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Optimal allocation of regional water resources in an arid basin: insights from Integrated Water Resources Management

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ABSTRACT

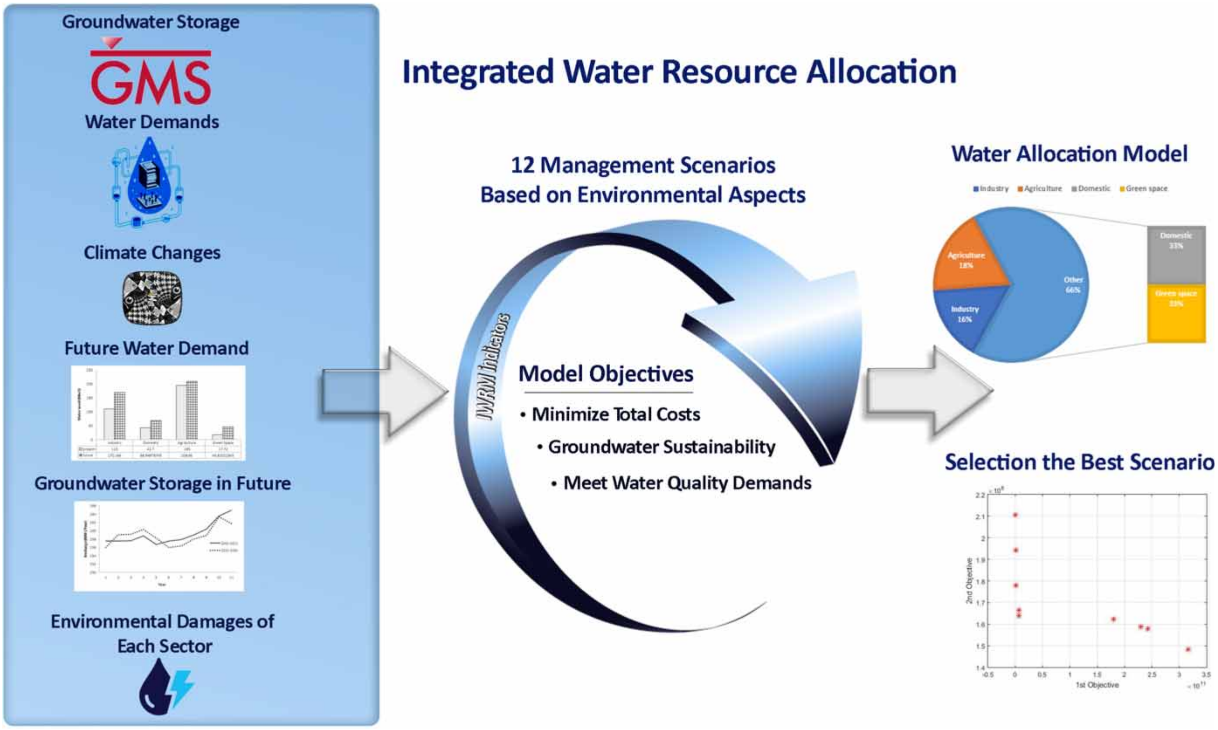
Viewing water management as a multifaceted issue is critical to achieving sustainable water management. This paper proposes an integrated optimal allocation model for aquifer sustainability and environmental benefits when managing conjunctive water resources. Optimization techniques such as genetic algorithm (GA) and non-dominated sorting genetic algorithm (NSGA-II) are used to balance economic benefit and demand management based on decision makers' preferences. The findings indicate that less water was allocated to industries with high water demand. The value of the allocated water to these industries is between 34 and 52%. Thus, it concluded that specific industries are unsustainable when environmental damage is considered. From the scenarios examined, scenario 10 (water resource conditions and water demands are determined based on existing conditions, considering domestic water management and aquifer restoration) was found to be the optimal water management scenario. The indicators of Integrated Water Resources Management (IWRM) for this scenario are 0.30, 0.15, 190, 40.9, and 0.55 for relative water stress, aquifer sustainability, aquifer attenuation period, aquifer recovery potential, and agricultural water productivity, respectively. This finding implies that considering demand management, wastewater treatment, and the absence of industrial development in development scenarios, it will be possible to conserve aquifers and meet water demands.

Key words: environmental sustainability, genetic algorithm, Integrated Water Resources Management, non-dominated sorting genetic algorithm, optimization

HIGHLIGHTS

- This study is an attempt to resolve water resource conflicts in an arid area.
- Water resource allocation between users considers an economic function based on environmental damage.
- Water resource allocation uses intelligent algorithms.
- Different management scenarios for the future management are considered.
- Integrated water resource management criteria to select the best scenario are concerned.

GRAPHICAL ABSTRACT



INTRODUCTION

Increased demand for water will inevitably result in conflict, particularly in developing countries where more pressure is being placed on scarcer water resources (Zhang *et al.* 2011). Water scarcity has exacerbated social tensions, escalating conflict between and within countries. Over the last century, there have been over 280 treaties relating to water (Wolf 2002). Despite increased efforts to organize negotiations, freshwater conflicts continue to exist and grow as population and land development increase (Nandalal & Simonovic 2002). The continued exploitation of water resources has resulted in the destruction of sustainability due to natural and man-made evolution over the centuries. The appropriate allocation of water resources is a solution to avoid conflict and further depletion.

A review of previous research on optimal water allocation revealed that this history could be divided into four distinct phases: 1 – the exploration phase, which began in the 1960s, and subsequent studies aimed to achieve real-time operation of a single reservoir. This stage saw the onset of cooperative water resource management. Simple research methods such as Fuzzy Logic and Decision-Making Methods were used throughout the process. 2 – The development phase involves applying new techniques to the simulation and optimization of water resources, where nonlinear programming (NLP) techniques, including search, quadratic, geometric, and separable programming techniques, were employed. Hicks *et al.* (1974), Haimes (1977), and Rosenthal (1980) documented the use of NLP in their research.

Additionally, several studies have documented the use of genetic algorithms (GAs) in water resource management, including East & Hall (1994) and Oliveira & Loucks (1997). 3 – Maturity phase: optimal allocation achieved overall development during this stage. Water allocation studies introduced novel concepts, such as sustainable development and highly efficient use of water resources. 4 – Rapidly developed extensional phase considers sustainable development and ecological concepts in water resource management. Additionally, IWRM was used at the basin scale in the studies.

IWRM is an effective strategy for preserving water bodies while meeting the competing demands of stakeholders. IWRM has recently received increased attention (Agarwal *et al.* 2000). Furthermore, decision-makers considered evaluating IWRM practically to gain access to this concept. Numerous scientific studies proposed a novel approach to achieving water resource sustainability. System analysis models are generally classified into two types: simulation and optimization. Optimization models are frequently used for preliminary evaluation or screening alternatives and identifying critical data requirements before extensive data collection and simulation modeling activities. The hydro-economic optimization model was used to simulate and address optimal conjunctive use of water resources in an arid region of Iran using IWRM principles.

In 1963, Buras proposed the concept of optimizing the conjunctive use of water resources. Numerous subsequent studies in this field have been conducted, including Coe Jack (1990), Latif (1991), Azaiez (2002), Pulido-Velázquez *et al.* (2006); Dale Larry *et al.* (2008), Chang *et al.* (2009), Kim & Chang (2013), Allawi *et al.* (2018), Ehteram *et al.* (2018, 2019), and Yaseen *et al.* (2019). These studies are classified into two groups: reservoir simulation and problem optimization. Typically, some simplifications were made during the simulation phase, most notably in the groundwater flow dynamics. This is due to (i) the heterogeneous nature of the aquifer, which results in complex flow patterns. Only mathematical and numerical models could be used to simulate these intricate patterns. (ii) Linking numerical models to optimization models leads to computational complexities (Dogrul *et al.* 2016).

Despite these challenges in groundwater simulation, some studies used numerical models for groundwater modeling in conjunction with other water resource management techniques. For instance, Emch & Yeh (1998); Belaineh *et al.* (1999); Labadie & Larson (2007); Rani & Moreira (2010); Singh & Panda (2013); Elçi & Ayvaz (2014); Fowler *et al.* (2015); Dogrul *et al.* (2016); Rossetto *et al.* (2019), and Jha *et al.* (2020) used a numerical model for aquifer simulation and linked it to an optimization model to manage a conjunctive water resource problem. Zhang *et al.* (2019) used an inexact joint probabilistic double-sided stochastic chance-constrained programming (IJDSCCP) model to resolve conflicts between decision-makers in order to achieve sustainable water resource management (Zhang *et al.* 2019). Li *et al.* (2021) presented an interval fuzzy credibility constrained two-level programming (IFCTP) model for water resource management under uncertainty in the henna section of China's South to North water diversion project.

Almost all research conducted prior to 2016 utilized an economic goal function based on cost and benefit without considering the environmental costs incurred by various users. Furthermore, researchers have applied ecological concepts to the economic function of surface reservoirs in recent years. However, due to the difficulties inherent in integrated modeling, environmental perspectives have received less attention in studies examining the concurrent use of water resources. Moreover, previous studies that applied IWRM principles reported some difficulties, including complexity in water body simulation, uncertainty in water environments, climate change, and data scarcity in the basin area. Thus, a comprehensive study incorporating numerical model simulations of aquifers, water allocation between basin users based on IWRM indices, and climate change effects could be beneficial. Despite the importance of the study area in terms of industry, agriculture, and population, and the growing trend of water conflicts between users, decision-makers lack access to comprehensive studies necessary to manage water allocation effectively. Water managers in the study area have made various attempts to balance the competing interests of various stakeholders.

Economic profitability and user satisfaction are primary considerations in decision-making processes. However, the degradation of aquifer quality and sustainability caused by human activities remains unaddressed. This study attempts to address this issue by incorporating environmental aspects of water use and social and economic indices into the study area's water allocation policies. This study aims to develop an integrated water resource allocation model based on an economic goal function that considers the environmental damages caused by each user's concurrent use of groundwater and surface water. Additionally, a numerical model was used to simulate the storage of groundwater and available aquifers under changing climate conditions. The findings of these studies may aid decision-makers in examining the consequences of utilizing various water allocation scenarios from different perspectives.

METHODS

This research is divided into two phases: the present and the future. Parameters such as exploitation wells, drainage, the type and amount of rainfall, water stakeholders, and various stakeholders' economic and social benefits were gathered to compile comprehensive data on the study area's water resources. Because the aquifer is the primary source of water in the study area, it was necessary to calculate the aquifer's water balance and available storage in monthly time steps to perform the water resource allocation process. The MODFLOW model was used to extract data on aquifer storage. Economic benefit was calculated by analyzing aquifer storage data; water transferred discharge and the environmental costs were associated with various exploitation groups. Optimization techniques were used to allocate water resources.

There are two stages to resource allocation optimization. The first stage is based on mathematical relations, such as objective functions and constraints. The second stage is concerned with the available data and the problem scales. Taking these two stages into account and the benefits of GA, such as global optimization, parallelism, and operation with nonlinear functions (Yang 2020), the GA was chosen to solve the problem. NSGA-II is an enhanced version of Deb's non-dominated sorting genetic algorithm (NSGA) from 2000. This is a well-known evolutionary algorithm that has been the subject of numerous studies. It is constructed using a GA with a multi-objective process. Survival of the fittest is the primary goal of the GA. This procedure enables them to transfer genomes from one generation to the next. This means that improved adaptations are formed in subsequent generations. This research compared the results of two optimization techniques, namely the GA and NSGA-II, to determine optimal solutions. Figure 1 depicts the study's flowchart.

Study area and data used

The research area is located in Iran's central region. The study site is located in Iran's Yazd province between 53° 30 and 55° east longitude and 31° 15 to 32° 30 north latitude (Figure 2). This area is a significant industrial and mineral resource

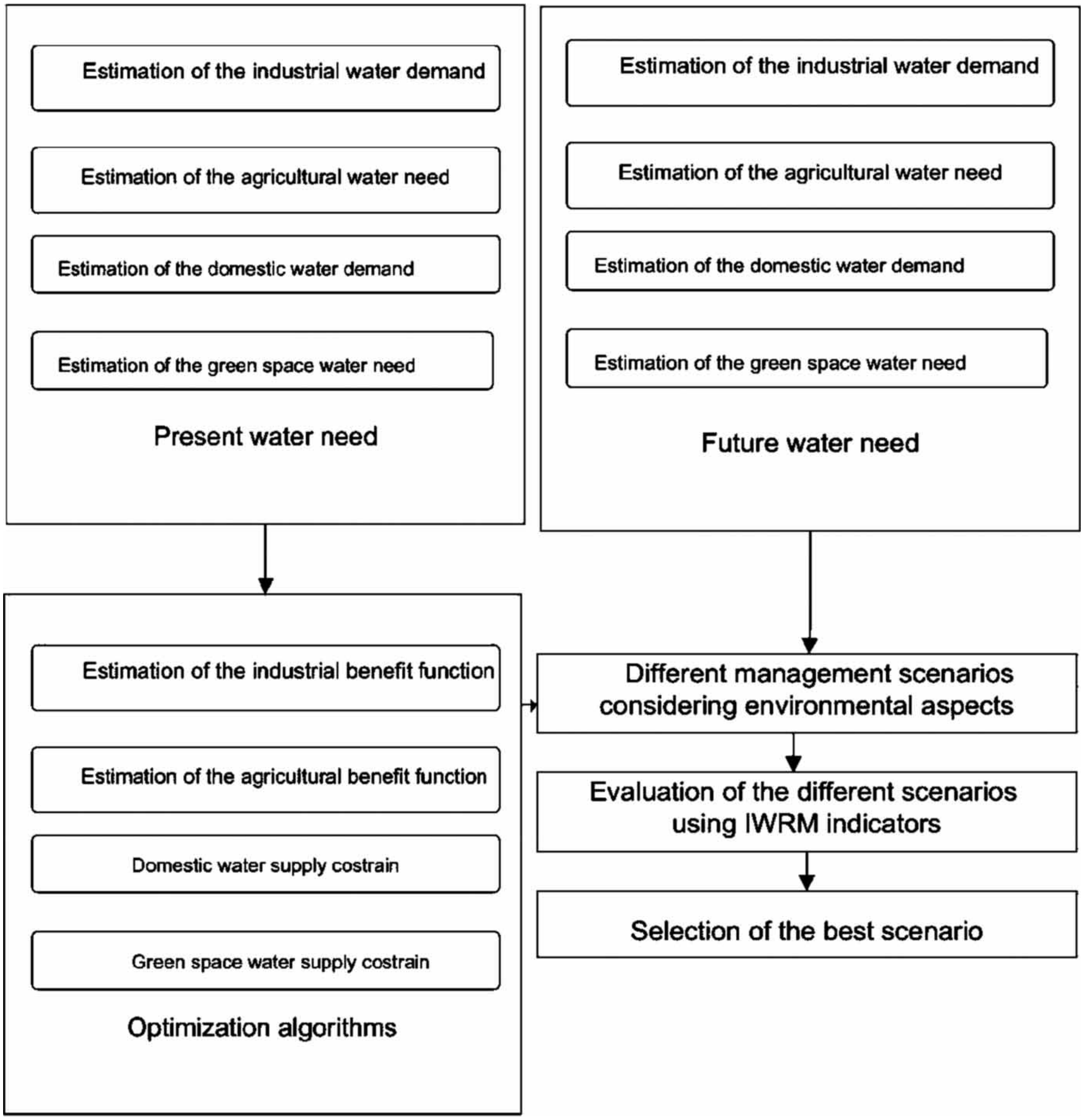


Figure 1 | Flowchart of the research.

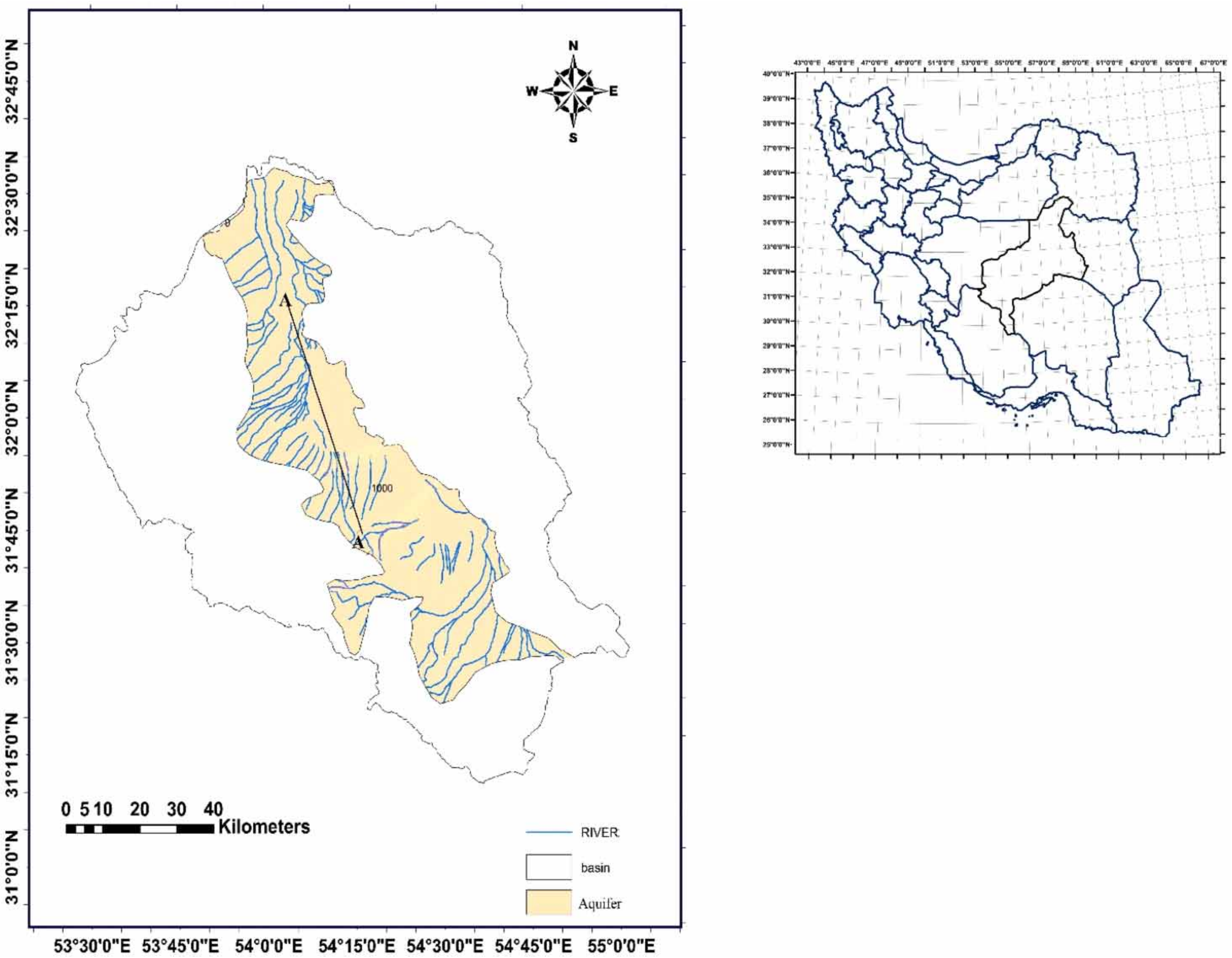


Figure 2 | Location of study area.

area. This region is comprised of four cities: Yazd, Ashkezar, Meybod, and Ardakan. There is no year-round surface water in the study area, and the region's primary water source is the Yazd-Ardakan aquifer. The region is characterized by a hot and arid climate. Precipitation and temperature averages for the year are 55 mm and 19.1 °C, respectively. The area has a warm and dry climate. Groundwater is critical for human survival and development due to these climatic factors.

A hydrogeologic cross-section of the Yazd-Ardakan aquifer along the A–A′, which is derived from data from the exploration wells, is depicted in Figure 3. A clay-rich aquitard layer taps the confined aquifer (light-blue layer in Figure 3).

According to Figure 3, the aquifer's geological materials are primarily unconsolidated sediments, and their thickness decreases from south to north (left to right). The thickness of the topmost clay unit (blue) reveals the confining aquitard layer.

Population growth and industrial and agricultural developments in the area have resulted in aquifer overexploitation of approximately 71 Mm^3/year and a water table decline of approximately 1.1 m/year (Malekinezhad & Banadkooki 2018). The mountainous area to the west and south of the basin plays a significant role in recharging the aquifer. The groundwater level fluctuated between October and April. The study area's primary water consumers are domestic, industrial, agricultural, and green spaces. In recent decades, unbalanced and accelerated development of the area, combined with intense competition among exploiters, resulted in a significant decline in aquifer storage and interbasin water transportation (Malekinezhad & Banadkooki 2018).

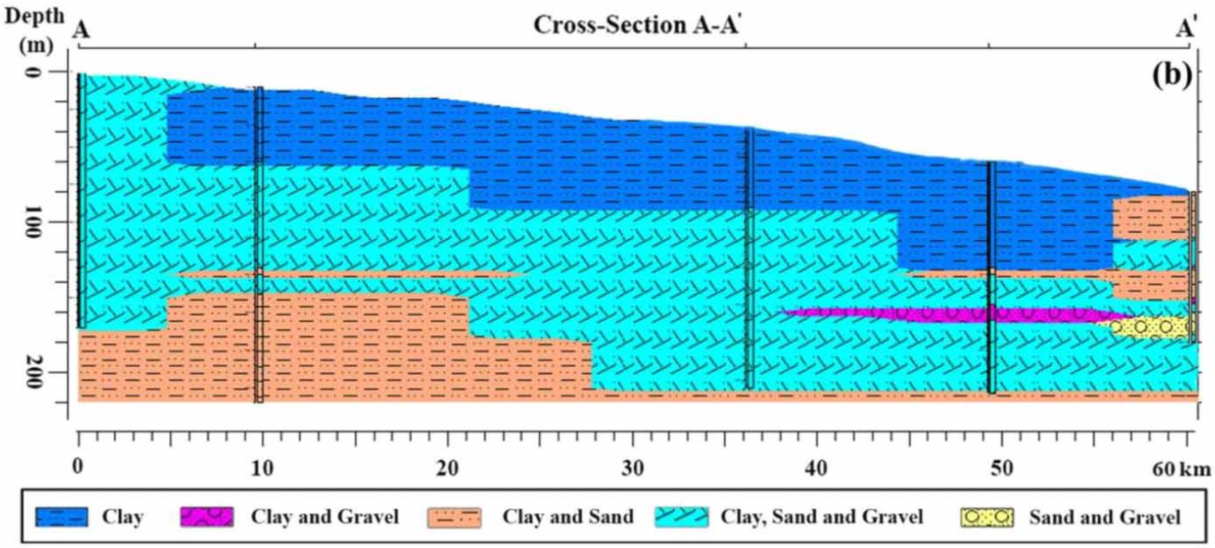


Figure 3 | Hydrogeological cross-section of the Yazd-Ardakan aquifer along the A–A′ line.

Future water demand

To develop the model, data related to the Yazd-Ardakan region's water supply system, such as land use, amount of water supply from various sources, and other relevant data, were gathered from various departments, including the Regional Water Company, Municipality, Agricultural Organization, and Industries and Mines department.

According to the Iranian Bureau of Statistics, the population growth rate is approximately 2.24%, which is used to forecast future population and associated domestic water demand in this study. The future industrial water demand is estimated using 2030 development scenarios. Since the basin's agricultural area cannot be increased, the future water demand of this sector is calculated using the currently cultivated area and projected climate changes. Malekinezhad & Banadkooki (2018) estimate that agricultural water requirements in the study area will increase by 7% due to climate change. With climate change in mind, the future water demand for green space was estimated based on the basin's future population and the standard 15 m^2 of green space per capita.

Estimating economic function based on environmental costs for industrial and municipal sections

For the municipal sector, the benefit of the water supply system is set to zero, or when the environmental costs of this section are considered, it contains a negative value. Due to the critical nature of this section's water supply, no benefit function was estimated, and municipal water supply was treated as a constraint in the optimization model. The quantity and quality of water used in the industrial sector are determined by the country's level of development, the type of industry, and the manufacturing process. The questionnaires requested water quantity and quality data, product type, production rate, wastewater volume, and wastewater treatment (Appendix A). Marginal water and benefit functions are calculated by considering the environmental cost of wastewater treatment for each industry, using available data derived from questionnaires. In nearly all cases, industries dumped industrial waste into the ground. According to studies, the wells drilled to bury these wastes are insufficiently deep, allowing dangerous chemicals and waste to enter the aquifer that supplies a significant portion of the area's drinking water (Banadkooki 2016).

Estimating economic function based on environmental costs for the agricultural section

Apart from salt, nitrate is the most prevalent contaminant of groundwater. In cultivated areas, synthetic nitrogenous fertilizers may contaminate groundwater (Craswell 2021). The rate at which water moves from the root zone to the saturated area is determined by the depth of the water table and the properties of the aquifer. Farmers in Yazd-Ardakan province applied 200 kg/ha NO_3 fertilizer in 2015. According to studies, plants can absorb up to 50% of the total available nitrogen in the fertilizer. Nitrogen volatilizes into the surrounding air at 25% as ammonia and nitrogen gas. Nitrogen from fertilizers is discharged into runoff and surface water at less than 5%. Around 20% of the nitrogen is leached into the groundwater

(Harter 2009). Malekinezhad & Banadkooki (2018) estimate that agricultural land recharge in the study area is approximately 7,964.2 m^3/ha-year. Thus, the amount of nitrogen that contaminated groundwater is estimated to be 3.7 mg/L, which is negligible compared to the allowable nitrate limit of 10 mg/L. Hence, the agricultural sector's benefit function could be estimated by considering the marginal water requirements of each product (by using the CROPWAT software and estimating the water requirements of each crop) and the agricultural sector's net benefits.

Evaluation model

Two steps were considered when conducting the simulation.

1. A climate simulation process was used to forecast future climates. This stage was performed using a stochastic weather generator based on the LARS-WG model (Semenov *et al.* 1998) and historical weather data. The simulation was conducted using climatic parameters such as precipitation, solar radiation, and maximum and minimum temperatures on daily time scales.
2. A three-dimensional model (MODFLOW) simulated the groundwater process. This stage involved the creation of a database containing hydraulic parameters, budget components, and geological and aquifer boundary conditions to develop an aquifer model using the GMS 8.3 software. Because groundwater is the primary source of water supply in the study area, the effects of climate change on aquifer storage have been incorporated into the model in terms of variation in the aquifer's water availability. The stochastic weather generator (i.e., Lars-WG) was used to generate future climate change prediction scenarios. The A_2 scenario was selected for future climate prediction in this study based on the continuous trend of the socio-economic situation in the future. As a result, the groundwater budget was modeled using MODFLOW with the predicted aquifer recharge. The simulation results were used as available aquifer storage by the optimization algorithms.

The integrated water management model with consideration for environmental damage is a mathematical programming model used to determine the optimal allocation of water from various water supply sources to meet the water needs of various users while also considering environmental sustainability and various system constraints.

Optimal model

The model formulation process begins with the specification of objective functions and various constraints. The formulated model is a nonlinear mathematical programming problem that was solved using GA and NSGA-II due to the complexity and extensiveness of the equations. The model framework is depicted in Figure 4. The objective function has been defined to determine the amount of water supplied from various sources over various planning periods. The GA's objective function is presented in Equation (1), while the constraints are presented in Equations (2) and (3). The objective function is defined as the maximized benefits of the system while considering environmental sustainability and a penalty term to demonstrate user satisfaction. Equations (4) and (5) illustrate the objective functions of NSGA-II. Objective function 1 (Equation (4)) maximized the system's benefits while considering environmental sustainability, while objective function 2 (Equation (5)) minimized the difference between required and allocated water. The constraints of NSGA-II are identical to those of GA (Equations (2) and (3)).

$$Max\ Z = [\sum_{k=1}^{K}\sum_{i=1}^{n}\beta_{ik}\left(\alpha_{ik}\sum_{j=1}^{J}(S_{ijk}+\ G_{ijk})\right)^{x_{ik}} + C_{ik}] - \gamma\sum_{k=1}^{k}\sum_{j=1}^{J}\sum_{i=1}^{n}|(D_{ijk}-\ T_{ijk})| \tag{1}$$

St.:

$$V_{jk1} \le \sum_{i=1}^{n} G_{ijk} \ \le V_{jk2}, \quad G_{ijk},\ S_{ijk} \ge 0, \quad 1 \le j \le J\ ,\ 1 \le k \le K \tag{2}$$

$$\delta_1 \le \sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{n} S_{ijk} \le \delta_2 \tag{3}$$

$$Max\ Z = [\sum_{k=1}^{K}\sum_{i=1}^{n}\beta_{ik}\left(\alpha_{ik}\sum_{j=1}^{J}(S_{ijk}+\ G_{ijk})\right)^{x_{ik}} + C_{ik}] \tag{4}$$

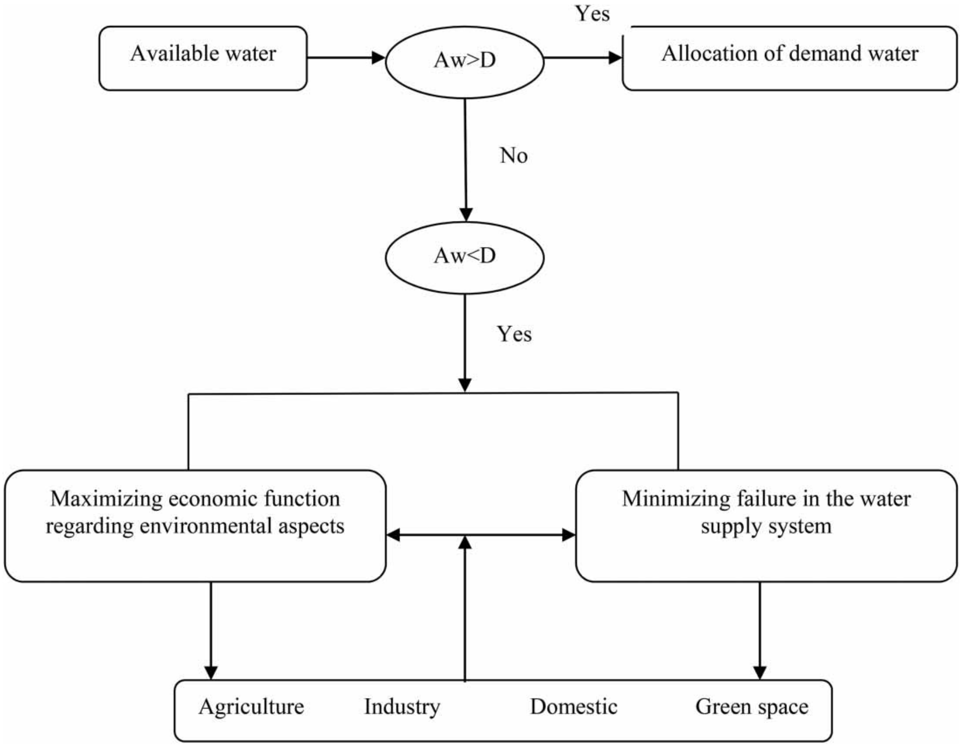


Figure 4 | Conceptual framework for the water allocation model.

$$Min\ F = \sum_{i=1}^{n}\sum_{j=1}^{J}\sum_{k=1}^{K}|(D_{ijk} - (S_{ijk} + G_{ijk}))| \tag{5}$$

where K is the index of area, j is the representative index of the month, i is the index of water demand sector, γ is the penalty coefficient, α_{ik}, β_{ik}, C_{ik} are coefficients associated with economic equations derived from each district K water demand sector, T_{ijk} is the water used by sector i in district k in month j, D_{ijk} is the water demand of sector i in district k in month j, S_{ijk} is the transitional water used by sector i in district k in month j, G_{ijk} is the groundwater used by sector i in district k in month j, V_{jk1} is the minimum amount of water that could be supplied from groundwater in district k and month j, V_{jk2} is the maximum amount of water that could be supplied from groundwater in district k and month j, δ_1 is the minimum amount of water that could be supplied from transitional water, δ_2 is the maximum of water that could be supplied from transitional water.

Water allocation in most studies on water resource management has been based on available water storage in monthly time steps. It is appropriate in these instances to supply water via surface water and storage dams. Thus, groundwater level fluctuations and changes in water demand do not occur concurrently; if groundwater serves as a source of water, annual storage is appropriate. Because the optimization model utilizes annually available storage, it is capable of allocating water needs efficiently. Increased groundwater extractions during the drier months can be offset by increased water recharge during the wetter months, provided that annual fluctuations in the groundwater table remain constant. Annual allocation from groundwater storage is shown in Equation (6):

$$V_{k1} \leq \sum_{i=1}^{n}\sum_{j=1}^{J} G_{ijk} \leq V_{k2}, \quad 1 \leq k \leq K \tag{6}$$

where V_{k1} is the minimum annual groundwater availability in district K and V_{k2} is the maximum annual groundwater availability in district K.

Mathematical model of the optimal operation of water resources based on one objective function

(1) The water allocation is considered the decision variable. Thus, the initial values of chromosomes represent the water allocation.
(2) Equation (1) is used as the objective function.
(3) Equations (2) and (3) were used as the constraints.
(4) The obtained values should satisfy the constraints.
(5) The mutation, selection, and crossover operators were used in each iteration to update the solution.
(6) The process continues until the convergence criterion is met.
(7) This process is performed for all the operational months.

Mathematical model of the optimal operation of water resources based on two objective functions

In this study, the NSGA-II was used to determine the optimal water allocation based on the following levels:

(1) In the first step, water allocation is considered as the decision variable. The algorithms should determine the optimal values of the water allocation. The population matrix, including the initial values of chromosomes, is initialized. The initial guesses of water allocation values are considered the initial population of chromosomes.
(2) Two objective functions are defined based on Equations (4) and (5) for the NSGA-II.
(3) Since these objective functions conflict, the multi-objective optimization problem was suggested to solve the problem.
(4) The operators of NSGA-II, including mutation, crossover, and selection, were used to update the solutions at each level.
(5) The best solutions are saved in an external archive.
(6) If the obtained values for water allocations were not feasible, the penalty function was used as a guide toward feasible solutions.
(7) The process continues until the stop convergence is met.
(8) The levels of 1–7 were performed for all operational months.
(9) The Pareto front presents a list of solutions, as observed in Figure 7.
(10) Each of the solutions is considered a candidate solution.
(11) A multi-criteria decision method (TOPSIS) was used to determine a rank for each solution.
(12) The solution with the best rank was considered the best solution.

An evaluation model comprised of IWRM indices

Various criteria from the IWRM approach, such as social, economic, and environmental indices, were used to assess the sustainability of water resources at the basin scale. These criteria evaluate various scenarios for integrated water resource management in the study area. Table 1 contains the selected criteria's name, calculation method, and basic characteristics.

RESULTS AND DISCUSSION

The study's findings are discussed in terms of current and future management scenarios. Additionally, IWRM indices are used as a criterion for selecting the optimal scenario.

Water demands in the present and future

Figure 5 illustrates comparisons of present and future water demand.

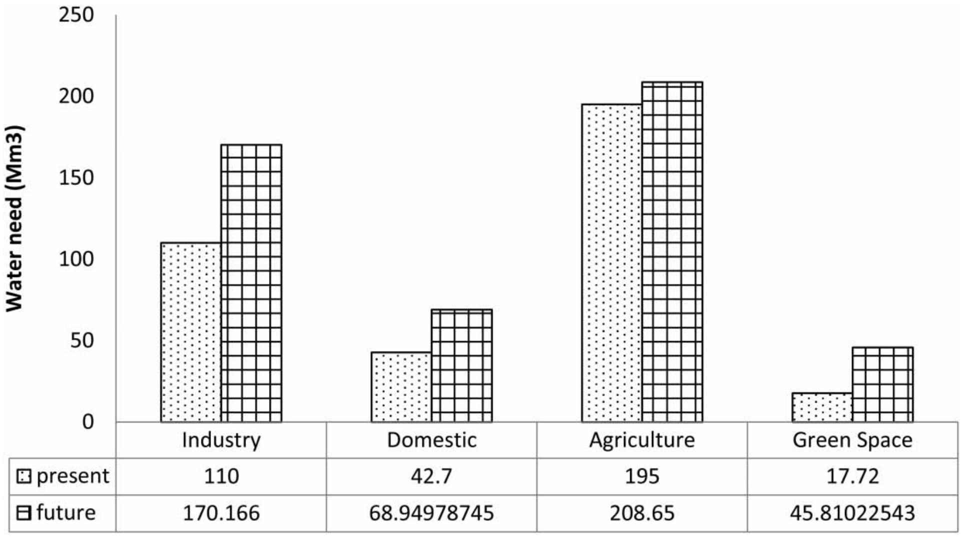
As depicted in Figure 5, the study area's total future water demand is 493.58 Mm^3/year. This extraction rate will result in a decrease in the groundwater level of approximately 2.43 m/year. With a 120-m-thick aquifer, attenuation will occur in 49 years.

Estimating the agricultural benefit function

As mentioned previously in the agriculture section, the agricultural benefit function related to water consumption should be defined in the model as a benefit equation. Evapotranspiration and required water were calculated to determine water used

Table 1 | Selected indices served to evaluate different management scenarios based on the IWRM approach

Index name	Unit	Calculation method	Commentary of index
Municipal, industrial, agricultural and landscape supply	%	Ratio of the allocated water to the water requirement	In municipal and industrial sectors, supply of 100% water demands is appropriate. About agricultural sector, supply of 90% water demands is acceptable.
Relative water stress	–	Ratio of the allocated water to the renewable water resources in the basin area	Between 0.2 and 0.4: water stress More than 0.4: severe water stress
Aquifer sustainability	–	Ratio of the water withdrawal from the aquifer to the aquifer recharges	Less than 0.4: sustainable Between 0.4 and 0.6: low sustainable Between 0.6 and 0.8: sustainable Between 0.8 and 1: very unsustainable More than 1: critical
Aquifer recovery potential	–	Ratio of the static volume of the aquifer to the annual withdrawal of the aquifer	Less than 10: high potential Between 10 and 30: average potential Between 30 and 50: weak potential More than 50: no recovery
Aquifer attenuation period	year	Ratio of the total aquifer volume to the annual withdrawal of the aquifer	The higher rate of aquifer attenuation period, the better scenario performance
Productivity of agricultural water	kg/m^3	Ratio of the agricultural production to its water usage	2 kg/m^3 is assumed a threshold for sustainable production in future



	Industry	Domestic	Agriculture	Green Space
▒ present	110	42.7	195	17.72
▦ future	170.166	68.94978745	208.65	45.81022543

Figure 5 | Composition of the present and future water demand.

for each product. Then, by plotting the calculated water requirements against the agricultural sector's net benefits, a nonlinear equation similar to that shown in Table 4 can be extracted.

Estimating the industrial benefit function

As mentioned previously, the environmental cost of industrial wastewater was estimated using the amount of industrial waste and the degree of pollutant ability of wastewater. Afterward, the net benefits of each industry were calculated using this data and marginal water. The proper equation was then extracted and presented in Table 2 by plotting industrial benefits against the amount of water required.

Table 2 | Industrial and agricultural benefit functions considering environmental costs

District name	Benefit function Agriculture	R^2	Industry	R^2
Ardakan	$Y = 2{,}720.9\times^{1.1331}$	0.82	$Y = 1 \times 10^6 x - 7 \times 10^7$	0.79
Meybod	$Y = 5{,}654.4\times^{0.9364}$	0.91	$Y = 8 \times 10^{10}\ x^{11.758}$	0.98
Ashkezar	$Y = 4{,}515.9\times^{1.0503}$	0.86	$Y = 320,\ 095x - 10^7$	0.94
Yazd	$Y = 1{,}404.3\times^{1.6415}$	0.78	$Y = 203,\ 474x - 8 \times 10^6$	0.97

Optimum water allocation using GA and NSGA-II

The GA and NSGA-II variables, including population size, the maximum number of iterations, crossover rate, mutation percentage, and mutation rate, were determined using the hit and trial method. The parameters of the optimization models are listed in Table 3. Table 4 depicts the optimal amount of water utilization in the agriculture, municipal, industrial, and green space sectors, which is calculated using GA and NSGA-II in MATLAB 2014 software, taking monthly and annual aquifer storage into account. Imported water is first allocated to the municipal sector, and then additional imported water is allocated to the industrial sector. Agriculture and green space sectors do not receive imported water.

The following conclusions were drawn from the Table 4 data:

Table 3 | GA and NSGA-II parameter setting

Parameters	Setting
Population size	50
Maximum number of iterations	100
Crossover rate	0.7
Mutation rate	0.02
Mutation percentage	0.4
Basis of chromosome selection	Bias variance

Table 4 | Results of optimum water allocation extracted from NSGA-II and GA

Model	Water-consuming sector	Unit	Ardakan	Meybod	Yazd	Ashkezar	Net benefits (Rial)
GA regarding monthly time step	Industry	%	84	134.2	93.7	60.069	-0.45×10^{14}
	Agriculture	%	87.6	85.4	90.83	85.97	
	Domestic	%	100	100	100	100	
	Green space	%	100	100	100	100	
GA regarding annual time step	Industry	%	53.96	380.85	42.52	56.25	6.12×10^{14}
	Agriculture	%	51.35	44.45	62.41	43.65	
	Domestic	%	100	100	100	100	
	Green space	%	100	100	100	100	
NSGA-II regarding monthly time step	Industry	%	89.59	202.78	85.25	76.92	-0.42×10^{14}
	Agriculture	%	86.33	85.44	80.44	79.34	
	Domestic	%	100	100	100	100	
	Green space	%	100	100	100	100	
NSGA-II regarding annual time step	Industry	%	52	477.5	39.44	48	6.74×10^{14}
	Agriculture	%	50.38	60.74	71.35	48	
	Domestic	%	100	100	100	100	
	Green space	%	100	100	100	100	

Water resources are prioritized for industries in the Meybod region. This region is home to low water-use industries that utilize water recycling systems to avoid producing significant wastewater. In other regions, high water consumption and high sewage and pollution discharge into the aquifer reduced the value of economic objects based on environmental damage, and eventually, they received a lower water allocation. Figure 6 illustrates the industrial wastewater discharge from various districts.

(1) Economic objectives are becoming increasingly important in NSGA-II operations. In other words, the NSGA-II allocates resources more efficiently than the GA.
(2) Considering groundwater storage on an annual basis is more efficient than groundwater storage every month in the optimization process. Since groundwater discharge and water demand fluctuations do not occur concurrently in monthly time steps, considering the annual aquifer storage allows the optimization algorithm to be highly flexible in achieving reasonable water storage to meet water demands.

In the case of NSGA-II, there are two objective functions: the first one is the maximization and the second one is the minimization. The Pareto front of this algorithm is presented in Figure 7.

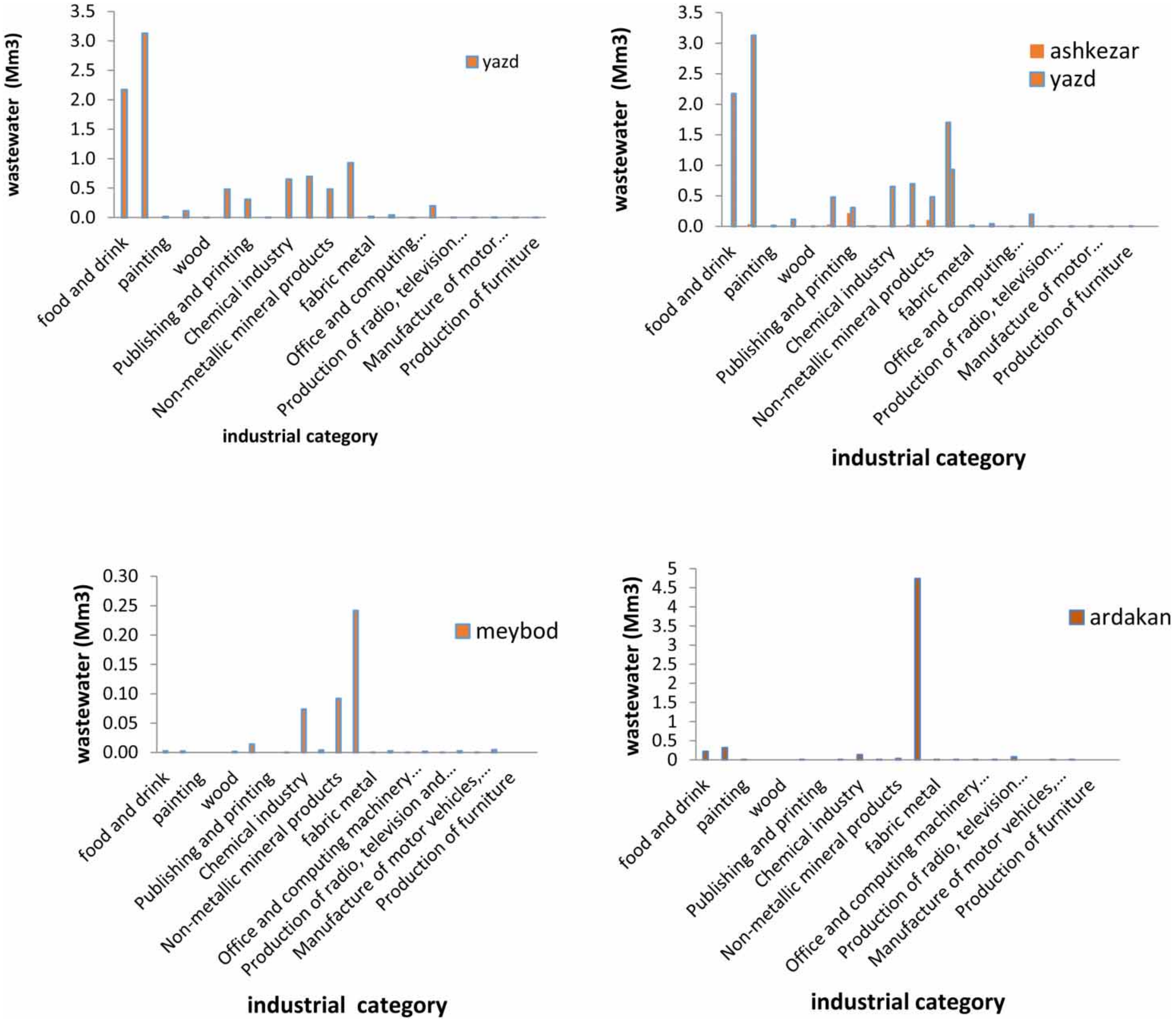


Figure 6 | Industrial wastewater discharges.

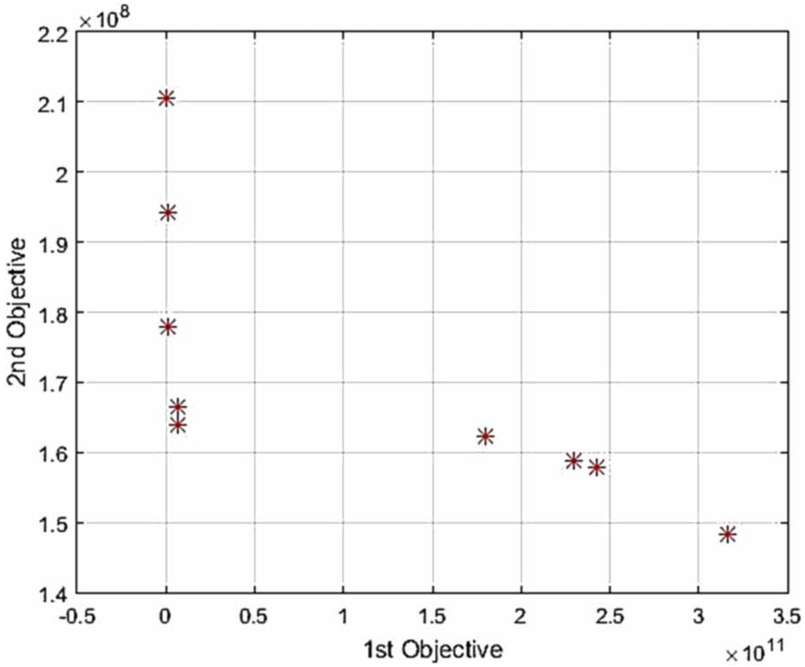


Figure 7 | Pareto front of the NSGA-II model.

Water allocation scenario definition

Various scenarios are considered to define a future perspective on the state of the study area's water resources. The scenario is defined as changes in agricultural, municipal, industrial, and green space water demand. Other strategies are investigated, including increasing irrigation water efficiency, industrial wastewater treatment, and implementing aquifer restoration programs. Based on the strategies above, 13 distinct scenarios are proposed and presented in Table 5.

Table 6 presents the results of an evaluation of various scenarios using IWRM indices.

Regarding results of the comparing optimization algorithms presented in Table 4, NSGA-II as a selected algorithm is used to allocate water resources based on 13 defined scenarios.

Table 5 | Different scenarios applied to define a perspective of the water resource condition in the study area

Scenario name	Scenario definition
Basic scenario	Water resource conditions and water demands are based on existing conditions
Scenario 1	Water resources based on the existing condition; higher water demands based on future growth in different sectors
Scenario 2	Scenario 1 considering agricultural water efficiency up to 70% and domestic water demand management
Scenario 3	Scenario 2 considering aquifer restoration
Scenario 4	Scenario 2 considering climate changes
Scenario 5	Scenario 3 considering climate changes
Scenario 6	Scenario 2 without any growth permission to the industrial sector
Scenario 7	Scenario 6 considering water demand management
Scenario 8	Scenario 6 considering climate changes
Scenario 9	Scenario 7 considering climate changes
Scenario 10	Basic scenario considering domestic water demand management and aquifer restoration
Scenario 11	Scenario 10 without industrial wastewater injection to the aquifer
Scenario 12	Water resources and water demands based on present conditions considering water demand management in all sectors, aquifer restoration without industrial wastewater injection to the aquifer

Table 6 | Evaluating different scenarios using IWRM indices

	Scenario name													
Indicator	**Unit**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Municipal supply	%	100	100	100	100	100	100	100	100	100	100	**100**	100	**100**
Industrial supply	%	53	51	52	51	53	53	49	71	48	74	**48**	61	**53**
Agricultural supply	%	69	67	67	69	59	65	73	71	73	72	**55**	54	**75**
Green space supply	%	100	100	100	100	100	100	100	100	100	100	**100**	100	**100**
Relative water stress	–	0.96	1.17	0.84	0.84	0.84	0.84	1.07	0.85	1.07	0.84	**0.30**	0.56	**0.52**
Aquifer sustainability	–	0.958	1.21	0.81	0.81	0.81	0.81	1.07	0.82	1.09	0.81	**0.15**	0.47	**0.42**
Aquifer attenuation period	year	44.1	35.0	52.3	52.3	52.4	52.4	38.9	51.6	38.9	52.3	**190**	89.7	**121.4**
Aquifer recovery potential	–	40.9	40.9	40.9	40.9	41.5	41.5	40.9	40.9	41.5	41.5	**40.9**	40.9	**40.9**
Productivity of agricultural water	kg/m^3	0.55	0.55	0.85	0.85	0.85	0.55	0.55	0.85	0.55	0.85	**0.55**	0.55	**0.85**

The best scenarios were marked with bold numbers.

These findings could be viewed from two perspectives: aquifer sustainability and total benefits. From the perspective of aquifer sustainability, scenario 10, in which water resource conditions and water demands are determined by existing conditions, considering domestic water demand management and aquifer restoration, is optimal. The aquifer balance becomes positive in this scenario. Additionally, aquifer sustainability and aquifer attenuation period have been improved. From a total benefits perspective, scenario 12, defined as water resources and water demands, is based on current conditions, considering water demand management in all sectors. The optimal scenario is aquifer restoration without industrial wastewater injection into the aquifer. In scenario 12, the improvement in water supply has been steadily increasing. Total benefits have increased as a result of increased industrial benefits. Finally, it should be noted that increasing water withdrawal from existing water resources is not possible. If the current rate of groundwater depletion continues, there will be no aquifer storage in the study area within the next 100 years.

CONCLUSIONS

The basin area is the most practical unit for integrated and sustainable water resource management. This management includes industrial, agricultural, municipal, and environmental aspects. The study area is located in a water-scarce region heavily reliant on groundwater resources. Over the last decade, excessive groundwater withdrawal has resulted in a 0.58 m/year decline in the water table. Groundwater depletion has accelerated in recent years, resulting in a water table drawdown of approximately 1.1 m/year. According to previous studies, the annual recharge rate of the aquifer will be increased to 3.5% in the future, while the pressure on water bodies will be increased by up to 7% in the agricultural section (Malekinezhad & Banadkooki 2018). These facts indicate that if water management policies are not sustainable, they will result in aquifer attenuation over the next 49 years. Thus, issues such as an overemphasis on the development of water-consuming industries in the basin, a disregard for environmental considerations in development programs, and accelerated groundwater depletion have caused severe damage to the area.

Optimization algorithms were used for water allocation between different sections. One of the study's advantages is that it considers environmental parameters in the goal function and IWRM indices when determining the optimal water management scenario. The study area's water allocation results indicated less water was allocated to high water-use industries. Moreover, future water allocation scenarios noted that if planners and decision-makers consider demand management, wastewater treatment, and no industrial development in the area's future development prospects, it will be possible to conserve the aquifer and surrounding environment and meet water demands.

For new studies, it is advisable to use other multi-objective optimization algorithms such as particle swarm optimization (PSO) or hybrid intelligence algorithms. It is also recommended to consider other climate change scenarios.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Agarwal, A., delos Angeles, M. S., Bhatia, R., Chéret, I., Davila-Poblete, S., Falkenmark, M., Villarreal, F. G., Jønch-Clausen, T., Kadi, M. A., Kindler, J. & Rees, J. 2000 *Integrated water resources management. TAC Background Paper 4, Stockholm: Global Water Partnership*, p. 22. Available from: http://www.gwp.org/Global/GWP-CACENA_Files/en/pdf/tec04.pdf.

Allawi, M. F., Jaafar, O., Ehteram, M., Mohamad Hamzah, F. & El-Shafie, A. 2018 Synchronizing artificial intelligence models for operating the dam and reservoir system. *Water Resources Management* **32** (10), 3373–3389.

Azaiez, M. N. 2002 A model for conjunctive use of ground and surface water with opportunity costs. *European Journal of Operational Research* **143**, 611–624. http://dx.doi.org/10.1016/S0377-2217(01)00339-3.

Banadkooki, F. B. 2016 *Optimal Allocation of Water Resources Using Appropriate Optimization Methods (Case Study: Yazd – Ardakan Plain).Ph.D. Thesis*. *Faculty of Natural Resources and Desert Studies*, Yazd University, Iran, p. 244.

Belaineh, G., Peralta, R. C. & Hughes, T. C. 1999 Simulation/optimization modeling for water resources management. *Journal of Water Research* **125** (3), 154–161. http:// dx.doi.org/10.1061/(asce)0733-9496(1999)125:3(154).

Chang, L. C., Ho, C. C. & Chen, Y. W. 2009 Applying multi objective genetic algorithm to analyze the conflict among different water use sectors during drought period. *Journal of Water Resources Plan Management* **136** (5), 539–546. http://dx.doi.org/10.1061/(ASCE)WR.1943-5452.0000069.

Coe Jack, J. 1990 Conjunctive use-advantages, constraints, and examples. *Journal of Irrigation and Drainage Engineering* **116** (3), 427–443. http://dx.doi.org/10.1061/(ASCE)0733-9437(1990)116:3(427).

Craswell, E. 2021 Fertilizers and nitrate pollution of surface and ground water: an increasingly pervasive global problem. *SN Applied Sciences* **3** (4), 1–24. https://doi.org/10.1007/s42452-021-04521-8.

Dale Larry, L., Vicuna, S. & Dracup, J. A. 2008 The conjunctive use of reservoirs and aquifers: trade-offs in electricity generation and water supply. In *Proceedings of the World Environmental and Water Resources Congress*, Honolulu, Hawaii. http://dx.doi.org/10.1061/40976(316)70.

Dogrul, E. C., Kadir, T. N., Brush, C. F. & Chung, F. I. 2016 Linking groundwater simulation and reservoir system analysis models: the case for California's Central Valley. *Environmental Modeling and Software* **77**, 168–182. http://dx.doi.org/10.1016/j.envsoft.2015.12.006.

East, V. & Hall, M. J. 1994 Water resources system optimization using genetic algorithms. In *Proceedings, Hydro Informatics 94, First International Conference on Hydro Informatics*, Rotterdam, the Netherlands, Balkema, pp. 225–231.

Ehteram, M., Singh, V. P., Karami, H., Hosseini, K., Dianatikhah, M., Hossain, M., Ming Fai, C. & El-Shafie, A. 2018 Irrigation management based on reservoir operation with an improved weed algorithm. *Water* **10** (9), 1267.

Ehteram, M., Binti Koting, S., Afan, H. A., Mohd, N. S., Malek, M. A., Ahmed, A. N., El-shafie, A. H., Onn, C. C., Lai, S. H. & El-Shafie, A. 2019 New evolutionary algorithm for optimizing hydropower generation considering multi-reservoir systems. *Applied Sciences* **9** (11), 2280.

Elçi, A. & Ayvaz, M. T. 2014 Differential-evolution algorithm-based optimization for the site selection of groundwater production wells with the consideration of the vulnerability concept. *Journal of Hydrology* **511**, 736–749. http://dx.doi.org/10.1016/j.jhydrol.2014.01.071.

Emch, P. G. & Yeh, W. W. G. 1998 Management model for conjunctive use of coastal surface water and ground water. *Journal of Water Research* **124** (3), 129–139. http://dx.doi.org/10.1061/(asce)0733-9496(1998)124:3(129).

Fowler, K. R., Jenkins, E. W., Ostrove, C., Chrispell, J. C., Farthing, M. W. & Parno, M. 2015 A decision-making framework with MODFLOW-FMP2 via optimization: determining trade-offs in crop selection. *Environmental Modeling & Software* **69**, 280–291. http://dx.doi.org/10.1016/j.envsoft.2014.11.031.

Haimes, Y. Y. 1977 *Hierarchical Analysis of Water Resources Systems*. McGraw Hill, New York.

Harter, T. 2009 Agricultural Impacts on Groundwater Nitrate. *Southwest Hydrology* **2009**, 22–35. http://www.swhydro.arizona.edu/archive/V8_N4/feature2.pdf.

Hicks, R. H., Gaguor, C. R., Jacoby, S. L. & Kowalikn, J. S. 1974 Large Scale Nonlinear Optimization of Energy Capability for the Pacific Northwest Hydroelectric System. *IEEE Transactions on Power Apparatus and Systems* **5**, 1604–1612.

Jha, M. K., Singh, L. K., Nayak, G. K. & Chowdary, V. M. 2020 Optimization modeling for conjunctive use planning in Upper Damodar River Basin, India. *Journal of Cleaner Production* **273**. https://doi.org/10.1016/j.jclepro.2020.123098.

Kim, Y. & Chung, E. S. 2013 Assessing climate change vulnerability with group multi criteria decision making approaches. *Journal of Climatic Change* **121** (2), 301–315. doi: 10.1007/s10584-013-0879-0.

Labadie, J. W. & Larson, R. 2007 *MODSIM 8.1: River Basin Management Decision Support System: User Manual and Documentation*. Available from: http://dwrftp.state.co.us/cdss/projects/MODSIM/MODSIMv8.1UserManual.pdf (accessed 06.10.2014).

Latif, M. 1991 Conjunctive water uses to control waterlogging and salinization. *Journal of Water Resources Planning and Management* **117** (6), 611–628. http://dx.doi.org/10.1061/(ASCE)0733-9496(1991)117:6(611).

Li, D., Zuo, Q., Wu, Q., Li, Q. & Ma, J. 2021 Achieving the tradeoffs between pollutant discharge and economic benefit of the Henan Section of the south-to-north water diversion project through water resources-environment system management under uncertainty. *Journal of Cleaner Production* **321**. https://doi.org/10.1016/j.jclepro.2021.128857.

Malekinezhad, H. & Banadkooki, F. B. 2018 Modeling impacts of climate change and human activities on groundwater resources using Modflow. *Journal of Water and Climate Change* **9** (1), 156–177. https://doi.org/10.2166/wcc.2017.147.

Nandalal, K. D. W. & Simonovic, S. P. 2002 *State-of-the-Art Report on Systems Analysis Methods for Resolution of Conflicts in Water Resources Management.* Department of Civil and Environmental Engineering, The University of Western Ontario. Available from: http://www.unesco.org/water/wwap/pccp/disciplinary_studies.shtml.

Oliveira, R. & Loucks, D. P. 1997 Operating rules for multi reservoir systems. *Water Resources Research* **33** (4), 839–852. https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/96WR03745.

Pulido-Velázquez, M., Andreu, J. & Sahuquillo, A. 2006 Economic optimization of conjunctive use of surface water and groundwater at the basin scale. *Journal of Water Resources Planning and Management* **132** (6), 454–467. http://dx.doi.org/10.1061/(ASCE)0733-9496(2006)132: 6(454).

Rani, D. & Moreira, M. M. 2010 Simulation-optimization modeling: a survey and potential application in reservoir systems operation. *Water Resources Management* **24** (6), 1107–1138. http://dx.doi.org/10.1007/s11269-009-9488-0.

Rosenthal, R. E. 1980 The Status of Optimization Models for the Operation of Multi-reservoir Systems with Stochastic Inflows and Non-separable Benefits*. Chattanooga, Tenn., Research Report* **75**, Tennessee Water Resources Research Center. Available from: http://www.jstor.org/stable/170390.

Rossetto, R., Filippis, G. D., Triana, F., Ghetta, M., Borsi, I. & Schmid, W. 2019 Software tools for management of conjunctive use of surface- and ground-water in the rural environment: integration of the farm process and the crop growth module in the FREEWAT platform. *Agricultural Water Management* **223**. https://doi.org/10.1016/j.agwat.2019.105717.

Semenov, M. A., Brooks, R. J., Barrow, E. M. & Richardson, C. W. 1998 Comparison of the WGEN and LARS-WG stochastic weather generators in divers climates. *Climate Research* **10** (2), 95–107. Available from: https://www.jstor.org/stable/24865958.

Singh, A. & Panda, S. N. 2013 Optimization and simulation modeling for managing the problems of water resources. *Water Resources Management* **27** (9), 3421–3431. http://dx.doi: 10.1007/s11269-013-0355-7.

Wolf, A. T. 2002 *Conflict Prevention and Resolution in Water Systems*. Edward Elgar Publishing Ltd, Cheltenham, UK.

Yang, X. S. 2020 *Nature-Inspired Optimization Algorithms*. Academic Press. Available from: https://www.sciencedirect.com/book/9780124167438/nature-inspired-optimization-algorithms.

Yaseen, Z. M., Ehteram, M., Hossain, M., Fai, C. M., Binti Koting, S., Mohd, N. S., Binti Jaafar, W. Z., Afan, H. A., Hin, L. S., Zaini, N. & Ahmed, A. N. 2019 A novel hybrid evolutionary data-intelligence algorithm for irrigation and power production management: application to multi-purpose reservoir systems. *Sustainability* **11** (7), 1953.

Zhang, X., Chen, S., Sun, H., Shao, L. & Wang, Y. 2011 Changes in evapotranspiration over irrigated winter wheat and maize in North China Plain over three decades. *Agricultural Water Management* **98**, 1097–1104. http://dx.doi.org/10.1016/j.agwat.2011.02.003.

Zhang, F., Engel, B. A., Zhang, C., Guo, S., Guo, P. & Wang, S. 2019 Agricultural production planning approach based on interval fuzzy credibility-constrained Bi-level programming and Nerlove Supply Response Theory. *Journal of Cleaner Production* **233**, 1158–1169. https://doi.org/10.1016/j.jclepro.2019.06.096.

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