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Trade-offs between crop-related (physical and virtual) water flows and the associated economic benefits and values: a case study of the Yellow River Basin

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Abstract. Water issues in many river basins associated with droughts, water over-exploitation and pollution are increasingly being driven by remote pressures through intensified virtual water (VW) flows. However, little attention has been paid to the internal trade-offs between the (physical and virtual) water flows and the associated economic benefits and incomes that the water generated. Here we estimate the concomitant reversed flows of economic benefits and values to the physical and VW flows in crop production and consumption at a basin level, by taking the Yellow River Basin (YRB) in both current three typical years (2003, 2004, and 2006, which were dry, average, and wet, respectively) and possible four scenarios for 2050 under climate-socio-economic changes as the study case. An algorithm for estimation of the economic net benefits of green and blue water use for crop production based on the water footprint (WF) accounting is developed. Results show that the net benefit of blue water (irrigation) was 13-42% lower than that of green water used in irrigated croplands in the basin. Cropping pattern has defined the spatial heterogeneity in the levels of net benefits of water used for crops within the YRB. Provinces located in the relatively drier upper and middle reaches had high irrigation withdrawal rates while a low economic return to farmers because of growing relatively cheap crops. The YRB got increasingly net income due to exports of wheat, cotton and apples even though as a crop-related net VW importer associated to the intra-national trades. Considered scenarios for 2050 suggested that the economic returns of crop-related physical and VW flows were more sensitive than the quantity levels of corresponding water flows. This study implies the importance of managing the internal trade-offs or mutual effects between the water resources consumption and economic returns, in order to get a win-win situation in maximizing both the water use efficiency and economic productivities per drop of water flows.

1 Introduction

Across the natural, social and economic systems in the Anthropocene, water flows physically through the hydrosphere as well as virtually as embedded virtual water (VW) into the trades among different places (Bierkens, 2015; Konar et al., 2016; Vörösmarty et al., 2015; Wu et al., 2016; Zhao et al., 2015; Savenije et al., 2014). It has been widely recognized that regional water issues associated with droughts, water over-exploitation and pollution are increasingly being driven by intensified VW trades (Marston and Konar, 2017; Marston et al., 2015; Vörösmarty et al., 2015; Dalin et al., 2014; Rulli et al., 2013; Hoekstra, 2011; 2013). The VW flows among countries account for one-fifth to one-fourth of the total water footprint (WF) in the world (Hoekstra, 2011; Hoekstra and Mekonnen, 2012; Vörösmarty et al., 2015). A sustainable VW flows can indirectly reduce the water-demand risks experienced by exporters (Chapagain et al., 2006). However, many nations and river basins are 'losing' water through unsustainable VW flows. Agriculture has been the largest water consumer and user. Over 70% of blue water withdrawals globally, 92% of humanity's WF and 76% of global VW flows are for agriculture (Hoekstra and Mekonnen, 2012). A recent study (Dalin et al., 2017) shows that approximately 11% of global non-renewable groundwater depletion flows virtually through the international crop trade, which leads to increased risk of water shortages in many populous but water-poor countries. The crop-related VW flows among regions within China are from the water-scarce North China to water-rich South China (Ma et al., 2006; Feng et al., 2014; Guan et al., 2007; Zhang and Anadon, 2014). The VW flows lead to losses of the China's blue water and exacerbate the water stress experienced by the water-exporting regions (Dalin et al., 2014; Zhao et al., 2015; Zhuo et al., 2016a).

As an indispensable input in crop production, water resources are consumed while generate economic benefits as that the products has economic values and the blue water withdrawal together with other inputs have costs. Regarding a crop-related VW flow network between different regions, the crop prices in the exporting places define the net economic income of each trade partner in per drop of VW flows across their boundary (Schwarz et al., 2015). In order to get higher economic benefits or income, the water consumers (i.e. farmers) could abstract more water even though there was improved water use efficiency (Ward and Pulido-Velazquez, 2008; Song et al., 2017). Studies available on physical and VW flow assessments related to crop production and consumption have been focusing on the impacts of the water flows on water scarcities (e.g. Dalin et al., 2014; Zhao et al., 2015; Zhuo et al., 2016b), or external climate/social/economic driving factors of the physical and virtual water networks (e.g. Tamea et al., 2014; Wang et al., 2016; Dalin et al., 2012). However, to our knowledge, there is little attentions paid to the internal trade-offs between the (physical and virtual) water flows and the associated economic benefits and incomes that the water generated.

In addition, the economic benefit contributed by green water, which represents most water consumed by agriculture, has been seriously neglected. Given the economic character of water, the economic water productivity (in USD/m^3) is measured as the ratio of product value (USD/kg) to the water consumed in production (m^3/kg), for being comparable to water productivity (kg/m^3) (Schyns and Hoekstra, 2014; Chouchane et al., 2015). Chouchane et al. (2015) provided the estimation of the crop green and blue economic water productivities separately for the case of Tunisia. While the economic water productivity index hides the effects of cost in the production. Most related studies have focused on blue water in examining how changes in the economic benefits of irrigation water affect irrigation efficiency (Cai et al., 2003; Schmitz et al., 2013) or how the cost effectiveness of different irrigation measures respond to changes in the blue WFs associated with crop production (Zou et al., 2013; Chukalla et al., 2017). Cai et al. (2003) analyzed the relationship between the physical and net economic benefit of irrigation water in the Maipo River Basin in an integrated economic-hydrologic modeling framework. The results of this case study indicated that higher water prices might result in higher levels of basin irrigation efficiency, whereas higher costs of implementing technologies or measures to improve physical water efficiency can result in lower incomes for farmers. 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. What's more, previous studies (Novo et al., 2009; Schwarz et al., 2015) on the economic income in VW flows have concentrated on the international crop trade, while intra-national crop transfers have not been analyzed.

In order to fill the knowledge gaps as described above, the current study objective is to investigate the trade-offs between the physical/virtual water flows and associated economic benefits and incomes related to crop production and consumption for a geographic area addition to evaluation of the related physical and virtual water flows. To make this possible, an algorithm for estimation of the economic net benefits of green and blue water use for crop production based on the WF accounting is developed. We take the crop production and consumption within the Yellow River Basin (YRB) as the study case, looking at both current three selected typical years (2003, 2004, and 2006, which were dry, average, and wet, respectively) and possible four scenarios for 2050 in responses to the climate and socio-economic changes.

2 Methods and Data

2.1 Case study setup

The YRB is selected as the study area given its representativeness. Firstly, the basin is facing increasing challenge in sustainable water management from its biggest water user — agriculture. As the second largest river basin of China, The The YRB has a drainage area of 795×10^3 km^2 (YRCC, 2013). The basin occupies 2% of the national water resources while produces 13% of national grain production (YRCC, 2013). Currently, the irrigation accounts for 67% of total blue water consumption in the basin (2016) (YRCC, 2017). Over the long-term average, the basin faces moderate to severe blue water scarcity for seven months a year. Due to the spatial mismatch between the blue water consumption and availability, half of the basin still suffers severe blue water scarcity in the wet months (Zhuo et al., 2016b). Secondly, 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 Inner Mongolia was 2.6 times higher than the lowest in Gansu province within the YRB (2016) (NBSC, 2018). Therefore, the price and cost of a same crop varied as well across the nine provinces. With spatial variation in climate as well as the planting structure and scales, the contribution of each province in the total WF of crop production varies. Thirdly, the basin participates in the VW networks related to either the intra-national domestic or in international crop transfers. According to the available studies on VW balance of the YRB through the top-down approach (i.e. Input-Output analysis) (Feng et al., 2012; Cai et al., 2009; Yin et al., 2016), the YRB has a net VW export in consideration of the primary industry.

For both the selected three typical years and the scenarios for 2050, at 5 by 5 arc minute grid level and crop by crop, we firstly calculate green and blue WFs of crop production aiming for describing the related physical water flows. Then we estimate WF of crop consumption as well as the associated VW flows at provincial scales through bottom-up approach. One step further than existing assessments of WFs and VW flows, we evaluate the economic net benefits of green and blue water use in crop production by proposing an algorithm based on WF accounting, and the net income along with international and domestic related VW flows. Sixteen crops (Table 4) are chosen; these crops accounted for approximately 87% of the harvested area and 93% of crop production in 2009 (NBSC, 2013).

2.2 Quantifying green and blue WFs and net benefit of each drop of water in crop production

Physical water flows within a region are associated with water withdrawals and the direct consumption of water by human activities. The physical water flow associated with the production of crop *i* within a region over the cropping period is described by the corresponding water inflow-outflow balance for the region:

$$PR[i] + IRS[i] - RF[i] = WF_{g,Prod}[i] + WF_{b,i,Prod}[i] \qquad (1)$$

where $PR[i]$ (m^3) refers to the precipitation over the cropping field, which is the green water supply for growing crop *i*; $IRS[i]$ (m^3) is the irrigation water supply; $WF_{g,Prod}[i]$ (m^3) is the green WF of producing crop *i*; $WF_{b,i,Prod}[i]$ (m^3) is the blue WF of producing crop *i*; and $RF[i]$ (m^3) represents the remainder of the inflows from precipitation and irrigation 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). The WF accounting was carried out at the grid level 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).The green and blue WFs of producing a crop within a grid cell (in m^3/y) were estimated as the product of the green and blue ET, respectively, over the growing period (m^3/ha) and the harvested area for the crop (in ha/y). The (green or blue) WF per unit of a crop (in m^3/ t) equals to be as dividing the (green or blue) ET over the growing period (m^3/ha) by the crop yield (Y, t/ ha). The ET and Y for each crop per year per grid cell were simulated by the FAO crop water productivity model AquaCrop plug-in program (version 4.0) (Steduto et al, 2009; Raes et al., 2009; Hsiao et al., 2009). More detailed information on calculation methods and data sources used for field WF accounting for crop production can be found in 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) and the blue WF of the irrigation supply network ($WF_{b\_e,Prod}[i]$, m^3); thus, it reflects evaporative losses, as well as the network (Schyns and Hoekstra, 2014; Cao et al., 2014):

$$WF_{b,Prod}[i] = WF_{b\_f,Prod}[i] + WF_{b\_e,Prod}[i] \quad (2)$$

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:

$$WF_{b\_e,Prod}[i] = \alpha \times IRS[i] \quad (3)$$

The α for each province in China is obtained from Cao et al. (2014). The *PR* of the croplands during each considered year are obtained from the 30-arc-minute monthly CRU-TS-3.10 data set (Harris et al., 2014). The *IRS* from surface water and groundwater 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, 2011).

We quantify the economic net benefit per drop of green and blue water, separately, along with the physical water flow in crop production by farmers' perspective at provincial levels within the YRB. Here we propose an algorithm based on the WF accounting. The underline assumption is that every drop of water consumption, either in green and blue, has a same contribution to forming the final products. For an irrigated crop, the total net benefit per unit of irrigation (blue) water supply (NB_b, USD/m^3) is estimated as:

$$NB_{b,ir}[i] = \frac{\frac{WF_{b,Prod}[i]}{WF_{Prod}[i]} \times P[i] \times (V[i] - FC[i]) - IRS[i] \times p_{irr}}{IRS[i]} \quad (4)$$

where $V[i]$ (USD/t) is the producer price of the crop i, $FC[i]$ (USD/t) refers to the cost of other inputs than irrigation water, including the costs of seed, fertilizer, pesticides, machinery, technical service, field management, maintenance, labors and tax. p_{irr} (USD/m^3) the price of irrigation water. The corresponding net benefit per unit of rainwater (green) supply at irrigated crop fields (NB_g, USD/m^3) is calculated as:

$$NB_{g,ir}[i] = \frac{\frac{WF_{g,Prod}[i]}{WF_{Prod}[i]} \times P[i] \times (V[i] - FC[i])}{PR[i]} \quad (5)$$

For a rainfed crop, the total net benefit of the green water used in producing rainfed crop ($NPRF_g$, USD/y) is estimated as:

$$NB_{g,rf}[i] = \frac{P[i] \times (V[i] - FC[i])}{PR[i]} \qquad (6)$$

The producer price of each considered crop per province per year was obtained from the *Compilation of National Agricultural Product Cost and Income Data* for the considered years (NDRC, 2004, 2005, 2007). Values on the price of irrigation per province were collected through relative literatures or news which were according to the local water authorities (Wen et al., 2009; Wang and Lou, 2016; Zheng and Zhang, 2017; Fu, 2007; PGIMG, 2014; Fan, 2005; Yang, 2011; Tian, 2010).

2.3 Quantifying WFs of crop consumption, green and blue VW flows and associated economic values

For the YRB, the green and blue WFs related to the consumption of a considered crop i within each province equals to the total consumption volume ($[i]$, in t/y) multiplied by the weighted average WF within a province ($WF_{prov}[i]$, in m^3/t). The $WF_{prov}[i]$ is estimated as (Hoekstra et al., 2011):

$$WF_{prov}[i] = \frac{P_{prov}[i] \times WF_{prod}[i] + \sum_e (NI_e[i] \times WF_{prod,e}[i])}{P[i] + \sum_e NI_e[i]} \qquad (7)$$

in which refers to the WF related to the consumption of crop *i* within a province; $P[i]$ (t/y) is the quantity of crop *i* produced; $NI_e[i]$ (t/y) is the net import quantity of crop *i* from exporter *e* (other regions in China or other countries); $WF_{prod}[i]$ (m^3/t) is the specific WF of crop production in the province; and $WF_{prod,e}[i]$ (m^3/t) is the WF of the crop, as produced in exporting place *e*. For provinces located partly within the basin, the proportion of the total provincial crop consumption accounted for by the basin is assumed to be the same as the international crop volume. The population of the YRB shared by each province is estimated according to the county-level statistics of each province (CYFD, 2017).

The net domestic crop import volume of the part of the basin in each province is calculated according to the following balance:

$$C[i] = P[i] + NI_{int}[i] + NI_{dom}[i] \qquad (8)$$

where$P[i]$(t/y) is the production of crop *i* in the region; $NI_{int}[i]$ (t/y) is the net import of crop i by the region through international trade; and $NI_{dom}[i]$ (t/y) is the net import of crop i from other places within the same country. The net import of a crop (t y^{-1}) in a province was estimated as its total crop utilization minus the local crop production. Following Zhuo et al. (2016b), the national use of a crop for direct and manufactured food as well as the national use of a crop for feed shown in FAO (2014) were projected into provinces according to provincial populations and the proportional to the national livestock units (LU) per province, respectively. LU is a reference unit which facilitates the aggregation of different livestock types to a common unit, via the use of a 'livestock unit coefficient' obtained by converting the livestock body weight into the metabolic weight by an exchange ratio (FAO, 2005). We used the LU coefficients for East Asia from Chilonda and Otte (2006): 0.65 for cattle, 0.1 for sheep and goats, 0.25 for pigs, 0.5 for asses, 0.65 for horses, 0.6 for mules, 0.8 for camels, and 0.01 for chickens. Finally, we downscale national variations in crop stock to provincial level by assuming provincial stock variations proportional to the provincial share in national production. The international crop imports and exports was distributed to the provinces following Ma et al.(2006). The crop-related net blue and green VW imports of the area of the basin within each province are equal to the net imported volume of the crop multiplied by the corresponding blue and green WFs per unit mass of the imported crop, respectively.

The economic values per drop of VW flows (in USD/m^3) is defined by the economic water productivity (i.e. the ratio of product producer price to the WF of crop production) of related crop in the exporting place (Chouchane et al. 2015; Schwarz et al., 2015; Schyns and Hoekstra, 2014). Then if a region exports VW through higher valued crops and imports VW with relatively lower valued crops, then there could be a net economic income per drop of VW flows across the region. The net income due to VW flows through the trade in crop i of a province (NI(VWF)[i], USD/y) is calculated as:

$$NI(VWF)[i] = \sum_e (E[i] \times V[i]) - \sum_i (I_e[i] \times V_e[i]) \qquad (9)$$

where $E[i]$ (t/y) refer to the export quantity of crop i, $V[i]$ the price of crop i in the considered province, $I_e[i]$ the import quantity of crop i from exporter e, and$V_e[i]$ the price of crop i in the place e. A negative $NI(VWF)[i]$ means a net expense through the VW flows. A positive NI(VWF)[i] means a net income in the VW flows. The national average prices of each considered crop in the international trades per year were obtained from FAOSTAT (FAO, 2014).

2.4 Scenario set-up for 2050

To investigate the responses of crop-related physical and VW flows as well as the associated water economic benefits and values under possible climate and socio-economic changes in the YRB, we carry out scenarios analysis for the YRB as a whole for 2050 by considering four key changing factors: (1) climate, (2) population growth, (3) technology and (4) diet. The green and blue WF simulation were at 5 arc-minute grid level driven by the Global Climate Models' (GCMs') outputs with the technology effects on yield increase and improved irrigation network efficiency. The VW balances related to each considered crop driven by were estimated taking YRB as a whole as driven by the population growth, diet change and the changes in crop production. Taking the average year of 2004 as the baseline year, we set four scenarios S1-S4 for YRB in consistent 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'Nell 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 level 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 an SSP3, respectively. More information in details on choosing the considered quadrants for scenarios in the matrix can be found in Zhuo et al. (2016c).

Table 1 lists the main the levels or relative changes in key driving factors compared to their baseline values. Scenarios ran under climate change projections by four GCMs including 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 the precipitation over the cropping seasons (Zhuo et al., 2016c), within the Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012). The downscaled GCMs 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 technology development are in line with 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 assumption of a linear increasing trend. The improvements in irrigation network efficiency compared to the baseline year are set to 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 Green and blue physical water flows and net benefit per drop of water used in crop production in the YRB

For the YRB as a whole, averaged over the considered years, annual total net benefit of water used for crop production was 2.45 billion USD/y, of which blue water contributed to 27%. Table 3 lists the crop-related physical water flows and associated basin's average net benefits per drop of green and blue water used in the basin at each selected year (2003, 2004, and 2006, which were dry, average, and wet, respectively). The drier year featured greater irrigation (blue water) withdrawals and higher blue WFs whereas a relatively lower net benefit per blue water was shown. Compared to the wet year of 2003, 36% less precipitation occurred over croplands in the dry year of 2006. Simultaneously, irrigation withdrawals increased by 25% and the blue WF of crop production grew by 14.3%. Within one year, the net benefit per drop of water differs among colors as well as among cropping methods. The net benefit per drop of blue water was 13-42% lower than of green water for irrigated crops, as mainly resulted from the cost of blue water use while the cost was zero for green water use. With relatively lower water productivity in most cases, the net benefit per drop of green water (rainwater) at rainfed fields was 11% smaller, averagely, than that of the level of green water at irrigated fields.

Among the nine provinces that contain the YRB, there was high spatial heterogeneity in net benefits of water used in crop production, because of variation in cropping structure as well as the economic water productivities per crop. Figure 2 shows, taking the average year 2004 as the example, the visible spatial variations in net benefits per drop of green and blue water in crop production. The provinces in middle and lower reaches, including Shaanxi, Shanxi, Shandong and Henan, tended to have higher net benefits of water used in crop production (>0.2 USD/m^3) than the provinces in the upper reach. Table 4 shows the YRB's average unit WFs, producer price and cost in producing each considered crop for the considered years. Among crops, cotton and tomato had the highest level of net profit per water consumption. And the four provinces in the middle and lower reaches with relatively higher net benefit of water use in crop production together produced 96% of basin's total cotton and 97% of tomato in the year of 2004. However, provinces with higher blue water withdrawal tended to have low net benefits of irrigation water. Given the high spatial variation in climate across the YRB, the level of annual precipitation differed significantly with the range averaged from 304 mm in Ningxia province (in the upper reach) to 874 mm in Shandong province (at lower reach). Inner Mongolia drew the largest volume of blue water (~22.9% of the basin's total) to irrigated crop land and had a more annual blue WF (~19.8% of basin's total blue WF) in annual average, with only 0.01 USD/m^3 as half of the basin's average level, of net benefit per drop of irrigation. The main reason behind was the cropping structure that maize and wheat, which are the crops with the lower net benefits per blue water, accounted for over 80% of total annual blue WF in Inner Mongolia.

3.2 Crop-related virtual water flows related crops and associated economic values of the YRB

Summing up the net VW imports related to the considered crops, the YRB is a net VW importer, of 13 billion m^3/y averagely over the considered years. The VW imports related to rice, which almost double the total net VW imports of the basin annually, defined the role of the basin as a net VW importer. Annually, the crop-related VW export accounted for 36% of total WF of production in the YRB, as a result of exports of wheat, maize, millet, potatoes, groundnuts and apples to other places within the country or abroad. Table 5 summaries the YRB's WF related to considered crop consumption, associated VW flows and economic values of the VW flows over the three typical years. Regarding the economic values of VW flows, per drop of crop-related international VW flows had relatively higher economic value than of intra-national domestic VW flows across the YRB (Table 5). When seeing the trade-offs between the gross economic values of VW exports (income) and of VW imports (expanse), the YRB had an increased net expanse via the net international VW import whereas an increased net income through the domestic net VW import. The net expanses in the international VW flows were dominated by imports of soybean and cotton, accounting for 89% (year 2004) -96% (year 2006) of the total economic values of international VW imports of the basin. Via the domestic VW flows, wheat (the biggest contributor of crop export), cotton and apples (the two with higher economic water productivities) contributed the net income by accounting for 60% (year 2003) -64% (year 2004) in the total economic values of domestic VW exports.

Figure 3 shows the economic values of crop-related VW exports and import, respectively, as well as the net VW imports per province within the YRB for the selected years. Three in the nine province including Shaanxi, Henan and Shandong province got net income of VW flows in all the three years, even though Shaanxi province was an all-time net VW importer. For

Shaanxi province, it was because of its main contribution in the apple exports, accounting for over 65% of basin's total. For Henan and Shandong, the only two exporters of cotton defined their net income through VW flows.

3.3 Scenarios for 2050

Table 6 shows the responses in the crop-related physical and VW flows, net benefits of water use and economic values of VW flows to the climate-socio-economic scenarios for 2050 of the YRB, as compared to the baseline year 2004's levels. With the consistent levels of cost, price and water price in crop production, as mainly driven by the increased crop economic productivity with higher yield levels, the net benefits of green and blue water used in irrigated crops increased at higher level than the corresponding water consumption levels in S1-S3. While the net benefits of the water used at irrigated fields decreased by 3% in S4 with increased irrigation while lower improvement in crop yields than the other three scenarios (~14% lower than S3). Net benefits of green water used for rainfed crops significantly increased (by 55% (S1) -134% (S3) from 2004's level) across the considered scenarios with visible increases in rainfed crop production (e.g. the production of rapeseed was tripled in S4). Although there were projected increased total annual precipitation by 2050 for the whole YRB (Table 1), the annual rainfall on croplands tend to decreased by 1% and 0.5%, at multi-GCM average levels, from the level of year 2004 under RCP26 and RCP85 respectively. While the WF of crop production increased by 5% and 1% under RCP26 (S1 and S2) and RCP85 (S3 and S4), respectively, as driven by the visible increases in blue WFs (by 18% under RCP 26 and by 17% under RCP85). Figure 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 2004 forced by RCP 26 and RCP85, respectively. It can be clearly seen that the increases in blue WFs mainly happened in the south basin, especially in Henan and Shandong provinces i.e. the lower reaches, by over 60%. While the increased green WFs mostly happened in the places where blue WF decreased. 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-S3 by 7%-2% thanks to the improvements in irrigation network efficiencies of 30%-20%, even though the increased blue WFs.

The only difference between S1 and S2 is the diet scenario. The 'less meat' diet leads to a 4% increase in the total food crop consumption and a 39% decrease in the feed crop consumption; the corresponding values for the 'current trend' diet are a 7% decrease and a 0.1% decrease, respectively. As a result, the WF of crop consumption decreased by 45% in S1 while by 38% in S2. 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, and the YRB becomes a bigger net VW exporter in all the scenarios. The net income form VW flows then was dominated by the economic values of VW exports.

3.4 Discussion

"People face trade-offs" (Mankiw, 2015). The current study reveals, through the case for the YRB, the trade-offs exist between the physical water flow and the net benefits per drop of water in crop production, as well as between the crop-related multi-regional VW flows and the associated net economic income of the trade partners. As shown in the Figure 5 with the data for 2004 in the study case, the directions of the economic benefits of water use and of economic values of VW flows are inverse to the corresponding water flows. Farmers consume water in crop production while get economic net benefits per drop of consumed water. A VW exporter consume local water resources in producing crops for exports and finally consumed in other places while gets income through the VW flows.

There are three phenomena shown in the current study highlight important aspects in water management for food production from the internal water-economic effecting mechanisms. (i) A drop of green water was found to be able to generate higher net economic benefits back to farmers, without cost in water supply, than blue water at a same crop fields. Meanwhile, the more irrigation withdrawal in relatively drier regions (the upper reach of the YRB) together with the cropping patterns dominated by crops with relatively lower water economic productivity in USD/kg resulted in a lower net benefit per drop of blue water than in a wet year. According to Jägermeyr et al. (2017), the integration of rainwater management into the current irrigation system could achieve a net increase in food production of 10%. The higher net economic benefits per green water implies the higher economic return rate in addition to the more harvest by using green water more efficiently and reducing blue water rate in the croplands. (ii) With varied economic values among crops, differences in cropping structures among provinces were found to have significant impacts not only on the total amount of water consumption (Sun et al., 2014; Zhuo et al., 2016a), but also on the spatial heterogeneity in the corresponding levels of the net benefits per drop of water used within the YRB. The low economic productivity of crops versus high blue water withdrawals and consumption, as shown in Inner Mongolia for instance (Fig. 2), alerts the importance of an economic benefit assessment in regional water supply and cropping pattern designing. (iii) The YRB was a net crop-related VW importer in the current three typical years, while the basin got a net income through domestic crop transfers within China, as mainly contributed by exports of wheat, cotton and apples. It suggests the economic driving forces in the VW networks. What's more, considered scenarios show the net benefits and incomes of physical and VW flows are more sensitive to climate-socio-economic changes than corresponding quantity of water use.

The current estimates include a number of limitations and assumptions that should be taken seriously. The uncertainties produced by the assumptions made in the parameterization and modeling of WF and VW flows have been clearly illustrated by Zhuo et al. (2016b). We compare the results of this study with those of previous studies (Feng et al., 2012; Hoekstra et al., 2012) that examine blue WF and net VW flows related to crops for the YRB (Table 7). Consistent results with the same order of magnitude are shown. Note that the role of the YRB as a crop-related net VW exporter, as determined by Feng et al. (2012), does not consider rice, which dominates the identification of the YRB as a 'net VW importer' in this study. The net income/expanses of the VW flows estimated in the current study measure the gross benefit without consideration of the cost in the VW trade. Thus there could be some over- or under-estimation according to that in practice, who would pay for the cost among the trade. Scenario studies embody uncertainties. All scenarios are set up based on assumptions regarding climate change and socio-economic developments including population growth, changes in diets and technological improvements. Projections with multiple GCMs can help to address variations in terms of climate projections among GCMs for a given emission scenario(Semenov and Stratonovitch, 2010). We considered four GCMs covering the range of climate changing levels projected by major GCMs for China (Zhuo et al., 2016c). Four scenarios capturing the available changing scales in socio and economic development are already a way to reduce possible uncertainties from assumptions.

4 Conclusions

This study develops an approach, which enables to quantifying separately the net benefits of green and blue water used in crop production based on WF accounting. With an application in a case study for YRB combined with the assessment of net incomes through crop-related VW flows for both current typical years and possible 2050 scenarios under climate-socio-economic developments, the trade-offs between the real green/blue water use and the net benefits per drop of water as well as between the VW flows and corresponding net incomes is shown. Results indicate that the levels of net benefits generated by water used in crop production varied among cropping methods and colors of water. One drop of blue water used in cropland generated 13-42% less net economic benefit than corresponding green water use in the YRB. Cropping pattern significantly impact the net economic productivity per drop of water used in crop production in a certain region. The case of YRB shows the economic unsustainable cropping pattern in the provinces located in the relatively drier upper and middle reaches, where there was high irrigation withdrawal while low economic return to farmers because of growing relatively cheap crops. The YRB was a crop-related net VW importer associated to the intra-national trades, however got increasingly net income due to exports of wheat, cotton and apples. Under possible projected climate and socio-economic changes in the considered scenarios for 2050, the economic returns of crop-related physical and VW flows are shown to be more sensitive than the quantity levels of corresponding water flows as driven by the increasing crop yield and economic water productivity.

The concomitant reversed flows of economic benefits and values to the physical and virtual water flows in crop production and consumption at a basin level are shown in the current analysis. It implies a highly importance of managing the internal trade-offs or mutual effects between the water resources consumption and economic returns, in order to get a win-win situation in maximizing both the water use efficiency and economic productivities per drop of water flows. Green water management is highlighted again according to the current result on higher economic benefits per drop of green water than blue water. The “green water credit” (Bai et al., 2015) that investing farmers in upstream for improving green water use efficiency and reducing green water consumption at both the rainfed and irrigated in the benefit of sustaining both the food production and ecosystem for the basin (Rockström et al., 2010) is one of the feasible measures. Too much focus has been on identifying the external natural or socio-economic driving factors on the physical green and blue water flows in crop production (Sun et al., 2013; Zhao et al., 2015; Zhao and Chen, 2014; Tunittee et al., 2015) or on the associated VW flows (Dalin et al., 2012; Tamea et al., 2014; Wang et al., 2016). Therefore, identifications on the internal driving factors on the water consumption relevant to the generated economic benefits and values are highly recommended in the future. As the very start, the current study identified, for example, the impacts of cropping patterns on the net benefits of green and blue water use by crops. So that modifying cropping pattern could be one of the suggested measures, while being of long-term effects, to maximum the economic benefits of physical and VW flows. With short-term effects on the current cropping lands, it has been proven quantitively that different tillage and irrigation strategies 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.

Balancing environmental and economic benefits is definitely the key to realizing the sustainable water-food-economic nexus. Of course, the current case study, which focuses on the agricultural sector, is still far from a comprehensive treatment of the entire socio-economic-hydrological system. Therefore, the current estimation can be improved in the future by adding modules that enable the assessment of water quality-related issues and other water sectors.

Data availability

The GIS polygon data for the YRB can be extracted from HydroSHEDS dataset at https://hydrosheds.cr.usgs.gov/ (Lehner et al., 2008). Data on monthly precipitation, ET_0 and temperature at 30 arc minute resolution can be obtained from CRU-TS-3.10.01 at https://crudata.uea.ac.uk/cru/data/hrg/ (Harris et al., 2014). Data on irrigated and rain-fed harvested area for each crop at 5 arc minute resolution are obtained from MIRCA 2000 dataset (Portmann et al., 2010) and Monfreda et al. (2008). The downscaled GCM outputs at 5 by 5 arc min grid level for the YRB on monthly precipiation, maximum and minimum were freely accessible at http://www.ccafs-climate.org/data/ (Ramirez-Villegas and Jarvis, 2010). AquaCrop model can be freely obtained at http://www.fao.org/land-water/databases-and-software/aquacrop/en/. The data in the current results can be obtained by contacting L. Zhuo.

Author contribution

PW and LZ and GZ designed the study, LZ carried out the study, MM, AY, YW revised the study design and the methodologie. PW and LZ prepared the manuscript with contributions by all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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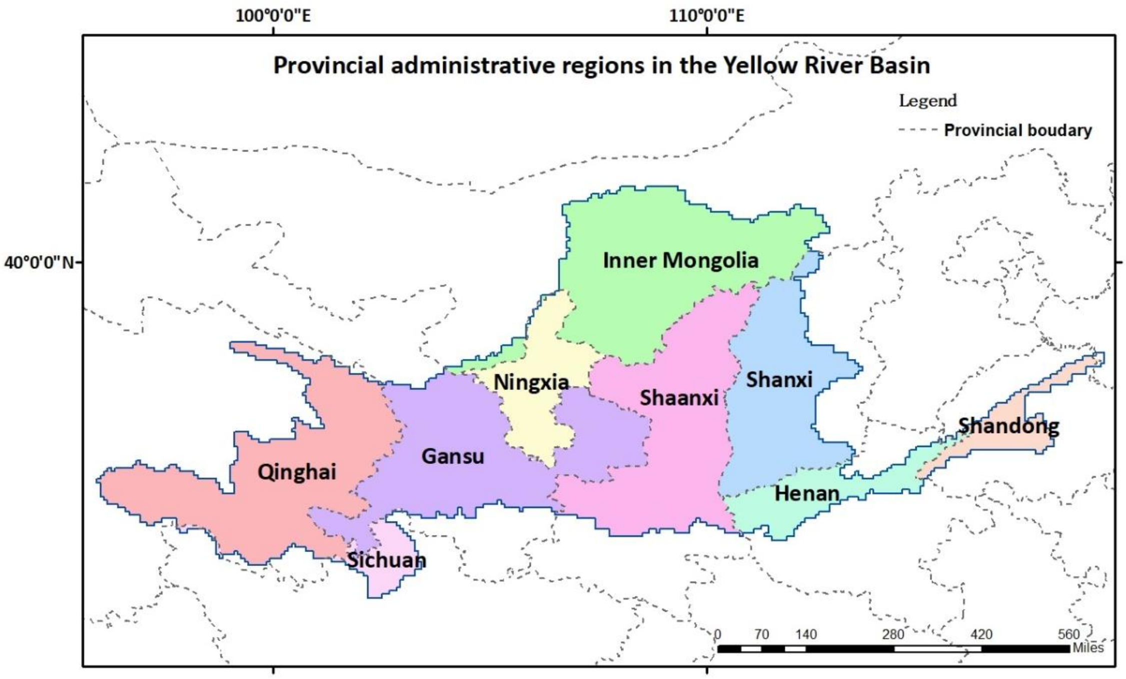


Figure 1. Provincial administrative regions in the Yellow River Basin.

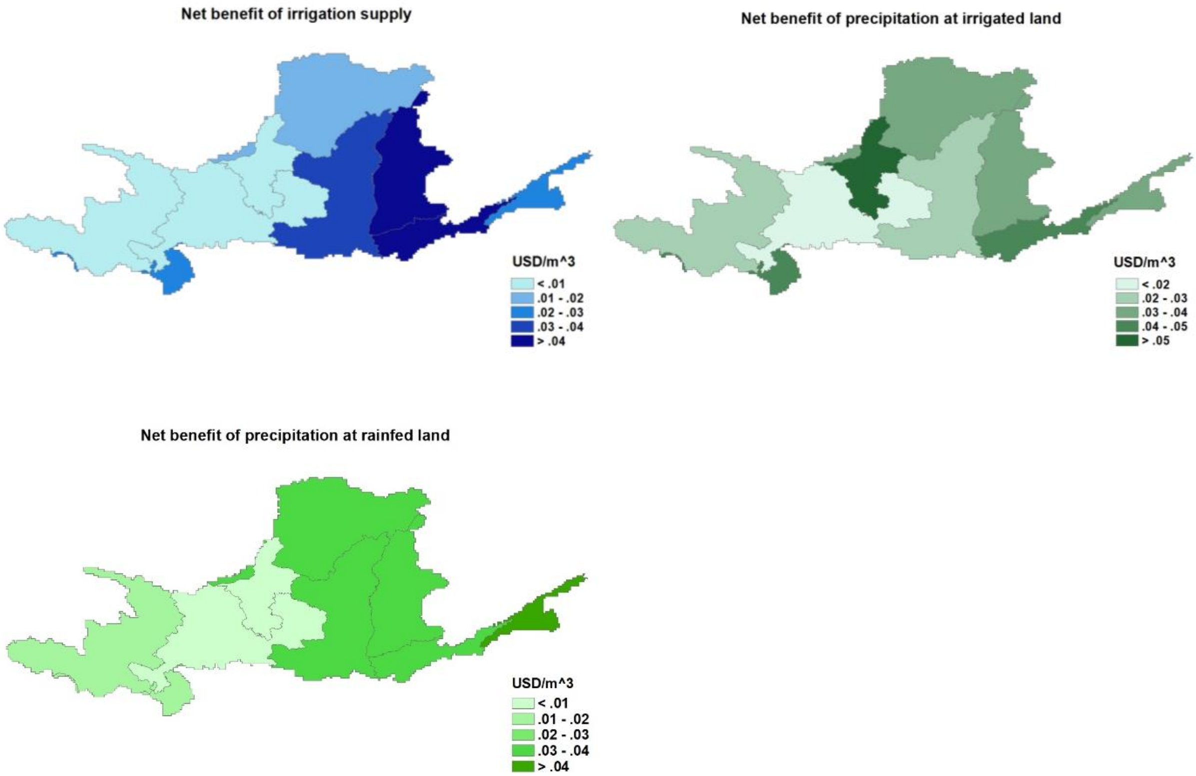
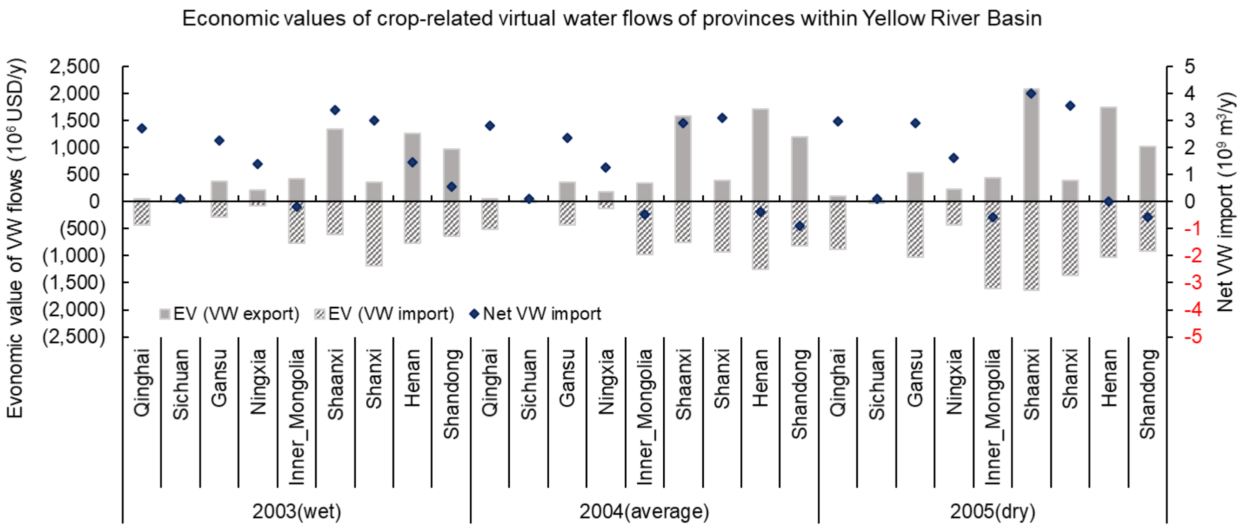


Figure 2. Net benefit of green and blue water supplied for, crop production among provinces across the Yellow River Basin. Year: 2004 (average).



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2 **Figure 3. Economic values of crop-related virtual water flows per province within the Yellow River Basin.**

3

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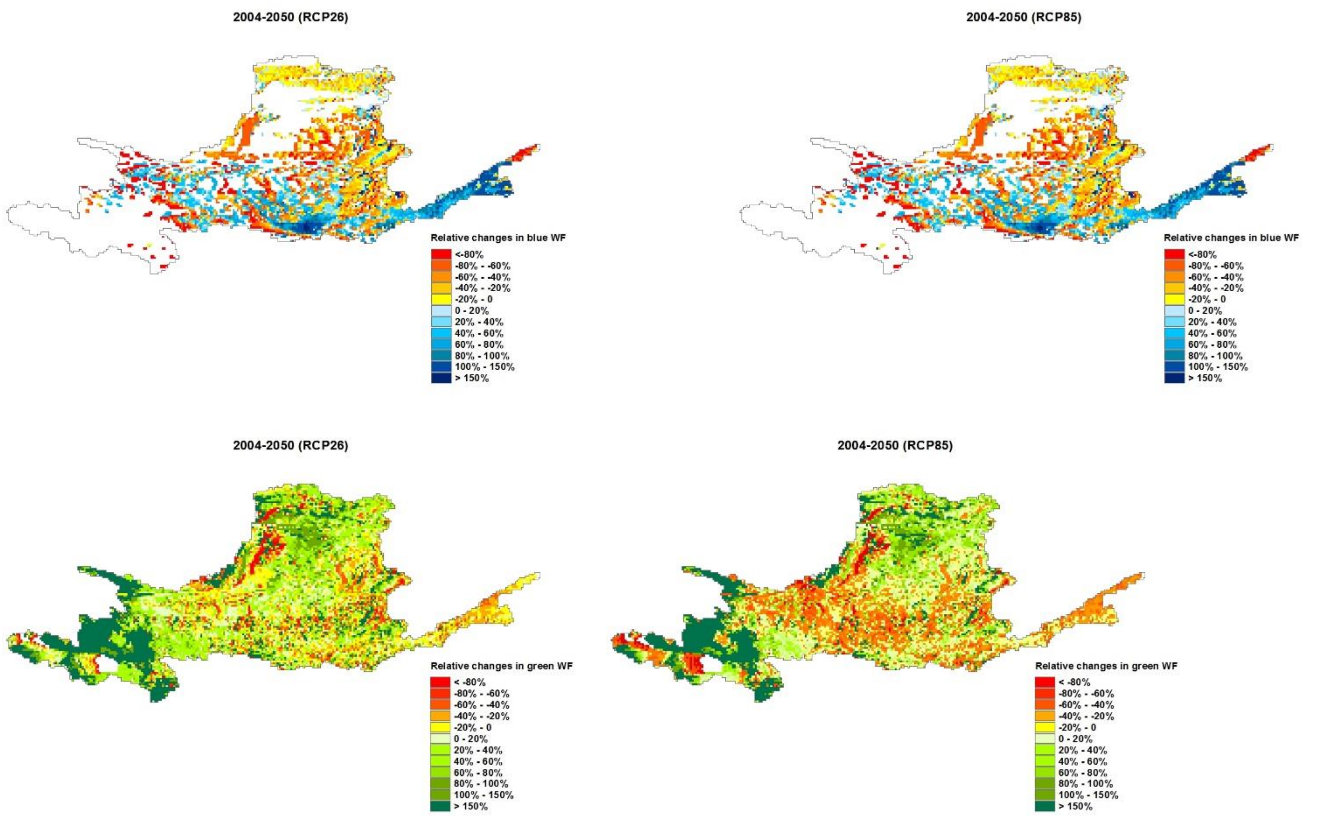

Figure 4. Multi-GCM average relative changes in green and blue WFs of crop production under climate change scenarios for 2050 as compared to 2004 in the Yellow River Basin.

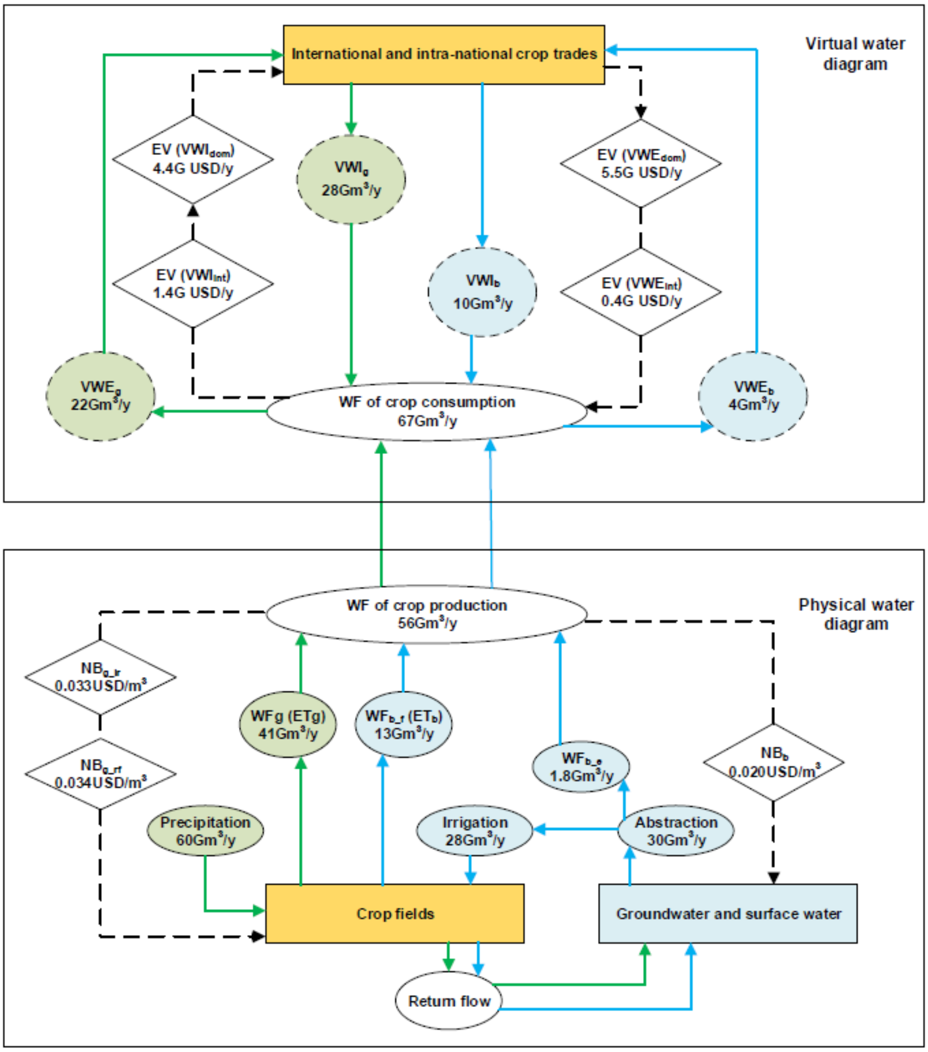

Figure 5. Crop-related green and blue physical and virtual water diagram within the Yellow River Basin for the year of 2004.

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]	25%	29%	11%	19%	31%	25%	16%	18%
Relative changes in annual ET_0[a]	5%	11%	1%	2%	6%	13%	3%	5%
Relative changes in CO_2 concentration	13%				18%			
Total population growth [b]	-5.8%		-5.8%		-2.8%		0.6%	
Yield increase through technology[c]	65%		38%		38%		19%	
Improvement in irrigation network efficiency	30%		30%		20%		10%	
Diet scenarios[d]	'less meat'		'less meat'		'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 2. Diet scenarios for 2050 and comparisons to the baseline year of 2004.

unit: Kcal/cap/d	2004[a]	2050 [b] 'Current trend' scenario	2050 [b] 'Less meat' scenario
Cereal	1473	1552 (5%)	1709 (16%)
Roots	189	149 (-21%)	201 (6%)
Sugar crops	59	85 (44%)	124 (110%)
Oil crops	234	288 (23%)	265 (13%)
Vegetables and fruits	239	205 (-14%)	219 (-8%)
Other crops	92	66 (-28%)	82 (-11%)
Animal products	575	612 (6%)	372 (-35%)
Total	2286	2957 (29%)	2973

a. Source: FAOSTAT (FAO,2014)

b. Values are generated according to the scenarios for East Asia by Erb et al. (2009); relative changes from the 2005 level are shown in parentheses.

Table 3. Crop-related physical water flows and associated net benefits per drop of water in the Yellow River Basin.

		2003 (wet)	2004 (average)	2006 (dry)
Physical water Supply ($10^9 m^3/y$)	Precipitation on croplands ($10^9 m^3/y$)	77	60	49
	Irrigation withdrawal ($10^9 m^3 y^{-1}$)	29	30	36
	Surface water	22	24	29
	Ground water	7	7	7
Physical water consumption ($10^9 m^3/y$)	WF of crop production	52	55	56
	Green WF	39	40	38
	Blue WF	13	15	17
	Blue WF at field level	12	13	15
	Blue WF irrigation network	1.7	1.8	2.1
Net benefit per water (USD/m^3)	Blue water	0.024	0.020	0.019
	Green water for irrigated crops	0.027	0.033	0.033
	Green water for rainfed crops	0.021	0.034	0.027

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Table 4. Basin's average water footprint (WF) in production, producer price and cost of producing each considered crop in the Yellow River Basin.

	2003				2004				2006			
	Green-blue WF (m^3/t)	Blue WF (m^3/t)	Producer price[a] (USD/kg)	Cost in production[a] (USD/kg)	Green-blue WF (m^3/t)	Blue WF (m^3/t)	Producer price (USD/kg)	Cost in production (USD/kg)	Green-blue WF (m^3/t)	Blue WF (m^3/t)	Producer price (USD/kg)	Cost in production (USD/kg)
Rice	772	165	0.15	0.11	618	153	0.20	0.11	630	224	0.21	0.13
Wheat	1696	514	0.14	0.14	1572	498	0.18	0.15	1573	559	0.19	0.17
Maize	667	163	0.13	0.09	565	139	0.14	0.11	862	263	0.17	0.12
Sorghum	714	41	0.12	0.07	666	36	0.15	0.10	981	72	0.16	0.09
Millet	1495	85	0.20	0.16	1478	81	0.20	0.17	1613	105	0.25	0.26
Barley	702	54	0.12	0.07	623	46	0.15	0.10	909	58	0.16	0.09
Soybean	2183	364	0.36	0.20	2110	409	0.34	0.33	2338	586	0.31	0.36
Potatoes	282	13	0.06	0.04	348	18	0.07	0.04	337	22	0.09	0.08
Cotton	2022	555	1.66	1.04	1585	375	1.37	1.04	1372	434	1.55	1.20
Sunflower	1632	148	0.29	0.21	1188	139	0.32	0.27	1217	210	0.31	0.31
Groundnuts	1935	251	0.39	0.27	1748	205	0.44	0.24	1809	304	0.51	0.34
Sugar beet	236	0	0.03	0.02	177	0	0.03	0.03	252	0	0.04	0.03
Rapeseed	3115	0	0.29	0.21	2823	0	0.32	0.27	2755	0	0.31	0.31
Tomato	272	21	0.08	0.04	161	17	0.10	0.05	252	19	0.12	0.07
Apples	498	51	0.10	0.07	455	50	0.12	0.08	607	71	0.19	0.10
Sweet potatoes	462	158	0.06	0.04	460	143	0.07	0.04	454	189	0.09	0.08

a. Sources: NDRC (2004, 2005, 2007).

Table 5. WF of crop consumption, related VW flows and associated economic values in the Yellow River Basin.

		2003 (wet)	2004 (average)	2006 (dry)
WF of crop consumption ($10^9 m^3$/y)	Total WF	67	67	70
	Green WF	50	49	51
	Blue WF	17	18	19
	External rate	41%	41%	42%
Crop-related net VW import ($10^9 m^3$/y)	Total	15	11	14
	International trade related	4	7	8
	Green	4	6	7
	Blue	0.3	0.9	1.1
	Domestic trades related	10	4	6
	Green	7	2	5
	Blue	4	2	1
Economic values of VW flows (USD/m^3)	International VW export	0.247	0.332	0.535
	International VW import	0.180	0.278	0.617
	Domestic VW export	0.176	0.239	0.297
	Domestic VW import	0.124	0.132	0.149
Net income of VW flows (10^6USD/y)	International VW flows	-23	-1005	-3480
	Domestic VW flows	267	1048	1135

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Table 6. Responses in crop-related physical and VW flows, net benefits of water use and economic values of VW flows to climate-socio-economic scenarios for 2050 of the Yellow River Basin.

	Relative changes from 2004 to 2050			
	S1	S2	S3	S4
Precipitation on croplands	-1%	-1%	-0.5%	-0.5%
Irrigation withdrawal	-7%	-2%	-2%	4%
WF of crop production	5%	5%	1%	1%
Green WF	1.87%	1.87%	-3%	-3%
Blue WF	18%	18%	17%	17%
Blue WF at field level	24%	24%	22%	22%
Blue WF irrigation network	-32%	-32%	-22%	-12%
Net benefit of water				
Blue water	69%	34%	39%	-3%
Green water for irrigated crops	50%	25%	30%	-16%
Green water for rainfed crops	55%	30%	134%	123%
WF of crop consumption	-45%	-38%	-35%	-24%
Green WF	-44%	-37%	-34%	-23%
Blue WF	-50%	-43%	-40%	-27%
Net VW import	-304%	-260%	-224%	-155%
Green water	-266%	-223%	-183%	-117%
Blue water	-412%	-365%	-343%	-265%
Economic value (VWE)	286%	194%	233%	154%
Economic value (VWI)	-25%	-20%	-19%	-11%

Table 7. Comparison of the blue water footprints and net virtual water flows related to crops for the Yellow River Basin determined in this study with the results of previous studies.

	Current study	Feng et al. (2012)	Hoekstra et al. (2012)
Total blue WF of crop production (Gm^3/y)	15.2 ~ 20.5	9.9	16.6 *
Crop-related net virtual water import (no rice) (Gm^3/y)	-4.8 ~ -12.9	-8.4	

* Based on the observation that the blue WF of crop production accounts for 73% of the total blue WF in the YRB in terms of the long-term average (Zhuo et al., 2016a).