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A coupled agent-based risk-based optimization model for integrated urban water management

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ABSTRACT

Integrated urban water management (IUWM) is a comprehensive mitigation strategy to control water deficit due to simultaneous effects of reduction in water resources capacity and increase in water demand. Here we develop a coupled agent-based risk-based optimization model, which is able to account for water resources capacity and water demand uncertainties to determine the optimum annual water allocation. An optimization model based on conditional value at risk (CVaR) is employed to minimize the water supply risk in a long-term horizon and obtain the annual probabilities of complete supply of water demand. According to the generated synthetic weather data by LARS-WG for different climate scenarios, surface water and groundwater resources are modeled using HMETS and MODFLOW, respectively. Then, the developed agent-based model considers agents' attributes, action roles and interactions by applying Borda scoring approach, and determines the most compatible IUWM strategies to increase water supply or modify water demand. The proposed framework is implemented for the Shiraz city in Iran, revealing a strong need to IUWM strategies to alleviate the water deficit over the period of 2018 to 2050. The proposed approach provides an efficient framework to achieve sustainable management strategies for cities with stressed water resources and rapid urban development.

1. Introduction

Access to safe water resources is believed to be one of the major issues related to sustainable development (World Health Organization, 2005). Climate change, especially the current global warming trend, has significantly affected the quality and quantity of available surface water and groundwater resources (Intergovernmental Panel on Climate Change, 2015). On the other hand, according to united nations (UN) (2015) predictions, the world population is expected to reach 8.5 billion by 2030, that would result in water demand increase up to 6350 km^3 (Statistica, 2018). The progressive water deficit, as a result of water resources reduction and population growth, has enforced the decision makers to map out urban water management (UWM) strategies in order to meet the water demands, especially domestic needs. A sustainable UWM needs to consider all factors affecting the water resources such as ecological conditions, social norms, water consumption patterns and impacts of climate changes in water resources capacity (Ghosh, 2017).

In many of the existing UWM models, the uncertainties and other major factors (e.g. concurrent effects of future climate changes and water demand increase) are not properly accounted for (e.g. Zeng, Cai, Jia, & Jee, 2012; Díaz, Stanek, Frantzeskaki, & Yeh, 2016). Moreover, in several situations the developed UWM models are not compatible with the social and environmental conditions such as stakeholders' priorities and goals (e.g. Díaz et al., 2016; Chen, Lu, Li, Ren, & He, 2017). Hence, the UWM strategies from these models are not fully reliable and may cause irreparable damages on a wider level.

Most often the UWM models neglect uncertainties of the water demands in the process of optimal allocation of the alternative water resources (Zeng et al., 2012; Díaz et al., 2016; Chen et al., 2017; Pérez-Uresti, Ponce-Ortega, & Jiménez-Gutiérrez, 2019; Vakilifard, Bahri, Anda, & Ho, 2019), while many studies indicate that the effects of changes on water use patterns cannot be ignored (Bellin, Majone, Cainelli, Alberici, & Villa, 2016; Stavenhagen, Buurman, & Tortajada, 2018). On the other hand, in recent decades, the development of computational models to simulate the behavior of society (e.g. agent-based models (ABMs), and social choices and bargaining methods) has empowered decision makers to evaluate the outcome of different social

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rules (e.g. changes on water use patterns) and their influence on the applicability of adopted UWM strategies (Fu et al., 2017; Ghodsi, Kerachian, Estalaki, Nikoo, & Zahmatkesh, 2016; Ali, Shafiee, & Berglund, 2017; Alizadeh, Nikoo, & Rakhshandehroo, 2017; Alizadeh, Nikoo, & Rakhshandehroo, 2017; Castonguay, Urich, Iftekhar, & Deletic, 2018). Water deficit cannot be alleviated merely by implementing either optimal water allocation or water demand reduction strategies, and the efficient UWM should be integrated by combining these two types of strategies (Nikoo, Karimi, & Kerachian, 2013; Willuweit & O'Sullivan, 2013; Safavi, Golmohammadi, & Sandoval-Solis, 2016; Sun, Liu, Shang, & Zhang, 2017). As a result, an integrated urban water management (IUWM) is needed to account for all the elements affecting the urban water supply (Fu et al., 2017; Garcia et al., 2016). Factors such as population growth, rainfall time-series and consumption patterns may significantly affect the IUWM, while their prediction is subject to immense uncertainties. Several studies proved that consideration of these uncertainties and their modeling methodology can significantly improve the applicability of the IUWM (Furlong, Brotchie, Considine, Finlayson, & Guthrie, 2017; Knox, Haro-Monteagudo, Hess, & Morris, 2018; Pingale, Jat, & Khare, 2014). Minimizing the water supply risk (due to the water deficit) is considered as one of the essential applications of an IUWM model (Yamout, Hatfield, & Romeijn, 2007). Conditional Value at Risk (CVaR), as a reliable method to measure the risk, is proven to provide maximum profit and shows a high sensitivity to vast deficits and can be used to measure the water deficit in a log-term horizon (Chow, Tamar, Mannor, & Pavone, 2015). Additionally, due to characteristics of complex adaptive systems (e.g. UWMs), water consumers play a significant role in water supply-demand balance (Berglund, 2015). ABMs have shown great potential to model water consumer groups and their interactions based on their authorities and behavioral rules. As a result, an IUWM model, populated with all society behavioral rules and environmental uncertainties, is believed to be an efficient approach to achieve sustainable urban water management (SUWM) goals (Deng et al., 2013; Karatayev et al., 2017).

In this study, a new IUWM model is proposed which considers simultaneous effects of water supply reduction and water demand increase, and determines managerial strategies, which are compatible with society, to alleviate water deficit in a long-term horizon. The annual water deficit is determined in the light of future weather data and water demand uncertainties. LARS-WG is obtained to determine local-scale time-series of rainfall and temperature for different climate scenarios. The available water resources are modeled using MODFLOW and HMETS simulation models (Alizadeh et al., 2017a, 2017b). Different water demand scenarios are determined based on historical data of water consumption. The proposed coupled agent-based risk-based optimization model estimates the water deficit for all applied water resources capacity and water demand scenarios. Determining the optimum groundwater allocation, the optimization model minimizes the risk of water supply (i.e. water deficit in a long-term horizon) using the CVaR approach. Then, the ABM determines the IUWM strategies compatible with the society to increase the water supply and/or reduce the water demand, relying on bargaining and social rule methods (i.e. Borda scoring approach in this study).

2. Methodology

The proposed methodology to obtain a reliable coupled agent-based risk-based optimization model to develop IUWM strategies is presented in Fig. 1. The methodology is conducted in seven consecutive steps described in the following sections.

2.1. Climate scenarios

The collected historical data of rainfall, temperature and evaporation, from local weather stations, are used to generate daily synthetic weather data for different climate scenarios using LARS-WG stochastic weather generator. The synthetic weather data, especially rainfall time-series, is used to estimate annual changes of groundwater level and dam inflow in future for different global climate models (GCMs), introduced in IPCC 4th assessment report (Semenov & Stratonovitch, 2010).

2.2. Water resources capacity scenarios

Water availability is highly dependent on climate variabilities. The annual rainfall, as the major source of groundwater recharge, is estimated using the developed rainfall time-series by LARS-WG model in a long-term horizon. The groundwater resources overexploitation is limited by the desired groundwater level at the end of the horizon. To determine the annual changes of groundwater level in a long-term horizon, MODFLOW (McDonald & Harbaugh, 1988) is employed to develop a steady-state groundwater model. It should be noted that groundwater conceptual model for the study area is developed based on the proposed frameworks by Izady et al. (2015); Farhadi, Nikoo, Rakhshandehroo, Akhbari, and Alizadeh (2016)) and Alizadeh et al. (2017a); Alizadeh et al., 2017b. The developed conceptual model for the study area, comprised of hydrogeological units, boundary conditions, groundwater abstraction, groundwater recharge and hydrodynamic properties, is mapped on the block centered finite difference grid with 300×300 m cells, in which the Shiraz city aquifer is an unconfined aquifer and it was considered as a single layer in the MODFLOW. The developed steady-state MODFLOW model is then calibrated and validated based on the annual groundwater level data using PEST algorithm (Doherty, 1998). More details are provided in the supplementary material (SM), section S3.

In order to determine the groundwater level for different climate scenarios in a long-term horizon, the groundwater model is substituted by MLP-ANN meta-model (Izady et al., 2013) (SM, section S.9, Fig. S13). The dataset used to train and validate the MLP-ANN consists of thousands scenarios of initial groundwater level, groundwater abstractions and rainfall datasets as input vectors and the decrease of groundwater level as the output vector. The MODFLOW model is linked with MATLAB® to run the groundwater model automatically for all scenarios. Finally, the coupled validated MLP-optimization model is used to determine the annual decrease of groundwater level in the process of minimizing the water supply risk.

Generally, both surface and groundwater resources are used to satisfy the water demand. The urban water share from dam reservoir, determined as a portion of dam reservoir inflow, is considered as the main resource of surface water. Given the direct relation of dam reservoir inflow and climate scenarios, dam reservoir inflow is modeled using the MATLAB®-based HMETS hydrological (rainfall-runoff) model. The values of the temperature and rainfall time-series, developed by the LARS-WG on the Droudzan dam watershed, are used to determine the amount of runoff into the dam reservoir.

2.3. Water demand scenarios

In addition to the climate changes, population growth, migrations and lifestyle changes can increase the water demand and alter the balance between water supply and demand. In this study, population growth is considered as a major driving force for water demand increase. The historical data of urban population growth is assessed to calculate the average annual growth. Given the historical relationship between population growth and water demand increase rates, m steps of water demand increase rates (e.g. three steps of zero, half of the maximum water demand increase rate and the maximum water demand increase rate) are identified for n urban water consumer groups, which results in m^n scenarios of water demand increase. In fact, thousands scenarios of water demand increase are developed with the assumption that the water demand rate of increase for all water consumption groups varies between zero and a maximum estimated rate (SM, section

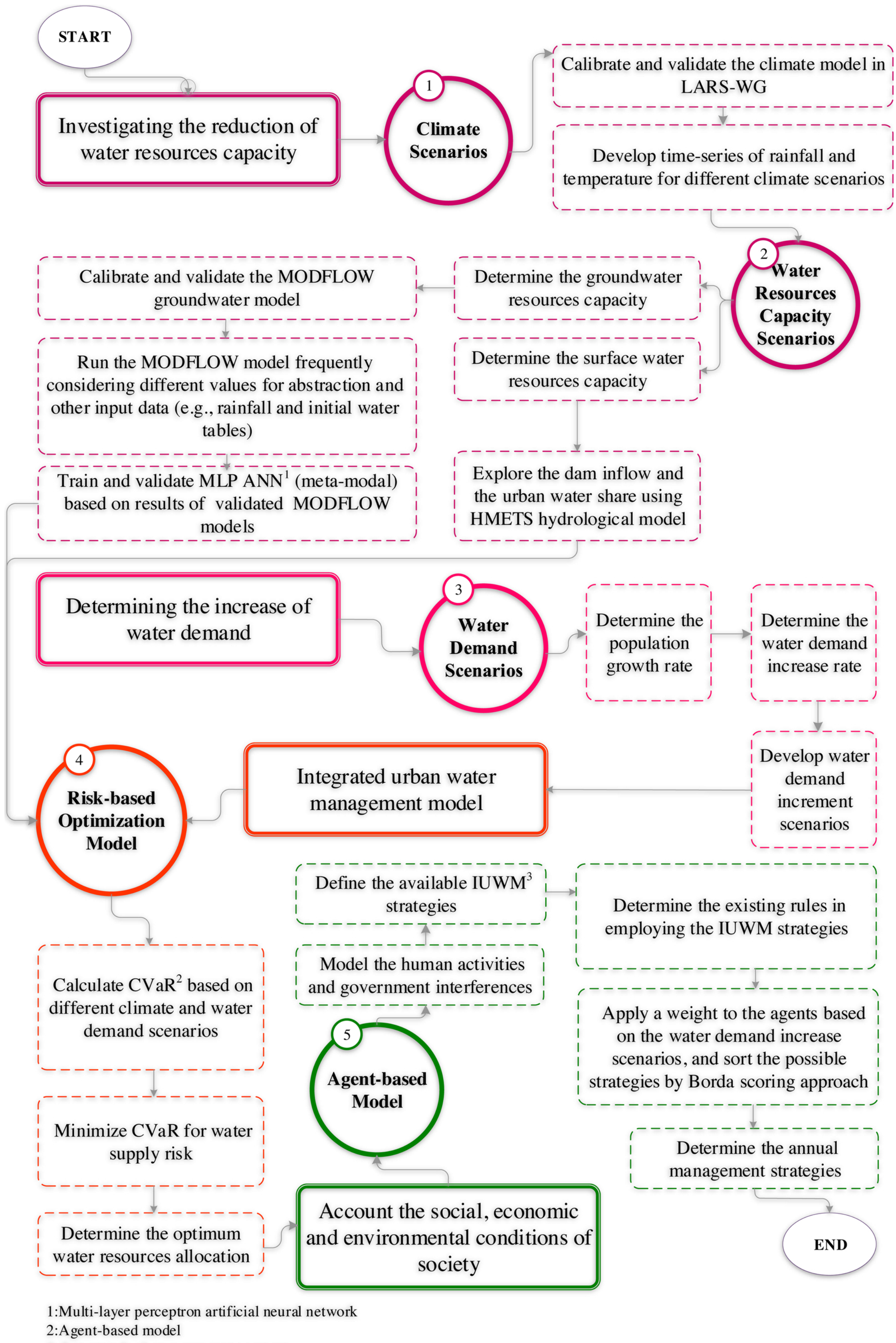

Fig. 1. Flowchart of the proposed methodology for the coupled agent-based risk-based optimization model.

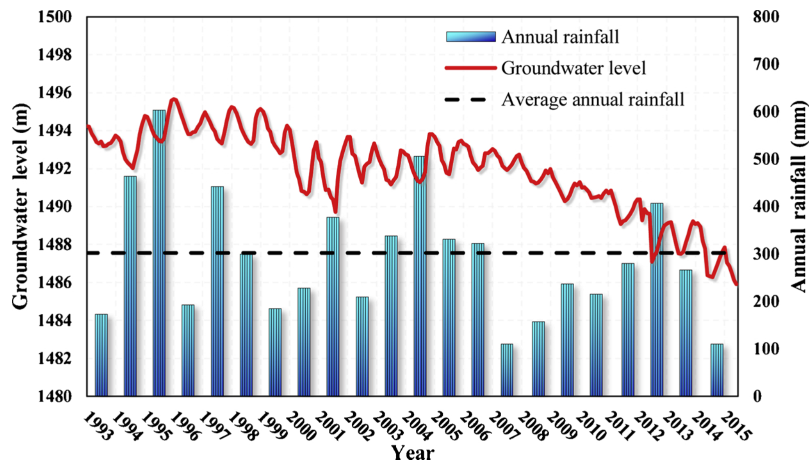

Fig. 2. Groundwater level, annual rainfall and average annual rainfall in Shiraz city.

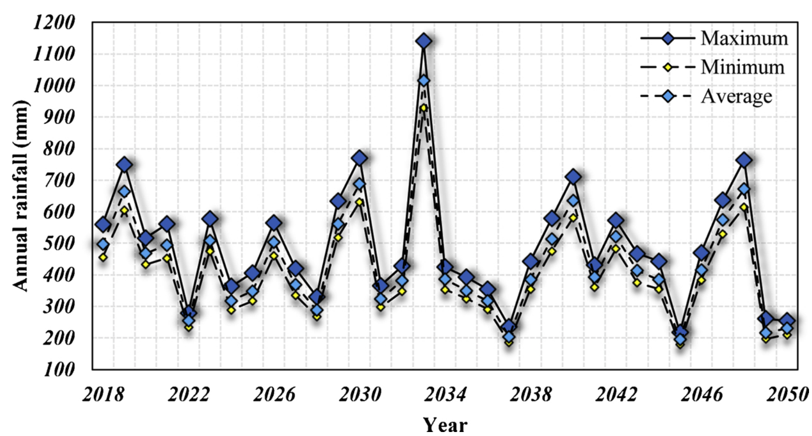

Fig. 3. Predicted maximum, minimum and average annual rainfall of Droudzan dam for.2018–2050.

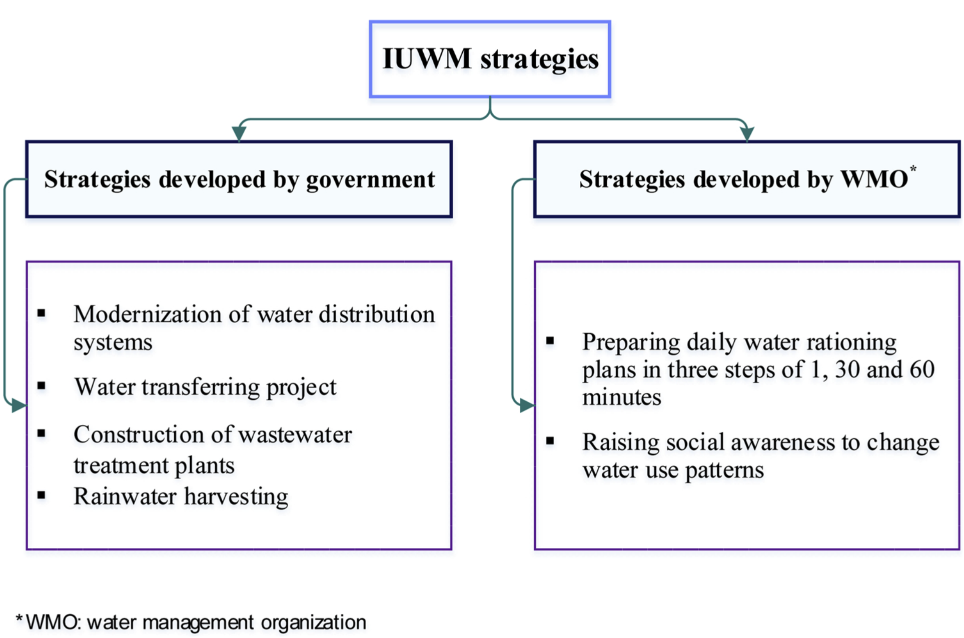

Fig. 4. IUWM strategies developed by the government and WMO.

Table 1
The influence level of Shiraz city water consumer groups (agents).

Agents	Influence level (%)	Agents	Influence level (%)
Domestic water consumers	17	Green spaces	3
Military centers	7	Official water consumers	8
Universities, educational and recreation centers	9	Other water consumers	5
Commercial water consumers	11	Government	15
Industrial water consumers	13	WMO	12

S.9, Fig. S14).

2.4. Risk-based optimization model

A risk-based optimization model employs the developed scenarios of annual water resources capacity and water demand increase to determine the water deficit ratio. Considering thousands of annual water deficit ratios, the optimization model attempts to allocate the groundwater resources optimally to fulfill the water demand when the required demand is more than the surface water supply, and minimizes the maximum water deficit in a long-term horizon (water supply risk) by manipulation of single-objective genetic algorithm (GA). In this study, the water supply risk is assessed by the conditional value at risk (CVaR) in a long-term horizon (SM, section S8). At the final stage, the probability of complete supply of water demand is calculated to determine the number of scenarios in which the water supply is sufficient.

2.5. Agent-based model

Agent-Based Models (ABM) and their applications in water resources management have significantly attracted researchers' attention, in which they have defined different approaches to model the agents' action (Berglund, 2015). In this study, a novel approach is developed to model attributes, action rules and interactions of three defined agents, named groups of water consumers, government and water management organization (WMO). The government and WMO develop the possible IUWM strategies considering both aspects of water supply increase and water demand modification. The developed ABM is a decentralized model, in which the agents rank the possible IUWM strategies based on their attributes and updated action rules. In fact, all agents annually receive feedbacks from prior years' strategies and update their action rules under the influence of existing urban rules and limitations. The modified Borda scoring approach, as the subset of social choices and bargaining methods, is implemented by the ABM to model the interaction of agents and determine the compatible IUWM strategies. Borda scoring is a decision-making model, in which the agents sort the feasible strategies based on their own priorities. The modified Borda scoring model sorts the feasible strategies the same as the original model; however, it multiplies the agents' scores by a weight based on their influence level and relative water demand (comparing to the total amount of water demand).

In summary, the coupled agent-based risk-based optimization model, proposed in this study, accounts for all possible affecting scenarios of water resources capacity and water demand, and determines the water supply risk in a long-term horizon. The allowable decrease of groundwater level is considered in the optimization model to avoid groundwater overexploitation. The ABM (comprised of the urban water consumers, the government and WMO) determines the compatible strategies to increase water supply and/or modify the water demand, which improves the probability of complete supply of water demand. Hence, adoption of compatible IUWM strategies can assist to achieve the sustainable urban water management (SUWM) goals.

2.6. The coupled agent-based risk-based optimization model

The proposed agent-based risk-based optimization model is applied to minimize the maximum water deficit in a long-term horizon (water supply risk) by minimizing CVaR at the specified confidence level as follows:

$$Minimize \quad z = CVaR_\alpha \tag{1}$$

Subjected to:

$$CVaR_\alpha = VaR_\alpha + \frac{1}{1-\alpha}\sum_{d=1}^{S_d}\sum_{r=1}^{S_r}\sum_{y=1}^{Y}\frac{[DEF_{d,r,y} - VaR_\alpha]^+}{S_d \times S_r \times Y} \tag{2}$$

$$DEF_{d,r,y} = \begin{cases} \dfrac{DEM_{d,y} - ALL_{r,y}}{DEM_{d,y}} & if\ DEM_{d,y} > ALL_{r,y} \\ 0 & if\ DEM_{d,y} \le ALL_{r,y} \end{cases} \tag{3}$$

$$ALL_{r,y} = SDR_{r,y} + SGW_{r,y} \tag{4}$$

$$SDR_{r,y} = f\,(INF_{c,y}) \tag{5}$$

$$DR_{r,y} = NET\,(H_{c,y},\ RAIN_{c,y},\ SGW_{r,y}) \tag{6}$$

$$\sum_{y=1}^{Y} DR_{r,y} \le DR_{\max} \tag{7}$$

where:

α = Confidence level,
$CVaR$ = Conditional value at risk,
VaR = Value at risk,
$DEF_{d,r,y}$ = Water deficit for the d^{th} water demand scenario, r^{th} water resources capacity scenario and y^{th} year,
$ALL_{r,y}$ = Water allocation for the r^{th} water resources capacity scenario and y^{th} year,
$DEM_{d,y}$ = Water demand for the d^{th} water demand scenario and y^{th} year,
$SDR_{r,y}$ = Water supply from dam reservoir for the r^{th} water resources capacity scenario and y^{th} year,
$SGW_{r,y}$ = Groundwater supply for the r^{th} water resources capacity scenario and y^{th} year,
$INF_{c,y}$ = Dam reservoir inflow for the c^{th} climate scenario and y^{th} year,
$DR_{r,y}$ = Groundwater depletion for the r^{th} water resources capacity scenario and y^{th} year,
$H_{c,y}$ = Groundwater abstraction for the c^{th} climate change scenario and y^{th} year,
$RAIN_{c,y}$ = Average rainfall for the c^{th} climate scenario and y^{th} year,
$DR_{\max}$ = Maximum groundwater depletion after Y years,
Y = Total optimization duration (year),
S_r = Total number of water resources capacity scenarios (related to total number of climate scenarios),
S_d = Total number of water demand scenarios.

To achieve a suitable measure for assessing the efficiency of managerial strategies, the probability of complete supply of water demand is calculated as follows:

$$PROB_y = \frac{N_{0,y}}{N_s} \tag{8}$$

Subjected to:

$$N_s = S_r \times S_d \tag{9}$$

where:

$N_{0,y}$ = Number of zero deficit ratio scenarios of water resources capacity-water demand in y^{th} year,

Agents of Shiraz city ABM

Urban water consumers

- Domestic water consumers
- Commercial water consumers
- Industrial water consumers
- Official water consumers
- Other water consumers
- military centers
- Universities, educational and recreation centers
- green spaces

Attributes:

- Domestic water rationing has the lowest desirability
- Reverse immigration is the last choice if strict water rationings exist
- Water rationing of other agents is more preferred than utilizing the reclaimed wastewater
- Water transfer is more preferred than water rationing
- "Modernization of water distribution systems" and "rainwater harvesting" are the second and third most preferred strategies
- "Raising social awareness to change water use patterns" is the most preferred strategy

Action rules:

- If restrict domestic water rationing is implemented, the reverse migration becomes more desirable
- If the probability of full supply of water demand is more than 90%, no strategy will be adopted

Government

Attributes:

- "Raising social awareness to change water use patterns" is the most preferred strategy
- Expensive strategies like "water transferring project", "construction of wastewater treatment plants" and "Modernization of water distribution systems" are less preferred
- The government attempts to prevent reverse immigration
- The government employs water rationing strategies considering the influence level of agents

Action rules:

- If restrict water rationings are implemented for any of agents, the water rationing will become less desirable in the subsequent years
- If "rainwater harvesting" strategy is adopted, the "rainwater harvesting" and "water transferring" strategies will become less desirable in the next years
- If "construction of water and wastewater treatment plants" strategy is adopted, the "construction of water and wastewater treatment plants" strategy will become less desirable in the next years
- If "reverse immigration" strategy is adopted, the "construction of water and wastewater treatment plants", "Modernization of water distribution systems", "rainwater harvesting" and "water transferring" strategies will become more desirable while water rationings will be less desirable in the subsequent years
- If the probability of full supply of water demand is more than 90%, no strategy will be adopted

WMO[1]

Attributes:

- If "rainwater harvesting" or "construction of wastewater treatment plants" strategy is adopted, the Modernization of water distribution systems strategy will become more desirable
- If the probability of full supply of water demand is more than 90%, no strategy will be adopted
- The WMO attempts to prevent reverse immigration

Action rules:

- "Raising social awareness to change water use patterns" is the most preferred strategy
- Strategies like "water transferring project", "construction of wastewater treatment plants" and "modernization of water distribution systems" are more preferred than water rationing of industrial and domestic water consumers and military centers

[1]WMO: water management organization

Fig. 5. The agents' attributes and their action rules.

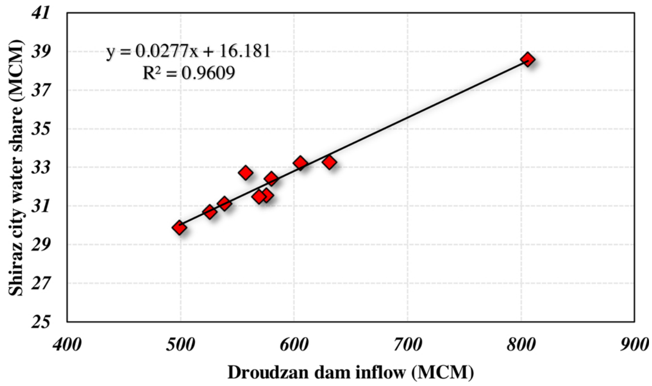

Fig. 6. Shiraz city water share from the inflow of Droudzan dam reservoir.

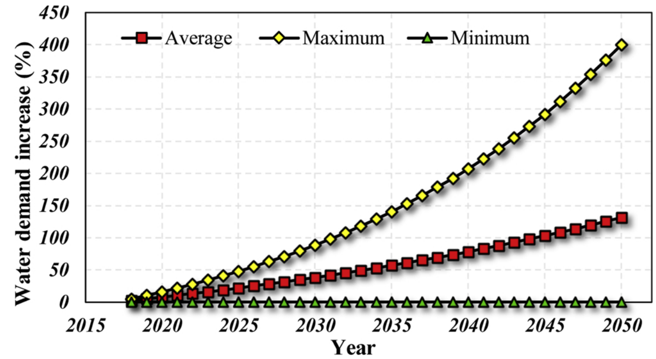

Fig. 8. Maximum, minimum and average water demand increases by 2050.

N_s = Total number of water resources capacity-water demand scenarios in y^{th} year.

3. Case study

The proposed coupled agent-based risk-based optimization model is tested during this study in Shiraz city, capital of Fars province, Iran. Average annual temperature and rainfall of Shiraz city are around 16.5 °C and 316 mm, respectively. According to 2016 national census data, the population of the city is about 1,870,000 with the area equal to 179 km^2. Due to persistent drought and destruction of farms in recent years, population migration from villages to Shiraz city has caused a 52 % increase of city population in 10 years since 2006, which is equal to average annual increase of 4.2 % (Iran national census center, 2016; Talebbeydokhti, Habibagahi, Raeisi, & Javan, 2017-2018Talebbeydokhti ., - et al., 2018Talebbeydokhti, Habibagahi, Raeisi, & Javan, 2017-2018).

The urban water demand of Shiraz city is supplied by both surface and groundwater resources. Droudzan dam, the main surface water resource, is constructed in 1972 to supply the domestic and agriculture water demands. The area of upstream lake of the Droudzan dam is 4372 Km^2 with reservoir normal and dead volume of 993 and 133 Km^3, respectively. The rest of water demand of Shiraz city is met by groundwater resources. The statistical data of groundwater abstraction from wells reflects the significant proportion of Shiraz aquifer to supply Shiraz water demand. Therefore, the Shiraz aquifer is considered as the main groundwater resource for the next 30 years since 2018. Observation wells in the study area are utilized to determine monthly groundwater level (SM, section S.1). Fig. 2 shows the monthly spatially-averaged groundwater level, in which the groundwater level decline is clearly notable.

To determine the amount of water available for urban consumption over the period of 2018–2050, possible future rainfall time-series, and maximum and minimum temperatures are determined using LARS-WG models for 35 different climate scenarios (SM, section S.2). As an example, the obtained values of maximum, minimum and average annual rainfall of Droudzan dam over the period of 2018–2050 are shown in Fig. 3.

Moreover, the water demand in future is determined because of its direct impacts on the capacity of water resources to fulfill the urban water demand. The population growth in Shiraz city, known to be the prime cause of increasing water demand, is historically investigated in order to predict the future patterns (SM, section S.6). Given the maximum annual water demand increase rate of 5 %, three steps of 0 %, 2.5 % and 5 % increase rates are assumed for eight urban water consumers (i.e. domestic, commercial, industrial, municipal, educational, military centers, water consumption for green spaces, and other water consumers) and water loss.

The water supply risk of Shiraz city is determined by varying scenarios of water resources capacity and water demand. As stated earlier, the main aim of this study is to reduce the water supply risk by implementing IUWM strategies, developed by the government and WMO, to increase the water supply or modify the water demand (Fig. 4).

Developing an effective and integrated social awareness campaign, “raising social awareness to change water use patterns” can be the most desired strategy for reducing the water consumption. With the help of mass media (e.g. newspaper, radio, magazines, the Internet, and television) and educational tools and materials (e.g. public presentations and seminars, informative water billing, school education, community extension training), “raising social awareness to change water use patterns” strategy can reduce the annual water demand by 1 % which may last for at least two years. Due to growing water deficits, the

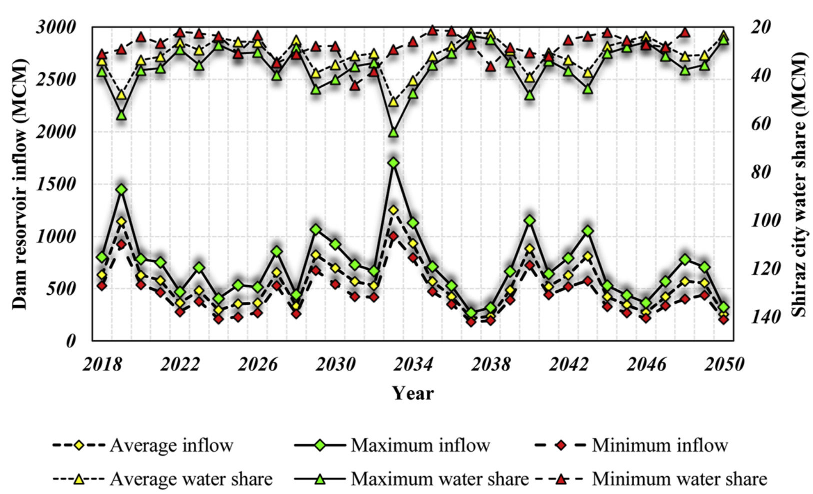

Fig. 7. Maximum, minimum and average values of Droudzan dam inflow and Shiraz city water share over 2018–2050 period.

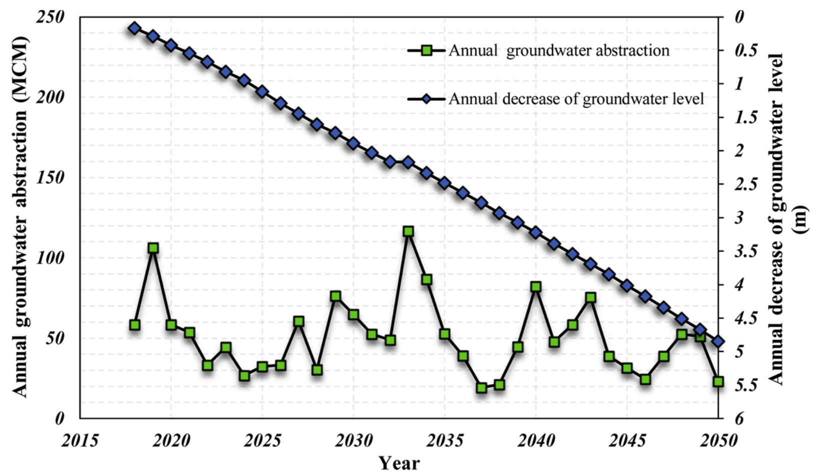

Fig. 9. The optimum annual groundwater abstraction and decrease of groundwater level.

Fig. 10. The annual probability of complete supply of water demand in Shiraz City over 33 years.

achieved water demand decrease through the social awareness is not sufficient. Hence, "water rationings" are the second most desired strategies, especially for the government, to reduce the annual water demand. However, strict water rationings impose severe limitations and set triggers to social dissatisfaction, which can lead to "reverse immigration". According to expert opinions, the city population decreases by 2 % with each wave of reverse immigration. Some other fundamental strategies are developed by the government to increase the annual water supply. In detail, "rainwater harvesting" is a cost-effective strategy to alleviate the water deficit; the rainfall water can be collected for irrigation of green spaces and landscapes. The "modernization of water distribution systems" strategy can increase the amount of available water by decreasing the water loss percentage while more than 5 % of water loss is caused by aging water distribution systems. Another effective strategy is the "construction of wastewater treatment plants", which are planned to commence for operation in three years and provide about 20 MCM water annually. The least desired strategy from the governmental perspective is the "water transferring project". National or international water transferring projects are incredibly expensive and can cause serious national security concerns. As the final solution for water deficit, the government can deliver 40 MCM of tap water to Shiraz city.

The agent-based model is developed to investigate the social structure of Shiraz city and choose the compatible strategy(s) that are more easily accepted by the society without producing significant problems. All groups of urban water consumers, the government and the WMO are included as agents. The agents have different economic, political and social positions, which results in different influence levels in acceptance or rejection of a strategy (see Table 1). The influence levels are considered in the manipulated modified Borda scoring approach.

The agents' attributes, actions and interactions are modeled in the developed ABM by defining the social rules and technical limitations for the implementation of possible IUWM strategies (Fig. 5). These social rules and technical limitations are particularly defined for Shiraz city based on local expert opinions and regional conditions.

4. Results and discussion

In the first stage of optimization, the water supply risk is investigated along with the uncertainties about water resources capacity and water demand over the period of 2018 to 2050. The groundwater resources capacity in Shiraz city is determined for 35 rainfall time-series scenarios, developed by LARS-WG. Also, Shiraz city surface water share from Droudzan dam is determined considering the 35 scenarios of Droudzan dam inflow and the historical relation between the dam inflow and Shiraz city water share. Droudzan dam inflow is calculated using HMETS (SM, section S.5) and its relation with Shiraz city water share is determined through the available data of dam reservoir inflow and Shiraz city water share (Fig. 6). As a result, the following

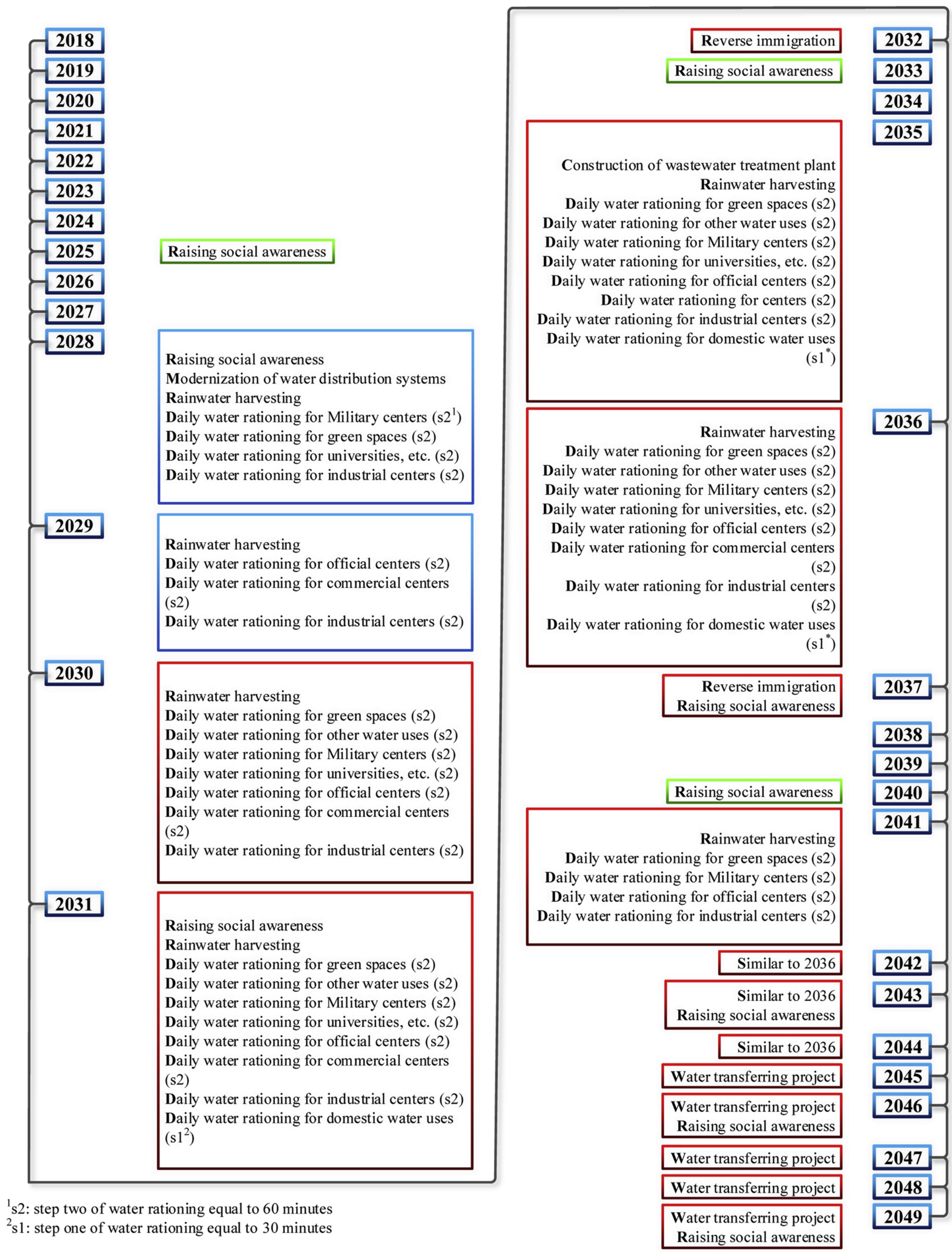

Fig. 11. Compatible IUWM strategies to improve the annual probability of complete supply of water demand for the period of 2018–2050.

relationship is obtained and used in the coupled agent-based risk-based optimization model to calculate the amount of available surface water:

$$y = 0.0277x + 16.181 \tag{10}$$

where y is Shiraz city share (MCM) and x is Droudzan dam reservoir inflow.

The maximum, minimum and average values of Shiraz city water share is calculated over 2018 to 2050 period based on the dam inflows obtained from the HMETS (Fig. 7).

The efficiency of available water resources is strongly dependent on the amount of water demand. The annual water demand scenarios are developed considering three steps of 0 %, 2.5 % and 5 % of annually water demand increase for eight water consumer groups and the water loss which is equal to 3^9 = 19, 683 scenarios. Maximum, minimum and average water demand increases are shown in Fig. 8.

The developed optimization model attempts to allocate the groundwater resources optimally and minimize the water supply risk (by minimizing the CVaR). The Shiraz aquifer is modeled in MODFLOW to determine the groundwater supply over the period of 2018–2050 (SM, section S.3). The groundwater level decline in Shiraz city is limited

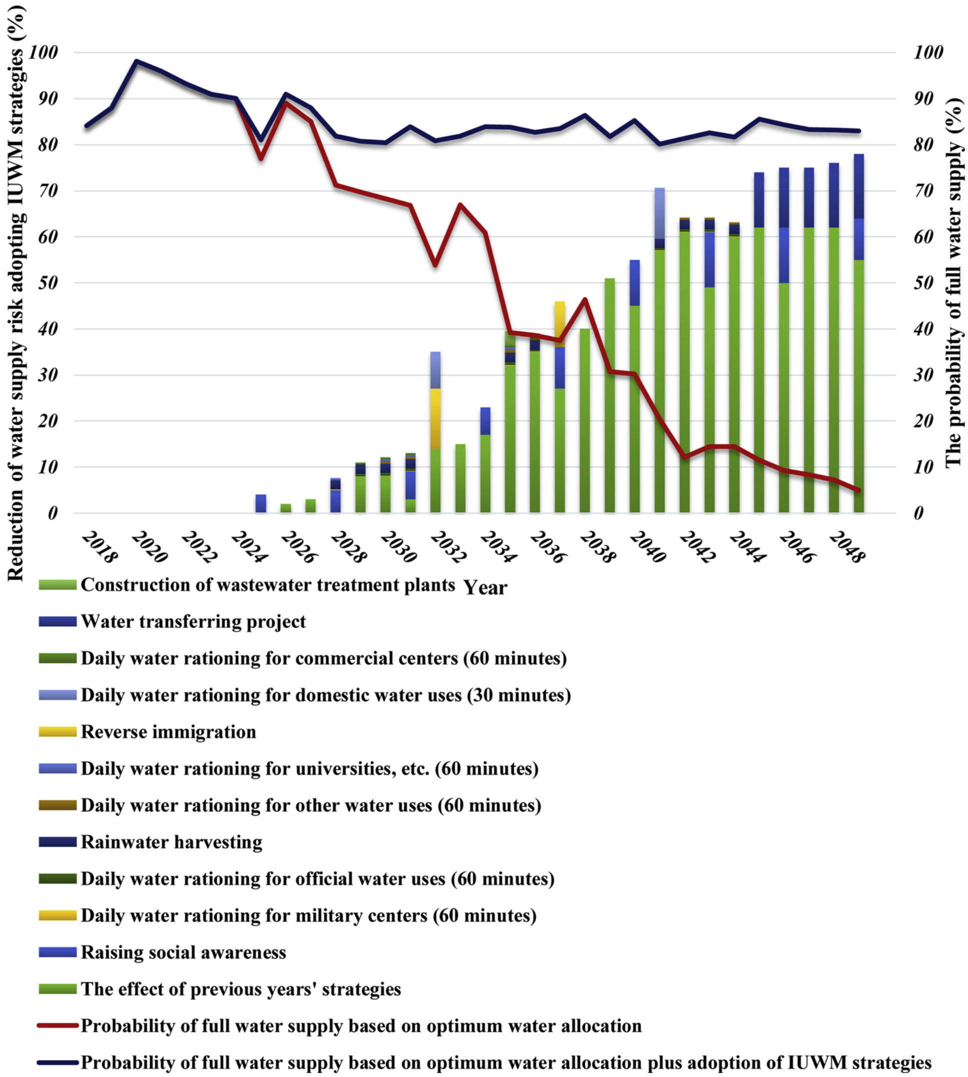

Fig. 12. Improvement of the probability of full water supply by reduction of water supply risk with the help of IUWM strategies.

to 5 m in 33 years to protect groundwater resources, which is added to the coupled agent-based risk-based optimization model as a penalty function.

Based on 35 future climate and 19,683 water demand scenarios, the optimization model considers $35 \times 19{,}683 = 688{,}905$ annual water deficits scenarios. To calculate the annual decrease of groundwater level in the optimization model, the MODFLOW model is replaced by the MLP-ANN (SM, section S.4). The applied dataset to train and validate the MLP-ANN is determined by considering 4 values for initial groundwater levels, 10 values for groundwater abstraction and 25 values for rainfall which vary in the range of 1480 and 1520 m above the sea level, 0 and 100 MCM and 0 and 500 mm, respectively. These $4 \times 10 \times 25 = 1000$ scenarios are applied to the MODFLOW model linked with MATLAB® to calculate the decrease of groundwater level. The optimum values of annual groundwater abstraction and decrease of groundwater level are shown in Fig. 9.

The obtained value of CVaR, with confidence level of 95 %, is equal to 74 % for the next 33 years (from 2018–2050) in the Shiraz city. In fact, the obtained CVaR reveals that the maximum expected deficit over the period of 2018–2050 is 74 %. The probability of complete supply of water demand is shown in Fig. 10, in which more than 90 % of water demand can be met by 2020. In contrary, the water demand increase and water resources capacity reduction is resulted in limited water supplies so that even in year 2033, which is recognized as a wet year by all climate scenarios, the probability of complete supply of water demand is equal to 70 %, due to the considerable amount of water demand.

At the next stage, the IUWM strategies are adopted by the ABM to improve the probability of complete supply of water demand and maintain the probability over 80 % for the next 33 years. As shown in Fig. 11, "raising social awareness to change water use patterns" is the most desired strategy to reduce the water demand. This strategy is repeated every three years to change the water use patterns profoundly. Due to severe water deficit, water rationings are inevitable and agents with less authority or low water consumption are more prone to water rationings (e.g. 60 min daily water rationings for military, official and educational (universities) centers and green spaces in 2028). Since 2029, "rainwater harvesting" turns out to be the most desired strategy to avoid strict water rationings. In the meantime, strict water rationings (60 min water rationings for more than four agents) in 2031 lead to a wave of reverse immigration in 2032. The social dissatisfaction rises dramatically after two waves of reverse immigration in 2032 and 2037, and more water rationings between years 2039 and 2042, which increases the pressure on the government to transfer water from the neighbor cities or countries.

Fig. 12 displays the influence of each strategy to increase the probability of complete supply of water demand. Several IUWM strategies are annually implemented to maintain the probability of complete supply of water demand over 80 %. The influence of strategies like "raising social awareness to change water use patterns", "construction of wastewater treatment plants" and "reverse migration" continue for the subsequent years, which is called "the effect of prior years' strategies". From 2035–2050 the obtained probability of complete supply of water demand substantially falls and "water transferring" is identified as the only solution to alleviate the water shortage.

5. Summary and conclusion

In recent decades, majority of developing countries have faced with water deficit resulted from population growth, urbanization, climate changes and lack of firm urban water managements. To cope with this issue, successful urban water management strategies need to be developed, considering all aspects of equity, applicability and sustainability. In this regard, accounting for the effects of the climate changes and agents' actions and interactions on reliability and compatibility of IUWM strategies are challenging tasks.

In this study, a novel managerial model is proposed that minimizes the annual water supply risk by optimal allocation of the water resources. It reduces the calculated annual water supply risk relying on compatible IUWM strategies. It should be noted that the proposed coupled agent-based risk-based optimization model is developed based on thousands of water resources capacity and water demand scenarios simultaneously. The results demonstrate that social awareness and strict water rationings should be implemented seriously to maintain the probability of complete supply of water demand over 80 %. However, these two strategies are not always sufficient and the government has to implement fundamental IUWM strategies to increase the water supply, especially for the period of 2035–2050.

Estimation of urban water demand increase in future is a very complex issue due to various influencing factors such as population growth, migrations, and civilizations. Application of more solid statistical models can help the agent-based risk-based optimization model to obtain more reliable annual water demands. Moreover, considering the decisive role of urban organizations in development of compatible IUWM strategies, their goals and conflicts can be investigated by developing accurate conflict resolution models, which is subject of ongoing research.

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.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.scs.2019.101922.

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