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Optimizing irrigation and drainage by considering agricultural hydrological process in arid farmland with shallow groundwater

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ABSTRACT

Agricultural production in arid and semi-arid area faces a global problem of water resources shortage and land salinization. Irrigation and drainage are the important measure to enhance crop yield and control soil salinity. Generally, at field scale only irrigation is optimized to pursue the higher water use efficiency and crop yield, while drainage is difficult to optimize owing to controlled by dynamic groundwater levels. Here, we develop a new collaborative optimization model of irrigation and drainage to improve irrigation water use efficiency and to control soil salinity. The model is formulated by integrating simulation of physical processes of field water - salt balance and a genetic algorithm-based optimization model. The new model is to search optimized irrigation and drainage strategic decision for enhancing field economic benefit with the condition controlling salinity with limited water resources. Then, a case study on optimally allocating irrigation and drainage water to different growth stages of maize field in the Hetao Irrigation District, arid area of northwest China shows enhanced applicability of the developed model. Five groundwater depth levels (1 m, 1.5 m, 2 m, 2.5 m and 3 m) and five groundwater salinity levels (2 g/L, 2.25 g/L, 2.5 g/L, 2.75 g/L and 3 g/L) are provided to show and compare the solutions of the optimal irrigation and drainage water allocation. Results indicate the developed model can supply reasonable field monthly irrigation and drainage decision with considering field hydrology, especially contribution of groundwater to crop water demand and groundwater role to soil salt accumulation. The contrary relationship between system benefit and irrigation water use efficiency was described successfully by the developed model. And compared with traditional single irrigation optimization model, the developed irrigation-drainage collaborative optimization model can enhance drainage function to keep the optimal groundwater levels and improve the system benefit by 0–8%. Overall, the developed model can provide more applicable irrigation water and drainage strategies to the sustainable development of irrigation agriculture.

1. Introduction

Increasing the crop yield is essential to meet the challenges of population growth and increased food demand (Boyer et al., 2012), while farmers in arid areas are facing increasing irrigation water resources shortage as the limited precipitation. Improving irrigation water productivity is a vital step for increasing more agricultural products with limited irrigation water resources (Surendran et al., 2016). It is noteworthy that soil salinity is another serious problem beside limit irrigation resources faced by irrigation agriculture in arid and semi-arid irrigated areas (Asgari et al., 2012; Mosaffa and Sepaskhah, 2019; Wichelns and Qadir, 2015). Lots practices have showed effective drainage management can improve field salinity (Ritzema et al., 2006). In these cases, there is a limitation for increasing total irrigation water amount, the most contribution of the increase in agricultural production will come from improvement and expansion of irrigation and drainage systems (Schultz et al., 2005). Therefore, it is significant and practical to make effective irrigation and drainage water management strategies for improving agricultural water use efficiency and ensuring sustainable agro-economy development.

It is reported that a large number of optimization models for agriculture water management, including traditional methods, like linear programming, nonlinear programming, dynamic programming (Anwar and Clarke, 2001; Ghahraman and Sepaskhah, 2004; Srinivasa Prasad et al., 2011); uncertain programming methods (Li et al., 2019; Li et al., 2017a,b; Zhang et al., 2019), like interval mathematical programming (IMP), stochastic mathematical programming (SMP), fuzzy mathematical programming (FMP); and artificial intelligence search methods,

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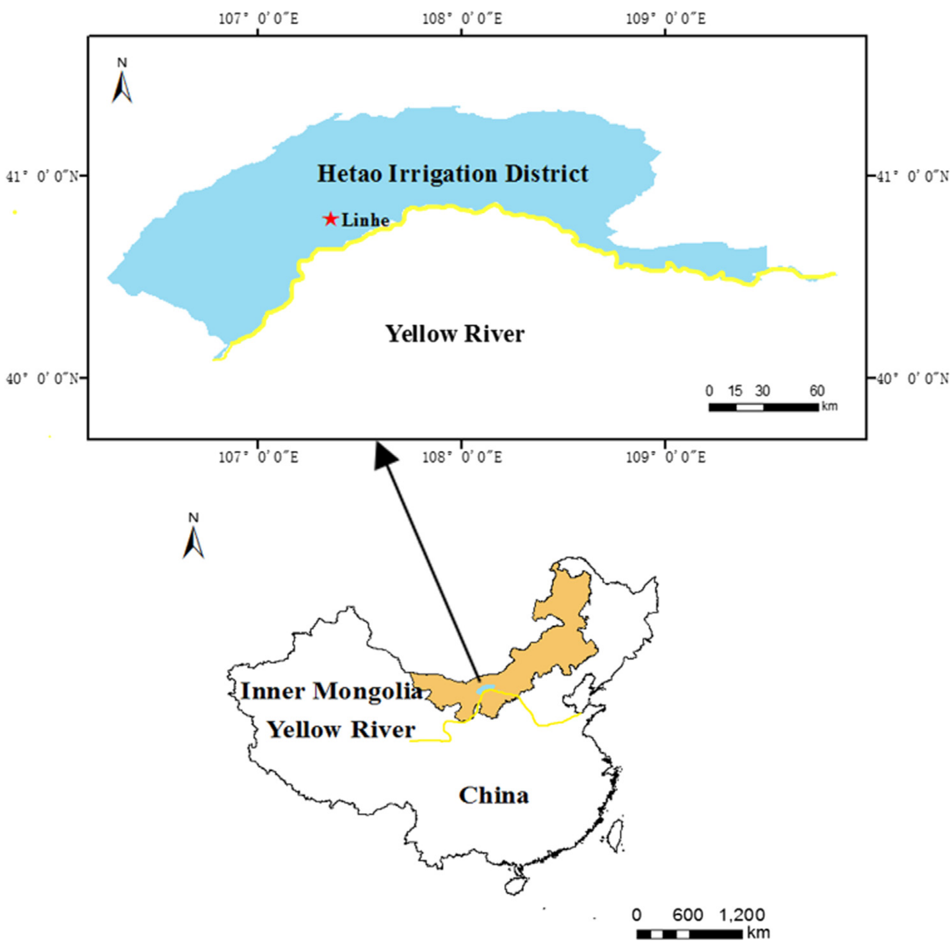

Fig. 1. Location of the study area.

like genetic algorithms (GA), artificial neural network (ANN), ant colony optimization (ACO), particle swarm optimization (PAO), simulated annealing algorithm (SA) (Brown et al., 2010; Hamed Ketabchi, 2015; Safavi and Enteshari, 2016; Safavi and Esmikhani, 2013). These models could obtain the irrigation optimal allocation solutions in irrigation water management. Furthermore, genetic algorithm (GA) is one of the frequently-used algorithms to solve optimization problems for water resource management and has been widely used in irrigation water allocation (Moghaddasi et al., 2010; Wen et al., 2017). It is noted that previous studies about the optimizing agriculture water allocation were limited to conjunctive use of surface water and groundwater for irrigation (Li et al., 2017a,b; Li et al., 2018a,b; Mandare et al., 2008). The impact of shallow-saline groundwater on agricultural production and irrigation-induced environmental problems occurred concurrently with agricultural irrigation water allocation have less attention.

In recent years, more attention has been paid to the contribution of shallow groundwater evapotranspiration to crop evapotranspiration (Ayars et al., 2006; Gao et al., 2015; Huo et al., 2012; Xue et al., 2017). However, the shallow-saline groundwater may lead to accelerated salt accumulation in crop root zone (Karimov et al., 2014; Shah et al., 2011). Much modeling research on the relationship between soil salinization and groundwater depth has been undertaken (Gonçalves et al., 2006; Hammecker et al., 2012; Mirlas, 2012). Given groundwater depth was the main influencing factor of soil salinity (Yu et al., 2010). Moreover, Guang et al. (2012) and Hossain et al. (2011) concluded that land salinization and shallow groundwater level caused the crop yield reduction.

Controlled drainage, also known as drainage water management, is a best management practice to control groundwater level in the crop growth season for increasing crop production (Fisher et al., 1999; Li et al., 2018a,b). A well-planned drainage system can play a buffer role to much shallower groundwater levels. This is consistent with (Ritzema, 2016) conclusion that drainage is an effective tool to prevent soil salinity in arid and semi-arid regions. Riley et al. (2009) showed that crop yield differences between traditional drainage and drainage management. Some studies have shown that controlled drainage may lead to a 10–20%, even 64% increase in maize production (Fisher et al., 1999; Hunt, 1993; Ng et al., 2002). Some simulation models are used to quantitatively describe controlled drainage management in the complex agro-hydrological process (Du et al., 2017; Jouni et al., 2018; Wahba, 2017). Since numerous computer-based model and field experiment may vary depending on scenario analysis, optimization model is needed to obtain the best one strategy in different environments and under different weather conditions (Singh, 2014). Prathapar et al. (1997) developed a hierarchical multi-criterion salt water and groundwater management framework for optimal land uses by minimizing the water table rise and maintaining soil salinity. Singh (2018) applied SaltMod model to evaluate the optimal management strategies for preventing from salinization. To reflect conflicting between agriculture production and ecosystem, irrigation and drainage management should be done simultaneously. However, there are few attempts to develop methods aiming at water allocation in irrigation-drainage collaborative systems.

For arid and semi-arid area, there are two types of decision variables including irrigation water amount and drainage water amount in a subarea of an irrigation-dominated where salinity is one of the major restrictions to the irrigation sustainable development. Therefore, an irrigation-drainage collaborative optimization model is developed for

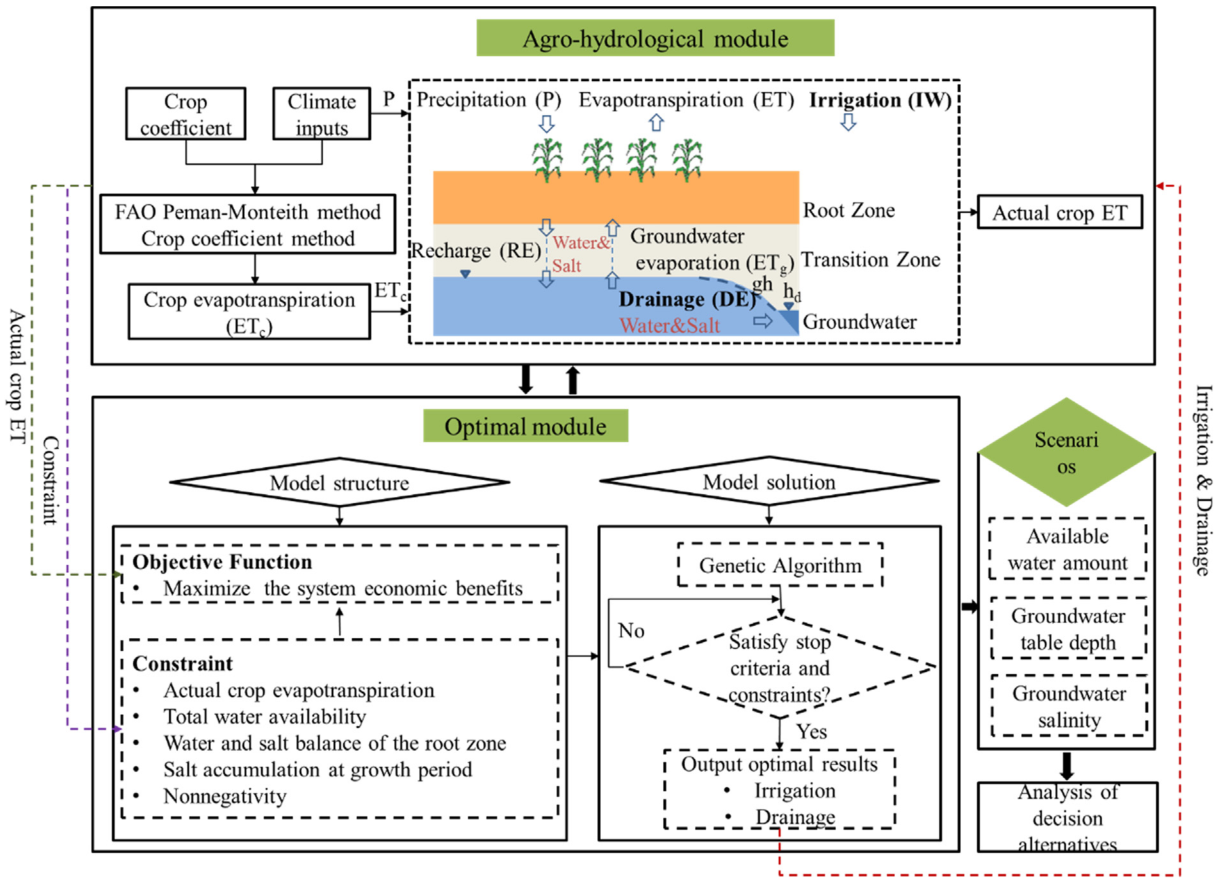

Fig. 2. Decision making framework of irrigation-drainage management. The Agro-hydrological module is incorporated into the Genetic Algorithm as the fitness simulator. Output (actual evapotranspiration) of Agro-hydrological module as input of optimal module is used to calculate economic benefit. Actual ET is a function of dynamic soil moisture and soil salinity. This coupled framework is employed to search for the irrigation and drainage amount that maximize field system economic benefits.

supporting irrigation-drainage water management. The model is coupled an agro-hydrological process in order to better describe complex interactions among crop, soil, water, climate and groundwater within a general optimization model. This model is similar to controlled drainage strategy with effective hydrology-based optimal model. Controlled drainage management focus on simulation models or single drainage, while the specific goal of this research is to allocate limited irrigation water resource and drainage to different growth stages in order to obtain benefit of crop increase. To demonstrate its applicability, the developed model is then applied to a real-world case study in the Hetao Irrigation District, northeast China. Results of optimal irrigation water and drainage allocation under different groundwater levels and groundwater salinity concentrations are generated, which can be used for providing strategies for decision makers to make irrigation-drainage water allocation.

2. Methodology

2.1. Site description

The Hetao Irrigation District (HID) is one of three largest irrigation districts in China, located in upper Yellow River basin (Fig. 1). The HID covers a total area of 10.68 × 10^3 km^2 and more than 60% are the irrigated land (Chen et al., 2020). About 4.7 billion m^3 water is irrigated from the Yellow River every year, with salinity of approximately 0.5 g/L. It is a typical arid or semi-arid agricultural area. Average annual precipitation is 170 mm (mainly happens between June and September) and annual pan evaporation is 2300 mm. Average annual temperature is 8.8 °C while the minimum and maximum are −12.3 °C in January and 23.8 °C in July, respectively (Chen et al., 2018). The topography is relative flat with only 0.2‰ slope. The groundwater is very shallow and the water table depth varies between 0.5 m and 3.0 m within one year period (Liu et al., 2017; Ren et al., 2016). The three major crops in the HID are wheat, maize, and sunflower (Sun et al., 2016). Irrigation water and farmland drainage naturally flow into the drainage canal because of gravity. Poor drainage and soil salinization are a threat to irrigated agriculture in the region. Such irrigation-drainage collaborative management is necessary on irrigated areas.

2.2. Optimization model development

An irrigation-drainage water collaborative allocation system is considered in a maize land which is the largest proration of farmland in the study area. The decision maker is responsible for allocating irrigation water resources and drainage amount in growth stages (April, May, June, July, August and September) for sustainable agricultural irrigation development. Different from other field irrigation decision optimization models (Sepahvand et al., 2019; Soundharajan and Sudheer, 2009; Zhai et al., 2019) irrigation and drainage amount are considered as the decision factors in the developed optimization model. The interactive irrigation water and drainage should be allocated efficiently, especially in arid and semi-arid areas with shallow-saline groundwater. Given shallow groundwater can contribute to crop water requirement and resulted in salt accumulation in root zone, irrigation and drainage can result in various groundwater levels which finally produce different crop yields. In fact, the developed optimization model is to identify the critical groundwater levels by drainage optimization. During the process of irrigation-drainage collaborative allocation, considering the physical soil water and salt process in the study area with shallow groundwater, there are two modules, namely, the agro-hydrological module and the optimal module. In a certain land, farmers pay close attention to the economic benefits of crop yield. The massive response of crop yield to water and salt stress cannot be glossed over in water shortage and soil salinization area. And the crop growth process is a simplified version by considering the stress of temperature, water and salt. We use the soil water and salt balance process to represent water and salt movement in soil. In addition, groundwater water and salt balance are developed for shallow aquifer movement, with various inputs and outputs involving in deep percolation, groundwater evaporation and drainage. The agro-hydrological module can be calculated at a month time step. Finally, crop yield can be generated by the field hydrological model. Maximizing net economic benefit determined by crop yield is the objective of optimal module. The objective should be subject to constraints of water demand, available water supply of Yellow River irrigation water resource and groundwater, and soil salt content threshold. The decision-making framework is depicted in Fig. 2.

2.2.1. Objective function

Based on the subjectivity of farmers, whose aim is to maximize the economic benefits per unit. The objective is to pursue maximized economic benefits which is the difference between the profit from crop yield and water costs. Eq. (1a) represents this concept as an objective function:

$$MaxY = C\cdot Y_m\cdot\left(1-k_y\left(1-\frac{TET}{TET_m}\right)\right)-Cw\cdot\sum_t^T(IW_t/\eta) \tag{1a}$$

where, t is index of the monthly stages, $t = 1, 2, ..., 6$, representing April, May, June, July, August and September, respectively. Y is the system net economic benefit per ha for the farmers (Yuan ha^{-1}); C is the crop net price with consideration of crop market price and the planting costs (Yuan kg^{-1}), in this study, C is average 1.9 Yuan kg^{-1} for maize from local statistical data; Y_m is the maximum crop yield (kg ha^{-1}), Y_m is 10000 kg ha^{-1} for maize from the local survey; $Y_m\cdot\left(1-k_y\left(1-\frac{TET}{TET_m}\right)\right)$ is actual crop yield estimated by the FAO expression (Ren et al., 2016); k_y is yield responses factory (–), indicating the effect of evapotranspiration reduction on production loss, adopting the recommended value in FAO56-1.25 for maize; TET and TET_m are the actual and maximum cumulative evapotranspiration of the total growth stage (mm); Cw is irrigation water price (Yuan m^{-3}); IW is the amount of irrigation per month, mm month^{-1}; η is the utilization coefficient of irrigation water; $\sum_t^T(IW_t/\eta)$ is the gross amount of irrigation during crop growth period (m^3 ha^{-1}).

2.2.2. Constraints

The above objective is subject to the following constraints.

(1) Crop evapotranspiration constraint

Total actual crop evapotranspiration during growth stage is limited to the maximum total crop evapotranspiration. The actual crop evapotranspiration of a certain time period t is also limited to the maximum crop evapotranspiration at time period t.

$$TET \leqslant TET_m \tag{2a}$$

$$ET_t \leqslant ET_{mt} \tag{2b}$$

Moreover, the actual crop evapotranspiration is used to estimate the crop yield depending on the water stress and salinity stress in arid saline region. It is calculated with Eqs. (2c)–(2g) from FAO-56 (Allen et al., 1998; Domínguez et al., 2011):

$$TET = \sum_t^T ET_t \tag{2c}$$

$$ET_t = K_{cbt}\cdot K_{wt}\cdot K_{st}\cdot ET_{0t} \tag{2d}$$

$$K_{wt} = \begin{cases} 0 & \theta_t < \theta_{wpsalt_t} \\ \frac{\theta_t-\theta_{wpsalt_t}}{\theta_c-\theta_{wpsalt_t}} & \theta_{wpsalt_t} \leqslant \theta_t \leqslant \theta_c \\ 1 & \theta_t \geqslant \theta_c \end{cases} \tag{2e}$$

$$K_{st} = \begin{cases} \left(1-\frac{b}{100k_y}\cdot(EC_{et}-EC_m)\right) & EC_{et} > EC_m \\ 1 & EC_{et} \leqslant EC_m \end{cases} \tag{2f}$$

$$\theta_{wpsalt_t} = \theta_{wp} + b\cdot\left(\frac{EC_{et}-EC_m}{100}\right)\cdot(\theta_{fc}-\theta_{wp}) \tag{2g}$$

where ET and ET_m is the monthly actual evapotranspiration and monthly maximum evapotranspiration (mm month^{-1}); ET_O is reference crop evapotranspiration (mm month^{-1}), K_{cb} is the basal crop coefficients, ET_O and K_c are calculated according to the FAO-56 Penman-Monteith approach, and meteorological data were collected from the Linhe meteorological station; K_s is soil salinity stress coefficient (–); K_w is water stress(–); θ is the average soil water content of the root zone (m^3 m^{-3}); θ_{fc} is the soil water content at saturation of the root zone (m^3 m^{-3}); θ_{wp} is the soil water content at wilting point (m^3 m^{-3}), θ_{wpsalt} is the soil water content at wilting point under saline conditions (m^3 m^{-3}); θ_c is the soil water content at the critical point of water stress (m^3 m^{-3}); EC_e is the electrical conductivity of the saturation extract of the soil (dS m^{-1}), and 1 dS m^{-1} = 0.64 g L^{-1} (Abrol et al., 1988; ASCE, 1996); EC_m is the threshold of the electrical conductivity of the saturation extract of the soil (dS m^{-1}); b is the reduction factor (% dS^{-1} m).

(2) Total water availability constraints

The gross amount of irrigation water allocation should not be larger than irrigation water availability during growth period.

$$\sum_t^T(IW_t/\eta) \leqslant Q_{yw} \tag{2h}$$

where, Q_{yw} is the maximum available irrigation water amount, m^3.

(3) Soil water and salt balance of the root zone constraints

The soil water and salt balance model with monthly temporal step describes the change of soil water and salt storage of root zone. The soil water storage of the root zone during a certain time period equals to the soil water storage of the last time period and inflow to root zone minus the outflow. In the HID, the surface runoff can be neglected because of low rainfall and relatively flat topography. Groundwater evaporation must be considered due to an intense exchange between the shallow groundwater and soil water. Inflow to root zone includes irrigation (IW), precipitation (P), groundwater evaporation (ET_g). The outflow includes deep percolation (RE) and crop actual evapotranspiration (ET). There is deep percolation only when the soil water content is greater than the water content at saturation of the root zone. The root zone's water balance is calculated as:

$$W_{t+1} = W_t + P_t + IW_t + ET_{g_t} - RE_t - ET_t \tag{2i}$$

$$W_t = z\cdot\theta_t \tag{2j}$$

where W is the soil water storage (mm month^{-1}); P is the precipitation (mm month^{-1}); IW is the amount of irrigation (mm month^{-1}); ET_g is the groundwater evaporation (mm month^{-1}); RE is the deep percolation (mm month^{-1}); ET is the evapotranspiration (mm month^{-1}), and z is the depth of root zone, here z = 1 m.

Table 1
Maximum maize evapotranspiration in different month.

Month	Apr	May	Jun	Jul	Aug	Sep	Total
maximum evapotranspiration (mm)	16.86	85.77	169.36	240.90	179.32	38.05	730.26

Groundwater water balance (Eq. (2k)) is used to get monthly groundwater table depth. Groundwater may flow along several different pathways, including vertical groundwater evaporation, horizontal drainage and deep seepage from the root zone. Groundwater evaporation is estimated as an empirical function of groundwater table depth and the water evaporation (Xu et al., 2010), as follows:

$$1000\cdot\mu\cdot(gh_{t+1} - gh_t) = (ET_{gt} - RE_t + DE_t) \tag{2k}$$

$$ET_g = a\cdot e^{-b\cdot gh_t}\cdot E_{0t} \tag{2l}$$

where μ is the specific saturated soil water content (Hao et al., 2013), indicating the volumetric fraction of water yielded by a given aquifer under gravity, $\mu = 0.07$; *gh* is the groundwater table depth (m); *DE* is the drainage; a and b are dimensionless empirical parameters related to soil type, land use, and vegetation obtained from experimental data of the Shahaoqu experimental station, a = 1.81, b = −1.42 (Xu et al., 2010); E_0 is the open water evaporation (mm month^{-1}).

Salt transports with soil water flow in vertical soil profile of root zone. The downward movement of salt is caused by deep percolation, while the upward movement is caused by capillary rise from groundwater. When we calculated the salinity of groundwater, it is assumed that groundwater salinity concentration changes in the major fluctuation range of groundwater table. For the groundwater, the salt input is due to the percolation from root zone, while the output is due to the drainage. The salt balance in the soil and the groundwater is calculated as follows:

$$RS_{t+1} = RS_t + IW_t\cdot Sy + ET_{g_t}\cdot Sg_t - RE_t\cdot Sc_t \tag{2m}$$

$$GS_{t+1} = GS_t - (ET_{g_t} + DE_t)Sg_t + RE_t\cdot Sc_t \tag{2n}$$

$$GS_{t+1} = (Zg + gh_t - gh_{t+1})Sg_{t+1} \tag{2o}$$

where *RS* is the soil salt storage (mg m^{-2}); *Sy* is the salt concentration of the irrigation water (mg L^{-1}); *Sg* is the salinity concentration in the groundwater (mg L^{-1}); *Sc* is the salt concentration of the soil (mg L^{-1}); *GS* is the salt storage of groundwater (mg m^{-2}); *Zg* is the difference between the groundwater table depth and the depth that groundwater fluctuations cannot reach (mm).

(4) Salt accumulation at the end of growth period constraint

We assume that salt accumulation should not exceed 640 mg L^{-1} during the growth stage for the agriculture sustainable development (Li, 2017).

$$Sc_{end} - Sc_{ini} \leqslant 640 \tag{2p}$$

(5) Nonnegativity constraint

All the decision variables of the model should not be negative. The constraint can be expressed as:

$$IW_t,\ \ DE_t \geqslant 0\ \ \forall\ t \tag{2q}$$

Irrigation decision could be restricted by multiple factors, such as constraints on water resources and groundwater depth. Different available water resources and groundwater depth scenarios have different effects on irrigation-drainage decisions. 6 different maximum available irrigation water amount (3000 m^3/ha, 3300 m^3/ha, 3600 m^3/ha, 3900 m^3/ha, 4200 m^3/ha, 4500 m^3/ha) scenarios, 5 different groundwater depth scenarios (1 m, 1.5 m, 2 m, 2.5 m, 3 m) and 5 different groundwater salinity scenarios (2 g/L, 2.25 g/L, 2.5 g/L, 2.75 g/L, 3 g/L) were set.

2.3. Model solution. Genetic algorithm

Genetic algorithm (GA) is a heuristic search method based on the evolutionary mechanisms of natural selection and genetics (Holland, 1975). GA has recently received enough attention and successfully been used to many complex optimization problems (Liu, 1998).

2.4. Data collection

Table 1 shows the maximum maize evapotranspiration in different month. The maximum maize evapotranspiration considered to potential crop evapotranspiration is calculated as$ET_m = K_c\cdot ET_0$, K_c is the crop coefficient with different values at different growing stages which can be calculated according to the FAO-56, ET_0 is the reference crop evapotranspiration (mm) calculated by the FAO Penman-Monteith methods. The required meteorological data were from the Linhe meteorological station (Fig. 1). Table 2 presents the basic input parameters of the model, including all parameters of optimal module and agro-hydrological module. These parameters in optimal module are acquired from government reports and statistical data. And the used parameters in agro-hydrological module were obtained from (Xue et al., 2018).

3. Results

3.1. Optimal results of total irrigation and drainage with various groundwater levels and salinity

Fig. 3 shows the optimal irrigation allocation, drainage and system benefit (objective function values) under different maximum available irrigation water amount levels and groundwater depths. Generally, irrigation and drainage allocation are closely linked with the maximum available irrigation water amount and groundwater depth. In a certain groundwater depth, with an increased available irrigation water amount, the value of irrigation and drainage water allocation shows an increasing trend, and system benefit experienced a rapid-increasing trend first and then kept a slow-increasing trend. It is obvious that the optimal irrigation water allocation reached the maximum available irrigation water amount level. Taking 1.5 m of groundwater depth scenario as an example, the optimal irrigation water allocation increases

Table 2
Basic related input parameters.

Parameter	Value
Optimal module	
maximum crop yield (kg/ha)	10,000
net price (Yuan/kg)	1.9
Water price (Yuan/m^3)	0.083
yield responses factory, k_y	1.25
Agro-hydrological module	
the threshold of the electrical conductivity of the saturation extract of the soil, EC_{et} (dS/m)	2
the reduction factor, b (%/(ds/m))	12
the specific saturated soil water content	0.12
the soil water content at saturation of the root zone (m^3/m^3)	0.36
the soil water content at wilting point (m^3/m^3)	0.10
the salt concentration of the irrigation water(g/L)	0.50

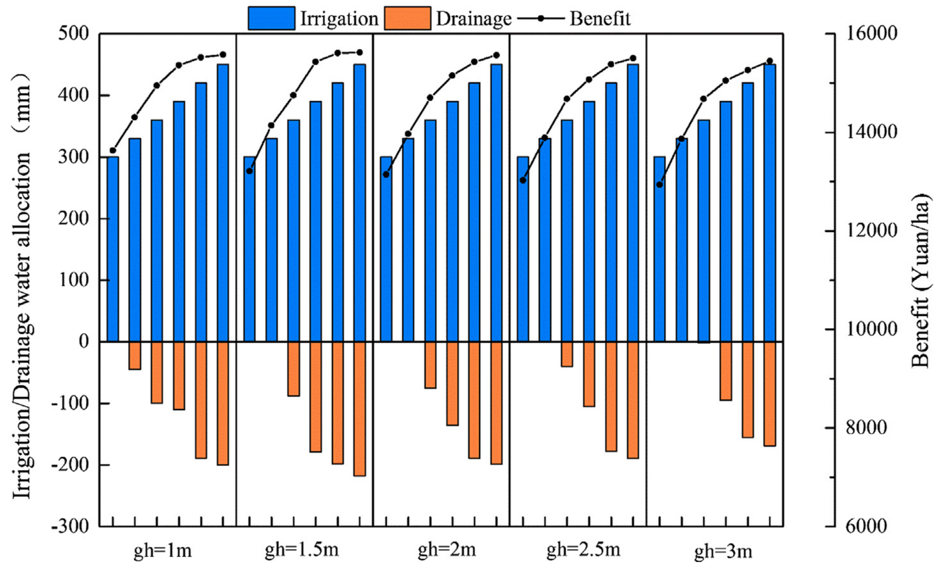

Fig. 3. Irrigation, drainage water allocation and system benefit at different maximum available irrigation water amount levels and different groundwater depth (gh).

from 300 mm to 450 mm, drainage allocation increases from 0 mm to 218 mm, and system benefit increases from 13,212 Yuan/ha to 15,623 Yuan/ha when the maximum available irrigation water amount = 3000 m^3/ha to 4500 m^3/ha, respectively. As we expect, no drainage present when the available irrigation water is relative deficit and groundwater depth (gh) is deeper. Specifically, we noticed that there is no drainage under scenarios of gh = 1 m, irrigation water = 300 mm and gh = 1.5, 2, 2.5, 3 m, irrigation water = 300, 330 mm. Field irrigation benefit have significant change with various irrigation amount. As groundwater levels are controlled by drainage, initial groundwater depth has almost no impact to final field irrigation benefit. System benefit grows rapidly from 13190.4 Yuan/ha 15,213 Yuan/ha to averagely with irrigation water from 300 mm to 390 mm, while weak benefit growth experiences when irrigation amount is more than 390 mm. Correspondingly, the drainage decreases with increasing of groundwater depth under smaller irrigation water (< 390 mm), and the maximum drainage is obtained with gh = 1.5 m under larger irrigation water (> 390 mm). The system benefit has the same trend as drainage. At a smaller water supply level (< 390 mm), the system benefit decreased as increasing of groundwater depth, while at a larger water supply level (> 390 mm), the maximum system benefit is obtained with 1.5 m of groundwater depth. For example, the drainage decreases from 100 mm to 2 mm, the benefit decreases from 14,950 Yuan/ha to 14,677 Yuan/ha with irrigation water supply 3600 m^3/ha under different groundwater level scenarios; while the maximum drainage is 198 mm and the greatest benefit is 15,612 Yuan/ha with irrigation water 4200 m^3/ha under gh = 1.5 m.

The irrigation allocation and drainage are also greatly affected by the salinity of groundwater (Fig. 4). The drainage increases with the increase of groundwater salinity and irrigation water supply level, and the increasing magnitude is more obvious with high salinity. The salinity of groundwater has no effect on the drainage when the irrigation amount is deficit. But the drainage is most sensitive to the increase of irrigation when the groundwater salinity is higher (3 g/L). Especially, there is no the drainage with irrigation water of 300 mm and 330 mm when some groundwater salinity is less than 3 g/L, while the drainage is 25 mm, 50 mm under the same irrigation amount with groundwater salinity 3 g/L. Furthermore, the results also demonstrate that the irrigation system benefit increases with the increase of irrigation water amount but benefit change scope is obvious difference for various groundwater salinity. When groundwater salinity is less than 2.75 g/L, full irrigation can enhance averagely the irrigation system benefit from 15,453 Yuan/ha to 15,651 Yuan/ha, while when groundwater salinity is higher than 2.75 g/L, it is from 15,149 Yuan/ha to 15,663 Yuan/ha.

3.2. Optimal monthly irrigation and drainage water allocation

The monthly irrigation-drainage schemes are optimized based on the optimization model. Take the optimal irrigation allocation, drainage and groundwater depth changes under groundwater depth of 1.5 m and groundwater salinity of 2.5 g/L as an example (Fig. 5). The results indicated that the more allocating irrigation water amount promoted the more drainage, influencing the deeper groundwater depth. A large amount of drainage makes the groundwater depth drop sharply, while the irrigation increases resulting in deep leakage to raise groundwater level. And the groundwater depth does not change obviously without drainage. There existed fluctuations of monthly irrigation amount and drainage among different total irrigation quota. From the figure, there is no drainage with less total irrigation quota (300 mm and 330 mm). The optimal irrigation water amount is mainly affected by soil water and salinity stress. When total irrigation quota increases, drainage occurs in the early stage of crop growth which is mainly related to the model salt threshold constraint.

4. Discussion

4.1. Field net water consumption under different irrigation and drainage management

In our study, drainage is managed with irrigation decision. Usually, drainage have higher salinity and can't be used directly. Such, drainage is also considered the water consumption to keep crop within a suitable growth environment. Unlike traditional field water consumption which generally is only field evapotranspiration (Cui et al., 2019; Jiang et al., 2012; Tripler et al., 2011), here, the sum of actual evapotranspiration and drainage was defined as the field net water consumption. As can be seen from Table 3, the averagely field net water consumption increases from 461 mm to 719 mm with irrigation water allocation 300 mm to 450 mm. It is obvious that the field net water consumption under the maximum irrigation water allocation are higher than that under the minimum irrigation water allocation. When irrigation water allocation is smaller (300 mm − 390 mm), every 10% increment of irrigation water allocation results in averagely 39% improvement of system net water consumption and further 15% improvement of system benefit. Increased irrigation water allocation will bring a higher increase rate of system net water consumption and benefit. However, when irrigation

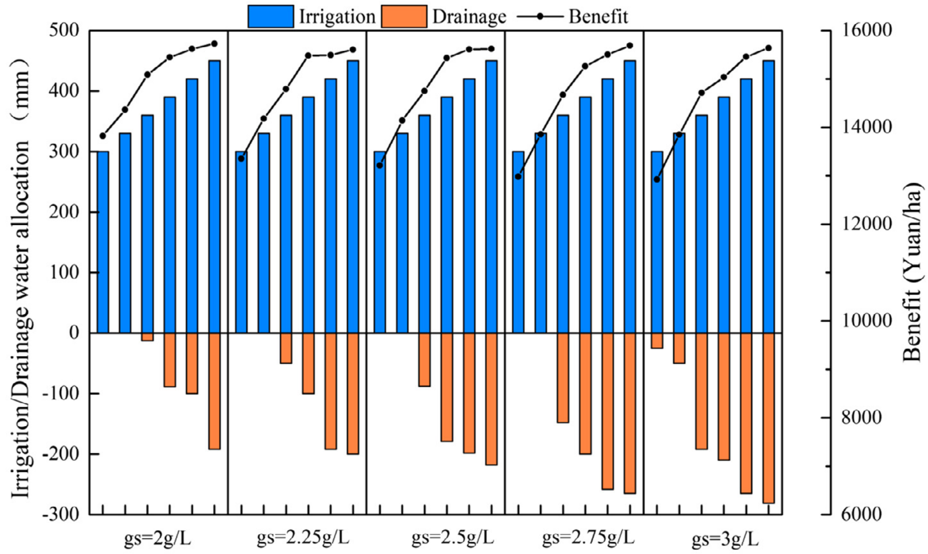

Fig. 4. Irrigation, drainage water allocation and system benefit at different maximum available irrigation water amount levels and different groundwater salinity (gs).

water allocation is larger (390 mm − 450 mm), every 10% increment of irrigation water allocation results in averagely 13% improvement of system net water consumption and only 2% improvement of system benefit. This indicates that full irrigation results in a lot of water consumption but little increment of system benefit. Costa et al. (2007), Karimi and Gomrokchi (2011) and Martínez-Romero et al. (2019) also found that limited irrigation can potentially save agricultural water with no or only slight decline of yield. Thus, in semi-arid regions with shallow groundwater, appropriate deficit irrigation could reduce net water consumption and save water resources without affecting crop growth and income. Moreover, based on the optimized irrigation and drainage management, the net water consumption of maize field shows a slow downward trend with the increase of groundwater depth under smaller irrigation water allocation (< 390 mm). The result is also one

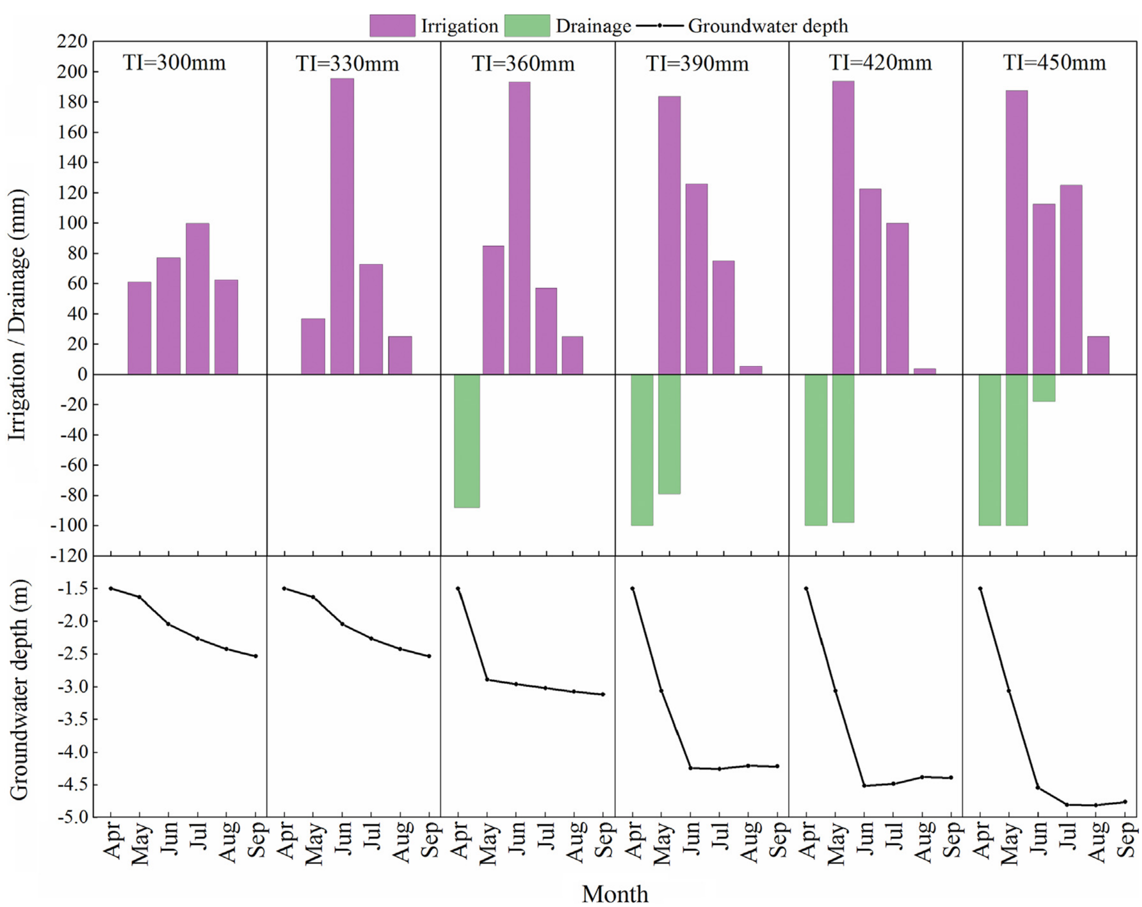

Fig. 5. Irrigation, drainage water allocation and groundwater depth at different month. Note: TI is total irrigation water quota during the growth stage.

Table 3
Field net water consumption at different irrigation water allocation and groundwater depth.

Field net water consumption (mm)	300 mm	330 mm	360 mm	390 mm	420 mm	450 mm
1 m	472.23	535.24	606.90	627.97	711.84	724.06
1.5 m	461.60	483.12	589.90	696.28	722.90	743.88
2 m	459.40	481.30	575.55	648.62	709.28	723.40
2.5 m	456.93	479.44	539.98	615.61	697.09	711.83
3 m	455.17	478.76	500.81	605.01	671.06	690.36

of the reasons which the system benefit decreased as increasing of groundwater depth at a smaller water supply level (< 390 mm) (Fig. 3).

4.2. Response of irrigation water productivity to different irrigation and drainage management

The irrigation water productivity (defined as the value of the output produced per unit amount of irrigation water consumed) shows a decreasing trend with the drawdown of groundwater depth when less irrigation is applied, ranging from averagely 4.34 to 4.20 Yuan/m^3; the irrigation water productivity experiences an increasing trend and then decreasing trend when larger irrigation is applied, ranging from averagely 3.69 to 3.72 Yuan/m^3 and 3.72 to 3.64 Yuan/m^3, respectively (Table 4). Obviously, this range of change is narrow. Groundwater depth of 1.5 m will bring greatest irrigation water productivity is larger when irrigation water allocation is larger (390 mm − 450 mm). The response of irrigation water productivity to salinity of groundwater is different to the response under the condition of groundwater depth. At 300 mm to 450 mm irrigation water allocation, with the increase of groundwater salinity, although the irrigation water productivity shows different trend, it is generally slow downward trend. On the other hand, under 1 m, 1.5 m, 2 m, 2.5 m and 3 m groundwater depth or 2 g/L, 2.25 g/L, 2.5 g/L, 2.75 g/L, 3 g/L groundwater salinity condition, with the increase of irrigation water allocation, the irrigation water productivity shows a averagely 27% decreasing trend. The results are similar to researches of Pereira et al. (2012) and Howell (2006) who stated that water productivity tended to increase with declining of irrigation. Totally, the responses of irrigation water productivity to irrigation water allocation amount were significant than those to groundwater depth and groundwater salinity. The main reason is that could be climate conditions, response of crop yield was highly dependent on irrigation water amount applied because of less precipitation in arid areas.

We found that the irrigation water productivity has a negative correlation with the system benefit. The normalization method is used

Table 4
Irrigation water productivity under different groundwater depth and groundwater salinity (Yuan/m^3).

Groundwater depth (m)	Irrigation water allocation (mm)					
	300	330	360	390	420	450
1	4.544	4.335	4.153	3.939	3.695	3.461
1.5	4.404	4.285	4.098	3.957	3.717	3.472
2	4.381	4.232	4.083	3.885	3.673	3.459
2.5	4.343	4.210	4.077	3.865	3.662	3.445
3	4.312	4.202	4.077	3.858	3.634	3.432
Groundwater salinity (g/L)						
2	4.608	4.352	4.192	3.96	3.719	3.495
2.25	4.450	4.297	4.109	3.970	3.689	3.468
2.5	4.404	4.285	4.098	3.957	3.717	3.472
2.75	4.327	4.199	4.075	3.913	3.691	3.486
3	4.308	4.198	4.087	3.855	3.68	3.475

to transform variables to standard scores bounded by 0.0 and 1.0 (Schenatto et al., 2017). The rate of irrigation water productivity decline and system benefit increase expressed by slope was obtained from their own simple curve, respectively (Fig. 6). As a result, piecewise function with two slopes is used to describe curve characteristic of the system benefit. The slope of the irrigation water productivity curve ranges from −0.0065 to −0.0054 under different groundwater depth and −0.0064 to −0.005 under different groundwater salinity. The slope of the system benefit has a bigger magnitude than that of irrigation water productivity when irrigation water allocation is less, and then this showed no further big magnitude and actually smaller. Overall, these results mean that the growth rate of system benefit is greater than the decrease rate of irrigation water productivity with a certain proportion of irrigation water allocation.

4.3. Effectiveness and superiority of the model

The soil root zone showed desalination with the increase of irrigation water allocation under different groundwater depths (Fig. 7a) and groundwater salinity scenarios (Fig. 7b). From the figure, it is remarkable that the salt will be accumulated in the root zone when irrigation water allocation is less, and the root zone will be desalinated when irrigation water allocation is larger in any case. The accumulated salt content in the root zone during the growing period was mostly in the range of −0.4–0.05 g/kg. This means the highest desalinization achieved is 0.4 g/kg by the irrigation-drainage collaborative optimization model. (Ji, 2017) got conclusion by simulation model that the total salt content of soil increased by 0.29 g/kg with the irrigation allocation 338 mm. Thus, the developed model could effectively alleviate the aggravation of soil salinization.

To further demonstrate the advantages of optimizing the irrigation-drainage collaborative allocation in agriculture water management, a conventional optimal irrigation allocation model (only irrigation water amount is optimized) was also developed to compare the performances between these two models. The objective and constraints of the conventional model are the same as the new developed model. The decision variables are only the irrigation targets in the conventional model. Drainage as a pathway of in which the groundwater may move along can be obtained through the following formula (Tang et al., 2007):

$$DE = \begin{cases} \gamma_d \cdot (h_d - gh) & h_d \geq gh \\ 0 & h_d < gh \end{cases}$$

where γ_d is drainage coefficient, describing groundwater table decrease ratio due to the difference between groundwater table and drainage level, $\gamma_d = 0.04$based on experimental data at the Shahaoqu experimental station in the Hetao irrigation district (Xue et al., 2017); h_d is the bottom level of drainage (m); gh is groundwater depth (m).

Optimized irrigation solutions of conventional irrigation decision model were obtained with 1.5 m and 2 m of the bottom level of drainage under the same groundwater depth and groundwater salinity levels. It can be observed that this change of model structure lead to significant variations of objective values. The system benefits of conventional model would be 12936–15329 Yuan/ha with 1.5 m of the bottom level of drainage under groundwater depth scenarios, and 12936–15401 Yuan/ha with 2 m of the bottom level. Besides, the system benefits of conventional model would be 12751–15537 Yuan/ha with 1.5 m of the bottom level of drainage under groundwater salinity scenarios, and 12834–15572 Yuan/ha with 2 m of the bottom level. Fig. 8 shows the variations in the system benefit under different groundwater depth and groundwater salinity when comparing the conventional model results against the new developed model solutions. The conventional model could achieve lower system benefit under all the scenarios than that of the new developed model. The results show that irrigation allocation schemes without collaborative drainage allocation would lead to 0–4.2% less system benefits under different

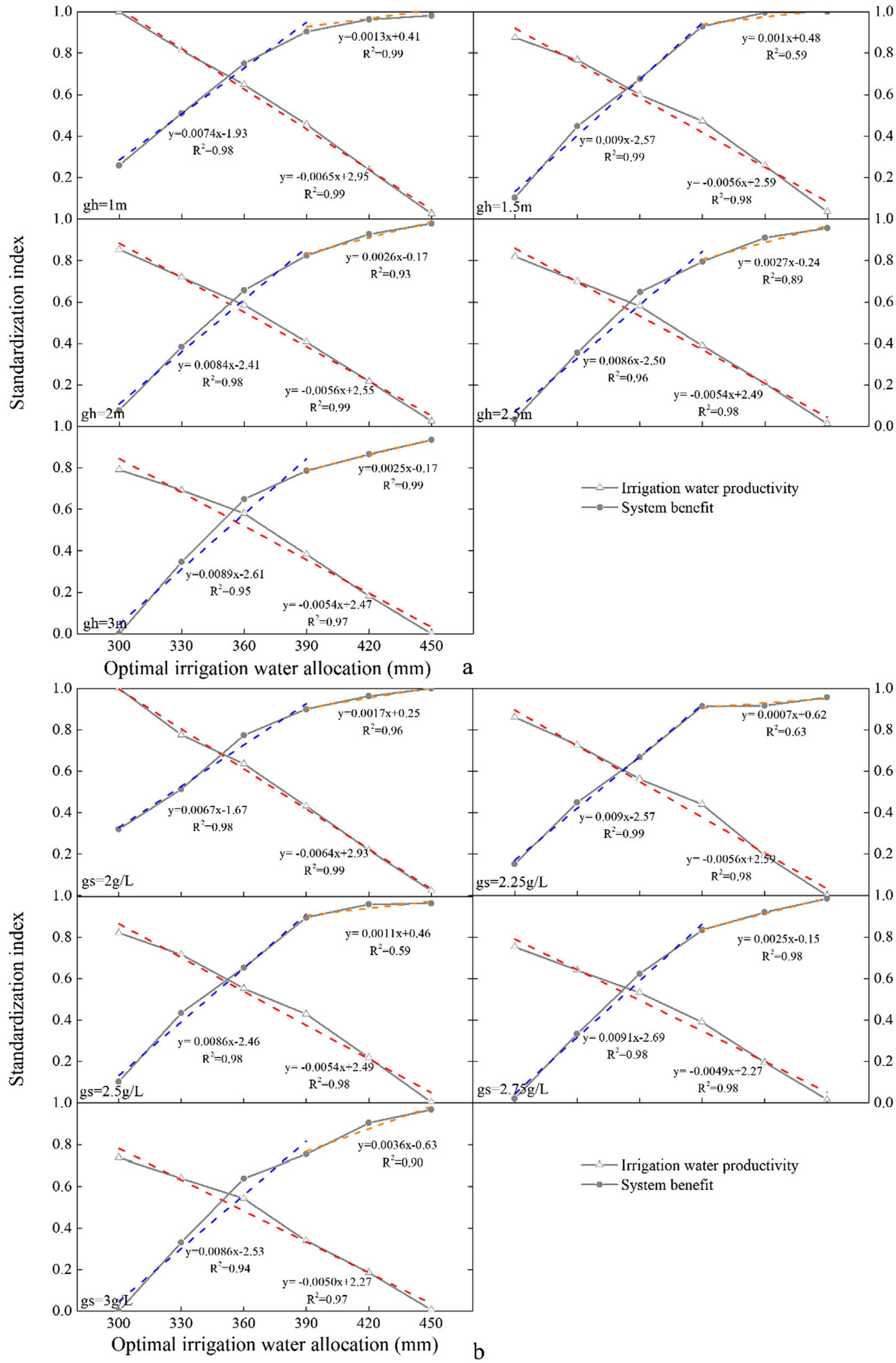

Fig. 6. Standardization index of irrigation water productivity and system benefit under different groundwater depth (a) and groundwater salinity (b).

groundwater depth. While 0–8% less system benefits under different groundwater salinity.

From Fig. 8a, the system benefits under 1.5 m of the bottom level of drainage are higher than that under 2 m of the bottom level of drainage when irrigation water allocation is 300 mm and 330 mm and groundwater depth is 1 m and 1.5 m, respectively. Conversely, the system benefits under 1.5 m of the bottom level of drainage are less than that under 2 m of the bottom level of drainage when irrigation water allocation is more than 330 mm and groundwater depth is 1 m and 1.5 m, respectively. The results demonstrate a higher bottom level

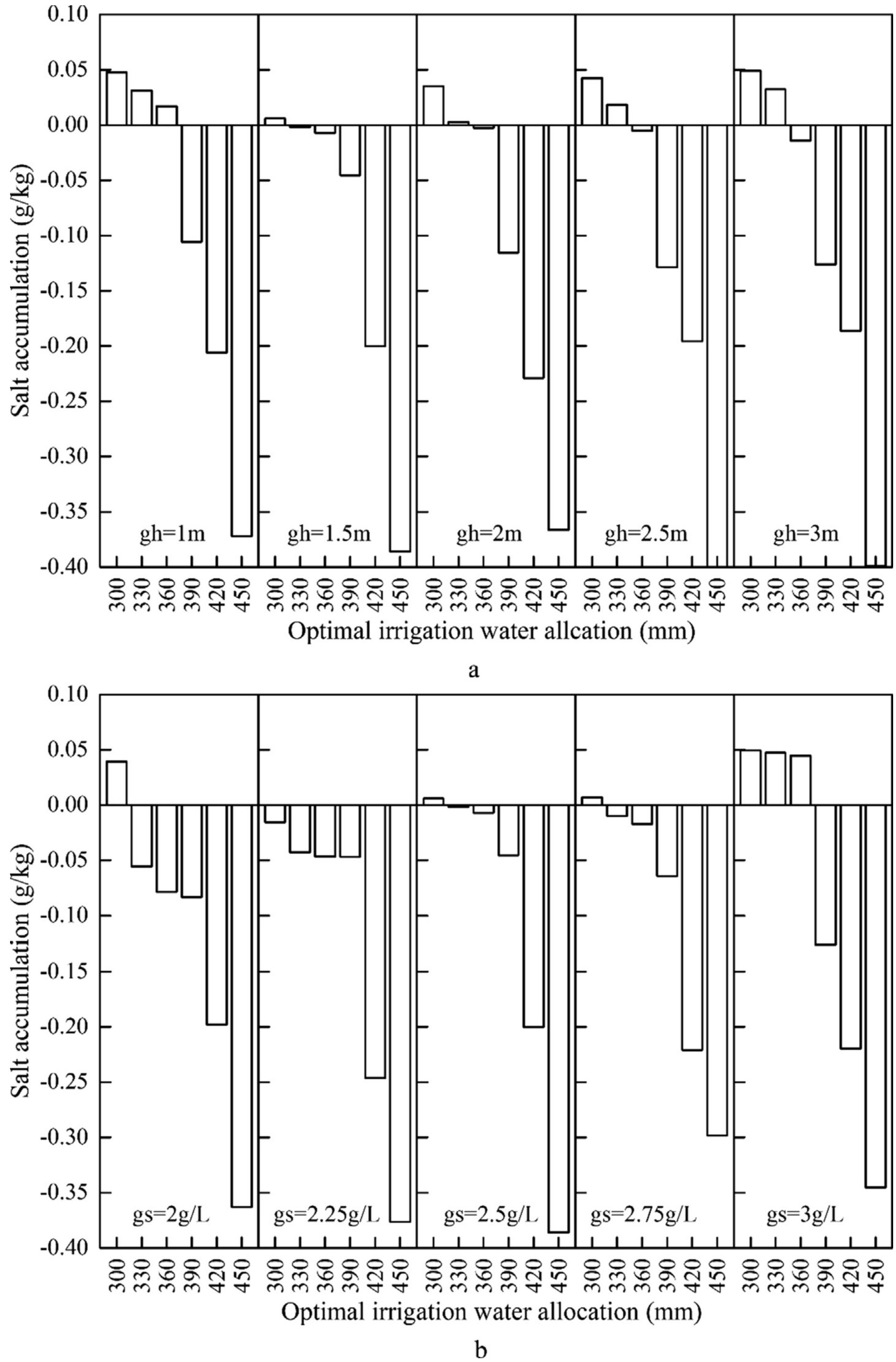

Fig. 7. Salt accumulation under different groundwater depth (a) and groundwater salinity (b). Positive number means salt accumulation, negative number means desalination.

of drainage (1.5 m) with larger drainage would not always lead to a lower system benefits than a lower bottom level of drainage (2m). Additionally, the system benefits have little difference between 1.5 m and 2 m of the bottom level of drainage under deeper groundwater depth conditions. However, the system benefits for shallower groundwater depth are different, which means gave different irrigation strategies with different drainage schemes. This is the same results under different groundwater salinity. Singh (2016) believed that appropriate drainage systems are essential to control salinization problems in irrigated areas. The results from the study also indicate that an acceptable and suitable drainage amount should be decided based on irrigation water allocation and actual situation associated with groundwater depth, groundwater salinity and so on.

Therefore, compared with the conventional optimal irrigation allocation model the established I-D collaborative model has following advantages: (1) It could provide the suitable water allocation schemes to reduce the accumulation of soil salt and the aggravation of soil salinization for enhancing the capacity of agriculture sustainable development; (2) The optimal water allocation schemes obtained by the proposed with higher economic benefit.

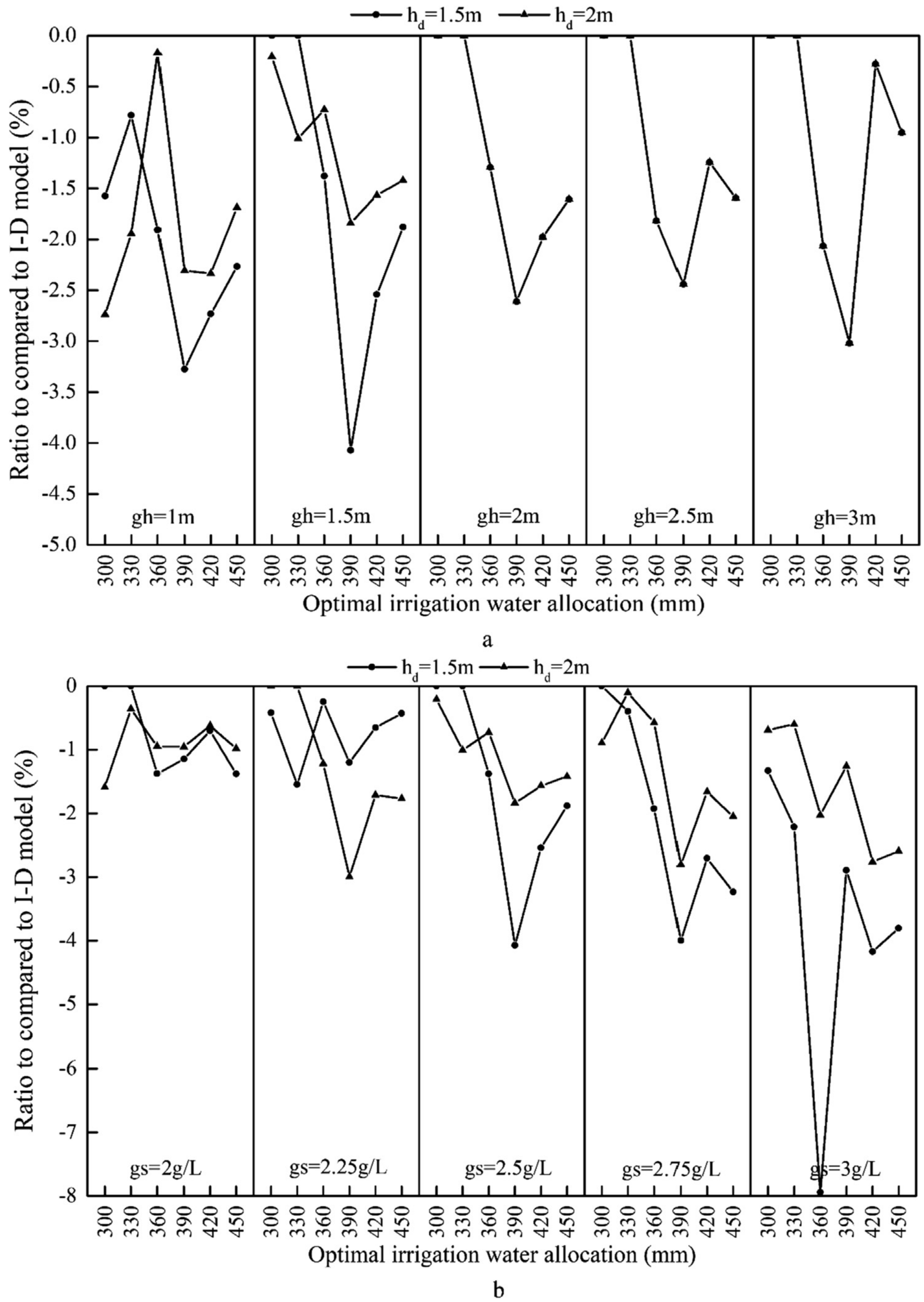

Fig. 8. Comparison of conventional model benefit results against the developed model under different groundwater depth (a) and groundwater salinity (b).

5. Conclusion

An innovative model framework of irrigation-drainage collaborative optimal allocation is developed to enhance field irrigation efficiency and control land salinization in arid and semi-arid area. The framework integrating the agro-hydrological process with optimization model could generate the solutions of irrigation-drainage water allocation associated with various groundwater depth and groundwater salinity scenarios. Compared with previous studies, the new model provides the collaborative irrigation and drainage water allocation alternatives for decision makers who can enhance field irrigation benefit. The results also demonstrate that the proposed model framework is applicable, especially for arid area with shallow groundwater in which agriculture development is closely constrained by water shortage and soil salinization. For the irrigated agricultural area, it is also an important problem to improve irrigation water productivity and other specific objectives. For the irrigated agricultural area, the performance of the developed model depends on field hydrological process which is difficult to apply. In the future study, the innovative model framework should be improved for irrigation area scale, also multiple objectives of economic, productivity and ecology will be considered in our studies.

CRediT authorship contribution statement

Xuemin Li: Methodology, Formal analysis, Writing - original draft. **Chenglong Zhang:** Writing - review & editing. **Zailin Huo:** Conceptualization, Resources, Writing - review & editing, Funding acquisition.

Declaration of Competing Interest

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

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