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A CASE STUDY FOR THE YELLOW RIVER BASIN

VALUE OF WATER

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**SENSITIVITY AND UNCERTAINTY IN CROP WATER FOOTPRINT
ACCOUNTING: A CASE STUDY FOR THE YELLOW RIVER BASIN**

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Summary

Water Footprint Assessment is a quickly growing field of research, but as yet little attention has been paid to the uncertainties involved. This study investigates the sensitivity of water footprint estimates to changes in important input variables and quantifies the size of uncertainty in water footprint estimates. The study focuses on the green and blue water footprint of producing maize, soybean, rice and wheat in the Yellow River Basin in the period 1996-2005. A grid-based daily water balance model at a 5 by 5 arc minute resolution was applied to compute green and blue water footprints of the four crops in the Yellow River Basin in the period considered. The sensitivity and uncertainty analysis focused on the effects on water footprint estimates at basin level (in m³/ton) from four key input variables: precipitation (PR), reference evapotranspiration (ET_0), crop coefficient (K_c) and crop calendar. The one-at-a-time method was carried out to analyse the sensitivity of the water footprint of crops to changes in the input variables. Uncertainties in crop water footprint estimates were quantified through Monte Carlo simulations.

The results show that the water footprint of crops is most sensitive to ET_0 and K_c , followed by crop calendar and PR . Blue water footprints were more sensitive to input variability than green water footprints. The smaller the annual blue water footprint, the higher its sensitivity to changes in PR , ET_0 and K_c . The uncertainties in the total water footprint of a crop due to combined uncertainties in climatic inputs (PR and ET_0) were about $\pm 20\%$ (at 95% confidence interval). The effect of uncertainties in ET_0 was dominant compared to that of precipitation. The uncertainties in the total water footprint of a crop as a result of combined key input uncertainties were on average $\pm 26\%$ (at 95% confidence level). The sensitivities and uncertainties differ across crop types, with highest sensitivities and uncertainties for soybean.

1. Introduction

More than two billion people live in highly water stressed areas (Oki and Kanae, 2006), and the pressure on freshwater will inevitably be intensified by population growth, economic development and climate change in the future (Vörösmarty et al., 2000). The water footprint (Hoekstra, 2003) is increasingly recognized as a suitable indicator of human appropriation of freshwater resources and is becoming widely applied to get better understanding of the sustainability of water use. In the period 1996-2005, agriculture contributed 92% to the total water footprint of humanity (Hoekstra and Mekonnen, 2012).

Water footprints within the agricultural sector have been extensively studied, mainly focusing on the water footprint of crop production, at scales from a sub-national region (e.g. Aldaya and Llamas, 2008; Zeng et al., 2012; Sun et al., 2013), and a country (e.g. Ma et al., 2006; Hoekstra and Chapagain, 2007b; Kampman, et al., 2008; Liu and Savenije, 2008; Bulsink et al., 2010; Ge et al., 2011) to the globe (Hoekstra and Chapagain, 2007a; Liu et al., 2010; Siebert and Döll, 2010; Mekonnen and Hoekstra, 2011; Hoekstra and Mekonnen, 2012). The green or blue water footprint of a crop is normally expressed by a single volumetric number referring to an average value for a certain area and period. However, the water footprint of a crop is always estimated based on a large set of assumptions with respect to the modelling approach, parameter values, and datasets for input variables used, so that outcomes carry substantial uncertainties (Mekonnen and Hoekstra, 2010; Hoekstra et al., 2011). In order to provide realistic information to stakeholders in water governance, analysing the sensitivity and the magnitude of uncertainties in the results of a Water Footprint Assessment in relation to assumptions and input variables would be useful (Hoekstra, et al., 2011; Mekonnen and Hoekstra 2011).

Together with the carbon footprint and ecological footprint, the water footprint is part of the “footprint family of indicators” (Galli et al., 2012), a suite of indicators to track human pressure on the surrounding environment. Nowadays, it is not hard to find information in literature on uncertainties in the carbon footprint of food products (Röös et al., 2010, 2011) or uncertainties in the ecological footprint (Parker and Tyedmers, 2012). But there are hardly any sensitivity or uncertainty studies available in the water footprint field (Hoekstra et al., 2011), while only some subjective approximations and local rough assessments exist (Mekonnen and Hoekstra, 2010, 2011; Hoekstra et al., 2012; Mattila et al., 2012). Bocchiola et al. (2013) assessed the sensitivity of the water footprint of maize to potential changes of certain selected weather variables in Northern Italy. Guieysse et al. (2013) assessed the sensitivity of the water footprint of fresh algae cultivation to changes in methods to estimate evaporation.

The objectives of this study are (1) to investigate the sensitivity of the water footprint of a crop to changes in key input variables, and (2) to quantify the uncertainty in green, blue and total water footprints of crops due to uncertainties in input variables at river basin level. The study focuses on the water footprint of producing maize, soybean, rice and wheat in the Yellow River Basin, China, for each separate year in the period 1996-2005. Uncertainty in this study refers to the output uncertainty that accumulates due to the uncertainties in inputs that is propagated through the water footprint accounting process and is reflected in the resulting estimates (Walker et al., 2003).

2. Study area

The Yellow River Basin (YRB), drained by the Yellow River (*Huanghe*), is the second largest river basin in China with a drainage area of $795 \times 10^3 \text{ km}^2$ (YRCC, 2011). The Yellow River is 5,464 km long, originates from the Bayangela Mountains of the Tibetan Plateau, flows through nine provinces (Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shanxi, Henan and Shandong), and finally drains into the Bohai Sea (YRCC, 2011). 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) (see Figure 1).

The YRB is vital for food production, natural resources and socioeconomic development of China (Cai et al., 2011). The cultivated area of the YRB accounts for 13% of the national total (CMWR, 2010). In 2000, the basin accounted for 14% of the country's crop production with about 7 million ha of irrigated land at a total agriculture area in the basin of 13 million ha (Ringler et al., 2010). The water of the Yellow River supports 150 million people with a per capita blue water availability of 430 m^3 per year (Falkenmark and Widstrand, 1992; Ringler et al., 2010). The YRB is a net virtual water exporter (Feng et al., 2012) and suffering severe water scarcity. The blue water footprint in the basin is larger than the maximum sustainable blue water footprint (runoff minus environmental flow requirements) during eight months a year (Hoekstra et al., 2012).

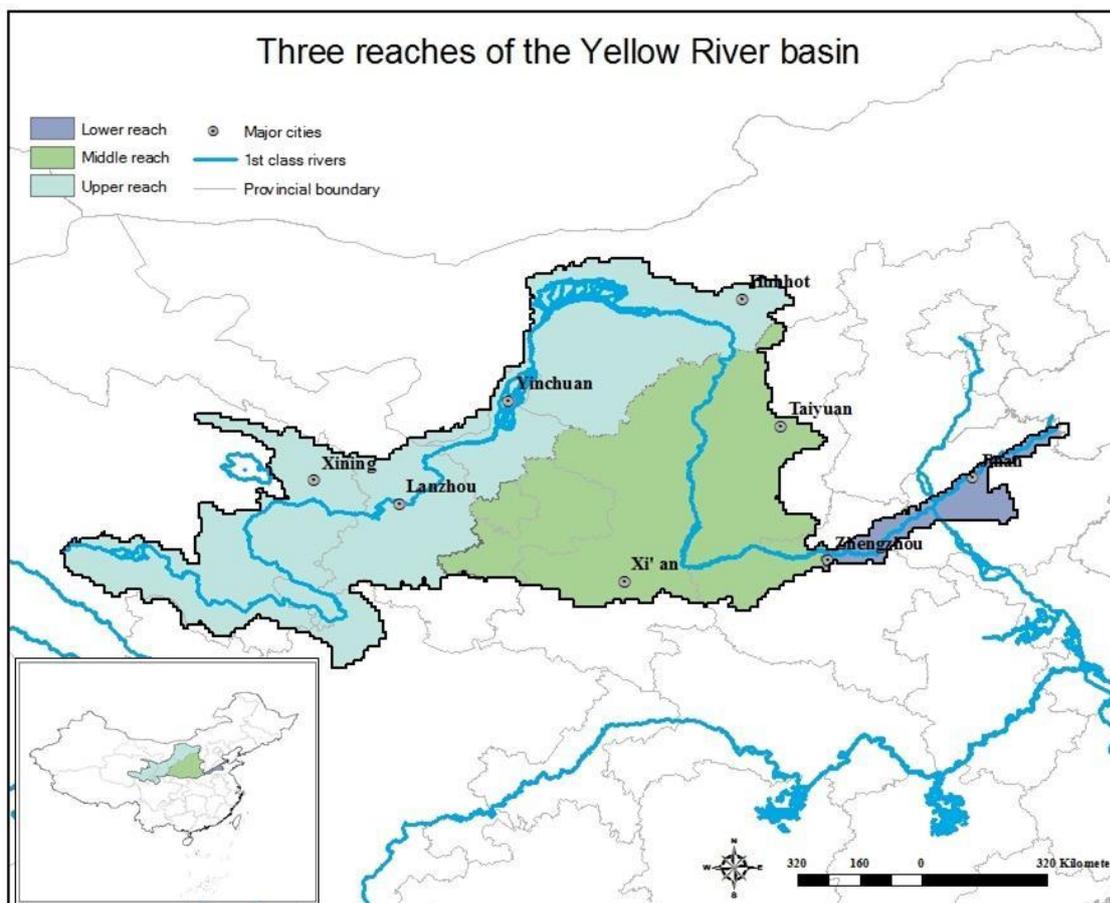


Figure 1. The three reaches of the Yellow River Basin.

3. Method and data

3.1 Crop water footprint accounting

Annual green and blue water footprints (WF) of producing maize, soybean, rice, and wheat in the YRB for the study period were estimated using the grid-based dynamic water balance model developed by Mekonnen and Hoekstra (2010). The model has a spatial resolution of 5 by 5 arc minute (about $7.4 \text{ km} \times 9.3 \text{ km}$ at the latitude of the YRB). The model is used to compute different components of crop water use (CWU) according to the daily soil water balance (Mekonnen and Hoekstra, 2010, 2011). The daily root zone soil water balance for growing a crop in each grid cell in the model can be expressed in terms of soil moisture ($S_{[t]}$, mm) at the end of the day (Mekonnen and Hoekstra, 2010):

$$S_{[t]} = S_{[t-1]} + I_{[t]} + PR_{[t]} + CR_{[t]} - RO_{[t]} - ET_{a[t]} - DP_{[t]} \quad (1)$$

where $S_{[t-1]}$ (mm) refers to the soil water content on day (t-1), $I_{[t]}$ (mm) the irrigation water applied on day t, $PR_{[t]}$ (mm) precipitation, $CR_{[t]}$ (mm) capillary rise from the groundwater, $RO_{[t]}$ (mm) water runoff, $ET_{a[t]}$ (mm) actual evapotranspiration and $DP_{[t]}$ (mm) deep percolation on day t.

The green water footprint (WF_{green} , $\text{m}^3 \text{ ton}^{-1}$) and blue water footprint (WF_{blue} , $\text{m}^3 \text{ ton}^{-1}$) per unit mass of crop were calculated by dividing the green (CWU_{green} , $\text{m}^3 \text{ ha}^{-1}$) and blue (CWU_{blue} , $\text{m}^3 \text{ ha}^{-1}$) CWU by the crop yield (Y , ton ha^{-1}), respectively (Hoekstra, et al., 2011). The total WF refers to the sum of green and blue WF :

$$WF_{green} = CWU_{green} / Y \quad (2)$$

$$WF_{blue} = CWU_{blue} / Y \quad (3)$$

$$WF_{total} = WF_{green} + WF_{blue} \quad (4)$$

CWU_{green} and CWU_{blue} over the crop growing period (in $\text{m}^3 \text{ ha}^{-1}$) were calculated from the accumulated corresponding actual crop evapotranspiration (ET , mm day^{-1}) (Hoekstra et al., 2011):

$$CWU_{green} = 10 \times \sum_{d=1}^{lgp} ET_{green} \quad (5)$$

$$CWU_{blue} = 10 \times \sum_{d=1}^{lgp} ET_{blue} \quad (6)$$

The accumulation was done over the growing period from the day of planting ($d=1$) to the day of harvest (lgp , the length of growing period in days). The factor 10 converts water depths (in mm) into water volumes per unit land surface area in $\text{m}^3 \text{ ha}^{-1}$. The daily actual ET (mm day^{-1}) was computed according to Allen et al. (1998) as:

$$ET = K_s[t] \times K_c[t] \times ET_0[t] \quad (7)$$

where $K_c[t]$ is the crop coefficient, $K_s[t]$ a dimensionless transpiration reduction factor dependent on available soil water and $ET_0[t]$ the reference evapotranspiration (mm day^{-1}). The crop calendar and K_c values for each crop were assumed to be constant for the whole basin as shown in Table 1. $K_s[t]$ is assessed based on a daily function of the maximum and actual available soil moisture in the root zone (Mekonnen and Hoekstra, 2011):

$$K_s[t] = \begin{cases} \frac{s[t]}{(1-p) \times S_{max}[t]}, & S[t] < (1-p) \times S_{max}[t] \\ 1, & otherwise \end{cases} \quad (8)$$

where $S_{max}[t]$ is the maximum available soil water in the root zone (mm, when soil water content is at field capacity), and p the fraction of S_{max} that a crop can extract from the root zone without suffering water stress.

WF of the four crops in the YRB were estimated covering both rain-fed and irrigated agriculture. In the case of rain-fed crop production, blue CWU is zero and green CWU (m^3/ha) was calculated by aggregating the daily values of actual crop evapotranspiration over the length of the growing period. In the case of irrigated crop production, the green water use was assumed to be equal to the actual crop evapotranspiration for the case without irrigation. The blue water use was estimated as the CWU simulated in the case with sufficient irrigation water applied minus the green CWU in the same condition but without irrigation (Mekonnen and Hoekstra, 2010, 2011).

Table 1. Crop characteristics for maize, soybean, rice and wheat in the Yellow River Basin.

	K_{c_ini}	K_{c_mid}	K_{c_end}	Planting date	Length of growing period (days)
Maize	0.70	1.20	0.25	1 April	150
Soybean	0.40	1.15	0.50	1 June	150
Rice	1.05	1.20	0.90	1 May	180
Wheat	0.70	1.15	0.30	1 October	335

Sources: Allen et al. (1998); Chen et al. (1995); Chapagain and Hoekstra (2004).

The crop yield is influenced by water stress (Mekonnen and Hoekstra, 2010). The actual harvested yield (Y , ton ha^{-1}) at the end of crop growing period for each grid cell was estimated following the equation proposed by Doorenbos and Kassam (1979):

$$\left(1 - \frac{Y}{Y_m}\right) = K_y \left(1 - \frac{\sum_{d=1}^{l_{gp}} ET}{CWR}\right) \quad (9)$$

where Y_m is the maximum yield (ton ha^{-1}), K_y the yield response factor, and CWR the crop water requirement for the whole growing period (mm period^{-1}) (which is equal to $K_c \times ET_0$).

3.2 *Sensitivity and uncertainty analysis*

The estimation of *WF* of crop growing requires a number of input data, including: daily precipitation (*PR*), daily reference evapotranspiration (*ET₀*), crop coefficients in the different growing stages (*K_c*), and crop calendar (planting date and length of the growing period). The one-at-a-time method was applied to investigate the sensitivity of *CWU*, *Y* and *WF* to changes in these input variables. The uncertainties in *WF* due to uncertainties in the four input variables were assessed through Monte Carlo simulations.

3.2.1 *Sensitivity analysis*

The ‘one-at-a-time’ or ‘sensitivity curve’ method is a simple but practical way of sensitivity analysis to investigate the response of an output variable to variation of input values (Hamby, 1994; Sun et al, 2012). With its simplicity and intuitionism, the method is popular and has been widely used (Ahn, 1996; Goyal, 2004; Xu et al., 2006a,b; Estévez et al., 2009). The method was performed by introducing fractional changes to one input variable while keeping other inputs constant. The ‘sensitivity curve’ of the resultant relative change in the output variable was then plotted against the relative change of the input variable. The sensitivity analysis was carried out for each year in the period 1996-2005. For each cropped grid cell, we varied each input variable within the range of the mean value $\pm 2SD$ ($2\times$ standard deviation), which represents the 95% confidence interval for the input variable. Then, the annual average level of the responses in *CWU*, *Y* and (green, blue and total) *WF* of the crops for the basin as a whole were recorded.

3.2.2 *Uncertainty analysis*

The advantage of uncertainty analysis with Monte Carlo (MC) simulation is that the model to be tested can be of any complexity (Meyer, 2007). MC simulations were carried out at the basin level to quantify the uncertainties in estimated *WF* due to uncertainties in individual or multiple input variables. We assumed that systematic errors in original climate observations at stations have been removed under a strict quality control and errors indicated as a proportion of input climatic variables are random, independent and close to a normal (Gaussian) distribution. The uncertainty analysis was carried out separately for three years within the study period: 1996 (wet year), 2000 (dry year) and 2005 (average year). For each MC simulation, 1,000 runs were performed. Based on the set of *WF* estimates from those runs, the mean (μ) and standard deviation (SD) is calculated; with 95% confidence, *WF* falls in the range of $\mu \pm 2SD$. The SD will be expressed as a percentage of the mean.

3.2.3 *Input uncertainty*

Uncertainty in precipitation (PR)

Uncertainties in the CRU-TS grid precipitation values come from two sources: the measurement errors inherent in station observations, and errors which occur during the interpolation of station data in constructing the grid database (Zhao and Fu, 2006; Fekete et al, 2004; Phillips and Marks, 1996). Zhao and Fu (2006) compared the spatial distribution of precipitation as in the CRU database with the corresponding observations over China and revealed that the differences between the CRU data and observations vary from - 20% to 20% in the area where

the YRB is located. For this study, we assume a $\pm 20\%$ range around the CRU precipitation data as the 95% confidence interval ($2SD = 20\%$).

Uncertainty in reference evapotranspiration (ET_0)

The uncertainties in the meteorological data used in estimating ET_0 will be transferred into uncertainties in the ET_0 values. The method used to estimate the CRU-TS ET_0 dataset is the Penman-Monteith (PM) method (Allen et al., 1998). The PM method has been recommended (Allen et al., 1998) for its high accuracy at station level within $\pm 10\%$ from the actual values under all ranges of climates (Jensen et al., 1990). With respect to the gridded ET_0 calculation, the interpolation may cause additional error (Thomas, 2008; Phillips and Marks, 1996). There is no detailed information on uncertainty in the CRU-TS ET_0 dataset. We estimated daily ET_0 values (mm day^{-1}) for the period 1996-2005 from observed climatic data at 24 meteorological stations spread out in the YRB (CMA, 2008) by the PM method. Then we compared, station by station, the monthly averages of those calculated daily ET_0 values to the monthly ET_0 values in the CRU-TS dataset (Figure 2a). The differences between the station values and CRU-TS values ranged from -0.23 to 0.27mm day^{-1} with a mean of 0.005mm day^{-1} (Figure 2b). The standard deviation (SD) of the differences was 0.08mm day^{-1} , 5% from the station values, which implies an uncertainty range of $\pm 10\%$ ($2SD$) at 95% confidence interval. We added the basin level uncertainty in monthly ET_0 values due to uncertainties in interpolation ($\pm 10\%$ at 95% confidence level) and the uncertainty related to the application of the PM method (another $\pm 10\%$ at 95% confidence level) to arrive at an overall uncertainty of $\pm 20\%$ ($2SD$) for the ET_0 data. We acknowledge that this is a crude estimate of uncertainty, but there is no better.

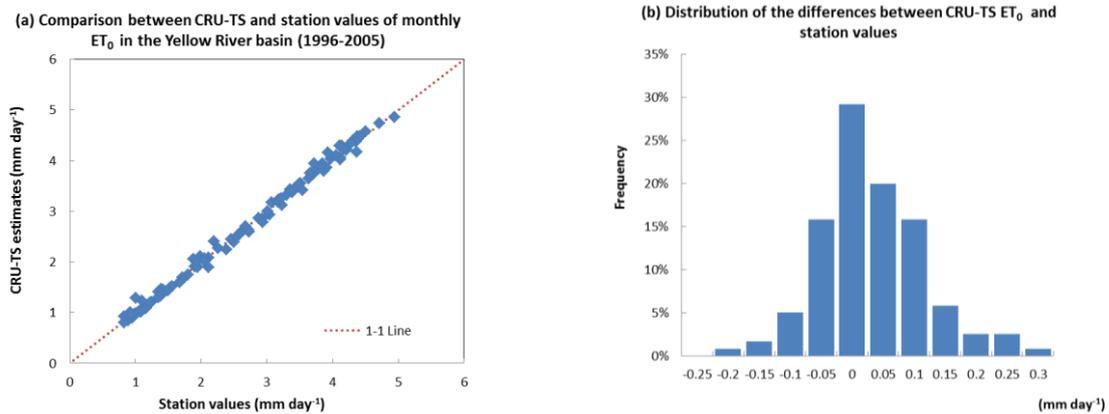


Figure 2. Differences between monthly averages of daily ET_0 data from CRU-TS and station-based values for the Yellow River Basin, 1996-2005.

Uncertainty in crop characteristics

We used the K_c values from Table 1 for the whole basin. According to Jagtap and Jones (1989), the K_c value for a certain crop can vary by 15%. We adopted this value and assumed the 95% uncertainty range falls within $\pm 15\%$ ($2SD$) from the mean K_c values. Referring to the crop calendar, we assumed that the planting date for each crop fluctuated within ± 30 days from the original planting date used, holding the same length of the crop growing period. Table 2 summarises the uncertainty scenarios considered in the study.

Table 2. Input uncertainties for crop water footprint accounting in the Yellow River Basin.

Input variable	Unit	95% confidence interval	Distribution
Precipitation (PR)	mm day^{-1}	$\pm 20\%$ (2SD)	Normal
Reference evapotranspiration (ET_0)	mm day^{-1}	$\pm 20\%$ (2SD)	Normal
Crop coefficient (K_c)	-	$\pm 15\%$ (2SD)	Normal
Planting date (D)	days	± 30	Uniform (discrete)

3.3 Data

The GIS polygon data for the YRB were extracted from the HydroSHEDS dataset (Lehner, et al., 2008). Total monthly PR , monthly averages of daily ET_0 , number of wet days, and daily minimum and maximum temperatures at 30 by 30 arc minute resolution for 1996-2005 were extracted from CRU-TS-3.10 and 3.10.01 (Harris, et al., 2013). Figure 3 shows PR and ET_0 for the YRB in the study period. Daily values of precipitation were generated from the monthly values using the CRU-dGen daily weather generator model (Schuol and Abbaspour, 2007). Daily ET_0 values were derived from monthly average values by curve fitting to the monthly average through polynomial interpolation (Mekonnen and Hoekstra, 2011). Data on irrigated and rain-fed areas for each crop at a 5 by 5 arc minute resolution were obtained from the MIRCA2000 dataset (Portmann et al., 2010). Crop areas and yields within the YRB from MIRCA2000 were scaled to fit yearly agriculture statistics per province of China (MAPRC, 2009; NBSC, 2006, 2007). Total available soil water capacity at a spatial resolution of 5 by 5 arc minute was obtained from the ISRIC-WISE version 1.2 dataset (Batjes, 2012).

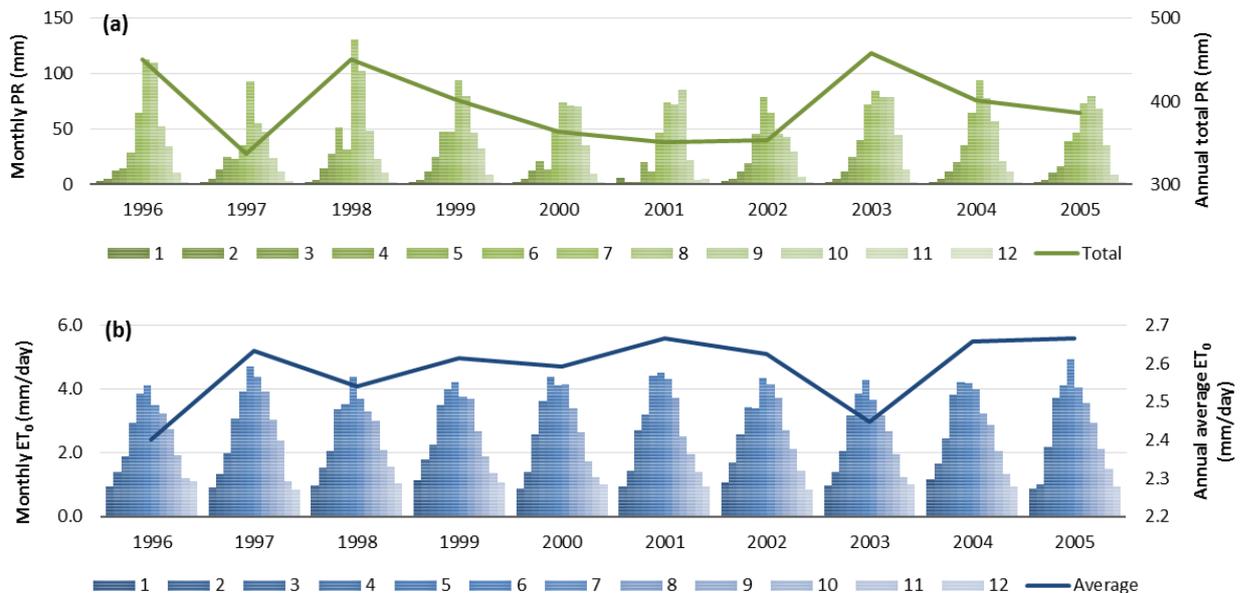


Figure 3. Monthly precipitation (PR) and monthly averages of daily reference evapotranspiration (ET_0) in the Yellow River Basin from the CRU-TS database, for the period 1996-2005.

4. Results

4.1 Sensitivity of *CWU*, *Y* and *WF* to variability of input variables

4.1.1 Sensitivity to variability of precipitation (*PR*)

The average sensitivities of *CWU*, *Y* and *WF* to variability of precipitation for the study period were assessed by varying the precipitation between $\pm 20\%$ as shown in Figure 4. An overestimation in precipitation leads to a small overestimation of green *WF* and a relatively significant underestimation of blue *WF*. A similar result was found for maize in the Po valley of Italy by Bocchiola et al. (2013). The sensitivity of *WF* to input variability is defined by the combined effects on the *CWU* and *Y*. Figure 4 shows the overall result for the YRB, covering both rain-fed and irrigated cropping.

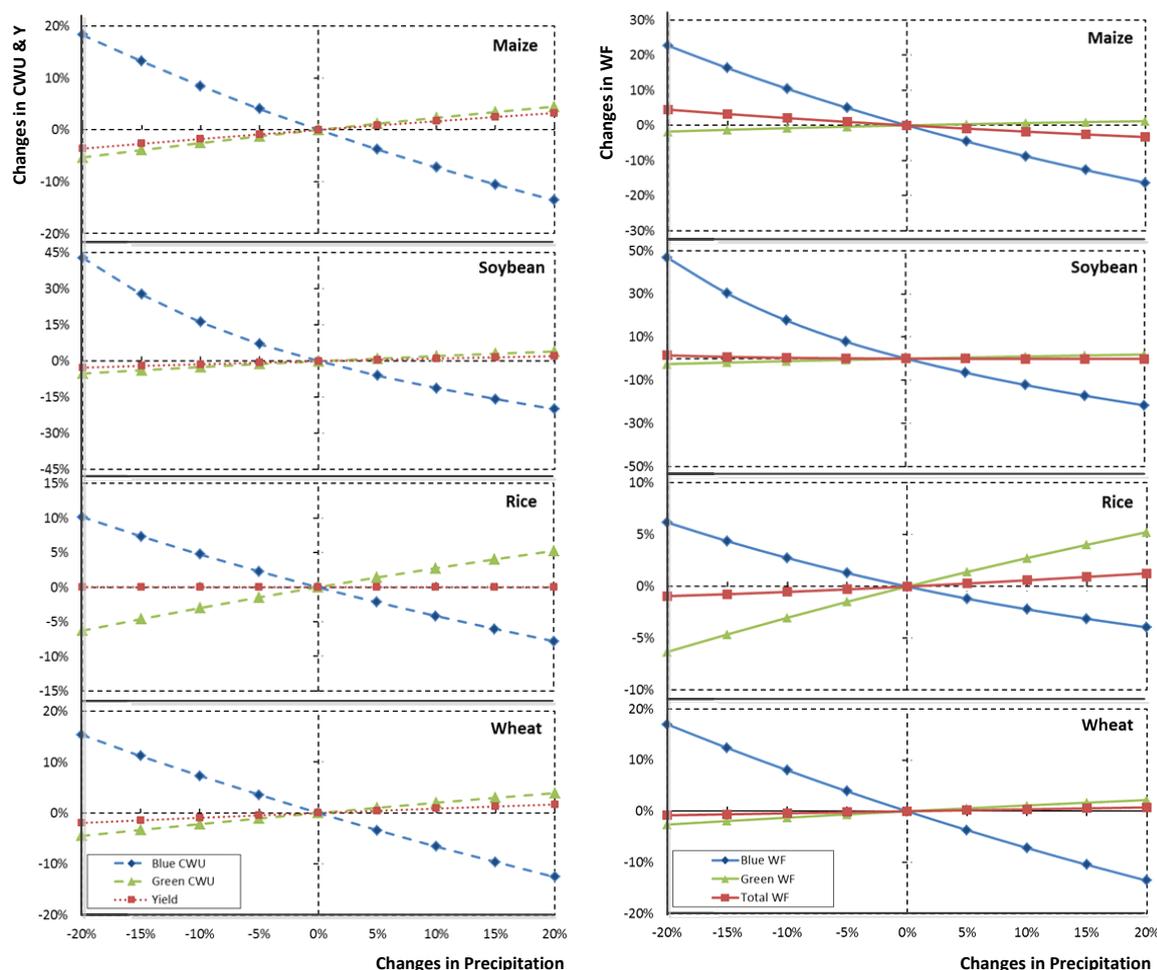


Figure 4. Sensitivity of *CWU*, *Y* and *WF* to changes in precipitation (*PR*), 1996-2005.

For irrigated agriculture, a reduction in green *CWU* due to smaller precipitation will be compensated with an increased blue *CWU*, keeping total *CWU* and *Y* unchanged. Therefore, the changes in *Y* were due to the changes in the yields in rain-fed agriculture. The relative changes in total *WF* were always smaller than $\pm 5\%$ because of the opposite direction of sensitivities of green and blue *WF*, as well as the domination of green *WF* in the total. It

can be noted that the sensitivity of *CWU*, *Y* and *WF* to input variability differs across crop types, especially evident in blue *WF*. Regarding the four crops considered, blue *WF* of soybean is most sensitive to variability in precipitation and blue *WF* of rice is least sensitive. The explanation lies in the share of blue *WF* in total *WF*. At basin level, the blue *WF* of soybean accounted for about 9% of the total *WF*, while the blue *WF* of rice was around 44% of the total, which is the highest blue water fraction among the four crops. The larger sensitivity of the blue *WF* of soybean to change in precipitation compared to that of rice shows that the smaller the blue water footprint the larger its sensitivity to a marginal change in precipitation.

4.1.2 Sensitivity to variability of ET_0 and K_c

Figure 5 shows the average sensitivity of *CWU*, *Y* and *WF* to changes in ET_0 within a range of $\pm 20\%$ from the mean for the period 1996-2005. The influence of changes in ET_0 on *WF* are greater than the effect of changes in precipitation. Both green and blue *CWU* increase with the rising ET_0 . An increase in ET_0 will increase the crop water requirement. For rain-fed crops, the crop water requirement may not be fully met, leading to crop water stress and thus lower *Y*. For irrigated crops under full irrigation, the crop will not face any water stress, so that the yield will not be affected. The decline in yield at increasing ET_0 at basin level in Figure 5 is therefore due to yield reductions in rain-fed agriculture only.

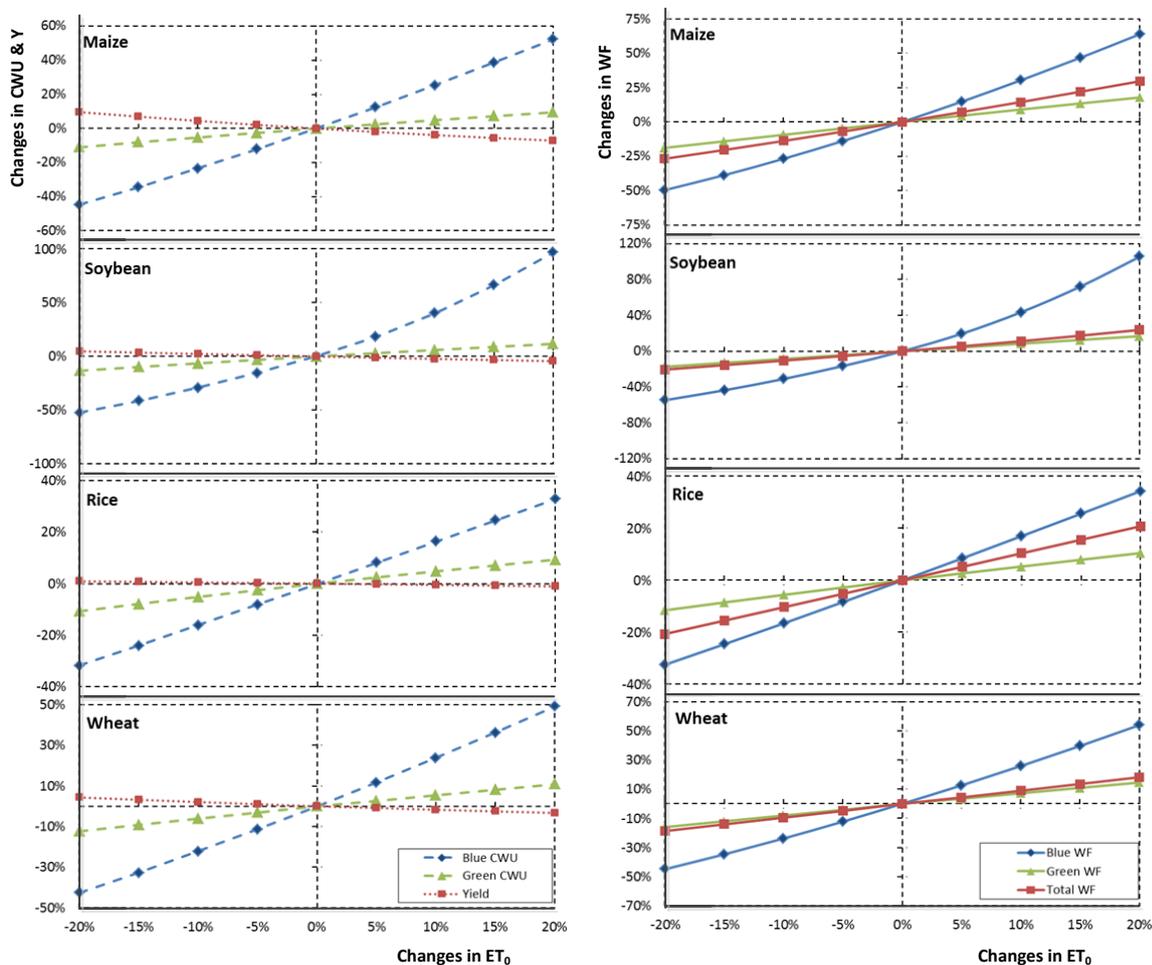


Figure 5. Sensitivity of *CWU*, *Y* and *WF* to changes in reference evapotranspiration (ET_0), 1996-2005.

Due to the combined effect of increasing CWU and decreasing Y at increasing ET_0 , an overestimation in ET_0 leads to a larger overestimation of WF . The strongest effect of ET_0 changes on blue WF was found for soybean, with a relative increase reaching up to 105% with a 20% increase in ET_0 , while the lightest response was found for the case of rice, with a relative increase in blue WF of 34%. The sensitivities of green WF were similar among the four crops. The changes in total WF were always smaller and close to $\pm 30\%$ in the case of a $\pm 20\%$ change in ET_0 .

As shown in Equation 7, K_c and ET_0 have the same effect on crop evapotranspiration. Therefore, the effects of changes in K_c on CWU , Y and WF are exactly the same as the effects of ET_0 changes as shown in Figure 6. The changes in total WF were less than $\pm 25\%$ in the case of a $\pm 15\%$ change in K_c values.

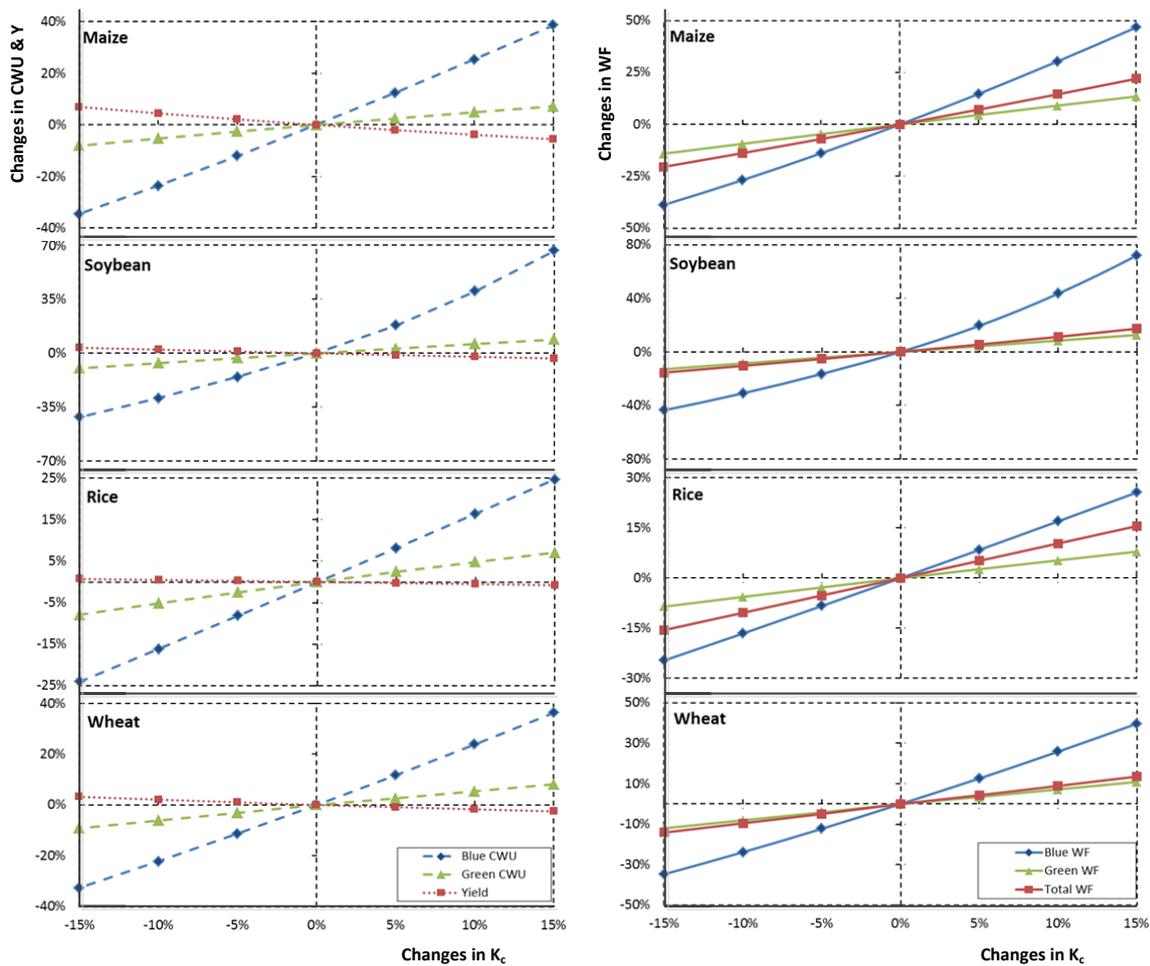


Figure 6. Sensitivity of CWU , Y and WF to changes in the crop coefficient (K_c), 1996-2005.

4.1.3 Sensitivity to changing crop planting date (D)

The responses of CWU , Y and WF to the change of crop planting date with constant growing period are plotted in Figure 7. There is no linear relationship between the cropping calendar and WF . Therefore, no generic information can be summarised for the sensitivity of WF of crops to a changing cropping calendar. But some interesting regularity can still be found for maize, soybean and rice: WF was smaller at later planting date,

mainly because of the decreased blue CWU and increased Y . We found a reduced ET_0 over the growing period with delayed planting of the three crops, which leads to a decrease in the crop water requirement, while precipitation over this later period was higher for maize and slightly lower for soybean and rice. Since blue WF is more sensitive to ET_0 than to PR , the decreased crop water requirement was the dominant factor, resulting in a decreased blue CWU and increased Y . This is consistent with the result observed for maize in western Jilin Province of China by Qin et al. (2012). Late planting, particularly for maize and rice, could save blue water, while increasing Y (for maize). Meanwhile, a different response curve was observed for wheat. Green WF increased when the planting date was delayed and blue WF decreased, but changes are small in both cases. The explanation for the unique sensitivity curve for wheat is that the crop is planted in October after the rainy season (June to September) and the growing period lasts 335 days (Table 1), which leads to a low sensitivity to the precise planting date. In general, the results show that the crop calendar is one of the factors affecting the magnitude of crop water consumption. A proper planning of the crop-growing period is therefore vital from the perspective of water resources use, especially in arid and semi-arid areas like the YRB.

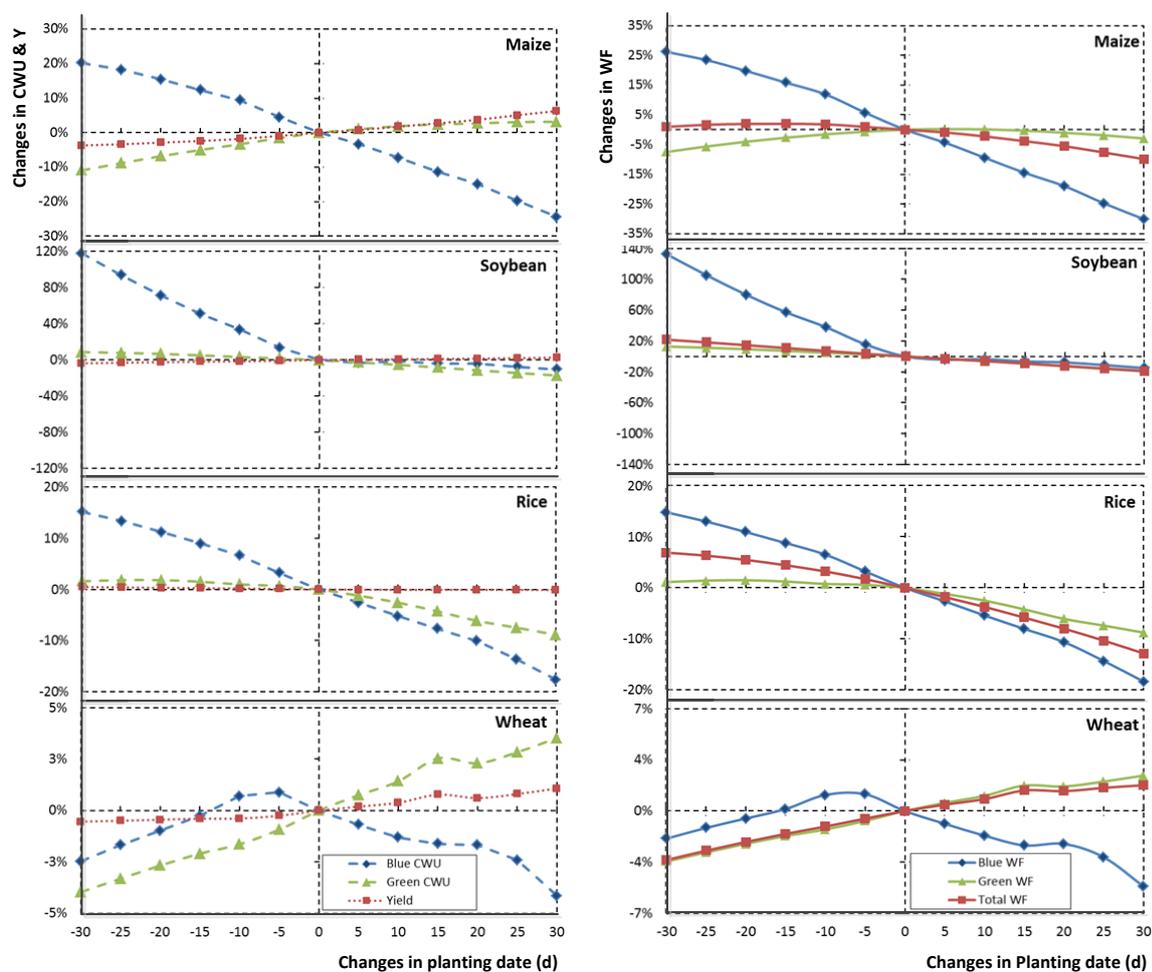


Figure 7. Sensitivity of CWU , Y and WF to changes in crop planting date, 1996-2005.

4.1.4 Annual variation of sensitivities in crop water footprints

As an example of the annual variation of sensitivities, Table 3 presents the sensitivity of blue, green and total WF of maize to changes in key input variables for each specific year in the period 1996-2005. As can be seen from the table, the sensitivity of green WF to the four key input variables was relatively stable around the mean annual level. But there was substantial inter-annual fluctuation of sensitivity of blue WF , observed for all four crops. For each year and each crop, the slope (S) of the sensitivity curve of change in blue WF versus change in PR , ET_0 and K_c was computed, measuring the slope at mean values for PR , ET_0 and K_c . The slopes (representing the percentage change in blue WF per percentage change in input variable) were plotted against the corresponding blue WF (Figure 8). The results show – most clearly for maize and rice – that the smaller the annual blue WF , the higher the sensitivity to changes in PR , ET_0 or K_c . As shown by the straight curves through the data for maize (Figure 8), we can roughly predict the sensitivity of blue WF to changes in input variables based on the size of blue WF itself. The blue WF of a specific crop in a specific field will be more sensitive (in relative terms) to the three inputs in wet years than in dry years, simply because the blue WF will be smaller in a wet year.

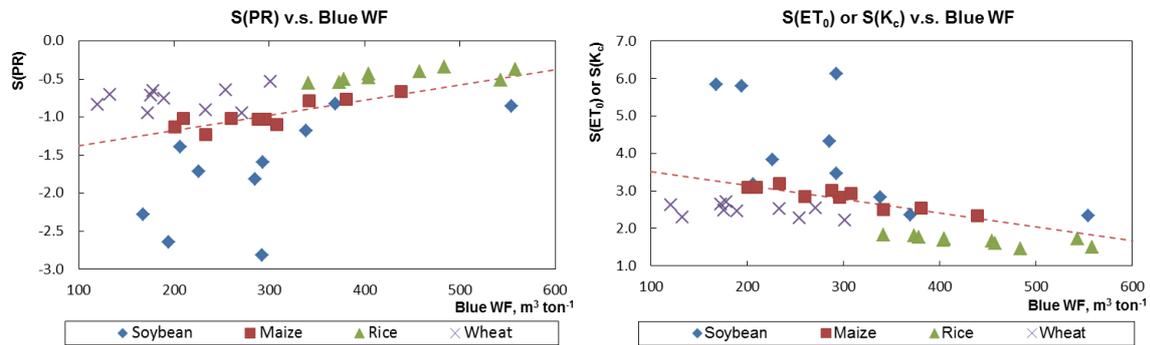


Figure 8. The slope (S) of the sensitivity curve for the blue WF for each crop for each year in the period 1996-2005 (vertical axis) plotted against the blue WF of the crop in the respective year (x -axis). The graph on the left shows the relative sensitivity of blue WF to PR ; the graph on the right shows the relative sensitivity of blue WF to ET_0 or K_c . The sensitivities to ET_0 and K_c were the same. The trend lines in both graphs refer to the data for maize.

4.2 Uncertainties in WF per unit of crop due to input uncertainties

In order to assess the uncertainty in WF (in $m^3 \text{ ton}^{-1}$) due to input uncertainties, Monte Carlo (MC) simulations were performed at the basin level for 1996 (wet year), 2000 (dry year) and 2005 (average year). For each crop, we carried out a MC simulation for four input uncertainty scenarios, considering the effect of: (1) uncertainties in PR alone, (2) uncertainties in ET_0 alone, (3) uncertainties in the two climatic input variables (PR and ET_0), and (4) combined uncertainties in all four key input variables considered in this study ($PR+ET_0+K_c+D$). The resultant uncertainties in blue, green and total WF of the four crops for the four scenarios and three years are shown in Table 4. The uncertainties are expressed in terms of values for 2SD as a percentage of the mean value; the range of $\pm 2SD$ around the mean value gives the 95% confidence intervals.

Table 3. Sensitivity of annual water footprint of maize to input variability at the level of the Yellow River Basin, for the period 1996-2005.

	WF (m ³ ton ⁻¹)	PR		ET ₀		K _c		D		
		-20%	20%	-20%	20%	-15%	15%	-30d	30d	
Blue WF	1996	201	27.3	-18.1	-52.2	71.9	-41.1	52.3	58.3	-40.7
	1997	381	16.7	-14.0	-46.9	55.0	-36.1	40.7	-1.9	-11.3
	1998	209	24.8	-15.8	-53.0	70.4	-41.6	51.4	25.7	-34.4
	1999	308	26.1	-17.7	-50.1	67.4	-39.3	49.1	32.3	-32.1
	2000	342	17.6	-13.9	-45.6	54.4	-35.3	40.2	35.7	-42.7
	2001	439	14.6	-12.2	-43.7	49.9	-33.6	37.0	22.8	-27.1
	2002	296	23.2	-17.9	-50.5	62.4	-39.3	45.9	-13.0	-6.2
	2003	233	28.7	-20.5	-55.5	72.0	-43.5	52.7	35.7	-37.2
	2004	260	23.6	-16.9	-49.2	64.6	-38.5	47.1	46.5	-37.7
	2005	288	24.6	-16.7	-49.8	71.0	-39.3	51.3	19.8	-31.7
	Mean	295	22.7	-16.4	-49.6	63.9	-38.8	46.8	26.2	-30.1
Green WF	1996	754	-1.4	0.9	-18.4	18.2	-13.8	13.7	-7.3	-2.1
	1997	820	-2.0	1.3	-19.1	17.8	-14.2	13.5	-10.7	-1.1
	1998	792	-1.3	0.7	-19.0	18.3	-14.2	13.8	-7.0	-2.1
	1999	864	-2.1	1.3	-19.0	17.7	-14.1	13.4	-8.2	-3.4
	2000	831	-2.0	1.3	-18.9	17.8	-14.1	13.5	-6.9	-3.8
	2001	819	-2.3	1.7	-18.6	16.9	-13.9	12.9	-8.5	-2.6
	2002	865	-1.7	1.2	-18.4	17.6	-13.8	13.3	-6.3	-3.7
	2003	882	-1.4	1.0	-18.8	18.4	-14.1	13.9	-6.0	-3.5
	2004	838	-1.5	0.9	-19.2	18.5	-14.4	14.0	-5.2	-5.3
	2005	733	-2.1	1.6	-19.1	17.2	-14.2	13.1	-9.0	-1.8
	Mean	820	-1.8	1.2	-18.9	17.9	-14.1	13.5	-7.5	-2.9
Total WF	1996	955	4.7	-3.1	-25.5	29.5	-19.6	21.8	6.5	-10.2
	1997	1200	3.9	-3.6	-27.9	29.6	-21.2	22.1	-7.9	-4.3
	1998	1001	4.2	-2.8	-26.1	29.2	-19.9	21.7	-0.2	-8.9
	1999	1172	5.3	-3.7	-27.1	30.8	-20.7	22.7	2.4	-10.9
	2000	1172	3.7	-3.1	-26.7	28.5	-20.3	21.3	5.5	-15.1
	2001	1257	3.6	-3.1	-27.4	28.4	-20.8	21.3	2.4	-11.2
	2002	1160	4.7	-3.7	-26.6	29.0	-20.3	21.6	-8.0	-4.3
	2003	1116	4.9	-3.5	-26.5	29.6	-20.2	22.0	2.7	-10.5
	2004	1098	4.4	-3.3	-26.3	29.4	-20.1	21.8	7.0	-13.0
	2005	1021	5.4	-3.6	-27.7	32.4	-21.3	23.9	-0.9	-10.2
	Mean	1115	4.5	-3.3	-26.8	29.6	-20.4	22.0	1.0	-9.9

Table 4. 2SD for the probability distribution of the blue, green and total WF of maize, soybean, rice and wheat, expressed as % of the mean value.

Crop	Perturbed inputs	1996 (wet year)			2000 (dry year)			2005 (average year)		
		Blue WF	Green WF	Total WF	Blue WF	Green WF	Total WF	Blue WF	Green WF	Total WF
Maize	<i>PR</i>	14	4	0.2	10	4	0.2	8	4	0
	<i>ET₀</i>	48	12	20	38	12	20	36	12	18
	<i>PR+ET₀</i>	48	12	20	42	12	20	38	14	20
	<i>PR+ET₀+K_c+D</i>	76	18	24	64	18	24	52	18	24
Soybean	<i>PR</i>	22	1.2	0.2	18	2	2	14	2	0.8
	<i>ET₀</i>	56	16	18	50	14	16	40	14	16
	<i>PR+ET₀</i>	62	16	18	56	14	18	44	14	18
	<i>PR+ET₀+K_c+D</i>	98	26	30	94	26	32	68	26	28
Rice	<i>PR</i>	10	6	0	8	6	0	7	6	0
	<i>ET₀</i>	34	12	20	30	12	20	30	12	20
	<i>PR+ET₀</i>	34	12	20	32	12	20	32	13	20
	<i>PR+ET₀+K_c+D</i>	62	16	28	56	20	30	50	18	28
Wheat	<i>PR</i>	14	2	0.4	14	2	0.4	16	2	0
	<i>ET₀</i>	48	16	20	46	16	18	52	16	18
	<i>PR+ET₀</i>	52	16	20	48	16	18	54	16	18
	<i>PR+ET₀+K_c+D</i>	68	20	24	66	20	24	74	20	24

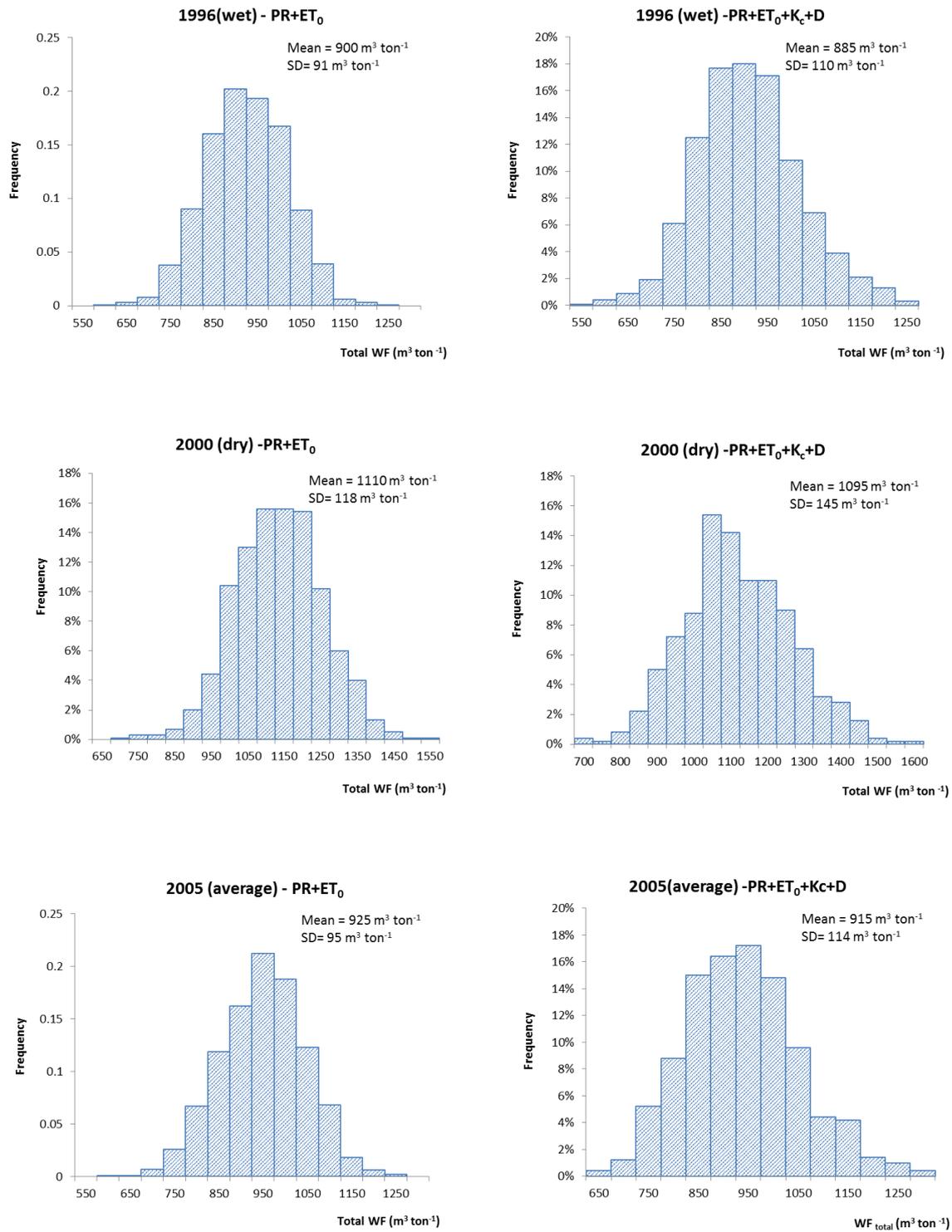


Figure 9. Probability distribution of the total WF of maize given the combined uncertainties in PR and ET₀ (graphs at the left) and given the combined uncertainties in PR, ET₀, K_c and D (graphs at the right), for the years 1996, 2000 and 2005.

In general, for all uncertainty scenarios, blue *WF* shows higher uncertainties than green *WF*. Uncertainties in green *WF* are similar for the three different hydrologic years. Uncertainties in blue *WF* are largest (in relative sense) in the wet year, conform our earlier finding that blue *WF* is more sensitive to changes in input variables in wet years. The uncertainties in *WF* due to uncertainties in *PR* are much smaller than the uncertainties due to uncertainties in *ET₀*. Uncertainties in *PR* hardly affect the assessment of total *WF* of crops in all three different hydrologic years. Among the four crops, soybean had the highest uncertainty in green and blue *WF*. The uncertainty in total *WF* for all crops was within the range of ± 18 to 20% (at 95% confidence interval) when looking at the effect of uncertainties in the two climate input variables only, and within the range of ± 24 to 32% (again at 95% confidence interval) when looking at the effect of uncertainties in all four input variables considered. In all cases, the most important uncertainty source is the value of *ET₀*. Figure 9 shows, for maize as an example, the probability distribution of the total *WF* (in $\text{m}^3 \text{ton}^{-1}$) given the uncertainties in either the two climatic input variables or all four input variables.

5. Conclusion

This report provides the first detailed study of the sensitivities and uncertainties in the estimation of green and blue water footprints of crop growing related to input variability and uncertainties at river basin level. The result shows that at the level of the Yellow River Basin: (1) WF is most sensitive to errors in ET_0 and K_c followed by the crop planting date and precipitation; (2) blue WF is more sensitive and has more uncertainty than green WF ; (3) uncertainties in total (green+blue) WF as a result of climatic uncertainties are around $\pm 20\%$ (at 95% confidence level) and dominated by effects from uncertainties in ET_0 ; (4) uncertainties in total WF as a result of all uncertainties considered are on average $\pm 26\%$ (at 95% confidence level); (5) the sensitivities and uncertainties in WF estimation, particularly in blue WF estimation, differ across crop types and vary from year to year.

An interesting finding was that the smaller the annual blue WF (consumptive use of irrigation water), the higher the sensitivity of the blue WF to variability in the input variables PR , ET_0 and K_c . Furthermore, delaying the crop planting date was found to potentially contribute to a decrease of the WF of spring or summer planted crops (maize, soybean, rice), most in particular relevant for the blue WF . Therefore, optimizing the planting period for such crops could save irrigation water in agriculture.

The study confirmed that it is not enough to give a single figure of WF without providing an uncertainty range. A serious implication of the apparent uncertainties in Water Footprint Assessment is that it is difficult to establish trends in WF reduction over time, since the effects of reduction have to be measured against the background of natural variations and uncertainties.

The current study shows possible ways to assess the sensitivity and uncertainty in the water footprint of crops in relation to variability and errors in input variables. Not only can the outcomes of this study be used as a reference in future sensitivity and uncertainty studies on WF , but the results also provide a first rough insight in the possible consequences of changes in climatic variables like precipitation and reference evapotranspiration on the water footprint of crops. However, the study does not provide the complete picture of sensitivities and uncertainties in Water Footprint Assessment. Firstly, the study is limited to the assessment of the effects from only four key input variables; uncertainties in other input variables were not considered, like for instance uncertainties around volumes and timing of irrigation. Secondly, there are several models available for estimating the WF of crops. Our result is only valid for the model used, which is based on a simple soil water balance (Allen et al., 1998; Mekonnen and Hoekstra, 2010). Furthermore, the quantification of uncertainties in the four input variables considered is an area full of uncertainties and assumptions itself. Therefore, in order to build up a more detailed and complete picture of sensitivities and uncertainties in Water Footprint Assessment, a variety of efforts needs to be made in the future. In particular, we will need to improve the estimation of input uncertainties, include uncertainties from other input variables and parameters, and assess the impact of using different models on WF outcomes. Finally, uncertainty studies will need to be extended towards other crops and other water using processes, to other regions and at different spatial and temporal scales.

References

- Ahn, H. (1996) Sensitivity for correlated input variables and propagated errors in evapotranspiration estimates from a humid region, *Water Resource Research*, 32(8): 2507-2516.
- Aldaya, M. M. and Llamas, M. R. (2008) Water footprint analysis for the Guadiana river basin, Value of Water research Report Series No 35, UNESCO-IHE, Delft, the Netherlands, www.waterfootprint.org/Reports/Report35-WaterFootprint-Guadiana.pdf.
- Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1998) Crop evapotranspiration: guidelines for computing crop water requirements, FAO Drainage and Irrigation Paper 56, Food and Agriculture Organization, Rome, Italy.
- Batjes, N.H. (2012) ISRIC-WISE global data set of derived soil properties on a 5 by 5 arc-minutes grid (version 1.2). Report 2012/01, ISRIC - World Soil Information, Wageningen, the Netherlands, www.isric.org.
- Bocchiola, D., Nana, E. and Soncini, A. (2013) Impact of climate change scenarios on crop yield and water footprint of maize in the Po valley of Italy, *Agricultural Water Management*, 116: 50-61.
- Bulsink, F., Hoekstra, A.Y. and Booij, M.J. (2010) The water footprint of Indonesian provinces related to the consumption of crop products, *Hydrology and Earth System Sciences*, 14(1): 119–128.
- Cai, X.M., Yang, Y-C.E., Ringler, C., Zhao, J.S. and You, L.Z. (2011) Agricultural water productivity assessment for the Yellow River Basin, *Agricultural Water Management*, 98(8): 1297–1306.
- Chapagain, A.K. and Hoekstra, A.Y. (2004) Water footprints of nations, Value of Water Research Report Series No. 16, UNESCO-IHE, Delft, The Netherlands, www.waterfootprint.org/Reports/Report16Vol1.pdf.
- Chen, Y., Guo, G., Wang, G., Kang, S., Luo, H. and Zhang, D. (1995) Main crop water requirement and irrigation of China, Hydraulic and Electric Press, Beijing, China.
- CMA (2008) SURF_CLI_CHN_MUL_MON_CES v3.0, China Meteorological Data Sharing Service System, Chinese Meteorological Administration, <http://cdc.cma.gov.cn>.
- CMWR (2010) China Water Resources Bulletin 2009, China Ministry of Water Resources, www.mwr.gov.cn, accessed in October 2010 (in Chinese).
- Doorenbos, J. and Kassam, A.H. (1979) Yield response to water, FAO Drainage and Irrigation Paper 33, FAO, Rome, Italy.
- Estévez, J., Gavilán, P. and Berengena, J. (2009) Sensitivity analysis of a Penman-Monteith type equation to estimate reference evapotranspiration in southern Spain, *Hydrological Processes*, 23(23): 3342-3353.
- Falkenmark, M. and Widstrand, C. (1992) Population and water resources: a delicate balance. *Population Bulletin*, Population Reference Bureau, Washington, D.C., USA.
- Fekete, B.M., Vörösmarty, C.J., Roads, J.O. and Willmott, C.J. (2004) Uncertainties in precipitation and their impacts on runoff estimates, *Journal of Climate*, 17(2): 294-304.
- Feng, K.S., Siu, Y.L., Guan, D. and Hubacek, K. (2012) Assessing regional virtual water flows and water footprints in the Yellow River Basin, China: A consumption based approach, *Applied Geography*, 32(2): 691-701.
- Galli, A., Wiedmann, T., Ercin, E., Knoblauch, D., Ewing, B. and Giljum, S. (2012) Integrating ecological, carbon and water footprint into a “footprint family” of indicators: Definition and role in tracking human pressure on the planet, *Ecological Indicators*, 16: 100-112.

- Ge, L., Xie, G., Zhang, C., Li, S., Qi, Y., Cao, S. and He, T. (2011) An evaluation of China's water footprint, *Water Resources Management*, 25(10): 2633–2647.
- Goyal, R. K. (2004) Sensitivity of evapotranspiration to global warming: a case study of arid zone of Rajasthan (India), *Agricultural Water Management*, 69(1): 1-11.
- Guieysse, B., Béchet, Q. and Shilton, A. (2013) Variability and uncertainty in water demand and water footprint assessments of fresh algae cultivation based on case studies from five climatic regions, *Bioresource Technology*, 128: 317-323.
- Hamby, D.M. (1994) A review of techniques for parameter sensitivity analysis of environmental models, *Environmental Monitoring and Assessment*, 32(2): 135-154.
- Harris, I., Jones, P.D., Osborn, T.J., and Lister, D.H. (2013) Updated high-resolution grids of monthly climatic observations, *International Journal of Climatology*, doi:10.1002/joc.3711.
- Hoekstra, A.Y. (ed.) (2003) Virtual water trade: Proceedings of the International Expert Meeting on Virtual Water Trade, IHE Delft, the Netherlands, 12-13 December 2002, Value of Water Research Report Series No.12, UNESCO-IHE, Delft, the Netherlands, www.waterfootprint.org/Reports/Report12.pdf.
- Hoekstra, A.Y. and Chapagain, A.K. (2007a) Water footprints of nations: water use by people as a function of their consumption pattern, *Water Resources Management*, 21(1): 35-48.
- Hoekstra, A.Y. and Chapagain, A.K. (2007b) The water footprints of Morocco and the Netherlands: Global water use as a result of domestic consumption of agricultural commodities, *Ecological Economics*, 64(1): 143-151.
- Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M. and Mekonnen, M.M. (2011) The water footprint assessment manual: Setting the global standard, Earthscan, London, UK.
- Hoekstra, A.Y., Mekonnen, M.M., Chapagain, A.K., Mathews, R.E. and Richter, B.D. (2012) Global monthly water scarcity: Blue water footprints versus blue water availability, *PLoS ONE*, 7(2): e32688.
- Hoekstra, A.Y. and Mekonnen, M.M. (2012) The water footprint of humanity, *Proceedings of the National Academy of Sciences*, 109(9): 3232–3237.
- Jagtap, S.S. and Jones, J.W. (1989) Stability of crop coefficients under different climate and irrigation management practices, *Irrigation Science*, 10(3): 231-244.
- Jensen, M.E., Burman, R.D. and Allen, R.G. (eds.) (1990) Evaporation and irrigation water requirements, ASCE Manuals and Reports on Engineering Practices No.70, American Society of Civil Engineers, New York, USA.
- Kampman, D.A., Hoekstra, A.Y. and Krol, M.S. (2008) The water footprint of India, Value of Water Research Report Series No.32, UNESCO-IHE, Delft, the Netherlands.
- Lehner, B., Verdin, K. and Jarvis, A. (2008) New global hydrography derived from spaceborne elevation data, *Eos*, 89(10): 93-94.
- Liu, J. and Yang, H. (2010) Spatially explicit assessment of global consumptive water uses in cropland: green and blue water, *Journal of Hydrology*, 384(3-4): 187–197.
- Liu, J. and Savenije, H.H.G. (2008) Food consumption patterns and their effect on water requirement in China, *Hydrology and Earth System Sciences*, 12(3): 887–898.

- Liu, Q., Yang, Z., Cui, B. and Sun, S. (2010) The temporal trends of reference evapotranspiration and its sensitivity to key meteorological variables in the Yellow River Basin, China, *Hydrological Processes*, 24(15): 2171-2181.
- Ma, J., Hoekstra, A.Y., Wang, H., Chapagain, A.K., and Wang, D. (2006) Virtual versus real water transfers within China. *Philosophical Transactions of the Royal Society B*, 361(1469): 835–842.
- MAPRC (2009) Sixty years agricultural statistics of New China, Ministry of Agriculture of the People's Republic of China, China Agriculture Press, Beijing, China.
- Mattila, T., Leskinen, P., Soimakallio, S. and Sironen, S. (2012) Uncertainty in environmentally conscious decision making: beer or wine? *International Journal of Life Cycle Assessment*, 17: 696-705.
- Mekonnen, M.M. and Hoekstra, A.Y. (2010) A global and high-resolution assessment of the green, blue and grey water footprint of wheat, *Hydrology and Earth System Sciences*, 14(7): 1259–1276.
- Mekonnen, M.M. and Hoekstra, A.Y. (2011) The green, blue and grey water footprint of crops and derived crop products, *Hydrology and Earth System Sciences*, 15(5): 1577-1600.
- Meyer, V.R. (2007) Measurement uncertainty, *Journal of Chromatography A*, 1158(1-2): 15-24.
- NBSC (2006) China agricultural statistical yearbook assembly 1949-2004, National Bureau of Statistics of China, China Statistics Press, Beijing, China.
- NBSC (2007) China Rural statistical yearbook 2006, National Bureau of Statistics of China, China Statistics Press, Beijing, China.
- Oki, T. and Kanae, S. (2006) Global hydrological cycles and world water resources, *Science*, 313(5790): 1068-1072.
- Parker, R.W.R., and Tyedmers, P.H. (2012) Uncertainty and natural variability in the ecological footprint of fisheries: A case study of reduction fisheries for meal and oil, *Ecological Indicators*, 16: 76-83.
- Phillips, D.L. and Marks, D.G. (1996) Spatial uncertainty analysis: propagation of interpolation errors in spatially distributed models, *Ecological Modelling*, 91(1-3): 213-229.
- Portmann, F.T., Siebert, S. and Döll, P. (2010) MIRCA2000 – Global monthly irrigated and rain-fed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling, *Global Biogeochemical Cycles*, 24, GB 1011.
- Qin, L.J., Jin, Y.H. and Duan, P.L. (2012) Impact of different planting dates on green water footprint of maize in western Jilin Province, *Acta Ecologica Sinica*, 32(23): 7375-7382.
- Ringler, C., Cai, X.M., Wang, J.X., Ahmed, A., Xue, Y.P., Xu, Z.X., Yang, E.T., Zhao, J.S., Zhu, T.J., Cheng, L., Fu, Y.F., Fu, X.F., Gu, X.W. and You, L.Z. (2010) Yellow River basin: living with scarcity, *Water International*, 35(5): 681-701.
- Röös, E., Sundberg, C. and Hansson, P.A. (2010) Uncertainties in the carbon footprint of food products: a case study on table potatoes, *International Journal of Life Cycle Assessment*, 15: 478–488.
- Röös, E., Sundberg, C. and Hansson, P.A. (2011) Uncertainties in the carbon footprint of refined wheat products: a case study on Swedish pasta, *International Journal of Life Cycle Assessment*, 16: 338–350.
- Schuol, J. and Abbaspour, K.C. (2007) Using monthly weather statistics to generate daily data in a SWAT model application to West Africa, *Ecological Modelling*, 201(3-4): 301-311.
- Siebert, S. and Döll, P. (2010) Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation, *Journal of Hydrology*, 384(3-4): 198-217.

- Singh, V.P. and Xu, C.Y. (1997) Sensitivity of mass transfer-based evaporation equations to errors in daily and monthly input data, *Hydrological Processes*, 11(11): 1465-1473.
- Sun, S.K., Wu, P.T., Wang, Y.B. and Zhao, X.N. (2013) Temporal variability of water footprint for maize production: The case of Beijing from 1978 to 2008, *Water Resources Management*, 27(7): 2447-2463.
- Sun, X.Y., Newham, L.T.H., Croke, B.F.W. and Norton, J.P. (2012) Three complementary methods for sensitivity analysis of a water quality model, *Environmental Modelling & Software*, 37: 19-29.
- Thomas, A. (2008) Development and properties of 0.25-degree gridded evapotranspiration data fields of China for hydrological studies, *Journal of Hydrology*, 358(3-4): 145-158.
- Vörösmarty, C.J., Green, P., Salisbury, J. and Lammers, R.B. (2000) Global water resources: Vulnerability from climate change and population growth, *Science*, 289(5477): 284-288.
- Walker, W.E., Harremoës, P., Rotmans, J., Van der Sluis, J.P., Van Asselt, M.B.A., Janssen, P. and Krauss, M.P. (2003) Defining uncertainty: a conceptual basis for uncertainty management in model-based decision support. *Integrated Assessment*, 4(1): 5-17.
- Xu, C.Y., Tunemar, L., Chen, Y.Q.D. and Singh, V.P. (2006a) Evaluation of seasonal and spatial variations of lumped water balance model sensitivity to precipitation data errors, *Journal of Hydrology*, 324(1-4): 80-93.
- Xu, C.Y., Gong, L.B., Jiang, T., Chen, D.L. and Singh, V.P. (2006b) Analysis of spatial distribution and temporal trend of reference evapotranspiration and pan evaporation in Changjiang (Yangtze River) catchment, *Journal of Hydrology*, 327(1-2): 81-93.
- YRCC (2011) Yellow River water resource bulletin 2010, Yellow River Conservancy Commission, Zhengzhou, China, www.yellowriver.gov.cn (in Chinese).
- Zeng, Z., Liu, J., Koene, P.H., Zarate, E., and Hoekstra, A.Y. (2012). Assessing water footprint at river basin level: a case study for the Heihe River Basin in northwest China, *Hydrology and Earth System Sciences*, 16(8): 2771-2781.
- Zhao, T.B. and Fu, C.B. (2006) Comparison of products from ERA-40, NCEP-2, and CRU with station data for summer precipitation over China, *Advances in Atmospheric Sciences*, 23(4): 593-604.

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