Journal of Cleaner Production 213 (2019) 944–955

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Development of a coupled quantity-quality-environment water allocation model applying the optimization-simulation method

Yimin Wang, Jie Yang, Jianxia Chang*

State Key Laboratory of Eco-hydraulics in Northwest Arid Region of China (Xi'an University of Technology), Xi'an, 710048, China

ARTICLE INFO

Article history:
Received 8 May 2018
Received in revised form
7 November 2018
Accepted 6 December 2018
Available online 7 December 2018

Keywords:
Optimization-simulation method
Multi-water resources
Multiagent
Water resources allocation
Water quantity and quality

ABSTRACT

A river basin usually provides water for multiagent. Imperfect coordination mechanisms among these agents, however, usually lead to serious water shortage, pollution, and ecological degradation. Therefore, it is vital to conduct research on allocating different kinds of water resources among multiagent including the water quantity agent, water quality agent and environment agent within a river basin. This paper proposes an optimization-simulation method that takes into consideration engineering measures, including water transfer projects, reservoirs, canal heads, and pump stations; multi-water resources such as local surface water, transferred water, groundwater, and reused sewage; and multiagent for remitting serious water problems. In the proposed optimization-simulation method, the groundwater and reused sewage are first allocated according to the water resources allocation simulation module (Module 1). Then, local surface and transferred water are allocated based on the water resources allocation optimization module (Module 2), which comprises water quantity, water quality and environment agents' objectives based on synergism. Finally, the instream water quality is simulated according to the water quality simulation module (Module 3). Results show that, compared to the current situation, the water quantity and environment agent guarantee rates can satisfy the design requirements in the planning year of 2020. The regulated instream water quality is also improved; although, it still remains relatively poor. Water quality in the downstream is worse than that in the upstream. In addition, the water quality shows a positive correlation with the instream streamflow. These results certify the proposed optimization-simulation method can provide support for efficacious multiagent water resources allocation.

1. Introduction

Water is the irreplaceable, fundamental natural resource for life, ecology, and economic production (Gleick, 1993). For China, under the double impacts of climate change and human activities, runoff presents a descending trend (Yang et al., 2018). Concurrently, with the rapid growth of the population and accelerated urbanization, water demand has greatly increased, creating a greater gap between water demand and water supply (Liu et al., 2016; Ren et al., 2017). In addition, due to rising industry and production, a significant amount of industrial sewage has been drained off into rivers by companies. It has resulted in serious water pollution and the destruction of ecological balance, both of which will block sustainable development (Lu et al., 2015). To solve or reduce the severity of these problems, sustainable water resources allocation has been proposed. This allocates multi-water resources (i.e. different kinds of water resources) among multiagent (various water users) by engineering or non-engineering measures (George et al., 2011; Ross, 2017). The goal is to achieve the sustainable utilization of water resources and harmonious development between economy and environment (Liu et al., 2016; World Bank, 2016).

Comprehensive utilization of multi-water resources for sustainable development has gained much attention. Afzal et al. (1992) analyzed the net profit of irrigation systems by considering groundwater and canal water with different qualities simultaneously. Percia et al., 1997, analyzed the water supply and water quality within a system containing surface water, groundwater, and reused sewage. Emch and Yeh (1998) assessed the water supply cost and seawater erosion through the joint utilization of surface water and groundwater. Yamout and EI-Fadel (2005) proposed a model for water supply which considered the economy, environmental factors, conventional water sources (surface water and groundwater), and non-conventional sources (rainwater

* Corresponding author.
E-mail address: chxiang@xaut.edu.cn (J. Chang).

https://doi.org/10.1016/j.jclepro.2018.12.065
0959-6526/

harvesting, reused sewage, and seawater desalination). Pulido-Velazquez et al. (2008) proposed a model for water utilization which coupled surface water and groundwater with environmental constraints. Paredes et al. (2010) established a water quality support system to analyze the impact of reservoirs and sewage treatment on water quality improvement and proposed methods to enhance the ecological environment. Manshadi et al. (2015) assessed the water quantity and quality based on virtual water, blue water and transferred water. Ross (2017) emphasized the significance of integrating different water resources for better policy making.

These studies were mostly conducted by either the optimization or simulation model (Kamali and Niksokhan, 2017; Yazdi et al., 2017). An optimization model aims to acquire the best results to achieve the goal set by the decision-maker or designer (Brown et al., 2015; Kamali and Niksokhan, 2017). It always incorporates objectives, constraints, and decision variables (Brown et al., 2015). Also, it is always utilized to make plans that achieve the goal by optimization algorithms without prioritized rules (Lund and Ferreira, 1996). A simulation model is also called the rule-based simulation model. In this model, agents operate under configured rules (Jeuland and Whittington, 2014; Brown et al., 2015). When there are conflicting objectives, the simulation model is easier to gain a specific and accessible solution (Brown et al., 2015). Sustainable water resources allocation is a complex question, as it considers multiagent and multi-water resources. Different river basins may have various water supply guidelines or rules, but ultimately the primary goal is to better satisfy the water demand. For example, some rivers may prefer to utilize surface water first while other rivers may be inclined to consume groundwater or other types of water in the first place. With this in mind, sustainable water resources allocation may not be realized by using just the optimization or simulation model (Kamali and Niksokhan, 2017). Hence, it is essential to conduct sustainable water resources allocation by applying the optimization and simulation method simultaneously.

Despite the importance of this issue, there is still limited research seeking to integrate surface water, groundwater, reused sewage, and transferred water for the purpose of sustainable social, economic, and environmental development. Without deeper consideration of multi-water resources, the water demand satisfaction may be not very accurate. To fill in this gap, the main purpose of this study is to reasonably allocate multi-water resources to multiagent via the water conservancy project by applying the optimization and simulation method simultaneously.

Guanzhong Plain was chosen as the study area for its composition of complex multi-water resources (surface water, groundwater, reused sewage, and transferred water). In addition, one in-progress water transfer project and some already existing reservoirs, canal heads, and pump stations are located in this area. Without reasonable water resources allocation, these projects cannot have their intended effect, and may also lead to serious water problems. Therefore, this region requires a systematic water resources allocation model to provide multi-water resources to multiagent based on these in-progress and existing water conservancy projects. As the region is facing serious challenges—severe water shortages, water quality deterioration, and environmental degradation (Huang et al., 2014), this study selected three agents: a water quantity agent (water consumers in economic sectors, i.e. domestic, industrial, agricultural, and off-stream ecological water demand), a water quality agent (water consumers most concerned with the improvement of the river water quality), and an environment agent (water consumers looking to maintain the river health). In addition, this river was selected because it has its own preferred priority for multi-water resources utilization for the sustainable water resources utilization in the Guanzhong Plain. Thus, results obtained by the optimization-simulation method will provide reliable support that can be practically applied for better water allocation in this area.

2. Study area and data

2.1. Study area and key issues

The Guanzhong Plain (tinted red in Fig. S1 in the supplemental materials) is located in the Wei River Basin (the largest tributary of the Yellow River) (Chang et al., 2016; Yang et al., 2018). It is in a sub-humid continental monsoon climate zone characterized by cold and dry winters and summers that are hot and rainy. Precipitation is mainly concentrated in the flood season (July to October), which accounts for 60% of the annual precipitation. The minimum precipitation and runoff mainly occur in December or January (Yang et al., 2018). Guanzhong Plain is the industrial, agricultural, and educational base of the Wei River Basin. It is also the most developed region in the Shaanxi Province. However, there are some key issues in the Wei River Basin that have hindered the social and economic development:

(1) The water resources are scarce, and the distribution of water resources is uneven. It is inharmonious between the distribution of water resources and water demand. In addition, runoff in the region is showing a downward trend. More importantly, water demand has been rising. To satisfy the greater need, local surface water and groundwater have been excessively exploited, resulting in serious environmental and geological problems, such as groundwater depression cones, ground fissures and phreatic water pollution. The growing disparity between water demand and the total water supply capacities has restricted the social and economic development.
(2) Sewage and water quality pollution are very serious concerns. Industrial and urban sewage discharge have exacerbated water pollution levels, affecting the water's self-purification capacity and destroying the river's health. In return, contaminated water in the river also pollutes the surface and groundwater, which further amplifies the discordance between water supply and demand.
(3) Water ecology has degraded drastically, and biodiversity has been destroyed due to the water quality pollution, the illegal occupation of the river channel, and limited ecological water utilization diverted to economic water utilization.

The optimization-simulation method is this study's proposal to help resolve the above-mentioned problems and better allocate multi-water resources among multiagent to sufficiently meet the future water demand (planning year of 2020). For the Guanzhong Plain, total water demand—especially agricultural irrigation water demand—is vastly insufficient. Therefore, analyses on the water supply to 12 irrigation areas in the Guanzhong Plain are given primary focus (shown in Fig. 1). The detailed water supply system is illustrated in Table 1.

2.2. Data

2.2.1. Total water supply capacities

Data needed to calculate the total water supply capacities mainly consists of: water inflow with a time step of ten days, groundwater, reused sewage, and water conservancy project properties (reservoirs, canal heads, water pumped projects, and inter-basin water transfer projects, as seen in Table 1).

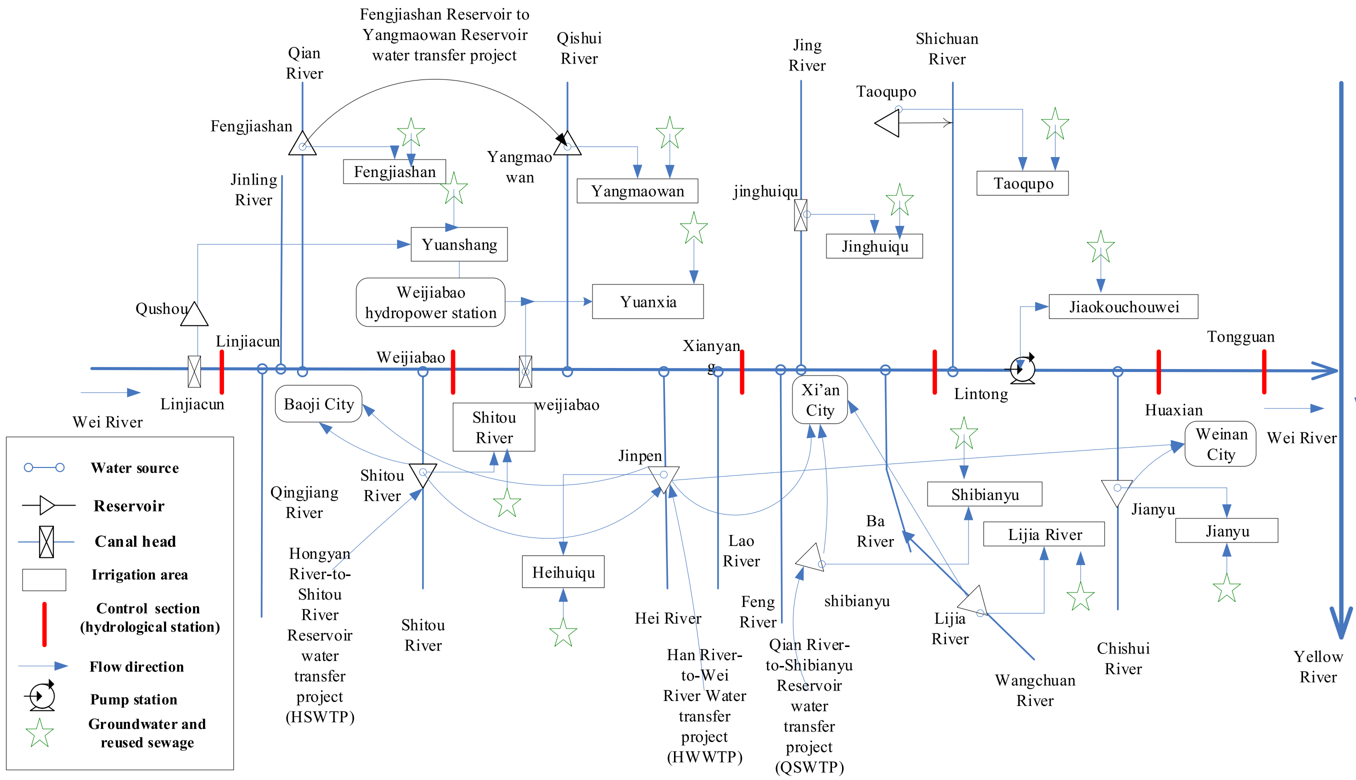

Fig. 1. Network of the water supply system of the Guanzhong Plain in 2020.

Table 1
Water supply system of the Guanzhong Plain in 2020.

Irrigation areas	Local surface water supply system			Groundwater	Reused sewage	Inter-basin water transfer projects
	Water storage projects (reservoirs)	Water diversion project (canal heads)	Water pumped projects			
Yuanshang	Qushou			★	★	
Fengjiashan	Fengjiashan			★	★	
Shitou River	Shitou River			★	★	HSWTP
Yuanxia		Weijiabao		★	★	
Yangmaowan	Yangmaowan			★	★	
Heihuiqu	Jinpen			★	★	HWWTP
Jinghuiqu		Jinghuiqu		★	★	
Shibianyu	Shibianyu			★	★	QSWTP
Lijia River	Lijia River			★	★	
Taoqupo	Taoqupo			★	★	
Jiaokouchouwei			★	★	★	
Jianyu	Jianyu			★	★	

Note: ★ signifies the existence of the water pumped project, groundwater, or reused sewage in this irrigation area.

Water inflow data consists of local water inflow (including water inflow in the main stream of the Wei River and its tributaries, canal heads, pump stations, and reservoirs) and transferred water from other rivers. Water inflow in the main stream are collected from five hydrological stations (control sections): Linjiacun, Weijiabao, Xianyang, Lintong, and Huaxian listed from upstream to downstream (shown in Fig. S1). Tributaries of the Wei River Basin contain Jinling River, Qian River, Qishui River, Jing River, Shichuan River, Qingjiang River, Shitou River, Hei River, Feng River, Lao River, Ba River and Chishui River (Fig. 1). It is noteworthy that the Hongyan River-to-Shitou River Reservoir water transfer project (HSWTP) and Qian River-to-Shibianyu Reservoir water transfer project (QSWTP) are constructed already; their water inflows are included in the Shitou River Reservoir and Shibianyu Reservoir, respectively. The local water inflow data period is from July 1960 to June 2007 (a total of 47 years). Annual transferred water in the planning year of 2020, i.e. annual water transfer quantity, of the Han River-to-Wei River Water transfer project (HWWTP) is 10×10^8 m^3.

2.2.2. Water demand

Future water demand includes the water quantity agent water demand, water quality agent water demand, and environment agent water demand. In this study, the instream ecological basic flow in the non-flood season (from November to June) is set as the environment agent water demand to reflect the river's health. Ecological basic flows in the non-flood season (of five control sections) are gathered from the Research Report on Ecological Basic Flow in the Guanzhong Plain of the Wei River Basin. The ecological basic flows of the Linjiacun, Weijiabao, Xianyang, Lintong, and

Huaxian control sections in the non-flood season are 9 m^3/s, 12 m^3/s, 16 m^3/s, 24 m^3/s, and 26 m^3/s, respectively. The annual water quantity agent water demands in the planning year of 2020 are shown in Table 2. In Table 2, agricultural water demand changes with the annual water quantity. Four typical years (dry, semi-dry, normal, and wet year) correspond to 95%, 75%, 50%, and 25% water inflow frequencies, respectively. In dry years, there will be little water that can be utilized for agriculture; therefore, agricultural water demand in dry year is the highest.

2.2.3. Water quality

For the Guanzhong Plain, there are 13 water quality monitoring stations (13 water function areas). The detailed sketch map of 13 water quality monitoring stations and 5 hydrological stations are shown in Fig. 2.

For the Wei River Basin, two main pollutants measure indicators' (including COD and NH_3-N) data for 2005 and 2006 were collected from 13 water quality monitoring stations to reflect organics content. These two main indicators provide a basic reflection of the water quality. Therefore, the two indicators (COD and NH_3-N) are assessed. The annual sewage quantity in the planning year of 2020, concentrations of COD and NH_3-N in the sewage are calculated based on the method in the Twentieth Fifth Year Technical Guidelines for the Total Quantity Control of Major Pollutants (Table 3).

3. Development of an optimization-simulation method

In this study, an optimization-simulation method (Fig. 3) is proposed considering the utilization priority of water resources in combination with satisfaction of the future water demand. For the study area, there are multi-water resources. Surface water (including the local surface water and transferred water) is closely related to climate change, such that climate change will result in unstable surface water yield under different typical years. Groundwater and reused sewage would be more stable. Thus, to better prevent uncertain drought, groundwater and reused sewage are used first, according to the utilization priority of Module 1, the water resources allocation simulation module. The outputs of Module 1 are the groundwater and reused sewage allocation results, as well as the regulated instream streamflow ("regulated streamflow 1"). Then, local surface water and transferred water are utilized based on Module 2, the water resources allocation optimization module, to maximize the water supply satisfaction. To coordinate supply and sustainable development among various agents, this module includes all agents' objectives based on synergism. The outputs of Module 2 include the local surface and transferred water allocation results, and the regulated instream streamflow ("regulated streamflow 2"). Finally, the instream water quality is calculated based on the output of Module 2 "regulated streamflow 2" and Module 3, the water quality simulation module. This proposed method is beneficial for allocating multi-water resources to multiagent. The detailed explanations of three modules are denoted in Section 3.1, 3.2, and 3.3, respectively.

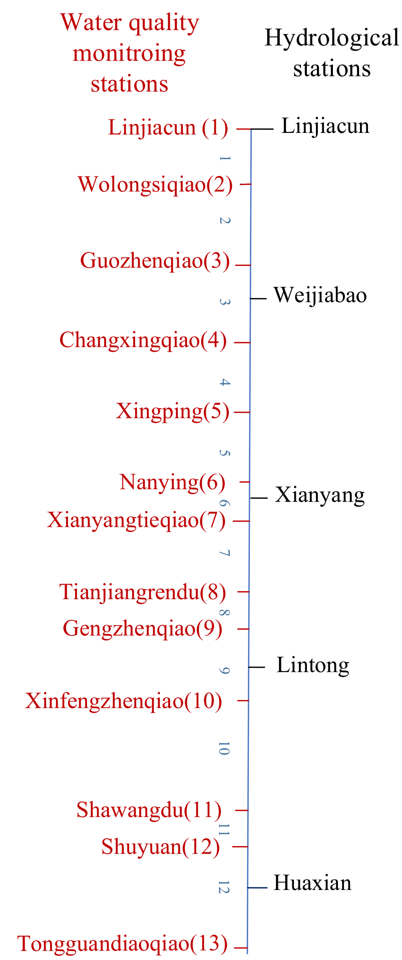

Fig. 2. Sketch map of hydrological stations and water quality monitoring stations.

Table 2
Domestic, industrial, agricultural and off-stream ecological water demand.

Irrigation areas	Water demand (10^4 m^3)					
	Domestic	Industrial	Off-stream ecological	Agricultural		
				Wet year	Normal year	Semi-dry or dry year
Yuanshang	3212	10474	285	32073	40750	46008
Fengjiashan	2962	1872	239	16319	20982	23951
Shitou River	0	0	0	3251	3154	4319
Yuanxia	4836	15712	428	11749	16570	19592
Yangmaowan	761	467	37	4399	5722	6573
Heihuiqu	0	0	0	8975	12239	13442
Jinghuiqu	3441	11199	248	24192	32360	36677
Shibianyu	0	0	0	3459	4967	5147
Lijia River	0	0	0	1839	2132	2504
Taoqupo	1268	1848	91	1989	2720	3169
Jiaokouchouwei	1791	4261	30.6	18734	23763	27003
Jianyu	0	0	0	886	1187	1587

Table 3
Predicted concentrations of COD and NH_3-N in the sewage.

Water quality monitoring stations	Water quality target (mg/L)		Sewage quantity (m^3/s)	Concentration in the sewage (mg/L)	
	NH_3-N (≤)	COD (≤)		NH_3-N	COD
Linjiacun (1)	0.5	15	0.90	4.47	48.67
Wolongsiqiao (2)	1	20	1.80	4.47	48.67
Guozhenqiao (3)	1.5	30	2.69	4.47	48.67
Changxingqiao (4)	1	20	3.59	4.47	48.67
Xingping (5)	1.5	30	5.65	5.21	56.78
Nanying (6)	1	20	7.71	5.21	56.78
Xianyangtieqiao (7)	1.5	30	10.95	5.96	64.89
Tianjiangrendu (8)	1	20	14.19	5.96	64.89
Gengzhenqiao (9)	1.5	30	17.43	5.96	64.89
Xinfengqiao (10)	1	20	20.67	5.96	64.89
Shawangdu (11)	1	20	21.05	6.70	73.00
Shu yuan (12)	1.5	30	21.43	6.70	73.00
Tongguandiaoqiao (13)	1.5	30	21.81	6.70	73.00

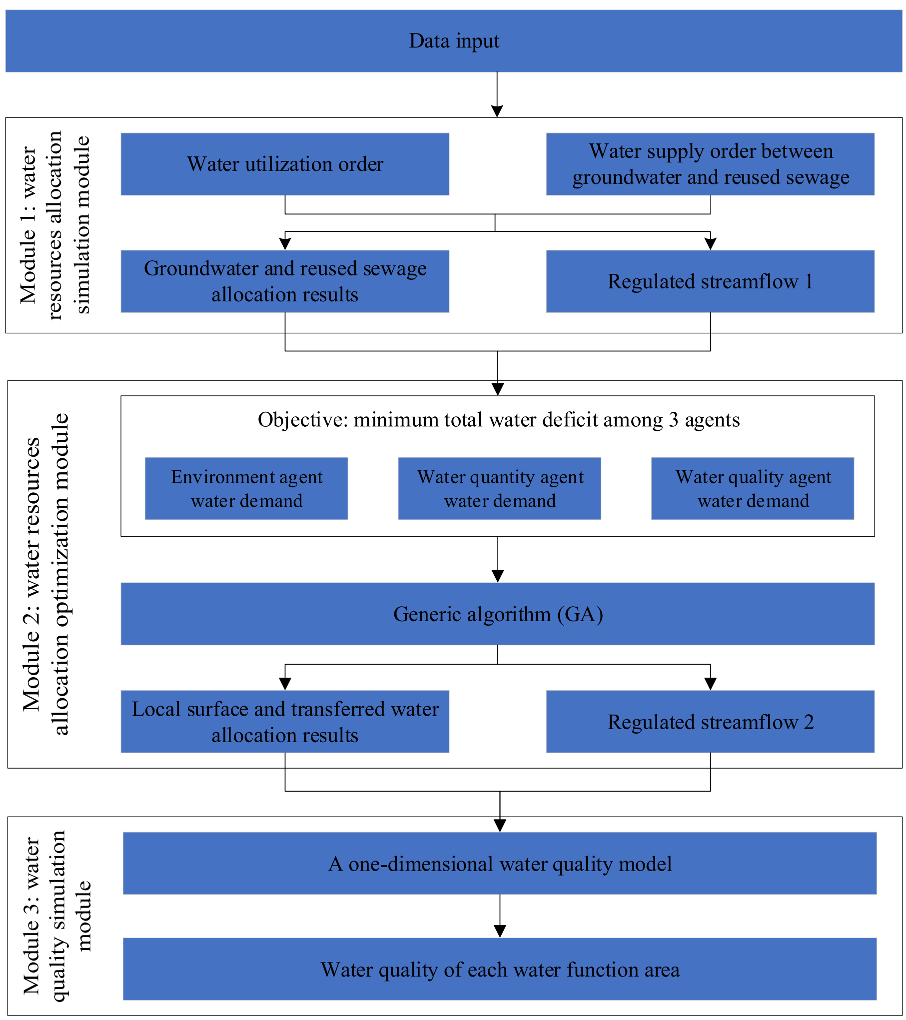

Fig. 3. Flowchart of the optimization-simulation method.

3.1. Module 1: water resources allocation simulation module

In this study, the principles of the groundwater and reused sewage allocation simulation module are as follows:

(1) Water supply mandate of multi-water resources: the reused sewage is used first, followed by the groundwater.

(2) Water utilization mandates: the primary is the instream ecological water supply with an annual average guarantee rate of no less than 90%. The water allocation to instream ecology allows for the instream regulated streamflow ("regulated streamflow 1") to be calculated. The next mandate is the domestic, off-stream ecological, and industrial water supplies with an annual average basin guarantee

rate of no less than 98%, 90%, and 95%, respectively. The final mandate is the agricultural water supply with an annual average basin guarantee rate ranging from 50% to 75%. Reused sewage should first satisfy the off-stream ecological water demand, then the rest of reused sewage can be used for industry. In principle, it cannot be utilized in residents' living.

3.2. Module 2: water resources allocation optimization module

After allocating the groundwater and reused sewage, the local surface water and transferred water are utilized based on the water resources allocation optimization module solved by the genetic algorithm (GA) (Peralta et al., 2014). The objective function and main constraints are as follows:

3.2.1. Objective function

In this study, based on the synergism, the objective function is the minimum total water deficit (for coordinating sustainable development among three agents) given as follows.

$$\min(w) = \sum_{t=1}^{T}\sum_{j=1}^{3}\{\theta(t)[Q_{awd}(j,t) - S_{tws}(j,t)]\Delta T(t)\} \quad (1)$$

where w is the total water deficit; $j = 1$, 2, and 3 represent three agents: the environment, water quality, and water quantity; $Q_{awd}(j,t)$ is the absent water demand of each agent after water supply by groundwater and reused sewage at t time; $Q_{awd}(j,t)$ for each agent is calculated based on the following equations: $S_{tws}(j,t)$ denotes total water supply of each agent in Module 2 by surface and transferred water at t time; $\theta(t)$ is the water deficit discriminant coefficient such that if $Q_{awd}(j,t) - S_{tws}(j,t) < 0$, $\theta(t) = 0$, if the contrary, then: $\theta(t) = 1$.

$$Q_{awd}(1,t) = \sum_{h=1}^{5}\left[\tau(t)(Q_{EBL}(h,t) - Q_{IRS}(h,t))\right] \quad (2)$$

where $Q_{awd}(1,t)$ is the absent water demand to the environment agent at t time; $h = 1, 2, \cdots, 5$ represents the five control sections; $Q_{EBL}(h,t)$ denotes the ecological basic flow in the non-flood season for each control section (9 m^3/s, 12 m^3/s, 16 m^3/s, 24 m^3/s, and 26 m^3/s for Linjiacun, Weijiabao, Xianyang, Lintong, and Huaxian control sections, respectively); $Q_{IRS}(h,t)$ is the instream regulated streamflow 1 obtained from Module 1 of each control section; $\tau(t)$ is the environment agent water deficit discriminant coefficient such that if $Q_{EBL}(h,t) - Q_{IRS}(h,t) < 0$, $\tau(t) = 0$, on the contrary, $\tau(t) = 1$.

Water quality agent water demand changes with the instream streamflow. Greater river flow means that less water will be needed to improve the water quality. Based on the water quality target (Table 3), the demand for water quality improvement in the planning year of 2020 was calculated by the mass balance method (Zhang et al., 2010).

$$Q_{awd}(2,t) = \max[\upsilon(t)(Q_{SPWR}(f,t) - Q_{IRS}(f,t))]\ (f = 2, 3, \cdots, or\ 13) \quad (3)$$

$$C_{WQT}(f) = \frac{C_S(f) \times Q_S(f)}{Q_{SPWR}(f) + Q_S(f)} \quad (4)$$

where $Q_{awd}(2,t)$ is the absent water demand to the water quality agent at t time; $f = 2, 3, \cdots, 13$ represents the twelve water function areas; $Q_{SPWR}(f,t)$ denotes the water demand to improve the water quality of each water function area at t time; $Q_{IRS}(f,t)$ is the instream "regulated streamflow 1" obtained from Module 1 of each water function area; $\upsilon(t)$ is the water quality agent water deficit discriminant coefficient such that $Q_{SPWR}(f,t) - Q_{IRS}(f,t) < 0$, $\upsilon(t) = 0$, on the contrary, $\upsilon(t) = 1$; $C_{WQT}(f)$ represents the water quality target of each water function area (Table 3); $C_S(f)$ and $Q_S(f)$ are the pollutant measure indicator concentration in the sewage and the sewage quantity of each water function area, respectively (Table 3). As two indicators were selected to study, water demands to improve the water quality in each water function area are different calculated by two indicators. This study selected the higher value for the final water requirement in each water function area.

$$Q_{awd}(3,t) = \sum_{ir=1}^{12}\left[\xi(t)(Q_{WQAWD}(ir,t) - Q_{WSM}(ir,t))\right] \quad (5)$$

where $Q_{awd}(3,t)$ is the absent water demand to the water quantity agent at t time; $ir = 1, 2, \cdots, 12$ represents the twelve irrigation areas; $Q_{WQAWD}(ir,t)$ denotes the water quantity agent water demand of each irrigation area (future water quantity demand is shown in Table 2); $Q_{WSM}(ir,t)$ is the water supply from Module 1 of each irrigation area; $\xi(t)$ is the water quantity agent water deficit discriminant coefficient such that if $Q_{WQAWD}(ir,t) - Q_{WSM}(ir,t) < 0$, $\xi(t) = 0$, on the contrary, $\xi(t) = 1$.

3.2.2. Constraints

The main constraints are as follows:

(1) reservoir water balance constraint

$$V(m,t+1) = V(m,t) + QRu(m,t) \times \Delta T(t) - LW(m,t) - sum(m,t) \quad (6)$$

where $V(m,t+1)$ and $V(m,t)$ are the storage capacity of m reservoir at t+1 time and t time, respectively; $QRu(m,t)$ denotes reservoir inflow of m reservoir; $\Delta T(t)$ represents time; $LW(m,t)$ is the reservoir water supply; and $sum(m,t)$ is the water loss.

(2) reservoir storage capacity constraint

$$V\min(m,t) \le V(m,t) \le V\max(m,t) \quad (7)$$

where $V\min(m,t)$ refers to the dead storage capacity of m reservoir at t time; $V(m,t)$ is real-time storage capacity of m reservoir; $V\max(m,t)$ represents the maximum storage capacity below the normal storage water level in the non-flood seasons and below the flood-control water level in the flood season.

(3) water supply balance constraint

$$TS(j,t) = TR(j,t) \quad (8)$$

where $TS(j,t)$ refers to the total water supply by local surface water, groundwater, reused sewage, and transferred water to each agent at t time; $TR(j,t)$ is the total water quantity received by each agent.

(4) water deficit balance constraint

$$Tws(j,t) = Grec(j,t) + Qque(j,t) \quad (9)$$

where $Tws(j,t)$, $Grec(j,t)$, and $Qque(j,t)$ denote the water demand, the received water quantity, and the water deficit of each agent at t time, respectively.

(5) Hydropower plant power output constraint

$$N\min(m,t) \le N(m,t) \le N\max(m,t) \quad (10)$$

where $N\min(m,t)$ represents the hydropower plant minimum output of m hydropower plant at t time; $N(m,t)$ is the real-time output; $N\max(m,t)$ denotes maximum output.

(6) nonnegative variables constraint

3.3. Module 3: water quality simulation module

In this study, after allocating multi-water resources according to Section 3.1 and 3.2, the instream regulated streamflow ("regulated streamflow 2") can be calculated. Then, a one-dimensional water quality model (Zhu et al., 2013) is used to analyze the water quality of water function areas based on the instream "regulated streamflow 2" after running the Module 2 and sewage data. The formula for water quality calculation is as follows:

$$CR(f) = \frac{CU(f) \times Q(f-1) + C_S(f) \times Q_S(f)}{Q(f)} \quad (11)$$

$$CU(f) = CR(f-1)e^{-kt} + g_f \quad (12)$$

where $CR(f)$ and $CR(f-1)$ are the river pollutant measure indicator concentrations of f and f-1 water function areas, respectively; $CU(f)$ represents the pollutant measure indicator concentration coming from upstream; $Q(f-1)$ and $Q(f)$ are the "regulated streamflow 2" of f-1 and f water function areas, respectively; t is the water flow time in stream segment i; g_f and k are the coefficients.

The parameters g_f and k of COD and NH_3-N are calculated based on the data in 2006 and validated according to the data in 2005. The main parameters of COD and NH_3-N are shown in Table 4; the designated wet season is from July to October; the normal season includes April, May, June, and November; the dry season refers to January, February, March, and December.

4. Results

4.1. Water supply to the environment agent

To demonstrate the application of the proposed optimization-simulation method, two scenarios in the planning year of 2020 are compared systematically: a baseline scenario with completed water conservancy projects (scenario 1) and an alternative scenario with one water conservancy project under construction (scenario 2). Scenario 1 means the construction of Han River-to-Wei River Water Transfer Project will not be fulfilled in 2020. Scenario 2 represents the construction of the Han River-to-Wei River Water Transfer Project will be completed in 2020. In this scenario, the transferred water of the project will be considered in the total water supply capacities.

Through the optimization-simulation method, the optimal water resources allocation results in the planning year of 2020 under the two scenarios were obtained based on water inflow data and future water demand. Results display that in both scenarios the annual average ecological water supply for Linjiacun, Weijiabao, Xianyang, Lintong, and Huaxian control sections during the non-flood season all met the design's stipulated water supply rate of 90%. Fig. 4 shows the average instream streamflow processes under four typical years in the non-flood season for the five control sections. The horizontal axis, 11.01 and 6.01, represents the early November and early June, respectively. Because the average instream streamflow processes of scenario 1 and scenario 2 in the same typical year are similar, their streamflow processes sometimes coincide visually in Fig. 4, and the ecological water supply guarantee rates are the same.

Regulated instream streamflow varies with the water frequency, more water will lead to higher streamflow. In a wet year, the regulated instream streamflow can meet the ecological basic flows in the five control sections. However, in a normal, semi-dry, and dry year, the streamflow in Linjiacun and Weijiabao sometimes could not meet the standard while the ecological basic flow standards could be attained in Xianyang, Lintong, and Huaxian. Generally, in the two scenarios, under four typical years, ecological basic flows in Xianyang, Lintong, and Huaxian control sections are all met. Meanwhile, for the downstream control sections (Xianyang, Lintong, and Huaxian), the environmental demands are relatively well satisfied in comparison to those of the upstream sections (Linjiacun and Weijiabao).

The comparison between measured streamflow and the regulated streamflow was also conducted. Here, results in a wet year are taken as an example. Measured data shows that for Linjiacun, the measured streamflow from early December to the end of February failed to meet the ecological basic flow. For Weijiabao, the ecological basic flows in late January and early February could not be satisfied. For Xianyang, Lintong, and Huaxian, the ecological basic flows all met the requirements. However, in a wet year, regulated instream streamflow is sufficient for the ecological basic flows in all five control sections. In addition, under other typical years, the regulated streamflow can better meet the requirement than measured streamflow. This indicates that the optimization-simulation method can better satisfy the environment agent water demand.

Table 4
Coefficients of the water quality model in 12 water function areas.

Parameter	Pollutant	Season	Water function area											
			2	3	4	5	6	7	8	9	10	11	12	13
k	NH_3-N	Wet	0.13	0.13	0.08	0.08	0.11	0.11	0.11	0.11	0.09	0.09	0.08	0.08
		Normal	0.10	0.10	0.07	0.07	0.08	0.08	0.08	0.08	0.08	0.08	0.07	0.07
		Dry	0.09	0.09	0.05	0.05	0.06	0.06	0.06	0.06	0.04	0.04	0.04	0.04
	COD	Wet	0.26	0.26	0.17	0.17	0.21	0.21	0.21	0.21	0.18	0.18	0.17	0.17
		Normal	0.20	0.20	0.13	0.13	0.16	0.16	0.16	0.16	0.15	0.15	0.14	0.14
		Dry	0.17	0.17	0.10	0.10	0.12	0.12	0.12	0.12	0.09	0.09	0.08	0.08
g_f	NH_3-N	Wet	0.52	0.35	0.55	0.16	0.10	0.32	0.30	0.20	1.40	4.50	2.50	1.60
		Normal	0.60	0.70	0.70	1.40	1.90	5.50	2.60	2.70	3.00	4.00	3.00	3.50
		Dry	0.50	0.90	0.52	0.16	0.25	11.00	8.20	4.60	3.70	2.40	2.10	9.00
	COD	Wet	8.5	16.0	20.0	21.0	22.0	65.0	25.0	14.0	55.0	33.0	31.0	25.0
		Normal	13.0	20.0	16.0	53.0	30.0	22.0	73.0	3.0	55.0	68.0	28.0	55.0
		Dry	17.0	35.0	12.0	58.0	27.0	28.0	90.0	22.0	75.0	135.0	60.0	120.0

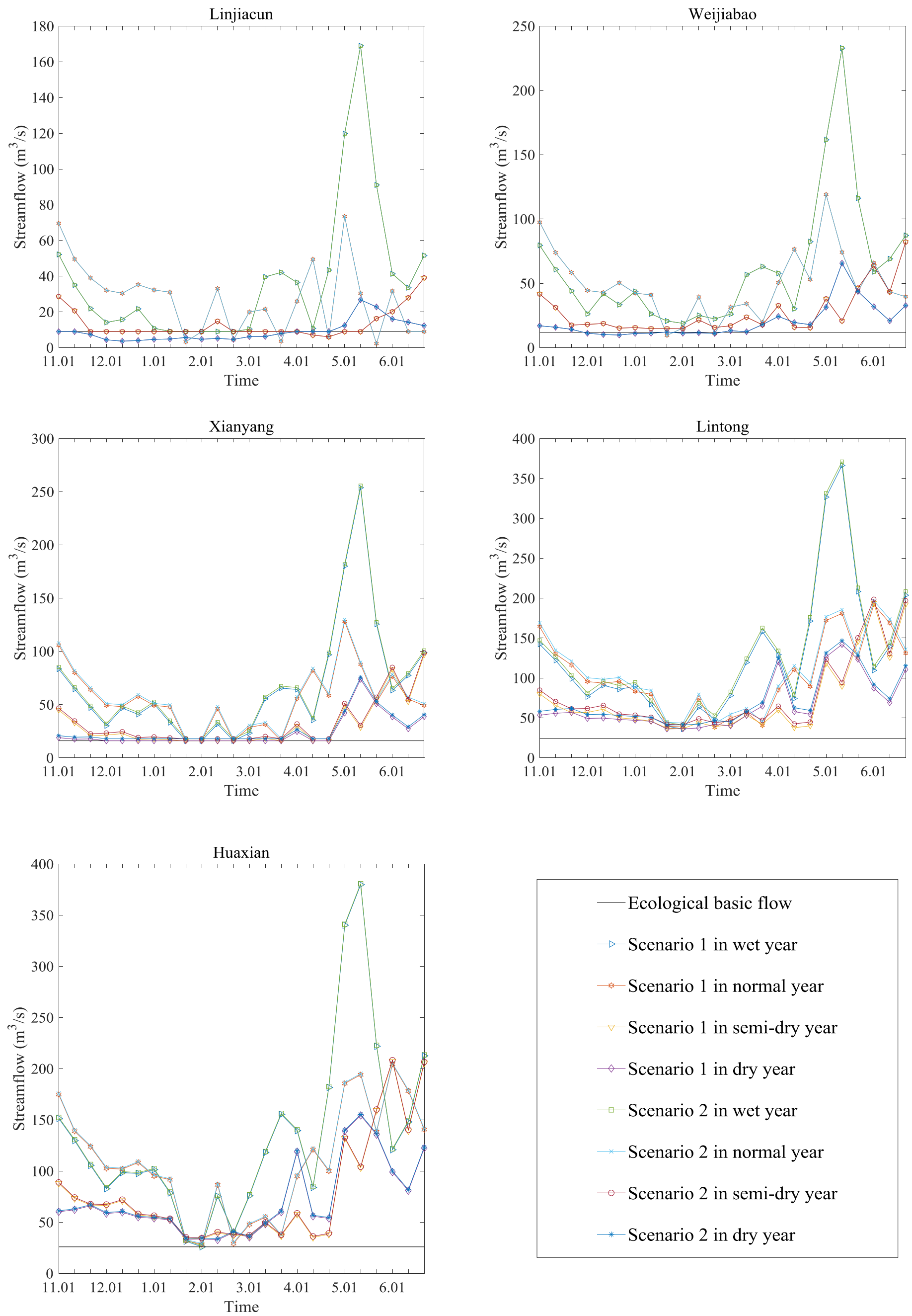

Fig. 4. Instream streamflow processes of five control sections in two scenarios.

4.2. Water supply to the quantity agent

Based on the optimal water resources allocation results calculated in Section 4.1, the long-term water supply to the quantity agent of 12 irrigation areas in the planning year of 2020 under two scenarios can be acquired. Here, water supply to the quantity agent of the Yuanxia irrigation area under semi-dry and dry years in scenario 2 are taken as examples (Table 5).

Table 5 indicates that, under the semi-dry year in scenario 2, water supplies to domestic, industrial, agricultural, and off-stream ecological sectors by local surface water were 0 m^3, 7162 $\times$ 10^4 m^3, 16433 $\times$ 10^4 m^3, and 0 m^3, respectively. Similarly, the water supply to economic sectors via groundwater, reused sewage, and the corresponding water deficit can be obtained. The total water demand, water supply, and water deficit for Yuanxia in scenario 2 were 40568 $\times$ 10^4 m^3, 37409 $\times$ 10^4 m^3, and 3159 $\times$ 10^4 m^3, respectively.

Based on the water resources allocation results, multi-year average guarantee rates (average of allocation results based on data from 1960 to 2007) for different water users of 12 irrigation areas in scenario 1 and scenario 2 are shown in Table 6.

Table 6 displays that the domestic and ecological water supply guarantee rates were all 100%. The agricultural water supply guarantee rates in the two scenarios were within the planned range (50%–75%). The industrial water supply guarantee rates varied between 77% and 100%. Based on Table 6, the basin guarantee rates of different water users of economic sectors in two scenarios (averages of different guarantee rates in different irrigations areas) can be calculated. The results illustrate that the basin domestic,

Table 5
Water supplies and demands of the quantity agent in scenario 2 of Yuanxia irrigation area.

Semi-dry year (10^4 m^3)						
Water demand of quantity agent		Domestic	Industrial	Agricultural	Ecological	Total
		4836	15712	19592	428	40568
Water supply	Local surface water	0	7162	16433	0	23595
	Groundwater	4836	8078	0	0	12914
	Reused sewage	0	472	0	428	900
	Total	4836	15712	16433	428	37409
Water deficit		0	0	3159	0	3159
Dry year (10^4 m^3)						
Water demand of quantity agent		Domestic	Industrial	Agricultural	Ecological	Total
		4836	15712	19592	428	40568
Water supply	Local surface water	0	7156	11181	0	18337
	Groundwater	4836	8078	0	0	12914
	Reused sewage	0	472	0	428	900
	Total	4836	15706	11181	428	32151
Water deficit		0	6	8411	0	8417

industrial, agricultural, and off-stream ecological water supply guarantee rates in scenario 1 were 100%, 95%, 71, and 100%, respectively. The basin domestic, industrial, agricultural, off-stream ecological water supply guarantee rates in scenario 2 were 100%, 95%, 75%, and 100%, respectively. Guarantee rates in the two scenarios all comply with the design basin guarantee rates.

Table 6 also shows that the agricultural water supply guarantee rate for Lijia River irrigation (53%) was the lowest in scenario 1. In scenario 2, the agricultural water supply guarantee rate of the Taoqupo irrigation area (70%) was the lowest. The industrial water supply guarantee rates of the Taoqupo irrigation area (77% in both scenarios) were the lowest followed by that of the Yuanshang irrigation area (89% in both scenarios). These indicate without future water conservancy project constructed, more attention should be paid to the agricultural water demand in the Lijia River irrigation area and industrial water demand in Taoqupo irrigation area. With the future projects built, the agricultural water deficit in the Lijia River irrigation area can be basically mitigated. And we should pay more attention about the water demand in Taoqupo irrigation area. It is also worth noting that the agricultural water supply guarantee rates of the Shitou River, Heihuiqu, Shibianyu, Lijia River, and Jianyu irrigation areas in scenario 1 were lower than that in scenario 2.

4.3. Water supply to the quality agent

It is widely known that concentrations of COD and NH_3-N in the non-flood season are greatest. To confirm the validity of the optimization-simulation method proposed in this study, a comparative analysis of water qualities during the non-flood season between regulated and unregulated results was conducted.

Based on the measured runoff, the water quality simulation model (one-dimensional water quality model) and future sewage, the unregulated water quality (concentrations of COD and NH_3-N) in 2020 can be derived as shown in Fig. 5. Then, based on the optimal water resources allocation results calculated in Section 4.2, the regulated instream streamflow “regulated streamflow 2” can be obtained. The average regulated instream streamflow of 13 water function areas during the non-flood season in two scenarios are shown in Table 7. Based on the regulated instream streamflow and the future sewage quantity, the regulated instream concentrations of COD and NH_3-N in scenario 1 and scenario 2 were calculated using the water quality simulation model (also shown in Fig. 5).

Fig. 5 shows that for the same water function area in the non-flood season, concentrations of COD and NH_3-N from high to low are in dry, semi-dry, normal, and wet years. Concentrations were positively correlated with the instream streamflow. For unregulated water quality, the concentrations of COD from Wolongsiqiao (2) to Changxingqiao (4) were relatively smaller. Concentrations generally continued to increase, reaching their peak in the Shangwangdu (11) water function area. Similarly, the concentrations of NH_3-N from Wolongsiqiao (2) to Changxingqiao (4) were relatively low but rose in later areas. In a wet year, the concentration of NH_3-N in Xianyangtieqiao (7) was the highest while in other typical years,

Table 6
Water supply guarantee rates of 12 irrigation areas in scenario 1 and scenario 2.

Irrigation areas	Water supply guarantee rate (%)							
	Scenario 1				Scenario 2			
	Domestic	Industrial	Agricultural	Ecological	Domestic	Industrial	Agricultural	Ecological
Yuanshang	100	89	75	100	100	89	75	100
Fengjiashan	100	100	75	100	100	100	75	100
Shitou River	\	\	74	\	\	\	75	\
Yuanxia	100	99	75	100	100	99	75	100
Yangmaowan	100	100	75	100	100	100	75	100
Heihuiqu	\	\	68	\	\	\	75	\
Jinghuiqu	100	100	75	100	100	100	75	100
Shibianyu	\	\	65	\	\	\	75	\
Lijia River	\	\	53	\	\	\	75	\
Taoqupo	100	77	70	100	100	77	70	100
Jiaokouchouwei	100	100	75	100	100	100	75	100
Jianyu	\	\	70	\	\	\	75	\

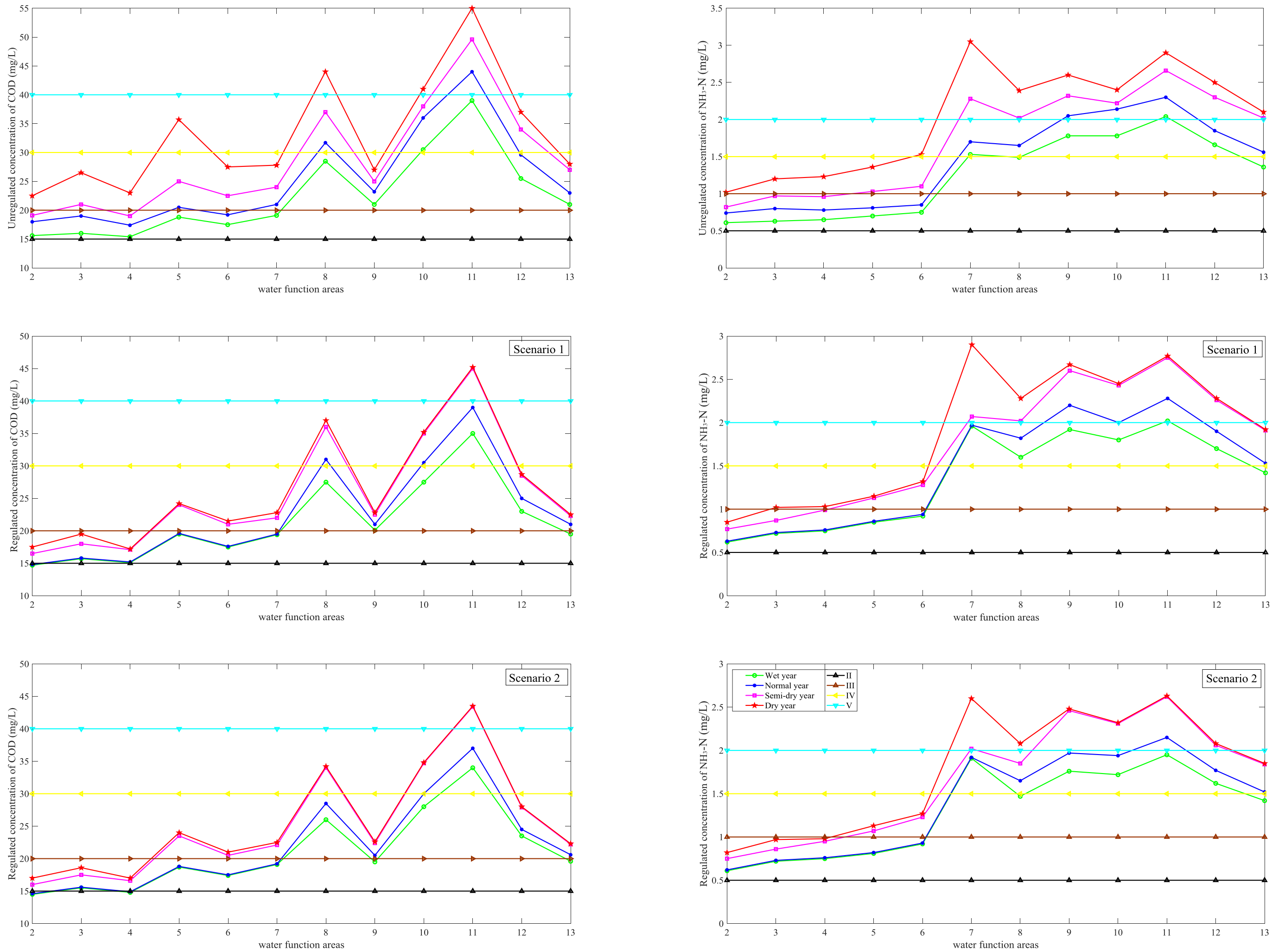

Fig. 5. Unregulated and regulated instream concentration of COD and NH_3-N in the non-flood season.

Table 7
Regulated streamflow of 13 water function areas of two scenarios in the non-flood season.

Scenario		Scenario 1				Scenario 2			
Typical year		Wet	Normal	Semi-dry	dry	Wet	Normal	Semi-dry	dry
Water function area	1	33.9	31	13.2	5.8	34	31.1	13.4	5.9
	2	32.8	30.9	16.4	11.4	33.1	31.2	16.7	12.3
	3	33.7	31.8	17.3	12.4	34.1	32.2	17.6	13.3
	4	31.4	31	14.4	13.9	34.7	34.5	16.8	15.3
	5	32.5	32.1	15.5	15	35.8	35.6	17.9	16.4
	6	35.4	35.2	17.5	16	37.3	37.1	19.4	17.9
	7	42.2	42	23.4	21.4	45.9	45.7	28	26.5
	8	59.9	45.9	32.6	30.8	70.2	56.3	37.1	36.6
	9	67	53	39.7	37.9	76.7	62.9	43.7	43.2
	10	79.4	65.5	46.3	45.8	84.2	70.4	51.2	50.7
	11	80.5	66.6	47.4	46.9	86.3	72.4	53.2	52.7
	12	81.5	67.7	48.5	48	88.3	74.5	55.3	54.8
	13	81.7	68	47.5	46.9	82.7	68.9	48.5	47.9

concentrations of NH_3-N in Shawangdu (11) were the highest. For regulated water quality, the COD and NH_3-N concentration variance in scenario 1 and scenario 2 were similar to those of unregulated water quality. The concentration of COD in Shawangdu (11) and of NH_3-N in Xianyangtieqiao (7) and Shawangdu (11) were the highest relatively.

According to the Environmental Quality Standard for Surface Water, surface water quality is divided into many classes: I, II, III, IV, V, and <V (worse than V), which ranges in a spectrum from good to bad. According to the surface water quality classification standard, the unregulated and regulated average surface water quality classes of 12 water function areas were calculated based on the fuzzy comprehensive evaluation method (Li et al., 2009), shown in Table 8.

Table 8
Surface water quality classes of the unregulated and regulated water quality.

Streamflow	Typical year	Surface water quality classes in each water function area											
		2	3	4	5	6	7	8	9	10	11	12	13
Unregulated streamflow	Wet	II	II	II	III	II	IV	IV	III	IV	<V	IV	III
	Normal	III	III	III	III	III	III	IV	<V	<V	<V	IV	IV
	Semi-dry	III	III	III	III	III	<V	<V	<V	<V	<V	<V	<V
	Dry	III	IV	III	IV	IV	<V	<V	<V	<V	<V	<V	<V
Regulated streamflow Scenario 1	Wet	I	II	II	III	III	V	IV	III	IV	<V	IV	III
	Normal	I	II	II	III	III	V	IV	<V	IV	<V	V	IV
	Semi-dry	II	III	III	III	III	<V	<V	<V	<V	<V	<V	V
	Dry	III	III	III	III	III	<V	<V	<V	<V	<V	<V	V
Regulated streamflow Scenario 2	Wet	I	II	I	III	III	III	IV	III	IV	V	IV	III
	Normal	I	II	I	III	III	III	IV	III	V	<V	IV	IV
	Semi-dry	II	III	III	III	III	<V	V	<V	<V	<V	<V	III
	Dry	III	III	III	III	III	<V	<V	<V	<V	<V	<V	III

Table 8 shows that the comprehensive water quality in the downstream of Xianyangtieqiao (7), i.e., the downstream water qualities of the Guanzhong Plain, were inferior to those upstream. This is consistent with the characteristics shown in Fig. 5. In addition, Fig. 5 show that the unregulated pollutant measure indicator concentrations were higher than regulated pollutant measure indicator concentrations (both in scenario 1 and scenario 2). Similarly, Table 8 displays that the unregulated surface water qualities were mostly worse than the regulated surface water quality (regardless of scenario). This indicates that reasonable water resources allocation may lead to water quality improvement.

Furthermore, Fig. 5 and Table 8 reveal that the regulated surface water qualities in scenario 2 are superior to those in scenario 1; although, the difference is relatively small. Better satisfaction of quantity and quality agent in scenario 2 (see the results in Section 4.2 and 4.3) indicates that the construction of the inter-basin water transfer project (HWWTP) can better aid in water storage while also improving the water quality in the Guanzhong Plain. Reasonable water resources allocation that considers future water conservancy projects is advantageous for the sustainable utilization of water resources and the harmonious development between economic and environmental water demand.

5. Discussions

5.1. Results analysis

The downstream control sections' environment demands are relatively well satisfied compared to those of the upstream control sections from Section 4.1. The reason is as follows: Fig. 1 demonstrates that upstream water conservancy projects and tributaries are smaller in comparison to those downstream. The Wei River is a rain-fed river, and so more tributaries in the downstream will decrease the low flow uncertainty in the non-flood season. In addition, more water conservancy projects can better regulate the streamflow, which may also reduce the extreme low flow events downstream. Section 4.2 shows that the agricultural water supply guarantee rates of five irrigation areas in scenario 1 are lower than in scenario 2 because these five irrigation areas are in the water-receiving area of the Han River-to-Wei River Water Transfer Project (details in Fig. 1). In scenario 1, this project is not supposed to be completed, so the transferred water is not considered, and the water supply to the agricultural sector is used by the industrial sector. Therefore, the agricultural water supply guarantee rates of these five irrigation areas (especially the Lijia River) were inferior in scenario 1. These indicate that the inter-basin water transfer project construction is beneficial for reducing water scarcity. Also, the upstream water quality is better than that of the downstream, as seen in Section 4.3. Downstream of the Guanzhong Plain is the most developed region—especially the Xi'an region (provincial capital of Shaanxi Province), which is the political and economic center with the densest factories, population, and agriculture. With this density comes increased sewage, and this results in the growth of pollutant concentration.

5.2. Limitations and potential future work

In this paper, only two pollutant measure indicators (COD and NH_3-N) were considered to reflect organics content, which affect the results. In addition, due to the data limitation, two available years' water quality data were collected from the water quality monitoring stations. The one-dimensional water quality model calibrated and validated by limited data affects the model parameters (Liu et al., 2016). More data should be incorporated in the water quality model and the model uncertainty should also be analyzed (Zhai et al., 2017). In addition, we assumed that there was no significant change between future streamflow (in the planning year of 2020) and the current streamflow. Streamflow is related to multiple factors such as social economic development and climate change, rendering this assumption an oversimplification. Coupling hydrological models with the current optimization-simulation method to predict future streamflow can provide more reliable support for future policy makings. Furthermore, this study attempts to improve the water quality from the water quantity perspective. That means the water demand to improve the water quality is considered in the coupled model and this will improve the water quality to some extent. However, the water quality issue cannot be solved simply by water allocation in quantity. Water quality issue is affected by multiple factors: such as pollutant emission-time, social and economic development, riverine water quantity, and pollutant types. How to solve or remit the water quality from other perspective (such as government policy making, public education and technology development) is beyond the scope of this paper, and these should be our future research directions.

The Wei River Basin is a large basin affecting and affected by many complex factors. This study's perspective attempts to better meet the various, largescale water demands that the basin supplies. A more localized distribution of stakeholders is not considered. Future research can investigate the allocation of water to different stakeholders, as well as the effect of different pollutants, and the coupling of optimization-simulation method with hydrological models. Overall, this study can be seen as a small step to applying the optimization-simulation method while considering multi-water resources and multiagent simultaneously.

6. Conclusions

This study proposes an optimization-simulation method for managing the complex water resources allocation considering multi-water sources (local surface water, transferred water, groundwater, and reused sewage), water conservancy projects (water transfer projects, reservoirs, canal heads, and pump stations) and multiagent (water quantity, quality, and environment). First, groundwater and reused sewage are utilized by the water resources allocation simulation module with predetermined rules. Then, local surface water and transferred water are allocated to multiagent based on the water resources allocation optimization module considering all agents' objectives and the genetic algorithm. Finally, the instream water quality is calculated through the water quality simulation module. The primary results for the planning year of 2020 are as follows:

(1) Instream design ecological basic flow guarantee rates of five control sections: Linjiacun, Weijiabao, Xianyang, Lintong, and Huaxian during the non-flood season of two scenarios were all achieved. (2) The domestic, industrial, agricultural, and off-stream ecological water supplies (water supplies to the quantity agent) in two scenarios all obey their design basin water supply guarantee rates. In addition, the guarantee rates of different water users of economic sectors in scenario 1 are basically inferior to those in scenario 2. (3) Water quality is positively correlated with the instream streamflow. The downstream of the Guanzhong Plain is facing more serious water quality pollution, and greater measures need to be taken to improve the water quality in this area. (4) the regulated comprehensive water qualities of different water function areas in the two scenarios are better than unregulated water qualities. In addition, the regulated water qualities in scenario 2 are better than those in scenario 1; although, the difference is not very significant. The water resources allocation results considering the water transfer project (HWWTP) are even more encouraging, as this revealed that the total water supply capacity in the water-receiving area can be increased. And, in general, that the project can better cultivate sustainable development of the water-receiving area. The proposed optimization-simulation method can be applied to other regions for mitigating the adverse impact of water shortages.

Conflicts of interest

Authors declare that they have no conflict of interest.

Acknowledgements

This study is supported by The National Key Research and Development Program of China (2016YFC0400906) and the National Natural Science Foundation of China (91647112, 51679187, 51679189). The authors thank the editors and reviewers for their technical comments.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2018.12.065.

References

Afzal, J., Noble, D.H., Weatherhead, E.K., 1992. Optimization model for alternative use of different quality irrigation waters. J. Irrigat. Drain. Eng. 118 (2), 218–228.
Brown, C.M., Lund, J.R., Cai, X., Reed, P.M., Zagona, E.A., Ostfeld, A., Hall, J., Characklis, G.W., Yu, W., Brekke, L., 2015. The future of water resources systems analysis: toward a scientific framework for sustainable water management. Water Resour. Res. 51 (8), 6110–6124.
Chang, J., Li, Y., Wang, Y., Yuan, M., 2016. Copula-based drought risk assessment combined with an integrated index in the Wei River Basin, China. J. Hydrol. 540, 824–834.
Emch, P.G., Yeh, W.W., 1998. Management model for conjunctive use of coastal surface water and ground water. J. Water Resour. Plann. Manag. 124 (3), 129–139.
George, B., Malano, H., Davidson, B., Hellegers, P., Bharati, L., Massuel, S., 2011. An integrated hydro-economic modelling framework to evaluate water allocation strategies I: model development. Agric. Water Manag. 98 (5), 733–746.
Gleick, P.H., 1993. Water and conflict: fresh water resources and international security. Int. Secur. 18 (1), 79–112.
Huang, S., Hou, B., Chang, J., Huang, Q., Chen, Y., 2014. Copulas-based probabilistic characterization of the combination of dry and wet conditions in the Guanzhong Plain, China. J. Hydrol. 519, 3204–3213.
Jeuland, M., Whittington, D., 2014. Water resources planning under climate change: assessing the robustness of real options for the Blue Nile. Water Resour. Res. 50 (3), 2086–2107.
Kamali, A., Niksokhan, M.H., 2017. Multi-objective optimization for sustainable groundwater management by developing of coupled quantity-quality simulation-optimization model. J. Hydroinf.
Li, T., Cai, S., Yang, H., Wang, X., Wu, S., Ren, X., 2009. Fuzzy comprehensive-quantifying assessment in analysis of water quality: a case study in Lake Honghu, China. Environ. Eng. Sci. 26 (2), 451–458.
Liu, J., Liu, Q., Yang, H., 2016. Assessing water scarcity by simultaneously considering environmental flow requirements, water quantity, and water quality. Ecol. Indicat. 60, 434–441.
Lu, Y., Song, S., Wang, R., Liu, Z., Meng, J., Sweetman, A.J., Jenkins, A., Ferrier, R.C., Li, H., Luo, W., Wang, T., 2015. Impacts of soil and water pollution on food safety and health risks in China. Environ. Int. 77, 5–15.
Lund, J.R., Ferreira, I., 1996. Operating rule optimization for Missouri River reservoir system. J. Water Resour. Plann. Manag. 122 (4), 287–295.
Manshadi, H.D., Niksokhan, M.H., Ardestani, M., 2015. A quantity-quality model for inter-basin water transfer system using game theoretic and virtual water approaches. Water Resour. Manag. 29 (13), 4573–4588.
Peralta, R.C., Forghani, A., Fayad, H., 2014. Multiobjective genetic algorithm conjunctive use optimization for production, cost, and energy with dynamic return flow. J. Hydrol. 511, 776–785.
Paredes, J., Andreu, J., Solera, A., 2010. A decision support system for water quality issues in the Manzanares River (Madrid, Spain). Sci. Total Environ. 408 (12), 2576–2589.
Percia, C., Oron, G., Mehrez, A., 1997. Optimal operation of regional system with diverse water quality sources. J. Water Resour. Plann. Manag. 123 (2), 105–115.
Pulido-Velazquez, M., Andreu, J., Sahuquillo, A., Pulido-Velazquez, D., 2008. Hydro-economic river basin modelling: the application of a holistic surface–groundwater model to assess opportunity costs of water use in Spain. Ecol. Econ. 66 (1), 51–65.
Ren, C., Guo, P., Tan, Q., Zhang, L., 2017. A multi-objective fuzzy programming model for optimal use of irrigation water and land resources under uncertainty in Gansu Province, China. J. Clean. Prod. 164, 85–94.
Ross, A., 2017. Speeding the transition towards integrated groundwater and surface water management in Australia. J. Hydrol.
World Bank, 2016. High and Dry: Climate Change. Water, and the Economy, Washington, DC.
Yang, J., Chang, J., Wang, Y., Li, Y., Chen, Y., Huang, Q., Yao, J., 2018. Comprehensive drought characteristics analysis based on a nonlinear multivariate drought index. J. Hydrol. 557, 651–667.
Yamout, G., El-Fadel, M., 2005. An optimization approach for multi-sectoral water supply management in the Greater Beirut Area. Water Resour. Manag. 19 (6), 791–812.
Yazdi, J., Golian, S., Roohi, M., 2017. Determining checkdams layout for lood mitigation using simulation-optimization approach. Int. J. Environ. Res. 11 (3), 395–413.
Zhai, X., Xia, J., Zhang, Y., 2017. Integrated approach of hydrological and water quality dynamic simulation for anthropogenic disturbance assessment in the Huai River Basin, China. Sci. Total Environ. 598, 749–764.
Zhang, J.J., Ma, X.M., Huang, J.H., Xu, X.L., 2010. Study on self-purification water requirements for the Yellow River. J. Hydraul. Eng. 41 (8), 977–983.
Zhu, L., Song, J.X., Liang, L.H., Li, H., Wei, A.L., Zhang, B., 2013. Applicability analysis on the improved one-dimension steady-state river water quality model. In: Applied Mechanics and Materials, vols. 405–408, pp. 2254–2259.