Science of the Total Environment 844 (2022) 157253

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Irrigation plays significantly different roles in influencing hydrological processes in two breadbasket regions

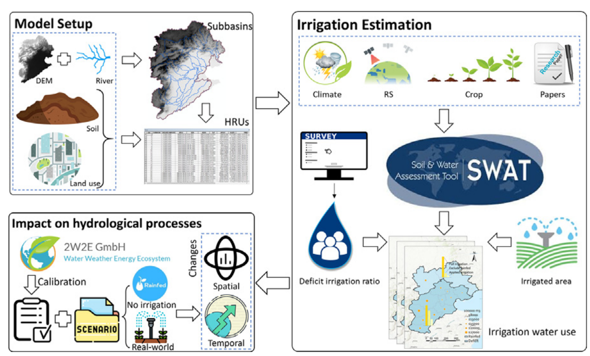
Yiming Wang [a], Yuyu Zhou [a,*], Kristie J. Franz [a], Xuesong Zhang [b], Junyu Qi [c], Gensuo Jia [d], Yun Yang [b]

[a] Department of Geological and Atmospheric Sciences, Iowa State University, Ames, IA 50011, USA
[b] USDA-ARS Hydrology and Remote Sensing Laboratory, Beltsville, MD 20705-2350, USA
[c] Earth System Science Interdisciplinary Center, University of Maryland, 5825 University Research Ct, College Park, MD, 20740, USA
[d] Key Laboratory of Regional Climate-Environment for East Asia, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China

HIGHLIGHTS

- Deficit irrigation is more common in JJJ than in NTX and reduces irrigation by 50 %.
- Irrigation impact on hydrology varies spatially and temporally in two watersheds.
- Irrigation influences upstream and downstream hydrology differently.
- The peak percentage change in runoff due to irrigation is higher than soil water.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Christian Herrera

Keywords:
Irrigation
SWAT
Deficit irrigation regime
Hydrological processes
Watershed

ABSTRACT

Agriculture is a major water user, especially in dry and drought-prone areas that rely on irrigation to support agricultural production. In recent years, the over-extraction of groundwater, exacerbated by climate change, population growth, and intensive agricultural irrigation, has led to a drop in water levels and influenced the hydrological cycle. Understanding changes in hydrological processes is essential for pursuing water sustainability. This study aims to estimate the amount and impact of irrigation on hydrological processes in two breadbasket regions, Jing-Jin-Ji (JJJ), China, and northern Texas (NTX), US. We used the Soil and Water Assessment Tool (SWAT) to explore spatiotemporal variations of irrigation from 2008 to 2013 and compared changes in hydrological processes caused by irrigation. The results indicated that deficit irrigation is more common in JJJ than in NTX and can reduce approximately 50 % of irrigation water use in areas with intensively irrigated cropland. The applied irrigation varies less over time in NTX but fluctuates in JJJ. Compared with NTX, the higher irrigation intensity in JJJ results in a more significant change in downstream peak streamflow of around 6 m^3/s. Moreover, the difference in crop growing seasons can lead to different impacts of irrigation on hydrological processes. For example, the percentage change of surface runoff under real-world relative to the no-irrigation scenario was the greatest, around 40 %, in JJJ and NTX. However, the peak change occurred at different times, with the nearing maturity of winter wheat in May in JJJ and corn in August in NTX. The great potential to reduce groundwater extraction by adopting water conservation irrigation techniques calls for policies and regulations to help farmers shift towards more sustainable water management practices.

1. Introduction

Irrigation plays an important role in the hydrology of watersheds in irrigated agricultural regions (Chen et al., 2020). Irrigation accounts for

* Corresponding author.
E-mail address: yuyuzhou@iastate.edu (Y. Zhou).

http://dx.doi.org/10.1016/j.scitotenv.2022.157253
Received 7 April 2022; Received in revised form 4 July 2022; Accepted 5 July 2022
Available online 9 July 2022
0048-9697/© 2022 Elsevier B.V. All rights reserved.

around 70 % of the total water withdrawn from surface water and groundwater globally (Wisser et al., 2008) and 90 % in areas with extensive, irrigated agriculture (Kang et al., 2017). In the future, agricultural water shortages are likely to intensify due to continuing economic development, rapid population increase, and the impact of global climate change (Du et al., 2015; Kang et al., 2017). As such, it is critical to estimate spatiotemporal irrigation water use, analyze the impact of irrigation on water resources, and explore sustainable water management solutions.

Multiple factors influence the amount of irrigation that occurs in a given region, including crop types (Li et al., 2018a; Li et al., 2018b; Segovia-Cardozo et al., 2019; Zhou et al., 2020a; Zhou et al., 2020b), climate conditions (Barnston and Schickedanz, 1984; Chen et al., 2017; DeAngelis et al., 2010; Jensen et al., 1990), and irrigation techniques (Guillet, 2006; Siebert, 2013). Generally, crops can be divided into rain-fed (no irrigation), paddy rice (waterlogged), and non-paddy crops (irrigation needs determined by climate) (Burek, 2018). With respect to irrigation demand, an increase in mean annual temperature of 2 °C is enough to counteract rises in precipitation of as much as 20 % (McCabe et al., 1992). By the end of the 21st century, the daily use of water for irrigation could increase by 0.8 mm day^{-1} (Shahid, 2011). In addition, under the premise of ensuring crop yield, the adoption of different irrigation techniques could result in a much different amount of irrigation (Guillet, 2006), such as border irrigation (Morris et al., 2015), sprinkler (Carrión et al., 2001), dripping (Camp, 1998), and flooding (Sharmasarkar et al., 2001).

The Food and Agriculture Organization (FAO)'s single crop coefficient approach and the dual crop coefficient approach are widely used to estimate irrigation water demand (Allen, 1998). The differences between these two approaches lie in that the dual crop coefficient approach considers the impact of soil water on irrigation needs when calculating the crop coefficient (Liu and Luo, 2010). Based on the FAO's irrigation estimation approaches, models considering different irrigation efficiency factors have been built, including hydrological models with irrigation modules. Commonly used process-based models include WaterGap (Alcamo et al., 2003), the Soil and Water Assessment Tool (SWAT) (Neitsch, 2011), the Agricultural Policy/Environmental eXtender (APEX) (Gassman, 2009), and the Root Zone Water Quality Model (RZWQM) (Ahuja et al., 2000). In addition to allowing users to prescribe irrigation water use as inputs, these models all include an auto-irrigation function to estimate irrigation use. For example, the SWAT allows both manual input of prescribed irrigation data and auto-irrigation based on crop growth stages, weather conditions, and soil water status. The manual irrigation method has rarely been used in spatial analysis due to the lack of spatially explicit surveyed irrigation data on a large scale, such as a watershed. Therefore, the auto-irrigation method in SWAT is most commonly used but shows a tendency to overestimate irrigation water use compared to actual field irrigation data due to the continuance of irrigation scheduling after crop harvest (Chen et al., 2017) and the lack of consideration of actual irrigation strategies. On the other hand, crop models, such as the Decision Support System for Agrotechnology Transfer (Jones et al., 2003), can provide information on automatic irrigation capacity for various plant growth stages based on soil moisture or evapotranspiration (ET) demand.

Different methods and models have been proved to simulate the hydrological processes under irrigation practice. The Mann-Kendall test has been used to evaluate how irrigation affects streamflow (Wen and Chen, 2006). The bucket hydrology model is a simple method for calculating the irrigation return flow and other related processes (Le Page, 2020; Poch-Massegú et al., 2014). The methods mentioned above lack the ability to explain the physical changes occurring in various parts of the hydrological system. The regional climate model (RCM) with a realistic irrigation scheme was employed to investigate the effect of irrigation on hydrology over California (Sorooshian et al., 2014). The SWAT model has been extensively used to study the hydrology of irrigated regions (Chen et al., 2017; Qiu et al., 2019). It can simulate well changes in soil water content (Hashem et al., 2020), runoff (Xie and Cui, 2011), discharge and ET (Qiu et al., 2019), groundwater storage (Dakhlalla et al., 2016), and recharge (Fallatah et al., 2019). SWAT considers two aquifers for the groundwater, including a shallow aquifer representing the unconfined aquifer and a deep aquifer representing the confined aquifer (Neitsch, 2011). To better explore the groundwater level change, the SWAT can be further coupled with MODFLOW (Aliyari et al., 2021; Wei and Bailey, 2019).

Irrigation can change the flow pattern, seasonal variability, and water exchanges among different water cycle components. Intensive irrigation can cause a decrease in slow components, such as baseflow, and an increase in fast components, such as streamflow, because fast components are subject to higher variability than slow components (Zeng and Cai, 2014). At the same time, irrigation can also change the groundwater storage regime (Wada et al., 2012). However, the improved irrigation system cannot significantly change the total inflow to the lake or river in comparison to the original irrigation system in the Zarrineh Rud catchment (Ahmadzadeh et al., 2016). Therefore, understanding the impact of irrigation on hydrological processes is needed when optimizing irrigation water strategies (Dechmi and Skhiri, 2013).

Previous studies have generally focused on improving methods to calculate irrigation or to model a specific watershed. In this study, a modeling framework to estimate irrigation water use and its impact on hydrological processes was developed. We compared two breadbasket regions in China and the US that are home to intensively irrigated cropland. We aimed to answer the following scientific questions: (1) What are the differences in irrigation water use and related irrigation regimes between Jing-Jin-Ji (JJJ) and northern Texas (NTX); and (2) what is the difference in the impact of irrigation on hydrological processes in the two regions? The remainder of this paper describes the study area and methods (Section 2), simulation results of irrigation water use and its impact on hydrological processes (Section 3), and concluding remarks and future perspectives (Section 4).

2. Study areas and method

2.1. Study areas

Irrigation water use and its impact on water resources were investigated in the JJJ region in China and NTX in the US (Fig. 1). Both regions are important breadbaskets for each country, relying heavily on intensively irrigated agriculture, which accounts for 65.5 % of farmland in JJJ and 61.3 % in NTX. The primary irrigated areas are located in the south of JJJ and east of NTX, all of which utilize deficit irrigation to some extent. The major crops include corn and winter wheat in both regions. Although the climate and water usage (e.g., domestic and industrial) are different in the two regions, the focus of this study is the evaluation of how irrigation influences hydrology under local climate and water usage conditions and the difference in such impacts in the two regions. Therefore, these two regions provide an opportunity to evaluate if the impacts of irrigation of crops on hydrology vary under different climate conditions and irrigation strategies.

The JJJ region is located in the Haihe River basin and is characterized by a warm temperate semi-humid continental monsoon climate. The average annual rainfall is around 600 mm, and the mean annual temperature is 12 °C. The monthly maximum temperature is 31 °C in July, and the minimum is −8 °C in January. The major crops include winter wheat, corn, and paddy rice. In this region, due to cold winters but warm summers, farmers usually rotate crops. For example, winter wheat is usually grown from November to early June. After the winter wheat is harvested, corn is planted in the same field and harvested in late October. The NTX region includes Texas's northern and western parts, from the Panhandle to the Pecos River in the southwestern US. The regional climate is semi-arid, with an average annual rainfall of around 500 mm and an average annual temperature of 14.1 °C. The monthly maximum temperature is 36 °C in August, and the minimum temperature is 3 °C in January. The annual standardized alfalfa reference ET is 1600 mm in the region (Chen et al., 2019a; Chen et al., 2019b). The primary land uses are irrigated corn, irrigated sorghum, and dual-purpose winter wheat (both as forage and grain) under irrigation and dryland conditions.

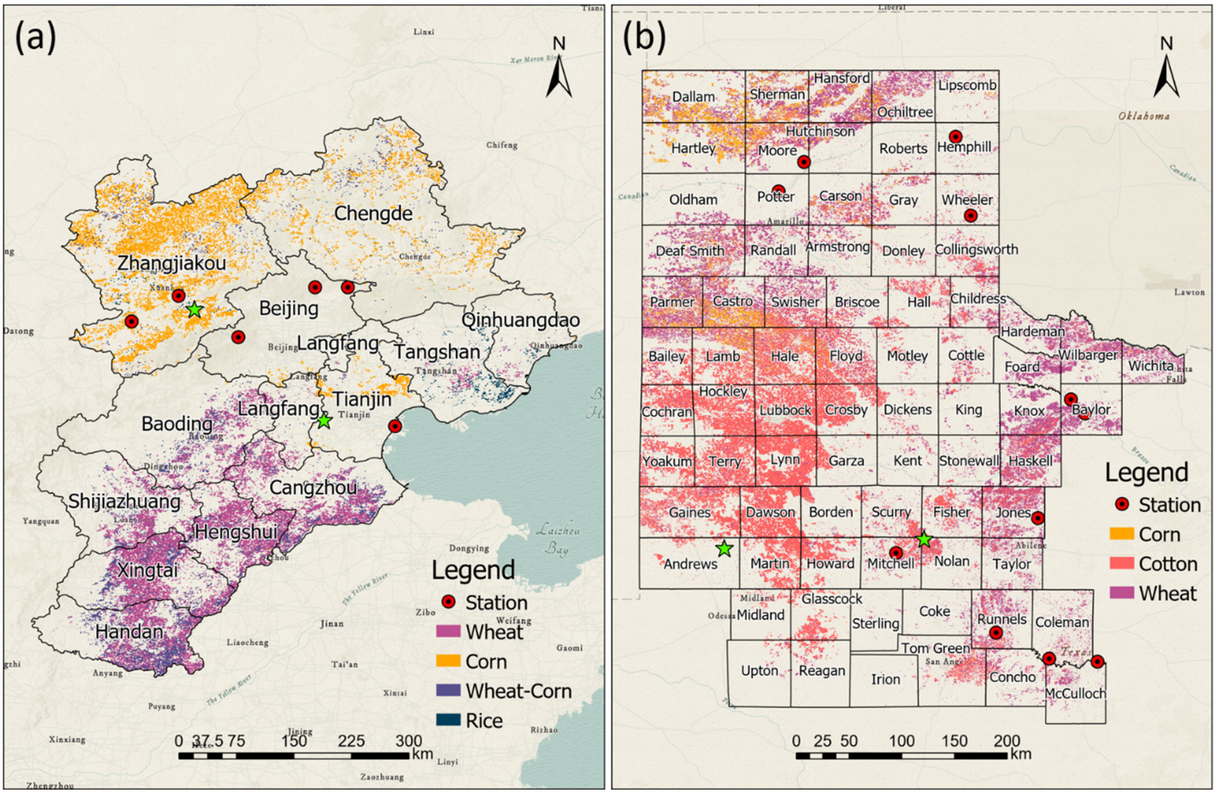


Fig. 1. The study areas of (a) JJJ in China, and (b) NTX in the US, showing the major crop types including winter wheat, corn, and cotton. In JJJ, there were 42.3 % wheat and 35 % corn. In NTX, there were 7.2 % corn, 49 % cotton, and 43.8 % wheat. The two green stars are the outlets of selected subbasins in Fig. 7.

2.2. Data

Various data were used to set up the SWAT model, including the Shuttle Radar Topography Mission (STRM) digital elevation model (DEM), the Global River Classification GloRiC data (Ouellet Dallaire et al., 2018), and the FAO-UNESCO Soil Map of the World. To better capture the spatial distribution of crops, the ChinaCropPhen1km (Luo et al., 2020) and CropScape with a 30 m spatial resolution were used as the land use data (Han et al., 2012) for JJJ and NTX, respectively. Meteorological data, including precipitation and temperature, were obtained from the China Meteorological Assimilation Driving Datasets for the SWAT model (CMADS) (Meng et al., 2019) and the Climate Forecast System Reanalysis (CFSR) dataset. Observed monthly streamflow data were from hydrological stations in JJJ and USGS in NTX (Fig. 1). Moreover, the Global Map of Irrigation Areas (GMIA) dataset from FAO (Siebert, 2013; Siebert et al., 2005) with a five arc-minute spatial resolution was used to separate rainfed and irrigated agriculture. The historical irrigation water use data were from Texas Water Development Board (https://www.twdb.texas.gov/index.asp).

2.3. Method

The SWAT model (Arnold, 1998), a process-based hydrologic model designed to simulate both the quality and quantity of surface and subsurface water in a watershed, was used to estimate the irrigation water use and its impact on hydrological processes. Processes such as erosion and irrigation, which are of interest in agricultural areas, were incorporated into SWAT. Two scenarios were set in this study, including the real-world and no irrigation scenarios (Table 1).

The SWAT model was configured and run for each basin using the data described in Section 2.2 (Fig. 2). Then, the applied irrigation water was calculated with the consideration of rain-fed farmland and a deficit irrigation regime based on the full irrigation water (Table 1). Next, the streamflow from the SWAT was calibrated using the applied irrigation water based on the SWAT-CUP (Calibration and Uncertainty Program). Finally, the effects of irrigation on hydrological processes were evaluated.

In this study, the SWAT model was set up using the ArcSWAT 2012 interface. Based on the DEM, the basin was discretized into 71 sub-basins with 1128 hydrologic response units (HRUs) in JJJ and 73 sub-basins with 608 HRUs in NTX. The model was run at a monthly time step for a period from 2006 to 2013. The full irrigation was first calculated using an auto-irrigation function. For improving crop growth simulation, the parameters related to crop growth were calibrated using Moderate Resolution Imaging Spectroradiometer (MODIS) Leaf Area Index (LAI). After calibrating the monthly LAI of crops in each subbasin, full irrigation was calculated based on an auto-irrigation function. The soil water content option in the auto-irrigation function was used in this study, under which irrigation is triggered when a predefined soil water deficit threshold is exceeded.

After calculating full irrigation, we excluded rain-fed farmland areas. The spatial distribution of irrigated areas can be obtained through GMIA data. The original GMIA data represents the percentage of the total five

Table 1
The description of terms and scenarios used in this study.

Terms or scenarios	Description
Irrigation intensity	Water amount per area for a specific crop type during its growth period
Full irrigation	Irrigation water for the full crop ET requirement
Applied irrigation	Real irrigation with the consideration of deficit irrigation and rainfed farmland
Real-world scenario	Scenario with applied irrigation extracted from groundwater
No irrigation scenario	Scenario without irrigation

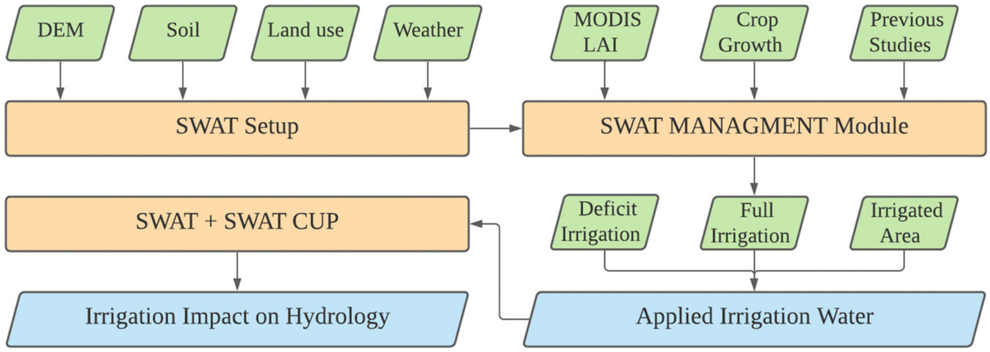


Fig. 2. The flowchart for estimating irrigation water use and its impact on watershed hydrology using SWAT. MODIS, Moderate Resolution Imaging Spectroradiometer, represents LAI from MODIS Leaf Area Index/FPAR product.

arc-minute grid cell areas. We transferred it to the proportion of irrigated areas in farmland based on Eq. (1).

$$GMIA_{new} = \frac{A_T \times GMIA}{A_C} \quad (1)$$

where A_T is the tile area, and A_C is the crop area in each tile.

Irrigated areas, farmers' behavior, and strategies for reducing irrigation usage were considered for irrigation practice. The deficit irrigation regime is an irrigation strategy in which water is only applied during drought-sensitive growth stages of the crop, with less water applied than the crop ET required (Fereres and Soriano, 2007). For each county or city, the deficit irrigation ratio (DIR) was calculated based on the survey irrigation water use data in 2008 and 2009, which represents the part of water saved due to a deficit irrigation regime (Baumhardt et al., 2009; Modala et al., 2015). Once the value of DIR is determined, its value does not change during simulation, which means that the farmer's irrigation schemes will not alter. With the consideration of irrigated area and DIR, the applied irrigation water was estimated at the pixel level. Statistics on the applied irrigation water at the city (JJJ) or county (NTX) scales are used to visualize the spatiotemporal pattern.

Streamflow was calibrated based on the SWAT-CUP, which is a software developed for the SWAT model that can be used to perform calibration, validation, sensitivity analysis, and uncertainty analysis (Abbaspour, 2013). Setting the first two years as a warm-up period, we calibrated and validated our model using observed monthly streamflow data from 2003 to 2010 and 2011 to 2013, respectively. In the Sequential Uncertainty Fitting (SUFI-2) algorithm, the objective function for the acceptability of measurements was percent bias (PBIAS). According to the parameter sensitivity analysis and previous studies (Zhang et al., 2009), sensitive parameters were calibrated, such as soil conservation service (SCS) runoff curve number (CN2), soil evaporation compensation factor (ESCO), the available water capacity of the soil layer (SOL_AWC) (Table 2). Because the delay time for aquifer recharge (GW_DELAY) varied greatly for different soil types, we used the replace adjustment method to calibrate GW_DELAY and the relative adjustment method to calibrate other parameters.

The applied irrigation water was input into the calibrated SWAT model in each subbasin to assess the irrigation impact on hydrological processes. Two types of aquifers are considered in the SWAT model, including an unconfined shallow aquifer and a confined deep aquifer. In this study, the shallow aquifer was assumed to be the source of irrigation (Chen et al., 2019a; Chen et al., 2019b; Harter et al., 2002). The SWAT model was simulated twice in real-world and no irrigation scenario. Irrigation's effects on hydrological processes, such as runoff, runoff, soil water, ET, and infiltration, are the difference between the two scenarios.

3. Results

3.1. Drivers of irrigation water use

In JJJ and NTX, the spatial patterns of precipitation and ET were different, which could have a considerable impact on irrigation practices (Fig. 3). The mean annual precipitation in JJJ regions was greater than that in NTX. Due to different crop coefficients, there was a different spatial distribution of reference evapotranspiration (ETo) and actual ET (ETa) in JJJ and NTX. In JJJ, the distribution of ETo and ETa was similar. In contrast, in the southwest subbasins in NTX, ETo was the highest, but ETa was nearly the lowest. In contrast to the southwestern NTX, a high ETa was found in the central region, where cotton was the major crop. Although ETo in NTX was much higher than that in JJJ regions, its ETa was lower, indicating that land cover types had an evident impact on ET. The spatial distribution of the difference in precipitation and ETa (ETa − Precipitation) in column d in Fig. 3 illustrated the variation in crop water demand. Precipitation in JJJ was much lower than ETa in the southern subbasins (corn-wheat rotation areas). In NTX, there were negative ETa − Precipitation values in the eastern subbasins. These subbasins mainly corresponded to low irrigation demand of irrigated crops (e.g., winter wheat) due to high precipitation.

In JJJ and NTX, the deficit irrigation regime could reduce irrigation water use significantly in the real-world scenario (Fig. 4). In deficit irrigation dominated regions, such as southern JJJ and middle NTX, compared with full irrigation, rainfed farmland could explain 30 % and 40 % of the reduction in irrigation (middle bar compared to the left bar), and deficit irrigation could explain an additional 45 % and a 55 % reduction (right bar compared to the middle bar). In the three northernmost cities in JJJ (i.e., Zhangjiakou, Chengde, and Qinhuangdao), most farmlands were

Table 2
Values of calibrated parameters.

Parameter	Adjustment method	JJJ	NTX
CN2	Relative[b]	0.149	−0.175
ESCO	Relative	−0.289	−0.119
SOL_AWC	Relative	0.298	0.089
SOL_K	Relative	−0.118	0.065
ALPHA_BF	Relative	0.235	0.113
GW_DELAY[a]	Replace[c]	40.48	100.53

Abbreviation: CN2, soil conservation service (SCS) runoff curve number; ESCO, soil evaporation compensation factor; SOL_AWC, available water capacity of the soil layer; SOL_K, saturated hydraulic conductivity; ALPHA_BF, baseflow recession constant; GW_DELAY, delay time for aquifer recharge.

[a] Unitless for parameters using relative method and days for GW_DELAY.

[b] The relative adjustment method means an existing parameter value is multiplied by (1 + given value).

[c] The replace adjustment method means the existing parameter value is to be replaced by a given value.

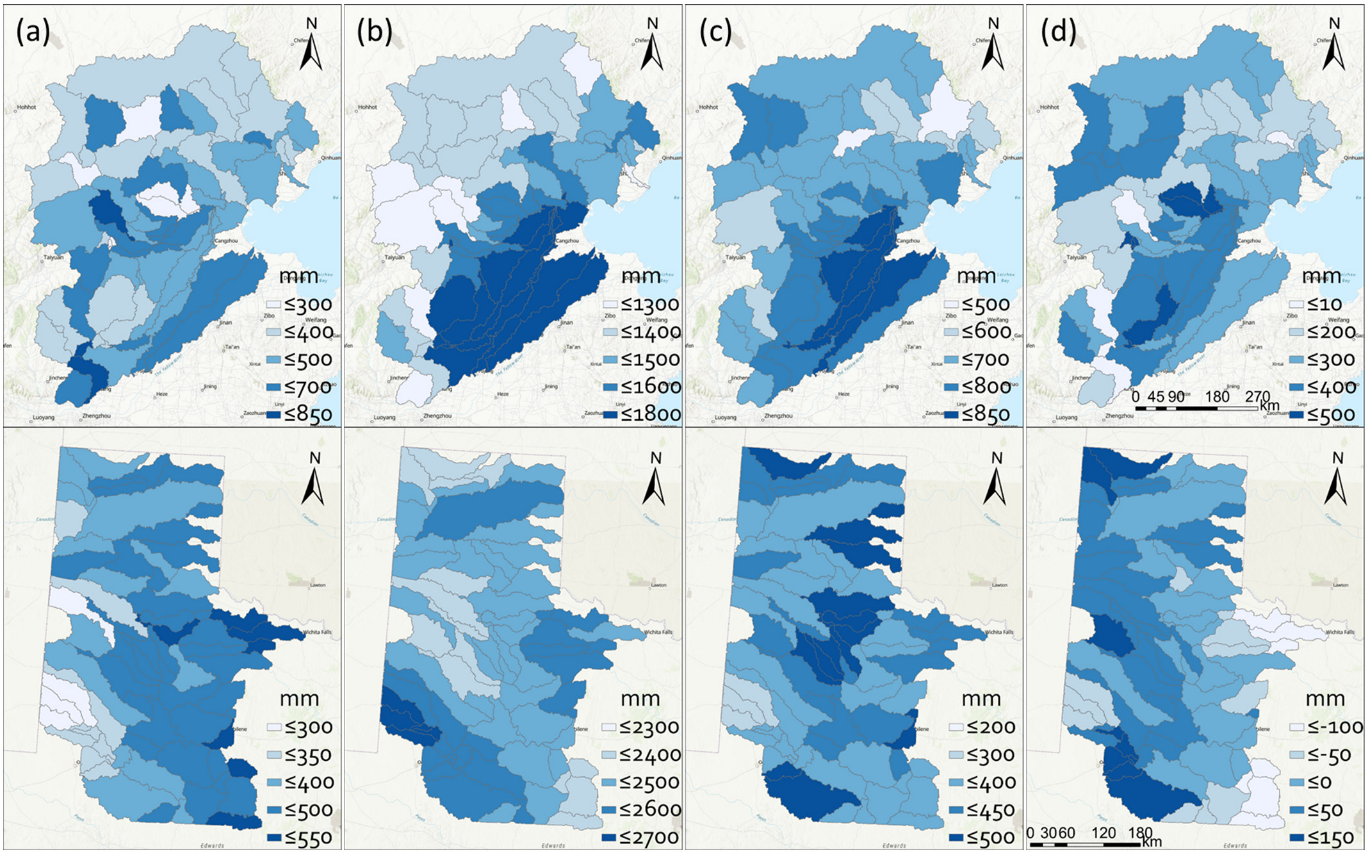


Fig. 3. Subbasin level (a) mean annual precipitation, (b) reference evapotranspiration, (c) actual evapotranspiration, and (d) difference between precipitation and actual ET in JJJ (upper row) and NTX (bottom row).

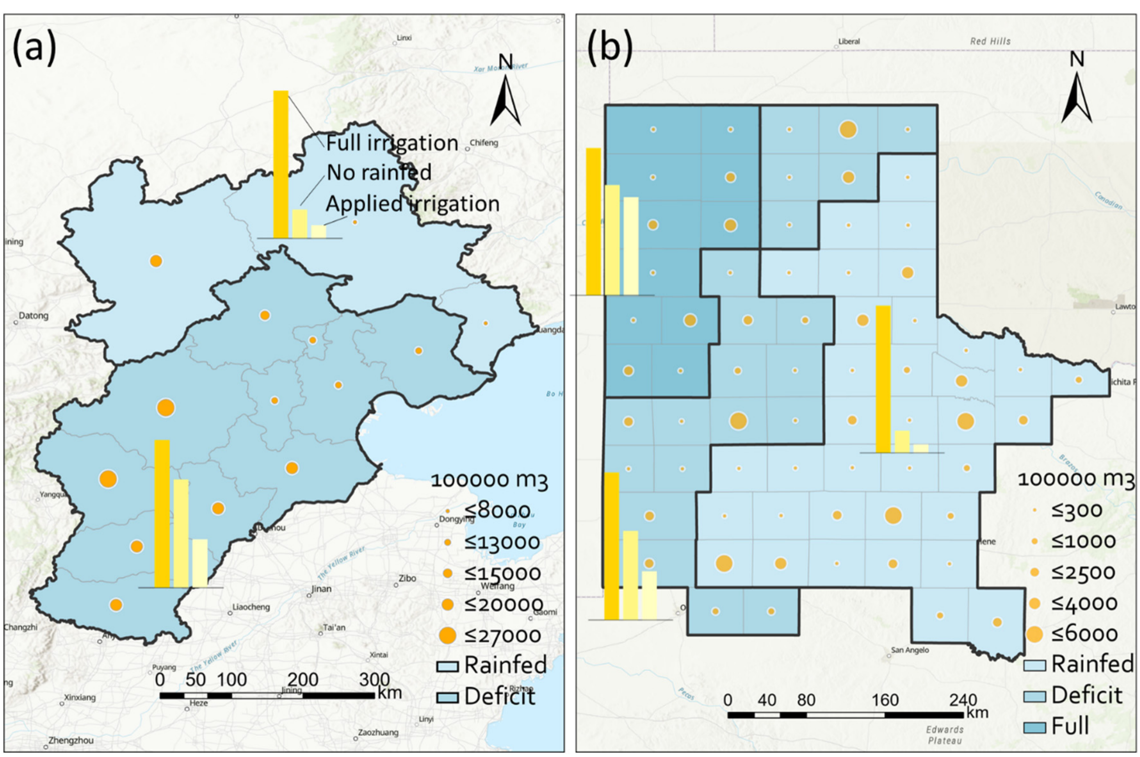


Fig. 4. Annual mean applied irrigation water in (a) JJJ and (b) NTX. The orange circles represent annual mean applied irrigation water in each administrative region. The background colour shows the dominant irrigation regime in three regions: rainfed farmland dominated, deficit irrigation dominated, and full irrigation dominated. Bar charts represent the relative amount of full irrigation, full irrigation without rainfed farmland, and applied irrigation.

rain-fed because the difference between ET and precipitation was low, indicating the crop water demand was low. In the north-central areas such as Beijing and Tianjin, the deficit irrigation regime was the major factor influencing the amount of applied irrigation. Compared to southern cities, the amount of applied irrigation was lower due to less farmland and a lower deficit irrigation ratio. Heavy irrigation was mainly concentrated in the south-central JJJ areas, where the deficit irrigation regime could reduce around 1/3 of full irrigation water. In NTX, the applied irrigation in western counties was higher than in eastern counties, especially in cotton-dominated regions, consistent with previous studies (Colaizzi et al., 2009; Modala et al., 2015). In counties with the highest irrigation, such as Dallam, Castro, and Lamb, the applied irrigation was close to the full irrigation, which indicated that farmers applied as much water as the full crop water requirements. In JJJ, the average DIR was 0.45, compared to 0.53 in NTX, showing that the deficit irrigation regime had a smaller impact in NTX. Furthermore, the internal DIR difference in NTX was greater than in JJJ. Moreover, rain-fed agricultural dominated regions had the lowest DIR (0.44), whereas full irrigation dominated regions had the greatest DIR (0.76). This demonstrated that farmers who grew winter wheat in JJJ (Du et al., 2015; Iqbal et al., 2014), cotton in NTX (Himanshu et al., 2021; Modala et al., 2015), and had croplands in areas with less irrigation had a more favorable attitude towards the deficit irrigation regime.

3.2. Spatial pattern and temporal trend of irrigation

The maximum magnitude of irrigation intensity, water amount per area, was similar, but the intensity of the same crops varied considerably in JJJ and NTX (Fig. 5). In addition, the irrigation intensity fluctuated over the years, influenced by precipitation during the crop growing season. Compared to corn, more water was needed for winter wheat in most years in JJJ, consistent with previous studies (Wang et al., 2015; Yang et al., 2010). However, the irrigation intensity of winter wheat in NTX was much lower than that in JJJ because most of the winter wheat in NTX was in the north and east, where rainfed farmlands were dominant. The irrigation intensity of corn was two times higher than cotton. Because a large part of the region in JJJ was wheat-corn rotation, the annual total irrigation intensity was larger than that in NTX.

The applied irrigation water by different crops exhibited less temporal variability in NTX but fluctuated in JJJ (Fig. 6). Eight cities/counties in JJJ and NTX with medium irrigation and eight cities/counties with intense irrigation were used for comparison. In Texas's south region of our study, cotton was the primary consumer of water for all years, consistent with previous findings (Chen et al., 2017). In JJJ, there was a decreasing trend in most cities. Winter wheat required more irrigation than corn in the south but not in the north, as also demonstrated by (Li et al., 2005). The reason for this is that there was a wheat and corn rotation in the south but no crop rotation in the north in the JJJ regions. In the southern JJJ, the months with the most rain correspond with the peak corn growing season, whereas the winter wheat growing season received little rain. The applied irrigation water for winter wheat was significantly different in these two regions. In NTX, most of the winter wheat was rainfed, but most of the winter wheat was irrigated in the JJJ region.

3.3. Irrigation impact on hydrology

Irrigation showed a more significant impact on streamflow in JJJ than NTX (Fig. 7). Two specific subbasins were selected to assess whether irrigation had different effects on upstream and downstream streamflow. In JJJ, the impact of irrigation on monthly streamflow was similar in both upstream and downstream subbasins, and there was a dramatic change in months during the growing season. The average streamflow could be around 6 m^3/s higher under no irrigation scenario in August in the downstream. However, due to adequate groundwater and lower irrigation intensity, there was only a minor difference in streamflow in real-world and no irrigation scenarios in NTX. The most significant change was in July, which was around 0.4 m^3/s higher in the downstream. The primary reason explaining the contrasting patterns in these two regions was that the overall irrigation intensity was much higher in JJJ than in NTX because the crop rotation in JJJ caused higher irrigation. This led to more water being extracted from the shallow aquifer in JJJ. Furthermore, because the change in ET in JJJ was smaller, there was more groundwater recharge in JJJ than that in NTX under the same precipitation conditions. Another reason for this difference was that JJJ was a water-scarce area.

The comparison of hydrological processes between the real-world and no irrigation scenarios in JJJ and NTX showed that the influence of irrigation on hydrological processes varied, and also such influence in JJJ cities was more significant than that in NTX counties (Fig. 8). There was an apparent increase in surface runoff under no irrigation scenario compared to the real-world scenario due to changes in irrigation practice in both regions, especially during crop growing seasons. Although the maximum change of runoff in the two regions was both higher than 40 %, the peak time of the difference between the two scenarios was different. In JJJ, the largest impact of irrigation on runoff was found during the corn growing season from July to September in the second half of the year. During the growing season of winter wheat in the first half of the year, such impact could be negligible. Compared to surface runoff, the magnitude of irrigation's impact on other components was much lower since slow components have lower variability than fast surface flow (Zeng and Cai, 2014). Because of different crop types and a higher temperature in NTX, there was a more obvious seasonal pattern of such impact on ET, with the highest in May at 10 %. In JJJ, two peaks of evapotranspiration difference were identified at 5 % in April and July, respectively, during the peak time of growing seasons for winter wheat and corn. Differences in soil water content and percolation did not show obvious seasonal patterns, but they were usually 2 % to 7 % higher in the summer. On the annual scale, the soil water content and percolation were slightly higher by around 3 % in the real-world scenario compared to the no irrigation scenario.

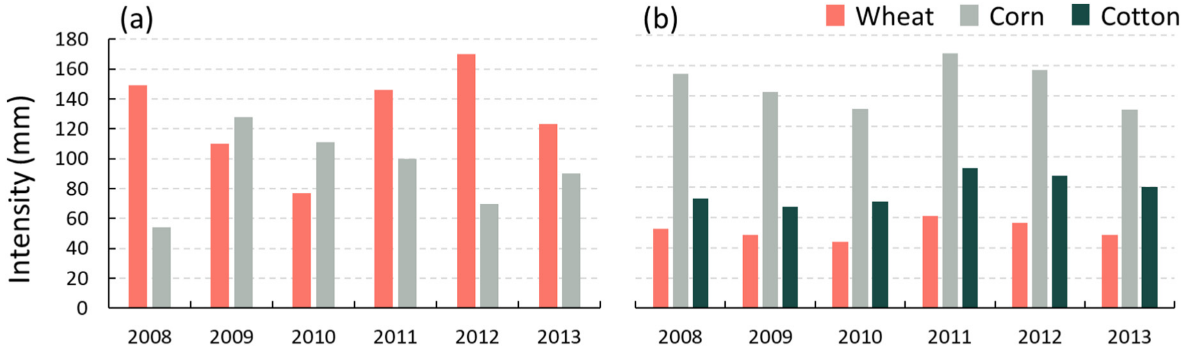


Fig. 5. Crop irrigation intensity in (a) JJJ and (b) NTX.

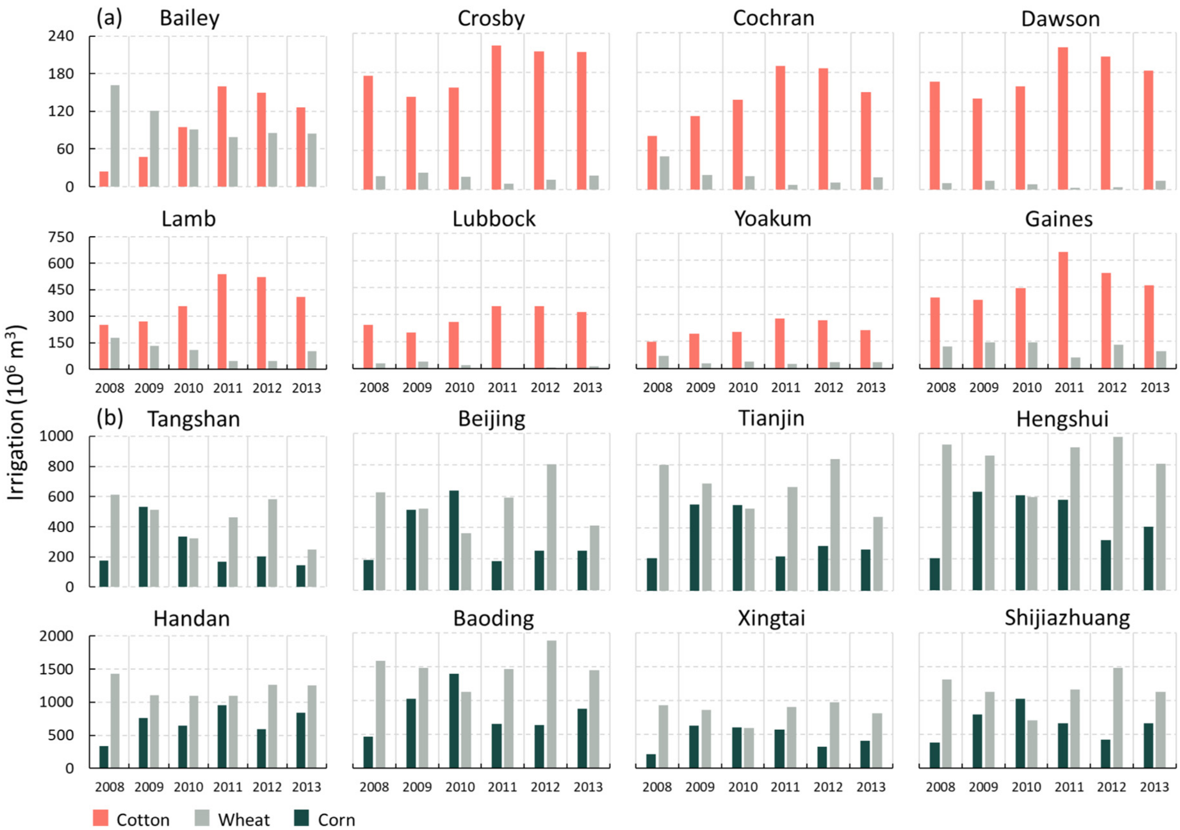


Fig. 6. The comparison of applied irrigation water of major crops in selected (a) NTX counties and (b) JJJ cities.

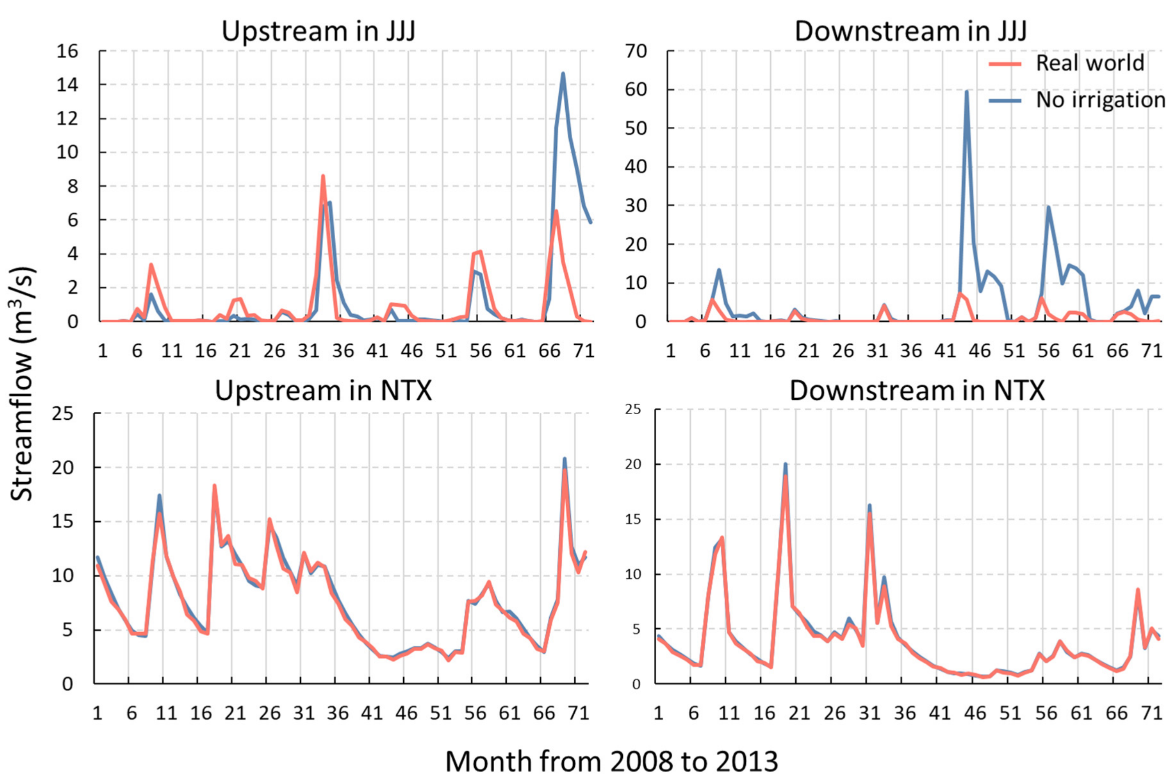


Fig. 7. Streamflow comparison from 2008 to 2013 in upstream and downstream subbasins under two scenarios: irrigation from shallow groundwater and no irrigation water use in (a) JJJ and (b) NTX. The locations of these subbasins are shown as green stars in Fig. 1.

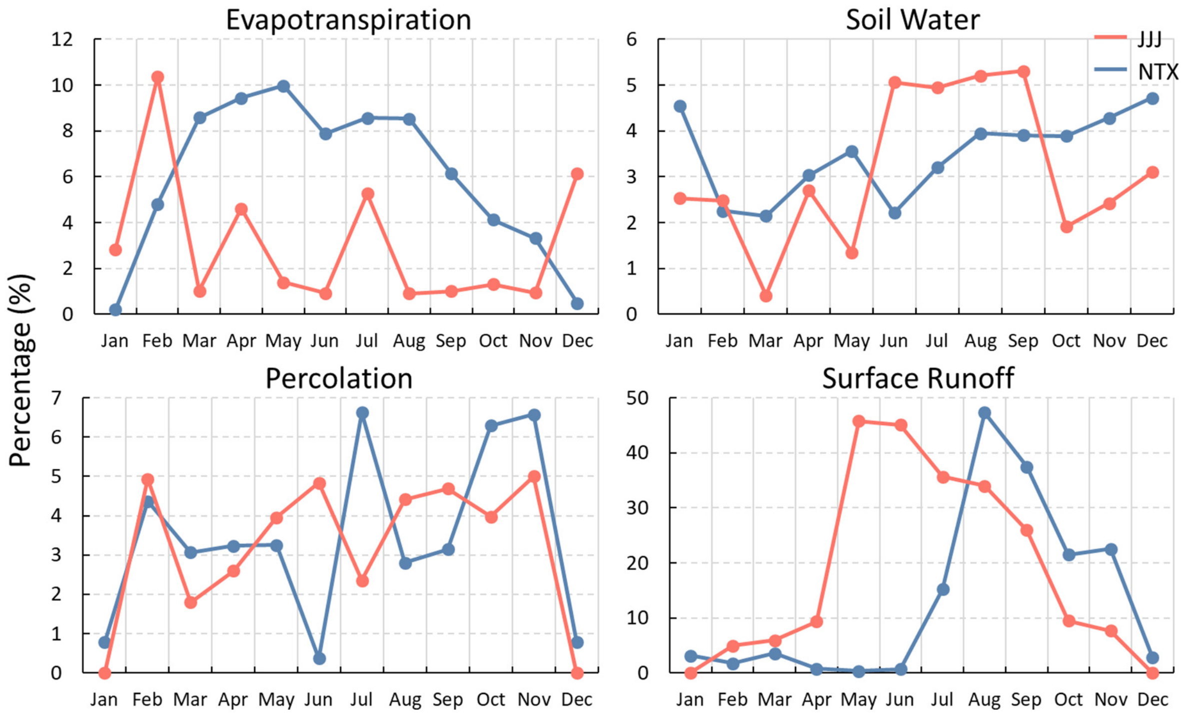


Fig. 8. The percentage change of hydrological processes under real-world relative to the no-irrigation scenario in JJJ and NTX.

4. Discussion

Water, food, and energy are three vital resources for human survival and the growth of the social economy (Li, 2019). Agriculture is the lifeblood of food security, and it necessitates a significant amount of groundwater (Tian et al., 2018). With rapid population growth, the collision between limited water resources and land resources with rising water demand has hampered agricultural development, further affecting energy and water security.

Agricultural water use can alter the magnitude and spatiotemporal patterns of a variety of hydrological processes and exacerbate water stress, resulting in unfavorable changes in surface-groundwater interaction. There are more changes in streamflow in JJJ than in NTX due to the higher irrigation intensity, especially in the downstream (Grogan et al., 2017; Huang et al., 2015; Li et al., 2018a; Li et al., 2018b). Although the magnitude of streamflow changes varies due to different catchment areas and local soil conditions, if there is no irrigation water use, the magnitude of percentage changes in other hydrological processes are similar in the two regions, but the timing of the changes is different. In JJJ, winter wheat requires more irrigation than corn during the growing season, whereas corn consumes more irrigation in NTX. Thus, the largest surface runoff change without irrigation in JJJ occurs in May, nearing the maturity of winter wheat, while in NTX, the largest change occurs in August, nearing maturity of corn. Overall, the difference in the growing season of crops can lead to different impacts of irrigation on hydrological processes. As a result, the challenges in water management increase with more complex crop rotations. Therefore, a specific water management strategy should be developed based on local crops, irrigation, and hydrological conditions. Even within the same watershed, the appropriate management needs to differ across their locations. Furthermore, irrigation is an effective way to maintain adequate soil water for crop growth, even though soil moisture content is not as strongly affected by irrigation as surface water on a monthly average scale. In this case, deficit irrigation and water conservation techniques can aid in the improvement of water resources and ensure adequate food production (Zhang et al., 2021).

It is complicated to optimize the food-energy-water (FEW) nexus in an irrigated agricultural region (Li et al., 2018a; Li et al., 2018b). Irrigation has an important role in both food and water components. Water is needed for food production, but intense irrigation may cause environmental changes, such as alterations in hydrological processes. In the context of the FEW nexus, this raises the dilemma of balancing conflicting goals of economic development and environmental protection. Estimating the amount of irrigation and its impact on hydrological processes is therefore crucial, particularly in water-scarce areas with intensive irrigation, such as JJJ and NTX. The deficit irrigation regime is vital to reduce irrigation water use in these droughty breadbasket regions. This does not necessitate updating or replacing current infrastructure, but it can reduce the total amount of extracted water because water is only applied during drought-sensitive growth stages of the crop (Fereres and Soriano, 2007). Compared to full irrigation, the deficit irrigation regime can reduce about half of the water. Similar findings can also be found in previous studies, such as around 60 % reduction in irrigation for cotton in NTX (Himanshu et al., 2021; Modala et al., 2015) and more than 50 % reduction in JJJ (Du et al., 2015; Zhou et al., 2020a; Zhou et al., 2020b). The issue of excessive groundwater extraction in droughty breadbasket regions can be effectively mitigated using the deficit irrigation regime. Furthermore, various irrigation techniques (e.g., drip irrigation) can promote water conservation by increasing conveyance and application efficiency while reducing groundwater extraction, thereby ensuring adequate water resources for food and energy. However, this study did not simulate how to maintain adequate food production while applying the deficit irrigation regime. It would be helpful to explore whether the water conservation scheme could be effective in these regions from the perspective of yield and production associated economic issues in future studies. In addition, water conservation projects can aid in protecting water resources in the watershed. For example, the South-to-North Water Diversion Project (SNWD) in JJJ, which began operations at the end of 2013, can alleviate severe water scarcity in northern China while also assisting in the preservation of sustainable water resources (Kattel et al., 2019). However, such a project introduced additional factors influencing streamflow in JJJ. Therefore, we performed the simulation before 2013 to make a fair comparison of irrigation impact on streamflow between two watersheds by excluding the impact of SNWD after 2013 in JJJ.

In addition to irrigation, there are other factors influencing the hydrological processes, such as weather conditions and other water usage sectors. Temperature and precipitation have a complex impact on streamflow. Due to climate change, there is an increasing influence of temperature on streamflow (Woodhouse et al., 2016) and a precipitation shift from snow to rain leads to a decrease in streamflow (Berghuijs et al., 2014). In addition, in watersheds with strong human activities, the impact of human activities on hydrological processes can be significant. There was a large amount of domestic and industrial water consumption (around 50 % of agricultural water use) that relied on groundwater extraction (Bureau of Beijing Water Affairs, 2010). If a considerable amount of water was extracted from groundwater, the reduction in groundwater level would be exacerbated compared to no irrigation scenario, and surface water would be altered as a result. For example, the direct water withdrawal can account for 23 % of the decrease in inflow into the Miyun reservoir in JJJ (Ma et al., 2010). However, the climatic factors and water usage of other sectors under two scenarios were consistent during the simulation in each watershed to represent their characteristics. What is important is the difference in hydrological processes between the irrigated and non-irrigated scenarios. Therefore, we used two scenarios with and without irrigation as a control variable to compare changes in various hydrological processes based on the local climate and water usage conditions in two watersheds. Nevertheless, the climate and water usage in other sectors are essential if a complete understanding of how each factor affects different watersheds is required, especially in highly urbanized areas with less farmland.

5. Conclusions

In this study, irrigation water use and its impact on hydrologic processes in JJJ and NTX were estimated using the SWAT model and multiple sources of data (e.g., agriculture, water, climate, and land use). Temporal and spatial characteristics of irrigation water use for major crops in the study areas were quantified. The substantial impacts of irrigation on the water cycle were found in the droughty breadbasket regions from this study. Notably, intensive irrigation significantly influenced downstream hydrological processes during the crop growing season. The impact of irrigation on hydrology varied significantly by region and time due to local crops, irrigation, and hydrological conditions.

Our findings herald the mounting water shortage challenges in agricultural regions for providing food to the growing population under changing climate, as a result of anticipated increases in irrigation water demands due to climate change and population growth. According to our study, the deficit irrigation regime has the potential to reduce around 50 % of irrigation water use. The great potential to reduce groundwater extraction by adopting water conservation irrigation techniques calls for policies and regulations that can help farmers shift towards more sustainable water management practices. Moreover, compared with NTX, irrigation has a more significant effect on the hydrological processes in JJJ. During the crop growing season, the peak change due to irrigation reached 6 m^3/s for streamflow and 40 % for runoff, while less than 10 % for the soil water and percolation.

The required data in the developed framework are easily accessible, making it transferrable to other regions to estimate irrigation water use and analyze the impact factors for water sustainability. It is worth noting that due to data availability, this study focused on irrigation for major crops and did not include vegetables and fruit trees with small areas and partial crop rotations. In future studies, water for other crops such as vegetables and fruit trees can be considered in evaluating the impact of irrigation on hydrological processes. In addition, a comprehensive assessment and understanding of the impacts of climate and water usage in other sectors on hydrological processes are needed.

CRediT authorship contribution statement

Yiming Wang: Conceptualization, Methodology, Software, Validation, Writing- Original draft preparation. **Yuyu Zhou:** Conceptualization, Supervision, Writing- Reviewing and Editing. **Kristie J. Franz:** Writing-Reviewing and Editing. **Xuesong Zhang:** Software, Writing- Reviewing and Editing. **Junyu Qi:** Software. **Gensuo Jia:** Investigation. **Yun Yang:** Writing- Reviewing and Editing.

Declaration of competing interest

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

Acknowledgements

This study was supported by the National Science Foundation (CBET-1803920) and the U.S. Department of Agriculture, Agricultural Research Service.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.157253.

References

Abbaspour, Karim C., 2013. Swat-cup 2012. SWAT Calibration and Uncertainty Program—A User Manual.
Ahmadzadeh, Hojat, et al., 2016. Using the SWAT model to assess the impacts of changing irrigation from surface to pressurized systems on water productivity and water saving in the zarrineh rud catchment. Agric. Water Manag. 175, 15–28.
Ahuja, Lajpat, Rojas, K.W., Hanson, J.D., 2000. Root Zone Water Quality Model: Modelling Management Effects on Water Quality and Crop Production. Water Resources Publication.
Alcamo, Joseph, et al., 2003. Development and testing of the WaterGAP 2 global model of water use and availability. Hydrol. Sci. J. 48 (3), 317–337.
Aliyari, Fatemeh, Bailey, Ryan T., Arabi, Mazdak, 2021. Appraising climate change impacts on future water resources and agricultural productivity in agro-urban river basins. Sci. Total Environ. 788, 147717.
Allen, Richard G., 1998. Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements-FAO Irrigation and Drainage Paper 56. 300.9. Fao, Rome D05109.
Arnold, Jeffrey G., 1998. Large area hydrologic modeling and assessment part I: model development 1. J. Am. Water Resour. Assoc. 34 (1), 73–89.
Barnston, Anthony G., Schickedanz, Paul T., 1984. The effect of irrigation on warm season precipitation in the southern Great Plains. J. Appl. Meteorol. Climatol. 23 (6), 865–888.
Baumhardt, R.L., et al., 2009. Modeling irrigation management strategies to maximize cotton lint yield and water use efficiency. Agron. J. 101 (3), 460–468.
Berghuijs, W.R., Woods, R.A., Hrachowitz, M., 2014. A precipitation shift from snow towards rain leads to a decrease in streamflow. Nat. Clim. Chang. 4 (7), 583–586.
Bureau of Beijing Water Affairs, 2010. Beijing Water Resources Bulletin 2010. China Water and Hydropower Publisher, Beijing.
Burek, Peter, 2018. Global Hydrological Model Community Water Model (CWATM).
Camp, C.R., 1998. Subsurface drip irrigation: a review. Trans. ASAE 41 (5), 1353.
Carrión, P., Tarjuelo, J., Montero, J., 2001. SIRIAS: a simulation model for sprinkler irrigation. Irrig. Sci. 20 (2), 73–84.
Chen, Yong, et al., 2017. Assessing the efficacy of the SWAT auto-irrigation function to simulate irrigation, evapotranspiration, and crop response to management strategies of the Texas High Plains. Water 9 (7), 509.
Chen, Jie, et al., 2019. Hydrogeochemical characteristics and quality assessment of groundwater in an irrigated region, Northwest China. Water 11 (1), 96.
Chen, Yong, et al., 2019. Simulating the impacts of climate change on hydrology and crop production in the northern High Plains of Texas using an improved SWAT model. Agric. Water Manag. 221, 13–24.
Chen, Yong, et al., 2020. Watershed scale evaluation of an improved SWAT auto-irrigation function. Environ. Model Softw. 131, 104789.
Colaizzi, Paul D., et al., 2009. Irrigation in the Texas High Plains: a brief history and potential reductions in demand. Irrig. Drain. 58 (3), 257–274.
Dakhlalla, Abdullah O., et al., 2016. Evaluating the impacts of crop rotations on groundwater storage and recharge in an agricultural watershed. Agric. Water Manag. 163, 332–343.
DeAngelis, Anthony, et al., 2010. Evidence of enhanced precipitation due to irrigation over the Great Plains of the United States. J. Geophys. Res. Atmos. 115, D15.
Dechmi, Farida, Skhiri, Ahmed, 2013. Evaluation of best management practices under intensive irrigation using SWAT model. Agric. Water Manag. 123, 55–64.
Du, Taisheng, et al., 2015. Deficit irrigation and sustainable water-resource strategies in agriculture for China's food security. J. Exp. Bot. 66 (8), 2253–2269.
Fallatah, Othman Abdurrahman, et al., 2019. Assessment of modern recharge to arid region aquifers using an integrated geophysical, geochemical, and remote sensing approach. J. Hydrol. 569, 600–611.
Fereres, Elias, Soriano, María Auxiliadora, 2007. Deficit irrigation for reducing agricultural water use. J. Exp. Bot. 58 (2), 147–159.

Gassman, Philip W., 2009. The Agricultural Policy Environmental Extender (APEX) Model: An Emerging Tool for Landscape and Watershed Environmental Analyses.

Grogan, Danielle S., et al., 2017. The use and re-use of unsustainable groundwater for irrigation: a global budget. Environ. Res. Lett. 12 (3), 034017.

Guillet, David, 2006. Rethinking irrigation efficiency: chain irrigation in northwestern Spain. Hum. Ecol. 34 (3), 305–329.

Han, Weiguo, et al., 2012. CropScape: a web service based application for exploring and disseminating US conterminous geospatial cropland data products for decision support. Comput. Electron. Agric. 84, 111–123.

Harter, Thomas, et al., 2002. Shallow groundwater quality on dairy farms with irrigated forage crops. J. Contam. Hydrol. 55 (3-4), 287–315.

Hashem, Ahmed A., et al., 2020. Evaluation of SWAT soil water estimation accuracy using data from Indiana, Colorado, and Texas. Trans. ASABE 63 (6), 1827–1843.

Himanshu, Sushil K., et al., 2021. Assessing the impacts of irrigation termination periods on cotton productivity under strategic deficit irrigation regimes. Sci. Rep. 11 (1), 1–16.

Huang, Shaochun, et al., 2015. Impact of intensive irrigation activities on river discharge under agricultural scenarios in the semi-arid Aksu River basin, Northwest China. Water Resour. Manag. 29 (3), 945–959.

Iqbal, M.Anjum, et al., 2014. Evaluation of the FAO AquaCrop model for winter wheat on the North China plain under deficit irrigation from field experiment to regional yield simulation. Agric. Water Manag. 135, 61–72.

Jensen, Marvin Eli, Burman, Robert D., Allen, Rick G., 1990. Evapotranspiration and Irrigation Water Requirements. American Society of Civil Engineers, New York, NY ASCE Manual No. 70.

Jones, James W., et al., 2003. The DSSAT cropping system model. Eur. J. Agron. 18 (3-4), 235–265.

Kang, Shaozhong, et al., 2017. Improving agricultural water productivity to ensure food security in China under changing environment: from research to practice. Agric. Water Manag. 179, 5–17.

Kattel, Giri R., et al., 2019. China's south-to-north water diversion project empowers sustainable water resources system in the north. Sustainability 11 (13), 3735.

Le Page, Michel, 2020. Potential for the detection of irrigation events on maize plots using sentinel-1 soil moisture products. Remote Sens. 12 (10), 1621.

Li, Mo, 2019. Stochastic multi-objective modeling for optimization of water-food-energy nexus of irrigated agriculture. Adv. Water Resour. 127, 209–224.

Li, Jiamin, et al., 2005. Optimizing irrigation scheduling for winter wheat in the North China plain. Agric. Water Manag. 76 (1), 8–23.

Li, Jian, et al., 2018. Underwater superoleophobic/underoil superhydrophobic corn cob coated meshes for on-demand oil/water separation. Sep. Purif. Technol. 195, 232–237.

Li, Xin, et al., 2018. Hydrological cycle in the Heihe River basin and its implication for water resource management in endorheic basins. J. Geophys. Res. Atmos. 123 (2), 890–914.

Liu, Yujie, Luo, Yi, 2010. A consolidated evaluation of the FAO-56 dual crop coefficient approach using the lysimeter data in the North China plain. Agric. Water Manag. 97 (1), 31–40.

Luo, Yuchuan, et al., 2020. ChinaCropPhen1km: a high-resolution crop phenological dataset for three staple crops in China during 2000–2015 based on leaf area index (LAI) products. Earth Syst. Sci. Data 12 (1), 197–214.

Ma, Huan, et al., 2010. Impact of climate variability and human activity on streamflow decrease in the miyun reservoir catchment. J. Hydrol. 389 (3-4), 317–324.

McCabe, Jr, Gregory, J., Wolock, David M., 1992. Sensitwity of irrigation demand in a humid-temperate region to hypothetical climatic change 1. J. Am. Water Resour. Assoc. 28 (3), 535–543.

Meng, X., Zhang, X., Yang, M., Wang, H., Chen, J., Pan, Z., Wu, Y., 2019. Application and evaluation of the China meteorological assimilation driving datasets for the SWAT model (CMADS) in poorly gauged regions in Western China. Water 11 (10), 2171.

Modala, Naga Raghuveer, et al., 2015. Evaluation of the CSM-CROPGRO-cotton model for the Texas rolling plains region and simulation of deficit irrigation strategies for increasing water use efficiency. Trans. ASABE 58 (3), 685–696.

Morris, Michael R., et al., 2015. Inflow rate and border irrigation performance. Agric. Water Manag. 155, 76–86.

Neitsch, Susan L., 2011. Soil and Water Assessment Tool Theoretical Documentation Version 2009. Texas Water Resources Institute.

Ouellet Dallaire, C., Lehner, B., Sayre, R., Thieme, M., 2018. A multidisciplinary framework to derive global river reach classifications at high spatial resolution. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/aad8e9 (open access).

Poch-Massegú, R., et al., 2014. Irrigation return flow and nitrate leaching under different crops and irrigation methods in Western Mediterranean weather conditions. Agric. Water Manag. 134, 1–13.

Qiu, J., Yang, Q., Zhang, X., Huang, M., Adam, J.C., Malek, K., 2019. Implications of water management representations for watershed hydrologic modeling in the Yakima River basin. Hydrol. Earth Syst. Sci. 23 (1), 35–49.

Segovia-Cardozo, Daniel Alberto, Rodríguez-Sinobas, Leonor, Zubelzu, Sergio, 2019. Water use efficiency of corn among the irrigation districts across the duero river basin: estimation of local crop coefficients by satellite images. Agric. Water Manag. 212, 241–251.

Shahid, Shamsuddin, 2011. Impact of climate change on irrigation water demand of dry season boro rice in Northwest Bangladesh. Clim. Chang. 105 (3-4), 433–453.

Sharmasarkar, F.Cassel, et al., 2001. Assessment of drip and flood irrigation on water and fertilizer use efficiencies for sugarbeets. Agric. Water Manag. 46 (3), 241–251.

Siebert, Stefan, 2013. Update of the digital global map of irrigation areas to version 5. Rheinische Friedrich-Wilhelms-Universität, Bonn, Germany and Food and Agriculture Organization of the United Nations, Rome, Italy.

Siebert, Stefan, et al., 2005. Development and validation of the global map of irrigation areas. Hydrol. Earth Syst. Sci. 9 (5), 535–547.

Sorooshian, Soroosh, AghaKouchak, Amir, Li, Jialun, 2014. Influence of irrigation on land hydrological processes over California. J. Geophys. Res. Atmos. 119 (23), 13–137.

Tian, Hanqin, et al., 2018. Optimizing resource use efficiencies in the food–energy–water nexus for sustainable agriculture: from conceptual model to decision support system. Curr. Opin. Environ. Sustain. 33, 104–113.

Wada, Yoshihide, van Beek, Ludovicus P.H., Bierkens, Marc F.P., 2012. Nonsustainable groundwater sustaining irrigation: a global assessment. Water Resour. Res. 48, 6.

Wang, Xiangping, et al., 2015. An assessment of irrigation practices: sprinkler irrigation of winter wheat in the North China plain. Agric. Water Manag. 159, 197–208.

Wei, Xiaolu, Bailey, Ryan T., 2019. Assessment of system responses in intensively irrigated stream–aquifer systems using SWAT-MODFLOW. Water 11 (8), 1576.

Wen, Fujiang, Chen, Xunhong, 2006. Evaluation of the impact of groundwater irrigation on streamflow in Nebraska. J. Hydrol. 327 (3-4), 603–617.

Wisser, Dominik, et al., 2008. Global irrigation water demand: variability and uncertainties arising from agricultural and climate data sets. Geophys. Res. Lett. 35, 24.

Woodhouse, Connie A., et al., 2016. Increasing influence of air temperature on upper Colorado River streamflow. Geophys. Res. Lett. 43 (5), 2174–2181.

Xie, Xianhong, Cui, Yuanlai, 2011. Development and test of SWAT for modeling hydrological processes in irrigation districts with paddy rice. J. Hydrol. 396 (1-2), 61–71.

Yang, Yanmin, et al., 2010. Estimation of irrigation requirement for sustainable water resources reallocation in North China. Agric. Water Manag. 97 (11), 1711–1721.

Zeng, R., Cai, X., 2014. Analyzing streamflow changes: irrigation-enhanced interaction between aquifer and streamflow in the Republican River basin. Hydrol. Earth Syst. Sci. 18 (2), 493–502.

Zhang, X., Srinivasan, R., Zhao, K., Liew, M.V., 2009. Evaluation of global optimization algorithms for parameter calibration of a computationally intensive hydrologic model. Hydrol. Process. 23 (3), 430–441.

Zhang, Manfei, Wang, Xiao, Zhou, Weibo, 2021. Effects of water-saving irrigation on hydrological cycle in an Irrigation District of northern China. Sustainability 13 (15), 8488.

Zhou, Xun Bo, et al., 2020. Double-double row planting mode at deficit irrigation regime increases winter wheat yield and water use efficiency in North China plain. Agronomy 10 (9), 1315.

Zhou, Wang, et al., 2020. Connections between the hydrological cycle and crop yield in the rainfed US Corn Belt. J. Hydrol. 590, 125398.