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LETTER

Divergent trends in irrigation-water withdrawal and consumption over mainland China

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Keywords: irrigation water use, water withdrawal and consumption, paradox of irrigation efficiency, water resource management, China

Supplementary material for this article is available online

Abstract

Knowledge of both irrigation-water withdrawal (IWW) and consumption (IWC, i.e. the evapotranspiration loss of applied irrigation water) is critical to sustainable water use and management. However, IWW and IWC are not well differentiated and an integrated analysis of their changes and causes is still lacking. Here we aim to close this gap and investigate the trends and drivers of IWW and IWC over mainland China using the logarithmic mean Divisia index approach and multivariate regression and fixed-effects panel regression models. We find that IWW decreased at a rate of -1.3 km^3 yr^{-1} (or -0.4% yr^{-1}) while IWC increased at a rate of 2.9 km^3 yr^{-1} (or 2.4% yr^{-1}) from 1999 to 2013, albeit both showed upward trends from 1982 to 1999. The reduction in IWW was due to the decreased water-withdrawal intensity (WWI) (i.e. IWW per unit area), while the increase in IWC was mainly due to the irrigated area expansion. We find opposite trends in IWW and IWC in about half of the Chinese provinces, with IWW decreasing and IWC increasing in most cases. Changes in irrigation efficiency (IE, defined as the ratio of IWC to IWW) and climatic factors explain a large proportion of the variance in WWI and water-consumption intensity (i.e. IWC per unit area). IE presents a strong negative correlation with WWI but a positive correlation with water-consumption intensity. The improved IE makes a nonnegligible contribution (~20%) to the irrigated area expansion, especially in water-scarce regions. The strong positive linkage between IE and IWC together with the significant rise in IWC with increasing IE suggest that the paradox of IE (i.e. higher IE tends to increase water consumption) has manifested in mainland China. Our findings highlight the importance of considering both IWW and IWC changes as well as farmer's behavior adjustments in water resource management.

1. Introduction

Irrigation accounts for ~70% of the global freshwater withdrawals while sustaining ~40% of the world's food production (Siebert and Döll 2010). Hence, irrigation plays a critical role in safeguarding food security for the growing population (Ward and Pulido-Velazquez 2008) and has great implications for attaining the sustainable development goals set forth by the United Nations (Xu *et al* 2020). Nevertheless, in recent decades, irrigation water use increases significantly due to climate change and rapid socioeconomic growth, which places unprecedented pressure on our planet's freshwater resources (Fishman *et al* 2015, Rosa *et al* 2020), leading to groundwater depletion, wetland and lake shrinkage,

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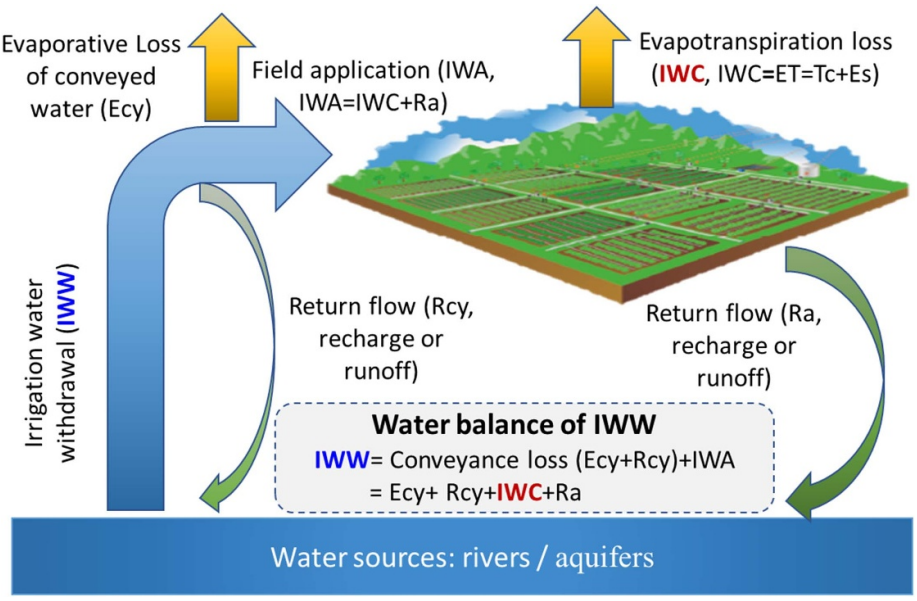

Figure 1. Schematic diagram of the water balance for IWW.

and ecosystem degradation (Liu *et al* 2013, Cheng *et al* 2014, Khazaei *et al* 2019, Li *et al* 2021a). A great challenge facing politicians and scientists in the 21st century is to increase productivity to meet the growing food demand while reducing the environmental impact of agricultural system (Foley *et al* 2011, Jägermeyr *et al* 2017, Rosa *et al* 2020).

Despite its importance, our knowledge of irrigation remains limited (Koch *et al* 2020, Nie *et al* 2020) because irrigation is not monitored adequately due to the technical, economic, and political challenges such as low coverage of metering facilities, scattered diversion points, high equipment maintenance costs, farmer resistance to meter installation (Foster *et al* 2020). Irrigation-water withdrawal (IWW) and consumption (IWC) are two important terms closely related to irrigation water use, but they are not well differentiated in the literature (Bretreger *et al* 2019, Zhang *et al* 2019a, Chen *et al* 2020, Foster *et al* 2020). In fact, as shown in figure 1, IWW and IWC have very different definitions and connotations. IWW refers to the total amount of irrigation water withdrawn from rivers and aquifers, and it ends up as: (a) evaporation loss of conveyed water, (b) return flow to water sources through groundwater recharge or lateral and surface runoff, and (c) field application (i.e. irrigation water application). Applied irrigation water is further ended as return flow (Ra), crop transpiration (Tc) and soil water evaporation (Es). IWC refers to the evapotranspiration (ET) loss of applied irrigation water (Koch *et al* 2020), i.e. IWC = Tc + Es. Researchers and managers seem to prefer IWW to IWC because IWW can be measured directly (Pereira *et al* 2012, Batchelor *et al* 2014). However, IWW alone may provide misleading information about water availability (Perry *et al* 2009, Marston and Lamsal 2020), as a proportion of IWW can return to the hydrological system (Simons *et al* 2015) and be reused locally or downstream (Grogan *et al* 2017). IWC, on the other hand, shows how much irrigation water is fully consumed through ET and can provide more realistic information on water use than the IWW on a basin or regional scale (Wu *et al* 2021). Hence, IWC has been widely adopted in newly proposed water resource management concepts such as the water footprint (Mekonnen and Hoekstra 2020), water planetary boundary (Gleeson *et al* 2020), and ET-based irrigation management (Lei *et al* 2020).

Knowledge of both IWW and IWC is critical to sustainable water use and management (Berbel *et al* 2018, Simons *et al* 2020). However, an integrated analysis of the changes and drivers of IWW and IWC is still lacking. To our knowledge, IWW and IWC are studied separately in most cases, focusing solely on IWW (Brocca *et al* 2018, Jalilvand *et al* 2019, Zhang *et al* 2022) or IWC (Romaguera *et al* 2014, Koch *et al* 2020, Vogels *et al* 2020). In some exceptions, researchers have attempted to convert IWW to IWC or vice versa using a predefined static irrigation efficiency (IE) (Döll and Siebert 2002, Hunink *et al* 2015, Van Eekelen *et al* 2015, Huang *et al* 2018, Zhou *et al* 2021), i.e. IWC = IWW × IE or IWW = IWC/IE. In these studies, IWW and IWC have the same spatiotemporal variability characteristics, which is at odds with reality (Malek *et al* 2018) and may yield misleading conclusions.

In this study, we aim to address the above gaps and investigate the trends and drivers of IWW and IWC at multiple spatial scales of mainland China. Our intent is to enhance the understanding of changes in irrigation water use and to answer three key

questions: (a) What are the commonalities and dissimilarities between the trends of IWW and IWC over the period 1982–2013? (b) What has driven the changes in IWW and IWC? (c) What is the linkage between the changes in IE and IWC?

2. Methods and materials

The workflow of this study is summarized in figure 2. We first detect the turning points within the IWW and IWC time series using the Pettitt's test (Pettitt 1979) and accumulated anomaly algorithm (Zhang *et al* 2019b), and estimate the trends of IWW, IWC, and IE using the linear regression model (supplementary, texts). The trend is defined as the slope of the regression line fitted to the time series data using the least squares method. The estimated trend is also expressed in units of percent change per year relative to the initial year of the analysis period (supplementary, texts). According to the definition of the Food and Agriculture Organization (FAO 2011), IE is calculated as the ratio of IWC to IWW (i.e. IE = IWC/IWW). The driving factors of IWW and IWC are then decomposed using the logarithmic mean Divisia index (LMDI) method (Ang and Liu 2001). Note that LMDI does not immediately provide insight into the mechanism behind the effects of various driving factors, as it is a decomposition of effects rather than a causal model (Zhou *et al* 2020). Therefore, we further conduct the contribution analyses to quantify the impacts of climatic factors, crop growth, and IE on water-withdrawal and water-consumption intensity (WCI) (i.e. IWW and IWC per unit area of irrigated cropland), and to isolate the contribution of IE improvements to irrigated area expansions.

2.1. IWWl and IWC datasets

The recently released long-term IWW data (Zhou *et al* 2020) and IWC data (Yin *et al* 2020) were used in the study. The IWW data was reconstructed from the first and second National Water Resources Assessment Programs and water resource bulletins. The data is provided at the prefecture scale and covers the period from 1956 to 2013. The IWC data was estimated from an upscaled ET product (Li *et al* 2018) using an irrigation cropland water model that incorporates irrigated cropland mapping and phenology (supplementary, texts). The IWC data has an 8 × 8 km spatial resolution and a monthly temporal resolution, covering the period from 1982 to 2016. The IWC data of Yin *et al* (2020) is the first high-resolution and long-term IWC dataset for China that has considered the irrigated area changes consistent with the IWW data (supplementary, figure S2) and allows a reasonable estimation of IE.

2.2. LMDI-based decomposition analysis

The LMDI method proposed by Ang and Liu (2001) is used to decompose the driving factors of IWW and IWC. The additive forms of the LMDI decomposition of IWW and IWC can be expressed as equations (1) and (2), respectively:

$$\Delta\mathrm{IWW} = \Delta\mathrm{IWW}_{\mathrm{IrrArea}} + \Delta\mathrm{IWW}_{\mathrm{WWI}} \quad (1)$$

$$\Delta\mathrm{IWC} = \Delta\mathrm{IWC}_{\mathrm{IrrArea}} + \Delta\mathrm{IWC}_{\mathrm{WCI}} \quad (2)$$

where ΔIWW and ΔIWC are the changes in IWW and IWC, respectively; $\Delta\mathrm{IWW}_{\mathrm{IrrArea}}$ and $\Delta\mathrm{IWW}_{\mathrm{WWI}}$ represent the irrigated area effect and water-withdrawal intensity (WWI) effect, respectively, and are calculated using equations (3) and (4); $\Delta\mathrm{IWC}_{\mathrm{IrrArea}}$ and $\Delta\mathrm{IWC}_{\mathrm{WCI}}$ represent the irrigated area effect and WCI effect, respectively, and are calculated using equations (5) and (6):

$$\Delta\mathrm{IWW}_{\mathrm{IrrArea}} = \left(\frac{\mathrm{IWW}_T - \mathrm{IWW}_0}{\ln(\mathrm{IWW}_T) - \ln(\mathrm{IWW}_0)}\right) \times \ln\left(\frac{\mathrm{IrrArea}_T}{\mathrm{IrrArea}_0}\right) \quad (3)$$

$$\Delta\mathrm{IWU}_{\mathrm{WWI}} = \left(\frac{\mathrm{IWW}_T - \mathrm{IWW}_0}{\ln(\mathrm{IWW}_T) - \ln(\mathrm{IWW}_0)}\right) \times \ln\left(\frac{\mathrm{WWI}_T}{\mathrm{WWI}_0}\right) \quad (4)$$

$$\Delta\mathrm{IWC}_{\mathrm{IrrArea}} = \left(\frac{\mathrm{IWC}_T - \mathrm{IWC}_0}{\ln(\mathrm{IWC}_T) - \ln(\mathrm{IWC}_0)}\right) \times \ln\left(\frac{\mathrm{IrrArea}_T}{\mathrm{IrrArea}_0}\right) \quad (5)$$

$$\Delta\mathrm{IWC}_{\mathrm{WCI}} = \left(\frac{\mathrm{IWC}_T - \mathrm{IWC}_0}{\ln(\mathrm{IWC}_T) - \ln(\mathrm{IWC}_0)}\right) \times \ln\left(\frac{\mathrm{WCI}_T}{\mathrm{WCI}_0}\right) \quad (6)$$

where the subscripts T and 0 denote the status at the beginning and end of the study period, respectively, and they are expressed as a 6 year average to ameliorate the effects of extreme values, following the approach of Zhang *et al* (2020a).

2.3. Regression-based contribution analysis

2.3.1. Quantifying the impact on water-withdrawal and consumption intensity

This study applies a multivariate linear regression model to evaluate the effects of changes in climatic factors, IE, and crop growth on WWI and WCI:

$$\mathrm{WWI}_s \text{ or } \mathrm{WCI}_s = \alpha_1 P + \alpha_2 T + \alpha_3 H + \alpha_4 R + \alpha_5 \mathrm{NDVI} + \alpha_6 \mathrm{IE} + b + \varepsilon \quad (7)$$

where WWI_s and WCI_s are the standardized WWI and WCI, respectively; α_i is the regression coefficient; b is the intercept; and ε is the error term. *P, T, H, R* are the climatic variables representing the growing season precipitation (mm), air temperature (°C), specific humidity (kg kg^{-1}), and solar irradiance (W m^{-2}),

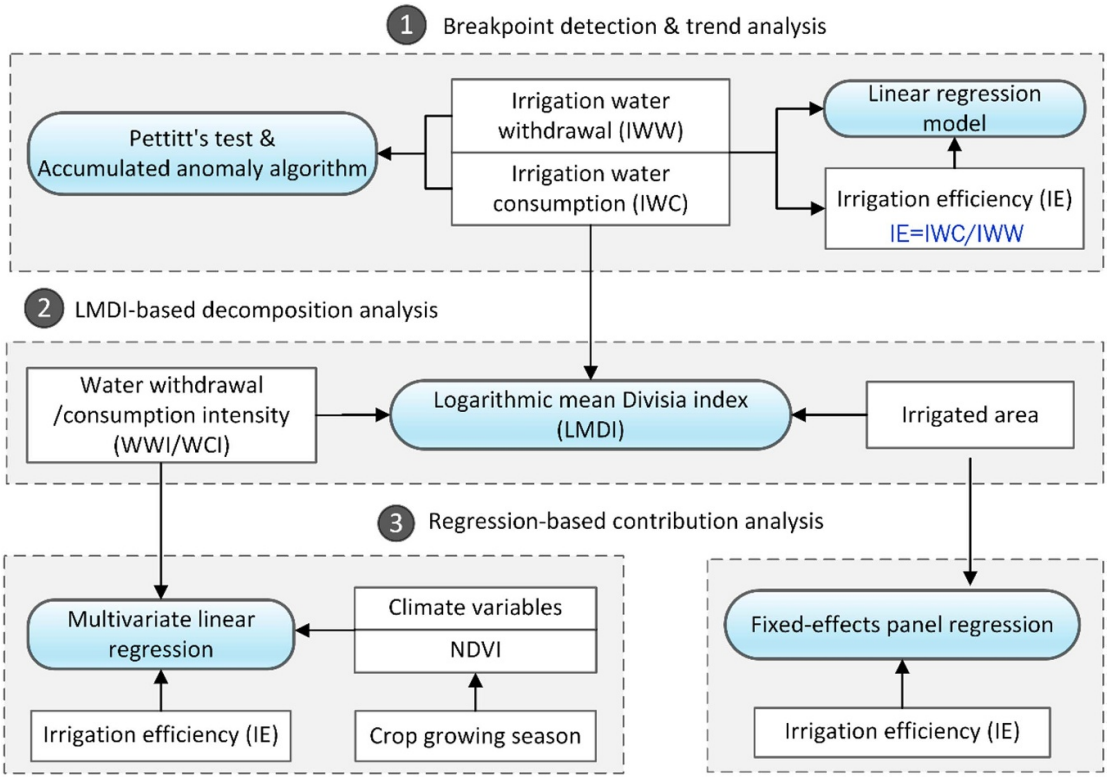

Figure 2. Workflow of this study. Number and gray boxes indicate the major steps involved in this study. White boxes are the input data sets or variables and the blue boxes are the analysis tools.

respectively. Normalized differene vegetation index (NDVI) is the growing season normalized difference vegetation index (as a proxy of crop growth) of the irrigated cropland. These factors are estimated using the China Meteorological Forcing Dataset (He and Yang 2016, He *et al* 2020), the third-generation NDVI product created by the Global Inventory Monitoring and Modeling System (NDVI3g) (https://ecocast.arc.nasa.gov/data/pub/gimms/3g.v1/), and the distribution and growth data of irrigated crops (Yin *et al* 2020) (supplementary, texts). Following García-Palacios *et al* (2018) and Wu *et al* (2020), we estimate the ratio between the parameter estimates of the predictor and the sum of all parameter estimates, as shown in equations (8)–(10), to quantify the relative effects of different driving factors on the WWI or WCI variations. Further, we tested the sensitivity of the relative effects to different time frames (i.e. 1982–2013, 1983–2013, …, 1994–2013) by repeating the analysis using data starting in 1982–1994:

$$\mathrm{WWI_{CC}\ or\ WCI_{CC}} = \frac{\sum_{i=1}^{4}|\alpha_i|}{\sum_{i=1}^{6}|\alpha_i|} \times 100\% \quad (8)$$

$$\mathrm{WCI_{NDVI}\ or\ WCI_{NDVI}} = \frac{|a_5|}{\sum_{i=1}^{6}|\alpha_i|} \times 100\% \quad (9)$$

$$\mathrm{WCI_{IE}\ or\ WCI_{IE}} = \frac{|a_6|}{\sum_{i=1}^{6}|\alpha_i|} \times 100\% \quad (10)$$

where α_i is the standardized regression coefficient of the ith variable shown in equation (7); and the subscripts CC, NDVI, and IE represent the relative effects of climatic factors, crop growth, and irrigation efficiency, respectively.

2.3.2. Isolating the contribution of IE improvements to irrigated area expansion

The expansion of irrigated areas is driven by many factors including the development of irrigation facilities, growth in food demand, and improvements of IE (Ward and Pulido-Velazquez 2008, Pfeiffer and Lin 2014, Perry 2017, Sese-Minguez *et al* 2017). Here, we focus on the impact of IE improvements on the irrigated area expansion to better understand the linkage between IE and IWC. To this end, a fixed-effects panel regression approach is used (Diffenbaugh and Burke 2019, Davenport *et al* 2021). A linear regression model (equation (11)) and two nonlinear regression models (equations (12) and (13)) are adopted to represent the relationship between IE and irrigated area and to account for model selection uncertainty:

$$\mathrm{IrrArea}_{it} = \beta_1 \mathrm{IE}_{it} + \beta_2 + c_i + \lambda_t + \varepsilon_{it} \quad (11)$$

$$\mathrm{IrrArea}_{it} = \beta_1 \mathrm{IE}_{it} + \beta_2 \mathrm{IE}_{it}^2 + \beta_3 + c_i + \lambda_t + \varepsilon_{it} \quad (12)$$

$$\mathrm{IrrArea}_{it} = \beta_1 e^{\beta_2 \mathrm{IE}_{it}} + c_i + \lambda_t + \varepsilon_{it} \quad (13)$$

where $\mathrm{IrrArea}_{it}$ and IE_{it} represent the irrigated area and irrigation efficiency, respectively, in province t and year t; c_i is the province fixed effects; λ_t is the time fixed effects; and ε_{it} is the error term. The province-time fixed effects subtract out interannual variations in the average irrigated area caused by many other unobservable time-invariant and time-varying factors such as the growth of irrigation infrastructures, government support, farmers' pursuit of economic returns, allowing us to isolate the effects of IE improvements. We first estimate the ensemble mean of the 'counterfactual' irrigated area that would have occurred without IE change based on the regression models and the detrended IE. Then, the contribution of IE improvements to the irrigation area expansion is quantified as the relative difference between the trends of the measured and 'counterfactual' irrigated areas (supplementary, texts and table S1).

3. Results

3.1. Trends of IWW and IWC

The turning points of the time-series IWW and IWC are detected as 2001 and 1999, respectively, by the Pettitt's test and accumulated anomaly algorithm (supplementary, table S2). Based on the turning points, we divide the entire study period (P3: 1982–2013) into two subperiods, i.e. P1: 1982–1999 and P2: 1999–2013. Figure 3 shows the trends of IWW, IWC and IE estimated using the linear regression model. IWW and IWC exhibit statistically significant increasing trends during P1, with values of 1.27 and 1.13 $\mathrm{km^3\,yr^{-1}}$, respectively. However, the IWW and IWC trends are opposite during P2, i.e. IWW decreases significantly at a rate of -1.3 $\mathrm{km^3\,yr^{-1}}$ (or -0.4% $\mathrm{yr^{-1}}$), while IWC increases at a rate of 2.9 $\mathrm{km^3\ yr^{-1}}$ (or 2.4% $\mathrm{yr^{-1}}$). IE presents a nonsignificant increasing trend during P1 but shows a significant upward trend (0.01 $\mathrm{yr^{-1}}$ or 2.4% $\mathrm{yr^{-1}}$) during P2.

For the agricultural zones (supplementary, texts), as shown in figure 4, both IWW and IWC show increasing trends in the Northeastern China Plain and Yunan–Guizhou Plateau during P1, P2 and P3. The variations of IWW and IWC in the northern arid and semiarid regions are similar to the entire mainland China. In the Huang-Huai-Hai Plain, IWW and IWC show upward trends during P1 but downward trends during P2, while the opposite is true in the middle-lower Yangtze Plain. In the Sichuan basin and surrounding regions, IWW consistently exhibits a decreasing trend, while IWC shows an upward trend. At the provincial scale, about 30% of the provinces have opposite trends in IWW and IWC during P1, while about 50% show opposite trends during P2 and P3, with IWW decreasing and IWC increasing in most cases. Over the period P3, the provinces with divergent trends of IWW and IWC are mainly located in eastern and northwestern China. The northeastern provinces show consistent upward trends in IWW and IWC during P1, P2, and P3.

3.2. Driving factors of IWW and IWC

Figure 5 shows the effects of irrigated area and water-withdrawal/consumption intensity on changes in IWW and IWC, which were decomposed using the LMDI method (section 2.2). The irrigated area and WWI have opposite effects on the IWW change in mainland China. The irrigated area expansion induces an increase in IWW, while the reduced WWI causes a decrease in IWW. The irrigated area effect is higher than the WWI effect during P1 but the opposite is true during P2 and P3. Similar results can be seen in most agricultural zones, with the exceptions of the Northeastern China Plain (I) and Yunan–Guizhou Plateau (VII), where the irrigated area effect is greater than the WWI effect. Regarding the changes in IWC, the effect of irrigated area expansion is significantly higher than the WCI effect. The reduced WCI exhibits appreciable effects on the IWC change in the Huang-Huai-Hai Plain (III), Middle-lower Yangtze Plain (VII) and Yunnan-Guizhou Plateau (VIII). WCI exerts both negative and positive effects on the IWC change in different agricultural zones. At the provincial scale, the irrigated area expansion contributes positively to the increase in IWW and IWC in most cases (supplementary, figure S3). WWI poses negative effects on the IWW change while WCI exhibits both positive and negative effects on the IWC change.

3.3. Impacts of climatic factors, crop growth and IE on water-withdrawal and consumption intensity

Figure 6 shows that IE, climatic factors, and crop growth (approximately represented by NDVI) are, on average, responsible for 38% (44%), 54% (46%), and 8% (10%) of the explained variance (>80%) in water-consumption (water-withdrawal) intensity across the 31 provinces of mainland China. The relative effects remain stable over the different time frames (figures 6(c) and (d)), indicating the results are robust to analysis using different data lengths. Precipitation shows a negative relationship with water-withdrawal and consumption intensity, while solar irradiance shows a positive relationship with them. Air temperature, humility and NDVI do not seem to have consistent relationships with water-withdrawal and consumption intensity (Nie *et al* 2020). In more than 90% of the provinces, IE is significantly and negatively correlated with WWI but positively correlated with water-consumption intensity. Higher IE can decrease WWI due to reduced return flow and soil water evaporation, but it can also increase WCI due to changes in planting structure or better satisfactions of crop water requirements (Batchelor *et al* 2014, Zhang *et al* 2020b). The IE effect on WCI might be partially captured by the satellite-based IWC data that

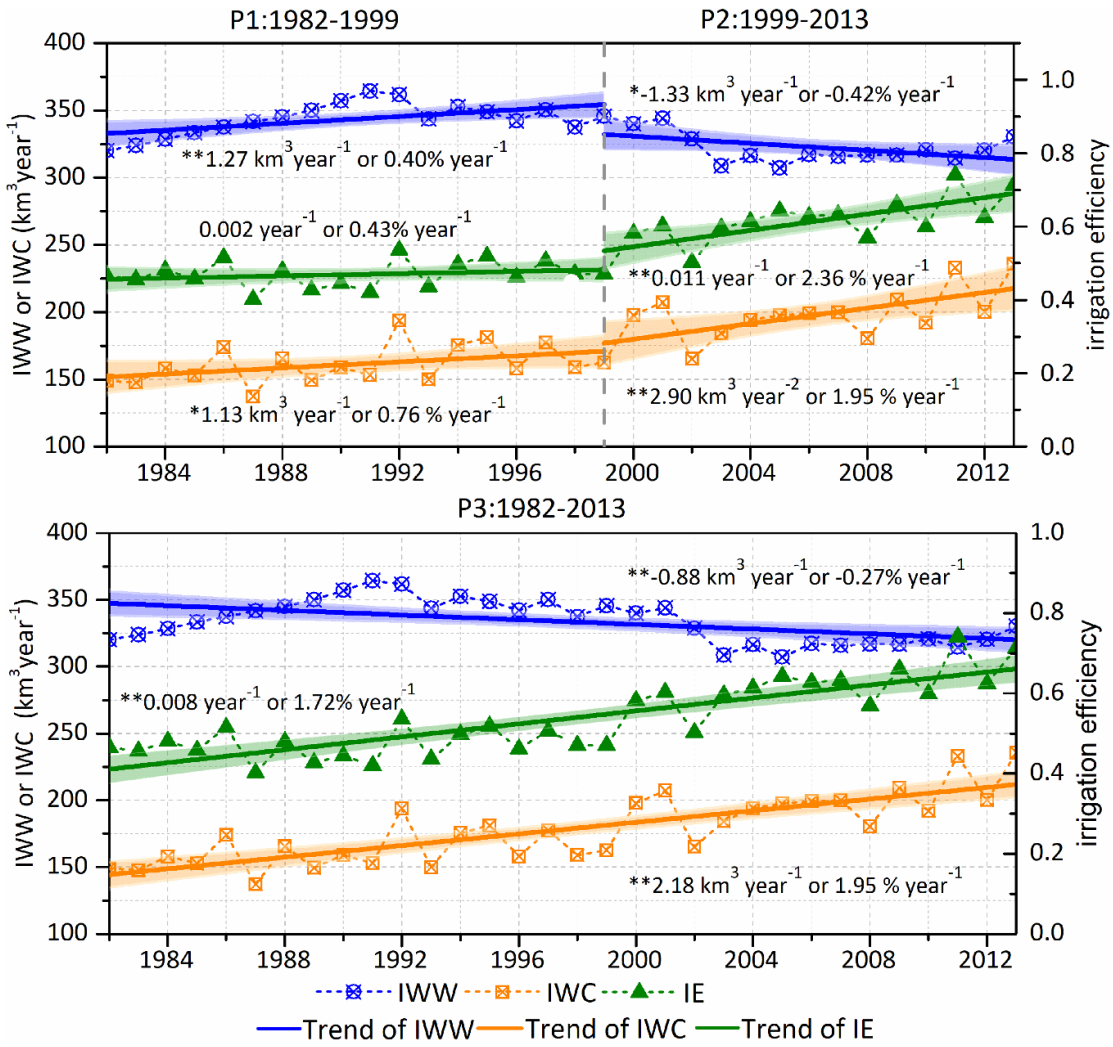

Figure 3. Variations of IWW, IWC and IE in mainland China along with their linear trends (solid lines, $^{*}P < 0.05$, $^{*}P < 0.10$) and 95% confidence intervals (shaded areas) during 1982–1999 (P1), 1999–2013 (P2), and 1982–2013 (P3).

incorporates NDVI, crop phenology and root depth information (Yin *et al* 2020).

3.4. Contribution of IE improvements to irrigated area expansion

Removing the IE trend and estimating the 'counterfactual' irrigation area that would have occurred without IE trends allow us to isolate the contribution of IE improvements to the irrigation area expansion (supplementary, texts). The trend of the measured irrigated area is 6353 $km^2\ yr^{-1}$ (or 1.4% yr^{-1}) in mainland China, while the trend of the 'counterfactual' irrigated area is 4942 $km^2\ yr^{-1}$ (or 1.1% yr^{-1}) (figure 7). The contribution of the improved IE to the irrigated area expansion is estimated to be 22.2%, and it is more prominent in water-scarce regions (31.5%) than in water-abundant regions (19.7%). This is reasonable because in water-scarce regions (e.g. the Xinjiang province), land is relatively plentiful, but water resources are limited; the water-withdrawal savings obtained from higher IE are more likely to be used to expand irrigated areas than in water-abundant regions. Our results show a low sensitivity to model selection and are robust to the use of different regression models (supplementary, figure S4).

4. Discussion

4.1. Implications for water resource management

This study highlights the necessity of considering both IWW and IWC in designing and evaluating water policies because they include complementary information on irrigation water use and may exhibit divergent trends. If managers focus solely on IWW, it would be easy to mistakenly believe that as IWW decreases, water availability increases and therefore their water conservation measures are successful. Meanwhile, our findings show that climatic factors can explain a large of the variance (~40%) in water-withdrawal and consumption intensity. Climate change may lead to greater irrigation water

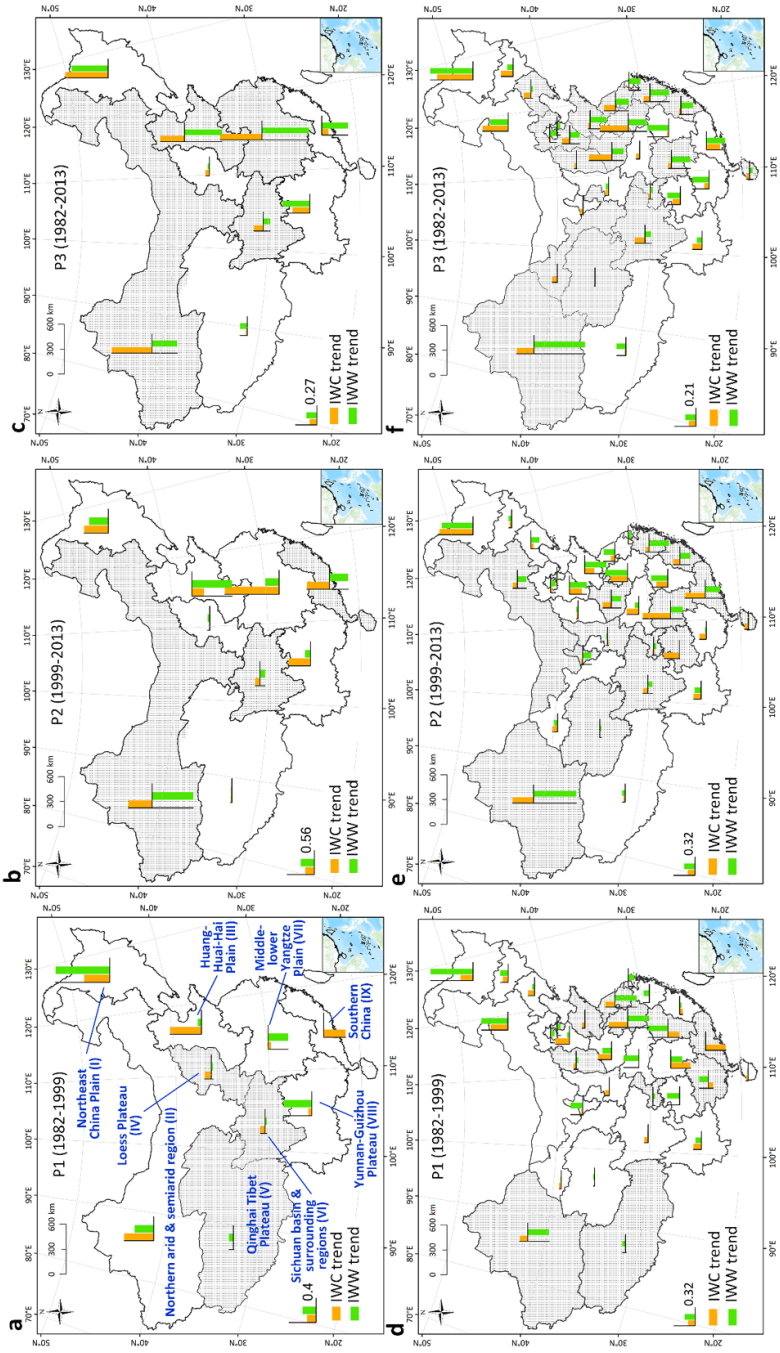

Figure 4. Trends of IWW and IWC in different agricultural zones (a)–(c) and provinces (d)–(f) of mainland China during 1982–1999 (P1), 1999–2013 (P2) and 1999–2013 (P3). Provinces or agricultural zones with gray background have opposite trends in IWW and IWC.

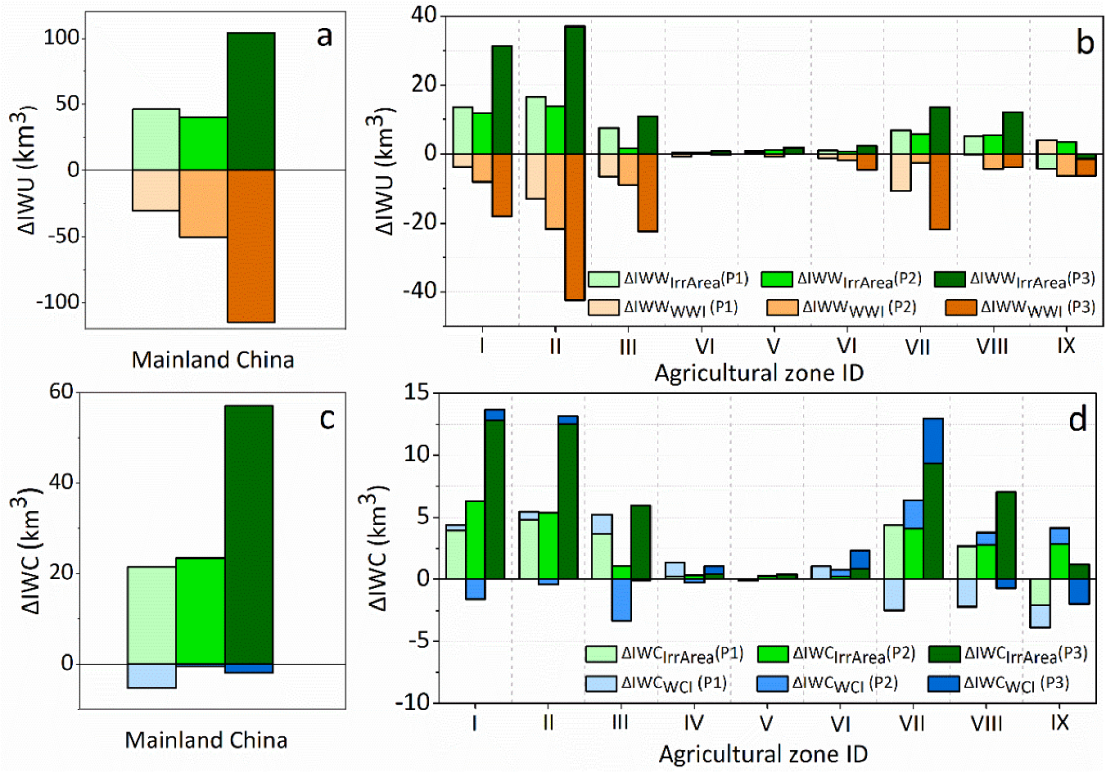

Figure 5. Driving factors of IWW and IWC in mainland China and the nine agricultural zones (see figure 4(a)) during 1982–1999 (P1), 1999–2013 (P2) and 1982–2013 (P3). Panels (a) and (b) show the irrigated area and WWI effects on IWW change (i.e. $\Delta IWW_{IrrArea}$ and ΔIWW_{WWI}), and panels (c) and (d) show the irrigated area and WCI effects on IWC change (i.e. $\Delta IWC_{IrrArea}$ and ΔIWC_{WCI}).

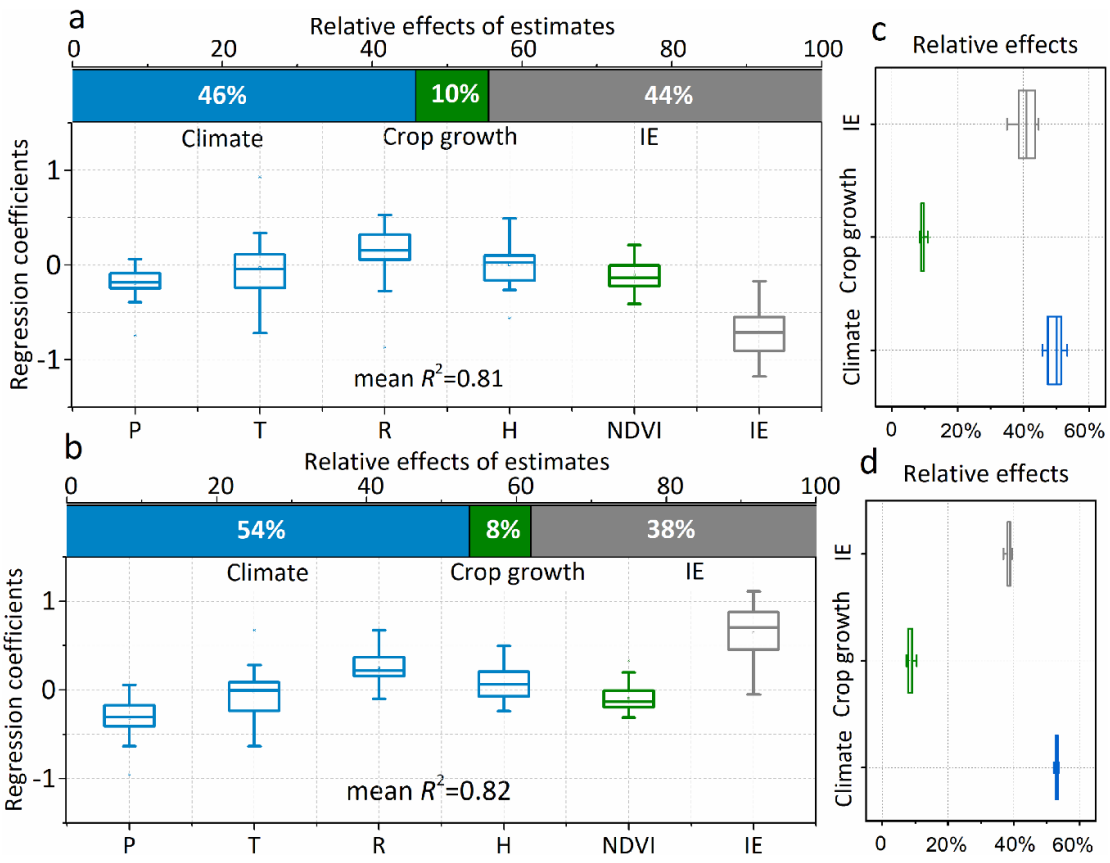

Figure 6. Relative effects of climatic factors, crop growth and IE on the WWI (a) and WCI (b). Panels (c) and (d) show the sensitivity of the relative effects to different time frames that started in the years ranging from 1982–1994. The climatic factors include precipitation (P), air temperature (T), solar irradiance (R), and specific humidity (H).

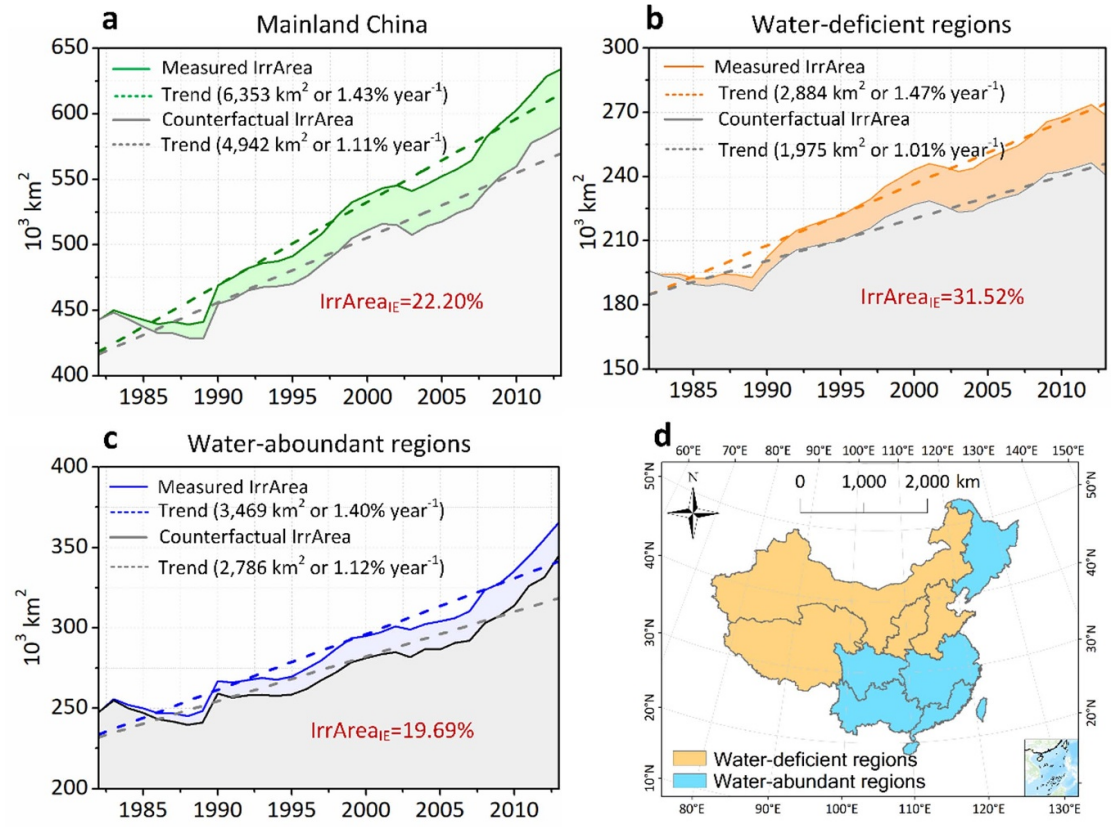

Figure 7. Trends of the measured and 'counterfactual' irrigated areas along with the contribution of IE improvements to the irrigated area expansion (i.e. $IrrArea_{IE}$). Panels (a), (b), and (c) show the results for the mainland China and for water-scarce and water-abundant regions (d), respectively. The 'counterfactual' irrigated area is the ensemble mean of the estimates of the linear, quadratic, and exponential regression models.

demands that can further exacerbate climate-induced water shortages and threaten ecological water security (Russo and Lall 2017, Nie *et al* 2020), thus requiring the attention of managers and policy makers.

Since irrigation is the largest global freshwater user (Hoekstra and Mekonnen 2012, Jägermeyr *et al* 2015), it is a widely-held belief that higher IE has great potential to conserve water and address water scarcity. However, a growing number of voices are questioning this viewpoint (Ward and Pulido-Velazquez 2008, Pfeiffer and Lin 2014), arguing that higher IE tends to increase water consumption, a phenomenon known as the paradox of IE (Grafton and Abadía 2018). This study shows that IWC increases significantly along with the improved IE from 1982 to 2013 in mainland China; and simultaneous increases in IE and IWC are observed in more than 80% of the provinces (figure 8). The improved IE makes a nonnegligible contribution (~20%) to the irrigated area expansion. Meanwhile, in most provinces, the regression coefficients of IE to WCI are statistically positive and the explained variance in WCI by IE is greater than 25% (supplementary, figures S5 and S6), indicating that the improved IE has a strong positive effect on water-consumption intensity. The significant rise in IWC with increasing IE together with their strong positive linkages provide empirical evidence for the paradox of IE in mainland China.

The paradox of IE is an example of a Jevons' paradox rooted in the field of environmental economics (Sears *et al* 2018), and therefore it is currently explained mostly from a microeconomic perspective, assuming that farmers are rational economic agents with the goal of maximizing revenues. As shown in supplementary figure S7, modernization of irrigation systems can lead to lower production costs through reduced water, labor, and chemical inputs, as well as government subsidies for water-efficient irrigation. Lower costs combined with upgraded irrigation systems enable farmers to increase yields and economic returns through the extensification and intensification of irrigated crops. This is one possible mechanism behind the paradox of IE in mainland China, since the government plays a leading role in promoting water-conserving irrigation (Central Government of the People's Republic of China 2014). For example, the central and local governments subsidize almost all investments in water-saving irrigation in large and medium-sized irrigation districts (The State Concile Information Office of the People's Public of China 2014). Meanwhile, upgrades in irrigation systems

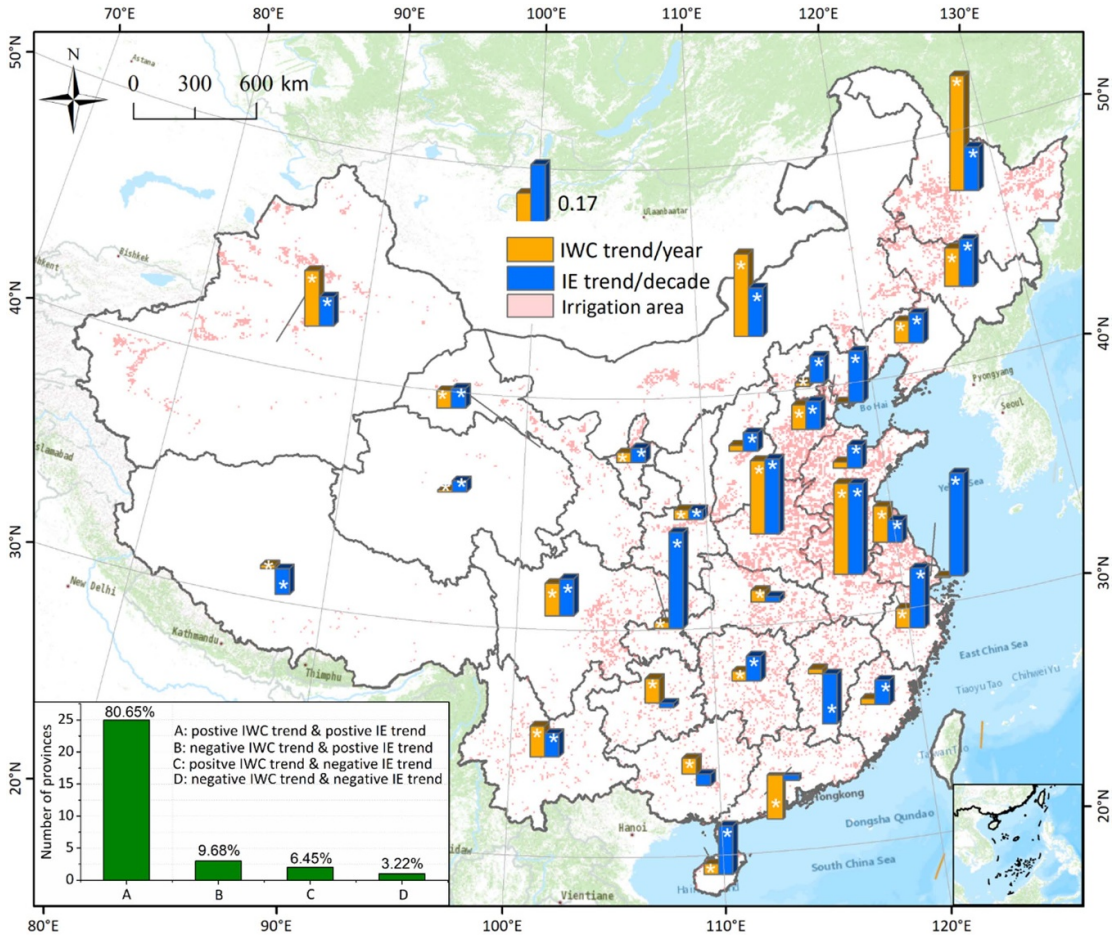

Figure 8. Comparison of the trends in IWC and IE over the 31 provinces of mainland China (* $P < 0.05$) during the 1982–2013 period.

(e.g. from flood to drip irrigation) may increase crop yields because of more reliable and flexible water supply and more efficient water distribution, which is associated with increases in crop water consumption (Perry 2017). This can also explain the paradox of irrigation efficiency, since water-saving irrigation measures were reported to increase grain yield by 10%–40% per mu in mainland China (The State Concile Information Office of the People's Public of China 2014). There are other possible mechanisms that may generate the paradox of IE (supplementary, figure S7), but given the various socioeconomic, climatic, hydrological, agronomic, policy and institutional influences, they are difficult to determine in our study and deserve further investigation in the future. Anyway, the paradox of IE is essentially a coupled socio-hydrology problem involving bidirectional human-water feedbacks (Sivapalan *et al* 2014). If our goal is to alleviate water crisis by improving IE, farmer's behaviors should be treated as an endogenous rather than exogenous factor when designing and implementing water conservation programs (Li *et al* 2021b); and meanwhile, it is necessary to impose strict limits on the extent of irrigated cropland or total IWW (Zhang *et al* 2019a).

4.2. Uncertainties, limitations and future perspectives

We acknowledge this study has some limitations and uncertainties. First, only one recently released IWC dataset was used in our study and we cannot evaluate the robustness of our results to the use of different IWC data. This is due to the fact that among the publicly available IWC datasets, only that of Yin *et al* (2020) has a long time frame and high spatial resolution and explicitly considers the expansion of irrigated area, and has been verified against the official statistics. Other available IWC datasets, including those of Zhuo *et al* (2016), Van Dijk *et al* (2018), and Huang *et al* (2018), have obvious deficiencies (supplementary, texts). We expect to address the limitation of IWC data in the future by developing new IWC products with higher resolution and accuracy using reliable satellite-based ET products and spatio-temporally continuous maps of irrigated cropland. Second, our study was limited to the 1982–2013 period due to the constraint of the IWW data. This may raise the question of whether our findings remain valid for the period beyond 2013. Recently, Han *et al* (2020) reported that IWW showed a downward trend while irrigated area exhibited an upward

trend from 2013 to 2017 in China. We can infer that the decreasing IWW trend and increasing IWC trend would continue after 2013, suggesting the reliability of our findings over a longer time horizon. Lastly, shifts in irrigated crop mix may influence the IWW and IWC trends; however, this was not incorporated into our driving force analysis due to data limitations. We further examined the changes in China's cropping structure during 1982–2013 based on official statistics and remote sensing-based land use/cover products (supplementary, texts). As shown in supplementary figure S10, rice and paddy field show very slight variations in acreage (<2% of the average total planted area), unlikely affecting the trends of IWW and IWC. Regarding the non-rice crops, the acreage and proportion of corn and vegetables show notable increases, their growth rates are relatively small (<0.4% yr^{-1}) compared to the average total planted area. Other non-rice crops, including wheat, oil crops, soybeans, tubers, and cotton, did not experience substantial changes during the study period. The crops can be both rain-fed and irrigated, but they are not distinguished in the statistics. It is therefore difficult to determine their impacts on the IWW and IWC trends, which may bring some uncertainties to our findings. Previous study indicated that crop structure shift is a relatively weak driver of changes in irrigation water demand in China (Zhang *et al* 2020a), but they did not distinguish between rainfed and irrigated crops and excluded some crops (e.g. vegetable) from their analysis. To quantitatively estimate the contribution of irrigated crop conversion to changes in IWW and IWC, it will be necessary to develop time-continuous data on irrigated crop types in the future by leveraging advances in both crop distribution and irrigated cropland products.

5. Conclusions

This study differentiated two important variables closely related to irrigation water use, i.e. IWW and IWC, and examined their trends and drivers over mainland China. IWW and IWC showed statistically significant increasing trends from 1982 to 1999, while they exhibited opposite trends from 1999 to 2013. IWW decreased at a rate of −1.3 $km^3\,yr^{-1}$ (or −0.4% yr^{-1}), while IWC increased at a rate of 2.9 $km^3\,yr^{-1}$ (or 2.4% yr^{-1}) during 1999–2013. The decrease in IWW was due to the reduced water-withdrawal intensity, while the increase in IWC was mainly due to the irrigated area expansion. The opposite trends in IWW and IWC are observed in about half of the provinces, mostly located in eastern and northwestern China.

Changes in climatic factors, IE and irrigated area, on average, accounts for 54% (46%), 38% (44%), and 8% (10%) of the explained variance in water-consumption (water-withdrawal) intensity across the 31 provinces of mainland China. Unsurprisingly, precipitation shows a negative relationship with the water-withdrawal and consumption intensity. IE is significantly and negatively correlated with the WWI but positively correlated with water-consumption intensity. The contribution of IE improvement to the irrigated area expansion is estimated to be 22% in mainland China and it is more prominent in water-scarce regions (32%) than in water-abundant regions (20%). Further analysis implies that the paradox of IE (i.e. higher IE tends to increase water consumption) has manifested in parts of mainland China. This study enhances the understanding of changes in irrigation water use and highlights the importance of considering both IWW and IWC changes as well as farmer's behavior adjustments in water resource management.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Code availability

Code from this study can be accessed via https://github.com/HydroRS/IrrTrendChina.

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References

Ang B W and Liu F L 2001 A new energy decomposition method: perfect in decomposition and consistent in aggregation *Energy* **26** 537–48

Batchelor C, Reddy V R, Linstead C, Dhar M, Roy S and May R 2014 Do water-saving technologies improve environmental flows? *J. Hydrol.* **518** 140–9

Berbel J, Gutierrez-Marín C and Expósito A 2018 Microeconomic analysis of irrigation efficiency improvement in water use and water consumption *Agric. Water Manage.* **203** 423–9

Bretreger D, Yeo I-Y, Quijano J, Awad J, Hancock G and Willgoose G 2019 Monitoring irrigation water use over paddock scales using climate data and landsat observations *Agric. Water Manage.* **221** 175–91

Brocca L, Tarpanelli A, Filippucci P, Dorigo W, Zaussinger F, Gruber A and Fernández-Prieto D 2018 How much water is

used for irrigation? A new approach exploiting coarse resolution satellite soil moisture products *Int. J. Appl. Earth Observ. Geoinf.* **73** 752–66

Central Government of the People's Republic of China 2014 National investment in water-saving irrigation projects has reached 34.5 billion yuan per year during 2001–2015 (available at: www.gov.cn/2014-09/29/content_2758383.htm)

Chen M, Luo Y, Shen Y, Han Z and Cui Y 2020 Driving force analysis of irrigation water consumption using principal component regression analysis *Agric. Water Manage.* **234** 106089

Cheng G, Li X, Zhao W, Xu Z, Feng Q, Xiao S and Xiao H 2014 Integrated study of the water–ecosystem–economy in the Heihe River Basin *Natl Sci. Rev.* **1** 413–28

Davenport F V, Burke M and Diffenbaugh N S 2021 Contribution of historical precipitation change to US flood damages *Proc. Natl Acad. Sci.* **118** e2017524118

Diffenbaugh N S and Burke M 2019 Global warming has increased global economic inequality *Proc. Natl Acad. Sci.* **116** 9808–13

Döll P and Siebert S 2002 Global modeling of irrigation water requirements *Water Resour. Res.* **38** 8–1

FAO 2011 *The State of the World's Land and Water Resources for Food and Agriculture (SOLAW)—Managing Systems at Risk* (Rome: Food and Agriculture Organization of the United Nations)

Fishman R, Devineni N and Raman S 2015 Can improved agricultural water use efficiency save India's groundwater? *Environ. Res. Lett.* **10** 084022

Foley J A *et al* 2011 Solutions for a cultivated planet *Nature* **478** 337–42

Foster T, Mieno T and Brozovic N 2020 Satellite-based monitoring of irrigation water use: assessing measurement errors and their implications for agricultural water management policy *Water Resour. Res.* **56** e2020WR028378

García-Palacios P, Gross N, Gaitán J and Maestre F T 2018 Climate mediates the biodiversity–ecosystem stability relationship globally *Proc. Natl Acad. Sci.* **115** 8400–5

Gleeson T *et al* 2020 The water planetary boundary: interrogation and revision *One Earth* **2** 223–34

Grafton R Q and Abadía R 2018 The paradox of irrigation efficiency *Science* **361** 748–50

Grogan D S, Wisser D, Prusevich A, Lammers R B and Frolking S 2017 The use and re-use of unsustainable groundwater for irrigation: a global budget *Environ. Res. Lett.* **12** 034017

Han S, Tian F and Gao L 2020 Current status and recent trend of irrigation water use in China *Irrig. Drain.* **69** 25–35

He J and Yang K 2016 China meteorological forcing dataset (1979–2015) (National Tibetan Plateau Data Center) (https://doi.org/10.3972/westdc.002.2014.db)

He J, Yang K, Tang W, Lu H, Qin J, Chen Y and Li X 2020 The first high-resolution meteorological forcing dataset for land process studies over China *Sci. Data* **7** 25

Hoekstra A Y and Mekonnen M M 2012 The water footprint of humanity *Proc. Natl Acad. Sci.* **109** 3232–7

Huang Z *et al* 2018 Reconstruction of global gridded monthly sectoral water withdrawals for 1971–2010 and analysis of their spatiotemporal patterns *Hydrol. Earth Syst. Sci.* **22** 2117–33

Hunink J E, Contreras S, Soto-García M, Martin-Gorriz B, Martinez-Álvarez V and Baille A 2015 Estimating groundwater use patterns of perennial and seasonal crops in a Mediterranean irrigation scheme, using remote sensing *Agric. Water Manage.* **162** 47–56

Jägermeyr J, Gerten D, Heinke J, Schaphoff S, Kummu M and Lucht W 2015 Water savings potentials of irrigation systems: global simulation of processes and linkages *Hydrol. Earth Syst. Sci.* **19** 3073–91

Jägermeyr J, Pastor A, Biemans H and Gerten D 2017 Reconciling irrigated food production with environmental flows for sustainable development goals implementation *Nat. Commun.* **8** 15900

Jalilvand E, Tajrishy M, Hashemi G Z and Brocca L S A 2019 Quantification of irrigation water using remote sensing of soil moisture in a semi-arid region *Remote Sens. Environ.* **231** 111226

Khazaei B, Khatami S, Alemohammad S H, Rashidi L, Wu C, Madani K, Kalantari Z, Destouni G and Aghakouchak A 2019 Climatic or regionally induced by humans? Tracing hydro-climatic and land-use changes to better understand the Lake Urmia tragedy *J. Hydrol.* **569** 203–17

Koch J, Zhang W, Martinsen G, He X and Stisen S 2020 Estimating net irrigation across the North China Plain through dual modelling of evapotranspiration *Water Resour. Res.* **56** e2020WR027413

Lei X, Zhenzhong H and Mingqi C 2020 Evapotranspiration-based irrigation management technology and its application in China *Irrig. Drain.* **69** 127–34

Li Q, Li X, Ran Y, Feng M, Nian Y, Tan M and Chen X 2021a Investigate the relationships between the Aral Sea shrinkage and the expansion of cropland and reservoir in its drainage basins between 2000 and 2020 *Int. J. Digit. Earth* **14** 661–77

Li X *et al* 2018 Spatiotemporal pattern of terrestrial evapotranspiration in China during the past thirty years *Agric. For. Meteorol.* **259** 131–40

Li X *et al* 2021b Novel hybrid coupling of ecohydrology and socioeconomy at river basin scale: a watershed system model for the Heihe River basin *Environ. Model. Softw.* **141** 105058

Liu H, Yin Y, Piao S, Zhao F, Engels M and Ciais P 2013 Disappearing Lakes in Semiarid Northern China: drivers and environmental impact *Environ. Sci. Technol.* **47** 12107–14

Malek K, Adam J C, Stöckle C O and Peters R T 2018 Climate change reduces water availability for agriculture by decreasing non-evaporative irrigation losses *J. Hydrol.* **561** 444–60

Marston T *et al* 2020 Reducing water scarcity by improving water productivity in the United States *Environ. Res. Lett.* **15** 94033

Mekonnen M M and Hoekstra A Y 2020 Sustainability of the blue water footprint of crops *Adv. Water Resour.* **143** 103679

Nie W, Zaitchik B F, Rodell M, Kumar S V, Arsenault K R and Badr H S 2020 Irrigation water demand sensitivity to climate variability across the contiguous United States *Water Resour. Res.* **57** e2020WR027738

Pereira L S, Cordery I and Iacovides I 2012 Improved indicators of water use performance and productivity for sustainable water conservation and saving *Agric. Water Manage.* **108** 39–51

Perry C 2017 *Does Improved Irrigation Technology Save Water? A Review of the Evidence* (Cairo: FAO)

Perry C, Steduto P, Allen R G and Burt C M 2009 Increasing productivity in irrigated agriculture: agronomic constraints and hydrological realities *Agric. Water Manage.* **96** 1517–24

Pettitt A N 1979 A non-parametric approach to the change-point problem *J. R. Stat. Soc.* C **28** 126–35

Pfeiffer L and Lin C Y C 2014 Does efficient irrigation technology lead to reduced groundwater extraction? Empirical evidence *J. Environ. Econ. Manage.* **67** 189–208

Romaguera M, Krol M, Salama M, Su Z and Hoekstra A 2014 Application of a remote sensing method for estimating monthly blue water evapotranspiration in irrigated agriculture *Remote Sens.* **6** 10033–50

Rosa L, Chiarelli D D, Sangiorgio M, Beltran-Peña A A, Rulli M C, Odorico D and Fung P I 2020 Potential for sustainable irrigation expansion in a 3 °C warmer climate *Proc. Natl Acad. Sci.* **117** 29526–34

Russo T A and Lall U 2017 Depletion and response of deep groundwater to climate-induced pumping variability *Nat. Geosci.* **10** 105–8

Sears L, Caparelli J, Lee C, Pan D, Strandberg G, Vuu L and Lin Lawell C Y 2018 Jevons' paradox and efficient irrigation technology *Sustainability* **10** 1590

Sese-Minguez S, Boesveld H, Asins-Velis S and van der Kooij S 2017 Transformations accompanying a shift from surface to

drip irrigation in the Cànyoles Watershed, Valencia, Spain *Water Altern.* **10** 81–99
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 *J. Hydrol.* **384** 198–217
Simons G W H G, Bastiaanssen W G M W and Immerzeel W W W 2015 Water reuse in river basins with multiple users: a literature review *J. Hydrol.* **522** 558–71
Simons G W H, Bastiaanssen W G M, Cheema M J M, Ahmad B and Immerzeel W W 2020 A novel method to quantify consumed fractions and non-consumptive use of irrigation water: application to the indus basin irrigation system of Pakistan *Agric. Water Manage.* **236** 106174
Sivapalan M, Konar M, Srinivasan V, Chhatre A, Wutich A, Scott C A, Wescoat J L and Rodríguez-Iturbe I 2014 Socio-hydrology: use-inspired water sustainability science for the anthropocene *Earth's Future* **2** 225–30
The State Concile Information Office of the People's Public of China 2014 Press conference on the state of water-saving irrigation in China (available at: www.scio.gov.cn/xwfbh/xwbfbh/wqfbh/2014/20140929/index.htm)
Van Dijk A I J M, Schellekens J, Yebra M, Beck H E, Renzullo L J, Weerts A and Donchyts G 2018 Global 5 km resolution estimates of secondary evaporation including irrigation through satellite data assimilation *Hydrol. Earth Syst. Sci.* **22** 4959–80
Van Eekelen M W *et al* 2015 A novel approach to estimate direct and indirect water withdrawals from satellite measurements: a case study from the Incomati basin *Agric. Ecosyst. Environ.* **200** 126–42
Vogels M F A, de Jong S M, Sterk G, Wanders N, Bierkens M F P and Addink E A 2020 An object-based image analysis approach to assess irrigation-water consumption from MODIS products in Ethiopia *Int. J. Appl. Earth Observ. Geoinf.* **88** 102067
Ward F A and Pulido-Velazquez M 2008 Water conservation in irrigation can increase water use *Proc. Natl Acad. Sci.* **105** 18215–20
Wu B, Zeng H, Zhu W, Yan N and Ma Z 2021 Enhancing China's three red lines strategy with water consumption limitations *Sci. Bull.* **66** 2057–60
Wu W-Y, Lo M-H, Wada Y, Famiglietti J S, Reager J T, Yeh P J F, Ducharne A and Yang Z-L 2020 Divergent effects of climate change on future groundwater availability in key mid-latitude aquifers *Nat. Commun.* **11** 3710
Xu Z, Chen X, Liu J, Zhang Y, Chau S, Bhattarai N, Wang Y, Li Y, Connor T and Li Y 2020 Impacts of irrigated agriculture on food–energy–water–CO_2 nexus across metacoupled systems *Nat. Commun.* **11** 5837
Yin L, Feng X, Fu B, Chen Y, Wang X and Tao F 2020 Irrigation water consumption of irrigated cropland and its dominant factor in China from 1982 to 2015 *Adv. Water Resour.* **143** 103661
Zhang K, Li X, Zheng D, Zhang L and Zhu G 2022 Estimation of global irrigation water use by the integration of multiple satellite observations *Water Resour. Res.* **58** e2021WR030031
Zhang L, Chen F and Lei Y 2020a Climate change and shifts in cropping systems together exacerbate China's water scarcity *Environ. Res. Lett.* **15** 104060
Zhang L, Ma Q, Zhao Y, Wu X and Yu W 2019a Determining the influence of irrigation efficiency improvement on water use and consumption by conceptually considering hydrological pathways *Agric. Water Manage.* **213** 674–81
Zhang L, Nan Z, Wang W, Ren D, Zhao Y and Wu X 2019b Separating climate change and human contributions to variations in streamflow and its components using eight time-trend methods *Hydrol. Process.* **33** 383–94
Zhang Z, Li X, Liu L, Wang Y and Li Y 2020b Influence of mulched drip irrigation on landscape scale evapotranspiration from farmland in an arid area *Agric. Water Manage.* **230** 105953
Zhou F *et al* 2020 Deceleration of China's human water use and its key drivers *Proc. Natl Acad. Sci.* **117** 7702
Zhou X, Zhang Y, Sheng Z, Manevski K, Andersen M N, Han S, Li H and Yang Y 2021 Did water-saving irrigation protect water resources over the past 40 years? A global analysis based on water accounting framework *Agric. Water Manage.* **249** 106793
Zhuo L, Mekonnen M M and Hoekstra A Y 2016 The effect of inter-annual variability of consumption, production, trade and climate on crop-related green and blue water footprints and inter-regional virtual water trade: a study for China (1978–2008) *Water Res.* **94** 73–85