as well as that of corresponding virtual water (VW) flows related to crop transfers within the basin are comparable. Fourteen major crops in current three typical years and four scenarios for the year 2050 under climate-socio-economic changes are examined. Results show that value of blue water was approximately 3 times that of green water for irrigated crops, whereas at similar level to the value of green water for rain-fed crops. Visible trade-offs between the regional volume and value of water used in crop production and that of the intra-national VW flows exist in terms of magnitude in time and space, as well as the structure by crops. The total volumes of the water footprint (WF), i.e., water consumption, in crop production and VW exports changed little over years, however the corresponding total water values was tripled and seven-folded, respectively, due to apple production expansions. Wheat was the biggest contributor in volume of VW export while apple accounted the most in value of VW export of the basin. The considered scenarios for 2050 suggested that the reduced values of crop-related WF and VW flows were more sensitive than the corresponding water quantity. This study implies the importance of managing the internal trade-offs or mutual effects between water resources and economic returns.

1. Introduction

Across the natural, social and economic systems in the Anthropocene, water flows physically through the hydrosphere as well as virtually into the trades among different places (D'Odorico et al., 2019; Konar et al., 2016; Bierkens, 2015; Vörösmarty et al., 2015; Zhao et al., 2015; Savenije et al., 2014; Mekonnen and Hoekstra, 2020). Agriculture

is the largest consumer of water, responsible for over 70% of blue water (surface and groundwater) withdrawals, 92% of humanity's water footprint (WF) (i.e., water appropriation of human activities) (Hoekstra, 2003), and 76% of virtual water (VW) trades (Hoekstra and Mekonnen, 2012) globally. Approximately 11% of global nonrenewable groundwater depletion flows virtually through the international crop trade, which leads to an increased risk of water shortages in many populous

but water-poor countries (Dalin et al., 2017). As an indispensable input and natural capital in crop production, water resources are consumed to generate economic value (Garrick et al., 2017); the products have economic value while the blue water withdrawal together with other inputs have costs. In order to obtain greater economic benefits or income, the water consumers (i.e., peasants) could consume relatively more water despite improved efficiency in water use (Grafton et al., 2018; Ward and Pulido-Velazquez, 2008). Valuing water in crop production and trade is becoming essential to provide not only guidance of measuring both biophysical and economic sustainability of agricultural water resources (Fenichel et al., 2016), but also crucial information for investors and authorities engaged in land and water allocations (D'Odorico et al., 2020; Savenije and van der Zaag, 2020).

The value of each drop of agricultural water resources is a measure of the net economic benefit, or the marginal value produced by the drop of water in consideration of the market value of the agricultural production outputs minus the cost of obtaining water during production (Bierkens et al., 2019; D'Odorico et al., 2020). The majority of studies available have improved the estimation of the value of blue water in agricultural production in space and time. Cai et al. (2003) analysed the relationship between the volume and net economic benefits of irrigation water in the Maipo River Basin in an integrated economic-hydrologic modelling framework. The results of this case study indicated that higher water prices may result in higher levels of irrigation efficiency, whereas higher costs of implementing technologies or measures to improve physical water efficiency could result in lower incomes for farmers. Bierkens et al. (2019) quantified the country-specific value of irrigation water for five staple crops and revealed the economic inefficiency of irrigation water use, especially for that abstracting nonrenewable groundwater. At a higher spatial resolution of 10-km at the global scale, D'Odorico et al. (2020) estimated the value of irrigation water for growing sixteen major crops through a mechanistic biophysical algorithm and showed unsustainability of current crop distribution in terms of agricultural water value maximization. Both the above latest studies show the visible potential of blue water saving and economic benefit gaining at current croplands. However, the economic valuation of green water, which is the rainwater and represents over eighty percent of consumptive agricultural water resources in either globe (Hoekstra and Mekonnen, 2012) or major agricultural nations (Zhuo et al., 2016a), has been severely disregarded. Chouchane et al. (2015) and Yang et al. (2021) conducted the estimation of the crop green and blue economic water productivities, separately, for the case of Tunisia and China, respectively. The economic water productivity (in USD/m³) is measured as the ratio of the product value (USD/kg) to the water consumed in production (m³/kg), and is comparable to water productivity (kg/m³). But the economic water productivity index excludes the cost in the production. Although Hoekstra et al. (2001) estimated the value of green water for the Zambezi Basin, only the total amount was presented; the comparisons with blue water values as well as the contributions of diverse products were not shown. Although Grammatikopoulou et al. (2020) highlighted the importance of green water valuation in agriculture, the case for rain-fed cereal production in the Czech Republic lacks information about the differences between green and blue water values in irrigated agriculture. In addition, previous studies (Novo et al., 2009; Schwarz et al., 2015) on the economic value of VW flows have focused on international crop trade, and intra-national crop transfers have not been analysed.

In order to fill the aforementioned knowledge gaps, taking the Yellow River Basin (YRB) as the study case, the current study estimates, for the first time, the value of green water used in crop production considering costs at croplands in addition to a comprehensive valuation of blue water. Thus, the corresponding values of both blue and green VW flows related to either international or intra-national crop transfers are comparable. Three selected typical years (2003, 2006, and 2013, which were wet, dry, and average respectively) and four possible scenarios for the year 2050 in response to climate and socio-economic changes are examined. The differences in values of water between irrigated and rain-fed agriculture are recorded. The trade-offs between the volume and value of physical and virtual water flows are further identified.

The YRB was selected as the study area because of its representativeness. First, the sustainable water management of this basin from its biggest water user—agriculture—is becoming increasingly challenging. The YRB is the second largest river basin in China, with a drainage area of 795×10^3 km² (YRCC, 2014). With only 2% of the national water resources, 13% of national grain is produced in this basin (YRCC, 2014; MWR, 1999). Currently, irrigation accounts for 68.6% of total blue water consumption in the basin (2018) (YRCC, 2019). Second, the basin spreads across nine provinces (Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan and Shandong) with varied levels of economy (Fig. 1). The highest provincial per capita gross domestic product (GDP) in Shandong was 2.1 times higher than the lowest in Gansu province (2019) (NBSC, 2020). Third, the basin is part of the VW networks related to either the intra-national or international crop transfers (Feng et al., 2012; Cai et al., 2009; Yin et al., 2016; Zhuo et al., 2020). For the three selected typical years and the scenarios for year 2050, crop by crop, we calculated simultaneously the economic values of green and blue water use in crop production as well as of the international and domestic related VW flows of the YRB. Fourteen crops (Table 4) were selected, accounting for approximately 77% of the harvested area and 84% of crop production in 2013 (NBSC, 2020).

2. Methods and data

2.1. Valuation of green and blue water in crop production

The value of green and blue water, separately, in crop production is estimated at provincial levels by crops within the YRB for each considered year. The algorithm is consistent with the mechanistic biophysical method for the valuation of blue water for crops proposed by D'Odorico et al. (2020). For irrigated crop i, the value per unit volume of blue (irrigation) water supply ($V_{b,ir}[i]$, USD/m³) is calculated as:.

$$V_{b,ir}[i] = \frac{Y_{ir}[i] - Y_{rf}[i]}{Y_{ir}[i]} \times \frac{P_{ir}[i] \times (pc[i] - FC[i]) - IRS[i] \times pw_{ir}}{IRS[i]} \quad (1)$$

where $Y_{irr}[i]$ and $Y_{rf}[i]$ (t/ha) refer to irrigated and rain-fed yield level, respectively, of crop i in a certain province, $P_{ir}[i]$ (t/y) the production of irrigated crop i in the province, $pc[i]$ (USD/t) the producer price of the crop i, $FC[i]$ (USD/t) the cost of other inputs than irrigation water, including the costs of seed, fertilizer, pesticides, machinery, technical service, field management, maintenance, labours and tax. pw_{irr} (USD/m³) the price of irrigation water. $IRS[i]$ (m³/y) is the irrigation water supply. The corresponding value of per unit volume of green water (effective rainwater) at irrigated crop fields ($V_{g,ir}[i]$, USD/m³) is calculated as:.

$$V_{g,ir}[i] = \frac{Y_{rf}[i]}{Y_{ir}[i]} \times \frac{P_{ir}[i] \times (pc[i] - FC[i])}{PR_{e,ir}[i]} \quad (2)$$

The effective precipitation ($PR_{e,ir}[i]$, m³/y) at irrigated crop field is calculated by using the USDA SCS method (Smith, 1992).

For a rain-fed crop, the value of the green water used in producing rain-fed crop ($V_{g,rf}[i]$, USD/m³) is estimated as:.

$$V_{g,rf}[i] = \frac{P_{rf}[i] \times (pc[i] - FC[i])}{PR_{e,rf}[i]} \quad (3)$$

The producer price and cost of each considered crop per province per year were obtained from the *Compilation of National Agricultural Product Cost and Income Data* for the considered years (NDRC, 2004, 2007, 2014) (see Tables S2 and S3). The price of irrigation water per province was obtained from Mao (2005) (see Table S4).
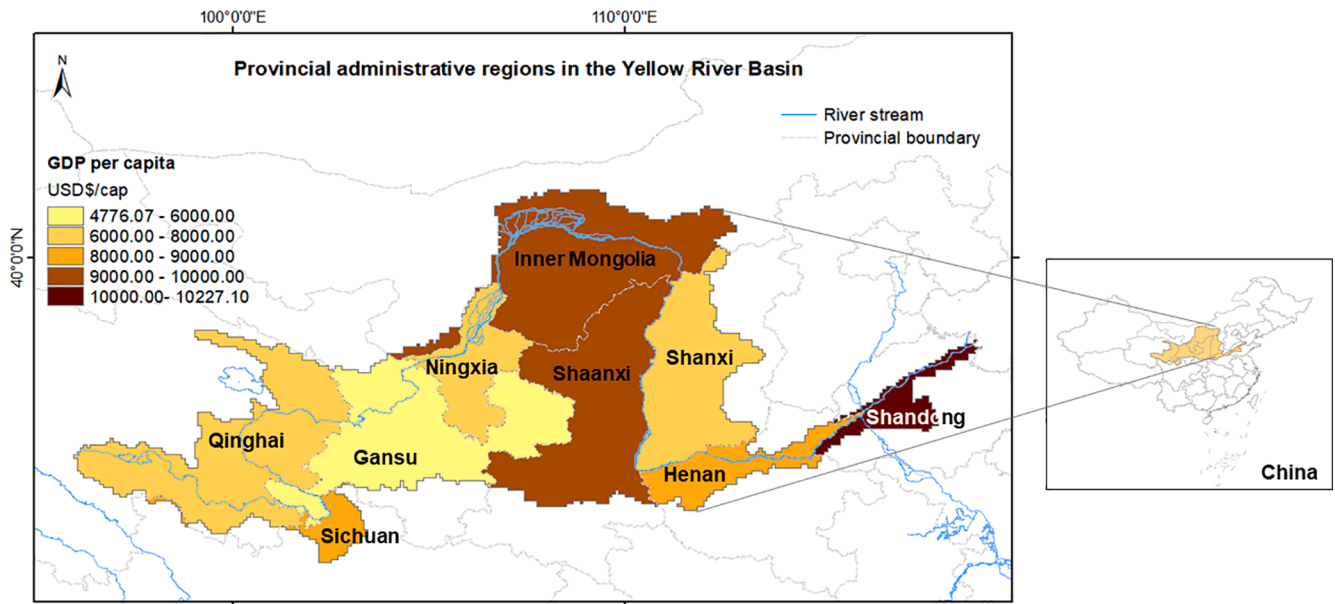
Fig. 1. Provincial administrative regions in the Yellow River Basin.

2.2. Valuation of VW flows related to crops

Based on the estimates of valuation of water in crop production within the YRB, the current analysis evaluates the value of green and blue VW exports related to crops per province in the basin, by dividing the international and intra-national crop transfers. Following Novo et al. (2009), taking the blue VW exports as an example, the total economic value of the blue VW exports related to a crop i of a province in a certain year ($VVW_b[i]$, USD/y) equals to the product of the value per cubic metre of blue water for producing the crop in the province ($V_{b,ir}[i]$, USD/m^3) and the corresponding volume of blue VW exports ($VWE_b[i]$, m^3/y).

$$VVW_b[i] = V_{b,ir}[i] \times VWE_b[i] \qquad (4)$$

2.3. Quantifying crop-related water footprints and virtual water flows

The physical water flow associated with the production of crop i within a region over the cropping period is defined using the corresponding water balance for the region as follows:.

$$PR[i] + IRS[i] - RF[i] = WF_{g,Prod}[i] + WF_{b,i,Prod}[i] \qquad (5)$$

where $PR[i]$ (m^3/y) refers to the precipitation over the cropping field, which is the green water supply for growing crop i; $IRS[i]$ (m^3/y) is the irrigation water supply; $WF_{g,Prod}[i]$ (m^3/y) is the green WF of producing crop i; $WF_{b,i,Prod}[i]$ (m^3/y) is the blue WF of producing crop i; and $RF[i]$ (m^3/y) represents the remainder of the inflows from precipitation and irrigation that are not included in the WF, including surface runoff, drainage and percolation.

The annual total green and blue WFs of crop production at the field level measure the green and blue evapotranspiration (ET) from croplands over the cropping period (Hoekstra et al., 2011). WF accounting was carried out at a spatial resolution of 5 by 5 arc-minute (~7.4 km × 9.3 km at the latitude of the YRB) by following the WF assessment framework by Hoekstra et al. (2011) and using the FAO AquaCrop plug-in program (version 4.0) (Steduto et al., 2009; Raes et al., 2009; Hsiao et al., 2009). The calculation methods and data sources used for field WF accounting for crop production are detailed in the study by Zhuo et al. (2016b).

The regional blue WF related to crop production consists of the blue WF at the field level ($WF_{b\_f,Prod}[i]$, m^3/y) and the blue WF reflects evaporative losses of the irrigation supply network ($WF_{b\_e,Prod}[i]$, m^3/y)

(Schyns et al., 2014; Cao et al., 2014):.

$$WF_{b,Prod}[i] = WF_{b\_f,Prod}[i] + WF_{b\_e,Prod}[i] \qquad (6)$$

The blue WF of the irrigation supply network is estimated based on the evaporation loss coefficient α (%) of the $IRS[i]$, according to the efficiencies of irrigation canals and fields:.

$$WF_{b\_e,Prod}[i] = \alpha \times IRS[i] \qquad (7)$$

The α for each province in China is obtained from the study by Cao et al. (2014), which is estimated according to the "Code for Design of Irrigation and Drainage Engineering" (MWR, 1999) and widely accepted as the official reference for irrigation engineering designers in China (Li, 2006). The *PR* of the croplands during each considered year was obtained from the 30-arc-minute monthly CRU-TS-3.10 dataset (Harris et al., 2014). The *IRS* from the surface water and groundwater supply distributed to each province per year is derived from the annual water resource bulletins for the YRB produced by the Yellow River Conservancy Commission (YRCC, 2014).

Regarding the VW flow estimation, both the international and domestic inter-provincial crop trades were considered in the current analyses. For the YRB, VW exports ($VWE[i]$, m^3/y) related to a considered crop i of each province equals to the product of the export quantity ($E_e[i]$, t/y) and the corresponding WF of producing a unit mass of the crop ($UWF_{prod,e}[i]$, m^3/t) in exporting province e.

$$VWE[i] = \sum_e (E_e[i] \times UWF_{prod,e}[i]) \qquad (8)$$

The international trade and crop consumption data were derived from FAOSTAT (FAO, 2020) and downscaled to the provincial level following the methods in Ma et al. (2006). The domestic inter-provincial crop trade volumes are estimated by the linear optimization model taking the minimum transportation cost as the optimization objective and the annual food balance in each province as constraint conditions (Dalin et al., 2014; Wang et al., 2019; Zhuo et al., 2019; Gao et al., 2020). We then downscaled to the provinces located partly within the basin by the population distribution. The population of the YRB shared by each province is estimated according to the county-level statistics of each province (CYFD, 2017).

2.4. Scenario setup for 2050

To investigate the responses of volume and values of crop-related WFs and VW flows under possible climate and socio-economic changes in the YRB, we carried out scenario analysis for the YRB as a whole for the year 2050 by considering four key changing factors: (1) climate, (2) population growth, (3) technology and (4) diet. The green and blue WFs of crop production in the YRB were simulated at 5 by 5 arc minute grid level driven by the outputs of Global Climate Models (GCMs) along with the effects of technology on yield increase and improved irrigation network efficiency. The VW balances related to each considered crop driven by were estimated considering YRB as a whole to be driven by the population growth, diet change and the changes in crop production. Considering the average year 2013 as the baseline year, we set four scenarios (S1-S4) for YRB in consistence with the four scenarios set by Zhuo et al. (2016c) for mainland China. The scenarios were built on the scenario matrix of the shared socio-economic pathways (SSPs) (O'Neill et al., 2012) and the representative concentration pathways (RCPs) (Van Vuuren et al., 2011) as approved in the 5th IPCC Assessment Report (IPCC, 2014). In order to represents scenarios under varied levels of climate changes and socio-economic developments, S1 and S2 combine climate scenarios forced by RCP2.6 with SSP1 and SSP2, respectively. S3 and S4 combine climate scenarios forced by RCP8.5 with SSP2 and SSP3, respectively. Table 1 lists the main levels or relative changes in key driving factors compared to their baseline values. RCP2.6 and RCP8.5 refer to the lowest and highest climate change impacts below the 10th percentile and 90th percentile, respectively, of the reference emission range in the IPCC (2014) (Moss et al., 2010). Combining the characteristics of corresponding SSP and RCP under each scenario, the most sustainable S1 represents a world under relative satisfied progress towards sustainability with relative low challenges to both climate change mitigation and adaptation. S2 and S3 represent two scenarios under the middle-of-the-road trends of socioeconomic changes which continuing the current decadal developments with relatively low and high climate change levels, respectively. S4 represent a relative worse condition under which there are large challenges in both respects of climate change and socioeconomic change. Additional details on the selection of the considered quadrants for scenarios in the matrix can be found in the study by Zhuo et al. (2016c).

Scenarios were run under climate change projections by four GCMs namely, CanESM2 (Canadian Centre for Climate Modelling and Analysis), GFDL-CM3 (NOAA Geophysical Fluid Dynamics Laboratory), GISS-E2-R (NASA Goddard Institute for Space Studies), and MPI-ESM-MR (Max Planck Institute for Meteorology), which span the full range of projections for China on precipitation over the cropping seasons (Zhuo et al., 2016c), within the Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012). The former two GCMs represent relatively wetter climates whereas the latter two project relatively drier climates in the YRB (Table 1). The downscaled GCM outputs at 5 by 5 arc minute resolution driving the WF assessment of crop production were obtained from Ramirez-Villegas and Jarvis (2010). The population scenarios with increasing levels of population growth from SSP1 to SSP2 were obtained from IIASA (2013). The scenarios on crop yield increase through technological development are in line with the findings by Zhuo et al. (2016c) who set the increasing levels per SSP according to global 2000–2050 scenarios by De Fraiture et al. (2007) and the findings of a linear increasing trend. The improvements in irrigation network efficiency compared to the baseline year are set from 10% to 30% from SSP3 to SSP1. The diet scenario for each SSP (Table 2) is selected from the East Asia scenarios by Erb et al. (2009).

3. Results

3.1. Volume versus value of green and blue water for crop production in the YRB

Table 3 lists the volume versus values of water in crop production per selected year (2003, 2006, and 2013, which were wet, dry, and average, respectively). For the YRB as a whole, over the considered years, the annual total volume of WF change little with an average level of 61 billion m^3/y of which blue water contributed 34%, thanks to the reductions in WF per unit mass of the most crops (see Table 4). Wheat was the biggest contributor to the basin's total crop WF by 36%, however apples accounted the most by 42% in total value of water for croplands till 2013. With doubled apple production with tripled market value (Table S2), the total value of water in crop production in the YRB has reached to 7.3 billion USD/y, 2.5 times the 2006's level, that blue water contributed to 26%. This is also the main reason of much higher value of water for crops in 2013. Compared to the wet year of 2003, 28% less precipitation occurred over croplands in the dry year of 2006. It resulted in 25% and 20% more irrigation withdrawals and blue WF of crop production, respectively. Within one year, the value of water for crops differs among water colours as well as among cropping methods (Table 4). For irrigated crops, the value of blue water was around 3 times the value of green water. Whereas the value of green water for rain-fed crops was at similar level of corresponding blue water value at a same

Table 2
Diet scenarios for 2050 and comparisons to the baseline year of 2013.

unit: Kcal/cap/d	2013[a]	2050[b]	
		'Current trend' scenario	'Less meat' scenario
Cereal	1427	1552 (9%)	1709 (20%)
Roots	154	149 (−4%)	201 (31%)
Sugar crops	66	85 (29%)	124 (88%)
Oil crops	271	288 (6%)	265 (−2%)
Vegetables and fruits	338	205 (−39%)	219 (−35%)
Other crops	129	66 (−49%)	82 (−36%)
Animal products	724	612 (−15%)	372 (−49%)
Total	3109	2957 (−5%)	2973 (−4%)

[a] Source: FAOSTAT (FAO,2020)

b. Values are generated according to the scenarios for East Asia by Erb et al. (2009); relative changes from the 2013 level are shown in parentheses.

Table 1
Climate-socio-economic scenarios for the Yellow River Basin at 2050.

	S1		S2		S3		S4	
	RCP2.6				RCP8.5			
	SSP1		SSP2		SSP2		SSP3	
GCMs	CanESM2	GFDL-CM3	GISS-E2-R	MPI-ESM-MR	CanESM2	GFDL-CM3	GISS-E2-R	MPI-ESM-MR
Relative changes in annual precipitation [a]	27%	31%	13%	20%	33%	26%	18%	20%
Relative changes in annual ET_0[a]	3%	10%	−1%	1%	5%	12%	2%	3%
Relative changes in CO_2 concentration	12%				36%			
Total population growth [b]	−10.0%		−7.2%		−7.2%		−3.9%	
Yield increase through technology [c]	45%		30%		30%		14%	
Improvement in irrigation network efficiency	30%		30%		20%		10%	
Diet scenarios [d]	'less meat'		'current trend'		'current trend'		'current trend'	

Sources: a. Ramirez-Villegas and Jarvis (2010); b. IIASA (2013); c. De Fraiture et al. (2007); d. Erb et al. (2009).

Table 3
Volume versus values of water in crop production in the Yellow River Basin.

	2003 (wet)	2006 (dry)	2013 (average)
PR (10^9m^3/y)	70	51	63
IRS (10^9m^3/y)	28.7	35.9	35.6
Surface water	22.0	29.0	29.7
Ground water	6.7	6.9	5.9
WF (10^9m^3/y)	58.9	61.3	63.2
WF_g	40.0	38.7	42.5
WF_b	18.9	22.7	20.8
$WF_{b,f}$	17.3	20.6	18.7
$WF_{b,e}$	1.6	2.1	2.0
$V_{b,ir}$ (USD/m^3)	0.06	0.08	0.21
$V_{g,ir}$ (USD/m^3)	0.02	0.02	0.08
$V_{g,rf}$ (USD/m^3)	0.05	0.08	0.22

year.

Water used for different crop types has different values within a same place. In the YRB, water for tomatoes and apples had higher values than water for the other crops (see Table 4). Because of the low market price of wheat and higher cost for growing rapeseed (Table S3), both intensive green and blue water for wheat as well as the green water for rapeseed have generated net costs till the year 2013. With much smaller unit WF than other considered grain crops, values of water for potatoes were relatively high. Among the nine provinces that contain the YRB, there was high spatial heterogeneity in values of water used in crop production, because of variation in cropping structure as well as the economic water productivities per crop (Fig. 2) (see also Table S2). Shaanxi province is the biggest apple producer (Fig. 2d) so that had higher value of both green and blue water than most of the other provinces. With a relatively higher price and lower cost in planting barley and potatoes in Qinghai (see Tables S2 and S3), the value of green water there was higher among provinces.

3.2. Volume versus value of crop-related virtual water flows of the YRB

Summing up the net VW imports related to the considered crops, the YRB was a net VW importer of 15 billion m^3/y in 2013. The VW imports related to rice, which were almost 8 times the total net annual VW imports of the basin, defined the role of the basin as a net VW importer. Annually, the crop-related VW export accounted for 42% of the total WF of production in the YRB. Domestic VW exports to other places within China accounted for 96% of the total VW exports. Total crop export volume of crops increased by 62% while the corresponding total VW exports even decreased (Table 5) slightly because of the reduced unit WF of crops (Table 4). On the other hand, with over double exports of apples (by 2.75 times from 2003 to 2013), maize (by 2.46 times), sunflower (by

2.26 times) and groundnuts (by 2.13 times), the total value of crop VW exports of the YRB was almost seven-folded, accounting for 73% of total value of water for crop production within the basin. Given the high green water intensity in high valued crops, green VW exports contribute over eighty percent of basin's total value of VW exports.

Fig. 3 shows visible differences in terms of crop contributions to the volume and value of VW exports of each province within the YRB taking the year 2013 for instance. Wheat and maize were the biggest contributors to the total VW exports by 32% and 25%, respectively. However, the apple and potato were the biggest contributors to the corresponding value of VW exports by 68% and 15%, respectively. Among the provinces, Henan province, the biggest wheat exporter in the basin, accounted for the most as 23% of total VW exports. Whereas Shaanxi province made more value of VW exports as the biggest apple exporter.

3.3. Scenarios for 2050

Table 6 shows the responses in volume and value of crop-related WFs and VW flows of the YRB in the climate-socio-economic scenarios for 2050, as compared to the baseline year 2013's levels. With the consistent levels of cost, price and water price in crop production, as mainly driven by the low crop economic productivity in Shanxi, Sichuan and Shaanxi provinces with higher yield levels, the value of green and blue water for irrigated crops decreased at higher levels than the corresponding water consumption levels in S1-S4. With the increments in the production of crops like wheat (by 60%–85%) and rapeseed (by 106%–161%) with low value or even net cost of water for croplands whereas the decreases in high water valued crop production including apples (by 8%–29%) and tomatoes (by 48%–56%), the overall average value per drop of green and blue water for crops in scenarios became net costs.

Fig. 4 shows the spatial distribution of the relative changes in the annual green and blue WF (in m^3/y) of crop production by year 2050 as compared to 2013 forced by RCP2.6 and RCP8.5, respectively. It can be clearly seen that the increases in blue WFs mainly happened in the south basin, especially in Shanxi, Henan and Shandong provinces, i.e., the lower reaches, where the precipitation tended to decrease (see Figure S2) while the ET$_0$ increased (see Figure S3). While the increased green WFs mostly happened in the places where blue WF decreased with relatively greater precipitation as projected (see Figure S2). We considered only the increased irrigation network efficiencies in responses in the responses in the amount of annual irrigation (blue water) withdrawal. The blue water abstraction decreased in S1-S4 by 25%-15% thanks to the improvements in irrigation network efficiencies of 30%-10%, even though the increased blue WFs. Consequently, as driven by the increases in crop productivity and the reduced rates of population growth, the crop-related net VW imports of the YRB decrease drastically,
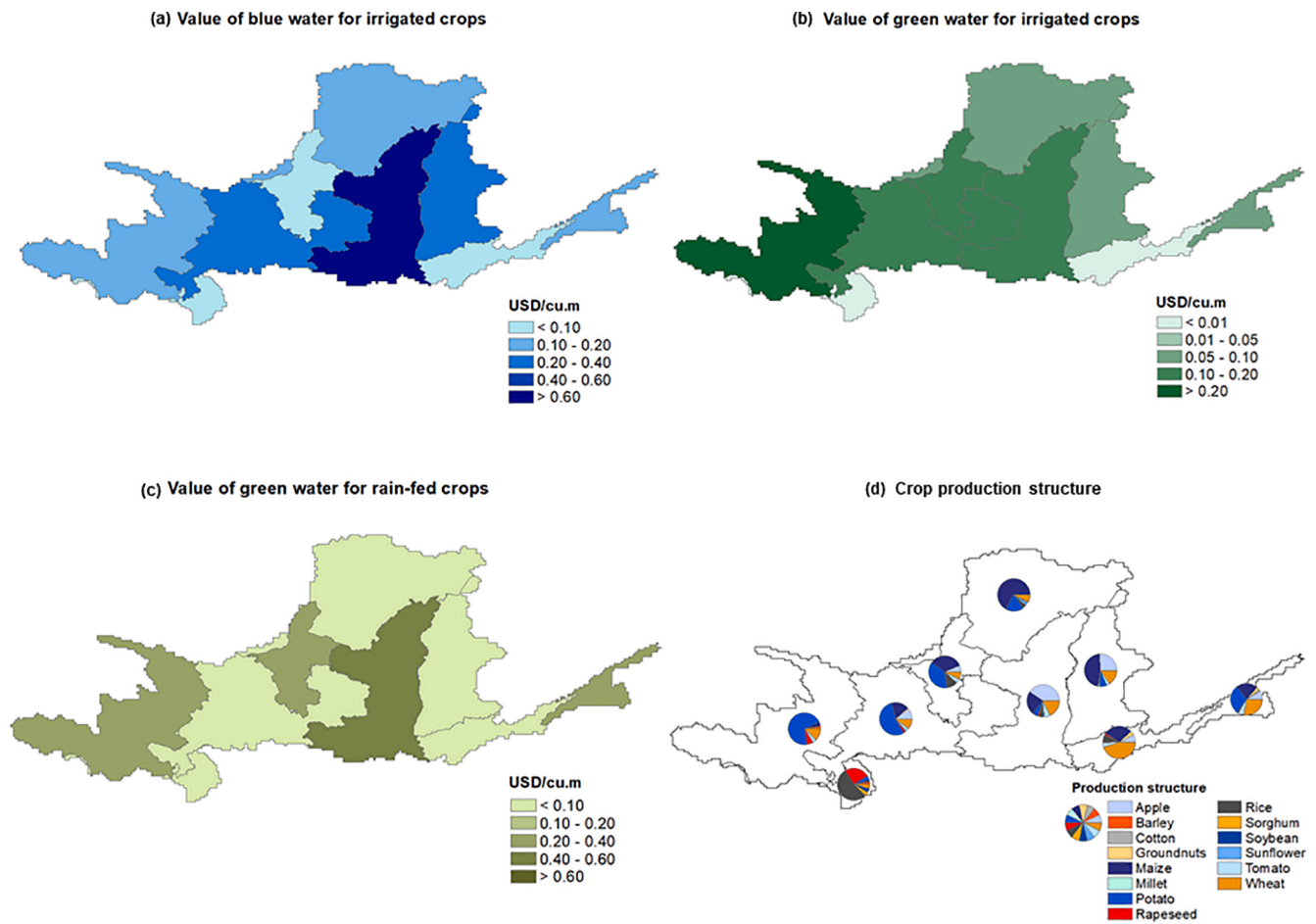
Table 4
Average unit water footprint (UWF) versus value of water in crop production in the Yellow River Basin.

	2003(wet)				2006 (dry)				2013 (average)			
	UWF (m^3/t) (blue fraction %)	$V_{b,ir}$ (USD/ m^3)	$V_{g,ir}$ (USD/ m^3)	$V_{g,rf}$ (USD/ m^3)	UWF (m^3/t) (blue fraction %)	$V_{b,ir}$ (USD/ m^3)	$V_{g,ir}$ (USD/ m^3)	Vg,rf (USD/ m^3)	UWF (m^3/t) (blue fraction %)	$V_{b,ir}$ (USD/ m^3)	$V_{g,ir}$ (USD/ m^3)	$V_{g,rf}$ (USD/ m^3)
Rice	961 (41%)	0.04	0.00	0.03	837 (48%)	0.09	0.00	0.10	785 (48%)	0.07	0.00	0.22
Wheat	1391 (47%)	0.00	0.00	−0.01	1243 (50%)	0.01	0.07	0.05	1115 (49%)	−0.01	−0.09	−0.13
Maize	864 (22%)	0.04	0.01	0.01	772 (25%)	0.08	0.03	0.03	618 (22%)	0.12	0.01	0.01
Sorghum	1327 (16%)	0.00	0.01	0.03	1328 (20%)	0.01	0.04	0.05	1378 (17%)	0.02	0.07	0.09
Millet	2398 (8%)	0.05	0.00	0.00	2293 (10%)	0.09	0.01	0.01	2143 (9%)	0.68	0.05	0.06
Barley	252 (5%)	0.00	0.02	0.02	237 (6%)	0.00	0.07	0.06	255 (10%)	0.00	0.01	−0.05
Soybean	4111 (16%)	0.01	0.03	0.02	3301 (23%)	0.00	0.03	0.02	3008 (22%)	0.02	0.03	0.00
Potato	188 (4%)	0.36	0.28	0.09	184 (5%)	0.54	0.12	0.03	219 (3%)	1.34	1.20	0.30
Cotton	2341 (28%)	0.30	0.20	0.27	1655 (35%)	0.18	0.16	0.19	2214 (39%)	−0.30	−0.32	−0.33
Sunflower	2603 (6%)	0.01	0.07	0.07	2126 (14%)	0.00	0.05	0.05	1537 (9%)	0.00	−0.03	−0.13
Groundnut	1576 (17%)	0.02	0.04	0.04	1310 (22%)	0.18	0.14	0.17	1216 (21%)	0.10	0.06	0.08
Rapeseed	2786 (28%)	0.00	0.01	0.02	2690 (33%)	0.00	0.00	0.01	2554 (28%)	0.00	−0.20	−0.15
Tomato	98 (24%)	0.52	0.52	0.58	83 (30%)	0.53	1.02	0.88	65 (24%)	2.58	4.31	3.91
Apple	531 (17%)	0.00	0.07	0.05	401 (23%)	0.01	0.33	0.28	358 (16%)	0.09	1.19	1.02

Fig. 2. Value of green and blue water for crop production among provinces and the crop production structure per province within the Yellow River Basin. Year: 2013.

Table 5
Volume versus values of international and domestic virtual water exports (VWE) related to crops of the Yellow River Basin.

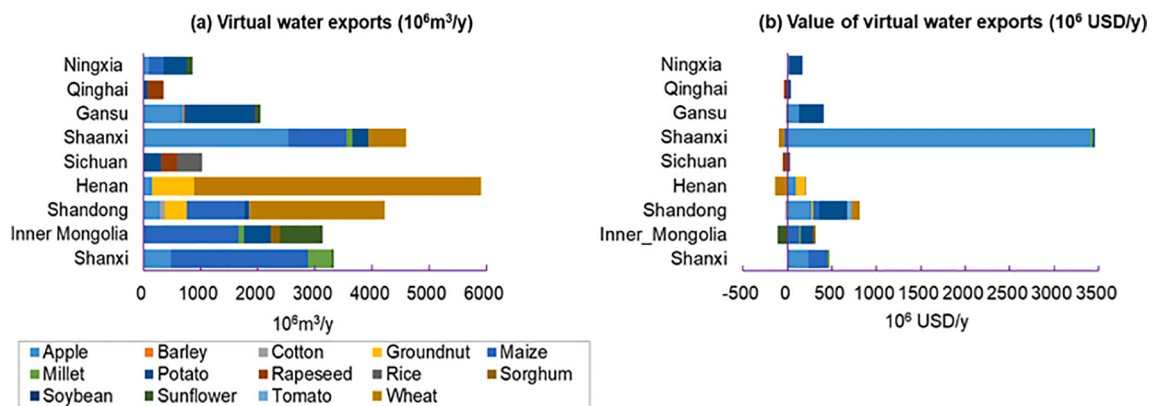| Year	International VWE (10^9m^3/y)		Domestic VWE (10^9m^3/y)		Total	International VVW (10^6 USD/y)		Domestic VVW (10^6 USD/y)		Total
	green	blue	green	blue		green	blue	green	blue	
2003 (wet)	3.8	1.2	16.5	7.8	29.3	146.07	51.31	493.32	87.39	778.10
2006 (dry)	2.3	0.8	14.0	6.9	24.0	139.08	125.56	1477.24	300.79	2042.67
2013 (average)	0.7	0.2	18.1	6.4	25.5	297.24	23.08	4526.49	564.60	5411.41

Fig. 3. Crop contributions to volume (a) and value (b) of virtual water exports per province within the Yellow River Basin. Year: 2013.

Table 6
Responses in volume and value of crop-related water footprint and virtual water exports to climate-socio-economic scenarios for 2050 of the Yellow River Basin.

	Relative changes from 2013 to 2050			
	S1	S2	S3	S4
PR ($10^9 m^3$ /y)	22%	22%	23%	23%
IRS ($10^9 m^3$ /y)	−25%	−25%	−19%	−15%
WF of crop production ($10^9 m^3$ /y)	4%	4%	19%	19%
WF_g ($10^9 m^3$ /y)	13%	13%	33%	33%
WF_b ($10^9 m^3$ /y)	−13%	−13%	−10%	−9%
$WF_{b,f}$ ($10^9 m^3$ /y)	−11%	−11%	−9%	−9%
$WF_{b,e}$ ($10^9 m^3$ /y)	−30%	−30%	−20%	−10%
Vb,ir (USD/m^3)	−106%	−106%	−106%	−106%
Vg,ir (USD/m^3)	−161%	−154%	−155%	−148%
Vg,rf (USD/m^3)	−83%	−85%	−95%	−96%
VWE ($10^9 m^3$ /y)	47%	22%	50%	26%
VWE_g ($10^9 m^3$ /y)	41%	15%	48%	23%
VWE_b ($10^9 m^3$ /y)	66%	41%	56%	33%
VVW (10^6 USD/y)	−103%	−102%	−107%	−104%
VVW_g (10^6 USD/y)	−101%	−100%	−105%	−102%
VVW_b (10^6 USD/y)	−123%	−119%	−121%	−117%

and the YRB becomes a bigger net VW exporter, however, with total net cost of the total VW exports in all the scenarios.

4. Discussion

Through the case for the YRB, the current study reveals that trade-offs exist between the volume and value of green and blue WFs in crop production as well as the volume and value of crop-related VW flows. As shown in Fig. 5 with the 2013 data in the study case, the directions of values of the physical water and VW are inversely related to the corresponding water flows (Hoekstra et al., 2001; Savenije and van der Zaag, 2020). Farmers consume water in crop production while receiving economic net benefits. A VW exporter consumes local water resources in producing crops for exports and finally consumed in other places while gets income through the VW flows.

Two phenomena shown in the current study highlight important aspects in water management for food production from the internal water-economic effecting mechanisms.

(i) Blue water was found to be able to generate higher economic values back to farmers than green water at the same irrigated

crop field. According to Jägermeyr et al. (2017), the integration of rainwater management into the current irrigation system could register a net increase of 10% in food production. Without the specific cost of achieving green water, the lower green water value implies the recommendations to increase green water use efficiency in irrigated field not only for saving more blue water, but also enhancing economic feedbacks of rainwater.

(ii) With varying economic values among crops, differences in cropping structures among provinces were found to have a significant impact on the total amount of water consumption (Zhuo et al., 2016a), as well as the spatial heterogeneity in the corresponding levels of the water values. The phenomenon that wheat production in the YRB consumed a lot of water but generate small values shows again the importance of valuating the regional water supply for crop production pattern design.

The current study valuates, for the first time, the green water for crops accounting for the costs in production processes. The attribution of crop yields to blue and green water is based on crop modelling with consideration of water stress effects, although the weighted average crop yield levels were validated from the provincial statistics (Zhuo et al., 2016b). Therefore, uncertainties were generated during the simulations. It is not possible to calibrate the results exactly for such a large basin scale. But we highly recommend to take field measurements when implementing the algorithm at a small scale where the absolute figures of water values matter. However, for the current study objective, we believe that the shown significant temporal and spatial variabilities in values of green and blue water for different types of crops in a same geographical region through the case for the YRB are valid. Regarding the green and blue WF and VW flow estimates, some parameters including the crop calendars, the evaporation loss coefficient, settings for irrigation techniques were based on assumptions with data limitations, which are also should be in caution when downscaling the test scales.

Many researchers have focused on identifying the external natural or socio-economic driving factors on the physical green and blue water consumption in crop production (Zhao et al., 2015; Zhao and Chen, 2014; Tuninetti et al., 2015) or on the associated VW flows (Dalin et al., 2012; Tamea et al., 2014; Wang et al., 2016). Therefore, identifying the internal driving factors on the water consumption relevant to the generated economic benefits and values is highly recommended in the
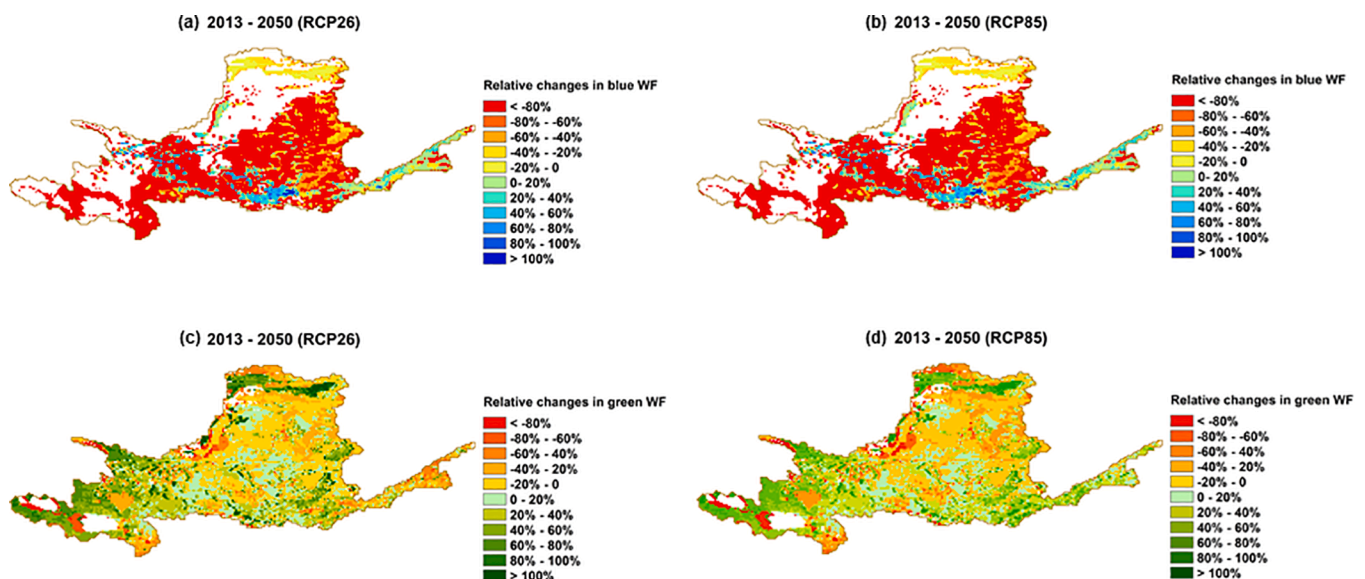

Fig. 4. Multi-GCM average relative changes in green and blue WFs of crop production under climate change scenarios for 2050 as compared to 2013 in the Yellow River Basin.
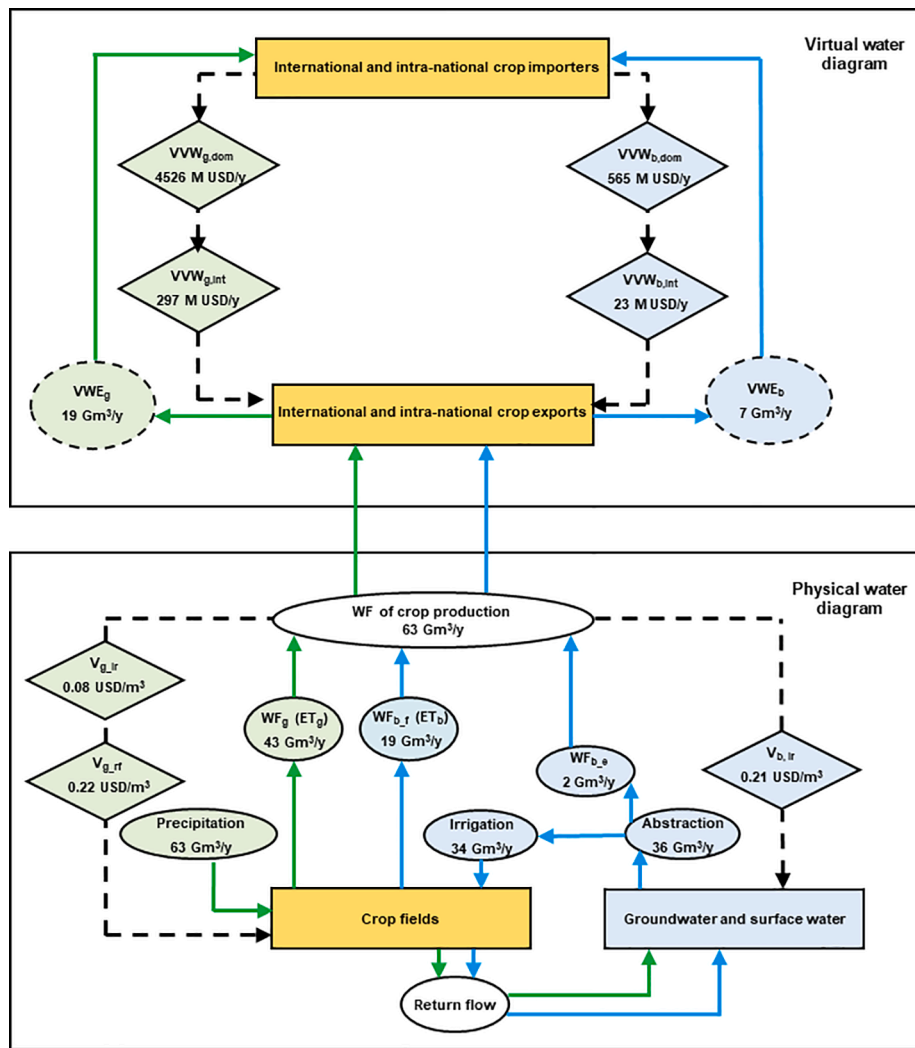
Fig. 5. Crop-related green and blue physical and virtual water diagram within the Yellow River Basin for the year of 2013.

future. As the very start, the current study identified, for example, the impacts of crop production structure on the valuation of green and blue water for crops. So that modifying crop production structure could be one of the suggested measures, while being of long-term effects, to maximize the economic value of both crop WFs and VW flows. With short-term effects on the current cropping lands, it has been proven quantitively that different tillage and irrigation strategies have been quantitatively proven to differ significantly in terms of their cost effectiveness (Chukalla et al., 2017). Reasonable costs and prices of water are effective stimulus measures that promote reductions in blue water withdrawals and consumption. Furthermore, the combination of increased water prices or taxes with WF benchmarks could also be considered.

Last but not least, the current analysis shows alternative and feasible approaches to tackle two key methodological or conceptual flaws in measuring the Sustainable Development Goal (SDG) 6.4 "By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity" (UN, 2015). First, the valuation of green water as comparable to blue water in agriculture based on WF and VW flow estimation enables drawing the whole picture on water-use efficiency (the SDG 6.4.1 indicator) and net water scarcity (the SDG 6.4.2 indicator) related to agricultural sector. Effective indicators are shown to further investigate possible diverse measures to save and use more productively not

only blue water resources, the focus of the SDG 6.4, but also rainwater, which is the only water resources for rain-fed agriculture (Vanham and Mekonnen, 2021; Vanham et al., 2018). Second, the SDG 6.4.1 indicator is supposed to measure relationships between economic growth and water use, however, ignores the truth that the simple ratio of gross economic value added by sectors to water withdrawal hides complex integrations of natural and socioeconomic drivers (Hellegers and van Halsema, 2021). The shown values of blue and green water for each crop type in consideration of production costs with dividing irrigated and rain-fed croplands in time and space, is helpful to identify the share of crops, the contribution of higher economic value per product, the contribution of less water per crop, or even the trade-offs between economic benefits and the water productivities making up the eventual water-use efficiencies.

CRediT authorship contribution statement

La Zhuo: Software, Methodology, Validation, Formal analysis, Writing – original draft, Conceptualization, Writing – review & editing. **Meng Li:** Software, Methodology, Validation, Formal analysis, Writing – original draft. **Guoping Zhang:** Conceptualization, Methodology, Writing – review & editing. **Mesfin M. Mekonnen:** Conceptualization, Methodology, Writing – review & editing. **Arjen Y. Hoekstra:** Conceptualization, Methodology, Writing – review & editing. **Yoshihide Wada:** Conceptualization, Methodology, Writing – review &

editing. **Pute Wu:** Conceptualization, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2022.127674.

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