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A distributed constraint multi-agent model for water and reclaimed wastewater allocation in urban areas: Application of a modified ADOPT algorithm

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ABSTRACT

Distributed Constraint Optimization (DCOP)-based approaches, as the distributed version of constraint optimization, provide a framework for coordinated decision making by a team of agents. In this paper, an agent-based DCOP model is developed to allocate water and reclaimed wastewater to demands considering the conflicting interests of involved stakeholders. One of the well-known DCOP algorithms, ADOPT[1], is modified to incorporate an agent responsible for monitoring and conserving water resources. This new algorithm considers the social characteristics of agents and a new form of interaction between agents. For the first time in the literature, a real-world water and reclaimed wastewater allocation problem is formulated as a DCOP and solved using the Modified ADOPT (MADOPT) algorithm. To evaluate the MADOPT algorithm, it is applied to a water and reclaimed wastewater allocation problem in Tehran, Iran. The results illustrate the applicability and efficiency of the proposed methodology in dealing with large-scale multi-agent water resources systems. It is also shown that agents' selfishness and social relationships could affect their water use policies.

1. Introduction

Large-scale water resources systems are often characterized by multiple institutionally independent decision-makers (DMs) (Giuliani et al., 2015; Ahmadi et al., 2019). A water resources system with multiple agents and conflicting desires usually leads to disputes (Emami-Skardi et al., 2013; Ahmadi et al., 2020; Eyni et al., 2021; Aghaie et al., 2021). Conflicts in a multi-stakeholder environment could lead to the tragedy of commons (Hardin, 2009; Emami-Skardi et al., 2021).

Many researchers have emphasized incorporating the characteristics of stakeholders in analyzing water and environmental problems, including ecosystem services management (Ashrafi et al., 2021; Paing et al., 2022), wildlife management and protection (Drijfhout et al., 2022), Water Governance (Nabiafjadi et al., 2021), sustainable development in growing cities (Mahjouri and Pourmand, 2017; Kalantari et al., 2019), water quantity and quality management (Pourmand and Mahjouri, 2018), social-ecological systems resilience (Moghaddasi et al., 2022) and water infrastructures planning (Lienert et al., 2013). In large-scale water resources systems, classical top-down management approaches might neglect the principle of individual-rationality and only focus on finding solutions that maximize the system-level efficiency (Loucks and Beek, 2017; Giuliani and Castelletti, 2013; Zoltay et al., 2010; Emami-Skardi et al., 2021). In top-down management, especially in large-scale systems, the characteristics of stakeholders of the system management are usually ignored, their considerations and differences are not taken into account, which ultimately reduces their satisfaction. In this approach, the stakeholders' cooperation decreases, and the management plans' applicability will be questionable.

In recent years, multi-agent approaches have been successfully applied to water resources planning and management. The merits of agent-based approaches can be classified as follows:

I. Simulate heterogeneous and autonomous elements in a comprehensive model (Pouladi et al., 2019).
II. Simulate agents with local vision without global knowledge: Agents act locally, parallel, and distributed with limited global knowledge. Small actions can propagate through the entire system and trigger network effects (Helbing et al., 2014; Gómez-Cruz et al., 2017).
III. Simulate interactions in a complex system: Agent-based simulation allows researchers to model interactions between individuals and organizations and assess their behavior (Gómez-Cruz et al.,

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2017; Fioretti and Lomi, 2012). Darbandsari et al. (2017) proposed an agent-based model for simulating urban households' behaviors and their reactions and suggested that rather than focusing on the precise forecasting of the future, the agent-based modeling paradigm provides a clear description and improved understanding of the complexity of stakeholders and their interactions.

In the next section, using a pictorial introduction, the roles and necessity of the distributed (decentralized) approach for modeling large-scale water resources systems are explained.

1.1. The importance of distributed decision-making approaches in water resources management

To achieve proper and efficient management of water resources systems and the physical and engineering aspects, the utilities of various stakeholders should be taken into account. In a fully centralized, small-scale system, the system manager can find the system's optimal condition using optimization techniques (point A in Fig. 1). In many water resource systems, a solution with the maximum acceptance by stakeholders (point B in Fig. 1) is different from the optimum solution. As a system-wide optimum solution may decrease the utilities of some stakeholders, in many cases, the acceptability of the solutions is decreased by increasing the efficiency and vice versa.

In Point C in Fig. 1, the stakeholders' satisfaction and the system efficiency are at their highest levels. Although this point is ideal, this solution is not obtainable in most water resources systems.

In large-scale water resources systems, which have a large geographic scale and involve several stakeholders, the overall shape of Fig. 1 (a) is changed to Fig. 1 (b). Because of this change in the nature of the system from small to large scale, the management approach needs to be changed and modified. In this case, due to the large scale of the system, a stakeholder does not necessarily have access to all components and information of the system. In a large-scale centralized system, the stakeholder who manages the system may not find the absolute optimal policy, and instead of the point, A_{ii} stands on point E_{ii} in Fig. 1. Point B_{ii} in Fig. 1 is the same as point B_i where the stakeholders have the highest level of satisfaction because they do anything they want without collaborating. It may keep the system away from the optimal status. Point C_{ii} is similar to point C_i, the ideal point which may not be obtainable in many water resources systems.

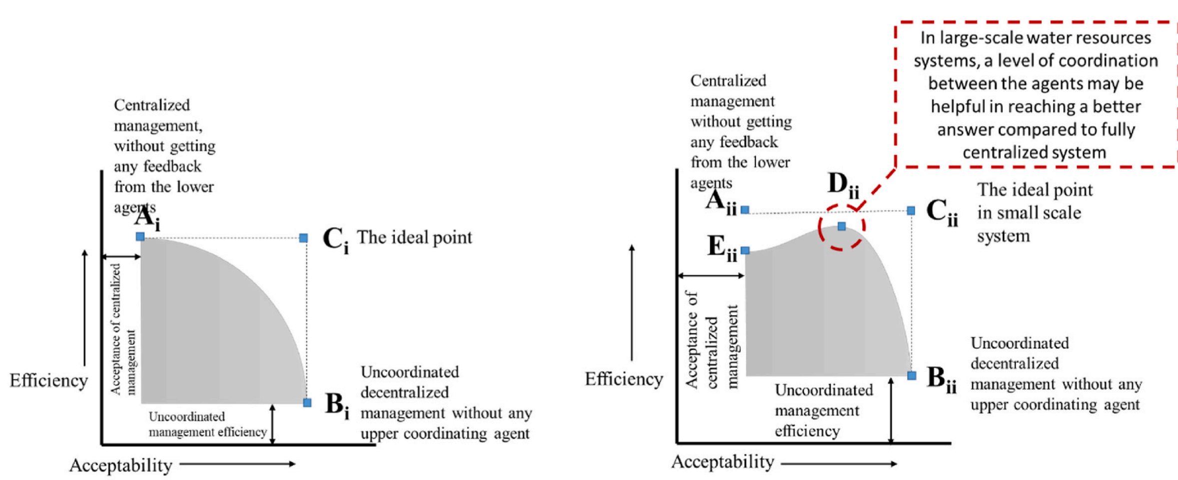
The other main difference between these two parts of Fig. 1 is point D_{ii}, in which stakeholders may reach a near-optimal solution, even better than a centralized management condition, by having cooperation.

Most water resource systems can be modeled as a Distributed Constraint Optimization (DCOP) problem. Several algorithms solve DCOPs (Woldeyohanes et al., 2021). One of the well-known algorithms is ADOPT, developed by Modi et al. (2005). ADOPT is a polynomial-space algorithm that allows agents to act asynchronously and in parallel. Finding the globally optimal solution is guaranteed in ADOPT (Modi et al., 2005). The applications of the ADOPT algorithm in computer science and artificial intelligence have been considerable (Fioretto et al., 2018). Giuliani et al. (2015) applied the ADOPT algorithm to a hypothetical problem and showed that it could be used for regulatory mechanism design in water management. Woldeyohanes et al. (2021) listed various solution algorithms, including ADOPT algorithm, which can be employed to solve agent-based water resources management problems.

A well-written review of the DCOP based algorithms has been presented by Fioretto et al. (2018), in which various classes of DCOP algorithms can be found, such as decentralized and partially centralized synchronous and asynchronous algorithms. The water resources management problem, which is studied in the current paper, is decentralized and asynchronous. Based on Fig. 5 of the paper written by Fioretto et al. (2018), AFB, ConcFB, and ADOPT algorithms are the decentralized and asynchronous ones and based on Table 4 of the mentioned paper, ADOPT is the only algorithm in this class in which the local communication can be considered. Besides, in most large-scale water resources systems, the involved agents have a local view of the problem, which can be modeled using the ADOPT algorithm (Modi et al., 2005). Therefore, ADOPT algorithm is selected as the base DCOP model and modified to be applicable to the study area.

The ADOPT algorithm has not been applied to a real-word water resources management problem to the best of the authors' knowledge. In this paper, for the first time, a modified ADOPT algorithm, called MADOPT, is developed and applied to a water and reclaimed wastewater allocation problem, and its effectiveness is evaluated.

This paper provides three main contributions: (1) Proposing a multi-agent approach for developing water allocation policies considering system-level efficiency and agent acceptability (point D_{ii} in Fig. 1). This policy outperforms the centralized policies in large-scale systems, including multiple non-cooperative decision-makers, (2) Proposing a modified version of ADOPT algorithm that allows having a monitoring agent which usually exists in real-world water resources and environmental systems. MADOP considers a new interaction among agents, a



(a) Small Scale System (b) Large Scale Systems

Fig. 1. The role and necessity of distributed approaches in managing large scale water resources systems.

new local cost function, and the social characteristics of agents, (3) Evaluate the applicability and efficiency of the MADOPT algorithm by applying it to a real-world, large-scale water resources management problem.

The rest of the paper is organized as follows: the next section presents details of the proposed methodology. Section 4 describes the study area. Then, the results are presented, and in the final section, a summary of the paper, concluding remarks, and some suggestions for further studies are conferred.

2. Methodology

This paper develops a new MADOPT algorithm to deal with urban water and reclaimed wastewater allocation problems. The proposed methodology incorporates social parameters to provide a more realistic distributed decision-making framework. A flowchart of the methodology is presented in Fig. 2.

2.1. Physical system delineation and agents identification

The first step in analyzing a water resources system is system identification, which includes two main parts: the physical system delineation and the identification of agents. Determining the study area's hydrological, geological, and geographical characteristics and evaluating the main water resources and demands are the main steps of the physical system delineation. In this phase, the main challenges related to water and environmental resources in the study area should be recognized.

Identifying the main agents and determining their characteristics are the core of agents identification. Snowball sampling was applied in the identification and data collection stages to identify all related and key stakeholders (Goodman, 1961; Ahmadi et al., 2020). The snowball sampling method involves a primary data source, which nominates other potential data sources that can participate in the data collection process. The utilities and constraints of the agents and their interactions should be determined in this step.

2.2. MADOPT algorithm

A classical ADOPT problem has n variables (i.e., $V = \{x_1.x_2....x_n\}$) so that each variable is assigned to an agent. Each agent has a function for its decision-making. The agents select their decisions from their finite and discrete domains $\{D_1.D_2....D_n\}$. Each agent has control over its variables and is aware of his domain. d_i denotes the choice of agent i for its variable x_i. A solution to an ADOPT problem is a set of values assigned to the variables to minimize the system's total cost function.

The objective function (i.e., total cost function) can be defined as the sum of several cost functions. The cost function for a pair of variables x_i and x_j is defined as $f_{ij} : D_i \times D_j \rightarrow N$. Cost functions are calculated based on the violations of the constraints.

Initially, the existing agents in an ADOPT problem should be arranged in a tree-like diagram called Depth First Search (DFS), in which the connections between the various agents are presented. Agents are arranged in a tree structure, with a single parent and several children for each. There are no constraints between agents in different subtrees of the DFS tree in the classical ADOPT algorithm. In other words, no loops are allowed. Fig. 3 shows a sample of this DFS diagram, where agent 1 is the root and parent of agent 2. Also, agent 2 is the parent of agents 3 and 4.

Other components of the ADOPT algorithm are as follows:

- Value message: This message is sent by an agent in the role of parent to all children who are direct neighbors of him. Also, he only receives messages from parents who are directly connected to him in the upper order in the DFS tree.
- Cost message: An agent sends this message to his parent agent in the DFS diagram. If an agent has multiple parents, he sends the cost message to the parent with the lowest id number. This message consists of three separate parts (Modi et al., 2005):
  1) Current Context: Contains the current information of agent i from all of its parents. The current context is represented as $\{(x_j.d_j), (x_k.d_k)...\}$, where j and k represent the parent and neighboring agents of agent i.
  2) Local Cost (LC): LC of decision d_i of agent i ($d_i \, \varepsilon \, D_i$) is equal to the sum of the costs of constraints between agent i and its higher neighbors (Figueiredo and Perkins, 2013). In the proposed MADOPT algorithms, the LC function is modified to incorporate both the constraints and utility costs:

$$LC(d_i) = \sum_{(x_j.d_j) \in CurrentContext} f_{ij}(d_i, d_j) + Utility\ Cost_i(d_i) \quad (1)$$

where, $f_{ij}(d_i, \ d_j)$ represents the cost of the constraint between agent i with decision d_i, and agent j with decision d_j. $Utility\ Cost_i(d_i)$ denotes the cost of the unfulfilled utility of agent i by making the decision d_i.

A cost message has the following two parts:

$$\forall \ d \in D_i, \ LB(d) = LC(d_i) + \sum_{x_l \in Children} lb(d, x_l) \quad (2)$$

$$\forall \ d \in D_i, \ UB(d) = LC(d_i) + \sum_{x_l \in Children} ub(d, x_l) \quad (3)$$

where, $lb(d, x_l)$ and $ub(d, x_l)$ are respectively the lower and upper bounds of the local cost of children agent x_l when its parent makes decision d.

a) Lower Bound (LB): $LB(d)$ shows the lower bound for the local cost of a subtree that agent i with decision d is the root of it:
b) Upper Bound (UB): $UB(d)$ shows the upper bound for the local cost of a subtree that agent i with decision d is the root of it:

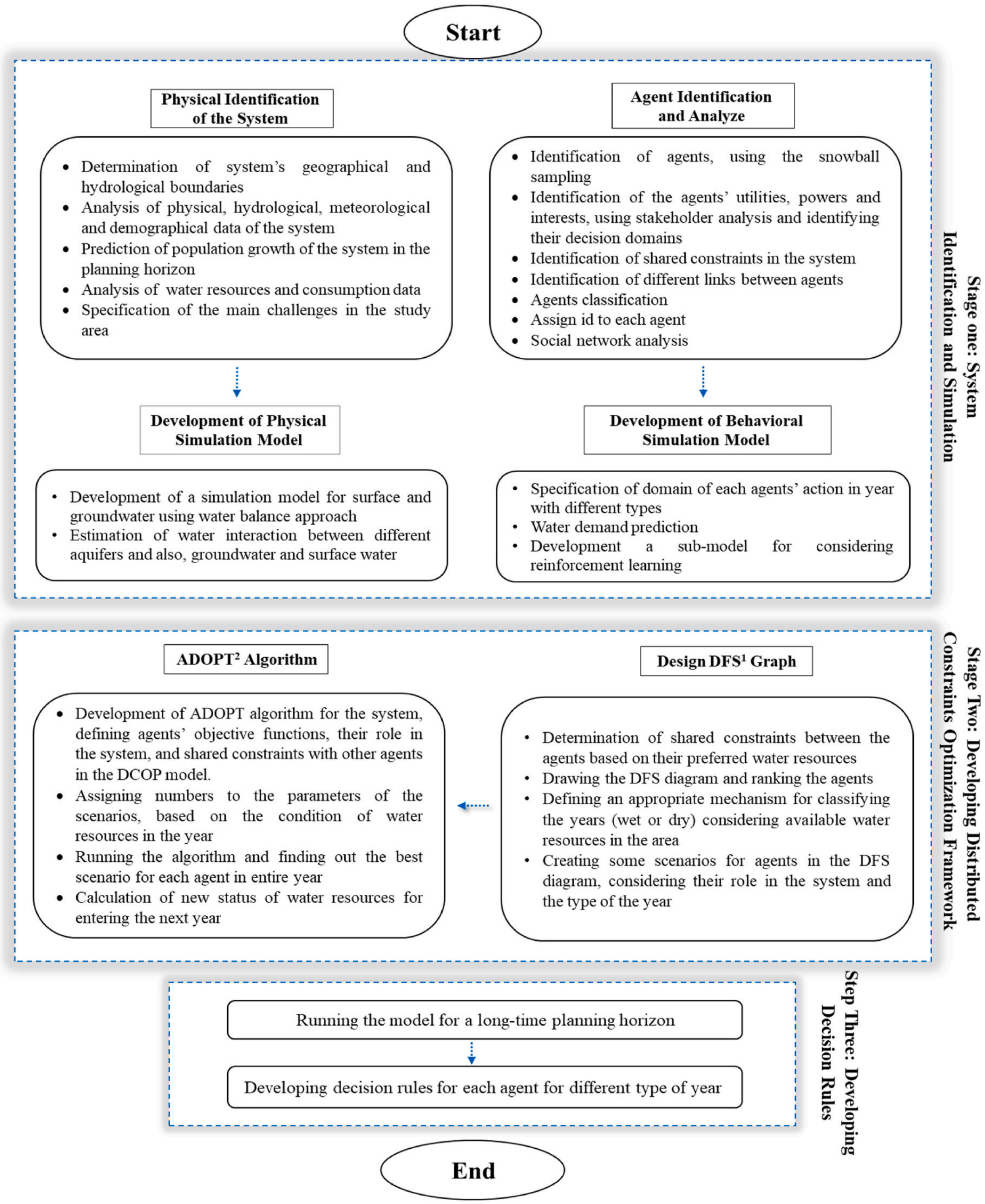
It is worth noting that for a leaf agent with no subtree, the following equation is valid for all values of d.

$$\forall \ d \in D_i, \ LC(d_i) = \ UB(d) = LB(d) \quad (4)$$

3) Threshold message: The ADOPT algorithm employs a cached lower bound as a backtrack threshold, allowing agents to recover previously investigated solutions efficiently. Each agent's backtrack threshold is stored in a variable named threshold, initialized to zero. There are three ways for updating its value: a) its value should be increased if x_i determines that the optimal solution's cost within its subtree is greater than the current value of the threshold; b) Its value should be decreased if x_i determines that the optimal solution's cost within its subtree is lower than the current value of the threshold; c) Receiving a threshold message from a parent. More details about different messages and the algorithm are available in Modi et al. (2005).

In the original form of the ADOPT (Modi et al., 2005), no agent can have access to the decisions of all agents in the DFS tree. Therefore, a monitoring agent, which usually exists in real-world water resources systems, cannot be modeled using the ADOPT algorithm.

The pseudo-code of the proposed MADOPT algorithm is presented in Figure A-1 in the Appendix. These modifications provide the possibility of having a monitoring agent that can monitor agents' decisions on the whole system. The new lines 21 to 25 are responsible for storing all cost messages of the upper agents of the monitoring agent. After receiving all massages, the monitoring agent makes his decision by assessing the condition of the whole system. The MADOPT algorithm also uses the modified version of local cost functions that incorporate agents' unfulfilled utilities.



1. Decision First-search Tree
2. Asynchronous Distributed Constraint Optimization

Fig. 2. A flowchart of the proposed methodology for MADOPT-based water and reclaimed wastewater allocation in urban areas.

2.2.1. *Drawing the DFS tree*

Drawing the DFS tree regarding existing constraints is the first step in developing the MADOPT algorithm. There are some excellent references for ordering agents in the DFS tree (e.g., Giuliani et al. (2013) and Modi et al. (2005)). An important rule for drawing the tree in the ADOPT algorithm is that "there should be no constraints between agents in different subtrees" (Figueiredo and Perkins, 2013). After drawing the DFS tree, the *ids* should be allocated to agents. In the current paper, the following factors are taken into account for assigning *ids*:

o Role of the agents in the social network of agents
o Parameters of the social network such as interest and access to information

The results and discussion section presents details of using social parameters for assigning ids.

2.2.2. *Management scenarios*

This paper develops management scenarios considering various

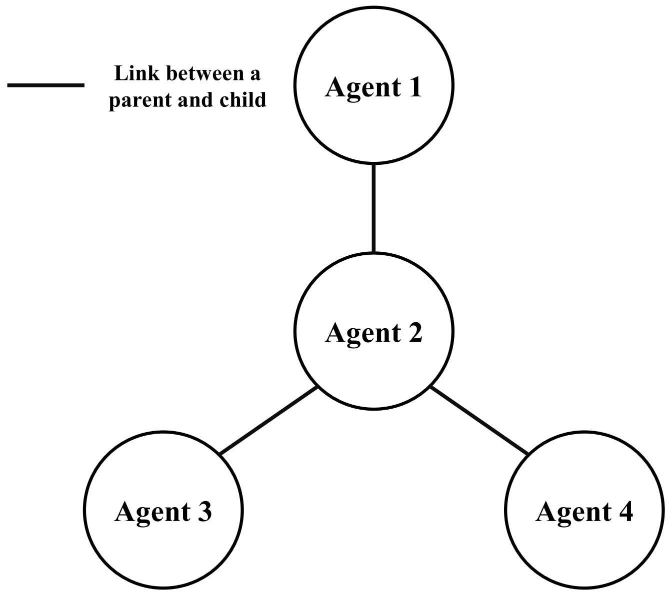


Fig. 3. A sample DFS tree.

water and reclaimed wastewater resource allocation policies. In developing the management scenarios, the hydrological condition of the water year is also considered.[1]

2.2.3. Hydrological conditions

In this paper, the modified SWSI[2] is used for classifying the hydrological condition (type) of water years (Giuliani and Castelletti, 2013):

$$SWSI = \frac{P-50}{12} \tag{5}$$

where P is the probability of non-exceedance of the summation of both reservoirs' water storage at the beginning of a water year and the forecasted inflow to reservoirs during the year (in percent), the range variation of SWSI index is between −4.17 and + 4.17 (Giuliani and Castelletti, 2013). In this paper, three types have been considered for each water year (Table 1).

2.2.4. Management scenarios of agents

Considering the following criteria, management scenarios are developed for each agent:

- o Agent's role in the system and its position in the DFS tree
- o Agent's utility function
- o Hydrological type of each water year based on the SWSI

Before implementing the algorithm, the hydrological types of all water years during the planning horizon are estimated. Then the physical and behavioral simulation models are calibrated and verified. In the next step, the MADOPT algorithm is linked with the simulation models and provides the best decision (scenario) for each agent in each water year.

Table 1
Assumed ranges for the SWSI index.

Type of water year	SWSI	
	Lower bound	Upper bound
Dry	−4.17	−2
Normal	−2	2
Wet	2	4.17

2.2.4.1. Surface and ground water simulation model.

This paper uses a water balance model for the surface and groundwater simulation. A schematic picture of the physical model (i.e., the water balance model) is presented in Fig. 4. Details of the physical model are presented in Emami-Skardi et al. (2020).

2.2.5. Behavioral model

The first step in developing a behavioral model is the identification of the involved agents. The main agents are usually defined based on a pre-interview with experts and reviewing previous studies and reports. This paper develops the behavioral simulation model using the DCOP approach. DCOPs contain n decision variables, $x = [x_1.x_2....x_n]$, each of which belongs to an agent. The values of decision variables are selected from the finite, discrete domains, $D_1, D_2, \dots, D_n$. A solution to a DCOP problem maximizes (or minimizes) a specific objective function g. Usually, the objective function is considered as minimizing a weighted sum of functions that indicate the costs of constraint violations:

$$min_x g = min_x \sum_{j=1}^{r} w_j * c_j(x) \tag{6}$$

where w_j is the weight of cost function $c_j(x)$ corresponding to constraint j. r denotes the total number of constraints.

In this paper, the modified ADOPT algorithm is used for solving the DCOP problem. The interactions among agents can be presented using a network. In this network, nodes represent the agents, and the lines between nodes represent the relationships between agents. Two agents who have a link between them are named neighbors. In the ADOPT algorithm, agents transmit messages with a specific mechanism only to their neighbors to limit transmitted messages. ADOPT is one of the earliest algorithms for determining the best solutions to local and asynchronous communication amongst DCOP agents. Local relations mean that each agent sends messages only to its neighbors. The algorithm depends on a root agent to calculate the overall cost boundaries of the system and identify the ending of the algorithm. This concept gives the algorithm a percentage of centralization; on the other hand, it has different distributional properties, including all agents' ability to calculate in parallel (Figueiredo and Perkins, 2013). Each agent can change the value of its variable whenever it finds a better solution. This characteristic allows asynchronous computation, as each agent needs local information to decide. Agents can communicate with their neighbors through local connections and optimize the global objective function. The ability of agents to perform simultaneous computation can significantly reduce the computational cost.

2.2.6. Local costs

The Local Cost (LC) evaluation for agents is one of the main steps in developing ADOPT algorithm. LC should contain each agent's unique desires and properties. In water allocation problems, agents decide on their water uses considering water resources conditions and the water year type.

In ADOPT algorithm, the LC for an agent is estimated based on the cost of its constraints. In the MADOPT algorithm, the cost of unfulfilled utility functions is also considered for the first time. Therefore, the LC of each agent includes two parts:

1. The summation of cost of the constraints that agent i shares with its neighbor agents. Agents only have access to their parents' decisions (due to receiving the *Value message* from their parents), but they do

[1] Modified Asynchronous Distributed Constraint Optimization.
[2] Surface Water Supply Index.

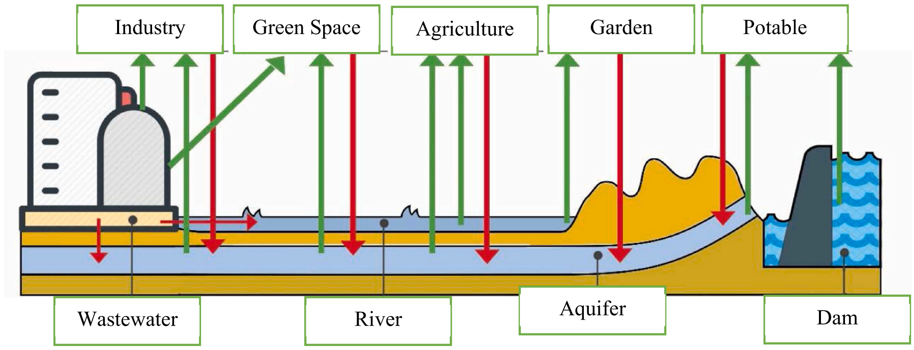


Fig. 4. A schematic picture of water resources, water withdrawals, and return flows in an urban area (Emami-Skardi et al., 2020).

not know their children's decisions (since the cost messages do not contain the values of the children's decisions).
2. The cost of unfulfilled utility corresponding to the agent's decision.

This paper uses the proposed MADOPT-based model for a long-term planning horizon with annual time steps. The best decisions for each agent are derived from each year, considering the hydrological type of year, the condition of water resources, and the impacts of other agents' decisions. By simulating the impact of decisions proposed by the algorithm, the conditions of water resources are estimated at the beginning of the following water year.

3. Case study

The Kan river basin, located in the western part of Tehran City in Iran, is selected as the study area (Fig. 5). Surface water reclaimed wastewater and GW are the study area's main water resources (Khorasani et al., 2020). Agricultural lands, residential zones, a large recreational lake, green spaces, and industrial areas are the main water users in the study area (Emami-Skardi et al., 2020). The eastern and western borders of the study area are defined perpendicular to equipotential GW lines; hence, it can be assumed that there is no GW flow from the eastern and western borders of the region (Fig. 5). A water balance model is used for the groundwater simulation. The aquifer is divided into three regions to enhance the simulation model's accuracy (Emami-Skardi et al., 2020).

The water allocation priorities for different water resources and demands are presented in Table 2. In this table, green spaces No. 1 refers to the water demand of trees (i.e., 20% of green spaces' water demand), green spaces No. 2 refers to the remaining part of this water demand.

3.1. Key stakeholders

The main stakeholders in the study area have been identified and analyzed by Emami-Skardi et al. (2020). Ahmadi et al. (2020) categorized the key stakeholders and their responsibilities, which are presented in Table 3.

Ahmadi et al. (2020) categorized the selected stakeholders into two main categories, protective and developing organizations (Table 4). Protective agents are agents whose primary responsibility is to protect resources from depletion and contamination. Developing agents want to achieve their profit-making objectives. They usually rely on natural resources to achieve their goals (Ahmadi et al., 2020). More details about the study area are available in the online supplementary material.

4. Results and discussion

Ahmadi et al. (2020) analyzed the stakeholders and their social network. They evaluated the stakeholders based on interest, power, access to information, and institutional relationship criteria. These criteria can be defined as follows:

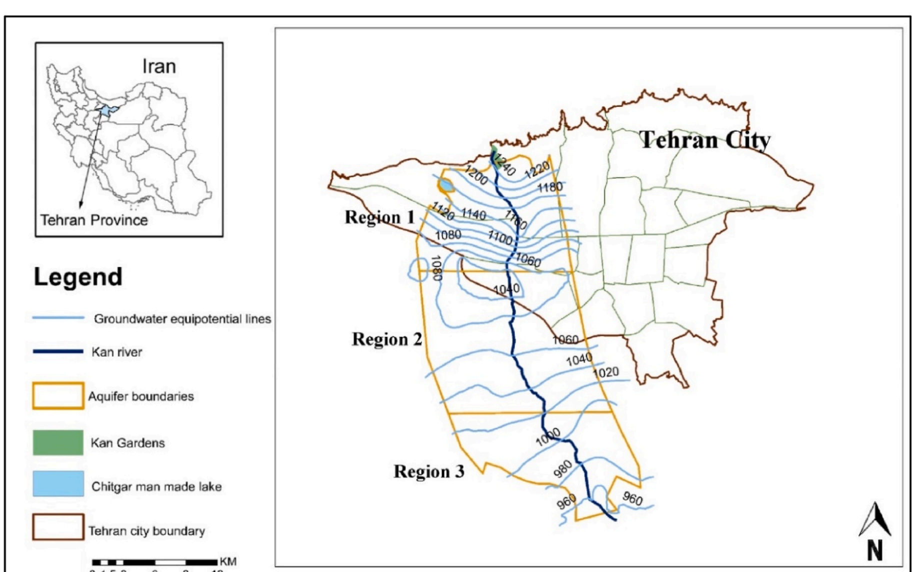


Fig. 5. The western part of Tehran city, Iran, and the groundwater equipotential lines (adapted from Emami-Skardi et al., 2020).

Table 2
Water resources and demands in the study area (Darbandsari et al., 2020).

Water Resources	Water Allocation Priority				
	First	Second	Third	Fourth	Fifth
Transferred water from dams	Domestic (drinking and sanitation)	–	–	–	–
Surface water (the Kan river)	Gardens	Downstream water needs (Environmental demands)	Agriculture	–	–
Groundwater	Domestic (drinking and sanitation)	Industries and minimum demand for green space	Green spaces No. 1	Agriculture	Green spaces No. 2
Reclaimed wastewater	Industries and minimum demand of green space	Downstream water needs (Environmental demands)	Green spaces No. 1	Agriculture	Green spaces No. 2

Table 3
The main identified stakeholders and related responsibilities (adapted from (Emami-Skardi et al., 2020)).

No.	Stakeholders	Responsibilities
1	Tehran Provincial Government (TPG)	Implementing public policy by coordinating various governmental and private institutions
2	Tehran Regional Water company (TRW)	Supplying water for domestic and other needs and conserving water resources
3	Tehran Municipality (TM)	Providing municipality services in the urban areas
4	Tehran Province Water and Wastewater company (TPWW)	Distributing domestic water in urban areas and treating and reusing wastewater
5	Ministry of Industry, Mine, and Trade (MIMT)	Industrial regulation and management
6	Ministry of Agriculture Jihad (MAJ)	Management of agricultural activities

Table 4
Classification of the agents in the study area based on their institutional roles (Ahmadi et al., 2019).

Category	Stakeholders			
Developing	TM	TPWW	MIMT	MAJ
Protective	TPG	TRW		

- Power: The power of a stakeholder to influence the water resources management system;
- Interest: The level of influence of the water resources management system on the interests of a stakeholder; - Access to information: The level of access of a stakeholder to water resources data and information;
- Institutional relationship: The type of institutional relationship between two stakeholders. The online supplementary materials provide more details about the institutional relationships between agents.

Tables 5 and 6 present the estimated values for the interest, power, access to information and institutional relationship criteria.

4.1. DFS tree

According to Table 4, Tehran Regional Water company (TRW) and Tehran Provincial Government (TPG) are protective agents. TRW's main role is managing water resources in the system. Therefore, it has shared constraints with all water users. On the other hand, TPG monitors the system's security. Therefore, all developing agents should have constraints with TPG. Also, TPG has a direct constrain with TRW due to its role.

Table 5
The estimated values for interest, power, and access to information criteria for the agents in the study area (Ahmadi et al., 2020).

Agent	Interest	Power	Access to information
TRW	4.63	4	3
TM	3.63	3.27	2
TPWW	4.18	3.18	5
MAJ	3.18	2.18	4
MIMT	2.45	2.63	3
TPG	2.45	3.45	5

Table 6
The values of institutional relationship criterion derived from social network analysis (Ahmadi et al., 2020).

Agent	TRW	TM	TPWW	MAJ	MIMT	TPG
TRW	0	−1.2	4	2.4	−1.4	3
TM	2.2	0	0.6	−0.2	0	−0.2
TPWW	3.6	3.8	0	1.6	1.8	3.8
MAJ	2.6	1	2.2	0	1	2.8
MIMT	−2	−2.2	−1.4	−2.2	0	2
TPG	4.6	−0.2	2.4	4.2	3.8	0

The next step for drawing the DFS tree is assigning *ids* to the agents. TRW, as a protective agent, has the highest power and an intermediate level of access to information. ID number 1 is assigned to TRW because this agent can affect other agents by sending a message to them but does not have exact information about other agents' decisions. On the other hand, TPG has the highest access to information about the agents' decisions. Therefore, according to ADOPT algorithm, it should have the highest *id*. Other developing agents in the middle layer are prioritized considering their roles and interests. Table 5 shows that TPWW has the highest interest as a developing agent. Thus, its ID should be 2. The developed DFS tree and the agents' *ids* are shown in Fig. 6.

As shown in Fig. 6, all agents have a constraint with TPG. In this figure, the dashed lines represent a new form of constraints, in which only upper agents send their value messages to TPG but do not send or receive other types of messages. Using this new property, an agent, like TPG, can monitor the system's condition.

4.2. Developing management scenarios

Based on the role of each stakeholder in the system, the preferences of stakeholders and their desires are considered to develop the main scenarios in this paper. Besides, various consumers take different actions depending on the hydrological type of water year. For example, TPWW can use advertising to reduce consumption in drought years. Therefore, formulating different scenarios based on the type of water year makes decision-making processes more realistic. Table 7 provides a summary of the agents' management scenarios. More details about the agents' scenarios can be found in the Appendix.

Equation (5) is used for determining the hydrological type of each year. In this paper, there is an emphasis on the drinking water supply to urban areas. Therefore, the time series of the summation of transferred water from dams and the volume of allowable GW discharge (i.e., the time series of total available water, TAW) is used to estimate the probability distribution function of TAW. Based on equation (7), at the beginning of each year, TAW is calculated. Using TAW and the

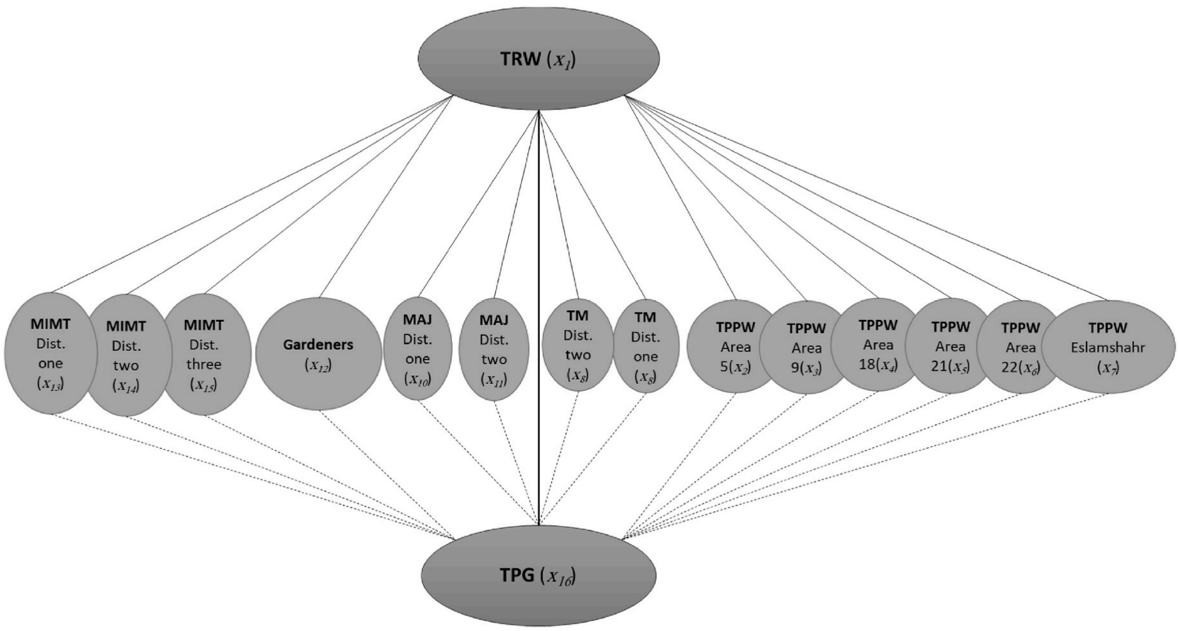


Fig. 6. The proposed DFS tree for the agents in the study area and their *ids*.

Table 7
A Summary of the agents' management scenarios.

Agent	Summary of the Scenarios
Tehran Regional Water (TRW)	Deciding on the water supply to demands of other agents (e.g. TPWW's drinking water demand) from different sources (i.e. groundwater, surface water, and treated wastewater)
Tehran Municipality (TM)	Deciding on how to supply water demand of green space in the city from groundwater or buying treated wastewater
Tehran Province Water and Wastewater company (TPWW)	Deciding on how to supply domestic water demands
Gardeners	Amount of water withdrawal from the Kan River to supply their demands
Ministry of Agriculture Jihad (MAJ, Districts 1 and 2)	Deciding on the area of cultivated lands and how to supply its water demands using the Kan river and groundwater based on the type of water year
Ministry of Industry, Mine, and Trade (MIMT, Districts 1 and 2)	Deciding on how to supply their demands using groundwater or buying treated wastewater
Water quality-sensitive industries	Amount of water withdrawal from groundwater to supply their demands

probability distribution function, SWSI is calculated, and accounting to Table 1, the hydrological type of each water year is determined.

It should be noted that, in each year, the available volume of GW depends on the hydrological type of year and the agents' decisions; therefore, P in equation (5) and the agents' decisions are not independent. To take this dependency into account, the following iterative process is used:

At first, when there is no background information about the available volume of the GW, only transferred water from the dams' time series is considered for developing a probability distribution function using an experimental method, and an initial value for P is estimated for each year. Using the estimated P values, the model is run, and an initial time series for the available volume of GW is obtained. The distribution function, P, is re-estimated in the second step, considering the time series of both available GW (obtained from the previous step) and transferred water from dams. The resulting P is used for calculating the SWSI. After running the model and obtaining a new available GW time series, the process stops if the new time series is similar to the previous one. A flowchart of this process is presented in Fig. 7.

A scenario is an option that an agent can select in each algorithm step. It should be noted that the transferred water from dams is only allocated to TPWW areas 5, 9, and 18, and the rest of the domestic water demands are supplied using GW. The developed scenarios for each agent are presented in Tables 8–14.

4.3. Determining cost and utility functions

LC is the main criterion for selecting the best scenario by an agent. The process of determining LC for protective and developing agents is as follows:

4.3.1. Protective agents

TRW: For this agent with id number 1, coefficient $w(i)$ is set considering social network parameters of power and interest:

$$w(i) = 2 - \frac{power(i)}{power(t)} - \frac{interest(i)}{interest(t)} \tag{7}$$

where i denotes each developing agent in the neighbor of TRW, and t denotes TRW. Power and interest values are presented in Table 6. The values of $w(i)$ for the agents are shown in Table 15.

In the next step, using w values presented in Table 15, TRW calculates the cost of each of its options by using equation (8):

$$LC(t,j) = \sum w(i) * \frac{(scenario(j,i) - \min\_allocation(i))}{(\max\_allocation(i) - \min\_allocation(i))} \tag{8}$$

where t denotes TRW, and $LC(t,j)$ shows the local cost of scenario j for TRW. $scenario(j,i)$ represents the amount of allocated water to agent i based on j th scenario of TRW. $\max\_allocation(i)$ and $\min\_allocation(i)$ represent the maximum and minimum volumes of allocated water to agent i among all of the TRW scenarios for that year, respectively.

TPG: The decision-making procedure and scenarios of TPG are different from other agents. TPG aims to monitor the performance of governmental agents and provide social security. Thus, it monitors the system's situation by receiving value messages from other agents. Using the messages containing each agent's decision about its water allocation scenario, TPG will check the system's balance in each step. As GW table

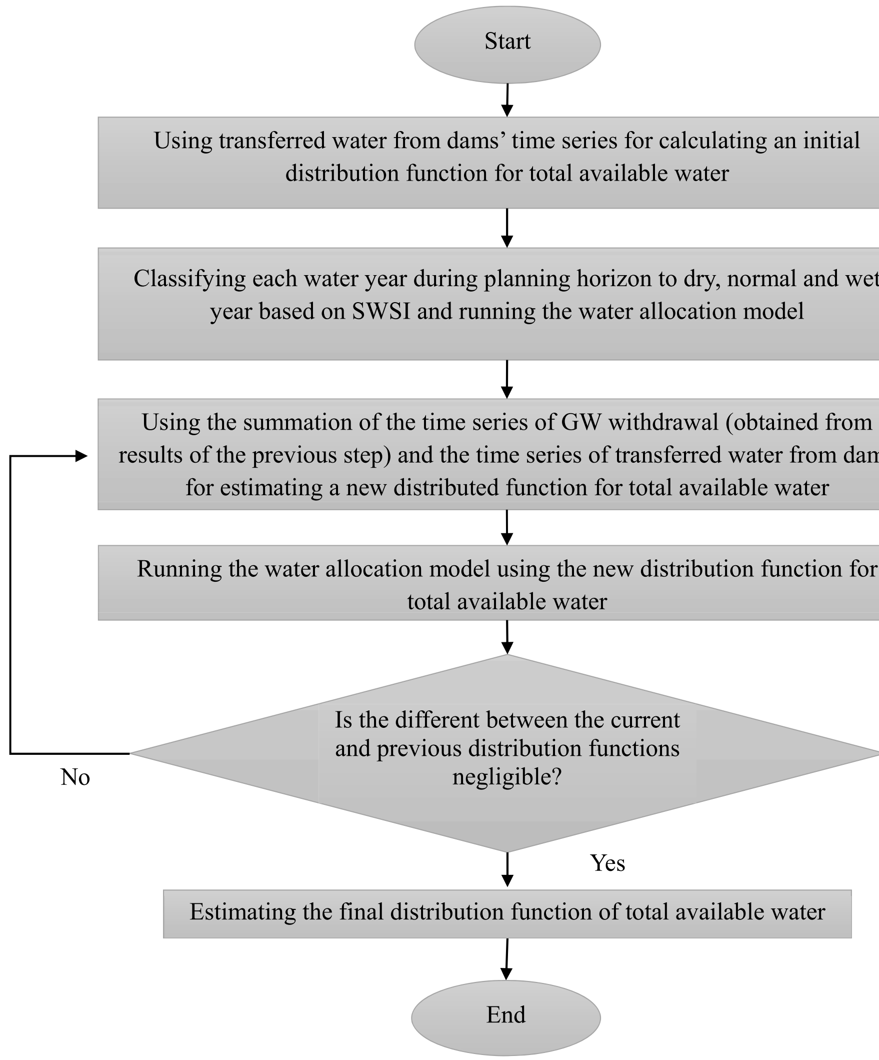


Fig. 7. A flowchart for obtaining the distribution function of total available water.

Table 8
Tehran Reginal Water (TRW) scenarios for water allocation to demands in different hydrological years (The codes are defined in Tables A-1 and A-2 in the appendix).

Type of year	No. of Scenario	TPWW[1]	Gardeners	TM[2]: Min. Green Space	Non-sensitive Industry	Water quality-sensitive industries	TM: Green spaces No. 1	MAJ[3]	Artificial Recharge of groundwater	TM: Green spaces No. 2
Wet Year	1	TRW-TPWW-1	TRW-Gardeners	TRW-Min. TM	TRW-NSI-1	TRW-SI	TRW-TM1-1	TRW-MAJ-1	TRW-ARG-1	TRW-TM2-1
	2	TRW-TPWW-2	TRW-Gardeners	TRW-Min. TM	TRW-NSI-1	TRW-SI	TRW-TM1-1	TRW-MAJ-2	TRW-ARG-2	TRW-TM2-1
	3	TRW-TPWW-1	TRW-Gardeners	TRW-Min. TM	TRW-NSI-1	TRW-SI	TRW-TM1-1	TRW-MAJ-1	TRW-ARG-1	TRW-TM2-1
	4	TRW-TPWW-1	TRW-Gardeners	TRW-Min. TM	TRW-NSI-2	TRW-SI	TRW-TM1-1	TRW-MAJ-1	TRW-ARG-1	TRW-TM2-1
Normal Year	5	TRW-TPWW-1	TRW-Gardeners	TRW-Min. TM	TRW-NSI-1	TRW-SI	TRW-TM1-1	TRW-MAJ-2	TRW-ARG-2	TRW-TM2-1
	6	TRW-TPWW-3	TRW-Gardeners	TRW-Min. TM	TRW-NSI-1	TRW-SI	TRW-TM1-1	TRW-MAJ-1	TRW-ARG-2	TRW-TM2-1
	7	TRW-TPWW-1	TRW-Gardeners	TRW-Min. TM	TRW-NSI-1	TRW-SI	TRW-TM1-1	TRW-MAJ-3	TRW-ARG-1	TRW-TM2-1
Dry Year	8	TRW-TPWW-3	TRW-Gardeners	TRW-Min. TM	TRW-NSI-1	TRW-SI	TRW-TM1-1	TRW-MAJ-1	TRW-ARG-1	TRW-TM2-2
	9	TRW-TPWW-3	TRW-Gardeners	TRW-Min. TM	TRW-NSI-1	TRW-SI	TRW-TM1-1	TRW-MAJ-1	TRW-ARG-1	TRW-TM2-1
	10	TRW-TPWW-1	TRW-Gardeners	TRW-Min. TM	TRW-NSI-1	TRW-SI	TRW-TM1-1	TRW-MAJ-1	TRW-ARG-1	TRW-TM2-1

Table 9
Tehran Municipality (TM) scenarios for water allocation to its demands in different hydrological years (The codes are defined in Tables A-1 and A-2 in the appendix).

Hydrological type of year					
No. of Scenario	Wet	No. of Scenario	Normal	No. of Scenario	Dry
1	TM-1	3	*TM-1*	5	*TM-1*
2	*TM-2*	4	*TM-2*	6	*TM-3*

Table 10
Tehran Province Water and Wastewater company (TPWW) scenarios for water allocation to its demands in different hydrological years (The codes are defined in Tables A-1 and A-2 in the appendix).

Hydrological Type of Year					
No. of Scenario	Wet	No. of Scenario	Normal	No. of Scenario	Dry
1	*TPWW-1*	3	*TPWW-1*	5	*TPWW-1*
2	*TPWW-2*	4	*TPWW-3*	6	*TPWW-3*

Table 11
Gardeners' scenarios for water allocation to their demands in different hydrological year (The codes are defined in Tables A-1 and A-2 in the appendix).

Hydrological type of year
Wet/Normal/Dry
Water demands of gardens are fully supplied from the Kan River

Table 12
Ministry of Agriculture Jihad (MAJ) scenarios for water allocation to its demands in different hydrological years (The codes are defined in Tables A-1 and A-2 in the appendix).

Hydrological type of year					
No. of Scenario	Wet	No. of Scenario	Normal	No. of Scenario	Dry
1	*MAJ-1*	3	*MAJ-1*	5	*MAJ-1*
2	*MAJ-2*	4	*MAJ-2*	6	*MAJ-3*

Table 13
MIMT scenarios for water allocation to its demands different hydrological years (The codes are defined in Tables A-1 and A-2 in the appendix).

Hydrological type of year					
No. of Scenario	Wet	No. of Scenario	Normal	No. of Scenario	Dry
1	*MIMT-1*	3	*MIMT-1*	5	MIMT-3
2	*MIMT-2*	4	*MIMT-2*	6	MIMT-4

Table 14
The scenario of water quality-sensitive industries in different years (The codes are defined in Tables A-1 and A-2 in the appendix).

Hydrological type of year
Wet, Normal, and Dry
Water demand is fully supplied from groundwater

Table 15
Values of coefficient *w* for the neighbors of TRW.

Agent	*w*
TPWW	0.3
TM	0.4
MAJ	0.64
MIMT	0.84

drawdown can cause many social and environmental problems in the study area, TPG checks the general performance of the system using the following equation:

$$\frac{E(k)}{A(k)} \tag{9}$$

where $E(k)$ represents the total volume of GW that all agents have decided to withdraw from aquifer k and $A(k)$ denotes the total allowable water discharge from aquifer k. TPG calculates the ratio for the three aquifers in each time step based on the messages it receives from the other agents. If the calculated ratio is bigger than one for each aquifer, the GW withdrawal is higher than the aquifer capacity, and TPG chooses to take action in that step of the algorithm.

4.3.2. Developing agents

In the decision-making process, the developing agents consider both their utilities and shared constraints:

4.3.2.1. Shared Constraints with TRW. Each developing agent calculates the cost of its shared constraint with TRW. Developing agents are informed by value messages from their upper neighbor's decision (TRW). $alfa(i)$ is the coefficient that developing agent *i* uses to weight its shared constraint with TRW:

$$alfa(i) = 1 - \frac{power(i)}{power(t)} \tag{10}$$

where *t* denotes TRW, and *i* shows the developing agent *i*. The calculated values for *alfa* are listed in Table 16.

4.3.2.2. Developing agents'utilities. A selfishness ratio is considered to incorporate the individual utility of each agent:

$$beta(i) = \frac{interest(i)}{ideal\_interest} \tag{11}$$

where *ideal_interest* is the maximum value of the interest in the social networks of the agents; in this paper, this value is considered to be 5. The calculated *beta* values are provided in Table 10. The simulation of the system only based on individual interest does not concur with reality. Therefore, by using the parameters of institutional relationships presented in Table 6, *beta* values are modified considering the institutional relationship between each agent and TRW:

$$beta\_m(i) = beta(i)^* \frac{1}{1 + \frac{t(o,\ i)}{5}} \tag{12}$$

where $t(o,i)$ denotes the institutional relationship between agent *i* and TRW (Table 6), the estimated values for *beta_m* are presented in

Table 16
Calculated *alfa* values for the developing agents.

Developing Agent	*alfa*
TPWW	0.2046
TM	0.1818
MAJ	0.2955
MIMT	0.3409

Table 17
Calculated *beta* and *beta_m* values for the developing agents.

Developing Agent	beta	beta *m*
TPWW	0.8364	0.4863
TM	0.7273	0.5050
MAJ	0.6364	0.4187
MIMT	0.4909	0.8182

Table 17.

The LC of developing agents are estimated as follows:

- TPWW

TPWW, based on the DFS tree, consists of 6 agents. The decision-making process and the utility and cost functions are the same for all six agents. These agents use GW and the transferred water from dams to supply their demands. For these agents, $LC(i,j)$ is calculated as follows:

$$LC(i,j)=alfa(tp)*(scenario'(t,i)-option(j,1))+beta.m(tp) *\left(\left(\left(Ad_{cost}*Ad(j)\right)-w_{p(n)}*|req.w(i,n)*(1+loss.rate)-option(j,1)| +PGTP(n)*option(j,3)+PSTP(n)*option(j,5)\right)\Big/\left(Ad_{cost}+PSTP(n) *option(j,5)+PGTP(n)(\max.extract(n))+PEE3(n)*option(j,3) *Z.m(i,n)\Big/PEE3(n)*max.bardasht(n)*Z.m(i,n)\right. \tag{13}$$

where:

*Tp:*TPWW agent

*n*No. of year.

*LC(i,j):*The cost of scenario*j* for agent *i*

*scenario'(t,i):*The volume of allocated water to*i*th TPWW based on the scenario of TRW

*option(j,1):*The first part of the*j*th scenario of agent *i* shows the total water allocation to that agent.

*PEE3(n):*Cost of pumping one cubic meter of GW for the height of 1 m in year ***n***.

*Z_m(i,n):*GW depth in aquifer related to agent*i* in year ***n***.

- TM

There are two agents for TM in the system. The role of TM is maintaining the green spaces in two districts in the system. These two agents allocate water to green spaces using TWW and GW when TWW is insufficient. The LC_s of TM agents are estimated as follows:

$$LC(i,j)=alfa(tm)*\left(\frac{(senario'(t,i)-option(j,1))}{\max\_dif}\right)+beta\_m(tm) *(PRR(n)*option(j,4)+POTG(n)*option(j,3)+PEE1(n)*option(j,3) *Z\_m(i,n))\Big/(demand(i)*PRR(n)) \tag{14}$$

where:

*Tm:*TM agent

*max_dif:*The maximum difference between the volume of allocated water to green spaces based on TM scenarios and the received message from TRW in (cubic meters).

*demand(i):*Green spaces water demand of agent *i*.

*PRR(n):*The cost of one cubic meter of treated wastewater (TWW) for allocating to green spaces demand in year ***n***

*option(j,4):*The 4th part of the scenario*j* shows water allocation using TWW.

*POTG(n):*The cost of one cubic meter of GW for allocating to green spaces.

*PEE1(n):*The cost of pumping one cubic meter of GW for the height of 1 m for TM agent, in year *n*.

- MAJ

MAJ consists of two agents responsible for agricultural activities in the second and third districts. The main resources for their demands are the Kan River and GW. These two agents calculate their LC_s using the following equation:

$$\mathrm{LC}(\mathrm{i},\mathrm{j})=alfa(ma)*\left(\frac{(|option(j,3)-senario'(a,i)|)}{\max\_dif}\right)+beta\_m(ma)*\left[\left(\frac{option(j,2)*POT(n)\ +(POTG(n)\ +PEE1(n)*z\_m(i,n))*option(j,3)}{option(j,2)*POT(n)+(POTG(n)+PEE1(n)*Z(i,n))*(req.pot(i)-option(j,2)}\right)\right. -\left(\frac{option(j,1)}{req.pot(i)}\right) \tag{15}$$

*Ad_{cost}:*The cost of using water demand management plans for reducing water demand up to 5%

*Ad(j):*A binary variable, for specifying that the scenario*j* does contain water consumption management plans or not

*$w_p(n)$:*The benefit of reducing water demand or the income of the extra water extraction and selling it to users out of the region in year*n*

*req_w(i,n):*The water demand of developing agent*i* in year *n*

*loss_rate:*The loss rate of the water distribution infrastructure. It is assumed to be 25%

*PTGP(n):*Cost of the GW for supplying drinking water in year*n*

*option(j,3):*The third part of scenario*j*, which shows the GW allocation to agent *i*.

*PSTP(n):*The cost of one cubic meter of transferred water from dams for supplying the drinking water demand in year*n*

*option(j,5):*The 5th part of scenario*j*, which is related to transferred water from dams

*max_extract(n):*The maximum GW extraction among all scenarios of agent*i*.

where:

*Ma:*MAJ agent

*max_dif:*The maximum difference between the volume of allocated water to agricultural demand in all MAJ scenarios and the received message from TRW in (cubic meters).

*req.pot(i):*The water demand of MAJ for expanding the area under cultivation to the potential area of*i*th region

*option(j,2):*The second part of the scenario*j* contains the water allocation from surface water.

*POTG(n):*The cost of the one cubic meter of GW for agricultural demand, in year*n*.

*PEE1(n):*The cost of pumping one cubic meter of GW for the height of 1 m for MAJ agents in year *n*.

- MIMT

MIMT consists of three agents responsible for industrial activities in three districts. These agents use TWW and GW to supply their demands.

MIMIT in district three is sensitive to the quality of allocated water and only uses GW. Therefore, it has just one scenario. The following equation is used for estimating LCs of MIMT:

$$LC(i,j) = alfa(mi) * \frac{(option(j,3) - senario^{'}(a,i))}{\max\_dif} + beta\_m(mi) * \left(\frac{PRW(n)*option(j,4) + \left(PEE2(n)*z_{m(i,n)} + PIN(n)\right)*option(j,3)}{\left(PIN(n) + PEE2(n)*z_{m(i,n)}\right)*req(i)} \right) \tag{16}$$

where:

*Mi:*MIMIT agent

*req(i):*MIMIT agent*i* 's water demand.

*PRW(n):*The cost of allocating one cubic meter of TWW to MIMT demand in year*n*.

*PIN(n):*The cost of allocating one cubic meter of GW to MIMT in year*n*.

*PEE2(n):*The cost of pumping one cubic meter of GW for the height of 1 m for MIMT agents, in year *n*.

This part presents the results of running the developed methodology for a 20-year planning horizon and four different cases (models). The equations of model A were presented in previous sections. Models B is similar to model A, but in this model, instead of using the modified selfishness ratio (*beta_m*), the selfishness ratio (*beta*) is used. In the third model (Model C), equation (17) is used instead of equation (15). In Model D, equation 23 has been used (like model C), but the relationships among the agents are not considered like model B (Equation (15)).

$$alfa(i) = 1 - 2*\frac{power(i)}{power(a)} \tag{17}$$

In this model, equation (17) is used (like model C), but the relationships among the agents are not considered (Equation (15) is used like model B).

Hydrological type of each year during the 20-year planning horizon is a function of a) Hydrological condition of that year, b) Effect of agents' decisions in previous years, and the condition of water resources at the beginning of that year. Therefore, in the four models, the types of the years are different. In addition, agents with the same category, including six agents of TPWW, two agents of TM, and two agents of MIMT choose similar scenarios in each time step.

4.4. Results of model A

This model detects 4 years from the 20-year planning horizon as dry years, 7 years as normal years, and 9 years as wet years. Based on the methodology described earlier, after determining the type of year at the first step, each agent must search among its scenarios related to that type of year to find the best scenario considering its condition. Then the agent informs the selected scenario to the other agents based on its role in the system (e.g., a protective agent explicitly informs its children agents through a value message, and developing agents implicitly inform others agents using a cost message). Considering Table 10 containing Tehran Province Water and Wastewater company (TPWW) scenarios; assume that a year that is detected as a dry year in the first step of the model. So, TPWW must look at the scenarios related to the dry year, including scenarios 5 and 6 (TPWW-1 and TPWW-3). As illustrated in Table A-1, scenario 5 says that water demand is fully supplied with no water transfer to out of the study area. Scenario 6 says that 95% of water demand is fully supplied by using water consumption management plans and there is no water transfer to out of study area. TPWW will select one of them based on his condition (see section 4-3 for more details). This procedure will continue, and each agent will select its scenario based on the type of the year and may change it based on the messages it receives from other agents. After completing this procedure for all of the years in the planning horizon, decision rules of all agents are obtained by analyzing the results. The obtained decision rules based on the results of model are presented in Table 18.

As shown in Table 18, TPWW selectes scenario 5 in dry years. Comparing TPWW's two dry-year scenarios in Table 10, selecting scenario 5 seems logical. Because in this scenario, water demand is less than the other one and this choice is in compliance with the system's condition in a dry year.

The MIMT district 3 is responsible for supplying the water demands of industries that are sensitive to water quality (e.g., food industries). Therefore, using GW is a hard constraint for this agent. On the other hand, the other two MIMT agents have the freedom to make their best decision considering their LCs. It is apparent from Table 18 that the MIMT districts 1 and 2 have made similar decisions in different years.

TPG has two general actions in different situations: A) doing nothing. b) sending a serious cost message to TRW. When TPG notices an unusual withdrawal from the GW (based on equation (14)), it will take action b. On the other hand, when the whole system has a desirable condition, it takes action a. Fig. 8 elaborates TPG decisions during the planning horizon.

Fig. 9 depicts the temporal variations of allowable GW withdrawal, a soft constraint in the model.

The correlation between TPG decisions (Fig. 8) and the GW condition is noteworthy. TPG takes action when the available GW volume is very low (e.g., 18th year). In the 18th year, the level of the second aquifer is low. This aquifer supplies drinking water demand in district 2. Also, the second aquifer is the main water source for reducing the drinking water deficit in district 1. Therefore, the ratio mentioned in equation (14) is greater than 1 for aquifer 2.

4.5. Results of model B (model a without considering relationships between the agents)

This model is similar to Model A, but instead of *beta_m*, *beta* is used in the equations. The results of this model are quite similar to Model A. In other words, eliminating the relationships between the agents does not

Table 18
The selected scenarios by each agent in different hydrological years (model A).

		Agent					
		TRW	TPWW (Districts 1 to 6)	TM (Districts 1 and 2)	MAJ, District 1	MAJ, District 2	MIMT (Districts 2 and 3)
Type of Year	No. of Selected Scenario in Dry Years	8	6	5	5	5	5
	No. of Selected Scenario in Normal Years	6	4	3	3	3	3
	No. of Selected Scenario in Wet Years	1	1	1	2	1	1

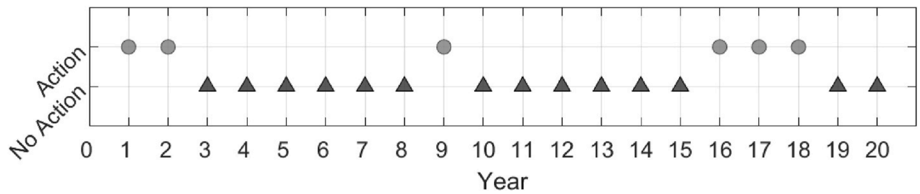


Fig. 8. Details of decisions made by TPG during the 20-year planning horizon (Model A).

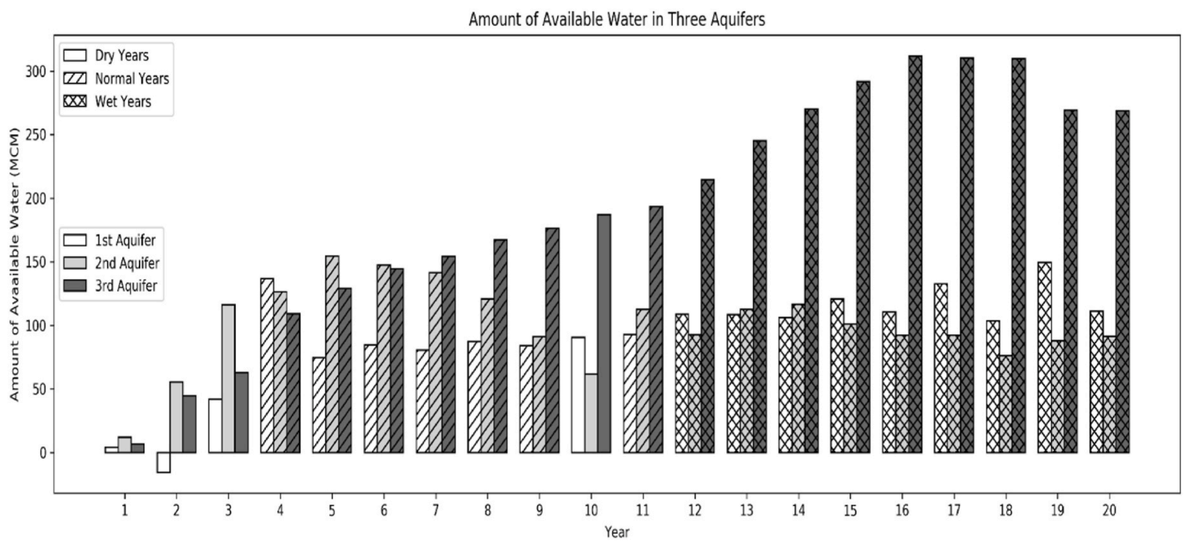


Fig. 9. The temporal variations of allowable groundwater withdrawal in the three aquifers during the 20-year planning horizon (Model A).

Table 19
The selected scenarios by each agent in different hydrological years (Model C).

		Agent					
		TRW	TPWW (Districts 1 to 6)	TM (Districts 1 and 2)	MAJ, District 1	MAJ, District 2	MIMT (Districts 2 and 3)
Type of Year	No. of Selected Scenario in Dry Years	8 (93%) and 10 (7%)	5	6	6	6	5
	No. of Selected Scenario in Normal Years	6	3	4	4	4	3
	No. of Selected Scenario in Wet Years	1	2	1	1	2	1

affect the results of model A.

4.6. Results of model C

In this model, equation (15) is replaced by equation (17). The equation doubles water-consuming agents' power compared to Models A and B. Table 19 presents the agents' decisions in different types of years.

TRW, as a water supplier and distributor agent, usually selects scenario 8 in dry years to reduce the amount of GW withdrawal. As shown in Fig. 10, TRW has selected scenario 10 in two years. The proposed algorithm considers both the whole system efficiency and agents' utility. In this model, by doubling agents' power in equation (17), the effect of agents' utilities has increased compared to Model A. Therefore, scenario 10, which is not optimum for the whole system, is selected in two dry years. Fig. 11 illustrates the TPG decisions in different years. Compared with TPG decisions in Model A (Fig. 8), the rate of taking action by TPG has increased from 30% to 75%.

Fig. 12 depicts the temporal variations of allowable GW withdrawal, a soft constraint in the model. There is a significant correlation between TRW decisions and the condition of the aquifers in each year in Fig. 12. In comparison with model A, the condition of the GW is worse, and in 14 out of 20 years, the TRW choose to have an action due to the low volume of GW.

4.7. Results model D (model C without considering the relationships among the agents)

According to the results of Model D, there are 5 and 15 normal and dry years on the planning horizon, respectively. Table 20 presents the agents' decisions in different types of years.

Fig. 13 presents the decisions of TPG based on the results of model D. In 13 out of 20 years, this agent decides to take action, and it shows the bad condition of the aquifer. More details about the allowable GW withdrawal in different years are conferred in Fig. 14.

A comparison between Models A and B results shows that having institutional relationships with TRW does not change the selected scenarios of agents. Comparing the results of models A and C shows a significant difference between the selected scenarios. Table 21 shows the impacts of different models on the volume of GW. Model C has an

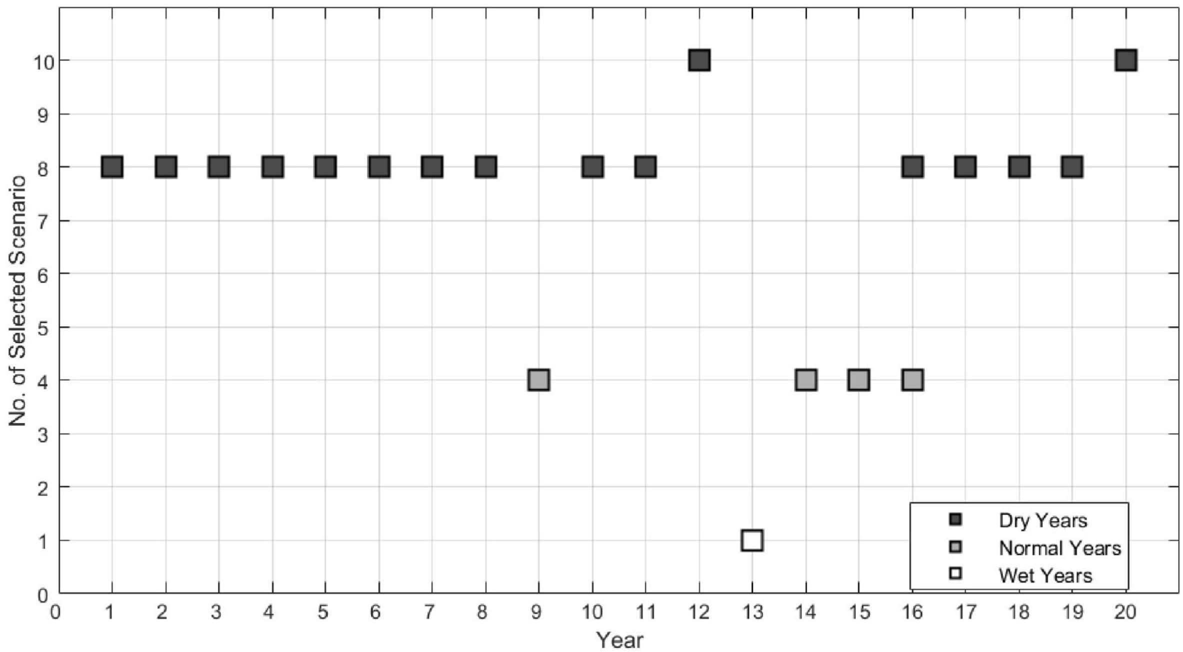


Fig. 10. The selected scenarios by TRW during the 20-year planning horizon (Model C).

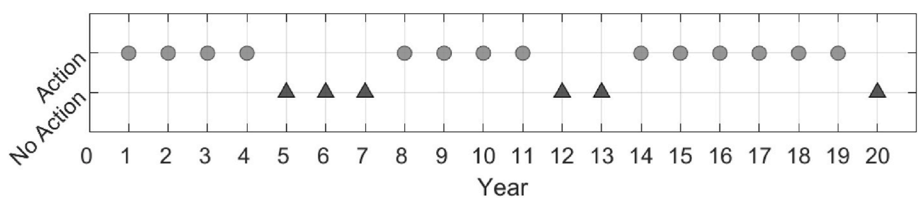


Fig. 11. The selected scenarios by TPG during the 20-year planning horizon (Model C).

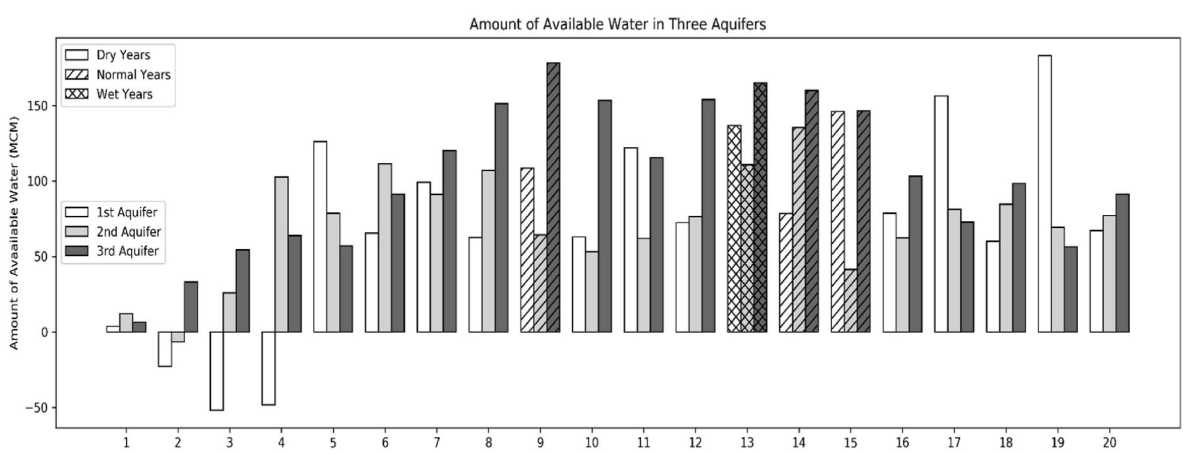


Fig. 12. The temporal variations of allowable groundwater withdrawal in the three aquifers during the 20-year planning horizon (Model C).

adverse impact on the GW condition. Models A and C differ from the *alfa* coefficient and the coefficient of shared constraints with TRW. The significant difference between the results of these two models shows the important role of these coefficients.

On the other hand, Models D and C are different in terms of *beta* and *beta_m* coefficients, which set the selfishness of agents. In these models, the agents' decisions are self-oriented, while in Models A and B, social attachments and relations are considered in the decision-making process. By ignoring the institutional relationships between agents and TRW, Model D has slightly degraded the system.

By comparison of the results of Models B (or A) and D, it can be concluded that the *alfa* coefficient is more important than the institutional relationships. Furthermore, in Model B, there are 6 years that TPG has decided to take action. Based on the Model D results, the number of these years is 13. It shows that the GW condition is not acceptable for TPG in the case of using Model D. According to equation (15), *alfa* coefficient shows the ratio of the power of agent *i* to the power of TRW. The results illustrate that changes in this ratio affect agents' decisions and

Table 20
The selected scenarios by each agent in different hydrological years (model D).

		Agent					
		TRW	TPWW (Districts 1 to 6)	TM (Districts 1 and 2)	MAJ, District 1	MAJ, District 2	MIMT (Districts 2 and 3)
Type of Year	No. of Selected Scenario in Dry Years	8 (80%) and 10 (20%)	5	6	6	6	5
	No. of Selected Scenario in Normal Years	6	3	4	3	4	3

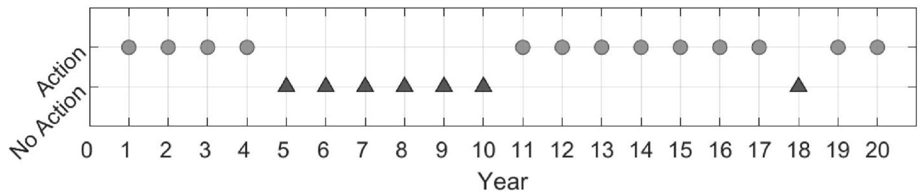


Fig. 13. The selected scenarios by TRW during the 20-year planning horizon (model D).

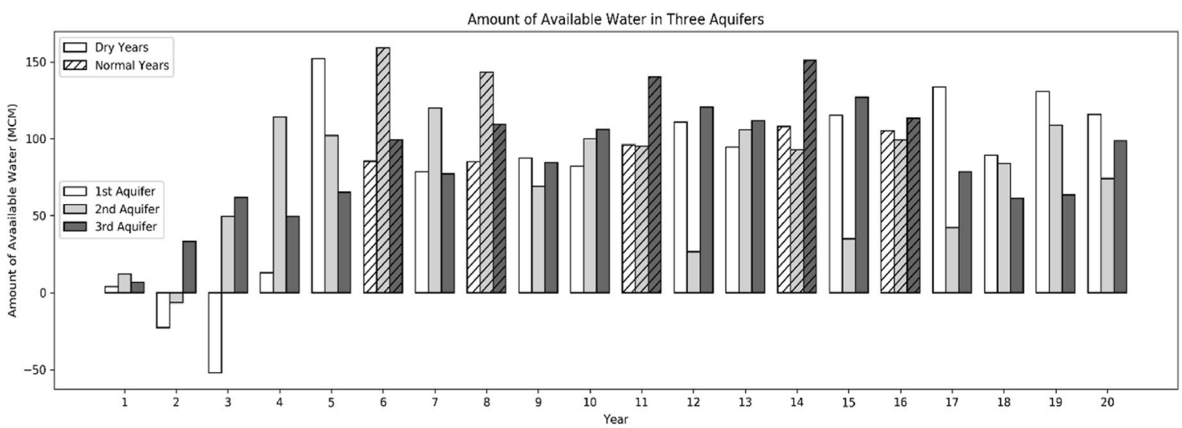


Fig. 14. An overview of condition of the permissible groundwater level of the three aquifers during the 20-year planning horizon (model D).

Table 21
The groundwater condition in the study area based on the results of different models.

	Models A and B	Model C	Model D
Average water storage of aquifer 1 (million m^3)	90.6	75.4	80.6
Average water storage of aquifer 2 (million m^3)	100.1	72.0	81.3
Average water storage of aquifer 3 (million m^3)	193.3	103.8	87.9
Maximum annual violation from allowable groundwater discharge (million m^3)	15.6	51.7	51.9
No. of years with the violation from allowable groundwater discharge during the planning horizon	1	3	2

GW conditions. Therefore, this ratio should be accurately set. Table 20 compares different models in terms of GW volume. In Models A and B, the GW condition is better than the two other models where agents can use GW more freely. Also, Table 22 compares the selected scenarios by agents in different types of years. As shown in this table, agreement among the numbers (codes) of the selected scenarios by agents is not important, but the multi-agent model controls the physical compatibility of the selected scenarios.

5. Summary and conclusion

Conventional water uses and management models have been mostly developed based on centralized governance and rule-based cooperation of agents. However, water use systems, usually involve several partially independent decision-makers with diverse and often conflicting utilities and non-cooperative behaviors (Woldeyohanes et al., 2021). Several DCOP models have been proposed to simulate agents' behaviors in complex multi-agent systems during the past decade. ADOPT uses a DFS pseudo-tree ordering of the agents as an asynchronous best-first search algorithm. Each agent in the DFS tree maintains lower and upper bounds on the solution cost for the subtree rooted at its node. Agents store lower bounds as thresholds and explore their solutions to increase lower bounds. Agents use cost messages (propagated upwards in the DFS-tree) and threshold and value messages (propagated downwards in the DFS tree) to iteratively decrease the distance between their lower and upper bounds (Fioretto et al., 2018). In this paper, for modeling behaviors of multiple self-interested stakeholders acting in a distributed decision-making context, a modified ADOPT algorithm (MADOPT) was proposed. MADOPT was able to model a monitoring agent and incorporate the social characteristics of agents. Also, a new form of the local cost function, which incorporated the utility function of agents, was used in the MADOPT algorithm. These new features and its low computational cost make MADOPT an efficient algorithm for modeling large-scale multi-agent water and environmental systems.

The proposed methodology was applied to a real-world case study,

Table 22
The selected scenarios by different models.

Model	Agent	Selected scenario		
		Dry Years	*Normal Years*	*Wet Years*
A and B	TRW	8	6	1
	TPWW (Districts 1 to 6)	6	4	1
	TM (Districts 1 and 2)	5	3	1
	MAJ, District 1	5	3	2
	MAJ, District 2	5	3	1
	MIMT (Districts 2 and 3)	5	3	1
C	TRW	8 (93%) and 10 (7%)	6	1
	TPWW (Districts 1 to 6)	5	3	2
	TM (Districts 1 and 2)	6	4	1
	MAJ, District 1	6	4	1
	MAJ, District 2	6	4	2
	MIMT (Districts 2 and 3)	5	3	1
D	TRW	8 (80%) and 10 (20%)	6	–
	TPWW (Districts 1 to 6)	5	3	–
	TM (Districts 1 and 2)	6	4	–
	MAJ, District 1	6	3	–
	MAJ, District 2	6	4	–
	MIMT (Districts 2 and 3)	5	3	–

including multiple agents with various utilities. The study area (i.e., the Kan river basin located in the western part of the Tehran metropolitan area in Iran) is currently suffering from several water and environmental issues. Based on the agents' utilities, some management scenarios were developed for each agent. The agents' decisions were considered dependent on the hydrologic type of each water year, which was estimated using the SWSI index. This allowed us to evaluate the behaviors of agents in various situations and estimate their decisions in different water years.

To evaluate the sensitivity of the results to the social parameters, four different models (i.e., Models A-D) were developed, and their results were compared. It was also shown that by adjusting different social parameters of different agents, including power, interest, and access to information, they would make better decisions, which were individually and system-wide more beneficial. The computational time of the MADOPT for estimating the behaviors of the agents in the study area was less than 1 min. This shows that this algorithm is computationally cost-effective. The results show the proposed method's efficiency for the water resources allocation problems. The runtime of the methodology using MATLAB is about 15 s, which means that the computational cost is efficient.

The capabilities of the proposed model allow us to achieve a more accurate physical-behavioral simulation of a large-scale water resources system. Also, its ability to simulate the relationships between stakeholders could be used as a framework for coordinating stakeholders in a system. In future studies, the existing uncertainties in social parameters could be considered. In addition, the proposed methodology could be extended to incorporate the process of social learning.

Credit author statement

Samaneh Moradikian: Conceptualization, Methodology, Writing – original draft preparation, Software. **Mohammad Javad Emami-Skardi**: Conceptualization, Methodology, Writing – original draft preparation, Software. **Reza Kerachian**: Supervision, Methodology, Writing- Reviewing and Editing, Validation.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.115446.

Appendix. The agents' scenarios

Table A-1
Description of TRW's scenarios and their codes.

Scenario No.	TPWW	Gardeners	TM: Min. Green Space	Non-sensitive industry	Water quality-sensitive industries	TM: Green spaces No. 1	MAJ	Artificial Recharge of groundwater	TM: Green spaces No. 2
TRW-1	Water demand is fully supplied/No water transfer to out of study area (TRW-TPWW-1)	The Kan River fully supplies this demand (TRW-Gardeners)	TWW[a](TRW-Min.TM)	TWW (TRW-NSI-1)	GW (as allowed) (TRW-SI)	TWW and if not sufficient GW (as allowed) (TRW-TM1-1)	Allocate SW[b] of the Kan river + GW[d] (as allowed) (TRW-MAJ-1)	20 MCM[c] by using rubber dams installed in the Kan river + remaining TWW by using wide artificial recharge wells (TRW-ARG-1)	TWW and if not sufficient GW (as allowed) (TRW-TM2-1)
TRW-2	Water demand is fully supplied+ 5% demand is transferred to out of the study area (TRW-TPWW-2)	The Kan River fully supplies this demand (TRW-Gardeners)	TWW (TRW-Min.TM)	TWW (TRW-NSI-1)	GW (as allowed) (TRW-SI)	TWW and if not sufficient GW (as allowed) (TRW-TM1-1)	Allocate SW of the Kan river + GW (as allowed) + Expand the area under cultivation to the potential (TRW-MAJ-2)	20 MCM to aquifer by using rubber dams installed in the Kan River (TRW-ARG-2)	TWW and if not sufficient GW (as allowed) (TRW-TM2-1)
TRW -3	Water demand is fully supplied/No water transfer to out	The Kan River fully supplies this demand	TWW (TRW-Min.TM)	TWW (TRW-NSI-1)	GW (as allowed) (TRW-SI)	TWW and if not sufficient GW (as allowed)	Allocate SW of the Kan river + GW (as allowed) (TRW-MAJ-1)	20 MCM[7] by using rubber dams installed in the Kan river + remaining	TWW and if not sufficient GW (as allowed)

(*continued on next page*)

Table A-1 (*continued*)

Scenario No.	TPWW	Gardeners	TM: Min. Green Space	Non-sensitive industry	Water quality-sensitive industries	TM: Green spaces No. 1	MAJ	Artificial Recharge of groundwater	TM: Green spaces No. 2
	of study area (TRW-TPWW-1)	(TRW-Gardeners)				(TRW-TM1-1)		TWW by using wide artificial recharge wells (TRW-ARG-1)	(TRW-TM2-1)
TRW -4	Water demand is fully supplied/No water transfer to out of study area (TRW-TPWW-1)	The Kan River fully supplies this demand (TRW-Gardeners)	TWW (TRW-Min.TM)	GW (TRW-NSI-2)	GW (as allowed) (TRW-SI)	TWW and if not sufficient GW (as allowed) (TRW-TM1-1)	Allocate SW of the Kan river + GW (as allowed) (TRW-MAJ-1)	20 MCM[7] by using rubber dams installed in the Kan river + remaining TWW by using wide artificial recharge wells (TRW-ARG-1)	TWW and if not sufficient GW (as allowed) (TRW-TM2-1)
TRW -5	Water demand is fully supplied/No water transfer to out of study area (TRW-TPWW-1)	The Kan River fully supplies this demand (TRW-Gardeners)	TWW (TRW-Min.TM)	TWW (TRW-NSI-1)	GW (as allowed) (TRW-SI)	TWW and if not sufficient GW (as allowed) (TRW-TM1-1)	Allocate SW of the Kan river + GW (as allowed) + Expand the area under cultivation to the potential (TRW-MAJ-2)	20MCM by using rubber dams installed in the Kan River (TRW-ARG-2)	TWW and if not sufficient GW (as allowed) (TRW-TM2-1)
TRW -6	95% water demand is supplied + using water consumption management plans/ No water transfer to out of study area (TRW-TPWW-3)	The Kan River fully supplies this demand (TRW-Gardeners)	TWW (TRW-Min.TM)	TWW (TRW-NSI-1)	GW (as allowed) (TRW-SI)	TWW and if not sufficient GW (as allowed) (TRW-TM1-1)	Allocate SW of the Kan river + GW (as allowed) (TRW-MAJ-1)	20MCM by using rubber dams installed in the Kan River (TRW-ARG-2)	TWW and if not sufficient GW (as allowed) (TRW-TM2-1)
TRW -7	Water demand is fully supplied/No water transfer to out of study area (TRW-TPWW-1)	The Kan River fully supplies this demand (TRW-Gardeners)	TWW (TRW-Min.TM)	TWW (TRW-NSI-1)	GW (as allowed) (TRW-SI)	TWW and if not sufficient GW (as allowed) (TRW-TM1-1)	Allocate SW of the Kan river + GW (as allowed) (TRW-MAJ-1)	20 MCM[7] by using rubber dams installed in the Kan river + remaining TWW by using wide artificial recharge wells (TRW-ARG-1)	TWW and if not sufficient GW (as allowed) (TRW-TM2-1)
TRW -8	95% water demand is supplied + using water consumption management plans/ No water transfer to out of study area (TRW-TPWW-3)	The Kan River fully supplies this demand (TRW-Gardeners)	TWW (TRW-Min.TM)	TWW (TRW-NSI-1)	GW (as allowed) (TRW-SI)		Only SW of the Kan river (TRW-MAJ-3)	20 MCM[7] by using rubber dams installed in the Kan river + remaining TWW by using wide artificial recharge wells (TRW-ARG-1)	TWW and No GW (TRW-TM2-2)
TRW -9	95% water demand is supplied + using water consumption management plans/ No water transfer to out of study area (TRW-TPWW-3)	The Kan River fully supplies this demand (TRW-Gardeners)	TWW (TRW-Min.TM)	TWW (TRW-NSI-1)	GW (as allowed) (TRW-SI)	TWW and if not sufficient GW (as allowed) (TRW-TM1-1)	Allocate SW of the Kan river + GW (as allowed) (TRW-MAJ-1)	20 MCM[7] by using rubber dams installed in the Kan river + remaining TWW by using wide artificial recharge wells (TRW-ARG-1)	TWW and if not sufficient GW (as allowed) (TRW-TM2-1)
TRW -10	Water demand is fully supplied/No water transfer to out of study area (TRW-TPWW-1)	The Kan River fully supplies this demand (TRW-Gardeners)	TWW (TRW-Min.TM)	TWW (TRW-NSI-1)	GW (as allowed) (TRW-SI)	TWW and if not sufficient GW (as allowed) (TRW-TM1-1)	Allocate SW of the Kan river + GW (as allowed) (TRW-MAJ-1)	20 MCM[7] by using rubber dams installed in the Kan river + remaining TWW by using wide artificial recharge wells (TRW-ARG-1)	TWW and if not sufficient GW (as allowed) (TRW-TM2-1)

[a] Treated Wastewater.
[b] Surface Water.
[c] Million Cubic Meters (MCM).
[d] Groundwater.

Table A-2
Description of the agents' scenarios and their codes.

Agent Name	Code Name	Description of the Code
TPWW	*TPWW-1*	Water demand is fully supplied/No water transfer to out of study area
TPWW	*TPWW-2*	Water demand is fully supplied +5% demand is transferred to out of study area
TPWW	*TPWW-3*	95% water demand is fully supplied + using water consumption management plans/No water transfer to out of study area
TM	*TM-1*	• If TWW[a] + GW_{exp}[b] < Min. Green Space[c] Then: Min. Green spaces are fully supplied from TWW and GW[d] • Else: Allocate as TWW + GW_{exp} to all green spaces
TM	*TM-2*	• If TWW + GW_{exp} <Min. Green spaces Then: Min. Green spaces from TWW and GW • Elseif Min. Green spaces < TWW + GW_{exp} < {Min. Green spaces + Green spaces No. 1[e]}, Then: Allocate as {Min. Green spaces + Green spaces No. 1}, from TWW and GW

(*continued on next page*)

Table A-2 (*continued*)

Agent Name	Code Name	Description of the Code
		• Elseif {Min. Green spaces + Green spaces No. 1} < TWW+ GW_{exp} < {Min. Green spaces + Green spaces No. 1 + 50%Green spaces No. 2[f]}, then: Allocate as {Min. Green spaces + Green spaces No. 1 + 50%Green spaces No. 2}, from TWW and GW • Elseif {Min. Green spaces + Green spaces No. 1 + 50%Green spaces No. 2} < TWW+ GW_{exp} < {Min. Green spaces + Green spaces No. 1 + Green spaces No. 2}, then: Allocate as {Min. Green spaces + Green spaces No. 1 + Green spaces No. 2}, from TWW and GW
TM	*TM-3*	• If TWW + GW_{exp} < Min. Green spaces Then: Min. Green spaces from TWW and GW • Elseif Min. Green spaces < TWW+ GW_{exp} < {Min. Green spaces + Green spaces No. 1}, Then: Allocate as {Min. Green spaces + Green spaces No. 1}, from TWW and GW • Elseif {Min. Green S pace + Green spaces No. 1} < TWW+ GW_{exp} < {Min. Green spaces + Green spaces No. 1 + 50%Green spaces No. 2}, then: Allocate as {Min. Green spaces + Green spaces No. 1 + 50%Green spaces No. 2}, from TWW and GW
MAJ	*MAJ-1*	Agricultural water demands are supplied from the Kan river as much as possible.
MAJ	*MAJ-2*	• If SW[g] of the Kan River + $\mathbf{GW_{exp}}$[h] < 50%*Demand: allocate SW of the Kan River + $\mathbf{GW_{exp}}$ + $\mathbf{GW_{extra}}$ as demand • elseif 50%< SW of the Kan River + $\mathbf{GW_{exp}}$ <Demand: allocate SW of the Kan River + $\mathbf{GW_{exp}}$ + $\mathbf{GW_{extra}}$ as demand • elseif SW of the Kan River + $\mathbf{GW_{exp}}$ > Demand: allocate SW of the Kan River and $\mathbf{GW_{exp}}$ and increase the level of agricultural land
MAJ	*MAJ-3*	• If SW of the Kan River + $\mathbf{GW_{exp}}$ < 50% Demand: allocate SW of the Kan River + $\mathbf{GW_{exp}}$ + $\mathbf{GW_{extra}}$ as demand • elseif 50%< SW of the Kan River + $\mathbf{GW_{exp}}$ <Demand: allocate SW of the Kan River + $\mathbf{GW_{exp}}$ + $\mathbf{GW_{extra}}$ as demand
MIMT	*MIMT-1*	Water demand is supplied from groundwater
MIMT	*MIMT-2*	Buying treated wastewater
MIMT	*MIMT-3*	Water demand is supplied groundwater (illegally extraction is probable)
MIMT	*MIMT-4*	Buying treated wastewater (allocation less than demand is probable)

7Million Cubic Meter.

[a] Treated Wastewater.

[b] Expected Groundwater: Groundwater that Tehran Municipality expects will be allocated to its water demands based on the type of year.

[c] Water demand of trees.

[d] Groundwater.

[e] 20% of the green space's water demand after allocating water to trees.

[f] 80% water demand of the green space's after allocating water to trees.

[g] Surface Water.

[h] Expected Groundwater: Groundwater that the Ministry of Agriculture Jihad agent expects that will be allocated to its demand based on the type of year.

Initialize

(1) *threshold*←0; *CurrentContext* ←{};

(2) **forall** $d \in Di,xl \in$ *Children* **do**

(3) $lb(d, x_l)$←0; $t(d,x_l)$←0;

(4) $ub(d, x_l)$←*Inf* ; $context(d, x_l)$←{}; **enddo**;

(5) $d_i \leftarrow d$ that minimizes $LB(d)$;

(6) *counter*←*0*

(7) **backTrack**;

when received (**THRESHOLD**, *t*, *context*)

(7) **if** *context* compatible with *CurrentContext*:

(8) *threshold*←*t* ;

(9) **maintainThresholdInvariant**;

(10) **backTrack**; **endif**;

when received (**TERMINATE**, *context*)

(11) record TERMINATE received from parent;

(12) *CurrentContext* ←*context*;

(13) **backTrack**;

when received (**VALUE**, (*xj* ,*dj*))

(14) **if** TERMINATE not received from parent:

(15) add (x_j ,d_j) to *CurrentContext*;

(16) **forall** $d \in D_i$, $x_l \in$ *Children* **do**

(17) **if** $context(d, x_l)$ incompatible with *CurrentContext*:

(18) $lb(d, x_l)$←0; $t(d,x_l)$←0;

(19) $ub(d, x_l)$←*Inf* ; $context(d, x_l)$←{}; **endif**; **enddo**;

(20) **maintainThresholdInvariant**;

(21) if ***i* ==16**

(22) ***counter*=*counter*+1**

(23) if ***counte*r==(NumberOfAgents-1)**

(24) backTrack;endif;

(25) else

(26) backTrack; endif; endif;

when received (COST, x_k , *context*, *lb*, *ub*)

(27) d ←value of x_i in *context*;

(28) remove (x_i ,d) from *context*;

(29) **if** TERMINATE not received from parent:

(30) **forall** (x_j ,d_j) ∈ *context* and x_j is not my neighbor **do**

(31) **add** (x_j ,d_j) to *CurrentContext*;**enddo**;

(32) **foral**l $d \in D_i$, $x_l \in$ *Children* **do**

(33) **if** $context(d',x_l)$ incompatible with *CurrentContext*:

(34) $lb(d',x_l)$←0; $t(d',x_l)$←0;

(35) $ub(d',x_l)$←*Inf* ; $context(d',x_l)${};**endif;enddo;endif**;

(36) **if** *context* compatible with *CurrentContext*:

(37) $lb(d, x_k)$←*lb*;

(38) $ub(d, x_k)$←*ub*;

(39) $context(d, x_k)$←*context* ;

(40) **maintainChildThresholdInvariant;**

(41) **maintainThresholdInvariant; endif;**

(42) backTrack;

procedure backTrack

(43) **if** *threshold* == *UB*:

(44) $d_i \leftarrow d$ that minimizes $UB(d)$;

(45) **else if** $LB(d_i) >$ *threshold*:

(46) $di \leftarrow d$ that minimizes $LB(d)$; **endif;**

(47) SEND (VALUE, (x_i, d_i))

(48) to each lower priority neighbor;

(49) maintainAllocationInvariant;

(50) if *threshold* == *UB*:

(51) **if** TERMINATE received from parent

(52) or x_i is root:

(53) SEND (TERMINATE,

(54) *CurrentContext* ∪ {(x_i,d_i)})

(55) to each child;

(56) Terminate execution; endif;endif;

(57) SEND (COST, x_i, *CurrentContext*, *LB*, *UB*) to parent;

Fig. A-1. The pseudo-code of the MADOPT algorithm. All variables have been defined in the text.

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