Irrigation Science (2023) 41:49–68
https://doi.org/10.1007/s00271-022-00792-0

ORIGINAL PAPER

Optimizing the allocation of irrigation water for multiple crops based on the crop water allocation priority

Juan Gong[1] · Liuyue He[1] · Xiuxia Liu[1] · Sufen Wang[1]

Received: 2 September 2021 / Accepted: 2 April 2022 / Published online: 27 April 2022

Abstract

There is an urgent need to ensure regional food security and increase irrigation water productivity in response to water shortages in arid and semi-arid regions. Previous studies of the optimal allocation of irrigation water did not consider simultaneously optimizing across multiple crops or at different growth stages. This paper describes the development of an irrigation water optimization model that uses a crop water allocation priority (CWAP) model. The CWAP value was determined by quantifying the changes in three indicators: yield, economic benefits, and irrigation water productivity. Maximum yield, maximum economic benefits, and minimum irrigation shortage (at the critical crop and growth stage) were used as the objective functions of a non-linear multi-objective optimization model. The largest irrigation district in the northern arid area of China, Hetao Irrigation District (HID), was chosen to prototype this model. The optimization results, using CWAP, showed that yield, economic benefits, irrigation water productivity, and water productivity could be increased, respectively, by up to 13.38%, 13.40%, 2.30%, and 6.29%, for most crops when compared with optimization results without CWAP. Comparison of the optimized net irrigation quantities with the actual net irrigation quantities showed that optimization reduced water usage by up to 60.77% for wheat, 51.24% for corn, and 63.59% for sunflower. Blue water utilization under optimal irrigation conditions decreased by 1.12% for wheat, 2.91% for corn, and 9.91% for sunflower, compared with those in actual irrigation scenario. This method of optimizing irrigation water allocation in arid areas using CWAP provides decision-makers with accurate water-saving irrigation protocols that will reduce demand for water resources and promote sustainable agriculture.

Introduction

Climate change, population growth, and environmental destruction have intensified the incompatibility of increased water shortages and increased food demand. Water shortage is the principal constraint of sustainable agriculture, especially in arid and semi-arid regions (FAO 2013; Doulgeris et al. 2015; Mandal et al. 2020). The Yellow River Basin (YRB) is one of the driest basins in the world. Its population is 100 million, the irrigated area is 4.59 million hectares, and annual water withdrawal is 49.8 billion cubic meters (Omer et al. 2021). In the late 1990s, YRB suffered 226 consecutive days of drought in the downstream basin, due mainly to excessive water diversion for upstream irrigation (Omer et al. 2021; Tang et al. 2008). Hetao Irrigation District (HID), in the upper and middle reaches of YRB, is the largest irrigation district in YRB. About 14.3% of the water in YRB is diverted into HID, and about 90% of that water is used for agricultural irrigation (White et al. 2020; Xue et al. 2020). However, allowable annual water diversions from YRB in HID have recently been reduced from 5 to 4 billion cubic meters (Niu et al. 2016). Wang (2017) estimated that the irrigation water use coefficient (the ratio of irrigation water consumed by field crops to water from natural water sources diverted into the canal system) in HID was 0.487 in 2020, below the national average of 0.55 (Gao et al. 2018). Increased irrigation water demand, reduced water diversion in YRB, and low irrigation water use efficiency have exacerbated regional water shortages (Li et al. 2020c; Omer et al. 2020). Thus, there is an urgent need to ensure more effective allocation of irrigation water in HID.

An optimization model is commonly used to allocate water resources in a region. Optimization techniques include linear programming, non-linear programming, multi-objective programming, and interval programming (Naghdi et al. 2021; Zhang et al. 2019a; Li et al. 2016). Irrigation water management is a complex task due to climate variability,

✉ Sufen Wang
wwwsf71@163.com

[1] Center for Agricultural Water Research in China, China Agricultural University, Beijing 100083, China

complex soil conditions, long-term human activity, a multiplicity of stakeholders, and delicate social economies (Tang et al. 2019; Liu et al. 2014). An effective irrigation water allocation scheme must therefore balance conflicts among various stakeholders. A number of approaches can be taken to achieve this goal. Different water users can be prioritized by importance to assist water managers (Karatayev et al. 2017; Gómez-Limón et al. 2020). Irrigation areas can be prioritized for water distribution, and an optimized water resource allocation model can then determine the best allocation of irrigation water resources to meet the priorities assigned (Zhang et al. 2019a; Luo et al. 2021b). The studies mentioned investigated the criteria used to prioritize irrigation water allocation that were not specific to the crops in the region. Some studies have used the crop-specific water sensitivity index (WSI) to prioritize irrigation water allocation in the water resources allocation model (Tang et al. 2019; Zhang et al. 2019b). WSI is defined in such a way that it can only be used to prioritize water allocation for different growth stages of a specific crop, and cannot be used to prioritize allocation among different crops (Shang 2013; Doorenbos and Kassam 1979; Jensen 1968). Thus, it is impractical to use WSI to determine water allocation for multiple crops.

A crop water allocation priority (CWAP) model is proposed to optimize irrigation water allocation based on the prioritization of different crops and their growth periods. CWAP takes into account the complex responses of crop growth to natural environmental factors (climate and soil) and agricultural management factors (irrigation schemes and economic benefits). CWAP also makes trade-offs between multiple crops by allocating irrigation water in conformity with any allocation principles used in water deficient regions, such as prioritizing allocation at critical crop growth stages or to crops with high water productivity or great economic benefits (Zhang et al. 2021c; Mandal et al. 2020; Stetson et al. 2011). The CWAP model can be optimized to allocate water to ensure growth of the crop that needs it most, thereby increasing water productivity and ensuring food security.

The CWAP model was used to optimize irrigation water allocation for various crops in HID, to alleviate the effects of the water shortage in HID. The study was divided into four components. (1) Establish the CWAP model by determining the values of three weighted evaluation indexes. (2) Develop a non-linear multi-objective optimization model based on CWAP model to allocate irrigation water for multiple crops. (3) Apply the optimized model to HID, where an optimal allocation of irrigation water is urgently needed. (4) Compare the optimized results using CWAP with the results of optimized allocation that did not use CWAP. This study provides an empirical template for decision-makers in similar regions to optimize irrigation and meet economic goals with reduced irrigation water resources.

Study system

Study area

Hetao Irrigation District (HID) (40°9′36″–41°20′24″ N, 106°19′48″–109°34′48″ E) is an important commodity grain and oil production region in China, in the west of the Inner Mongolia Autonomous Region (Fig. 1). It is one of three super-large irrigation districts in China with an area of 11,900 km^2 and an irrigation area of 5700 km^2 (Zhang et al. 2021c). It includes five irrigation subareas: UulanBuh, Jiefangzha, Yongji, Yichang, and Urat.

The climate of the study area is semi-arid temperate continental that is characterized by low rainfall and high evaporation. Average annual precipitation is less than 200 mm. Precipitation varies greatly within the year, with 70% in July–September. Average annual evaporation is more than 2000 mm. Agriculture in the region depends critically on irrigation water.

The major irrigation method is surface irrigation; the ratio of surface irrigation to groundwater irrigation is almost 9:1 in HID (Gao et al. 2018). Irrigation water is diverted from the middle reaches of YRB. Irrigation water salinity is approximately 0.58 g L^{-1}. Average annual irrigation water use is about 4.84 billion m^3 per year (Luo et al. 2021a). However, allowable annual water diversion from YRB has recently been reduced from 5 billion m^3 to 4 billion m^3 (Niu et al. 2016). Growers over-irrigate, resulting in inefficient and wasteful water use, and shallow groundwater. Groundwater depth dropped from 1.90 m in 2004 to 2.22 m in 2019. It is still very shallow and varies between 0.5 and 3.0 m within a year (Zhang et al. 2021c; Ren et al. 2016). The shallow groundwater causes severe salinity, and about 70% of arable land is saline to some degree (Zhang et al. 2021a). The reduction in water diversion from YRB and consequently lower irrigation water use coefficient have led to a water shortage in HID. Water shortage and soil salinization are two critical problems facing sustainable agricultural development in HID (Zhang et al. 2021c; Li et al. 2020a; Sun et al. 2016; Qi et al. 2018).

The main crops in the study area are wheat, corn, and sunflower; they account for more than 80% of total cropland land use (Luo et al. 2021a; Zhang et al. 2021b). Crop planting by area is 19.05% wheat, 30.67% corn, and 31.61% sunflower. Wheat is grown mainly from April to July, corn from May to September, and sunflower from June to September.

Data sources

This study was devised to optimally allocate irrigation water in an area of water shortage, HID. A typical dry year, 2011,

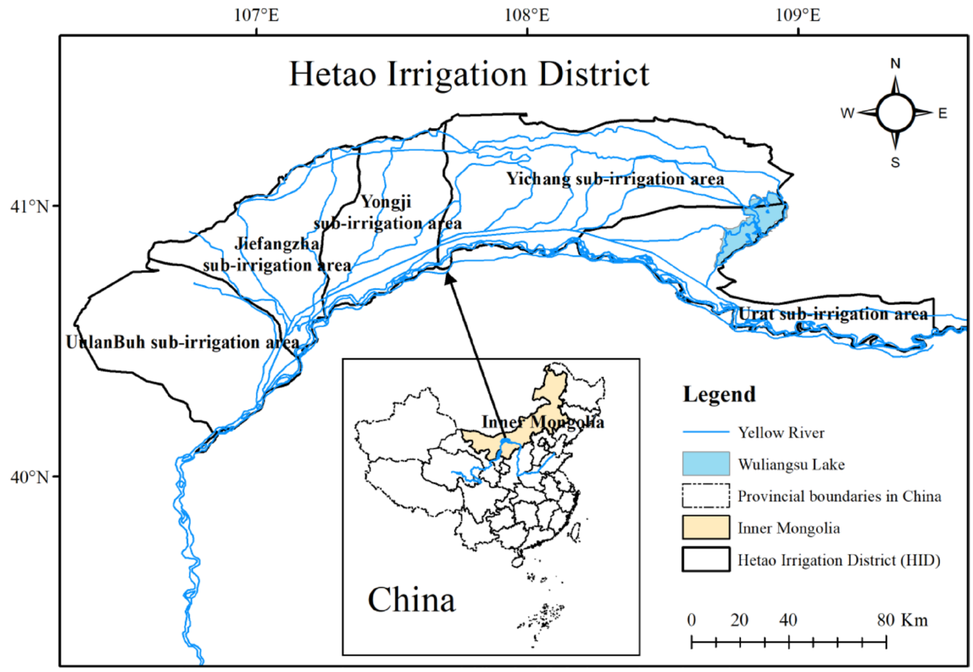


Fig. 1 The location of the study area

was selected as the baseline year (Zhang et al. 2021b), and the basic data used in the study were for 2011. Meteorological data were obtained from the China Meteorological Data Service System (http://data.cma.cn/) included precipitation (Table 1), wind speed, temperature, and sunshine hours. Reference evapotranspiration ET_0 was calculated using the Penman–Monteith equation (Allen et al. 1998). Maximum actual evapotranspiration ET_m (Table 1) was calculated using the single-crop coefficient method recommended in FAO56 (Allen et al. 1998; Gao et al. 2018). Crop information and field data (Table 2) were derived from the local statistical yearbook and previous research results (Zeng et al. 2016a; Tong et al., 2015; Gao et al., 2018; Miao et al., 2016; Ren et al. 2018). WSI (Table 1) was obtained from published research (Tian et al. 2015; Zeng et al. 2016b; Yun et al. 2015; Tang et al. 2019). Previous research was also the source of characteristic crop parameters and seasonal yield impact factors, and electrical conductivity of the soil obtained from saturated solution of soil in the crop root layer (Allen et al. 1998; Zeng et al. 2016a; Tong et al. 2015; Xue et al. 2020). The groundwater recharge coefficient in HID was 20% (Luo et al. 2021b). The crop purchase prices were \$0.43 for wheat, \$0.31 for corn, \$0.98 for sunflower (unit: USD kg^{-1}). The price of surface water was \$0.00465 and of groundwater was \$0.0124 (unit: USD m^{-3}). Available water diversion for irrigating these three crops from YRB (accounting for 80% of the total water diversion from YRB) was 2.08 billion m^3, and available well water was 232 million m^3, in 2011(Luo et al. 2021a).

Methods

Study framework

The framework of this study is shown in Fig. 2. The work was carried out in three stages, shown as three boxes in the Fig. 1 Crop growth simulation. The soil water balance equation and crop water production function (the Jensen model) were used to calculate crop water consumption and crop yield. The crop growth model simulates the complex response of crop growth to environmental factors (climate, soil, and water) in irrigated agricultural production. (2) Quantification of CWAP. Change in yield, change in economic benefit, and change in irrigation water productivity were chosen as the three evaluation indexes of CWAP. The coefficient of variation was used to determine two initial weightings for each evaluation index that were derived from growth period and crop type. The CWAP coefficient was then calculated by a function that combined the growth period weight and the crop type weight. The CWAP coefficient was then used to weight each evaluation index to produce the CWAP value for each crop type and each growth period. The CWAP value represents the irrigation priority for the crop and its growth period. (3) Optimal allocation of irrigation water for multiple crops. The non-linear multi-objective optimization model, which balances food security, economic benefits, and the environment, was created from the CWAP model to allocate irrigation water for each growth month of the various crops grown in HID.

Table 1 Precipitation, crop actual maximum evapotranspiration and water sensitivity index

Subarea	Month	Precipitation in 2011 (mm)	Maximum actual evapotranspiration in 2011 (ET_m, mm)			Water sensitivity index (WSI)		
			Wheat	Corn	Sunflower	Wheat	Corn	Sunflower
UulanBuh	April	0.00	90.558			0.481		
	May	0.70	170.128	112.406		0.729	0.031	
	June	10.00	235.167	167.716	127.610	0.340	0.248	0.117
	July	17.00	60.620	212.960	200.860	0.077	0.361	0.365
	August	17.30		138.513	138.513		0.070	0.387
	September	0.00		34.840	29.820		0.006	0.137
Jiefangzha	April	0.30	73.688			0.155		
	May	1.00	148.675	115.810		0.628	0.001	
	June	5.50	229.620	163.760	124.600	0.463	0.016	0.090
	July	6.70	80.010	192.060	181.148	0.080	0.239	0.357
	August	21.40		130.900	130.900		0.194	0.301
	September	3.20		35.620	41.820		0.011	0.063
Yongji	April	0.50	74.542			0.173		
	May	0.80	149.720	116.624		0.373	0.032	
	June	12.50	245.358	174.984	133.140	0.575	0.149	0.543
	July	4.10	75.530	202.400	190.900	0.566	0.347	0.402
	August	18.90		139.650	139.650		0.248	0.033
	September	4.00		46.085	57.720		0.068	0.002
Yichang	April	0.80	76.296			0.227		
	May	1.30	160.472	111.096		0.369	0.008	
	June	17.00	215.452	165.121	97.510	0.498	0.076	0.031
	July	11.00	53.136	206.655	194.525	0.252	0.404	0.171
	August	25.40		140.504	147.452		0.428	0.053
	September	4.00		36.381	61.180		0.086	0.003
Urat	April	2.00	75.684			0.227		
	May	3.50	153.712	107.894		0.369	0.008	
	June	16.60	220.942	168.423	101.850	0.498	0.076	0.031
	July	45.20	53.928	208.259	175.085	0.252	0.404	0.171
	August	34.90		143.558	192.480		0.428	0.053
	September	11.50		34.980	55.835		0.086	0.003

The crop water sensitivity index (WSI) indicates the effect of water shortage on yield during the crop growth period

Table 2 Crop information and field data

Subarea	Utilization coefficient of surface irrigation	Initial soil moisture content (%)	Soil dry bulk density (g cm^{-3})	Field capacity (%)	Wilting point (%)	Planting area in 2011 (ha)		
						Wheat	Corn	Sunflower
UulanBuh	0.39	14.27	1.48	21.40	8.00	5228	13,820	14,744
Jiefangzha	0.42	24.68	1.56	37.00	12.00	24,538	31,868	14,115
Yongji	0.40	15.01	1.45	22.50	6.00	19,659	50,135	43,915
Yichang	0.36	21.06	1.32	31.58	15.70	30,233	33,440	50,120
Urat	0.34	16.25	1.50	24.37	10.79	24,449	38,321	49,849

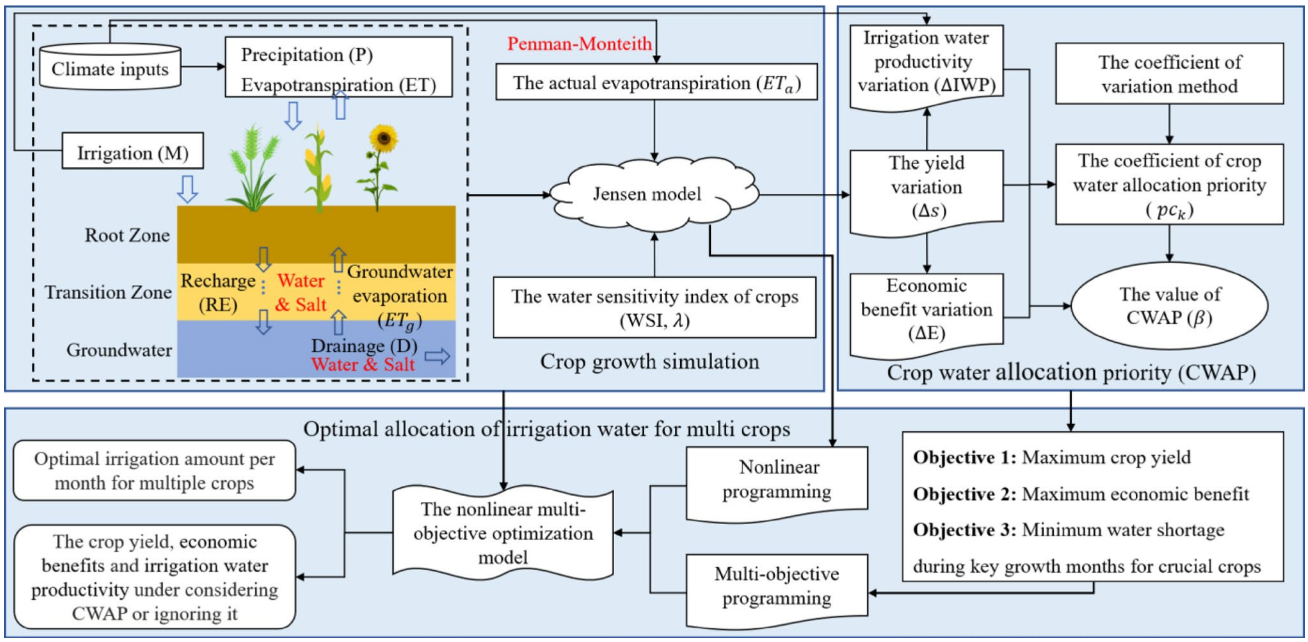


Fig. 2 Calculation of optimal allocation of irrigation water among multiple crops by developing the CWAP model

Crop growth simulation

Assuming that each crop grows independently, therefore crop root response to water and salt stress are also independent. There are differences in magnitude in the parameters for different crops (water and salinity sensitivity index, crop yield, planting area, and economic benefit), so they cannot be directly compared. Four irrigation scenarios therefore were identified: full irrigation and three deficit irrigation scenarios. Differences in parameters between deficit irrigation and full irrigation scenarios were used to eliminate the differences in magnitude. The three deficit irrigation scenarios were 70%, 50%, and 30% of full irrigation (O'Shaughnessy et al. 2017). The three deficit irrigation scenarios were applied in every growth month for each crop except for the final month of the growth period, which

Table 3 Irrigation schemes for three crops in four irrigation scenarios

Crop type	Irrigation scenarios	Irrigation treatments				
		April	May	June	July	August
Wheat	Full irrigation	M_{11}	M_{12}	M_{13}		
	Deficit irrigation	$0.7/0.5/0.3M_{11}$	M_{12}	M_{13}		
		M_{11}	$0.7/0.5/0.3M_{12}$	M_{13}		
		M_{11}	M_{12}	$0.7/0.5/0.3M_{13}$		
Corn	Full irrigation		M_{21}	M_{22}	M_{23}	M_{24}
	Deficit irrigation		$0.7/0.5/0.3M_{21}$	M_{22}	M_{23}	M_{24}
			M_{21}	$0.7/0.5/0.3M_{22}$	M_{23}	M_{24}
			M_{21}	M_{22}	$0.7/0.5/0.3M_{23}$	M_{24}
			M_{21}	M_{22}	M_{23}	$0.7/0.5/0.3M_{24}$
Sunflower	Full irrigation			M_{31}	M_{32}	M_{33}
	Deficit irrigation			$0.7/0.5/0.3M_{31}$	M_{32}	M_{33}
				M_{31}	$0.7/0.5/0.3M_{32}$	M_{33}
				M_{31}	M_{32}	$0.7/0.5/0.3M_{33}$

M_{11}, M_{12}, and M_{13} are the full irrigation quantities for wheat in April, May, and June, respectively; M_{21}, M_{22}, M_{23}, and M_{24} are the full irrigation quantities for corn in May, June, July, and August, respectively; M_{31}, M_{32}, and M_{33} are the full irrigation quantities for sunflower in June, July, and August, respectively was without irrigation as it was the period of maturity for the crop (Ren et al. 2018). Thus, there were 33 irrigation treatments for wheat, corn, and sunflower in HID, as shown in Table 3.

The soil water balance equation [Eq. (1)] modeled crop water consumption to calculate the irrigation quantity and water stress coefficient for each crop. The full irrigation quantity calculated by Eq. (1) was the irrigation quantity for which soil moisture content reached field capacity (as shown in Table 2) in the full irrigation scenario (O'Shaughnessy et al. 2017). Irrigation water amounts for deficit irrigation scenarios were calculated according to the desired ratio of deficit irrigation to full irrigation, as shown in Table 3. Soil moisture content was less than field capacity in the deficit irrigation scenarios, resulting in a decrease in water absorption by crop roots and thus crop water stress. The water stress coefficient K_{wlijt} indicated the effect of soil water stress on crops. Soil salinity is significant in HID, and the salinity stress coefficient K_{sj} indicated the effect of soil salinity on crop growth (Allen et al. 1998). Actual crop evapotranspiration was calculated using Eq. (8), which takes account of soil water stress and soil salinity. Crop yields for different irrigation treatments were calculated using the Jensen model. The specific model is described in the following paragraphs. Definitions of all parameters used in this paper are shown in Appendix Table 4.

(1) Calculation of irrigation quantity by the soil water balance equation

$$W_{lijt} = W_{lij(t-1)} + P_{eijt} + M_{lijt} + ET_{glijt} - ET_{alijt} - RE_{lijt} - D_{lijt}. \quad (1)$$

The parameters in Eq. (1) were calculated by

$$W_{lijt} = \theta_{lijt} Z_{rjt} \quad (2)$$

$$W_{0ij} = \theta_{0i} \times Z_{r0} \quad (3)$$

$$P_{eijt} = \eta_t \times P_{ijt} \quad (4)$$

$$ET_{glijt} = \delta \times ET_{alijt}. \quad (5)$$

There was no excess drainage, because soil moisture content did not exceed field capacity, so $D_{lijt}=0$ and $R_{lijt}=0$ (Sonkar et al. 2019; Moldero et al. 2021).

(2) Water stress coefficient (Allen et al. 1998)

$$k_{wlijt} = \begin{cases} 0 & \theta_{lijt} < \theta_{wpi} \\ \dfrac{\theta_{lijt} - \theta_{wpi}}{\theta_{fci} - \theta_{wpi}} & \theta_{wpi} \le \theta_{lijt} < \theta_{fci} \\ 1 & \theta_{lijt} \ge \theta_{fci} \end{cases}. \quad (6)$$

(3) Soil salinity stress coefficient (Allen et al. 1998)

$$k_{sj} = 1 - \frac{b_j}{100 \times k_{yj}} \left(EC_e - EC_{ethresholdj}\right). \quad (7)$$

(4) Actual crop evapotranspiration

$$ET_{alijt} = k_{wlijt} \times k_{sj} \times ET_{mijt} = k_{wlijt} \times k_{sj} \times k_{ijt} \times ET_{0ijt}. \quad (8)$$

(5) Crop yield (the Jensen model) in regions of water shortage (Henry et al. 2007)

$$\frac{Y_{lijt}}{Y_{mij}} = \prod_{t=1}^{T_j} \left(\frac{ET_{alijt}}{ET_{mijt}} \right)^{\lambda_{ijt}}. \quad (9)$$

Quantification of crop water allocation priority (CWAP)

Food security, indicated by crop yield, is a priority. Security is obtained by maximizing economic benefits from limited water in circumstances of extreme water scarcity. It is imperative to increase irrigation water productivity to maximize crop production (Bessembinder et al. 2005; Surendran et al. 2016). Change in yield, change in economic benefit, and change in irrigation water productivity were therefore selected as CWAP evaluation indexes in the deficit irrigation and full irrigation scenarios to eliminate the effects of index values having different orders of magnitudes among crops. The coefficient of variation (Li et al. 2020b) was used to determine two initial weights for each evaluation index, one based on growth period and one on crop type, to eliminate the effects of dimensional differences among indexes [Eqs. (14–17)]. The CWAP coefficient was calculated as a function of the two weights of each evaluation index. CWAP was quantified by combining the normalized values of the three evaluation indexes using the final CWAP coefficients as weights in a weighted linear equation (Mello et al. 2018; Moeinaddini et al. 2010). The calculation steps were as follows. In the following paragraphs, l=2,3,4 indicates the 70%, 50%, and 30% irrigation scenarios, respectively.

(1) Change in yield is the difference in yield between the deficit irrigation scenario and full irrigation

$$\Delta s_{lijt} = Y_{cij} - Y_{lijt}. \quad (10)$$

(2) Change in economic benefit is derived from change in yield

$$\Delta E_{lijt} = 10^3 \times \Delta s_{lijt} \times A_{ij} \times B_j. \quad (11)$$

(3) Change in irrigation water productivity is the ratio of change in yield to reduction in irrigation water per unit volume

$$\Delta IWP_{lijt} = 100 \times \frac{\Delta s_{lijt}}{\Delta M_{lijt}} \quad (12)$$

$$\Delta M_{lijt} = M_{cijt} - M_{lijt}. \tag{13}$$

(4) The weight of each evaluation index is determined from the coefficients of variation. The weight of the evaluation index is based on the coefficients of variation that are calculated from the mean and standard deviation of the evaluation indexes [Eqs. (14) and (16)] (Li et al. 2020b). Two weights for each evaluation index are calculated separately from the growth time (ω_{litk}) and the crop type (ω_{lijk}) [Eqs. (15) and (17)]. The two weights are then combined to calculate the CWAP coefficient as the final weight of each evaluation index [Eq. (18)]

$$C_{vlitk} = \frac{\sqrt{\frac{1}{J}\sum_{j=1}^{J}(x_{lijt} - \frac{1}{J}\sum_{j=1}^{J}x_{lijt})^2}}{\frac{1}{J}\sum_{j=1}^{J}x_{lijt}} \tag{14}$$

$$\varpi_{litk} = \frac{C_{vlitk}}{\sum_{k=1}^{K} C_{vlitk}} \tag{15}$$

$$C_{vlijk} = \frac{\sqrt{\frac{1}{T}\sum_{t=1}^{T}(x_{lijt} - \frac{1}{T}\sum_{t=1}^{T}x_{lijt})^2}}{\frac{1}{T}\sum_{t=1}^{T}x_{lijt}} \tag{16}$$

$$\varpi_{lijk} = \frac{C_{vlijk}}{\sum_{k=1}^{K} C_{vlijk}} \tag{17}$$

$$pc_{lijtk} = \frac{\varpi_{litk} \times \varpi_{lijk}}{\sum_{k=1}^{K}\left(\varpi_{litk} \times \varpi_{lijk}\right)}. \tag{18}$$

(5) Each index value is normalized in the interval [0.1, 0.9] to avoid dimensional differences and zero values. The weighted CWAP quantification model is shown as Eq. (19), which calculates the CWAP value. The average CWAP value β_{ijt} for each of the three deficit irrigation scenarios is calculated [Eq. (20)] to represent the crucial crop and the critical month in objective 3 of the optimization model

$$\beta_{lijt} = pc_{lijt1} \times \Delta s'_{lijt} + pc_{lijt2} \times \Delta E'_{lijt} + pc_{lijt3} \times \Delta IWP'_{lijt} \tag{19}$$

$$\beta_{ijt} = \frac{1}{3}\sum_{l=2}^{4}\beta_{lijt}. \tag{20}$$

Optimization model

A method that combined multiple water resources was used to distribute surface water and groundwater to different crops in each irrigation subarea. Multi-objective programming was used to balance constraints on different objectives. The Jensen model is commonly used to predict crop yield under water-deficit irrigation (Henry et al. 2007), so the optimization model is a non-linear programming model. A multi-objective non-linear optimization model based on CWAP was created to allocate irrigation water for multiple crops. The objective functions were maximum crop yield, maximum economic benefits, and minimum water shortage. Constraints included crop growth, available surface water, available groundwater, food security, and soil water storage. The components of the model are described in the following paragraphs.

(1) Maximum crop yield: Total yields are maximized for each crop using the Jensen model and scaled planting. The derivation of actual evapotranspiration in Eq. (21) was by Eq. (1)

$$\max f_1 = \sum_{i=1}^{I}\sum_{j=1}^{J} A_{ij}\left[Y_{mij}\prod_{t=1}^{T_j}\left(\frac{ET_{aijt}}{ET_{mijt}}\right)^{\lambda_{ijt}}\right]. \tag{21}$$

(2) Maximum economic benefit: The net benefit generated by crops is maximized by subtracting the costs of surface water and groundwater from crop benefits

$$\begin{aligned}\max f_2 = \sum_{i=1}^{I}\sum_{j=1}^{J}\Bigg[&A_{ij} \times B_j \times 10^3 \times Y_{mij}\prod_{t=1}^{T_j}\left(\frac{ET_{aijt}}{ET_{mijt}}\right)^{\lambda_{ijt}} \\ &-C_1 \times A_{ij} \times \sum_{t=1}^{T} 10\left(\frac{SW_{ijt}}{\mu_{i1}}\right) \\ &-C_2 \times A_{ij} \times \sum_{t=1}^{T} 10\left(\frac{GW_{ijt}}{\mu_2}\right)\Bigg].\end{aligned} \tag{22}$$

(3) Minimum water shortage during critical growth months for crucial crops: Crops and months with higher CWAP values should be given priority in irrigation water supply. Crop water shortage is water demand minus water supply. Water shortage for crucial crops during critical growth months is represented by the product of CWAP and water shortage, and it should be minimized

$$\min f_3 = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}\beta_{ijt}\left(ET_{aijt} - SW_{ijt} - GW_{ijt} - P_{eijt}\right). \tag{23}$$

If CWAP (b_{ijt}) is ignored in the optimization model, as much irrigation water as possible will be used in critical months (those having a high water sensitivity index, WSI) due to variation in the sensitivity of the crop to water deficit in each growth stage (Tang et al. 2019; Zhang et al. 2019b). In other words, the month with high WSI for an individual crop would be prioritized for irrigation even if the irrigation needs among crops were almost equal.

(4) Growth constraint: Actual crop evapotranspiration should be limited by maximum evapotranspiration (the maximum crop water demand) and minimum evapotranspiration. Actual evapotranspiration outside these limits will seriously reduce crop yield (Zhang et al., 2019c)

$$0.6ET_{mijt} \leq ET_{aijt} \leq ET_{mijt}. \tag{24}$$

(5) Available surface water constraint: Surface irrigation water used in the irrigation region during the total growth period of all crops should not exceed water diverted from YRB during this period

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} A_{ij}\times 10\left(\frac{SW_{ijt}}{\mu_{i1}}\right) \leq Q. \tag{25}$$

(6) Available groundwater constraint: Groundwater used for irrigation in the region should not exceed available well irrigation water

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} A_{ij}\times 10\left(\frac{GW_{ijt}}{\mu_{2}}\right) \leq QG. \tag{26}$$

(7) Food security constraint: Total yield of each crop should meet at least the minimum food demands of the local population

$$\sum_{i=1}^{I}\sum_{j=1}^{J} A_{ij}\left[Y_{mij}\prod_{t=1}^{T_j}\left(\frac{ET_{aijt}}{ET_{mijt}}\right)^{\lambda_{ijt}}\right] \geq 10\bar{y}\times S. \tag{27}$$

(8) Soil water storage constraint: Soil water storage should be limited by maximum and minimum soil water storage values (determined by field capacity and soil moisture content at the wilting point) (Evett et al. 2019)

$$W_{\min ijt} \leq W_{ijt} \leq W_{\max ijt}. \tag{28}$$

(9) Nonnegative constraints: All parameters in the optimization model are nonnegative.

Finally, optimal yield, optimal economic benefit, optimal irrigation water productivity, and optimal water productivity [Eq. (29)] are used as major indexes of the optimization results

$$WP_{ij} = \frac{\sum_{i=1}^{I}\sum_{j=1}^{J} A_{ij}\left[Y_{mij}\prod_{t=1}^{T_j}\left(\frac{ET_{aijt}}{ET_{mijt}}\right)^{\lambda_{ijt}}\right]}{\sum_{i=1}^{I}\sum_{j=1}^{J} A_{ij}\times\sum_{t=1}^{T_j} ET_{aijt}}. \tag{29}$$

Model solution process

The optimization model was solved using Lingo11 (https://www.lindo.com/). Multi-objective programming was transformed into single-objective programming using the minimum deviation method (MD) and the analytic hierarchy process (AHP) (Zhang et al. 2019a). The specific steps in the solution were as follows.

(1) Step 1: Collect the necessary parameter data for the model and write the Lingo code to solve the model.

(2) Step 2: Calculate the best and worst values for each objective function, $f_1^{\max}, f_1^{\min}, f_2^{\max}, f_2^{\min}, f_3^{\max}, f_3^{\min}$.

(3) Step 3: The weights given to the three objectives (ϖ_1, ϖ_2, and ϖ_3) by AHP were, respectively, 0.4, 0.2667, and 0.3333. This weighting indicated that in irrigation areas with water shortages, crop yield should be guaranteed foremost and economic benefit should be considered last. The three objective functions were then converted into one objective function using MD, as shown in Eq. (30), giving the final solution (x_{ijtopt}, f_{opt}) of the optimization model

$$\max F = \varpi_1 \times \frac{f_1 - f_1^{\min}}{f_1^{\max} - f_1^{\min}} + \varpi_2 \times \frac{f_2 - f_2^{\min}}{f_2^{\max} - f_2^{\min}} + \varpi_3 \times \frac{f_3^{\max} - f_3}{f_3^{\max} - f_3^{\min}}. \tag{30}$$

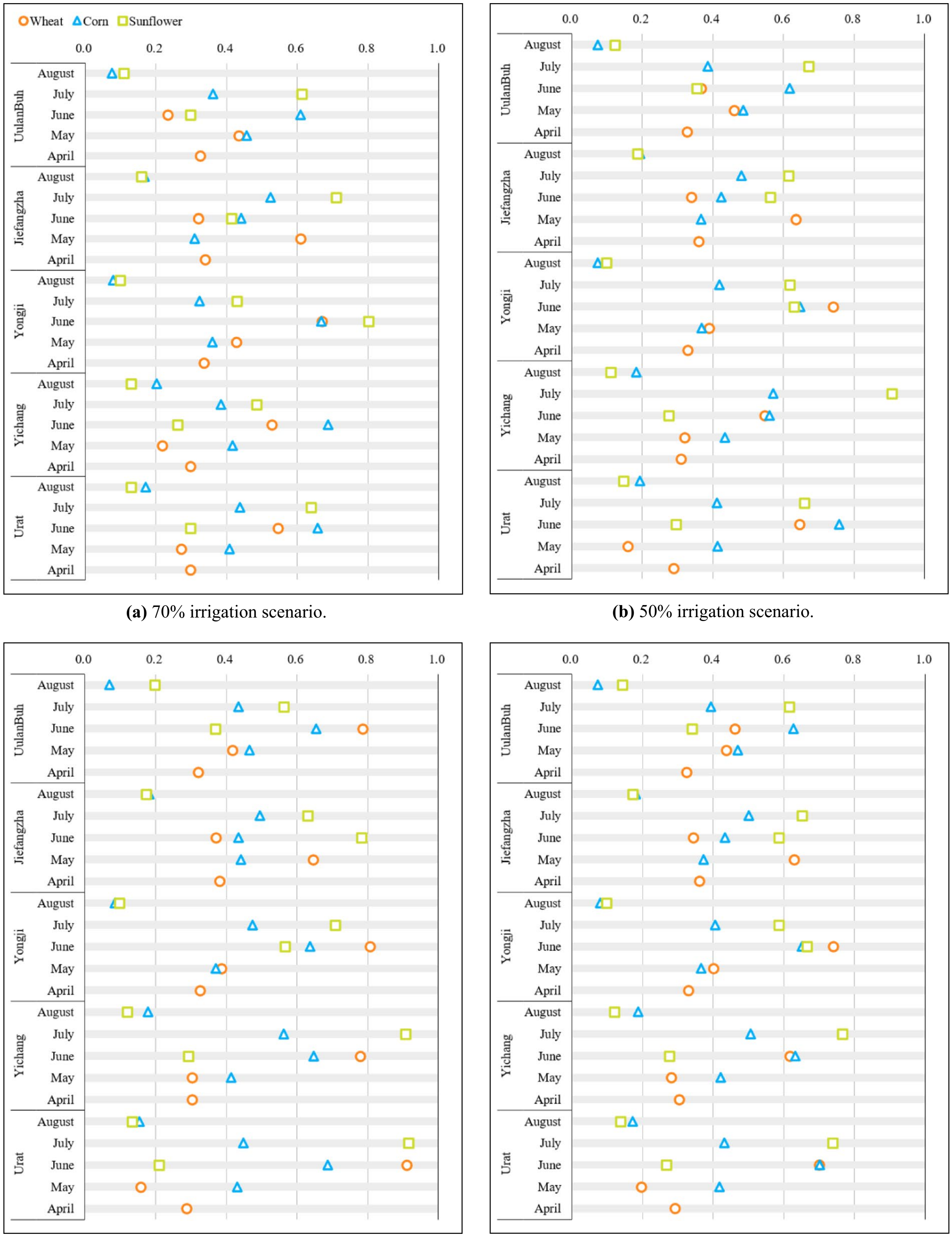
(4) Step 4: If CWAP is omitted in objective 3, the goal changes to become minimizing the irrigation water quantity [Eq. (31)]. The optimal solution when omitting CWAP (x'_{ijtopt}, f'_{opt}) is obtained by repeating steps 2–3

$$\min f_3' = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}\left(SW'_{ijt} + GW'_{ijt}\right). \tag{31}$$

Analysis and discussion of results

Quantification of crop water allocation priority

A CWAP value indicates the importance of the corresponding crop and month; a higher value gives greater irrigation priority. Figure 3 shows CWAP values for each crop for the 70%, 50%, and 30% irrigation scenarios and the combination of the three; the horizontal axis in the figure shows the CWAP value. It can be seen that the orders of crops prioritizing irrigation varied only in June under different irrigation scenarios for the five irrigation subareas, and there were no changes in other months. For individual crops, according to the combined CWAP value, the most critical month for wheat and corn was in June, except for May (wheat) and July (corn) in Jiefangzha. The most critical month for sunflower was July, except for June in Yongji. The CWAP values were consistent for Yichang and Urat. This was because the effects of deficit irrigation on yield and irrigation water



(a) 70% irrigation scenario.

(b) 50% irrigation scenario.

(c) 30% irrigation scenario.

(d) Integrated CWAP.

Fig. 3 Crop water allocation priority (CWAP) values for each crop represent the irrigation priority for the crop and its growth period (under three deficit irrigation scenarios and a combination of the three; the horizontal axis in the figure shows the CWAP value) productivity varied with climate, soil, and crop growth stage (Li et al. 2020d; Junaid et al. 2020; García-López et al. 2016; Shi et al. 2021; Mishra and Cherkauer 2010; Song et al. 2013). The various crops were in different growth stages in the same month in each irrigation subarea, and there were differences in climate, soil, the irrigation canal distribution capacity, and other environmental factors (Luo et al. 2021b). These differences were reflected in modeling crop growth with the soil water balance equation and the Jensen model and resulted in different effects on yield and irrigation quantity, so that the CWAP evaluation indexes and their weights (the CWAP coefficients) differed between irrigation scenarios in every irrigation subarea. In short, CWAP values varied.

To determine the reasons for the differences in the order of crucial crops in June under different irrigation scenarios, we examined the factors that had the most direct influence (the CWAP coefficients and the normalized values of each evaluation index) on the three crops in each irrigation subarea under the 70%, 50%, and 30% irrigation scenarios (Fig. 4). Taking Jiefangzha as an example [Fig. 4(b)], in the 70% irrigation scenario, the CWAP coefficients of three evaluation indexes for corn were 35.96%, 17.86%, and 18.80% less than those for wheat, 19.28%, 27.45%, and 29.27% less than those for sunflower. The value of the three evaluation indexes for corn were 99.49%, 99.49%, and 7.20% greater than those for wheat, and 766.53%, 766.53%, and – 88.09% (decrease) greater than those for sunflower. The CWAP value for corn was thus greatest when calculated by the CWAP model, thus indicating that corn was a crucial crop (i.e., it was critical to irrigate corn in this irrigation scenario). Similarly, the CWAP value of sunflower was higher than that of wheat, so irrigation of sunflower was prioritized over wheat. The values of the three evaluation indexes for each crop under the 50% irrigation scenario were not significantly different from those under the 70% irrigation scenario. However, the CWAP coefficients of two evaluation indexes (change in yield and change in irrigation water productivity) for corn under the 50% irrigation scenario increased by 16.85% and 30.52% over those under the 70% irrigation scenario, which for sunflower increased by 23.44% and 43.82%. The variations in CWAP coefficients of the two evaluation indexes for sunflower were 72.33% and 102.99% greater than for corn. Therefore, the CWAP value of sunflower was higher than that of corn under the 50% irrigation scenario, which differed from the 70% irrigation scenario. Similarly, the order of crucial crops in June was sunflower > corn > wheat under the 50% and 30% irrigation scenarios.

For individual crops, the critical months for wheat and corn in Jiefangzha were different from those in other areas. Figure 4(a) and (b) shows that the values of change in yield and change in economic benefit in May increased by 107.2% in Jiefangzha and 264.71% in UulanBuh over the June values; corresponding changes in other irrigation subareas were 19.35–73.12%. In Jiefangzha, the CWAP coefficients for change in yield and change in economic benefit in May were 14.77% less and 10.03% greater than in June; the corresponding CWAP coefficients were respectively 76.01–90.00% less and 6.51–72.38% less in other areas. There was no significant change in the index value and CWAP coefficient for change in irrigation water productivity in May or June. Thus in Jiefangzha, the CWAP value for wheat was greater for May than for June, but the opposite was found in other areas according to the CWAP model. In other words, in Jiefangzha, the most critical month for wheat was May instead of June, the most critical month in other areas.

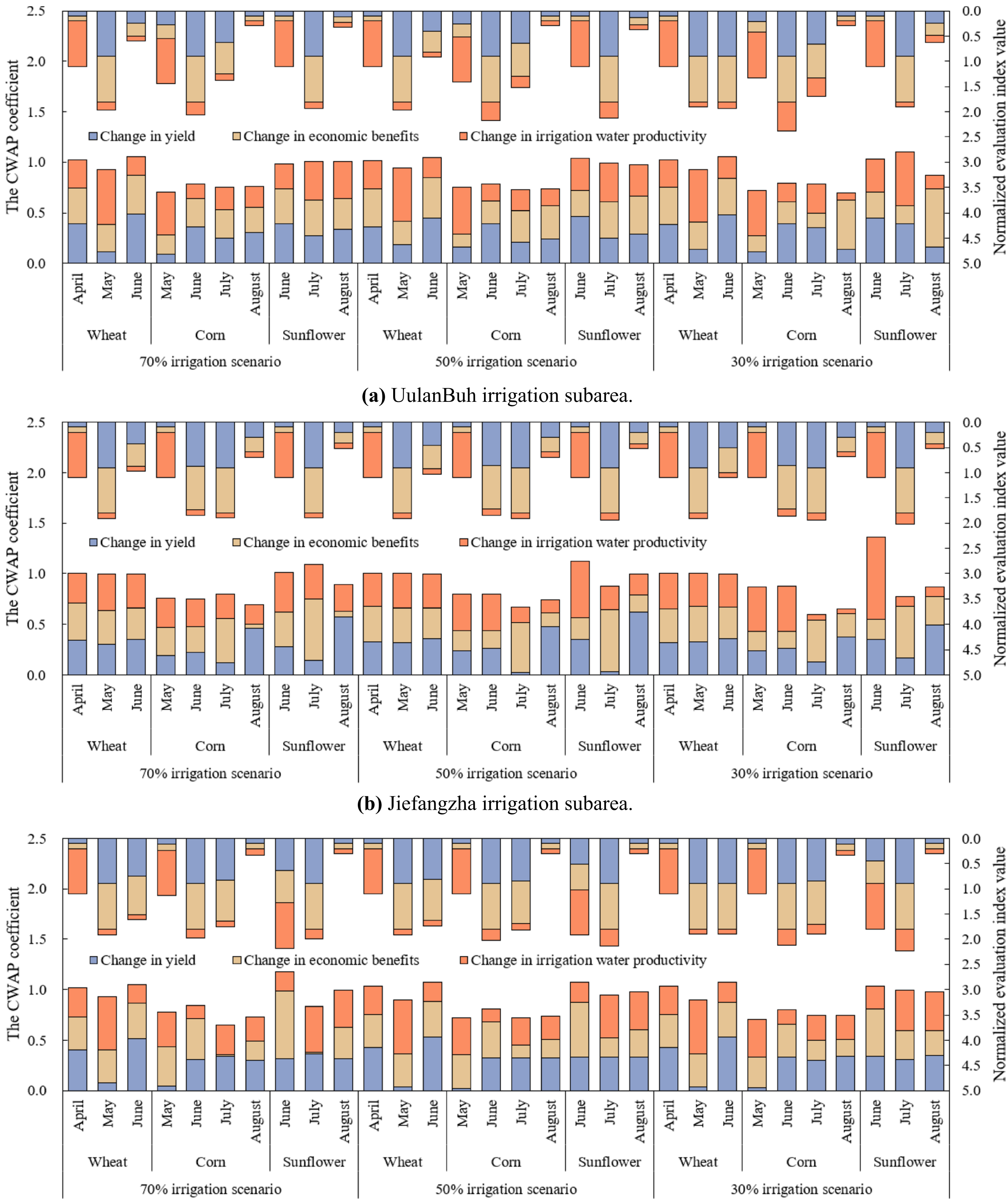
The critical irrigation period for sunflower is at the squaring and anthesis stage (He et al. 2016), which in subareas other than Yongji was in July. The sowing date of sunflower in Yongji was 7 days earlier than in other places, resulting in a critical irrigation period in late June. Consequently, the most critical month for sunflower irrigation in Yongji was June, earlier than that in other areas. In contrast, sunflower anthesis in UulanBuh was in early and mid-August, and the values of the three evaluation indexes in July increased on average by 269.16%, 269.16%, and 76.59% over the August values for all three irrigation scenarios. The CWAP coefficients of the three evaluation indexes in July increased on average by 39.18%, – 20.63% (decrease), and 110.23%. Thus the CWAP value for sunflower in July was higher than in August; that is, the critical month for sunflower in UulanBuh was July rather than August.

The results showed that there was a difference between CWAP and WSI in identifying critical months. WSI indicates only the effects of water shortage during the growth stage on yield, while CWAP also takes account of the effects of economic benefits and irrigation water productivity. The CWAP value depended on the CWAP coefficients as well as the values of the three evaluation indexes (change in yield, change in economic benefit, and change in irrigation water productivity). Therefore, the critical months determined by CWAP may not be consistent with those determined by WSI.

Yichang and Urat are geographically close to each other and experience similar natural conditions such as climate and soil geology as well as similar human activity (e.g., crop planting structure and irrigation canal distribution) (Qu et al. 2015). Thus CWAP value was the same in Urat as in Yichang.

Optimal results of irrigation scheme

On the whole, optimization with CWAP produced better results than optimization without CWAP. Figure 5 shows that, except for corn, results improved in most areas when

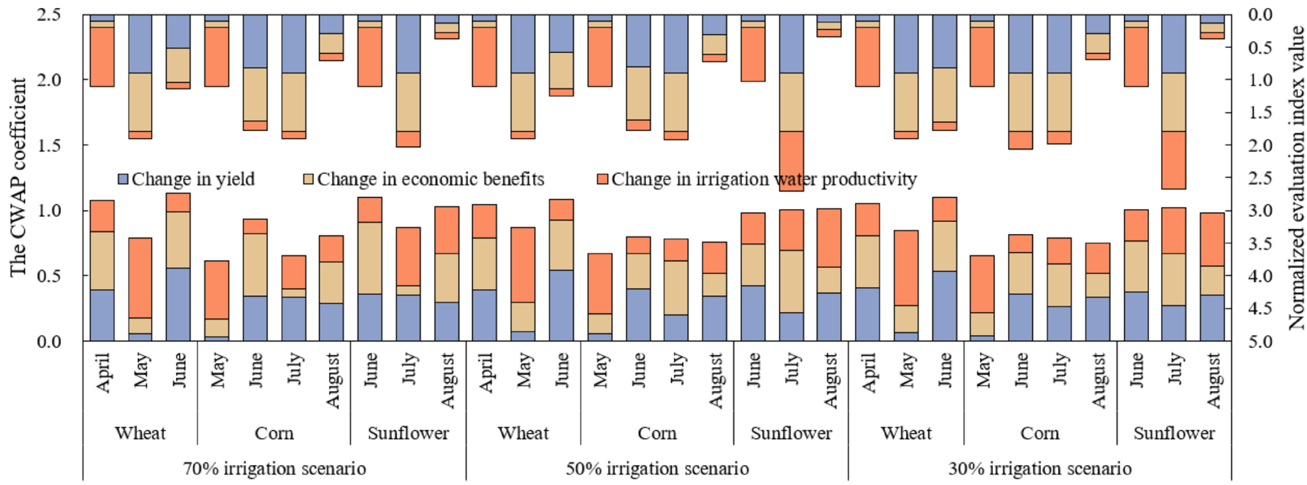


(a) UulanBuh irrigation subarea.

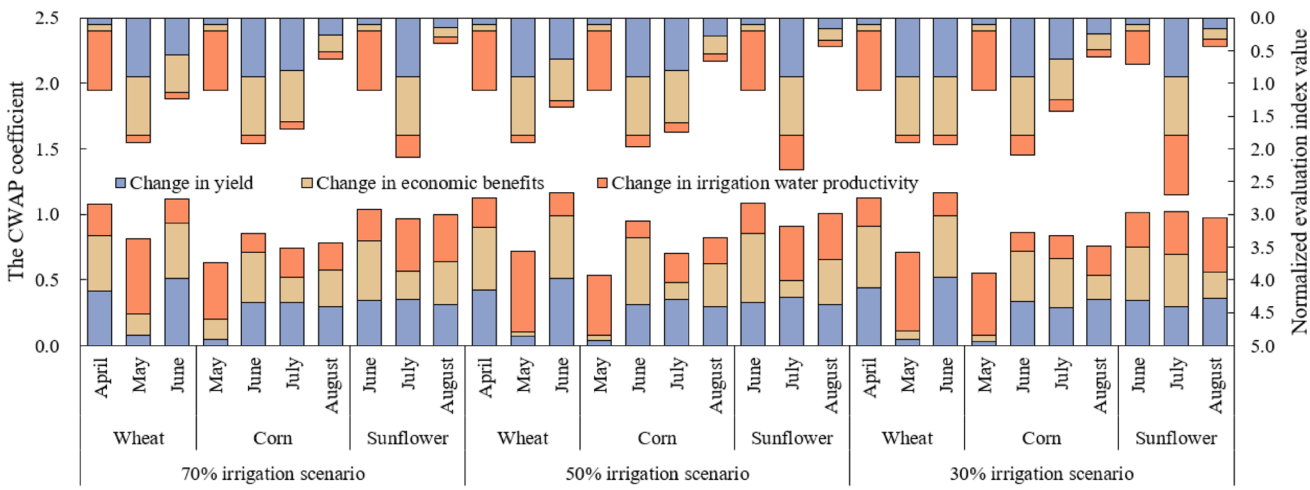
(b) Jiefangzha irrigation subarea.

(c) Yongji irrigation subarea.

Fig. 4 CWAP coefficients and normalized values of each evaluation index for three crops in each irrigation subarea



(d) Yichang irrigation subarea.



(e) Urat irrigation subarea.

Fig. 4 (continued)

optimized with CWAP. For wheat, optimization with CWAP increased the results for yield, economic benefits, irrigation water productivity, and water productivity by 4.19%, 4.25%, 2.30%, and 2.70% in UulanBuh, 13.38%, 13.4%, 1.72%, and 6.29% in Jiefangzha, and 0.34%, 0.35%, 0.16%, and 0.20% in Yichang. For corn, the results for yield and economic benefits increased by 1.00% and 0.99% in Jiefangzha, 0.19% and 0.19% in Yichang, 3.86% and 3.85% in Urat, but decreased by 6.41% and 6.39% in Yongji. Irrigation water productivity increased by 1.71% in Yongji, but decreased by 0.91% in Jiefangzha, 0.01% in Yichang, and 0.33%in Urat. Water productivity increased by 0.04% in Yichang, 1.13% in Urat, but decreased by 0.08% in Jiefangzha, 0.52% in Yongji. For sunflower, optimization results for yield, economic benefits, irrigation water productivity, and water productivity increased, respectively, by 4.85%, 4.86%, 0.91%, and 2.32% in UulanBuh. The reason for there being no difference in the optimization results for some crops was that the allocation of limited irrigation water for multiple crops using CWAP values did not necessarily match every crop need. A crop with a high CWAP value would be prioritized, but a crop with a low CWAP value may have been allocated insufficient. In optimization without CWAP, a maximum quantity of irrigation water might be allocated in a critical month with a high WSI, as crop water sensitivity was unequal in different months (Tang et al. 2019; Zhang et al. 2019b). In other words, the month with high WSI was prioritized for irrigation, but if there were multiple crops, it was a matter of chance which were irrigated. The available agricultural water allocation model established by Zhang et al. (2021b) based on CWAP values in this paper maximized the benefits of the whole Hetao Irrigation District.

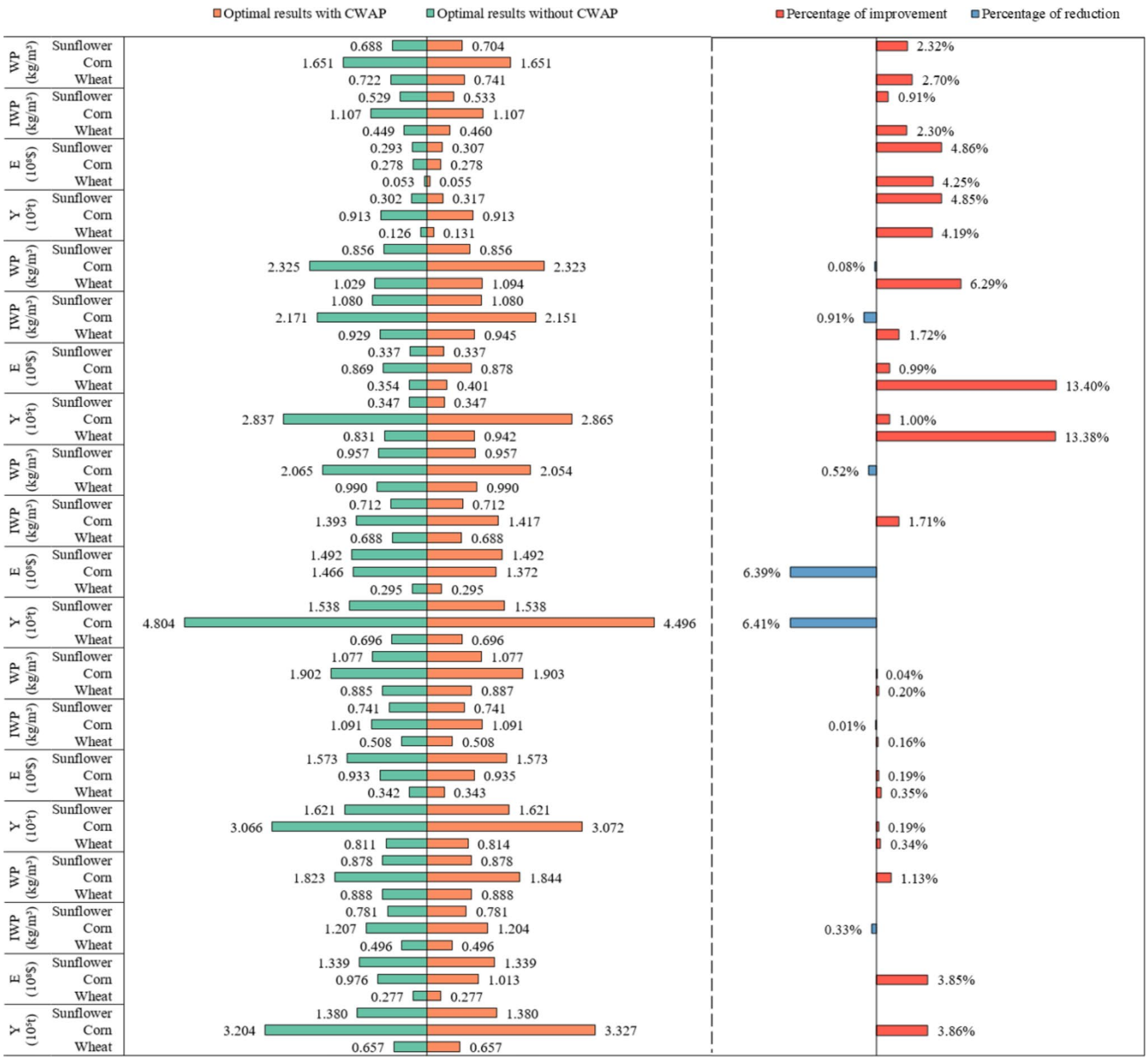


Fig. 5 Comparison of results of optimization with and without CWAP for the three crops in each irrigation subarea; *Y* is yield (10^5 *t*), *E* is economic benefit (10^8 \$), IWP is irrigation water productivity (kg/m^3), and WP is water productivity (kg/m^3)

For example, months with maximum WSI and high CWAP values for sunflower were the same for four irrigation subareas, but not for UulanBuh, so optimization results that considered CWAP showed little improvement over results of optimization without CWAP. For UulanBuh, corn was a crucial crop in May and June and had high CWAP values, so it was imperative to guarantee the corn yield first and a lesser priority to improve regional economic benefits. However, the maximum yield of corn in this area was the lowest (9.53 t/ha) of all irrigation subareas, much lower than the average level of 11.16 t/ha in HID. The area planted with corn was 924 ha less than the area planted with sunflower, so the economic benefits of corn were less than those of sunflower. The optimization results for corn therefore did not change whether or not CWAP was taken into consideration, and predicted a basic yield. Jiefangzha provides another example. The critical month for wheat with high WSI and high CWAP values, was May, but wheat was a crucial crop with high CWAP in May. Therefore, the optimal results of wheat were improved. Although the most crucial crop in July was sunflower, followed by corn, the planting area of corn was the largest, accounting for 45.19% of cropland, and sunflower accounted for only 20.02% of planted cropland. Corn could bring greater yield and economic benefits. Hence, the yield and economic benefits of corn were increased. For Yongji, the critical months with high WSI and high CWAP values for wheat and sunflower were the same, so the results of the two optimizations were consistent. However, corn had the lowest CWAP value in each growing month, losing out to the other two crops in the allocation of irrigation water. Therefore, optimal results of corn were decreased.

Figure 6(a) shows the optimal and actual net irrigation quantities in growth months for each crop when CWAP was included. The optimal net irrigation quantity was less than the actual net irrigation quantity by 103–264 mm (33.41–60.77%) for wheat, 44–184 mm (15.27–51.24%) for corn, and 103–188 mm (34.42–63.59%) for sunflower. These values were within the range of previous research results (Zhang et al. 2021c; Li et al. 2020c; Yu and Shang 2020). There was an anomaly in that optimal irrigation quantities for sunflower in Yichang and Urat were, respectively, 59.67 mm and 22.93 mm greater than the actual quantities. Autumn and spring irrigation, which are intended to conserve soil moisture, did not occur during the crop growth period and were not considered in this paper. In the study period, irrigation water was needed to increase soil moisture to ensure crop growth. In some cases, optimal irrigation quantity was less than the actual irrigation quantity. The optimal irrigation quantity was less than 10 mm for corn in May, which was reasonable, because the optimization model predicted net irrigation quantity (Tang et al. 2019). This can be ignored in practice. The largest irrigation quantity, more than 120 mm in a month, was distributed over different growth periods and different days. For example, the actual irrigation schedule of wheat in Yongji was 82.5 mm during May 8–12, 72 mm in late May, 82.5 mm during June 5–10, and 72 mm during June 20–26. The optimized irrigation scheme showed that no irrigation was required in August, which was consistent with the actual irrigation program.

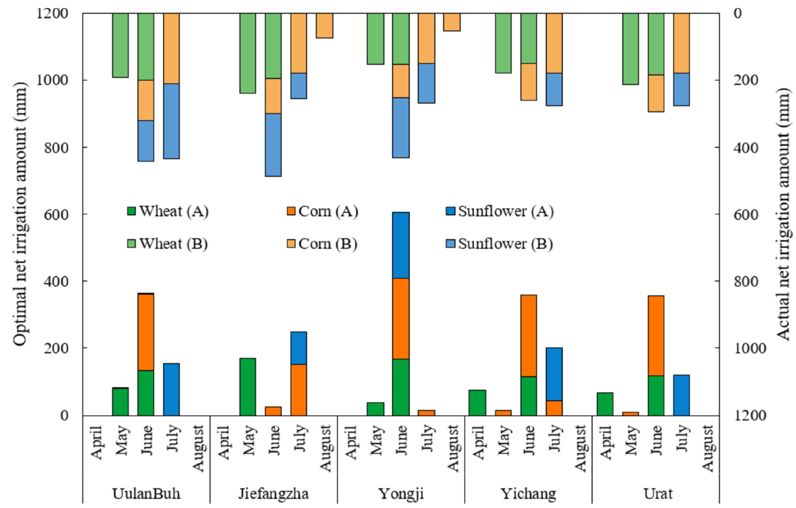
Figure 6(b) shows the optimal allocations of surface water and groundwater with the actual water diverted from YRB as well as total water resources in each irrigation subarea. It can be seen that optimal water allocation accounted for 20.64–77.31% of total water resources in each subarea. The optimal surface water amount was less than the actual water diversion from YRB by 56.20% in UulanBuh and 57.68% in Jiefangzha, but it increased above the actual quantity in other subareas due to irrigation water not being sourced from YRB. In Yongji, irrigation water supply from wells and canals reached 60.30% of total water resources and about 45.23% was from groundwater (Wang 2018). However, there was that groundwater only supply 10% of the irrigation quantities in Yongji. In Urat, about 32.02% of irrigation water was not supplied from YRB, according to the local water resources bulletin. Wuliangsu Lake positively influenced agricultural production in Yichang and Urat, but was not considered in this study. Thus, in practice, groundwater, rather than YRB, was a source of a considerable quantity of irrigation water in HID.

The actual water footprints and those calculated by optimization are shown in Fig. 6(c). The relative values for the three crops were consistent with other studies (Deepa et al. 2021; Luan et al. 2018). Differences in water footprints between the optimization calculation and the actual situation were as follows. The optimized green water footprint increased by 64.63–116.91% for wheat, 7.84–48.01% for corn, and 2.96–55.27% for sunflower. The blue water footprint decreased by 14.87% for wheat, 0.83–37.63% for corn, and 18.64–50.06% for sunflower. Blue water utilization decreased by 0.54–1.12% for wheat, 0.42–2.91% for corn, and 1.50–9.91% for sunflower. Blue water utilization for a crop is the ratio of the blue water footprint to the water footprint for the crop. A low value of blue water utilization indicates low blue water footprint consumption by the crop and high water use efficiency. The results indicated that the contribution of the blue water footprint to the total water footprint of the crop decreased and the contribution of the green water footprint increased. Water use efficiency was higher in the optimal scheme than in the actual situation. This analysis shows that the optimal scheme will meet the goal of sustainable agricultural development. The research results of Luan et al. (2018) showed that water footprints in HID were 1.38–2.89 $m^3\ kg^{-1}$ for wheat, 0.94–1.77 $m^3\ kg^{-1}$ for corn, and 2.10–4.86 $m^3\ kg^{-1}$ for sunflower. Water footprints in this study were reduced by 22.44–23.56% for wheat, 45.42–41.17% for corn, and 50.37–57.82% for sunflower compared with Luan's results. This comparison indicated that the optimal scheme significantly reduced the crop water footprint and saved agricultural water resources.

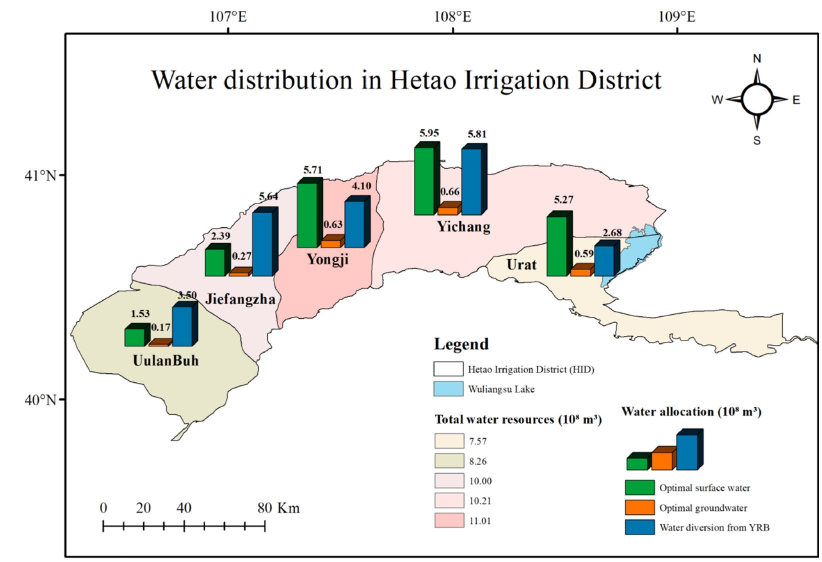
Conclusions

The CWAP quantification model was developed and incorporated the output into an optimization model to allocate irrigation water in Hetao Irrigation District (HID), the largest irrigation district in northern China, to apportion irrigation resources depending upon crop and growth period. CWAP quantifies the irrigation water allocation priority and it differs from WSI: CWAP takes into account the effects of economic benefits and irrigation water productivity on yield, while WSI reflects only the effect of water shortage on yield. Three indicators were selected to evaluate CWAP (change in yield, change in economic benefits, and change in irrigation water productivity). A nonlinear multi-objective optimization model was developed to determine optimal irrigation schemes based on CWAP. Comparison of the optimization results with the actual irrigation of wheat, corn, and sunflower showed that optimization reduced the net irrigation quantity by 60.77% (wheat), 51.24% (corn),

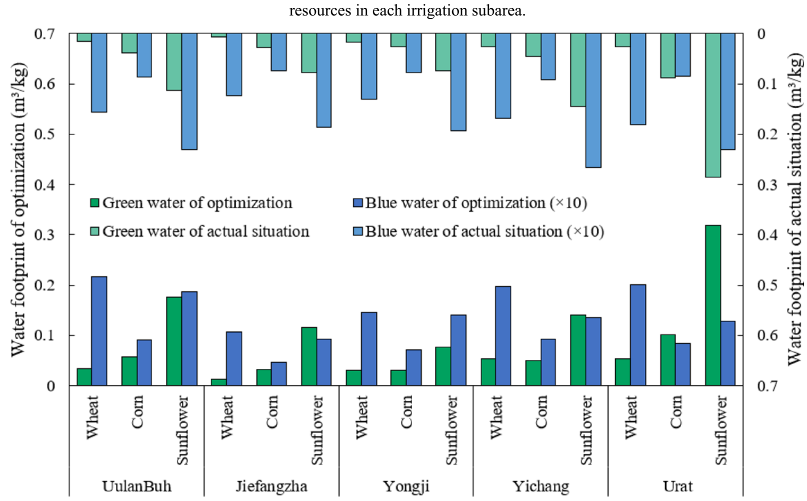
Fig. 6 Irrigation quantity, optimal, and actual water footprint in each irrigation subarea; in (**a**), the actual net irrigation quantity was obtained by Hetao Irrigation District Management Bureau through sampling representative experimental stations in each irrigation subarea



(a) Optimal and actual net irrigation quantity for each crop in every month by irrigation subarea; A is the optimal net irrigation quantity, B is the actual net irrigation quantity.



(b) Optimal allocation of surface water and groundwater, actual water diversions from YRB, and total water resources in each irrigation subarea.



(c) The green and blue water footprints calculated by optimization and the actual situation for the three crops in each irrigation subarea.

and 63.59% (sunflower); the green water footprint increased by up to 116.91% (wheat), 48.01% (corn), and 55.27% (sunflower); the blue water footprint decreased by 14.87% (wheat), 37.63% (corn), and 50.06% (sunflower); and blue water utilization decreased by 1.12% (wheat), 2.91% (corn), and 9.91% (sunflower). In other words, the optimal schemes saved irrigation water and increased water use efficiency.

Furthermore, surface water and groundwater were considered separately as decision variables in the optimization model to explore differences in distribution and the utilization of various agricultural irrigation water sources in different regions. To expeditiously develop irrigation schemes that are effective in a changing climate, we recommend that the proposed method is supplemented with real-time data (e.g., weather forecasts and crop growth monitoring data) to become a real-time optimization platform for irrigation systems. This will facilitate more precise agricultural management and promote digital agriculture to further sustainable development.

Appendix

See Table 4

Table 4 Definition of parameters and variables used in this paper

Parameters	Definition
i	Irrigation subarea index ($i=1, 2, \ldots, I$)
j	Crop type index ($j=1, 2, \ldots, J$)
t	The growth time of crop index ($t=1, 2, \ldots, T$)
l	Irrigation scenario index, $l=$c, 2, 3, 4 denotes full, 70%, 50%, and 30% irrigation scenario, respectively
W_{lijt}	Soil water storage of crop j in month t in irrigation scenario l, mm
W_{oij}	Initial soil water storage before crop j planted in irrigation subarea i, mm
P_{eijt}	Effective precipitation of crop j in month t in irrigation subarea i, mm
M_{lijt}	Net irrigation quantity of crop j in month t in irrigation scenario l, mm
ET_{glijt}	Groundwater recharge of crop j in month t, mm
ET_{alijt}	Actual evapotranspiration of crop j in month t in irrigation subarea i, mm
RE_{lijt}	Deep percolation caused by excessive rainfall or irrigation, mm
D_{lijt}	Drainage generated when the soil moisture content exceeds the field capacity, mm
θ_{lijt}	Average soil moisture content of the root zone of crop j in month t in irrigation scenario l, $m^3\ m^{-3}$
Z_{rjt}	Root depth of crop j in month t, m
θ_{0i}	Initial soil moisture content in irrigation subarea i, $m^3\ m^{-3}$
Z_{r0}	Depth of planned wetting layer before sowing, m
η_t	Effective precipitation coefficient in month t
P_{ijt}	Precipitation of crop j in month t in irrigation subarea i, mm
δ	Groundwater recharge coefficient
ET_{mijt}	Maximum actual evapotranspiration of crop j in month t in irrigation subarea i without water and soil salinity stress, mm
k_{ijt}	Crop coefficient of crop j in month t in irrigation subarea i
ET_{0ijt}	Reference evapotranspiration, mm
k_{wlijt}	Water stress coefficient of crop j in month t in irrigation subarea i in irrigation scenario l
θ_{wpi}	Soil moisture content at wilting point in irrigation subarea i, $m^3\ m^{-3}$
θ_{fci}	Field capacity in irrigation subarea i, $m^3\ m^{-3}$
k_{sj}	Salinity stress coefficient of crop j
b_j	Characteristic parameter of crop j, % $(dS\ m^{-1})^{-1}$
k_{yj}	Seasonal yield impact factor of crop j
EC_e	Electrical conductivity of soil saturated solution in crop root layer, $dS\ m^{-1}$
$EC_{ethresholdj}$	Threshold of EC_e when yield of crop j is below maximum yield, $dS\ m^{-1}$
Y_{lijt}	Actual crop yield of crop j in irrigation subarea i in irrigation scenario l carried out in month t, $t\ ha^{-1}$
Y_{mij}	Maximum yield of crop j in irrigation subarea i, $t\ ha^{-1}$
λ_{ijt}	Water sensitivity index of crop j in month t in irrigation subarea i
T_j	The number of growth months of crop j
M_{cijt}	Net irrigation quantity of crop j in month t in full irrigation scenario, mm
Y_{cij}	Actual crop yield of crop j in irrigation subarea i in full irrigation scenario, $t\ ha^{-1}$

Table 4 (continued)

Parameters	Definition
Δs_{lijt}	Change in yield of crop *j* in irrigation subarea *i* between irrigation scenario *l* (where *l* = 2, 3, 4) and full irrigation scenario carried out in month *t* h, t ha^{-1}
ΔE_{lijt}	Change in economic benefits, $ USD
A_{ij}	Planting area of crop *j* in irrigation subarea *i*, ha
B_j	Purchase price of crop *j*, $ kg^{-1}
ΔIWP_{lijt}	Change in irrigation water productivity, kg m^{-3}
ΔM_{lijt}	Irrigation quantity reduced by irrigation *l* (where *l* = 2, 3, 4) than full irrigation, mm
x_{lijt}	Each evaluation index value in irrigation scenario *l* (*l* = 2, 3, 4)
k	Evaluation index ($k = 1, 2, \ldots, K$, $K = 3$)
C_{vlitk}	Variation coefficient of index *k* in month *t* in irrigation subarea *i* in irrigation scenario *l* (*l* = 2, 3, 4)
ω_{litk}	Weight of index *k* in month *t* in irrigation subarea *i* in irrigation scenario *l* (*l* = 2, 3, 4)
C_{vlijk}	Variation coefficient of index *k* for crop *j* in irrigation subarea *i* in irrigation scenario *l* (*l* = 2, 3, 4)
ω_{lijk}	Weight of index *k* for crop *j* in irrigation subarea *i* in irrigation scenario *l* (*l* = 2, 3, 4)
pc_{lijtk}	CWAP coefficient of index *k* for crop *j* in month *t* in irrigation subarea *i* in irrigation scenario *l* (*l* = 2, 3, 4)
$\Delta s'_{lijt}$	The normalized value of change in yield index (Δs_{lijt})
$\Delta E'_{lijt}$	The normalized value of e change in economic benefits index (ΔE_{lijt})
$\Delta IWP'_{lijt}$	The normalized value of change in irrigation water productivity index (ΔIWP_{lijt})
β_{lijt}	CWAP value for crop *j* in month *t* in irrigation subarea *i* in irrigation scenario *l* (*l* = 2, 3, 4)
β_{ijt}	Average CWAP value in the three deficit irrigation scenarios
f_1	Objective 1: maximum crop yield, t
f_2	Objective 2: maximum economic benefit, $
f_3	Objective 3: minimum water shortage during critical growth months for crucial crops, mm
ET_{aijt}	Optimal actual evapotranspiration of crop *j* in month *t* in irrigation subarea *i*, mm
C_1	Local surface water price, $ m^{-3}
C_2	Local groundwater price, $ m^{-3}
SW_{ijt}	Net irrigation of surface water of crop *j* in month *t* in irrigation subarea *i*, mm
GW_{ijt}	Net irrigation of groundwater of crop *j* in month *t* in irrigation subarea *i*, mm
μ_{i1}	Utilization coefficient of surface water irrigation in irrigation subarea *i*
μ_2	Utilization coefficient of groundwater irrigation in irrigation subarea *i*
Q	Total surface water available amount, m^3
QG	Total groundwater available amount, m^3
$\bar{y}$	Minimum food demand per capita, which is 400 kg per person (FAO 2019), kg p^{-1}
S	Total local population, 10^{4}p
WP_{ij}	Water productivity of crop *j* in irrigation subarea *i*, kg m^{-3}
W_{maxijt}, W_{minijt}	Maximum and minimum water storage of crop *j* in month *t* in irrigation subarea *i*, mm
ω_1, ω_2, ω_3	Weights of three objective functions
x_{ijtopt}, f_{opt}	Decision solution of the optimization model considering CWAP
x'_{ijtopt}, f'_{opt}	Decision solution of the optimization model ignoring CWAP
f'_3	Objective 3 ignoring CWAP: minimum irrigation water amount, mm
$SW'_{ijt} + GW'_{ijt}$	Net irrigation of surface water and groundwater in optimization model ignoring CWAP

Acknowledgements This research was supported by the National Key Research and Development Program of China (No. 2018YFC1508705). We are extremely grateful to the anonymous reviewers and editors for their thoughtful suggestions and valuable comments, which helped us to improve the manuscript.

Author contributions CRediT taxonomy JG: conceptualization, methodology, original draft paper, formal analysis, and investigation; LH: conceptualization, paper review, and editing, supervision; XL: data review and paper review; SW: conceptualization, funding acquisition, project administration, paper review, and editing.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

Allen RG, Pereia LS, Raes D, Smith M (1998) Crop evapotranspiration-guidelines for computing crop water requirements–FAO irrigation and drainage Paper 56. FAO Rome 300:D05109

Bessembinder JJE, Leffelaar PA, Dhindwal AS, Ponsioen TC (2005) Which crop and which drop, and the scope for improvement of water productivity. Agric Water Manag 73(2):113–130. https://doi.org/10.1016/j.agwat.2004.10.004

Deepa R, Anandhi A, Alhashim R (2021) Volumetric and impact-oriented water footprint of agricultural crops: a review. Ecol Indic. https://doi.org/10.1016/j.ecolind.2021.108093

Doorenbos J, Kassam A H, Bentvelsen CIM (1979) Yield response to water. Food and Agriculture Organization of the United Nations, Rome

Doulgeris C, Georgiou P, Papadimos D, Papamichail D (2015) Water allocation under deficit irrigation using MIKE BASIN model for the mitigation of climate change. Irrig Sci 33(6):469–482. https://doi.org/10.1007/s00271-015-0482-4

Evett SR, Stone KC, Schwartz RC, O'Shaughnessy SA, Colaizzi PD, Anderson SK, Anderson DJ (2019) Resolving discrepancies between laboratory-determined field capacity values and field water content observations: implications for irrigation management. Irrig Sci 37(6):751–759. https://doi.org/10.1007/s00271-019-00644-4

FAO (2013) Climate-smart agriculture sourcebook. Food and Agriculture Organization of the United Nations, Rome. https://www.fao.org/3/i3325e/i3325e.pdf

FAO, IFAD, UNICEF, WFP, WHO (2019) The State of Food Security and Nutrition in the World 2019. Safeguarding against economic slowdowns and downturns. Food and Agriculture Organization of the United Nations, Rome. https://www.fao.org/3/ca5162en/ca5162en.pdf

Gao X, Huo Z, Xu X, Qu Z, Huang G, Tang P, Bai Y (2018) Shallow groundwater plays an important role in enhancing irrigation water productivity in an arid area: The perspective from a regional agricultural hydrology simulation. Agric Water Manag 208:43–58. https://doi.org/10.1016/j.agwat.2018.06.009

García-López J, Lorite IJ, García-Ruiz R, Ordoñez R, Dominguez J (2016) Yield response of sunflower to irrigation and fertilization under semi-arid conditions. Agric Water Manag 176:151–162. https://doi.org/10.1016/j.agwat.2016.05.020

Gómez-Limón JA, Gutiérrez-Martín C, Montilla-López NM (2020) Agricultural water allocation under cyclical scarcity: the role of priority water rights. Water 12(6):1835. https://doi.org/10.3390/w12061835

He X, Yang P, Ren S, Li Y, Jiang G, Li L (2016) Quantitative response of oil sunflower yield to evapotranspiration and soil salinity with saline water irrigation. Int J Agric Biol Eng 9(2):63–73. https://doi.org/10.3965/j.ijabe.20160902.1683

Henry EI, Andrew KPRT, Baanda AS, Henry FM (2007) Evaluation of selected crop water production functions for an irrigated maize crop. Agric Water Manag 94(1–3):1–10. https://doi.org/10.1016/j.agwat.2007.07.006

Jensen ME (1968) Water consumption by agricultural plants. In: Kozlowski TT (ed) Water deficit and plant growth. Academic Press, New York, Vol II, pp 1–22

Junaid NC, Allah B, Ragab R, Abdul K, Bernard AE, Muhammad R, Muhammad AS, Qamar N (2020) Modeling corn growth and root zone salinity dynamics to improve irrigation and fertigation management under semi-arid conditions. Agric Water Manag 230. https://doi.org/10.1016/j.agwat.2019.105952

Karatayev M, Kapsalyamova Z, Spankulova L, Skakova A, Movkebayeva G, Kongyrbay A (2017) Priorities and challenges for a sustainable management of water resources in Kazakhstan. Sustain Water Qual Ecol 9–10:115–139. https://doi.org/10.1016/j.swaqe.2017.09.002

Li M, Guo P, Singh VP (2016) An efficient irrigation water allocation model under uncertainty. Agric Syst 144:46–57. https://doi.org/10.1016/j.agsy.2016.02.003

Li C, Xiong Y, Cui Z, Huang Q, Xu X, Han W, Huang G (2020) Effect of irrigation and fertilization regimes on grain yield, water and nitrogen productivity of mulching cultivated maize (*Zea mays* L.) in the Hetao Irrigation District of China. Agric Water Manag. https://doi.org/10.1016/j.agwat.2020.106065

Li M, Bi D, Yang D (2020) The impact of climate change on country's fragility assessment. J Appl Math Phys 8(11):2447–2462. https://doi.org/10.4236/jamp.2020.811181

Li X, Zhang C, Huo Z (2020) Optimizing irrigation and drainage by considering agricultural hydrological process in arid farmland with shallow groundwater. J Hydrol. https://doi.org/10.1016/j.jhydrol.2020.124785

Li X, Zhang C, Huo Z, Adeloye AJ (2020) A sustainable irrigation water management framework coupling water-salt processes simulation and uncertain optimization in an arid area. Agric Water Manag. https://doi.org/10.1016/j.agwat.2019.105994

Liu J, Li Y, Huang G, Zeng X (2014) A dual-interval fixed-mix stochastic programming method for water resources management under uncertainty. Resour Conserv Recy 88:50–66. https://doi.org/10.1016/j.resconrec.2014.04.010

Luan X, Wu P, Sun S, Wang Y, Gao X (2018) Quantitative study of the crop production water footprint using the SWAT model. Ecol Indic 89:1–10. https://doi.org/10.1016/j.ecolind.2018.01.046

Luo B, Liu X, Zhang F, Guo P (2021) Optimal management of cultivated land coupling remote sensing-based expected irrigation water forecasting. J Clean Prod. https://doi.org/10.1016/j.jclepro.2021.127370

Luo B, Zhang F, Liu X, Pan Q, Guo P (2021) Managing agricultural water considering water allocation priority based on remote sensing data. Remote Sens 13:1536. https://doi.org/10.3390/rs13081536

Mandal S, Vema VK, Kurian C, Sudheer KP (2020) Improving the crop productivity in rainfed areas with water harvesting structures and deficit irrigation strategies. J Hydrol. https://doi.org/10.1016/j.jhydrol.2020.124818

Mello KD, Valente RA, Randhir TO, Vettorazzi CA (2018) Impacts of tropical forest cover on water quality in agricultural watersheds in southeastern Brazil. Ecol Indic 93:1293–1301. https://doi.org/10.1016/j.ecolind.2018.06.030

Miao Q, Rosa RD, Shi H, Paredes P, Zhu L, Dai J, Gonçalves JM, Pereira LS (2016) Modeling water use, transpiration and soil evaporation of spring wheat-maize and spring wheat-sunflower relay intercropping using the dual crop coefficient approach. Agric Water Manag 165:211–229. https://doi.org/10.1016/j.agwat.2015.10.024

Mishra V, Cherkauer KA (2010) Retrospective droughts in the crop growing season: implications to corn and soybean yield in the Midwestern United States. Agric For Meteorol 150(7–8):1030–1045. https://doi.org/10.1016/j.agrformet.2010.04.002

Moeinaddini M, Khorasani N, Danehkar A, Darvishsefat AA, Zienalyan M (2010) Siting MSW landfill using weighted linear combination and analytical hierarchy process (AHP) methodology in GIS environment (case study: karaj). Waste Manag 30(5):912–920. https://doi.org/10.1016/j.wasman.2010.01.015

Moldero D, López-Bernal Á, Testi L, Lorite IJ, Fereres E, Orgaz F (2021) Long-term almond yield response to deficit irrigation. Irrig Sci 39(4):409–420. https://doi.org/10.1007/s00271-021-00720-8

Naghdi S, Bozorg-Haddad O, Khorsandi M, Chu X (2021) Multi-objective optimization for allocation of surface water and groundwater resources. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2021.146026

Niu G, Li Y, Huang G, Liu J, Fan Y (2016) Crop planning and water resource allocation for sustainable development of an irrigation region in China under multiple uncertainties. Agric Water Manag 166:53–69. https://doi.org/10.1016/j.agwat.2015.12.011

O'Shaughnessy SA, Andrade MA, Evett SR (2017) Using an integrated crop water stress index for irrigation scheduling of two corn hybrids in a semi-arid region. Irrig Sci 35(5):451–467. https://doi.org/10.1007/s00271-017-0552-x

Omer A, Ma Z, Zheng Z, Saleem F (2020) Natural and anthropogenic influences on the recent droughts in Yellow River Basin, China. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2019.135428

Omer A, Ma Z, Yuan X, Zheng Z, Saleem F (2021) A hydrological perspective on drought risk-assessment in the Yellow River Basin under future anthropogenic activities. J Environ Manag. https://doi.org/10.1016/j.jenvman.2021.112429

Qi Z, Feng H, Zhao Y, Zhang T, Yang A, Zhang Z (2018) Spatial distribution and simulation of soil moisture and salinity under mulched drip irrigation combined with tillage in an arid saline irrigation district, northwest China. Agric Water Manag 201:219–231. https://doi.org/10.1016/j.agwat.2017.12.032

Qu Z, Yang X, Huang Y, Du B, Yang J (2015) Analysis of efficiency of water utilization in canal system in Hetao irrigation district based on Horton fractal. Trans CSAE 31(13):120–127. https://doi.org/10.11975/j.issn.1002-6819.2015.13.017 (**In Chinese**)

Ren D, Xu X, Hao Y, Huang G (2016) Modeling and assessing field irrigation water use in a canal system of Hetao, upper Yellow River basin: application to maize, sunflower and watermelon. J Hydrol 532:122–139. https://doi.org/10.1016/j.jhydrol.2015.11.040

Ren D, Xu X, Engel B, Huang G (2018) Growth responses of crops and natural vegetation to irrigation and water table changes in an agro ecosystem of Hetao, upper Yellow River basin: scenario analysis on maize, sunflower, watermelon and tamarisk. Agric Water Manag 199:93–104. https://doi.org/10.1016/j.agwat.2017.12.021

Shang S (2013) Downscaling crop water sensitivity index using monotone piecewise cubic interpolation. Pedosphere 23(5):662–667. https://doi.org/10.1016/S1002-0160(13)60058-2

Shi J, Wu X, Zhang M, Wang X, Zuo Q, Wu X, Zhang H, Ben-Gal A (2021) Numerically scheduling plant water deficit index-based smart irrigation to optimize crop yield and water use efficiency. Agric Water Manag. https://doi.org/10.1016/j.agwat.2021.106774

Song Z, Guo J, Zhang Z, Kou T, Deng A, Zheng C, Ren J, Zhang W (2013) Impacts of planting systems on soil moisture, soil temperature and corn yield in rainfed area of Northeast China. Eur J Agron 50:66–74. https://doi.org/10.1016/j.eja.2013.05.008

Sonkar I, Kotnoor HP, Sen S (2019) Estimation of root water uptake and soil hydraulic parameters from root zone soil moisture and deep percolation. Agric Water Manag 222:38–47. https://doi.org/10.1016/j.agwat.2019.05.037

Stetson L E, Mecham B Q (2011) Irrigation (6th ed). Irrigation Association, Falls Church, Virginia.

Sun S, Liu J, Wu P, Wang Y, Zhao X, Zhang X (2016) Comprehensive evaluation of water use in agricultural production: a case study in Hetao Irrigation District, China. J Clean Prod 112(5):4569–4575. https://doi.org/10.1016/j.jclepro.2015.06.123

Surendran U, Jayakumar M, Marimuthu S (2016) Low cost drip irrigation: impact on sugarcane yield, water and energy saving in semiarid tropical agro ecosystem in India. Sci Total Environ 573:1430–1440. https://doi.org/10.1016/j.scitotenv.2016.07.144

Tang Q, Oki T, Kanae S, Hu H (2008) Hydrological cycles change in the Yellow River Basin during the Last Half of the Twentieth Century. J Climate 21(8):1790–1806. https://doi.org/10.1175/2007JCLI1854.1

Tang Y, Zhang F, Wang S, Zhang X, Guo S, Guo P (2019) A distributed interval nonlinear multiobjective programming approach for optimal irrigation water management in an arid area. Agric Water Manag 220:13–26. https://doi.org/10.1016/j.agwat.2019.03.052

Tian D, Guo K, Lu H, Ye Z (2015) Optimizal irrigation systems of the main crops under wellcanal irrigation mode in Hetao Irrigation District. J Irrig Drain 34(1):48–52. https://doi.org/10.13522/j.cnki.ggps.2015.01.011 (**In Chinese**)

Tong W, Chen X, Wen X, Chen F, Zhang H, Chu Q, Dikgwatlhe SB (2015) Applying a salinity response function and zoning saline land for three field crops: a case study in the Hetao Irrigation District, Inner Mongolia, China. J Integr Agr 144(1):178–189. https://doi.org/10.1016/S2095-3119(14)60761-9

Wang Y (2017) Calculation of irrigation water utilization coefficient and analysis of total agricultural water consumption in Hetao irrigation District. Dissertation, Yangzhou University **(in Chinese)**

Wang L (2018) Area ratio of canal to well irrigation areas for combined use of groundwater and surface water in Hetao Irrigation District. Dissertation, Wuhan University **(in Chinese)**

White I, Xu T, Zeng J, Yu J, Ma X, Yang J, Huo Z, Chen H (2020) Changing climate and implications for water use in the Hetao Basin, Yellow River, China. Proc IAHS 383:51–59. https://doi.org/10.5194/piahs-383-51-2020

Xue J, Huo Z, Wang S, Wang C, White I, Kisekka I, Sheng Z, Huang G, Xu X (2020) A novel regional irrigation water productivity model coupling irrigation and drainage-driven soil hydrology and salinity dynamics and shallow groundwater movement in arid regions in China. Hydrol Earth Syst Sci 24(5):2399–2418. https://doi.org/10.5194/hess-24-2399-2020

Yu B, Shang S (2020) Estimating growing season evapotranspiration and transpiration of major crops over a large irrigation district from HJ–1A/1B data using a remote sensing-based dual source evapotranspiration model. Remote Sens 12(5):865. https://doi.org/10.3390/rs12050865

Yun W, Hou Q, Li J, Miao B, Feng X (2015) Yield prediction of sunflower based on crop coefficient and water production function. J Appl Meteor Sci 26(6):705–713. https://doi.org/10.11898/1001-7313.20150607 (**In Chinese**)

Zeng W, Wu J, Hoffmann MP, Xu C, Ma T, Huang J (2016) Testing the APSIM sunflower model on saline soils of Inner Mongolia, China. Field Crops Res 192:42–54. https://doi.org/10.1016/j.fcr.2016.04.013

Zeng W, Xu C, Wu J, Huang J (2016) Sunflower seed yield estimation under the interaction of soil salinity and nitrogen application. Field Crops Res 198:1–15. https://doi.org/10.1016/j.fcr.2016.08.007

Zhang F, Guo P, Engel BA, Guo S, Zhang C (2019) Planning seasonal irrigation water allocation based on an interval multiobjective multi-stage stochastic programming approach. Agric Water Manag. https://doi.org/10.1016/j.agwat.2019a.105692

Zhang F, Yue Q, Engel BA, Guo S, Guo P, Li X (2019) A bi-level multiobjective stochastic approach for supporting environment-friendly agricultural planting strategy formulation. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2019.133593

Zhang T, Ji X, Zhan X, Ding Y, Zou Y, Kisekka I, Chau H, Feng H (2021) Maize is stressed by salt rather than water under drip irrigation with soil matric potential higher than – 50 kPa in an arid saline area. J Agron Crop Sci 207(4):654–668. https://doi.org/10.1111/jac.12497

Zhang X, Guo P, Guo W, Gong J, Luo B (2021) Optimization toward sustainable development in shallow groundwater area and risk analysis. Agric Water Manag. https://doi.org/10.1016/j.agwat.2021.107225

Zhang X, Guo P, Zhang F, Liu X, Yue Q, Wang Y (2021) Optimal irrigation water allocation in Hetao Irrigation District considering decision makers' preference under uncertainties. Agric Water Manag. https://doi.org/10.1016/j.agwat.2020.106670