An ecological stability-oriented model for the conjunctive allocation of surface water and groundwater in oases in arid inland river basins

Zixu Qiao, Long Ma, Tingxi Liu and Xing Huang

ABSTRACT

With the continuous development of the population and social economy, the spatial and temporal distribution of water resources in arid inland river basins is severely uneven, and there is a sharp contradiction between agricultural water use and ecological water use. Irrational development and utilization of water resources has led to many problems, such as shrinking oases and drying lakes. To solve this problem, this study proposes a multiobjective, multiwater-source, ecological stability-oriented double-layer model for optimal allocation of water resources based on the large-scale system decomposition–coordination principle, the water balance principle, and a water supply and demand forecasting model. This model can resolve the contradiction between agricultural water use and ecological water use by optimizing and adjusting the crop planting structure, industrial structure, and the amount of water allocated to and groundwater level in each region and thereby achieve ecological stability and restoration of oases. The developed model was applied to the Heihe River Basin in an inland region of Northwest China. The long-term time series data of 2000–2016 were used to construct and calibrate the model. Finally, the practical ecological stability-oriented plan for conjunctive allocation of surface water and groundwater in different plan years was proposed. This model enriches the research results related to the conjunctive allocation of surface water and groundwater and provides a reference for the ecological restoration of oases in arid inland river basins.

Key words | arid inland river basin, conjunctive allocation, ecological stability-oriented, groundwater, surface water

Zixu Qiao
Long Ma (corresponding author)
Tingxi Liu
Xing Huang
College of Water Conservancy and Civil Engineering College,
Inner Mongolia Agricultural University,
Hohhot 010018,
China
E-mail: *malong4444333@163.com*

HIGHLIGHTS

- This study proposes a multiobjective, multiwater-source, ecological stability-oriented double-layer model for optimal allocation of water resources based on the large-scale system decomposition-coordination principle, the water balance principle, and a water supply and demand forecasting model.
- This model is suitable for conjunctive allocation of surface water and groundwater in oases in arid inland river basins. It can improve the water-use efficiency of the midstream agricultural irrigation districts and realize the ecological stability and restoration of the downstream oases.

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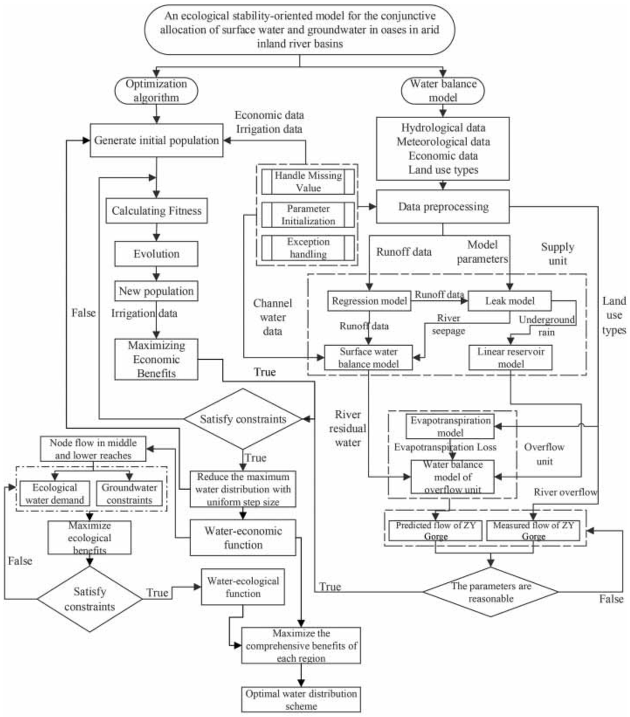
GRAPHICAL ABSTRACT



INTRODUCTION

In the past hundred years, climate change and human activities have had a great impact on water resources and ecosystems. The rapidly increasing global water demand and water shortages have formed a severe contradiction, the frequency of extreme water events has been continuously rising, and the ecological environment has been constantly deteriorating (Xuqiang *et al.* 2012; Junju *et al.* 2015). Rational allocation of water resources, as an effective means to solve these problems, has been extensively studied (Ryu *et al.* 2012; Ahmad *et al.* 2019). However, how to maintain and restore the ecology of oases while achieving coordinated ecological water use and agricultural water use is an urgent scientific problem to be solved in arid inland river basins.

Research on the allocation of water resources first originated from the optimization of reservoir operation in the 1940s. With the development of computer technology, the conjunctive allocation of surface water and groundwater has gradually become diverse and systematic. Relevant studies have been conducted across the globe, and the main research directions include the optimization of agricultural water use, water-use efficiency, and effluent quality. For example, relevant studies have been conducted in the irrigation districts in Colorado (Varzi *et al.* 2019), the irrigation districts in Najafabad (Safavi & Enteshari 2016; Sepahvand *et al.* 2019), Iran, the irrigation districts in Minqin, Gansu (Li & Guo 2014; Ren *et al.* 2019), Heping (Li & Singh 2020), and the midstream region of the Heihe River (Li *et al.* 2015; Yan *et al.* 2019), China, and the irrigation districts in Kasur, Pakistan (Ahmad *et al.* 2019), South Africa (Madende & Grove 2020) and the Mediterranean region (Rossetto *et al.* 2020). These have used a variety of strategies and schemes, including the reduction of the water deficit in irrigation districts (Xiaoling *et al.* 2016), minimization of the salinization in irrigation districts (Yanling *et al.* 2019), improvement of the irrigation water-use efficiency (Madende & Grove 2020), optimization of the crop planting structure (Yan *et al.* 2019; Yanling *et al.* 2019), control of effluent quality (Mou *et al.* 2019). They have also adopted various methodologies, such as system dynamics methods (Ryu *et al.* 2012), crop growth functions (Varzi *et al.* 2019), artificial neural networks (ANNs) (Safavi & Enteshari 2016), genetic algorithms (Safavi *et al.* 2009), the nondominated sorting genetic algorithm II (NSGA-II) (Heydari *et al.* 2016), stochastic programming (Yan *et al.* 2019), artificial fish swarm algorithms (Xiaoling *et al.* 2016), and queuing theory (Muqiang *et al.* 2016). Researches have proposed a series of reasonable water resource allocation schemes and have achieved the main goals of reducing agricultural water demand (Yan *et al.* 2019), improving agricultural water-use efficiency (Safavi *et al.* 2009; Safavi & Enteshari 2016), and controlling effluent quality (Mou *et al.* 2019). With the urbanization process, the techniques for the conjunctive allocation of surface water and groundwater for coordination of urban and rural water use are also constantly developing. For example, urban water demands have been met by water resource allocation in Morocco (Diao *et al.* 2008), Tehran (Karamouz *et al.* 2004) and Zabol (Yao *et al.* 2019), Iran, and regions of North China (Nianlei *et al.* 2014; Mou *et al.* 2019), Beijing (Men *et al.* 2019) and Hengshui City (Nianlei *et al.* 2012), China. In general, worldwide studies on the conjunctive allocation of surface water and groundwater have made great achievements in irrigation districts dominated by agricultural water use and urban regions with balanced domestic, industrial, and agricultural water use but have rarely explored water consumption by natural vegetation and agricultural water use in arid inland river basins.

The water resources of some arid inland river basins are located in mountainous regions; the midstream regions are mostly agricultural irrigation districts, and the downstream regions are mostly oases. These basins are mainly distributed in the Syr Darya and Amu Darya in Central Asia and inland rivers in Northwest China, as shown in Figure 3. The surface water and groundwater in the midstream and downstream regions of a river basin are closely related to each other and capable of mutual transformation, and the ecological environment in these regions is fragile (Leihua *et al.* 2002; Mergili *et al.* 2013). Currently, due to the continuous expansion of the irrigated area in the midstream region, the irrational exploitation and utilization of a large amount of surface water and groundwater drastically reduces the water resources of the downstream regions, making them unable to satisfy the basic water demands of the downstream oases that are dominated by ecological water use and causing a series of problems, such as drying lakes, shrinking oases, intensified desertification processes, drying rivers, and environmental deterioration in the downstream regions (Min *et al.* 2011; Mingjiang & Quan 2014). In the past, the relevant studies in such regions mainly focused on the allocation of water use in agricultural irrigation districts and the reduction of water pollution (Ge *et al.* 2013; Wang *et al.* 2015; Chang *et al.* 2018) but did not explore how to coordinate the ecological restoration and agricultural development by allocation of surface water and groundwater (groundwater level) to achieve the protection and restoration of natural vegetation in the oases. These limitations do not favor resolving the conflict between ecological water demands and ecological restoration in such regions. Therefore, there is an urgent need for studies on the conjunctive allocation of surface water and groundwater in such regions to come up with a new mode of ecological management that can restore and protect oasis ecology with water allocation.

In summary, the goal of this study is to propose an ecological stability-oriented model suitable for conjunctive allocation of surface water and groundwater in oases in arid inland river basins. This model is based on the large-scale system decomposition–coordination principle, the water balance principle and the water supply and demand forecasting model. It can improve the water-use efficiency of the midstream agricultural irrigation districts and conjunctively allocate the surface water and groundwater (groundwater level) at the same time to realize the ecological stability and restoration of the downstream oases. In addition, the application of this model in a typical inland river basin – the Heihe River Basin in Northwest China – enriches the research results of the conjunctive allocation of surface water and groundwater and provides a reference for the ecological stability and restoration of oases in arid inland river basins.

CONJUNCTIVE ALLOCATION MODEL OF SURFACE WATER AND GROUNDWATER

Model principle

The model was established based on the large-scale system decomposition–coordination principle, the water balance principle, and the water supply and demand forecasting model. The large-system decomposition–coordination principle can reduce the dimension of complex large-scale system problems, reduce the time required to solve the complex model, and better coordinate the competing water users, ultimately achieving coordinated ecological and agricultural development and sustainable use of water resources. The main steps of the large-scale system decomposition–coordination principle are as follows. (1) Decompose a large-scale system into several small-scale systems. (2) Use linear programming and other mathematical programming models to solve the bottom layer to ensure the optimal subsystem. (3) Under the requirements of the overall goals and constraints of the top layer, handle the structural relationship between the subsystems, and coordinate the input and output of the subsystems, and finally realize the optimization of the overall system. The water balance principle can improve the feasibility of the allocation scheme by generalizing the response relationship between the surface water and groundwater through models of the surface water balance, linear reservoirs, seepage, and evapotranspiration. The water supply and demand forecasting model uses the quota method to forecast the water supply and demand for water supply projects and water-demanding industries in future plan years, respectively, and it serves as the basis for water constraints.

Model construction

Model design

On the basis of the large-scale system decomposition–coordination principle, the water balance principle and the water supply and demand forecasting model, we constructed a multiobjective, multiwater-source, ecological stability-oriented double-layer model for optimal allocation of water resources. The bottom layer optimizes the water allocation within each subsystem and, by changing the amount of water allocated, establishes a functional relationship between the amount of water allocated to and benefit in each region. The top layer optimizes the water allocation among the subsystems and allocates the water to each subsystem through the overall objectives and constraints. The overall coordination of the subsystems in the two layers is based on the functional relationship between the amount of water allocated to and benefit in each region. Eventually, the conjunctive allocation of the surface water and groundwater is realized in each subregion of the study region, and the use of the water resources in the basin becomes sustainable. The structure of the model is shown in Figure 1.

The bottom layer

Objective function. The ecological stability-oriented conjunctive allocation of surface water and groundwater is mainly for the coordination of economic and ecological benefits. The upstream region (mainly natural systems that are barely developed and exploited) of an arid inland river basin provides the water resources, the midstream region is widely distributed with irrigation districts, and the downstream region is dominated by oases. Therefore, the allocation does not involve the upstream region. The main allocation goal is to increase the economic benefits while improving the agricultural

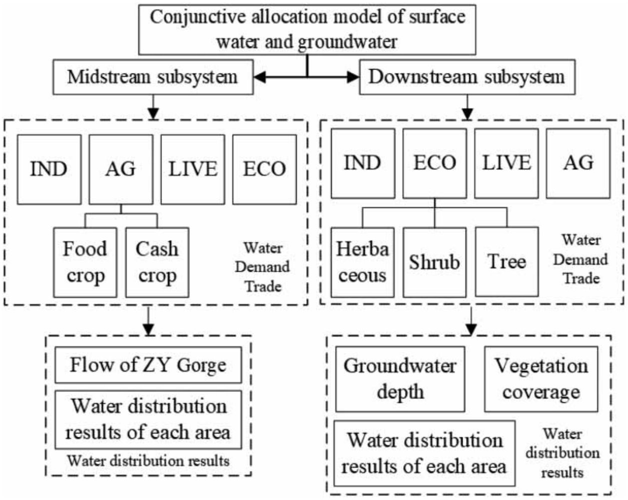


Figure 1 | Model structure. IND means industry; AG means agriculture; ECO means ecology.

water-use efficiency in the midstream region and to ensure the ecological restoration and stability of the oases in the downstream region. The ultimate goal is to realize the sustainable use of the water resources in the basin.

(1) Objective function of the midstream subsystem: maximizing the economic benefits within each subregion.

Agricultural and industrial benefits are the most important economic benefits in the midstream region. The maximization of the agricultural and industrial efficiency is selected as the objective function of the midstream subsystems. The objective function is as follows.

$$\mathrm{f}_1(X_z) = \max\left(\sum_{l=1}^{L}\mathrm{AB}_l + \sum_{l=1}^{L}\mathrm{IB}_l\right) \tag{1}$$

$$\mathrm{AB}_l = \sum_{j=1}^{J}\frac{\beta_n\sum_{n=1}^{N}X_{l1jn}}{e_j}B_jY_{lj} - \sum_{j=1}^{J}\sum_{n=1}^{N}SJ_nX_{l1jn} \tag{2}$$

$$\mathrm{IB}_l = \frac{\sum_{n=1}^{N}X_{l2n}}{IP} \tag{3}$$

where AB_l represents the agricultural benefits of irrigation district l (10,000 yuan); IB_l represents the industrial benefits of irrigation district l (10,000 yuan); N represents the type of water source, and its value is 1 (surface water) or 2 (groundwater); J represents the crop species, and its value is 1 (wheat), 2 (maize), 3 (potato), 4 (other food crops), 5 (oil crops), 6 (vegetable), 7 (Corn for seed), or 8 (other cash crops); L represents the water resource subregion; $\mathrm{f}_1(X_z)$ represents the economic benefit function of the midstream region; B_j represents the unit price of crop j (yuan/kg); Y_{lj} represents the yield of crop j per unit area in irrigation district l (kg/hm^2); X_{l1jn} represents the amount of water allocated to industrial from the type n water source to irrigation district l (m^3); X_{l2n} represents the amount of water allocated to the field from the type n water source to crop j in irrigation district l (m^3); SJ_n represents the unit price of the type n water source (yuan/m^3); e_j represents the irrigation quota of crop j (m^3/hm^2); IP represents the water consumption per 10,000 yuan increase in industrial added value (m^3/10,000 yuan); and β_n represents the water efficiency of the canal system in irrigation district n.

(2) Objective function of the downstream subsystem: the ecological water deficiency is the smallest in each subregion.

In the downstream region in an arid inland river basin, the water demand for socioeconomic development is low. Therefore, the ecological water demand within each subregion is the major concern (Xiaoyou 2006). By using the ecological water allocation in each subregion as the decision variable and representing the ecological benefits with the minimization of the water deficiency in the plants in each subregion, we obtain the objective function as follows.

$$\mathrm{f}_2(\mathrm{X}_x) = \min\left(\sum_{l=1}^{L}\sum_{n=1}^{N}\left(\frac{W_{emn}^{max} - X_{mn}}{W_e^{max}}\right)^2\right) \tag{4}$$

where $\mathrm{f}_2(\mathrm{X}_x)$ represents the downstream ecological benefit function; L represents the water resource subregion; N represents the calculation period, whose value is 1–12, representing 12 months; W_{emn}^{max} represents the ecological water demand in subregion m in month n of the target year (100 million m^3); W_e^{max} represents the total downstream ecological water demand in the target year (100 million m^3); and X_{mn} represents the actual amount of water allocated to subregion m in month n (100 million m^3).

Constraints.

(1) Midstream subsystem constraints

a. Surface water availability constraint

$$\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{j=1}^{J}X_{lij1} < Q_{max} \tag{5}$$

where Q_{max} represents the availability of surface water (100 million m^3) and I represents the water-demanding sector, and its value is 1 (agriculture), 2 (industry), 3 (daily living) or 4 (ecology).

b. Groundwater availability constraint

$$\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{j=1}^{J}X_{lij2} < R_{max} \tag{6}$$

where R_{max} represents the maximum volume of groundwater extracted (100 million m^3).

c. Water diversion constraint

$$\sum_{i=1}^{I}\sum_{j=1}^{J} X_{lij1} < Q_{\text{lmax}} \tag{7}$$

where Q_{lmax} represents the maximum water diversion capacity of the water conservancy project in each irrigation district (100 million m^3).

d. Irrigated area constraint

$$A_{lmax} \geq A_l \geq A_{lmin} \tag{8}$$

where A_{lmax} represents the irrigated area in the base year (hm^2); A_{lmin} represents the minimum irrigated area of each irrigation district (hm^2); and A_l represents the area of water allocation in each irrigation district (hm^2).

e. Food security restrictions

The grain yield should satisfy the food demand in all irrigation districts.

$$\sum_{j=1}^{J}\sum_{n=1}^{N} Y_{lj} X_{l1jn} > P_l N \tag{9}$$

where P_l represents the population in region l (number of persons) and N represents the minimum food requirement per person (kg/person).

f. Minimum agricultural water demand constraint

After the domestic and ecological water demands are met, the irrigation volume should be greater than the minimum agricultural water demand in each irrigation district; that is, the water demand can maintain local food security.

$$\sum_{j=1}^{J}\sum_{n=1}^{N} X_{l1jn} > \mathrm{D}_{min} \tag{10}$$

where D_{min} represents the minimum agricultural water demand (100 million m^3).

g. Maximum discharge constraint

$$Q_z > W_{xmin} \tag{11}$$

where W_{xmin} represents the minimum downstream water demand (100 million m^3) and Q_z represents the discharge at the midstream and downstream nodes.

h. Water-use efficiency constraint

$$E_{jmax} > e_j > E_{jmin} \tag{12}$$

where E_{jmax} represents the water use quota in the base year (m^3/hm^2) and E_{jmin} represents the water use quota in the subsequent plan years (m^3/hm^2).

i. Surface water balance constraint

$$Q(\mathrm{i}, \mathrm{k}+1) = Q(\mathrm{i}, \mathrm{k}) + Q_d(\mathrm{i}, \mathrm{k}) - Q_l(\mathrm{i}, \mathrm{k}) - Q_y(\mathrm{i}, \mathrm{k}) \tag{13}$$

where $Q(\mathrm{i}, \mathrm{k}+1)$ represents the water inflow at node $\mathrm{k}+1$ of the river channel in time period i; $Q(\mathrm{i}, \mathrm{k})$ represents the water inflow at node k of the river channel in time period i; $Q_d(\mathrm{i}, \mathrm{k})$ represents the groundwater overflow at node k in time period i and is given by the groundwater balance model; $Q_l(\mathrm{i}, \mathrm{k})$ represents the water loss between node k and node $\mathrm{k}+1$ of the river channel in time period i, which mainly includes the seepage loss and the evaporation from the river surface; $Q_y(\mathrm{i}, \mathrm{k})$ represents the diversion volume at node k of the river channel in time period i (100 million m^3).

j. Groundwater balance constraint

$$\Delta \mathrm{W} = \gamma_n R_{r,n} + \gamma_n R_{c,n} + R_{f,n} + R_p + R_m - Q_G - Q_d - R_e \tag{14}$$

$$R_{c,n} = (1-\beta_n) Q_{y,n} \tag{15}$$

$$R_{f,n} = (1-\eta_n) Q_{g,n} \tag{16}$$

$$R_p = \partial P A \tag{17}$$

$$R_e = \varepsilon_E A_E ET_0 + \varepsilon_L A_L ET_0 \tag{18}$$

$$\Delta \mathrm{W} = \frac{\mathrm{d}S_t}{\mathrm{dt}} \tag{19}$$

$$Q_{t+\Delta t} = C_s Q_t + (1-C_s)\overline{I_t} \tag{20}$$

where A_E represents the area of vegetation (km^2), A_L represents the area of bare land (km^2), A represents the area of study area (km^2), ε_L represents the evaporation coefficient of bare land (dimensionless), ε_E represents the vegetation transpiration coefficient (dimensionless), ET_0 represents the regional potential evaporation (mm), ∂ represents the precipitation infiltration coefficient (dimensionless), P represents the precipitation (mm), η_n represents the Field Water Utilization Coefficient of irrigation district N (dimensionless), β_n represents the water efficiency of the canal system in irrigation district n (dimensionless), $Q_{y,n}$ represents the diversion volume in irrigation district N (100 million m^3), $Q_{g,n}$ represents the water inflow into the field in irrigation district N (100 million m^3), Q_G represents the volume of groundwater extracted (100 million m^3); ΔW represents the change in the volume of groundwater (100 million m^3), γ_n represents the effective seepage coefficient for river channels and irrigation canals (dimensionless), R_p represents precipitation infiltration (100 million m^3), R_e represents the phreatic evaporation (100 million m^3), $R_{f,n}$ represents the seepage loss in the field (million m^3), $R_{c,n}$ represents the seepage loss in irrigation canals (100 million m^3), $R_{r,n}$ represents the seepage loss in rivers (100 million m^3), Q_d represents the groundwater overflow (100 million m^3), R_m represents the lateral recharge (100 million m^3), S_t represents the storage capacity of groundwater in time period t (m^3), $Q_{t+\Delta t}$ represents the groundwater discharge in time period $t+\Delta t$ (m^3/s), $\overline{I_t}$ represents the average inflow of groundwater (m^3/s) in time period t, and C_s represents the groundwater drainage coefficient (dimensionless).

k. Priority constraints

The domestic and ecological water uses have the highest priority among all water-demanding sectors.

l. Non-negative constraint

The variables in the model are all non-negative variables.

$$X_{lijn}, e_j, A_l \geq 0 \tag{21}$$

(2) Downstream subsystem constraints

a. Total water resource constraint

$$\sum_{m=1}^{M}\sum_{n=1}^{N} X_{mn} \leq Q_{lxs} + Q_g \tag{22}$$

where Q_{lxs} represents the discharge at the midstream and downstream nodes (100 million m^3); and Q_g represents the groundwater availability in the downstream region (100 million m^3).

b. Ecological groundwater level constraint

The ecological groundwater level in the oases should be controlled within a reasonable range. An overly high groundwater level can cause soil salinization. An overly low groundwater level can inhibit the growth of natural vegetation or lead to vegetation death.

$$\mathrm{H_{max}} < d_{mn} - 0.01a\frac{X_{mn}}{A_n} < \mathrm{H_{min}} \tag{23}$$

where d_{mn} represents the initial groundwater level in subregion n during period m (m), a represents the effective seepage recharge coefficient of the groundwater (dimensionless), A_n represents the area of subregion n (km^2), $\mathrm{H_{max}}$ represents the maximum suitable burial depth (m), and $\mathrm{H_{min}}$ represents the minimum suitable burial depth (m).

c. Minimum ecological water demand constraint

$$X_{mn} \geq W_{emn}^{min} \tag{24}$$

where W_{emn}^{min} represents the minimum ecological water demand in all subregions (100 million m^3); namely, the base-year ecological water use.

d. Priority constraint

The priority of domestic water usage should be guaranteed among all water-demanding sectors.

e. Non-negative constraints

The variables in the model are all non-negative variables.

$$X_{mn} \geq 0 \tag{25}$$

Top layer

Objective function. The objective function of the top layer is represented by the maximization of the comprehensive benefit of the basin. The objective function is as follows.

$$\mathrm{F} = \max(F_1(X_z) - F_2(X_x)) \tag{26}$$

where $F_1(X_z)$ represents the dimensionless economic benefit function, $F_2(X_x)$ represents the ecological benefit function, and F represents the comprehensive benefit of the basin.

Constraints.

(1) Water availability constraint

The amount of water allocated to each subsystem should not exceed the total water supply of the drainage basin.

$$X_z + X_x \leq W_{gmax} \tag{27}$$

where W_{gmax} represents the total water availability of the river basin (100 million m^3).

(2) Water allocation constraint

The amount of water allocated to the downstream subsystem is no greater than the discharge at the midstream and downstream nodes.

$$X_x \leq Q_{lxs} \tag{28}$$

where Q_{lxs} represents the discharge at the midstream and downstream nodes (100 million m^3).

(3) Non-negative constraint

The variables in the model are all non-negative variables.

$$X_z \geq 0, X_x \geq 0, W_x \geq 0, W_z \geq 0 \tag{29}$$

Solving the model

The model is solved using a genetic algorithm. The algorithm is shown in Figure 2. The steps are as follows.

(1) Long series water supply data are input into the midstream water balance model, and the least squares method and genetic algorithm are used to determine the model parameters.
(2) The multiyear mean water inflow data and the calibrated parameters of each water balance model are input into the midstream subsystem of the bottom layer to establish the functional relationship between the water inflow and discharge in the midstream region.
(3) The basic data of each irrigation district in each plan year are used as the basis for computation, and the maximum water availability is used as the initial amount of water allocated into the optimization model to calculate the maximum economic benefit, crop planting structures and discharge in each irrigation district in each plan year when the inflow equals the multiyear mean inflow.
(4) The uniform step size of 50 million m^3 is used to reduce the amount of water allocated, the economic benefits corresponding to the different amounts of water allocated in different plan years are calculated, and the water allocation–economic benefit function is determined for the midstream region in different plan years.
(5) The water demand in each downstream subregion in different plan years is determined, and the groundwater level and ecological benefits in each downstream subregion are calculated.
(6) The uniform step size of 20 million m^3 is used to reduce the amount of water allocated, the ecological benefits corresponding to the different amounts of water allocated in different plan years are calculated, and the water allocation–ecological benefit function is determined for the downstream region in different plan years.
(7) The obtained water allocation–economic benefit function and the water allocation–ecological benefit function are used to analyze the comprehensive benefit of the basin, and the amount of water allocated to each subsystem that maximizes the comprehensive benefit of the basin is calculated.

AN APPLICATION EXAMPLE

Overview of the study area

The arid inland river basins have issues regarding upstream water withdrawals, midstream irrigation, and downstream ecological water use of oases. The distribution of arid inland river basins is shown in Figure 3. Figure 3 is generated by ArcGIS. The model developed in this study is applied in a typical arid inland river basin, the Heihe River Basin in Northwest China. The Heihe River Basin is located between 97.1°–102.0° E and 37.7°–42.7° N (Tian *et al.* 2018). According to the current hydraulic connection between the surface water and groundwater, the area can be divided into three independent subsystems: east, middle and west.

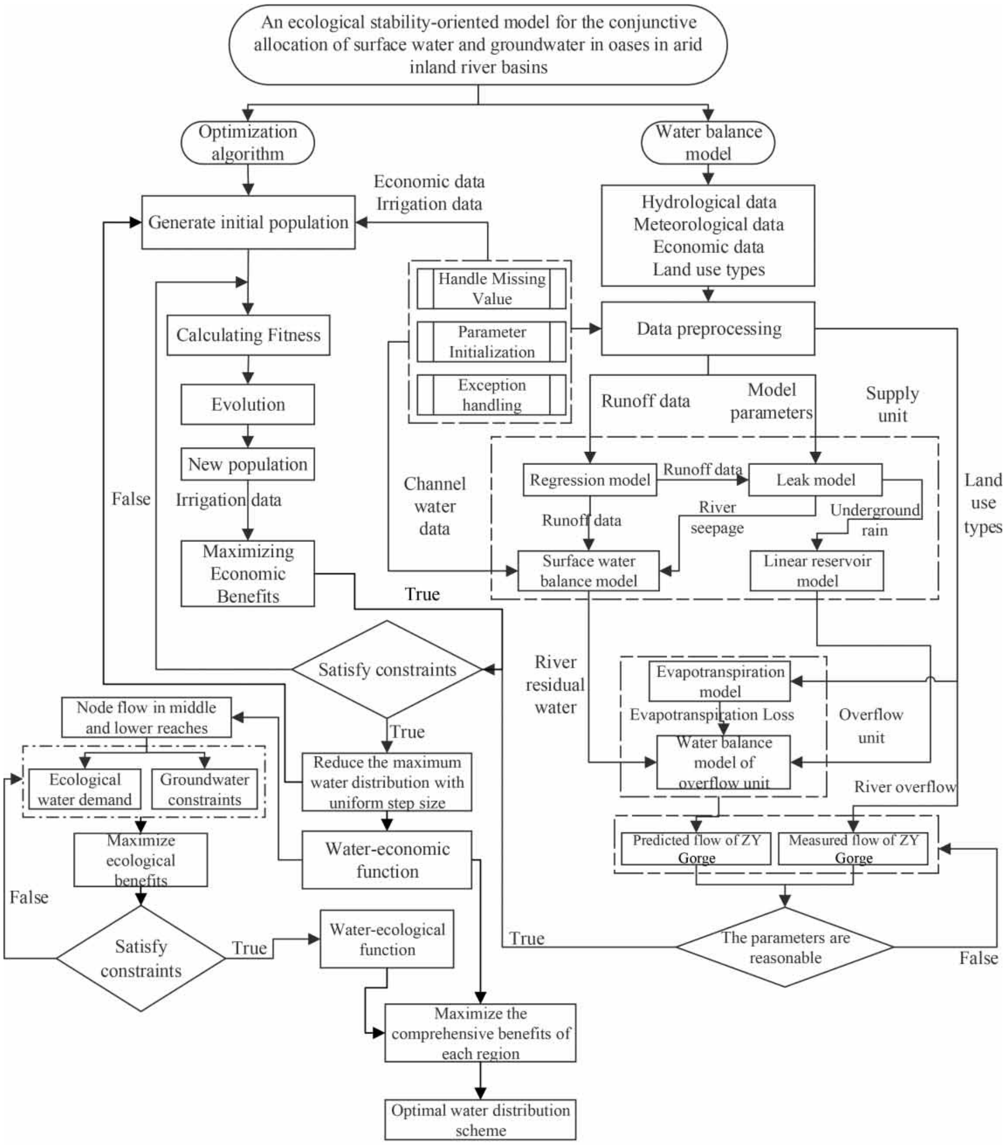


Figure 2 | Algorithm for the conjunctive allocation of surface water and groundwater in the Heihe River Basin.

Water resource partition

The mainstream of the Heihe River flows out of the Yingluo Gorge and flows through Ganzhou, Linze, and Gaotai and merges into the Liyuan River, and the midstream of the Heihe River spans from the Yingluo Gorge to the Zhengyi Gorge. Based on topography and geomorphology, water resources and land use types, the midstream study region is divided into three subregions, i.e., the GZ irrigation district, LG irrigation district, and LYH irrigation district.

The mainstream of the Heihe River flows out of the Zhengyi Gorge, passes through two control sections, Shaomaying and Langxinshan, and then enters the East and West Juyanhai Lakes, respectively. According to the water sources, groundwater depth, and vegetation types, the downstream study region is divided into ten subregions. Figure 4 shows the water resource partition. Figure 4 is generated by ArcGIS.

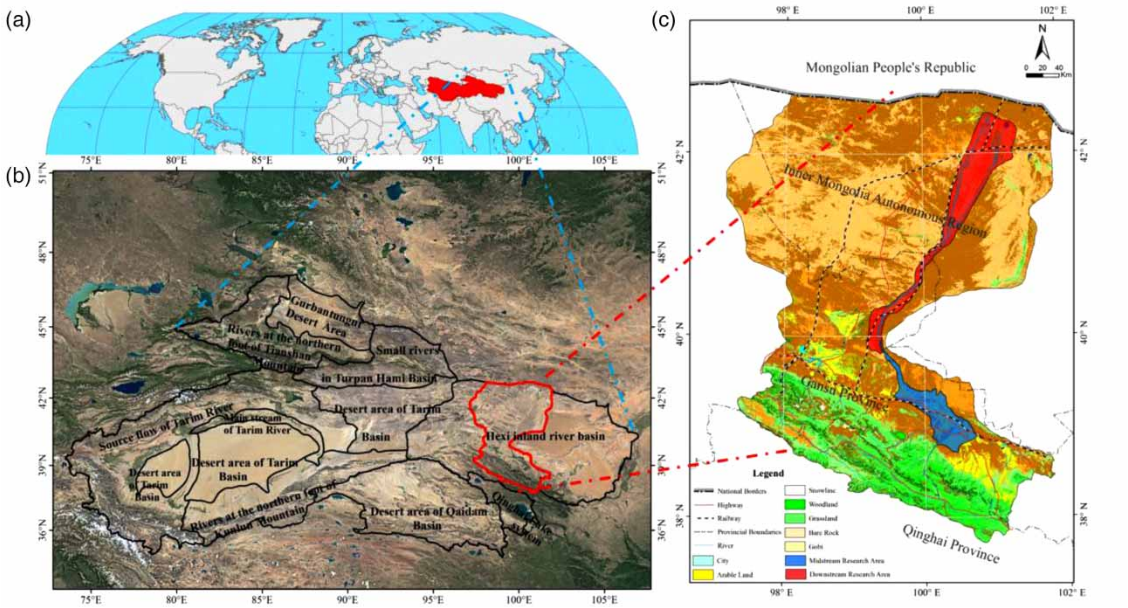


Figure 3 | (a) Distribution of arid inland river basins, (b) inland river basins in Northwest China, (c) Heihe River Basin.

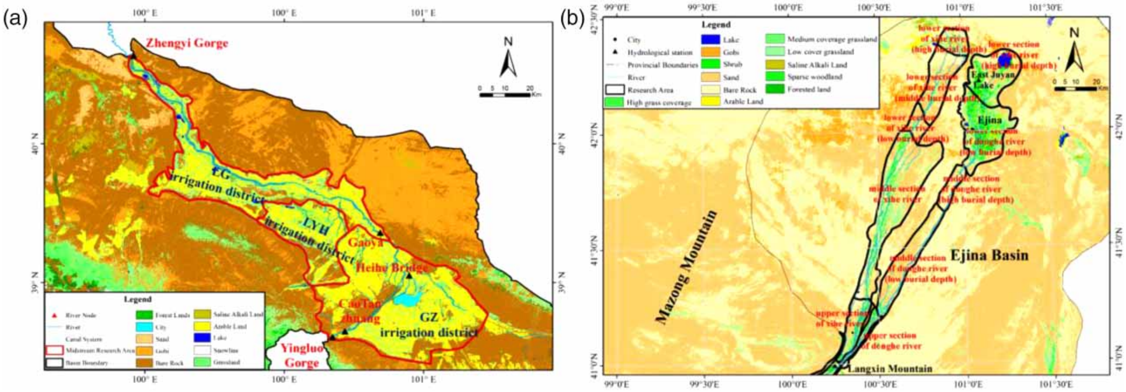


Figure 4 | (a) Water resource partition of midstream, (b) water resource partition of downstream.

Supply and demand forecast

In this study, we used 2016 as the base year and 2035 and 2050 as plan years. Under the premise of ensuring the coordinated development of the economy and ecology for each plan year, we forecast the water supply and demand for each subregion in the midstream and downstream regions of the Heihe River Basin based on the relevant planning.

In the multiyear mean inflow, according to the relevant planning, the surface water availability is 870 million m^3, groundwater availability is 481 million m^3, and the sum of the non-repeated groundwater volume and discharge of the Zhengyi Gorge (Guodong 2009) is used as the total water availability in the downstream study area. The agricultural, industrial, domestic and ecological water demands are calculated using the quota method. According to the relevant documents and planning, such as the Zhangye City Statistical Yearbook, the irrigated area of farmland in the study region is 1,690,500 mu (15 mu = 1 hm^2) in the base year. The base-year crop irrigation quota when the irrigated area is basically unchanged is shown in Table 1. The future crop irrigation quota is determined by the Gansu Province Industrial Water Use Quota (2017). The industrial added value (10,000 yuan) in the base year is 7.062 billion yuan, and the expected annual percentage increment of the industrial added value is 6% from 2016 to 2035 and 4% from 2035 to 2050. In the base year, the total population in the study area is 824,600, and the water use quotas are 199 L/person·d for urban residents and 55 L/person·d for rural residents., The predicted natural population growth rate in 2035 is 5.6 ‰, and the predicted water use quotas are 220 L/person·d for urban residents and 70 L/person·d for rural residents in Heihe River Basin. In 2050, the predicted natural population growth rate is 5.9 ‰, and the predicted water use quota is 240 L/person·d for urban residents and 90 L/person·d for rural residents in Heihe River Basin. According to the 'Short-term plan for management of the Heihe River Basin', the scale of the oases in the Heihe River Basin should be restored to that in the 1980s. In this study, we used the scale of the oases in 1987 as the scale of sustainable development and basic maintenance of the ecological stability of oases. Based on the 1987 and 2016 satellite image interpretation results of the determination, the area of vegetation in the study area is 3,910.41 km^2 in the base year and will be restored to 4,794.6 km^2 in 2035 and 6,481.1 km^2 in 2050. The potential evaporation data were 2000–2016 long series meteorological data obtained from the China Meteorological Data Network (http://data.cma.cn/) and the vegetation and bare land coefficients were determined using the water balance model.

The crop yield per unit area in the study area is shown in Table 2, which was obtained from the Zhangye City Statistical Yearbook. The unit price of the crop obtained from the crop economic benefit survey data from the Agriculture Bureau of Zhangye City is shown in Table 3. The minimum food demand was set at 400 kg/person (Yan *et al.* 2019), the recharge coefficient was set at 0.52 (Xiaoyou 2006); the measured groundwater level in 2016 was used as the initial groundwater level; the price of water with surface water as the source was 0.168 yuan/m^3, the price of water with groundwater as the source was 0.88 yuan/m^3 (Yao 2017); the inflow of the Yingluo Gorge and inflow of Liyuanbao

Table 1 | Crop irrigation quotas in the study area

	Food crop (m^3/hm^2)				**Cash crop (m^3/hm^2)**			
Crop species	**Wheat**	**Maize**	**Potato**	**Other**	**Oil crops**	**Vegetable**	**Corn for seed**	**Other**
Crop irrigation quota	5,531	7,345	5,246	5,305	5,600	6,698	7,334	5,919

Table 2 | Unit crop yield in the study area

	Food crop (kg/hm^2)				**Cash crop (kg/hm^2)**			
Partition	**Wheat**	**Maize**	**Potato**	**Other**	**Oil crops**	**Vegetable**	**Corn for seed**	**Other**
GZ irrigation district	8,100	12,000	14,923	7,536	2,575	60,922	9,500	6,003
LYH irrigation district	7,701	10,450	13,923	7,865	5,850	57,750	10,175	5,873
LG irrigation district	7,850	11,000	15,373	6,024	5,275	63,945	9,475	6,134

Table 3 | Unit price of crops in the study area

	Food crop (kg/yuan)				**Cash crop (kg/yuan)**			
Crop species	**Wheat**	**Maize**	**Potato**	**Other**	**Oil crops**	**Vegetable**	**Corn for seed**	**Other**
Price	2.5	2.2	1.8	2	5.4	1.3	3.8	4.2

were obtained from the Cold and Arid Regions Science Data Center of the Chinese Academy of Sciences; the area of vegetation was obtained through interpretation of Landsat satellite images; meteorological data were obtained from China Meteorological Data Network; the long series water supply data were from the Zhangye City Statistical Yearbook, the Water Resources Bulletin of Gansu Province and Inner Mongolia Autonomous Region, and the water census data.

ANALYSIS OF RESULTS

Calibration and verification of the midstream water balance model

We input the 2000–2016 long series of water supply data into the midstream water balance model. The simulated Zhengyi Gorge runoff process fits well with the actual runoff process, as shown in Figure 5. Figure 5 is generated by Python. For the model training period from 2000 to 2012, the NSE (Nash-Sutcliffe efficiency) coefficient reaches 0.59, and the correlation coefficient reaches 0.8. For the model verification period from 2013 to 2016, the NSE coefficient reaches 0.49, and the correlation coefficient reaches 0.62. The model results are reliable, and the process simulation error is small. Therefore, the model basically meets the requirements of the optimal water resource allocation model. The correlation coefficients from the model calibration are shown in Table 4.

Table 4 | Coefficients of the water balance model

Irrigation district	β_n	γ_n	η_n	C_s	∂	ε_L	ε_E
GZ irrigation district	0.63	0.79	0.84	0.97	0.45	0.06	0.1
LYH irrigation district	0.56	0.85	0.85				
LG irrigation district	0.55	0.81	0.8				

The midstream water balance model shows that from 2000 to 2016, the mean inflow of the Yingluo Gorge and Liyuanbao was 2.047 billion m^3, and the diversion volume of the canal irrigation system was 1.21 billion m^3, 43% of which recharged the groundwater by infiltration. In the composition of the groundwater recharge, 47% came from the canal irrigation system and infiltration of the irrigation water, 45% came from river channel seepage, and the rest came from lateral recharge and precipitation infiltration.

Results of conjunctive allocation of surface water and groundwater

After solving the model, we get the results of conjunctive allocation of surface water and groundwater, as shown in Figure 6 and Figure 7. We found that in 2035, the total amount of water allocated to the midstream region will be 1.311 billion m^3, including 654 million m^3 in the GZ irrigation district, 167 million m^3 in the LYH Irrigation district, and 490 million m^3 in the LG irrigation district, which accounts for 49.89% 12.74%, and 37.37% of the total inflow, respectively. The water allocation results are different in these three irrigation districts due to their differences in crop area, population distribution, and crop yield and unit price. In 2035, the total amount of water allocated to the downstream region will be 1.138 billion m^3,

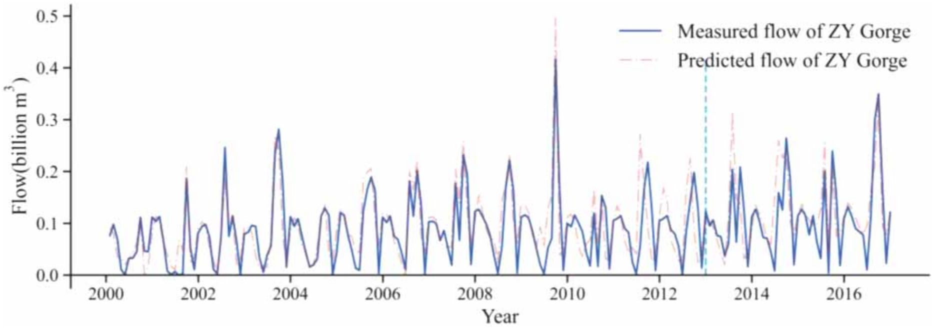


Figure 5 | Fitting results of the predicted values and the measured values.

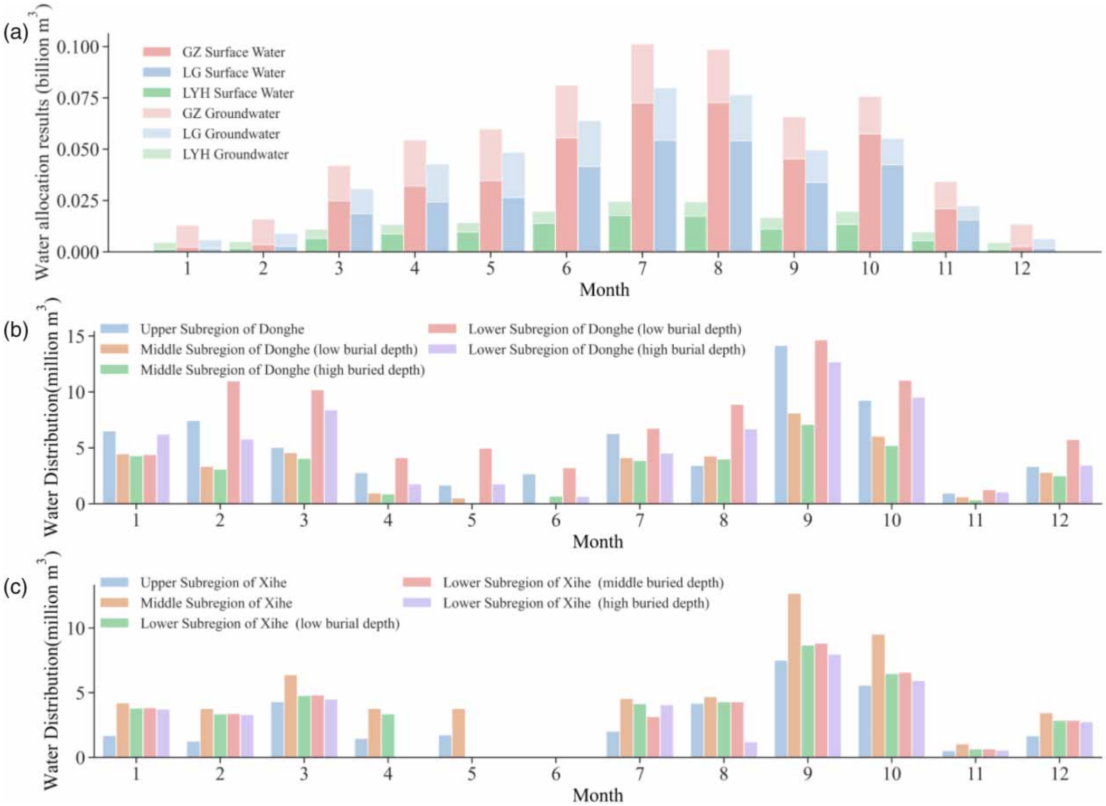


Figure 6 | Results of the optimal allocation of water resources in 2035 (a) midstream region, (b) Donghe region, (c) Xihe region.

including 979 million m^3 surface water and 159 million m^3 groundwater. In the Donghe region, the lower subregion (low burial depth) has the most amount of water allocated, and the middle subregion (high burial depth) has the least amount of water allocated. This is mainly due to the differences in vegetation area and type and groundwater level between these two subregions. The water demands in different subregions are positively correlated with the vegetation coverage and area. The overall water demand pattern in the Xihe region is consistent with that in the Donghe region. Overall, the amount of surface water and groundwater extracted in the midstream and downstream regions of the Heihe River Basin is smaller than the water availability. Such a water withdrawal model can effectively prevent environmental problems such as land subsidence and vegetation degradation and contribute to sustainable development within the basin.

In 2050, the total amount of water allocated to the midstream region will be 1.251 billion m^3 (the amount of groundwater will be 481 million m^3), including 625 million m^3 in the GZ irrigation district, 159 million m^3 in the LYH irrigation district, and 467 million m^3 in the LG irrigation district, which accounts for 49.96%, 12.71%, and 37.33% of the total inflow, respectively. The amount of water allocated to the midstream region in 2050 is smaller than that in 2035. This is because on the one hand, because of the industrial structure transformation in the midstream region, industrial benefits will become the main source of economic income, and on the other hand, to restore the ecology and maintain ecological stability in the downstream region, more water needs to be allocated to the oases. In 2050, the total amount of water allocated to the downstream region will be 1.209 billion m^3, including 1.05 billion m^3 surface water and 159 million m^3 groundwater, and the amounts of water allocated to the Donghe region and Xihe region will be 472 million m^3 and 231 million m^3. The overall water allocation pattern in 2050 is consistent with that in 2035. Overall, the amount of water allocated to each subregion is smaller than the water availability. This is conducive to the sustainable use of water resources in the Heihe River Basin.

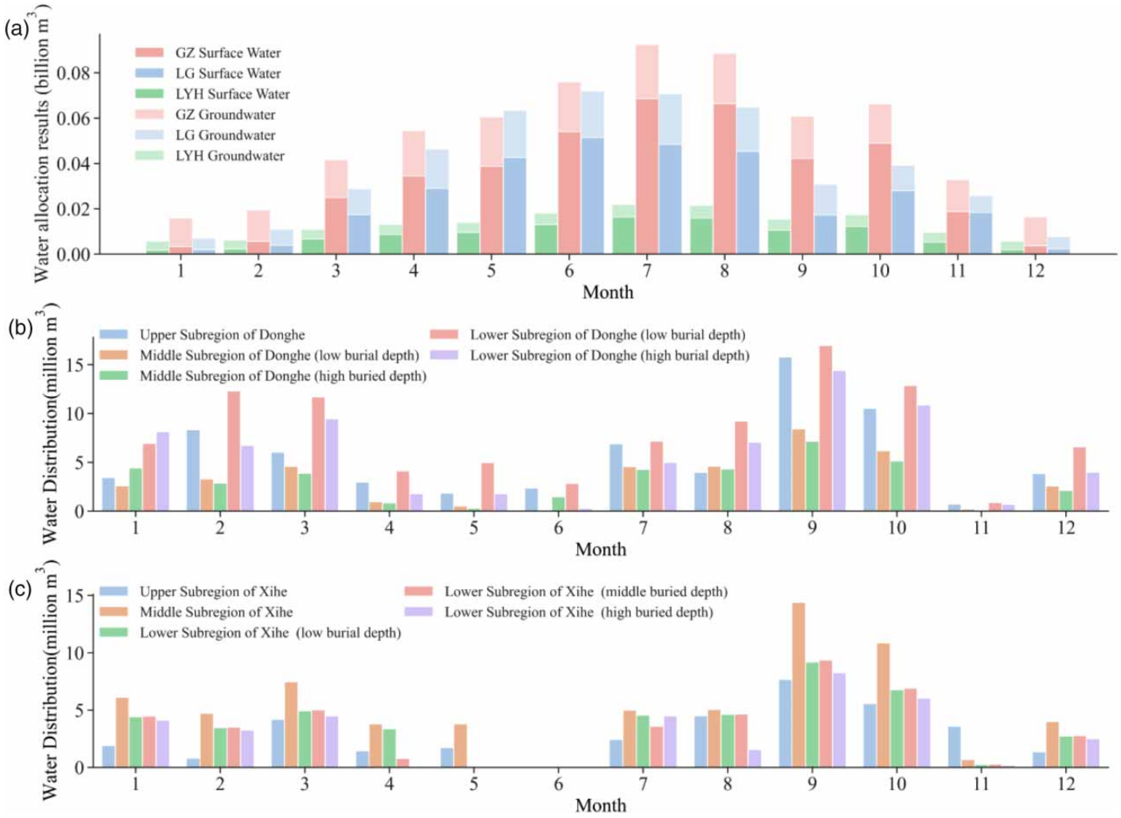


Figure 7 | Results of the optimal allocation of water resources in 2050 (a) midstream region, (b) Donghe region, (c) Xihe region.

Comparison between large-scale system decomposition–coordination model and single-objective model

To test the rationality of the large-scale system decomposition–coordination model, two single-objective planning models were constructed – one was economic benefit-oriented, and the other was ecology benefit-oriented. The constraints are the same as those of the large-scale system decomposition–coordination model. The indices of the ecological water allocation, agricultural water allocation, water productivity, agricultural benefit, and mean groundwater level obtained by the single-objective planning models were compared with those obtained by the large-scale system decomposition–coordination model. The comparison results are shown in Table 5.

Table 5 shows that the agricultural benefit in the economic benefit-oriented model reaches a maximum of 5.02 billion yuan. However, the blind pursuit of economic benefits increases the economic benefits at the expense of the ecological benefits and water-use efficiency. The ecological benefit-oriented model pushes to another extreme– it maximizes the amount of water allocated to the ecological sector but greatly reduces the amount of water allocated to agriculture. In contrast, the large-scale system

Table 5 | Comparison of the indices of different optimization models

Indices	Large-scale system decomposition–coordination model	Economic benefit-oriented model	Ecological benefit-oriented model
Agricultural water allocation (100 million m^3)	8.31	9.79	5.9
Ecological water allocation (100 million m^3)	13.2	8.63	14.64
Mean groundwater level (m)	2.67	3.1	2.57
Water productivity (kg/m^3)	1.85	1.75	1.88
Agricultural benefits (100 million yuan)	45.16	50.2	37.5

decomposition–coordination model tends to find a set of solutions that can balance each objective function. In addition to balancing different objectives, it is more prone to allocation of crops with high economic benefits and low water consumption. Therefore, this model can steadily increase the irrigation efficiency, water-use efficiency and ecological benefits in the study region.

Analysis of the rationality of the allocation results

In terms of intra-annual allocation, the amount of water allocated to the midstream region increases first and then decreases and is mainly concentrated in June, July, and August. This is consistent with the water demand patterns of the major local crops, such as maize and wheat. The downstream water demand is mainly concentrated in March to October, and the water shortage mainly occurs in March to June and November. These conditions result in a contradiction between the midstream inflow and the downstream water demands, which can only be resolved by raising the groundwater level in each region through irrigation during the wet season and by using groundwater to maintain vegetation in the dry season. From the perspective of the optimization of the crop planting structure, as shown in Figure 8, under the condition of ensuring the minimum food security for the residents in the region, the water resources tend to be allocated to crops such as maize and vegetables, which are cash crops with low-water consumption and high yield. In 2035, the amounts of water allocated to maize and vegetables will account for 40.6% and 39.75% of the total amount of water allocated to agriculture, respectively, and the total amount of water allocated to the two types of cash crops reaches 80.35% of the total amount of water allocated to agriculture. Under the further reduction of the total amount of water allocated to agriculture, the agricultural benefits in 2050 are basically the same as those in 2035 through the increase of water use efficiency and optimization of the crop planting structure. The overall proportion of water allocated to maize and vegetables in 2050 is less than that in 2035 because the increase in the population leads to an increase in the demand for basic food crops. Although the reduction in the total amount of water allocated to agriculture leads to a decreased proportion of water allocated to cash crops, they are still the major crops in this region.

The economic benefits and water-use efficiency of the river basin are continuously improved mainly because the objective function is optimized by the use of less water to achieve economic goals. Under the premise of ensuring food security in the river basin, more water resources are allocated to cash crops with low water consumption and high productivity. Additionally, the improvement of water-efficient facilities and the increase of industrial benefits are important reasons. Therefore, the model for conjunctive allocation of surface water and groundwater can improve the water-use efficiency and economic benefits from the holistic and regional perspective. Furthermore, in each subregion, the groundwater level is within a reasonable range, and the mean groundwater level has an uptrend. Compared with those in the base year, in 2035, the total area of

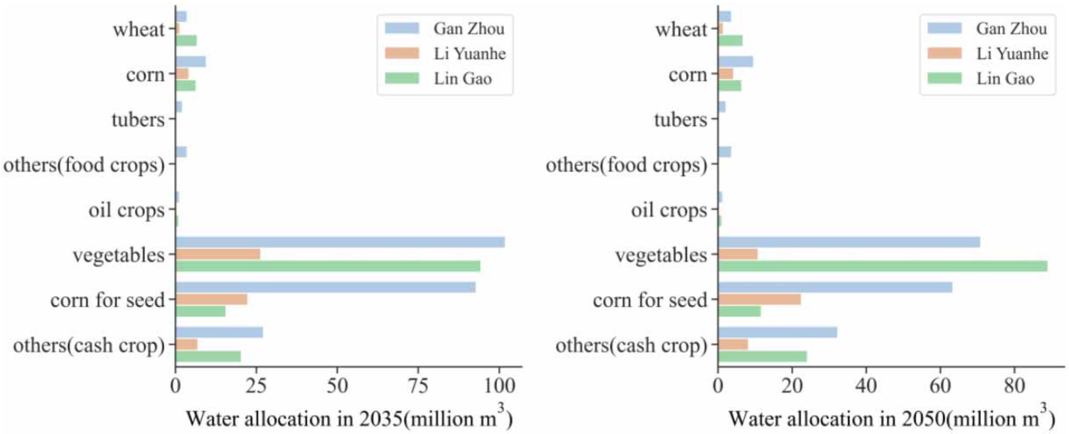


Figure 8 | Optimization of the planting structure.

vegetation will be186.5 km^2 larger than that in the base year; in 2050, the total area of vegetation will be 373.07 km^2 larger than that in the base year, the overall ecological condition will be good, and the ecological conditions in oases will tend to be stable. Therefore, the scheme of conjunctive allocation of surface water and groundwater is reasonable and feasible.

CONCLUSIONS

With the continuous population increase and development of the social economy, the sharp contradiction between agricultural water use and ecological water use in arid inland river basins lead to the deterioration of the ecological environment. To solve this problem, this study established a multiobjective, multiwater-source, ecological stability-oriented double-layer model for the optimal allocation of water resources. Finally, the genetic algorithm is used, and Python programs are used to obtain the amount of water allocated to each subregion in different plan years. This model can optimize the planting structure and industrial structure and regulates the ecological groundwater level to coordinate the contradiction between ecological water use and water use in agricultural irrigation districts, and thus achieve ecological stability and sustainable use of water resources.

This model was applied to the Heihe River Basin, an inland river basin in Northwest China. The results show that under the premise of increasing water-use efficiency, the amount of water allocated to agricultural use is steadily decreasing, and the water-demanding crops are transformed from food crops to cash crops with low water consumption and high yield. With the population increase and economic development, the amount of water allocated to domestic use continuously increases. The amount of water allocated to ecological use gradually increases, and the area of oases and the mean groundwater level are continuously improving. In general, the proportions of water allocated to the ecology and economy tend to balance, and the result of water allocation is conducive to the sustainable use of water resources in the basin. Compared with those in the base year, in 2035, the water productivity is 0.675 kg/person higher, and the total area of vegetation is by 373.07 km^2 larger; in 2050, the water productivity is 0.725 kg/person higher, and the total area of vegetation is by 373.07 km^2 larger. The objective water-use efficiency and ecological stability of the target model are reached. A comparison between this model and the single-objective models shows that this model tends to find a set of solutions that can balance each objective function and thus avoids the one-sidedness of the single-objective solutions. This model provides a reference for the stabilization and restoration of the ecological balance in oases in arid inland river basins.

AUTHOR CONTRIBUTIONS

This study was conceived, planned and designed by Zixu Qiao and Long Ma. All simulations, calculations, data analysis and manuscript drafting was done by Zixu Qiao, and Xing Huang, and was reviewed, modified and approved by Zixu Qiao.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories. China Meteorological Data Network. (http://data.cma.cn). Big data center of sciences in cold and arid regions (http://bdc.casnw.net).

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