Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2020.25275

187 (2020) 30–41
May

Efficient water-saving irrigation based on regional irrigation schedule optimisation

Congying Han[a,b], Baozhong Zhang[a,b,*], Yu Liu[a,b]

[a]*State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China, email: zhangbaozhong333@163.com (B. Zhang)*
[b]*National Center of Efficient Irrigation Engineering and Technology Research-Beijing, Beijing 100048, China*

Received 16 June 2019; Accepted 22 December 2019

ABSTRACT

Shortage of agricultural water resources and low agricultural water use efficiency (WUE, which is the economic output per unit of water, and is divided into WUE_{ET}, the ratio of yield to evapotranspiration and WU_{EI}, the ratio of yield to irrigation volume) have become important factors that restrict agricultural development in northwest China. In the middle oasis of the Heihe River Basin (HRB), the major causes for loss of agricultural water and low irrigation efficiency are large irrigation quotas, the uneven spatial distribution of agricultural water resources and unreasonable irrigation schedules. A full understanding of the spatial distribution of agricultural water consumption and water productivity in the middle oasis of HRB is a prerequisite for improving agricultural WUE and ensuring food production security under the premise of existing agricultural water supply. In this study, by using the AquaCrop-RS model, the spatial distribution of water consumption and water productivity in the middle oasis of HRB was analyzed under the current irrigation schedules. Simulations were conducted to study the deficit irrigation scenarios in this region, preliminarily arriving at appropriate irrigation quotas for different irrigation districts. A multi-objective optimization model and the genetic algorithm NSGA-II with an elitist strategy were used in optimizing the irrigation schedule for each irrigation unit. Irrigation schedules that meet the highest yield and the highest WUE_{ET} for the middle oasis were obtained. Results show that the irrigation quota of corn in the middle oasis after irrigation schedule optimization is reduced by 0–657 mm under different irrigation schedules, WUE_{ET} is increased by 4.13%–5.13% and WUE_{I} rises by 69%–91%, thereby preliminarily achieving the water-saving and high-yield goals for corn in the middle oasis.

Keywords: Genetic algorithm; Multi-objective optimization; Irrigation schedule optimization; AquaCrop-RS

1. Introduction

The expected increase of population in the coming 20 y imposes higher requirements on the security of agricultural production; thus, sustainable development of agriculture remains an issue for China [1]. The Heihe River Basin (HRB) is the second-largest inland river basin in China. The middle oasis of HRB is an important grain-producing area in the Hexi region, and the agricultural irrigation water accounts for 84% of the total surface water [2]. The climate of HRB is dry, and the annual rainfall is relatively small. The shortage of water resources especially limits agricultural development in the region. In recent years, to restore the downstream ecological environment, the surface water for the agricultural irrigation of the middle oasis has been reduced, thereby resulting in excessive exploitation of groundwater. Groundwater level has been seriously degraded, and the eco-environmental problems of the middle oasis have become increasingly apparent [3,4]. Extensive irrigation methods and unreasonable irrigation management resulted in severe leakage losses [5]. Therefore, developing water-saving irrigation, formulating scientific management indicators for irrigation quota, and optimizing the allocation of water resources during crop development are important means to minimize water

---

* Corresponding author.

wastage, improve agricultural water use efficiency (WUE) and ensure sustainable agricultural development [6,7].

In the 1970's, the Australian Institute of Continuous Irrigation Agriculture proposed the concept of regulated deficit irrigation, and the research of domestic scholars on field experiments in subsequent decades proved that it was an effective water-saving irrigation method [8], thereby contributing to considerable economic and ecological benefits for areas that suffer from water shortage [9]. Kang et al. [10] revealed the mechanism of water-saving and yield-increasing measures under regulated deficit irrigation and proposed a regulated deficit irrigation schedule to achieve the dual goals of the highest yield and highest WUE for corn in the Loess Plateau region of northern China. Kang et al. [11] also emphasized that the best irrigation practice for corn in semi-arid areas of northwest China was severe water deficit during the seedling stage (with soil moisture at 40%–50% of field capacity) and mild water deficit during the jointing stage (with soil moisture at 55%–65% of field capacity).

Improvement of irrigation schedule is not only essential to the efficient use of agriculture water in the middle oasis of HRB, but it is also the main research content of agricultural water management [12]. Scholars have attempted many times to optimize irrigation schedules. Wang et al. [13], by using the Jensen model and the dynamic programming model, optimized the irrigation schedule for the winter wheat of Jinzhong in Shanxi province and obtained the optimal irrigation schedules for different initial soil moistures and different irrigation quotas for each growth stage of crops. Shang and Mao [14] optimized the irrigation schedules for winter wheat in north China by using the water productivity function and the soil moisture balance model combined with the nonlinear search method, thus arriving at the maximum yield of winter wheat under limited irrigation quotas. Yu and Shang [15], based on the farmland water balance model and the Jensen model, optimized the irrigation schedule for crop rotation of winter wheat and summer corn in north China with multi-objective optimization and genetic algorithm (GA) and determined the optimal irrigation period of the crops. Wen et al. [16] optimized the irrigation time for mulched spring wheat in the Shiyanghe River Basin under different deficit irrigations based on the optimization simulation model to improve crop yield and water productivity. The above findings are all based on many field experiments. For a larger scale, however, the growth of crops is subject to climate, soil texture, and field management, which implies that the optimal irrigation schedules for crops will produce some spatial variability. Furthermore, the model based on the water productivity function needs to be validated with numerous long time series of field data, which involve regional constraints and are difficult to obtain [17].

Understanding the dynamic changes of agricultural hydrology in farming areas is the premise and basis for implementing water-saving irrigation. However, conducting a survey of crop water consumption, soil moisture dynamics, and spatial distribution of irrigation water loss throughout the middle oasis requires considerable labor and resources, and the resulting data are seldom regionally representative because they do not reflect the actual spatial variation for the study region. The AquaCrop model can be used to simulate water consumption, change in soil moisture, and deep-layer leakage. The AquaCrop-RS model, which was developed on the basis of 3'S technology, is an extension of the regional application of the AquaCrop model [18]. It considers the combined effects of spatial variability of meteorology, soil texture, management for irrigation, planting dates, and specifically, the effects of the underlying surface on crop parameters (mainly fertility stress in this paper). The AquaCrop-RS model provides a reasonable track and description of the dynamics of agricultural water in the region. In addition, the model is simple in structure and easy to combine with the optimization model, thereby providing good conditions for regional irrigation schedule optimization.

As reported by previous studies, the AquaCrop-RS model was first used to evaluate the current irrigation schedule in the middle oasis of HRB. The existing irrigation time was kept unchanged, and the irrigation quotas in the region were adjusted with different proportions, which allowed the model to obtain the appropriate range of irrigation quotas. The AquaCrop-RS model was then coupled with the multi-objective optimization model. With the simulation units as the basic optimization units and the maximization of yield and WUE for the entire middle oasis as the objectives, hierarchical optimization was conducted on the irrigation schedule in the region. The study may provide some technical support and guidance for the rational allocation of agricultural water resources in the middle oasis of HRB, thus helping improve agricultural WUE.

2. Materials and Methods

2.1. Experimental site

This study focuses on the middle oasis of HRB. The location spans 38°52′–39°52′ N and 98°57′–100°52′ E (Fig. 1). This district is dominated by typical continental arid and semi-arid climate with annual average temperatures from 6°C to 8°C, annual insolation duration of 3,000–4,000 h, annual evaporation capacity of 1,410 mm and an average annual rainfall of only 140 mm. The elevation varies between 1,200 and 3,600 m, and a significant spatial variation is observed in both temperature and soil type. The region is mainly governed by three counties (Ganzhou, Linze, and Gaotai) and divided into 24 irrigation districts, each of which is managed by an irrigation management office. Agricultural irrigation of the middle oasis is mostly supplied by surface water and supplemented by groundwater.

The total irrigated area of the oasis is ~2.2 million mu (147 ha.), of which farmland accounts ~85%. The major crops include wheat, corn, barley, melons, and other cash crops. In particular, corn and wheat comprise ~51% and 17% of the planting area, respectively. Rotation irrigation is practiced; however, the irrigation schedules vary from region to region based on statistics from the irrigation management offices in the districts.

2.2. Field experiments and data collection

Field experiments were conducted in the Yingke Irrigation District from April 2012 to October 2013, and the

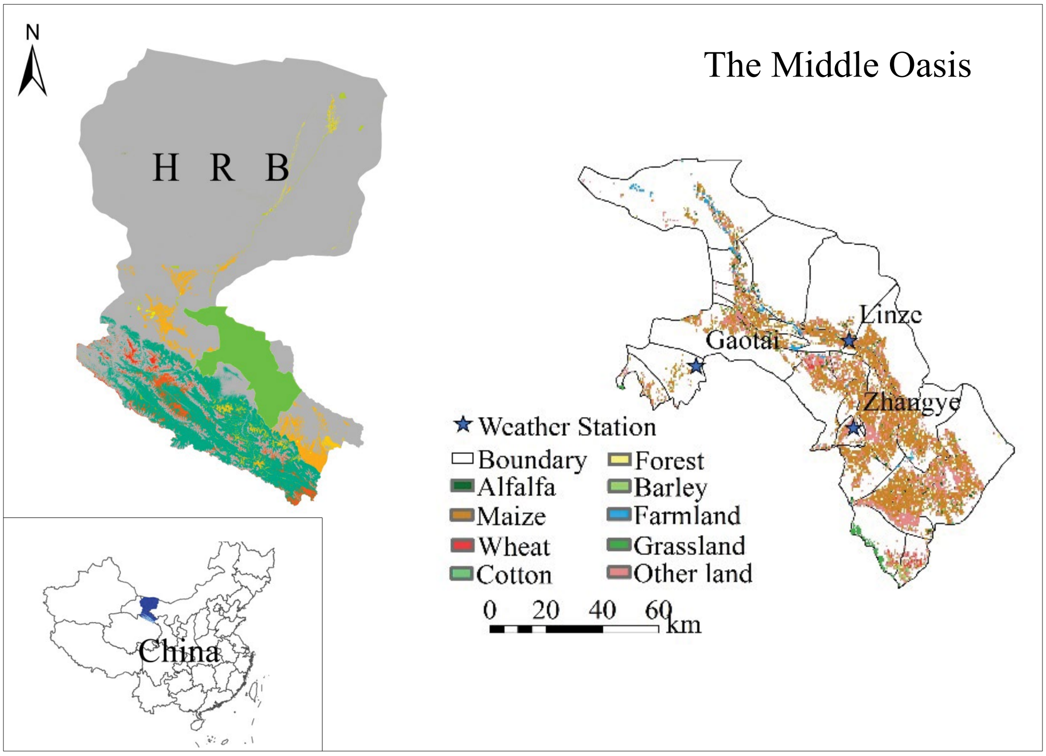


Fig. 1. Location of the study region.

data were used to calibrate and validate the model. The sowing date, irrigation schedule, and yield in the middle oasis were surveyed and sampled in 2012, 2015, and 2016, in which 14, 30, and 148 sampling points were obtained, respectively. The spatial distribution of the sampling points for these is shown in Fig. 2.

The meteorological stations in the study region include Zhangye, Linze, and Gaotai stations (Fig. 1). The meteorological data were obtained from the China Meteorological Data Service Center (http://data.cma.cn/). The dataset of land use in the HRB was obtained from the Heihe Planning Data Management Center [19,20].

The soil texture of the middle oasis, which was obtained from the Institute of Soil Science, Chinese Academy of Sciences, is characterized by two layers (0–30 cm and 30–100 cm in depth). The spatial distribution of soil texture is shown in Fig. 3. The 0–30 cm layer in this region involves multiple soil types, but the soil for the 0–100 cm depth layer is mostly sandy in the middle and lower reaches of the middle oasis, and the upper reaches is mostly loam. The soil hydraulic parameters were estimated with Rosetta software based on soil particle size composition [21–23].

2.3. Model description

2.3.1. AquaCrop-RS model

The AquaCrop-RS model is developed from the AquaCrop model by incorporating 3'aS technology. The model considers variations in the sowing date based on the meteorological conditions and uncertainties of crop parameters, which depend on the varying underlay surface, thereby significantly improving the simulation accuracies of regional yield and water consumption. The principle for the formation of crop yield in the model is shown as Eqs. (1)–(3). Additional information on the AquaCrop-RS model can be found in Han et al. [18].

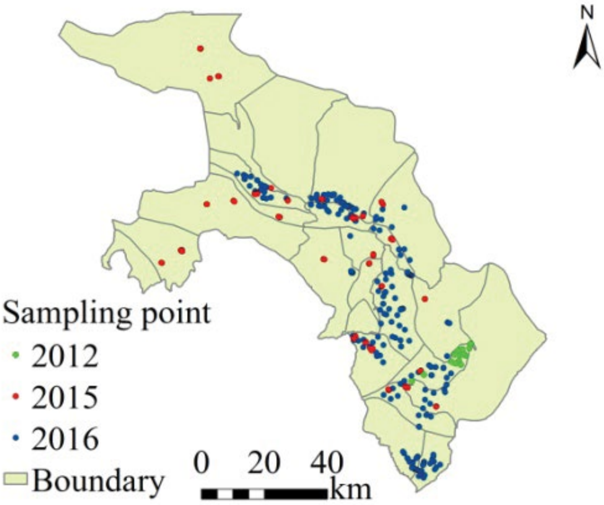
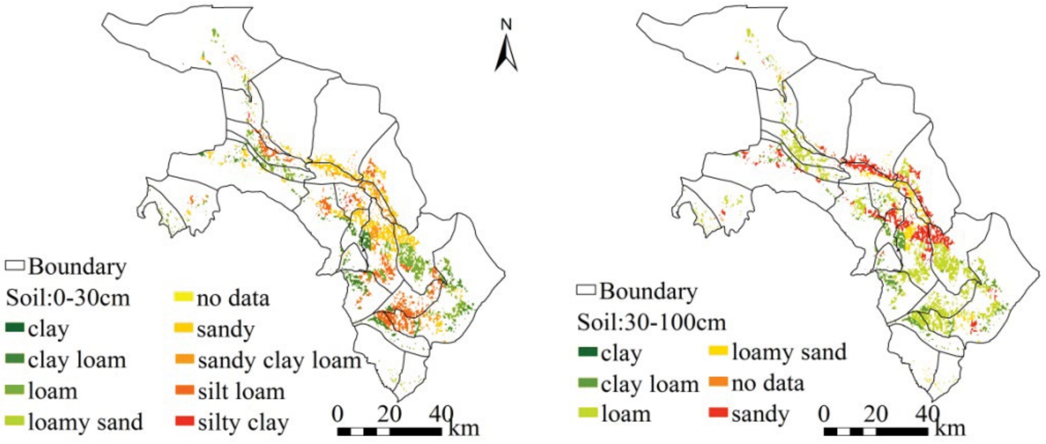


Fig. 2. Spatial distribution of sampling points in the middle oasis.

$$\mathrm{Tr} = (\mathrm{Ks}\ \mathrm{Kc}_{\mathrm{Tr}})\mathrm{ET}_0 \tag{1}$$



(a) (b)

Fig. 3. Spatial distribution of soil texture in the middle oasis for the planting region of corn, (a) 0–30 cm and (b) 30–100 cm.

$$B = \mathrm{Ks}_{\mathrm{WP}}\mathrm{WP}^{*}\sum\left(\frac{\mathrm{Tr}}{\mathrm{ET}_0}\right) \tag{2}$$

$$Y = \mathrm{H}I \times B \tag{3}$$

where Tr is crop transpiration (mm d^{-1}); ET_0 is reference crop evapotranspiration (mm d^{-1}) evaluated by the Penman–Monteith formula; Ks is the soil moisture stress coefficient (Ks ≤ 1); $\mathrm{Kc}_{\mathrm{Tr}}$ is the crop transpiration coefficient; B is aboveground dry biomass (mg ha^{-1}); $\mathrm{Ks}_{\mathrm{WP}}$ is the water productivity coefficient subject to soil fertility stress ($\mathrm{Ks}_{\mathrm{WP}} \leq 1$); WP* is normalized water productivity in terms of dry biomass (mg ha^{-1}), a coefficient related to atmospheric CO_2 concentration; Y is economic yield (mg ha^{-1}); and HI is the comprehensive harvest index (%).

The AquaCrop-RS model divides the crop water consumption process into two parts, namely, soil evaporation and crop transpiration. Crop transpiration capacity is affected by soil water content in the root zone. When the soil water content in the root zone of the crop cannot meet the atmospheric evaporation demand, Ks is <1, and then crop transpiration will be inhibited. When soil nutrient becomes insufficient, soil fertility stress increases, $\mathrm{Ks}_{\mathrm{WP}}$ decreases accordingly, and dry biomass accumulation will be inhibited.

The simulation of soil moisture changes is based on the water balance formula in the AquaCrop-RS model. The study area is located in the arid region of northwest China. The climate is dry, the evaporation is large, and rainfall mainly occurs in the flood season. Therefore, the surface runoff in the water balance formula is not considered. At the same time, in recent years, the groundwater level in the middle oasis has dropped seriously, and groundwater cannot sufficiently replenish root zone moisture; for this reason, the groundwater replenishment item is also not considered. Therefore, the soil water balance formula in this study can be written as Eq. (4).

$$W_{\mathrm{end}} - W_{\mathrm{ini}} = P + I - \mathrm{Tr} - E - D_p \tag{4}$$

where W_{end} and W_{ini} are the soil water content in the depth of 100 cm at the end of the growth period and the beginning of the growth period, respectively; P is precipitation during the development stages; I is irrigation quota; Tr and E are crop transpiration and soil evaporation, respectively; and D_p is leakage. All units are in mm.

2.3.2. Optimization objectives of irrigation schedules

The contradiction between the supply and demand of agricultural water in the middle oasis of HRB has become increasingly prominent. For the sake of food production security, improving agricultural WUE is the key method for the sustainable development of agriculture in this region. Here, we attempt to optimize irrigation schedules under certain irrigation quotas, with the maximum yield and the highest $\mathrm{WUE}_{\mathrm{ET}}$ of corn as the objectives. The total yield in the middle oasis is considered the sum of the yield of all the simulated units in this region, and the $\mathrm{WUE}_{\mathrm{ET}}$ is regarded as a comprehensive value of this region. The calculation formulas are shown as Eqs. (5) and (6).

$$\mathrm{Yield}_{\mathrm{oasis}} = \sum_{\mathrm{j}=1}^{24}\left(\sum_{\mathrm{i}=1}^{n}\mathrm{yield}_{j,i} \times \mathrm{area}_{j,i}\right) \tag{5}$$

$$\frac{\mathrm{WUE}_{\mathrm{EToasis}} = \text{The total yield}_{\mathrm{oasis}}}{\text{The total water consumption}_{\mathrm{oasis}}} = \frac{\sum_{j=1}^{24}\left(\sum_{i=1}^{n}\mathrm{yield}_{j,i} \times \mathrm{area}_{j,i}\right)}{\sum_{j=1}^{24}\left(\sum_{i=1}^{n}(E_{j,i} + \mathrm{Tr}_{j,i} \times \mathrm{area}_{j,i})\right)} \tag{6}$$

where i is the ith simulation unit in a certain irrigation district; n is the number of simulation units in a certain irrigation district; j is the number of irrigation districts in the middle oasis, with 24 irrigation districts being studied here; E is soil evaporation; Tr is crop transpiration; $\mathrm{area}_{j,i}$ is the area of the ith simulation unit in the jth irrigation district; and $\mathrm{yield}_{j,i}$ is the yield per unit of the ith simulation unit in the jth irrigation district.

2.3.3. Optimization model

With the consumption of water resources, the available water for agriculture is becoming increasingly scarce. Therefore, the maximum economic benefit cannot be used as the sole target for the optimization of agricultural water resources [24]. Socio-economic development and regional ecological benefits should be considered simultaneously, but the two are conflicting to a certain extent. Therefore, the traditional single-objective optimization method for water resources is no longer applicable. Multi-objective optimization has multiple optimization goals and can maximize the optimal use of limited water resources.

The multi-objective optimization model, with irrigation date (*D*) and irrigation quota (*I*) as the independent variables and yield (*Y*) and WUE as the dependent variables, is constructed as follows [25]:

The objective function is

$$\begin{aligned} &\max Y = f(D, I) \\ &\max \mathrm{WUE}_{\mathrm{ET}} = f(D, I) \end{aligned} \tag{7}$$

The constraint conditions are

$$I \le I_{\max},\ \sum_{i=1}^{n} I_i = I\ ,\ I_i \ge 60 \text{ mm [10]}, \tag{8}$$

$$30 < d_i < 140,$$

where Y is the total yield of corn in the middle oasis (kg); $\mathrm{WUE}_{\mathrm{ET}}$ is the comprehensive water use efficiency of corn (kg/m^3); $D = [d_1, d_2, d_3, ..., d_n]$, with d_i representing the *i*th irrigation date, to be counted consecutively following the sowing date (the average growth time of corn is reportedly 150 d in this region, and no irrigation is allowed within 10 d before the crop is harvested, and the first irrigation is done 30 d later after sowing date when the root of corn seedlings is deep enough); I_i is the *i*th irrigation quota (mm; given the local water supply conditions, the irrigation times are set as 3, 4, 5, and 6 times); and $I_{\max}$ is irrigation volume when the yield reaches the maximum under deficit irrigation.

2.3.4. Optimization algorithm

The application of the GA to multi-objective optimization has become a popular research topic in recent years. GA is a global optimization search technique inspired by the natural selection and genetic mechanism of natural evolution [26]. The optimization algorithm NSGA-II, with the introduction of the elitist strategy, is applied to our multi-objective optimization [27]. The algorithm expands the sampling space and ensures that good elements are not abandoned during the genetic calculation process, thereby improving the population level. At the same time, the fast non-dominated sorting approach, crowding-distance, and crowded-comparison operator are proposed to reduce computational complexity and ensure population diversity. The principle of the algorithm is shown in Fig. 4 [28,29].

2.4. Research path

The year 2015 was set as the "current year" in the study. The spatial distribution of water consumption and $\mathrm{WUE}_{\mathrm{ET}}$ of corn in the middle oasis were simulated by using the AquaCrop-RS model. Regulated deficit irrigation at proportions of 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%, 55%, 60%, and 65%, as compared to the current irrigation volume, was rendered. The yield and $\mathrm{WUE}_{\mathrm{ET}}$ for the regulated deficit irrigation scenarios were compared with current yield and $\mathrm{WUE}_{\mathrm{ET}}$. The irrigation quota was set as the lower limit when yield or $\mathrm{WUE}_{\mathrm{ET}}$ reached the maximum, and the irrigation volume was set as the upper limit when the reduction of yield or $\mathrm{WUE}_{\mathrm{ET}}$ reduced by 10%. Then, the irrigation schedule was optimized with the multi-objective optimization model and the NSGA-II algorithm based on the irrigation quota determined above for the lower limit, thereby resulting in comparatively high agricultural $\mathrm{WUE}_{\mathrm{ET}}$ in the middle oasis. The research path is shown in Fig. 5.

3. Results and Discussion

3.1. Evaluation of current irrigation schedule

Local farmers were asked to share information about irrigation time and irrigation amount based on traditional production experience. Reportedly, irrigation volume cannot be controlled reasonably by following the crop requirement, thereby causing serious leakage loss, and agricultural WUE was generally low. According to the survey, the average irrigation for the Heihe irrigation districts in the middle oasis was five times, and the average irrigation was three times for the irrigation districts along the mountain due to insufficient water supply. By using the AquaCrop-RS model, the spatial distribution of water consumption in the middle oasis in 2015 was simulated. The spatial distributions of irrigation volume for corn, leakage loss, crop transpiration, and WUE in the farming areas are shown in Figs. 6a–d.

As shown in Fig. 6a, the spatial distribution of agricultural water resources in the middle oasis is extremely uneven, and the spatial distribution is significantly different. The leakage loss in the farming area (Fig. 6b) and the irrigation amount is spatially and positively correlated to a certain extent, and both show an increasing trend from upstream to downstream. The leakage in the upper reaches of the middle oasis is between 58 and 281 mm, and that in the middle and lower reaches is between 282 and 534 mm. According to analysis, the evapotranspiration in the upper reaches is 102% of the irrigation amount, but the rate drops to 60% in the middle and lower reaches, which suggests that the irrigation volume in some areas of the middle oasis exceeds the amount of water needed for a crop, and great potential remains for water-saving measures in this region.

As shown in Fig. 6d, the $\mathrm{WUE}_{\mathrm{ET}}$ of corn in the middle oasis is between 2.0 and 2.3 kg/m^3, and the spatial difference is insignificant. However, the spatial variability of $\mathrm{WUE}_{\mathrm{I}}$ is obvious because it is generally between 1.24 and 3.35 kg/m^3, and this phenomenon is mainly caused by the uneven distribution of irrigation. By comparing their distribution, $\mathrm{WUE}_{\mathrm{I}}$ is generally greater than $\mathrm{WUE}_{\mathrm{ET}}$ in the upper reaches of the middle oasis, but the trend is opposite in the middle and lower reaches, thereby proving that agricultural irrigation

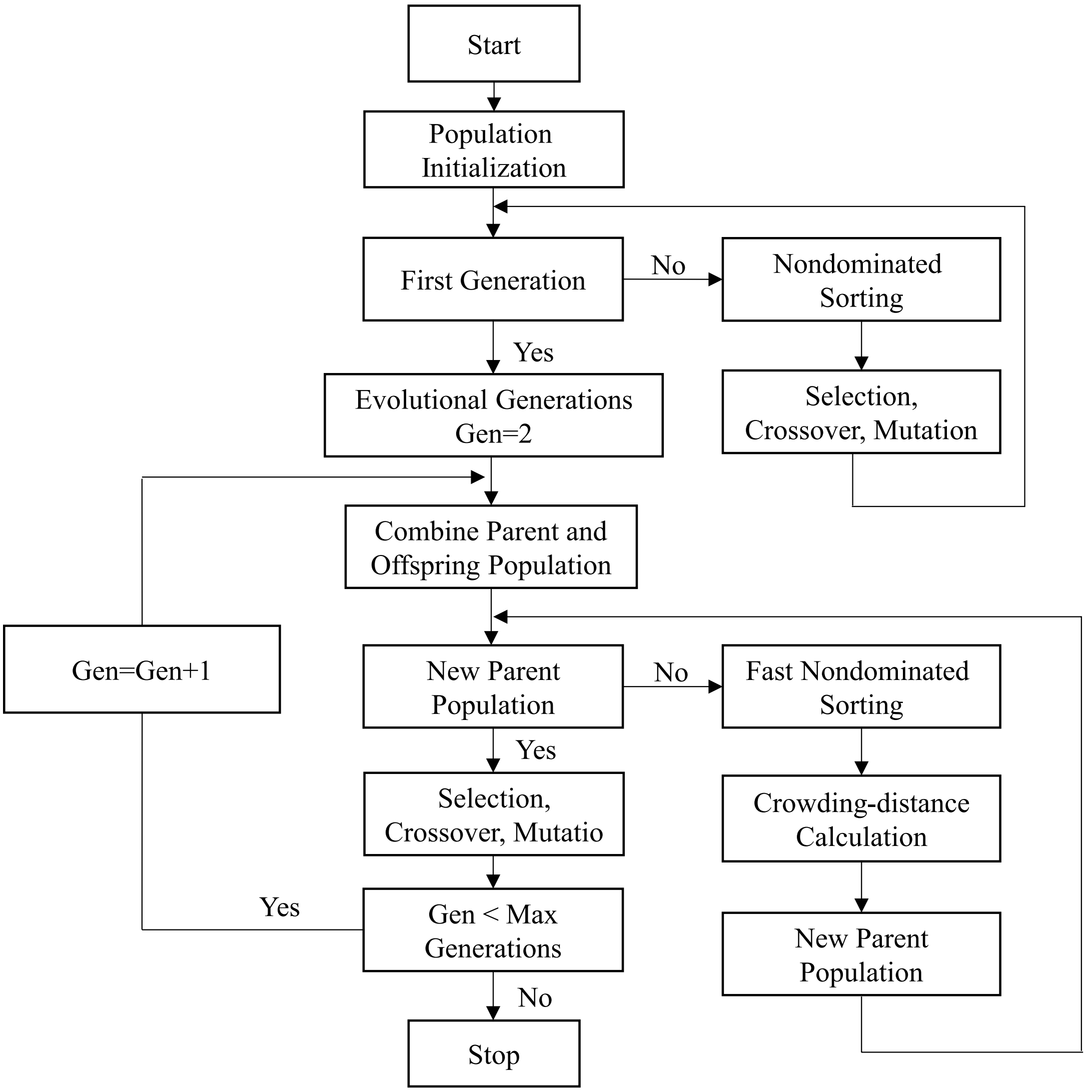


Fig. 4. Operating principle of NSGA-II.

water in the upper reaches is more effectively used than those in the middle and lower reaches.

As shown in Figs. 6c and e, transpiration and yield of corn are spatially correlated to a certain extent. However, yield depends not only on crop transpiration but is also affected by soil fertility. The content of sand in the lower reaches of the middle oasis is relatively high, and soil fertility is poor. Therefore, the nutrient supply during the growing period of corn is insufficient, and the accumulation of dry biomass is limited. Han et al. [18] confirmed this finding in their study by using the spatial distribution of B_{rel}, which is a crop parameter used to analyze soil fertility stress based on the inversion of remote sensing data. On the basis of yield distribution, the yield per unit in the upper and middle reaches of the middle oasis is relatively high, in which the values vary between 13.2 and 13.7 ton/ha, whereas it is low in the lower reaches at values between 11.7 and 12.7 ton/ha. The irrigation quota in the lower reaches of the middle oasis is 62% higher than that in the upper reaches, but the yield per unit is lower by 4%.

Fig. 7 shows the total irrigation volume, the ratio of soil evaporation to irrigation and the ratio of leakage to irrigation for the irrigation districts in the middle oasis of HRB. Considering that the irrigated area in upper reaches of the middle oasis (mainly Ganzhou) accounts for 58% of the total irrigated area, a large portion of irrigation volume (47% of total irrigation volume in the middle oasis) is consumed in this area. The middle reaches of the middle oasis (mainly Linze) accounts for 25% of the total irrigated area and consumes 27% of the irrigation volume. For the lower reaches (mainly Gaotai), the rates are 17% and 26%. In the middle oasis, corn is mulched, and thus, the spatial difference of soil evaporation is not obvious. As evident from the distribution of soil texture in the middle oasis, the sand content in the middle and lower reaches of the middle oasis is relatively high, which indicates poor water holding capacity for soil, thus resulting in extensive deep-layer leakage. The average leakage in this area is ~40% of the irrigation volume. However, the irrigation districts of Xiaotun, Nijiaying, Xinba,

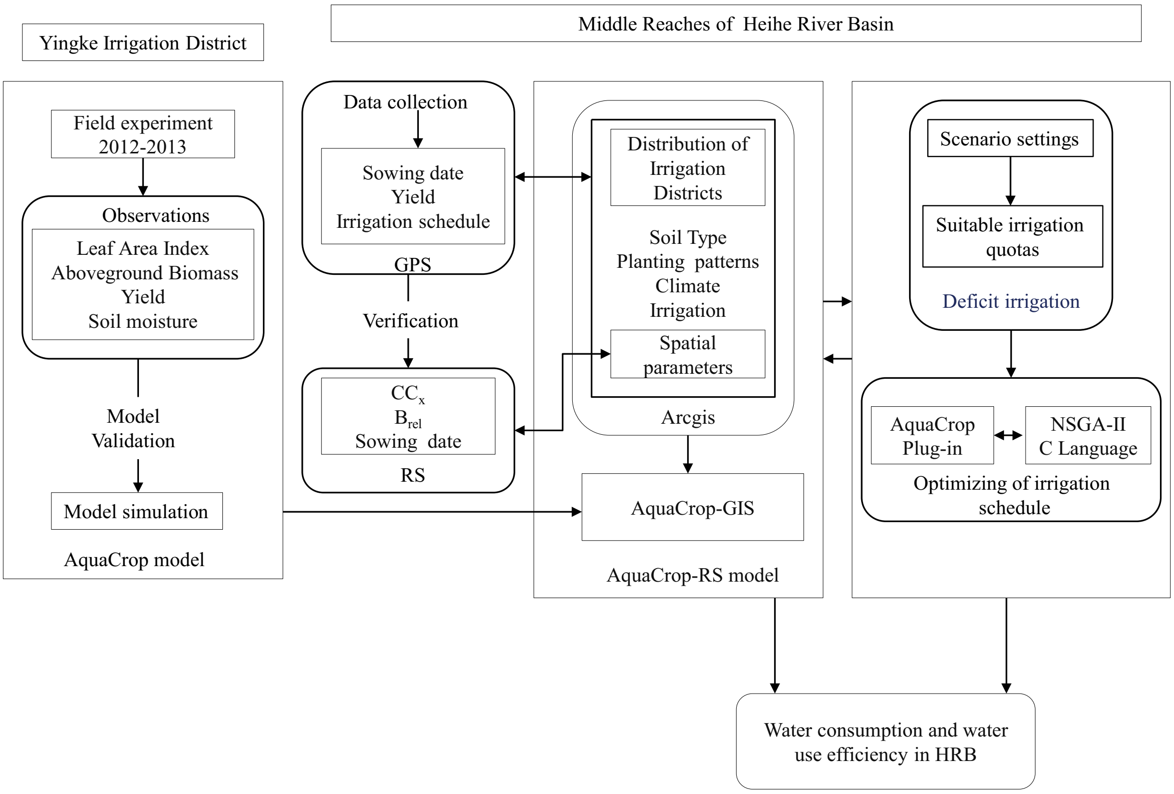


Fig. 5. Research path for the study.

and Hongyazi are mostly composed of loam, and therefore, leakage is relatively low at ~25% on the average.

In summary, the irrigation quota in the study area is high, which indicates serious leakage loss, and the spatial distribution is also unreasonable. Therefore, practising regulated deficit irrigation and further optimizing the irrigation schedule are important measures to minimize leakage loss, save agricultural water, and improve WUE under the current situation.

3.2. Water-saving effect of regulated deficit irrigation and analysis of appropriate irrigation quotas

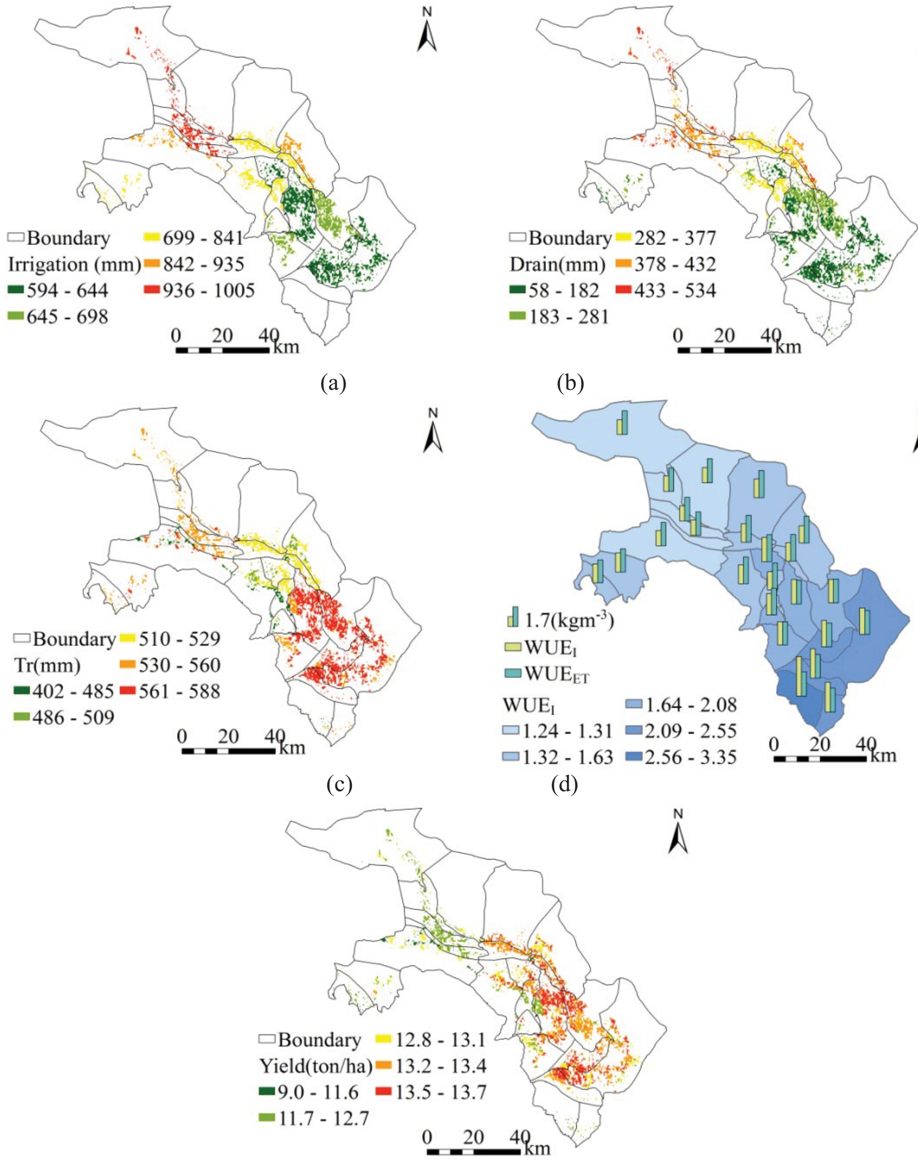
Figs. 8a and b show the spatial variation of Δyield and ΔWUE_{ET} for corn in the different irrigation districts under varying regulated deficit scenarios. Yield and WUE_{ET} have significantly decreased with the increase in the degree of deficit reduction in the upper reaches of the middle oasis after the deficit reduction has reached a certain level. However, the trends in the middle and lower reaches of the middle oasis are not obvious, which indicates that the amount of irrigation in the area is large and a certain degree of deficit adjustment will not have a significant effect on the yield and WUE_{ET} in the region.

By referring to the criteria for regulated deficit irrigation, the appropriate irrigation quotas for each irrigation district were obtained. The results are shown in Table 1. On the basis of the irrigation quota in Table 1, irrigation volume decreases by 205–371 mm on the average in the middle oasis, and leakage decreases by 180–233 mm on the average. Under the current conditions, the WUE_I of the middle oasis of HRB is 1.78 kg/m^3 and the WUE_{ET} is 2.06 kg/m^3. As for the lower and upper deficit limits, the corresponding WUE_I values are 2.48 and 3.39 kg/m^3, and the corresponding WUE_{ET} values are 2.07 and 2.04 kg/m^3. Therefore, the proposed regulated deficit irrigation can be adopted to significantly increase WUE_I without substantially changing WUE_{ET}.

3.3. Optimization of irrigation schedules and assessment of WUE

On the basis of the irrigation quotas determined in Section 3.2, the irrigation schedules are further optimized by using the optimization algorithm NSGA-II such that the limited water can be distributed more rationally throughout the development stages. One group of optimized irrigation schedules is shown in Table 2. The spatial distribution of the changes of corn yield, WUE_{ET}, and WUE_I for different irrigation times after optimization are shown in Figs. 9a–c. Fig. 9a shows that the spatial variation of Δyield is obvious in the middle oasis after optimization. As evident from Figs. 9b and c, both WUE_{ET} and WUE_I tend to increase after optimization, with WUE_{ET} increasing by 4.13%–5.13% on the average and WUE_I increasing by 69%–91% on the average.

The average irrigation quota for each irrigation district in the middle oasis after optimization is shown in Fig. 9d. Statistics show that the irrigation quotas for the irrigation districts decrease by 0–657 mm after optimization. However, the water-saving effect is not notable in the Huazhaizi and Anyang irrigation districts because the current irrigation quotas are already low, thus leaving not much room for further



(a) (b)

(c) (d)

(e)

Fig. 6. Production factors in the study area (a) irrigation quota, (b) leakage loss, (c) crop transpiration, (d) spatial distribution of WUE, and (e) yield.

reduction, but significant improvements in yield and WUE can be realized by both irrigation districts. Thus, the optimization of irrigation schedules can further improve the use efficiency of agriculture water of corn in the irrigation districts.

4. Conclusions

The distribution of water consumption of corn in the middle oasis of HRB was accurately simulated by using the distributed crop model (i.e., AquaCrop-RS model), particularly by considering the comprehensive effects of soil texture, soil fertility, and meteorology. The results show that the spatial distribution of irrigation volume in the middle oasis is significantly different. Owing to soil texture, meteorology, management, and other factors, WUE$_I$ is spatially heterogeneous and ranges from 1.24 to 3.35 kg/m^3. The leakage in the middle oasis is large, and the trends of spatial leakage variation and irrigation volume are essentially the same. The deep leakage in the middle and lower reaches of the middle oasis is high at 282–534 mm, and it accounts for ~40% of the irrigation volume. Therefore, the potential for water saving is high in the middle oasis.

Unreasonable field management is an important factor affecting agricultural WUE. In this study, the irrigation quota of corn in the middle oasis of HRB was initially determined by regulated deficit irrigation, and the multi-objective optimization model was used to optimize further the irrigation schedule of corn in the region. The results show that the irrigation quotas of the middle oasis can decrease by 0–657 mm with the optimized irrigation schedule, and WUE (WUE$_{ET}$

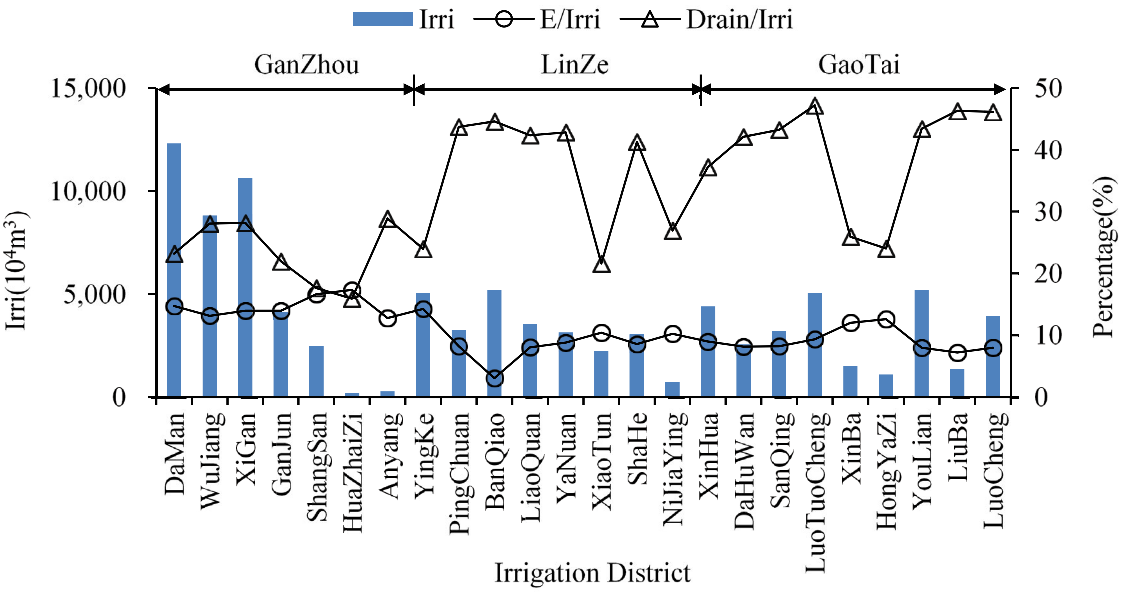
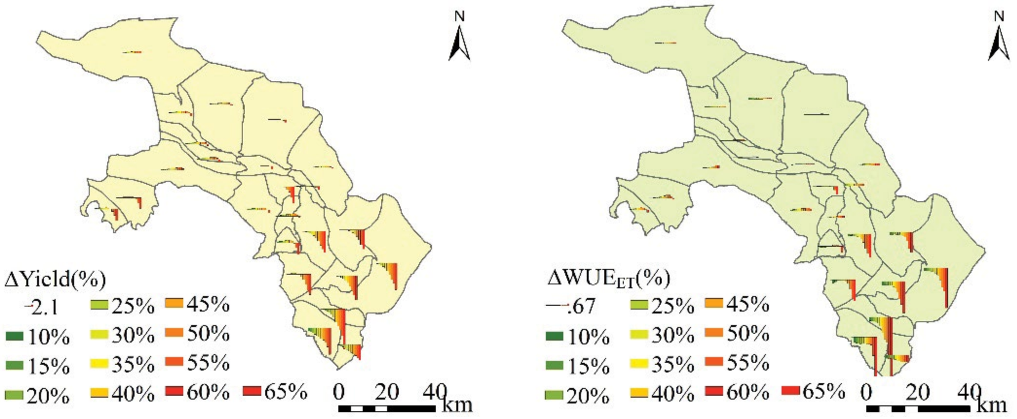


Fig. 7. Total irrigation volume and proportion of invalid water for the irrigation districts in the middle oasis of HRB.



(a) (b)

Fig. 8. Spatial variation of (a) Δyield and (b) ΔWUE$_{ET}$ in the middle oasis under different regulated deficit scenarios.

Table 1
Appropriate irrigation quotas for each irrigation district in the middle oasis of HRB

Ganzhou		Linze		Gaotai	
Irrigation district	Irrigation quota (mm)	Irrigation district	Irrigation quota (mm)	Irrigation district	Irrigation quota (mm)
Daman	386–594	Pingchuan	294–462	Dahuwan	381–476
Wujiang	371–675	Banqiao	315–405	Sanqing	378–473
Xigan	383–638	Liaoquan	294–420	Luotuocheng	327–421
Ganjun	361–460	Yanuan	294–504	Xinba	351–468
Shangsan	373–533	Xiaotun	323–419	Hongyazi	344–497
Huazhaizi	260–347	Shahe	294–420	Youlian	389–486
Anyang	318–489	Nijiangying	314–419	Liuba	345–444
Yingke	362–603	Xinhua	324–405	Luocheng	352–452

Table 2
Optimized irrigation schedules for each irrigation district in the middle oasis of HRB

Irrigation District		Irrigation Schedule					
Daman	Time	5/29	6/17	7/16	7/31	8/15	8/30
	Quota (mm)	83	61	87	105	73	63
Wujiang	Time	5/28	6/18	7/16	7/31	8/15	8/30
	Quota (mm)	72	67	80	97	78	70
Xigan	Time	6/6	6/23	7/21	8/6	8/22	–
	Quota (mm)	74	60	94	109	83	–
Ganjun	Time	5/30	6/21	7/16	8/1	8/17	9/1
	Quota (mm)	88	60	71	97	62	66
Shangsan	Time	6/6	6/30	7/23	8/7	8/23	9/7
	Quota (mm)	79	60	89	92	70	63
Huazhaizi	Time	–	6/20	7/20	8/4	–	–
	Quota (mm)	–	118	70	158	–	–
Anyang	Time	–	6/12	7/12	8/8	–	–
	Quota (mm)	–	114	159	152	–	–
Yingke	Time	6/7	6/24	7/22	8/10	8/29	–
	Quota (mm)	77	60	109	108	84	–
Nijiaying	Time	5/29	6/18	7/15	7/30	8/14	8/29
	Quota (mm)	87	60	62	85	61	61
Xiaotun	Time	5/25	6/12	7/8	7/23	8/7	8/22
	Quota (mm)	73	60	60	85	78	60
Pingchuan	Time	5/30	6/16	7/14	7/29	8/13	8/28
	Quota (mm)	60	60	72	100	70	63
Liaoquan	Time	5/27	6/14	7/9	7/24	8/8	8/23
	Quota (mm)	60	60	60	88	71	66
Xinhua	Time	5/30	6/18	7/13	7/28	8/12	8/27
	Quota (mm)	76	60	62	84	61	61
Banqiao	Time	5/30	6/16	7/8	7/24	8/7	8/23
	Quota (mm)	62	60	61	89	69	62
Shahe	Time	6/1	6/19	7/14	7/29	8/13	8/28
	Quota (mm)	74	60	60	89	61	60
Yanuan	Time	–	6/11	7/11	7/27	8/11	–
	Quota (mm)	–	100	71	133	89	–
Sanqing	Time	5/23	6/11	7/6	7/21	8/5	8/20
	Quota (mm)	79	60	60	108	86	63
Liuba	Time	6/4	6/20	7/8	7/23	8/7	8/22
	Quota (mm)	65	60	60	88	65	60
Youlian	Time	5/24	6/12	7/5	7/20	8/4	8/19
	Quota (mm)	71	60	61	95	82	65
Dahuwan	Time	5/21	6/10	7/6	7/21	8/5	8/20
	Quota (mm)	76	60	60	98	87	68
Xinba	Time	5/28	6/13	7/9	7/24	8/8	8/24
	Quota (mm)	82	62	61	101	79	65
Hongyazi	Time	5/26	6/20	7/20	8/4	8/19	–
	Quota (mm)	121	63	103	95	72	–
Luocheng	Time	6/2	6/23	7/23	8/7	8/23	–
	Quota (mm)	113	60	105	65	65	–
Luotuocheng	Time	6/7	6/22	7/19	8/3	8/18	–
	Quota (mm)	78	62	75	81	69	–

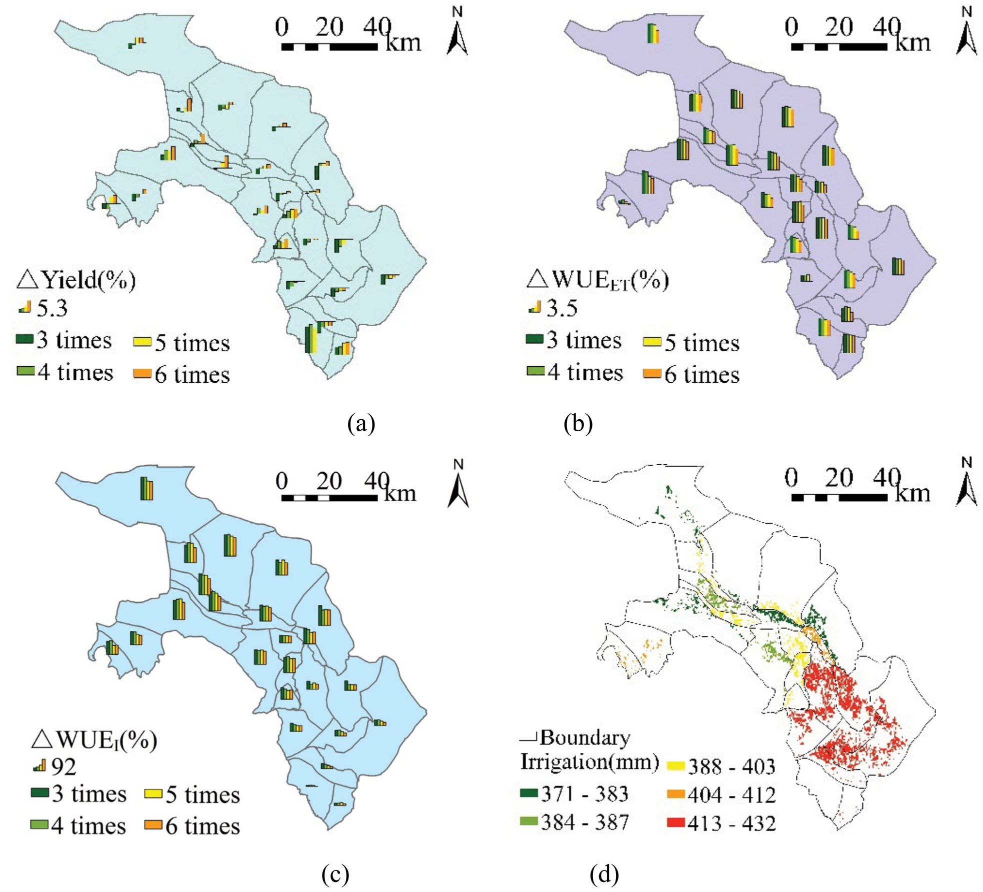


Fig. 9. Spatial distributions of (a) Δyield, (b) ΔWUE$_{ET}$, (c) ΔWUE$_I$, and (d) irrigation quotas for different irrigation districts after optimization.

and WUE$_I$) exhibits an increasing trend, with WUE$_{ET}$ increasing by 4.13%–5.13% and WUE$_I$ increasing by 69%–91% on the average, thus initially achieving the goal of high water productivity in the middle oasis.

Author contributions

Conceptualization, CH and YL; Methodology, CH and YL; Investigation, CH; Data Curation, CH; Writing and Original Draft Preparation, CH; Writing, Review and Editing, CH and BZ.

Acknowledgments

This research was funded by (Chinese National Natural Science Fund), grant number (51822907 and 51979287); (the Fund of China Institute of Water Resources and Hydropower Research), grant number (ID0145B742017 and ID0145B492017). We would like to acknowledge the State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research and National Center of Efficient Irrigation Engineering and Technology Research and Gansu Linze Agricultural Ecosystem National Field Scientific Observation and Research Station for the research grant.

References

[1] H.N. Lu, S.Z. Kang, T.S. Du, L. Tong, R.S. Ding, S.E. Li, Current status and future research trend on water-saving high-efficiency and eco-friendly agriculture, J. Agric., 8 (2018) 155–162.

[2] Y.C. Ge, X. Li, C.L. Huang, Z.T. Nan, A decision support system for irrigation water allocation along the middle reaches of the Heihe River Basin, Northwest China, Environ. Modell. Software, 47 (2013) 182–192, doi: 10.1016/j.envsoft.2013.05.010

[3] J. Zhou, B.X. Hu, G.D. Cheng, G.X. Wang, X. Li, Development of a three-dimensional watershed modelling system for water cycle in the middle part of the Heihe rivershed, in the west of China, Hydrol. Processes, 25 (2011) 1964–1978, doi: 10.1002/hyp.7952.

[4] L.N. Mi, H.L. Xiao, J.M. Zhang, Z.L. Yin, Y.P. Shen, Evolution of the groundwater system under the impacts of human activities in middle reaches of Heihe River Basin (Northwest China) from 1985 to 2013, Hydrogeol. J., 24 (2016) 971–986, doi: 10.1007/s10040-015-1346-y.

[5] Q. Tan, S. Zhang, R. Li, Optimal use of agricultural water and land resources through reconfiguring crop planting structure under socioeconomic and ecological objectives, Water, 9 (2017) 488, doi: 10.3390/w9070488.

[6] B. Yang, X.F. Wen, X.M. Sun, Irrigation depth far exceeds water uptake depth in an oasis cropland in the middle reaches of Heihe River Basin, Sci. Rep., 5 (2015) doi: 10.1038/srep15206, 1–12.

[7] J.M. Zhao, M. Li, P. Guo, C.L. Zhang, Q. Tan, Agricultural water productivity oriented water resources allocation based on

the coordination of multiple factors, Water, 9 (2017) 490, doi: 10.3390/w9070490.

[8] X.P. Guo, S.Z. Kang, Regulated deficit irrigation-a new thought of water-saving irrigation, Water Resour. Water Eng, 4 (1998) 22–27.

[9] H.J. Cai, S.Z. Kang, Z.H. Zhang, H.M. Chai, X.T. Hu, Proper growth stages and deficit degree of crop regulated deficit irrigation, Trans. CSAE, 16 (2000) 24–27.

[10] S.Z. Kang, W.J. Shi, X.T. Hu, Y.L. Liang, Effects of regulated deficit irrigation on physiological indices and water use efficiency of maize, Trans. CSAE, 14 (1998) 82–87.

[11] S.Z. Kang, W.J. Shi, J.H. Zhang, An improved water-use efficiency for maize grown under regulated deficit irrigation, Field Crop Res., 67 (2000) 207–214, doi: 10.1016/S0378–4290(00)00095–2.

[12] Y. Liu, Optimization of irrigation scheduling considering constraints of surface irrigation technology, Trans. CSAE, 19 (2003) 74–79.

[13] Y.R. Wang, X.P. Sun, Shanxi Agricultural Water Saving Theory and Crop Efficient Water Use Pattern, 1st ed., Science and Technology of China Press, Beijing, China, 2003, ISBN: 9787504635648.

[14] S.H. Shang, X.M. Mao, Application of a simulation based optimization model for winter wheat irrigation scheduling in North China, Agric. Water Manage., 85 (2006) 314–322, doi: 10.1016/j.agwat.2006.05.015.

[15] Z.J. Yu, S.H. Shang, Multi-objective optimization method for irrigation scheduling of crop rotation system and its application in North China, J. Hydraul. Eng., 47 (2016) 1188–1196, doi: 10.13243/j.cnki.slxb.20151427.

[16] Y.Q. Wen, S.H. Shang, P. Yang, Optimization of irrigation scheduling for spring wheat with mulching and limited irrigation water in an arid climate, Agric. Water Manage., 192 (2017) 33–44, doi: 10.1016/j.agwat.2017.06.023.

[17] M. Li, Methods and Models for Agricultural Water-Land Resources Multi-Scale Optimal Allocation Based on Uncertainty Analysis, PHD Thesis, China Agricultural University, Beijing, 2017.

[18] C.Y. Han, B.Z. Zhang, H. Chen, Z. Wei, Y. Liu, Spatially distributed crop model based on remote sensing, Agric. Water Manage., 218 (2019) 165–173, doi.org/10.1016/j.agwat.2019.03.035.

[19] B. Zhong, P. Ma, A.H. Nie, A.X. Yang, Y.J. Yao, W.B. Lu, H. Zhang, Q.H. Liu, Land cover mapping using time series HJ-1/CCD data, Sci. China Earth Sci., 57 (2014) 1790–1799, doi: 10.1007/s11430014448775.

[20] B. Zhong, A.X. Yang, A.H. Nie, Y.J. Yao, H. Zhang, S.L. Wu, Q.H. Liu, Finer resolution land-cover mapping using multiple classifiers and multisource remotely sensed data in the Heihe River Basin, IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens., 8 (2015) 4973–4992, doi: 10.1109/JSTARS.2015.2461453.

[21] M.G. Schaap, F.J. Leij, M.T. van Genuchten, A computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions, J. Hydrol., 251 (2001) 163–176, doi: 10.1016/S0022-1694(01)00466-8.Ł.

[22] Y. Jiang, X. Xu, Q.Z. Huang, Z.L. Huo, G.H. Huang, Assessment of irrigation performance and water productivity in irrigated areas of the middle Heihe River basin using a distributed agrohydrological model, Agric. Water Manage., 147 (2015) 67–81, doi: 10.1016/j.agwat.2014.08.003.

[23] J. Wen, J.S. Li, Z. Wang, Y.F. Li, Modelling water flow and *Escherichia coli* transport in unsaturated soils under drip irrigation, Irrig. Drain, 66 (2017) 738–749, doi: 10.1002/ird.2142.

[24] S.H. Shang, System Analysis of Water Resources: Methods and Applications, 1st ed., Vol. 130, Tsinghua University Press, Beijing, China, 2006, ISBN: 978–7-302-11961-6.

[25] T.L. Fan, B.A. Stewart, W.A. Payne, Y. Wang, S.Y. Song, J.J. Luo, C.A. Robinson, Supplemental irrigation and water–yield relationships for plasticulture crops in the Loess Plateau of China, Agron J., 97 (2005) 177–188, doi:10.1051/agro:2004062.

[26] J.H. Holland, Adaptation in Natural and Artificial Systems, USA; LONDON, ENGLAND, UK, 1992, pp. XV+211P.

[27] K. Deb, A. Pratap, S. Agarwal, T. Meyarivan, A fast and elitist multiobjective genetic algorithm: NSGA-II, IEEE Trans. Evol. Comput., 6 (2002) 182–197, doi: 10.1109/4235.996017.

[28] Q. Zheng, Elitist Non-dominated Sorting Genetic Algorithm and Its Application, Master's Thesis, Zhejiang University, Zhejiang, 2006.

[29] Y. Gao, Non-dominated Sorting Genetic Algorithm and Its Application, Master's Thesis, Zhejiang University, Zhejiang, 2006.