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Optimization of Dam Water Resource Allocation in Khuzestan Province using the Epsilon-Constraint Method

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Abstract

The present research aims to optimize the utilization of water resources from dams in Khuzestan province. To this end, this study seeks to optimize the cost and time of water delivery to each city from the total dams in Khuzestan province. The model was solved using the epsilon-constraint method. According to the results of the current research, water supply from Balarud Dam to the cities of Ahvaz, Izeh, Abadan, Bagh-e Malek, and Bandar Imam Khomeini was not optimal. While the same dam sends a specific amount of water to the cities of Andimeshk, Dezful, Shush, Shushtar, and Gotvand. Furthermore, according to the sensitivity analysis performed, it has been determined that an increase in water demand can increase delivery time by up to 1.9% and delivery cost by up to 0.6%. Therefore, the greater effect of water demand is on time rather than cost. An increase in budget, however, can affect both cost and time, although again the effect is more on time than on cost. The next parameter is the time interval between cities and the production complex, which is expected to increase water delivery time by up to 13% with its increase, showing a relatively significant effect, while this effect on cost is less than on time.

Keywords: Dam water management, Optimization, Epsilon-constraint

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1. Introduction

Water is one of the most fundamental elements of life. Access to safe water for human needs is recognized as a basic factor and a civilizing agent, so much so that it has always been respected by societies, and various rivers around the world have held great importance and sanctity for the populations living in those areas. No country can maintain its economic, social, and political stability without ensuring access to water, and without reducing air pollution, the security of future generations in terms of water and food will be uncertain, and thus, sustainable development will remain merely an attractive slogan. Today, water scarcity and pollution severely endanger the lives of millions of people on Earth, especially in poor countries. Statistically, 80% of the world's population has access to only 20% of safe and sanitary water reserves. Diseases caused by contaminated water are also responsible for many deaths in poor countries worldwide (Heydari Kushalshah et al., 2023).

The production of any type of goods and services requires water. The water consumed in the production process of an agricultural or industrial product is technically called "virtual water". The term virtual water was first introduced by Allan in 1998. In this regard, the paper presented by Professor Allan at the annual Knowledge Conference in London discussed water scarcity in the Middle East and resource management to overcome the crisis. In the 1960s and 1970s, research was conducted by the former Soviet Union to examine the global water balance. This research also referred to the availability and use of water .Today, many researchers, scientists, and scholars emphasize reviewing policies and management approaches for water resources. The alternative approach proposed by them is the virtual water management approach. Virtual water is the total sum of all water flows used to produce a good (Shahidi et al., 2019; Mehrani et al. 2019). In other words, virtual water is the amount of water that an industrial product or an agricultural product consumes during the production process to reach the final production stage, and its amount is equal to the total sum of water consumed in various stages of the production chain from start to finish. A country or region can free itself from pressure on its water resources by choosing to be a virtual water importer. Climatic and cultural conditions, production location, management, and planning are effective in the volume of virtual water of each commodity, and its amount will certainly differ for the same commodity in different regions. Virtual water trade can lead to importing products from other regions, thereby avoiding the negative effects of using water resources. Thus, incorporating virtual water trade into trade policies creates a trade-off between water resource conservation and food security (Delshad et al. 2024; Benchaiba et al., 2025; Nozari et al., 2025).

Compared to the past two or three centuries, the world has entered a critical era in natural resource conservation. Proper and proportionate management of existing natural resources is a crucial necessity for achieving sustainable development. Among all natural resources, fresh water is one of the most important resources that should be given special attention. Many countries, by exploiting their non-renewable fossil water to alleviate immediate pressure from water stress, have depleted water reserves and resources, weakened economic development, and reduced their long-term food security (Shahidi et al., 2019; Keihani et al., 2025). A number of researchers have argued that water-scarce regions can achieve high levels of global water use efficiency by importing products with high virtual water content and exporting products with very low virtual water content. Virtual water, along with local or indigenous water, enables the fulfillment of national water needs. This forms the concept of virtual water trade. Accordingly, importing countries receive not only goods but also the water consumed to produce those goods. This way, they save the water that would have been needed from domestic resources to produce these products. Virtual water trade within countries, between countries, and even continents can be used as a tool to enhance global water use efficiency, achieve water security in water-poor regions, and overcome environmental limitations by identifying suitable locations for production (Heydari Kushalshah et al., 2023). By considering the volume of virtual water embedded in food imports in water-scarce countries, a close relationship between water availability and reliance on food imports becomes evident. Therefore, food imports can be considered a strong indicator in determining the level of water scarcity in countries (Wang et al., 2017; Nozari et al., 2023).

Virtual water trade is not a new phenomenon. It expanded alongside the formation of markets and the growth of exchanges between human societies, primarily through the trade of agricultural products. However, the concept of virtual water and its trade has only recently entered scientific discussions and national and international policy-making regarding water resource management and development. In recent years, with the sharp increase in global population and water stress in many countries, this tool has been proposed as one of the effective solutions for ensuring water and food security in various communities, especially in water-scarce regions. Wichelns (2001) examined the role of virtual water in ensuring food security in different countries, with an emphasis on Egypt, and stated that the issue of the opportunity cost of water consumption is also a key component in the expansion of the virtual water concept and its trade, which should be considered in the effective and optimal allocation of available water resources. Given the importance of the topic, this paper aims to briefly review the concept of virtual water, virtual water trade, virtual water allocation, and ensuring food security for human societies (Asl-Rousta et al., 2025; Nozari et al., 2025).

Given that the main concern of the most important food industries and large food companies is ensuring food security and optimal allocation of virtual water. Considering the need and necessity of virtual water allocation in conditions of climatic fluctuations in Iran's food industry to create nutritional security, this research, as a case study, examines the food industry of Khuzestan province and designs a model for virtual water allocation. Therefore, introducing and providing a solution for virtual water allocation seems very necessary and essential. The proposed mathematical model in this research can be determined and explained based on the components of pricing the water consumed by the food industry and its transportation cost, the province's water supply sources, government incentive policies, and free trade. Therefore, the most important contribution of the research is the design of a mathematical model for virtual water allocation in the food industry of Khuzestan province to determine the role and position of virtual water trade in the water resource management of Khuzestan province's food industry sector (Nozari , 2024).

The remainder of the article is organized as specified. Section 2 provides a historical study of past research. Section 3 explains the mathematical modeling and its details. Section 4 presents the results of applying the mathematical model, and finally, Section 5 offers a conclusion along with suggestions for future research.

2. Literature Review

Fracasso et al. in 2016, in an article, examined the main determinants of bilateral virtual water (water used in the production of goods or services) related to international trade in agricultural goods across the Mediterranean basin. In this research, they considered the gross bilateral virtual water flow in the region and investigated whether specific export and import factors are significantly associated with virtual water flows. They followed a sequential approach. Through the trade gravity model, they obtained a "purified" version of the variable they intended to explain, one that is free from the amount of flow resulting from specific pair factors affecting bilateral trade flows and fully reflects the impact of specific determinants on virtual water trade. A number of potential explanatory variables, ranging from water to trade barriers, from per capita GDP to irrigation prices, are presented and tested. To identify the variables that help explain bilateral virtual water flows, they adopted a model selection method based on model averaging. The findings confirm one of the main controversial results in this field: water scarcity does not necessarily lead to larger "exports" of virtual water, as might be expected. They also found evidence that higher irrigation water prices reduce (increase) virtual water exports (imports). Chen et al. in 2017, in a study, investigated China's water footprint at the provincial level and international virtual water transfer. The concepts of water footprint and virtual water provide a new method for alleviating regional scarcity of Chinese water resources through the allocation of commercial water resources. In this study, a local input-output model was used to quantitatively assess the water footprint of each province in China and to quantify inter-provincial virtual water transfer. The results showed significant diversity in footprints across different provinces. The United States, with a larger population and higher GDP, had a larger water footprint, and developed regions had higher ratios of external water footprint. From the perspective of final demand, local consumption was the main factor in creating the water footprint of these provinces. From the perspective of sectoral structure, the agricultural water footprint had a larger proportion in these states. Virtual water transfer in China did not occur from regions with abundant water resources to those suffering from water scarcity, but generally from west to east, from arid to coastal areas, and from underdeveloped to developed regions. Many water-scarce regions also have large net virtual water exports. Water scarcity in China will be alleviated by increasing the efficiency of industrial water use in water-scarce regions, transferring water-intensive industries to regions with abundant water resources, and developing industries with low water consumption. Aviso et al. (2018), published an article titled "A Multi-Regional Input-Output Model for Optimizing Virtual Water Trade Flows in Agricultural Production." They stated that the onset of climate change leads to changes in weather patterns and can exacerbate water scarcity issues, which can potentially affect the economic productivity of countries, as economic activities, especially for countries with a highly water-dependent agricultural industry, are very sensitive to water. Environmental input-output models are often used to analyze interactions between economic and ecological systems. However, in this research, a multi-regional input-output model has been developed to optimize virtual water trade between different geographical regions, considering local environmental resource constraints, product demand, and economic efficiency.

Quanliang et al. (2018) studied the optimal allocation of physical water resources integrated with virtual water trade in water-scarce regions in a case study for Beijing, China. This study provides an innovative application of virtual water trade in the traditional allocation of physical water resources in water-scarce regions. A multi-objective optimization model has been optimized to allocate physical and virtual water resources to different water users in Beijing, considering the trade-off between economic benefits and environmental impacts of water consumption. Zhongwen et al. (2020), in an article titled "Water Allocation Inequality and Policy Response with Respect to Virtual Water Trade," studied a case study in Lanzhou City, China. They stated that water allocation management balances the trade-off between economic development and environmental protection. In this study, by introducing a relationship between water and food, they introduced virtual water trade into the proposed model and case study, and considering the impacts of climate change on seasonal water supply, this study divides the planning of each year into seasons and finally formulates and applies a dynamic two-objective model for water allocation in an arid region in China. The aim of this study was to produce an optimal water resource allocation strategy among industrial, domestic, agricultural, and environmental sectors and to reveal the impacts of variable precipitation on the water allocation strategy. Yao et al. (2020), published an article titled "A New Data-Driven Analytical Framework for Hierarchical Water Allocation Integrated with Blue and Virtual Water Transfer." This research ensures the optimal allocation of blue and virtual water transfer under various hydrological and economic conditions. Also, a Stackelberg-Nash-Harsanyi equilibrium model has been developed to address hierarchical conflicts between the water affairs office and multiple water-using sectors and to overcome problems related to water scarcity and uneven distribution. Brindha (2020), in an article, investigated virtual water flows, water footprint, and water savings resulting from Germany's trade in crop and livestock products. In this research, they comprehensively evaluated Germany's virtual water trade with the world and assessed the national water footprint through trade in crop and livestock products from 1991 to 2016.

Among domestic studies, research such as the following can be mentioned. For example, Tahami Pourzarandi and Abedi (2017), analyzed the virtual water trade in the industrial sector of Zanjan province. In this research, they used data from the statistical survey of industrial workshops with ten or more employees from the Statistical Center of Iran for the years 2010-2011. While categorizing industries by water demand and the products of these industries, their required water amount was estimated. The results showed that the highest virtual water content of Zanjan province belongs to the coke and refinery production industry, the paper and paper products industry, and the food and beverage industry, with an average of 32.70, 26.14, and 11.63 cubic meters per million Rials, respectively. Nafarzadegan et al. (2017), studied the use of interactive interval linear programming for optimal water and cultivation area allocation, considering virtual water content and socio-economic factors, in a case study in the Doroodzan-Karbaleh plain. The developed model includes four objectives encompassing socio-economic factors, virtual water content of products, and environmental water needs. To solve the model, four scenarios (assumptions) for cultivation levels were considered. Oveisi et al. (2019) also conducted a study titled "Investigation of Virtual Water and Water Ecological Footprint in Irrigated Wheat Product of Isfahan Province." In this research, they believe that Isfahan province, despite recent droughts, climate change, and increasing population growth, as well as the expansion of industrial and agricultural activities, faces a water crisis. Therefore, to combat this crisis, fundamental solutions such as investigating virtual water and the water ecological footprint of strategic products in the agricultural sector should be considered for managing endangered water resources. The purpose of this study is to investigate the virtual water and water ecological footprint of wheat product in Isfahan province from the agricultural year 2006-2007 to 2014-2015. Shahidi et al. (2019), investigated and evaluated the amount of virtual water and water footprint in the agricultural sector of South Khorasan province. Also, in that research, the results were compared with the virtual water amount of the water-intensive industrial sector of the province. In this research, the average virtual water of major agricultural products in South Khorasan province is about 2900 cubic meters per ton of product, which is estimated to be about 21 cubic meters per ton for the water-intensive industries of the province. Aboutorabi et al. (2022), estimated the water footprint and virtual water to determine the optimal cropping pattern in a case study for Qaenat and Zirkouh counties. They stated that to avoid the negative consequences of a negative water balance in Qaenat and Zirkouh counties, restricting the cultivation of high water-demand crops is necessary. In this research, using multi-objective nonlinear programming (MOP), an optimal cropping pattern with the aim of maximizing net profit and minimizing virtual water, green, blue, gray, and white water footprints of agricultural products in the Qaenat and Zirkouh region has been proposed. Baghbanyan et al. (2022), studied the application of goal programming in determining the optimal cropping pattern for agricultural products with an emphasis on virtual water in Kurdistan province. Therefore, their study was designed and implemented with the aim of economically evaluating the optimal cropping pattern of agricultural products in Kurdistan province, broken down by its counties, with an emphasis on minimum virtual water. Hekmatnia et al. (2020), also determined and evaluated the green, blue, and gray water footprints in the international trade of Iranian agricultural products. In this research, they stated that to reduce the water crisis, international trade of agricultural products can play a significant role in redistributing water resources because traded goods contain a large amount of virtual water. Kolahi et al. (2023), conducted a study titled "Optimization of Cropping Pattern Based on Virtual Water Concept Using Linear Programming" in the Omrani plain of Gonabad, Razavi Khorasan province. Accordingly, the objective of their research is to determine the optimal cropping pattern based on the virtual water concept and economic profitability using linear programming in the Omrani plain of Gonabad.Safdari et al. (2021), conducted a study titled "Water Footprint and Virtual Water Trade of Dates in Iran". Therefore, the aim of this research is to investigate the water footprint of date cultivation in Iran using three specific types of water: blue water, green water, and gray water. Then, using the concept of virtual water footprint, the water trade footprint for dates was calculated for the years 2001-2018.

By reviewing previous records and research conducted in the field of virtual water allocation, it was observed that the proposed method, by presenting a mathematical model, can have greater efficiency compared to other methods. Therefore, considering the review of theoretical foundations, two-level mathematical modeling has not been done so far; also, in the studied industry and the province in question, this important issue has not been addressed. Therefore, the present research, with an applied research approach, has emerged to take a step in addressing the needs of the relevant industry in the specified geographical area. Therefore, in this research, a two-level mathematical model for virtual water allocation in the food industry of Khuzestan province is designed.

3. Research Method

This research, in terms of its thematic scope, proceeds by presenting a bi-level mathematical model for virtual water allocation, which determines the exact solution of the mathematical model in GAMS software with the help of the epsilon-constraint algorithm. In terms of geographical scope, this research has extracted the necessary data from the food industries of Khuzestan province. The general specifications of all food production companies and factories in this province, including the type of product, specifications, and address, are provided below. Out of a total of 148 food industry companies, 134 active companies in 16 cities of this province have been identified. In terms of temporal scope, this research collected the necessary data from the desired sources during the period from winter 2019 to spring 2020. Therefore, this research aims to allocate virtual water in the food industry of Khuzestan province by presenting a bi-level model based on mathematical programming. Next, we will introduce the assumptions governing the model, parameters, variables, objective functions, and constraints of the mathematical model.

Mathematical model assumptions

First assumption: Budget constraint is considered.

Second assumption: Each dam can supply water to several cities.

Third assumption: Each city can receive water from several dams.

Notation

Sets:

I :Set of dams

J :Set of cities

K :Set of producers (towns or factories)

T: Set of periods

O: Set of sequences of water transfer to producers (towns or factories)

Indices:

$i \in I$: Index belonging to the set of dams

$j \in J$: Index belonging to the set of cities

$k \in K$: Index belonging to the set of producers (towns or factories)

$t \in T$: Index belonging to the set of periods

$o \in O$: Index belonging to the set of sequences of water transfer to producers (towns or factories)

Parameters:

dk_{kt} :The required amount of gray water for the production complex

U_j :The total number of production centers connected to city j.

cap_i :The capacity of dam i

b_t :Initial budget

M: A very large number

tdj_{jk} :The time distance between the city and the production complex k

ts_{jk} :The time distance within the production complex (townships) k located in city j.

$td_{kk'}$:The time distance between production complex k and production complex

cd_{ijt} :Water transfer cost based on flow rate per unit distance from dam i to city j

w_{jk} :The weighted time importance of production complex k in city j

$Velocity_{ijt}$:The speed of water from dam i to city j in period t

TE_{ijt}: The time it takes for water to reach city j from dam i

$$TE_{ijt} = \frac{dis_{ij}}{Velocity_{ijt}}$$

$perc_i$:Usable percentage of water capacity of the i-th dam

UTW_k: Upper limit of the time window for the k-th production unit

LTW_k :Lower limit of the time window for the k-th production unit

α_{kj} :If the k-th production set is in the j-th city, then 1, otherwise 0.

Variables:

x_{ijt} :If water is transferred from dam i to city j in period t, then 1, otherwise 0.

z_{jkot} :If the k-th production set belongs to city j in sequence (water transfer order) o at period t, then 1, otherwise 0.

y_{ijt} :The amount of virtual water transferred from the i-th dam to the j-th city in period t.

ct_{jkt} :The completion time of water transfer to the k-th production unit belonging to the city in period t.

TA_{jt} :Maximum time for water to reach city j from the dam in period t.

Objective functions and constraints:

$$Min(z_1) = \sum_{i \in I} \sum_{j \in J} \sum_{t \in T} CD_{ijt}.d_{ij}.x_{ijt}$$

$$Min(z_2) = \sum_{i \in I} \sum_{j \in J} \sum_{t \in T} ct_{jkt}.w_{jk}$$

$$\sum_{i \in I} y_{ijt} = \sum_{k \in K} Dk_{kt}.\alpha_{kj} \qquad \forall j \in J, t \in T \qquad (1)$$

$$y_{ijt} \leq M.x_{ijt} \qquad \forall i \in I, j \in J, t \in T \qquad (2)$$

$$y_{ijt} \geq x_{ijt} \qquad \forall i \in I, j \in J, t \in T \qquad (3)$$

$$\sum_{j \in J} y_{ijt} \leq perc_i.cap_i \qquad \forall i \in I, t \in T \qquad (4)$$

$$z_1 \leq b_t \qquad \forall t \in T \qquad (5)$$

$$TA_{jt} \geq TE_{ijt}.x_{ijt} \qquad \forall i \in I, j \in J, t \in T \qquad (6)$$

$$\sum_{o \in O; o \leq U_j} z_{jkot} = \alpha_{kj} \qquad \forall j \in J, k \in K, t \in T \qquad (7)$$

$$\sum_{k \in K} z_{jkot} = 1 \qquad \forall j \in J, o \in O, t \in T; o \leq U_j \qquad (8)$$

$$ct_{jkt} \geq (TA_{jt} + tdj_{jkt} + ts_{jk}) - M.(1 - z_{jkot}) \qquad \forall j \in J, o \in O, t \in T; o = 1 \tag{9}$$

$$ct_{jk't} \geq ct_{jkt} + (td_{kk't} + ts_{jk'}) - (1 - z_{jk'ot} + 1 - z_{jko-1t}).M \; \forall j \in J, \; k, k' \in K \; , o \in O, t \in T; 1 < o \leq U_j \tag{10}$$

$$\alpha_{kj}.LTW_k \leq ct_{jkt} \leq \alpha_{kj}.UTW_k \qquad \forall j \in J, o \in O, t \in T; o \leq U_j \tag{11}$$

The first objective function calculates the shipping cost to cities based on the flow. The second objective function calculates the weighted sum of water delivery time to each city. Constraint (1) specifies the amount of water transferred to cities. Constraints (2) and (3) specify variable x_{ijt} based on the positivity of variable y_{ijt}. Constraint (4) limits the amount of water transfer to cities based on capacity. . Constraint (5) guarantees that the cost amount should not exceed the allocated budget. Constraint (6) determines the maximum virtual water arrival time from dams to city j. Constraint (7) specifies the sequence of water delivery for each production unit in the cities. Constraint (8) guarantees that each sequence o in each city must belong to a production unit. Constraints (9) and (10) calculate the completion time of water transfer to each of the production units. Constraint (11) limits the time window for water transfer to each of the production units.

3-1. Problem-solving method

One of the precise methods for obtaining Pareto optimal solutions is the epsilon-constraint method, first introduced by Aljandan. The main advantage of this method over other multi-objective optimization methods is its applicability to non-convex solution spaces, as methods like weighted sum of objectives lose their effectiveness in non-convex spaces. The computational time of an algorithm is one of its important characteristics for evaluation. Since one of the fundamental weaknesses of exact search-based algorithms, including the epsilon-constraint method, is their high computational time, it is evident that using a metaheuristic algorithm will drastically reduce computational time. In this method, we always optimize one of the objectives, provided that we define the highest acceptable limit for other objectives in the form of constraints. For a two-objective problem, we will have the following mathematical representation.

$$\begin{aligned} &Min \; f_1(x) \\ &Subject\ to \; f_2(x) \leq \varepsilon_2, f_3(x) \leq \varepsilon_3, \ldots, f_p(x) \leq \varepsilon_p, \; x \in S \end{aligned} \tag{12}$$

By changing the values on the right side of the new constraints, the Pareto front of the problem will be obtained. One of the major problems with the epsilon-constraint method is the high computational volume, because for each of the objective functions converted into constraints ($p-1$ in number), several different values of ε_i must be tested. One of the most common approaches to implementing the epsilon-constraint method is to first obtain the maximum and minimum of each objective function in the $x \in S$ space, without considering other objective functions.Then, using the values obtained from the previous step, the range associated with each of the objective functions is calculated. If we denote the maximum and minimum values of the objective functions as $f_i^{\max}$ and $f_i^{\min}$, respectively, then the range of each of them is calculated as follows:

$$r_i = f_i^{\max} - f_i^{\min} \tag{13}$$

The range r_i is divided into q_i ranges. Then, for ε_i, $q_i + 1$ different values can be obtained from the following formula.

$$k = 0,1,\ldots,q_i \; \varepsilon_i^k = f_i^{\max} - \frac{r_i}{q_i} \times k \tag{14}$$

In the above relation, K indicates the new point number related to ε_i. With the help of the epsilon-constraint method, the above multi-objective optimization problem can be converted into $\prod_{i=2}^{p}(\mathrm{q_i} + 1)$ single-objective optimization sub-problems. Each sub-problem has a solution space S, which will be further constrained by inequalities related to the objective functions $f_2,\ldots,f_p$. Each sub-problem leads to a candidate solution for the desired multi-objective optimization problem, also known as the Pareto optimal front. Sometimes, some sub-problems create an infeasible space. Finally, after obtaining the Pareto optimal front, the decision-maker can choose and use the most suitable solution from their perspective.

4. Findings

To apply the proposed model in the food industries of Khuzestan province, first, problems in various dimensions are solved, and the resulting values, including objective function values and time, are calculated. The effects of increasing dimensions on these values are then compared. Another point is that sensitivity analysis is performed on one of the parameters, and the effect of increasing or decreasing the usable percentage of the dam is investigated. First, 8 problems, ranging from small to real-world dimensions, are introduced as examples. The results of these findings are presented in the tables and Figs below.

Table 1- Determined parameters for implementing the mathematical model

Sample Number	Dams	Cities	Manufacturing plants
1	3	4	20
2	4	4	30
3	5	6	40
4	6	8	50

Sample Number	Dams	Cities	Manufacturing plants
5	7	10	60
6	8	12	70
7	9	14	80
8	10	16	92

Table 2- Results of objective function values and computation time based on the provided examples

Sample Number	Cost	Time	Calculation time
1	1.05E+16	3.27E+06	10
2	1.05E+16	3.39E+06	24
3	1.05E+16	3.57E+06	37
4	1.05E+16	3.74E+06	54
5	1.05E+16	3.84E+06	72
6	1.05E+16	4.01E+06	90
7	1.05E+16	4.17E+06	110
8	1.05E+16	4.35E+06	125

As can be seen from Tables 1 and 2, the values of cost, time, and computation time have changed and increased with the increase in problem dimensions. To clarify the results, the changes are shown in Figs 1 to 3.

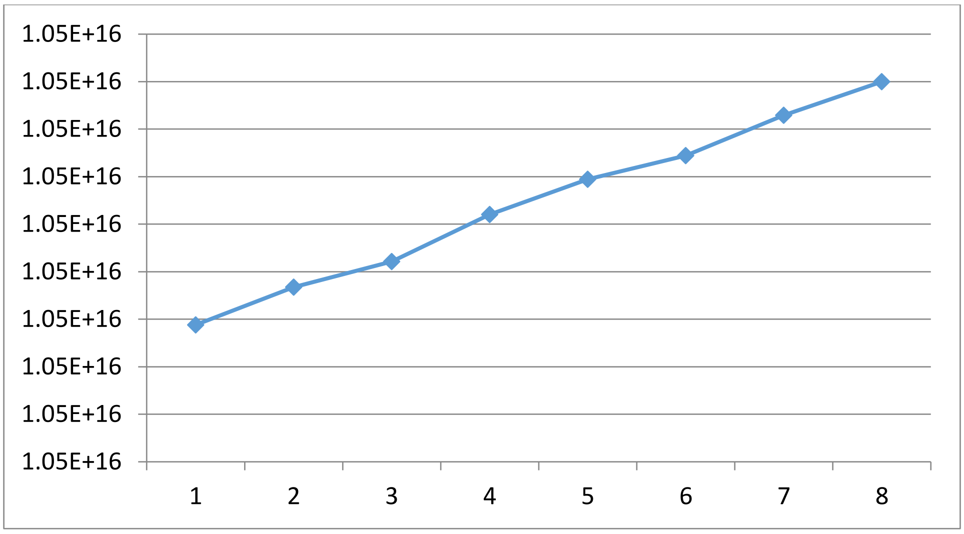

Fig 1- Cost increase due to dimension increase

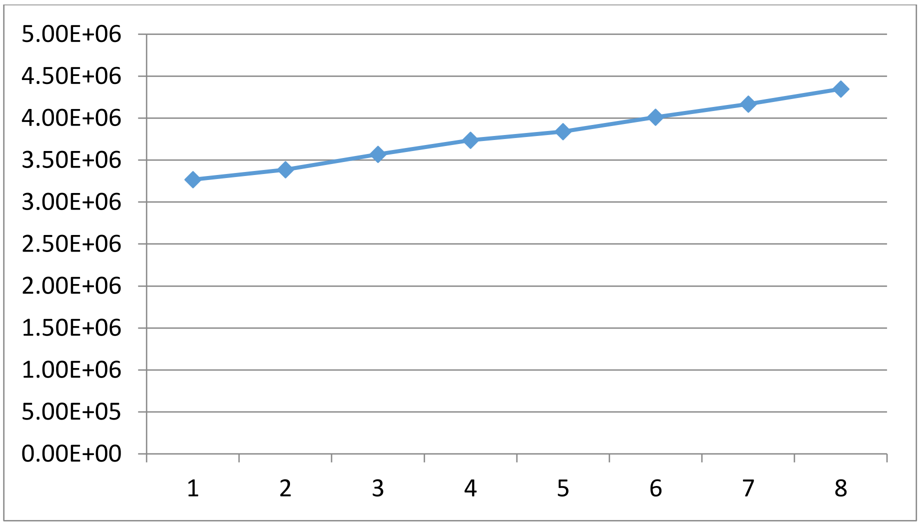

Fig 2- Time increase due to dimension increase

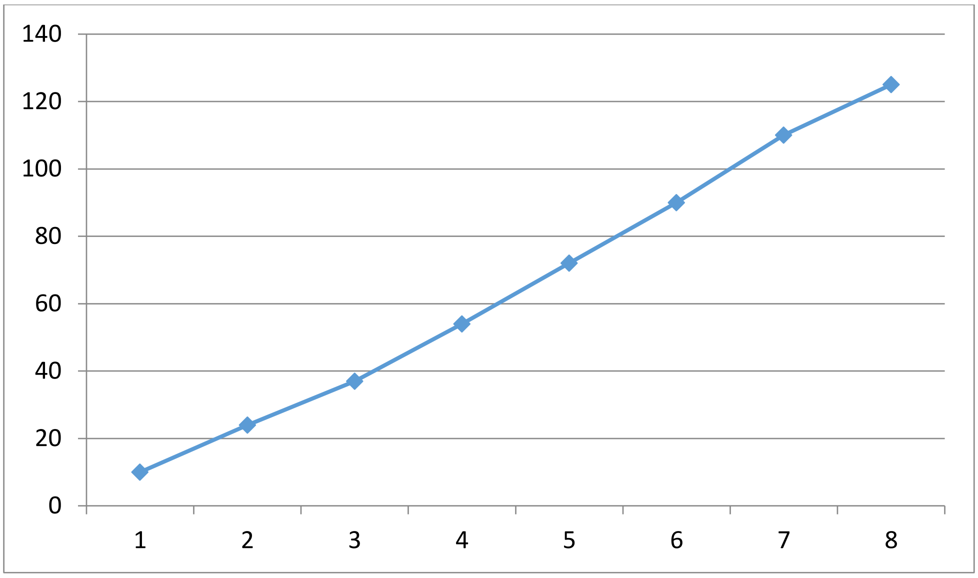

Fig 3- Solution time increase due to dimension increase

As can be seen, the response of cost, time, and computation time to the increase in problem dimensions was positive and upward, and therefore it can be said that the validity of the problem in terms of increasing dimensions is confirmable. However, another type of validation is performed below, which is presented in Table 3 and Fig 4.

Table 3- Change in the usable percentage of the dam

Usable percentage of the water dam	Dez Dam-Andimeshk	Karun Dam-Izeh	Jarreh Dam-Ramhormoz
70%	198147	19519	25579
75%	214004	21319	27357
80%	230581	23020	29144
85%	241543	24413	31140
90%	259370	25817	32428
95%	277136	27376	33791

As shown in Table 3, the usable percentage of the dam has changed. Naturally, an increase in the usable percentage of the dam can affect the dam's capacity and consequently increase the water transfer variable. This action has been taken in the table 3, and finally, the researcher is looking for the reaction of the decision variable to increase the usable percentage of the dam.

It is assumed that the usable capacity is initially 70% and then increases to 95%. The result is presented in the Fig 4.

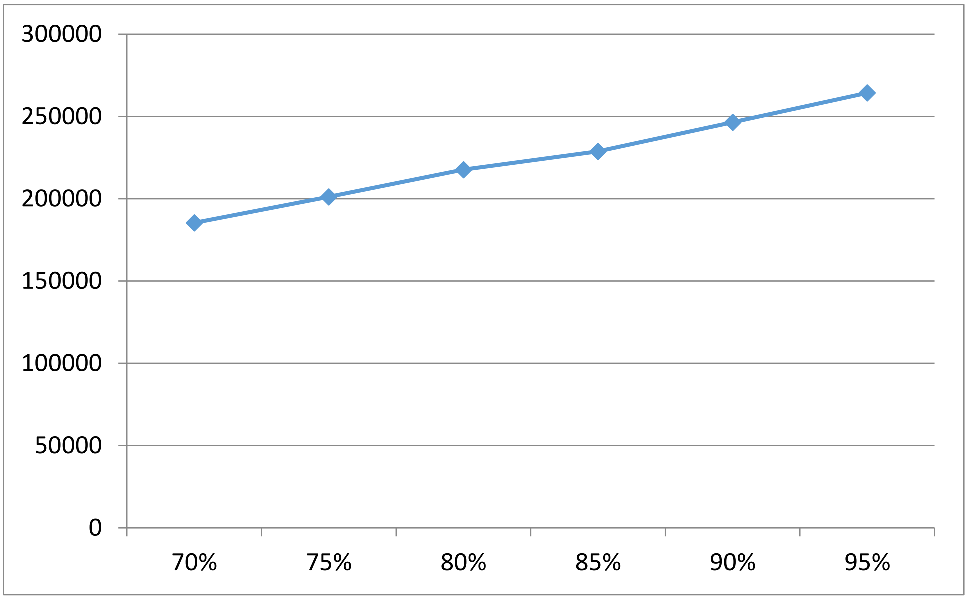

Fig 4- Change in the usable percentage of Dez Dam

As shown in Fig 4, with an increase in the usable percentage of Dez Dam's capacity, the amount of water sent to Andimeshk city, which is considered as the decision variable in the current problem, increases. This is also done for the other two dams presented as examples.

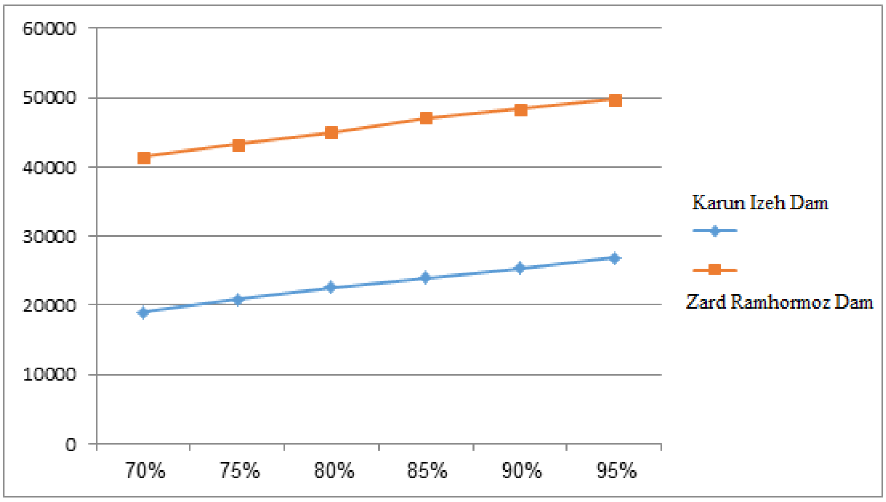

Fig 5- Change in the usable percentage of Karun Izeh Dam and Zard Ramhormoz Dam

As shown in Fig 5, this increase also occurred for Karun Izeh Dam and Zard Ramhormoz Dam. Therefore, it can be said that the decision variable of the problem, which is the amount of water transfer, is affected by the change in the usable percentage of the dams, and thus it can be said that the problem has the necessary validity. After confirming the model's validity, the numerical results obtained from solving the model are presented. These results are presented in the form of two main variables: the amount of water sent from each dam to each city, and the order and sequence of water supply to production complexes in each city. First, the amount of water supply from dams to cities is discussed in Table 4.

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Table 4- Amount of water supply from dams to each city

City Dam	Dez Dam	Karkheh Dam	Balarood Dam	Karun-3 Dam	Ariobarzan Dam	Marun Dam	Jarreh Dam	Gotvand Dam	Masjed Soleyman Dam	Shahid Abbaspour Dam
Andimeshk	628333901.2	1.54E+09	33229268	0	0	0	0	6.99E+08	74602102	78968553
Ahvaz	0	58939096	0	0	0	5.41E+08	59132328	3.82E+08	27484985	0
Izeh	0	0	0	0	0	0	31765120	0	3.77E+08	7.24E+08
Abadan	0	0	0	0	0	0	0	0	0	0
Baghmalek	0	0	0	2.08E+09	7830189	0	44844876	0	1.06E+08	1.38E+08
Bandar Imam Khomeini	0	0	0	0	10962264	28792099	10899796	0	0	0
Behbahan	0	0	0	0	55124528	4.66E+08	16505406	0	0	0
Khormshahr	0	0	0	0	0	0	0	0	0	0
Dezful	660674616.7	1.45E+09	30886179	0	0	0	0	7.7E+08	1.18E+08	1.58E+08
Ramhormoz	0	0	0	8.87E+08	25683019	1.64E+08	49827639	0	1.14E+08	1.51E+08
Susangard	0	0	0	0	0	0	1245691	0	6.75E+08	0
Shadegan	0	0	0	0	0	0	0	0	0	0
Shush	503591141.4	1.43E+09	24708943	0	0	0	0	5.76E+08	0	0
Shushtar	406568994.9	7.66E+08	18744715	0	0	0	14325446	9.58E+08	3.65E+08	5.66E+08
Gotvand	401948892.7	7.54E+08	18531707	0	0	0	4359918	1.16E+09	2.36E+08	3.55E+08
Solomon Mosque	110882453.2	0	4899187	0	0	0	27093779	5.37E+08	5.22E+08	9.67E+08
Total capacity of the dam	2712000000	6E+09	1.31E+08	2.97E+09	99600000	1.200.000.000	2.6E+08	5.08E+09	2.62E+09	3.14E+09

As observed, the amount of water supplied from each dam to each city is presented in the table 4. This amount is determined based on distance, and the results show that some dams do not supply water to certain cities due to suboptimal water distribution, thus their values are zero for those cities. On the other hand, the total amount of water supplied from a dam, for instance, Dez Dam, to all cities should not exceed the dam’s total capacity, which is reflected in the table 4. For example, the amount of water supplied from Dez Dam to Masjed Soleyman city is 110,882,453.2, while this dam does not supply water to Shadegan, Susangerd, and Ramhormoz cities, and therefore, their values are zero. Subsequently, the sequence of water supply to production complexes will be discussed. Due to the high volume of production complexes in each city, only one example, namely the production complexes located in Ahvaz city, will be considered. The results are presented in Table 5.

Table 5 - Order and Sequence of Water Supply to Production Complexes in Ahvaz City, along with Delivery Time

Order and Sequence	Name of Production Complex	Delivery Time
1	Salman Farsi Agriculture and Industry	1471
2	South Flour	1714
3	Bam Laban Tehran	1951
4	Amirkabir Sugarcane Agriculture and Industry	2140
5	Cooperative 262 Delicious Hamburger	2332
6	Beh Amine South	2601
7	Mahziyar Flour Ahvaz	2711
8	Ghoncheh Flour Production Ahvaz	2855
9	Beh Koorak Meat Products	3069
10	Cooperative Number 572 Isargaran Ahvaz	3237
11	Khuzestan Cannery	3483
12	Dez Macaroni	3606
13	Mahna Noosh	3873
14	Paniz South	4036
15	Gandomin South Macaroni	4310

Order and Sequence	**Name of Production Complex**	**Delivery Time**
16	Persian Medicine/Drug	4498
17	Momtazan Ahvaz Meat and Food Products	4636
18	Si Del Food Industries	4845
19	Behshad Khuzestan	5027
20	Ara Protein South	5133
21	Arman Dasht South	5278
22	Bahar Farah Noosh Company	5575
23	Khuzestan Meat Industries	5826
24	Parash Agriculture and Industry	5990
25	Ferdows Kar Khuzestan	6272
26	Youth, Hope, Future	6458
27	Ofogh Halvashakari	6657
28	Pasazh Food Industries	6823
29	Zamzam Ahvaz	6939
30	Mehrdad Farzam	7207
31	Tolou Ahvaz	7464
32	Mehrshad Resin	7637
33	Khorram Noosh Ahvaz	7866
34	Shadmehr South Company	8087
35	Ahvaz Sugar and Sugar Refining	8189
36	Asr	8323
37	South Buffalo Milk	8493
38	Hakim Farabi Agriculture and Industry	8606
39	De’bel Khazaei Agriculture and Industry	8903
40	Sakhavat Ahvaz Honey Cooperative	9081
41	Khuzestan Flour	9379
42	Sugarcane Development and Ancillary Industries Yeast and Alcohol	9491

Order and Sequence	Name of Production Complex	Delivery Time
43	Ahvaz Flour	9614

As shown in Table 5, the order and sequence of water supply for each production complex are presented. In fact, the order and sequence of water supply to the production complexes in Ahvaz city, according to Table 4, are in an optimal state, and based on the time spent, it is better for the water supply sequence to be as described above.

4-1. Sensitivity Analysis

This section deals with the parametric sensitivity analysis of the problem. Sensitivity analysis is a method for measuring the model's reaction to changes in parameters and ultimately finding the most influential parameters. In this section, the most important parameters that are likely to change are presented and increased by 10 to 50 percent, and then the reaction to this increase is examined. The results are presented in the tables and Figs below. For this purpose, the impact of different parameters on cost and time is compared, and it is determined which parameters have a greater impact. The results are presented in the tables and Figs below.

Table 6- Comparison of influential parameters on cost

Cost	Demand	Budget	Time distance between the city and the production complex	Time distance within the production complex	Time distance between production complexes	Water transfer cost	Water arrival time
10%	0.000957	0.001668	0.001481	0.000964	0.001032	0.018192	0.001415
20%	0.002331	0.003232	0.002821	0.002716	0.002653	0.03527	0.003236
30%	0.003277	0.005069	0.003807	0.004393	0.004085	0.048147	0.00422
40%	0.004883	0.006246	0.005407	0.005613	0.005893	0.061302	0.005798
50%	0.006708	0.007751	0.006756	0.006802	0.007208	0.069878	0.007352

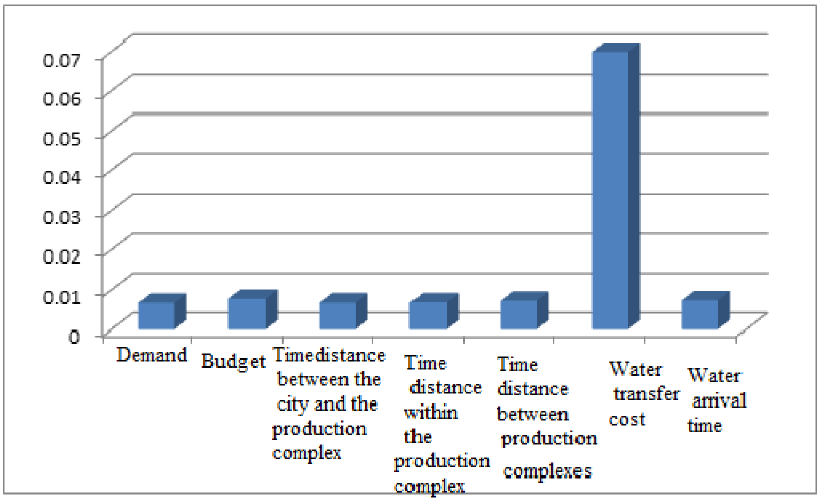

Figure 7 - Comparison of parameters affecting cost

As shown in Figure 7, the most influential parameter on cost at a 50% increase level is the water transfer cost parameter, which can lead to a 7% increase in cost, while the influence of other parameters is around 0.5% and rarely reaches 1%. In fact, other parameters are almost identical in terms of influence, and there is no difference between them, but only the water transfer cost parameter has a significant influence.

Table 7- Comparison of parameters affecting time

Time	**Demand**	**Budget**	**Time interval between the city and the production complex**	**Time interval within the production complex**	**Time interval between production complexes**	**Water transfer cost**	**Water arrival time**
10%	0.004588	0.003135	0.028758	0.024827	0.03554	0.004038	0.0237
20%	0.007138	0.006735	0.06766	0.047373	0.065165	0.008325	0.058386
30%	0.011622	0.010334	0.102476	0.087981	0.095422	0.012431	0.091643
40%	0.015919	0.012834	0.118233	0.107313	0.113714	0.015628	0.121867
50%	0.018921	0.01663	0.132082	0.132367	0.129649	0.018575	0.131448

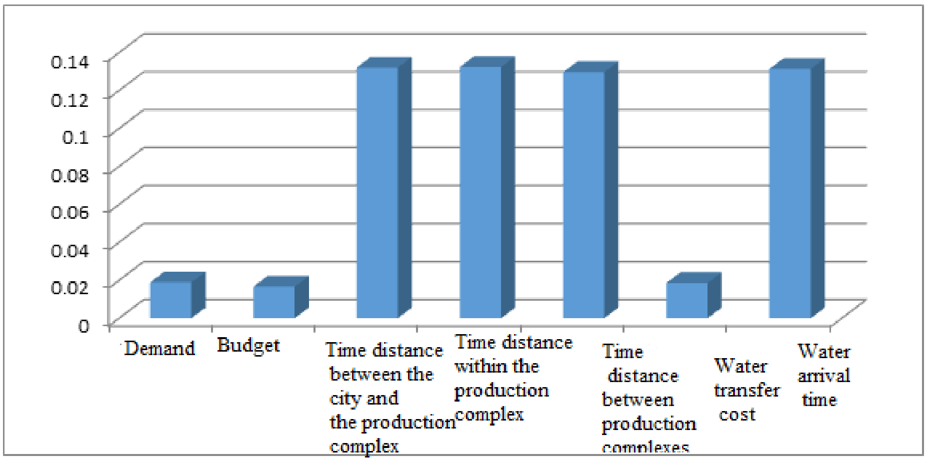

Fig 8 - Comparison of Parameters Affecting Time

In Graph 8, the parameters affecting time are compared. As can be seen, the time interval between the city and the production complex, the time interval within the production complex, the water arrival time, and the time interval between production complexes have the greatest impact, and this figure is close to 13%. In fact, the impact of the above parameters on water transfer time is generally almost equal and has a significant difference from the parameters of demand, budget amount, and water transfer cost. Based on the results obtained, it can be said that the parameters of demand, budget amount, and water transfer cost have a slight effect on water transfer time, and this effect is less than 2%. While the time interval parameters and water arrival time, due to their temporal nature, have the greatest effect, an effect close to 13%.

5. Conclusion

The aim of the present research is to optimize the operation of water resources of Khuzestan province dams. For this purpose, first, library studies were conducted, and the research gap in the studied area was identified. Then, based on the innovation, research objectives and assumptions were determined, and then a multi-objective mathematical programming model was designed based on the assumptions. This was followed by optimizing the cost and time of water delivery to each of the cities from the total dams in Khuzestan province. The model was optimized using the epsilon-constraint method. One of the issues identified in the present research is determining the optimality of water supply to cities from dams. Based on this variable, there were cities that were not supplied with water from some dams, which indicates the non-optimality of water delivery. For example, in the optimal state, it is better for Dez Dam not to supply water to Shushtegan, Susangerd, and Ramhormoz cities. Because water supply to these cities from Dez Dam is not cost-effective in terms of time and cost. While Dez Dam can supply water to Masjed Soleyman city to an acceptable volume. This issue is also observed for other dams. For example, according to the results presented in the present research, water supply from Balarud Dam to Ahvaz, Izeh, Abadan, Baghmalek, and Bandar Imam Khomeini cities has not been deemed optimal. While the same dam sends a specific amount of water to Andimeshk, Dezful, Shush, Shushtar, and Gotvand cities. Determining which dams are optimal for water supply and which are not is very important for the water delivery problem, as this can influence the policy-making for water delivery from dams and provide better planning to prevent water waste. Sensitivity analysis results indicated that an increase in water demand can increase delivery time by up to 1.9% and delivery cost by up to 0.6%. Therefore, the effect of water demand is more on time than on cost. An increase in budget, however, can affect both cost and time, although again the effect is more on time than on cost. The next parameter is the time interval between cities and the production complex, which is expected to increase water delivery time by up to 13% with its increase, showing a relatively significant effect. In contrast, this effect on cost is less than on time. The use of other meta-heuristic algorithms and their comparison with each other in terms of efficiency and considering other objectives such as risk and reliability of water delivery, are introduced as suggestions for future research to other researchers.

References

Aboutorabi, H. R. , Ramroodi, M. , Asgharipour, M. R. and Ghazanfari Moghadam, M. S. (2022). Use of Water Footprint and Virtual Water to Determine the Optimal Cropping Pattern; Case Study: Ghaenat and Zirkoh Counties. *Journal Of Agroecology,* 14(1), 173-191. doi: 10.22067/agry.2021.67480.1002

Allan, J. A. (1998). Virtual water: a strategic resource global solutions to regional deficits. *Groundwater* 36 (4): 545-546.

Asl-Rousta, B., & Mousavi, S. J. (2025). Bankruptcy rules and sustainable water management: A MODSIM-NSGAII simulation multi-objective optimization framework for equitable transboundary water allocation. *Environmental and Sustainability Indicators*, *26*, 100648.

Aviso, K. B., Holaysan, S. A. K., B. Promentilla, M. A., S. Yu, K. D., & R. Tan, R. (2018). A multi-region input-output model for optimizing virtual water trade flows in agricultural crop production. *Management of Environmental Quality: An International Journal*, *29*(1), 63-75.

Baghbanyan, M., taheri, A. and Ghaderzadeh, H. (2022). Determining the optimal cultivation pattern of crops with emphasis on virtual water in Qorveh and Dehgolan cities of Kurdistan province. *Iranian Journal of Irrigation & Drainage,* 16(5), 1026-1043.

Benchaiba, L., Moussouni, A., Zeghmar, A., & Maaliou, A. (2025). Wavelet and AI-based reservoir evaporation modeling for optimized water management: A case study of Koudiat Acerdoun Dam. *Theoretical and Applied Climatology*, *156*(4), 1-28.

Brindha, K. (2020), Virtual water flows, water footprint and water savings from the trade of crop and livestock products of Germany. *Water and Environment Journal,* 34: 656-66

Chen, W., Wu, S., Lei, Y., & Li, S. (2017). China's water footprint by province, and inter-provincial transfer of virtual water. *Ecological indicators*, *74*, 321-333.

Delshad, M. M., Chobar, A. P., Ghasemi, P., & Jafari, D. (2024). Efficient humanitarian logistics: multi-commodity location–inventory model incorporating demand probability and consumption coefficients. *Logistics*, *8*(1), 9.

Fracasso, A., Sartori, M., & Schiavo, S. (2016). Determinants of virtual water flow in the Mediterranean. *Science of The Total Environment,* 543, 1054-1062.

Hekmatnia, H. , hosseini, S. M. and safdari, M. (2020). Determination and Assessment of Green, Blue and Gray Water Footprints in the International Trade of Agricultural Products of Iran. *Iranian Journal of Irrigation & Drainage*, 14(2), 446-463.

Heydari Kushalshah, T., Daneshmand-Mehr, M., & Abolghasemian, M. (2023). Hybrid modelling for urban water supply system management based on a bi-objective mathematical model and system dynamics: A case study in Guilan province. *Journal of Industrial and Systems Engineering*.

Keihani, H. (2025). Transitioning corporate models and processes towards sustainable practices and adopting a circular economy approach. *Canadian Journal of Business, Economics and Health Managemen*, *8*(2), 31-46.

Kolahi, M., Hosseinali, F. and Karimaei Tabarestani, M. (2023). Determining the optimal cultivation pattern by considering the concept of virtual water and economic benefits (Case Study: Omrani Plain in Khorasan Razavi). *Iranian Journal of Irrigation & Drainage*, 16(6), 1221-1232.

Mehrani, K., Mirshahvalad, A., & Abbasi, E. (2019). Comparison of the accuracy of black hole algorithms and gravitational research and the hybrid method in portfolio optimization. *International Journal of Finance & Managerial Accounting*, *4*(14), 111-126.

Nafarzadegan, A. R. , Vagharfard, H. , Nikoo, M. R. and Nohegar, A. (2017). Application of interactive interval linear programming for optimal water and crop area allocation considering virtual water content and socio-economic factors (Case study: Dorudzan-Korbal Plain). *Journal of Ecohydrology*, 4(2), 601-613. doi: 10.22059/ije.2017.61498

Nozari, H. (2024). Green supply chain management based on artificial intelligence of everything. Journal of Economics and Management, 46, 171-188.

Nozari, H., & Edalatpanah, S. A. (2023). Smart systems risk management in IoT-based supply chain. In Advances in reliability, failure and risk analysis (pp. 251-268). Singapore: Springer Nature Singapore.

Nozari, H., Abdi, H., & Jahangard, S. (2025). Quantum Cognitive Intelligence Network Q-CIN as a Transformative Framework for Industry 6.0. ALL Bioscience, 1(1), 27-37.

Nozari, H., Abdi, H., & Rafiei, K. (2025). Edge Computing and Marketing in the Smart Economy: Processing Consumer Data in Real-Time. In H. Nozari (Ed.), Dynamic and Safe Economy in the Age of Smart Technologies (pp. 191-208). IGI Global Scientific Publishing. https://doi.org/10.4018/979-8-3693-4369-2.ch012

Oveisi F, Fattahi Ardakani A, Fehresti Sani M. Investigation of Virtual Water and Ecological Footprints of Water in Wheat Fields of Isfahan Province. jwss 2019; 23 (1) :87-99

Safdari, M. , Hosseyni, S. M. , Hekmatnia, M. and Dadres Moghadam, A. (2022). The Water Footprint of Consumption and Virtual Water Trade of Dates in Iran. *Water and Soil Science*, 32(4), 133-145. doi: 10.22034/ws.2021.12338

Shahidi, A., Dehghan, M. , Najafi, M. H. and Arabi Yazdi, A. (2019). Evaluation and Comparison of Water Footprint in Industry and Agriculture (Case Study: South Khorasan Province). *Iranian Journal of Irrigation & Drainage*, 13(3), 565-574.

Tahami Pourzarandi, M. and Abedi, S. (2017). Evaluation of Virtual Water Trade by the Industrial Sector of Zanjan Province. Journal of Water and Wastewater; Ab va Fazilab (in persian), 28(3), 36-45. doi: 10.22093/wwj.2016.40799

Wang, Y. B., Liu, D., Cao, X. C., Yang, Z. Y., Song, J. F., Chen, D. Y., & Sun, S. K. (2017). Agricultural water rights trading and virtual water export compensation coupling model: A case study of an irrigation district in China. *Agricultural water management,* 180, 99-106.

Wichelns, D. (2001). The role of 'virtual water'in efforts to achieve food security and other national goals, with an example from Egypt. *Agricultural water management*, *49*(2), 131-151.

Xu, Z., Yao, L., Zhang, Q., Dowaki, K., & Long, Y. (2020). Inequality of water allocation and policy response considering virtual water trade: a case study of Lanzhou city, China. *Journal of Cleaner Production*, *269*, 122326.

Yao, L., Xu, Z., Wu, H., & Chen, X. (2020). A novel data-driven analytical framework on hierarchical water allocation integrated with blue and virtual water transfers. *Hydrology and Earth System Sciences*, *24*(5), 2769-2789.

Ye, Q., Li, Y., Zhuo, L., Zhang, W., Xiong, W., Wang, C., & Wang, P. (2018). Optimal allocation of physical water resources integrated with virtual water trade in water scarce regions: A case study for Beijing, China. *Water research*, *129*, 264-276.