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Risk Assessment of Water Resources Development Plans Using Fuzzy Fault Tree Analysis

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Abstract
Water resources development plans (WRDPs) is a key element of evaluation for sustainable water supply due to growing needs for adequate and reliable water resources in the human communities by different biodiversity. The development plans should be assessed considering social, economic, and environmental aspects as the criteria of sustainable development and then the risk assessment of the plans should be carried out using the criteria. In this paper, for the first time, risk-based assessment of WRDPs were carried out under the sustainable development framework using Fuzzy Fault Tree Analysis (FFTA). The failure of the plans was considered as the top event based on sustainable development criteria in this approach and then the factors leading to failure occurrence including social, economic, environmental, and water resources failure indices were identified as 14 basic events (BE) through a top-down process in Fault Tree Analysis (FTA). The case study was the water supply system using conventional and non-conventional water resources for Homozgan province in South of Iran. The water resources development plans were evaluated in a model applying two different approaches of crisp and fuzzy for zone number 4 of Makran coastal area and Bandar Abbas city where play significant role in the economic growth of the country. In the both approaches, the failure probability were 38%, 90%, and 50% for the best, worst, and current situation Scenarios, respectively. Taking into account the high computed risk value in the both crisp and fuzzy approaches, the basic events were ranked based on their contribution in the occurrence of the top event. The proposed approach not only addresses the risk of WRDPs in compliance with sustainable development objectives but also facilitates decision-making for the risk management by prioritizing the factors in the failure of plans.

Keywords FFTA · Risk assessment · Sustainable development · Water resources development · Makran area

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1 Introduction

There has been an increasing water demand in recent years due to the rapid population growth in Iran, causing an intense pressure on renewable water resources (Loukas et al. 2007). Human communities are therefore encouraged to develop water resources projects considering sustainable criteria. In other words, sustainable development is to fulfil the economic, social, and environmental aspect of the project in order to enhance the people welfare without causing any irreversible damage to the future generations (WCED (world commission on environment and development) 1987; Hopwood et al. 2005).

A threat or crisis is defined as a likely event occurs, resulting in casualties, loss of property, and damaging to a country's infrastructures. In other words, threat is an event with a low probability of occurrence and a high probability of loss which its probability occurrence cannot be computed (FEMA 452 2005). The risk assessment has been defined differently (e.g. Huang 2009; Aven 2011); however, a precise and useful definition for risk measure could be defined as a function of the likelihood of specific hazard and its aftermaths considering system's vulnerability against hazards (Roozbahani et al. 2013; Anbari et al. 2017). In another definition of risk, the probability of failure or damage is defined as the occurrence of an undesired event and its adverse consequences (Fares and Zayed 2010). WRDPs are facing risk and uncertainty in pursuing sustainable development goals. Water resources management experts believe that the study of economic, social and environmental indicators as the sustainable development related risks, is an important factor in implementing water resources development plans. Thus the risk assessment of each WRDP is vital and it requires an efficient and novel method. Identifying management tools to evaluate WRDPs in compliance with sustainable development goals is of a great importance. Various techniques including Event Tree Analysis, Analytical Hierarchy Analysis, Bayesian Network, Fault Tree Analysis and etc., have been presented for risk assessment (Ghachlou et al. 2019). These tools should be capable of determining problems and contributing factors in the failure of the assessed WRDPs in order to formulate the management policies more reliably for a desired performance of these plans. One of the most applicable techniques for this purpose is FTA model.

Sadiq et al. (2008) applied FTA technique for the risk assessment of the top event termed as "improper water quality in urban distribution networks". Water contamination at the entrance point, material deterioration and failure of the treatment plant were considered as the BE in the presented FTA. Beauchamp et al. (2010) identified technical and operational hazards of treatment plant employing a quantitative FTA technique using operators' experiences as input data. The main object in their research was the improvement of technical and operational factors. Lindhe et al. (2012) carried out the risk assessment of drinking water supply systems using Dynamic Fault Tree analysis in Gothenburg, Sweden. Taheriyoun and Moradinejad (2015) assessed the risk of Tehran West Town wastewater treatment plant applying FTA technique. The failure probability of the top event was analyzed based on minimal cut sets. Stein et al. (2017) conducted a study on which the widespread use of FTA was examined. They concluded that the FTA technique as a decision support system can identify the relationship between the BE and their effects on the top event in treatment plants. Babaei et al. (2018) provided an exclusive structure for risk assessment using the FTA technique for the first time in agricultural water distribution and delivery systems considering adequacy, equity and water delivery efficiency. Ghachlou et al. (2019) presented a comprehensive approach to assess the risk using the FTA. They studied social, economic, water quality and quantity, and ecological criteria for the Urmia Lake basin in Iran.

Moreover, some researchers studied on evaluating WRDPs in the context of sustainable development. Karamouz et al. (2008) used the value engineering index to prioritize different scenarios for water transfer from Karun River to Rafsanjan plain based on the sustainable development criteria. They first weighted the criteria and ranked the scenarios and then computed the value engineering index. Yilmaz and Harmancioglu (2010) designed a water resource management model for decision -making based on sustainable development criteria with regard to biological, social, and economic aspects. Abadi et al. (2015) used the Vensim model for modeling a water resources system in the downstream of Karkheh Dam. In their research, the model was first verified and then the sustainability indicators were assessed for simulated scenarios and various policy packages. Banihabib et al. (2016) employed Multi Criteria Decision Making (MCDM) approach to rank water resource management strategies in Shahroud region using sustainable development criteria. Kefayati et al. (2018) developed an empirical approach to assess the sustainability of the Karun inter-basin water transfer project to Zayandehrud basin in the center of Iran. The Composite Indicators of Sustainability approach was used and Sustainable Indices including economic, social, and environmental indices were combined.

The difficulty in determining the failure probability is one of FTA's limitations according to the literature review. Regardless of the available databases, records, professionals and experts' opinions and, other sources lack of considering uncertainties in estimating BEs is another weakness of the FTA technique. Since the failure probability is a crisp value in the FTA, calculating this precise value is challenging issue due to the ambiguity or insufficiency of the information and data. Therefore, the fuzzy logic could address these challenges in the FTA technique indicating that the use of the FFTA is of a great significance in studies (Mahmood 2013). FFTA method was introduced as a useful and powerful approach to address not only the lack of data or missing data based on using expert opinions but also it determines system's weaknesses according to its graphical, quantitative ability and its risk-based feature (Shi et al. 2017; Babaei et al. 2018).

Regarding the previous studies, the FFTA technique has not been employed in either crisp or fuzzy set for examination of the water resource development scenarios in terms of sustainable development criteria in recent conducted studies. Indeed, although the issue of applying sustainable development criteria has been already addressed in previous studies, but these criteria have not been integrated in terms of a probabilistic risk assessment technique such as FFTA model. Most studies have focused on MCDM approaches without challenging the idea of implementing the risk-based approach for decision making. This study aims to assess the water resources development scenarios in Iran by presenting a FFTA model with the prevailing uncertainties and considering aforementioned challenges. Consequently, to comprehensively address the lack of a sustainable development plan, for the first time, this study presented a comprehensive framework for risk-based assessment of water resource development plans in the context of sustainable development by quantifying different social, economic, environmental and water resources indicators.

2 Materials and Methods

2.1 Risk Assessment Methods

Risk analysis methods are generally classified into three main categories: quantitative, qualitative and hybrid. In the quantitative assessment method, risk is probabilistic and estimated by mathematical relationships. Hence the recorded data in the system is used for computation. In the qualitative method, assessment is based on analytical estimation and judgment of engineers and managers which has a non-probabilistic structure. The hybrid method consists of the two quantitative and qualitative methods (Marhavilas et al. 2011). Owing to the deficiency and lack of quantitative data set on some of the contributing factors to the failure, the use of hybrid risk assessment method is noteworthy. This however requires referring to the experts' opinions and its analytical estimation.

2.2 The FTA Method

The FTA is a hybrid risk analysis method enjoying a deductive logic which an undesired event or state (the top event) can be determined by identifying key the BE resulting in failure. Boolean mathematical symbols (such as OR and AND gates) is used for the relationship between components. Therefore, the FTA technique is a graphical and logical illustration of different failures combined in a system (Vesely et al. 1981; Babaei et al. 2018; Ghachlou et al. 2019).

Different events in FTA technique are as follows:

- The top event: An undesired event resulted from a cause and effect sequence of the basic events which the probability of its occurrence is assessed by analyst.
- Basic Event: undeveloped events which are not further expanded due to the limits of analysis or lack of data.
- Intermediate event: events placed between the top event and the basic events.

2.2.1 Determination of the Failure Probability of the BEs

The evaluation of indices of WRDPs in terms of sustainable development criteria is introduced as the BEs in the presented technique. Therefore, these proposed indices have been used by valid organization and authorities, national and international articles and recorded data on the failure rate of the BEs. Since the datasets may occasionally be incomplete or missing to compute the failure probability of the BEs, the fuzzy method can be a useful tool to address these problems with uncertain data. The fuzzy sets will be defined rather than the crisp sets for the value of the failure probability of the BE in the fuzzy technique (Cai 1996). In other words, to use the FFTA technique, the crisp datasets should change into fuzzy datasets. The fuzzy sets introduced by Professor Zadeh (1965) enjoying various forms, and the triangular and trapezoidal form have been commonly used in the FFTA (Lee et al. 1985). Therefore, in this study, the triangular fuzzy set is used to represent the membership function.

2.2.2 Quantitative Analysis of the Top Event

The failure probability of the top event is estimated using the gate logic after calculating the failure probability of the basic events. Computing the gates in the FFTA is completely different from the FTA and fuzzy operators are used for computation. For example, if the triangular fuzzy numbers P_1 and P_2 can be expressed separately with (a_1, b_1, c_1) and (a_2, b_2, c_2), the algebraic algorithm for the fuzzy numbers P_1 and P_2 will be as follows:

For "AND" gate:

$$\widetilde{P}_{(a,b,c)} = \left[\prod_{i=1}^{n} a_i, \prod_{i=1}^{n} b_i, \prod_{i=1}^{n} c_i\right] \quad (1)$$

For "OR" gate:

$$\widetilde{P}_{(a,b,c)} = 1-\left[\prod_{i=1}^{n}(1-a_i), \prod_{i=1}^{n}(1-b_i), \prod_{i=1}^{n}(1-c_i)\right] \quad (2)$$

Where n is the number of events and i is the event number and Pi is the failure probability of the event i (Mahmood 2013).

2.2.3 Determination of the BEs

Ranking the BEs will be based on their contribution to the top event only if the occurrence of the top event is highly probable. Measuring the importance of the BEs and intermediate events which improves the reliability of the system and provides effective management instruction is a useful device. Enormous equations have been defined to measure the importance of BEs. If the failure probability of a BE is non-fuzzy numbers, the BI can be used to rank the events. This index can be defined using Eq. 3 (Pan and Tai 1988).

$$BI = Q_{qi=1} - Q_{qi=0} \quad (3)$$

$Q_{qi=1}$ denotes the failure probability function of the top event when the failure probability for i-th BE occurs completely and $Q_{qi=0}$ denotes the failure probability function of the top event when the failure probability for i-th BE never occurs. The greater index value is the greater contribution the event makes to the occurrence of the top event.

The Fuzzy Importance Measure (FIM) equation proposed by Suresh et al. (2011) can be applied in the fuzzy mode (Babaei et al. 2018) as follows:

$$Q = f\,(q_1, q_2, \ldots, q_i, \ldots, q_n) \quad (4)$$

$$FIM = ED\left[Q_{qi=0}, Q_{qi=1}\right] = \left(\left({Q_{qi=1}}^{L} - {Q_{qi=0}}^{L}\right)^2 + \left({Q_{qi=1}}^{U} - {Q_{qi=0}}^{U}\right)^2\right)^{0.5} \quad (5)$$

Where $Q_{qi=1}$ is the fuzzy function of the failure probability of the top event if the i^{th} event completely fails and $Q_{qi=0}$ is the fuzzy function of the failure probability of the top event when the i^{th} BE never fails. ${Q_{qi=1}}^{U}$ and ${Q_{qi=1}}^{L}$ are the upper and lower limits of this fuzzy set, respectively. Thus the FIM of all the BEs were calculated and then ranked in terms of their contribution to the top event failure. It is obvious that the greater index is the greater contribution makes to the failure of the top event. In this study, the top event's probability of failure is estimated based on the down to top analysis and this is a kind of diagnostic approach. Also when The BEs are ranked based on their contribution to the top event, a physical system identification approach is applied by top to down assessment.

2.3 Study Area

Makran coast area divided into four zones, is located in south of Iran stretching from the border of Pakistan in Sistan and Baluchestan province to Minab in Hormozgan province.. In this study, FTA technique was used for the risk assessment of water resource development plans in the west part of the coast (zone number 4) as shown in Fig. 1 (Iran's National Water & Wastewater Engineering Company, 2018).. The region was selected due to various available alternatives for water supply consisting conventional and non-conventional water resources (seawater resources). Reliability and sustainability of the water supply alternatives are different and it is important to select the best alternative based on risk analysis. As shown in the Fig. 1, Jegin, Minab, and Shamil&Nian dams are under operation, Sarney dam is under construction, and the rest of the dams are under investigation. Total allocated groundwater is estimated to be 164.91 million cubic meters per year for domestic, industrial, and agricultural use (Iran's National Water & Wastewater Engineering Company, 2018). Sirik and Bunji Desalination Plants (DP) are operational and Kargan, Bemani, and the extension of Bandar Abbas DPs are under construction for domestic water supply of Bandar Abbas city and rural areas.

Various WRDPs have been defined by Regional Water authority of Hormozagan e.g. water transfer from Jegin dam for domestic uses (current purpose of the dam is agriculture) and developing Gabrik dam for water demand of Gegin dam. In addition to conventional water resources, developing more desalination plants is the other solution to meet the domestic and industrial future demands of the zone 4 of Makran and Bandar Abbas city.

2.4 Scenarios of Water Resources Planning

The scenarios presented in this study are divided into three general groups; the first group of Scenarios named S_0 is the existing situation of water supply system. The second group named S1 includes all the existing and under construction projects in along with auxiliary desalination plants to fulfil the future water demands. In the third group of Scenarios (S2), in addition to the existing and under construction projects, under study plan for water transfer from Jegin dam to Bandar Abbas city and developing Gabrik dam has been taken into account. In this group, auxiliary desalination plants have also been considered (Rayab Consulting Engineering

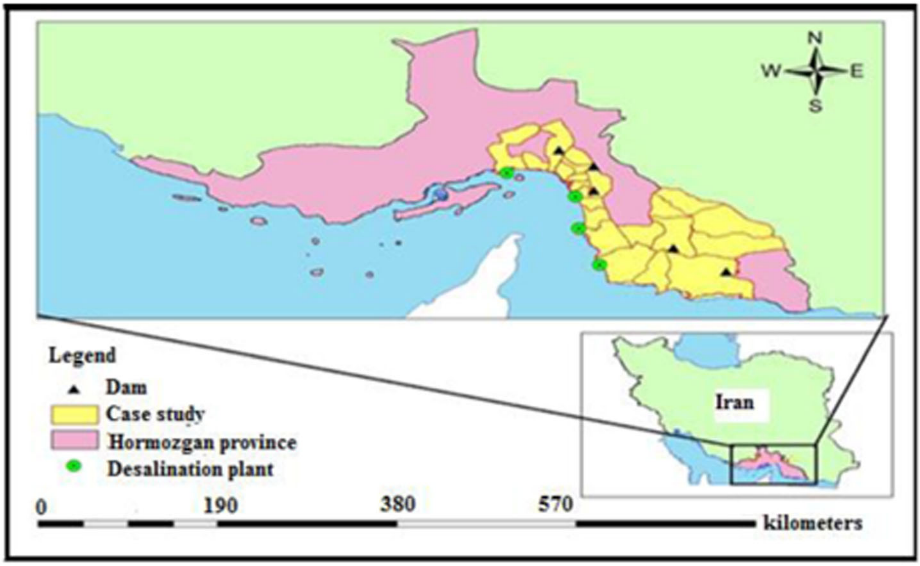

Fig. 1 Location of the study area and surface water resources

Company 2010; Lar Consulting Engineering Company 2017). Scenarios S1 and S2 have been divided into several sub-scenarios based on the feature of the projects. One of them is the capacity of water transfer lines. Also other factors are operating water level of the Gabrik dam,operation policies such as priority of supply from the desalination plants or dams and accepting/not accepting deficiency in agricultural demands. Figure 2 shows description of scenarios and sub-scenarios.

2.5 Water Resources Planning Model

In order to evaluate the scenarios, the first step is to determine water supply quantity and reliability through simulating the system in the monthly time step. Vensim Decision Support System (DSS) (1989–2019 Ventana Systems, Inc.) has broadly been used as a robust model for simulation, verification, and sensitivity analysis in the complex or dynamic systems (Abadi et al. 2015). In this study, Vensim DSS was used to model water resource plans.

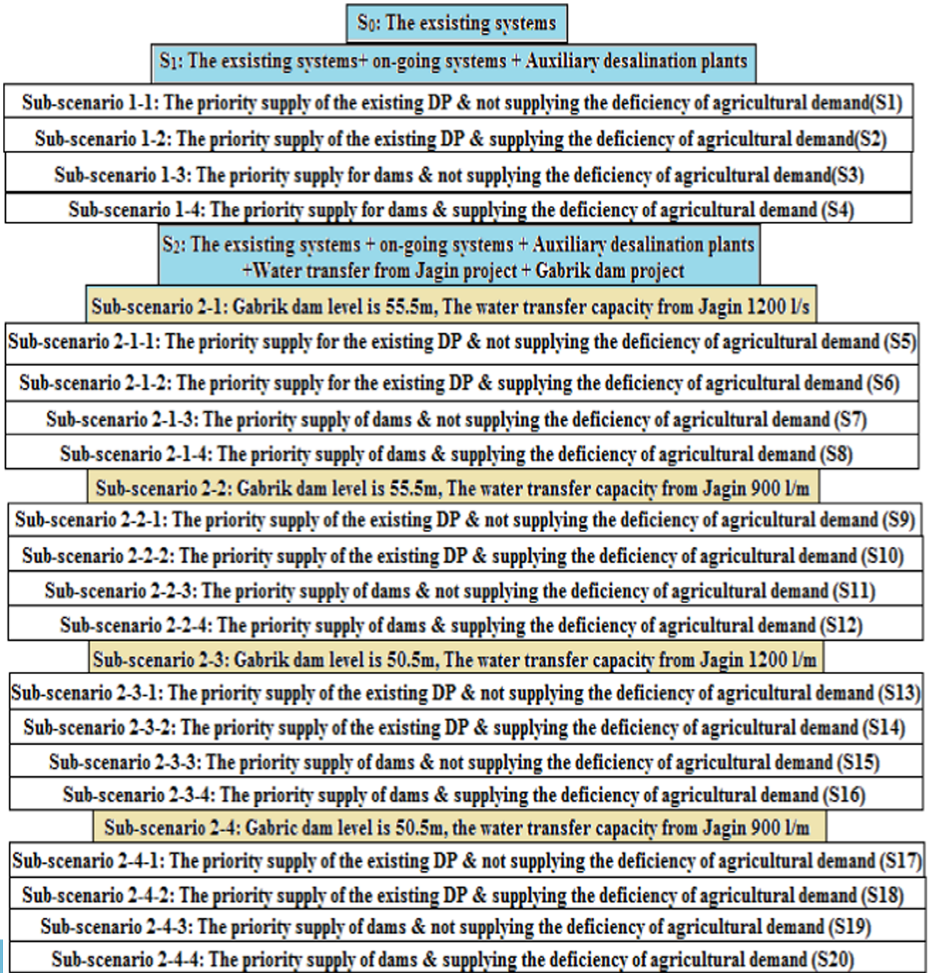

Fig. 2 Scenarios of water resources plans for water supply in south of Iran

A schematic of interconnection of water resources elements was first provided in the model based on the feature of water resources plans for each Scenarios separately. Input data of the model consist of dam inflow after removing trend from the historical time series, evaporation from the reservoirs, in stream environmental requirements, aquifer recharge and discharge, characteristic of reservoirs, available groundwater, capacity of water transfer lines, capacity of water desalination plants, irrigation demands, and so on.

The input data were used in monthly time step during period of 1966–2015. The Model determined water supply volume and reliability to meet environmental, domestic, industrial, and agricultural demands from different resources separately. Water demands of 2046 was considered for all WRDPs in the modeling.

2.6 The FTA Structure of the Risk Assessment

2.6.1 Identification of the General Hazards

In this study, the criteria of sustainable development including economic, social, and environmental aspects of the water resources plans were considered in the risk analysis. Accordingly, the threats and hazards of the plans were categorized to 14 BEs as contributing factors to the undesired event termed "the risk of failure of a WRDP" (shown in Table 1).

Table 1 Basic events in the FTA

Type	Symbol	Reference	Basic event
Society	BE1	ISO (www.iso.org/sdgs)	Employment decrease
	BE2	Banihabib et al. (2016)	Public dissatisfaction with water scarcity
	BE3	ISO (www.iso.org/sdgs)	Public dissatisfaction with poor water quality of desalination plant in comparison to conventional sources
Environment and water resources	BE4	ISO (www.iso.org/sdgs)	Water Quality failure of conventional sources due to high evaporation and sediment
	BE5	ISO (www.iso.org/sdgs)	Increasing marine pollution
	BE6	Kefayati et al. (2018)	Poor groundwater quality
	BE7	ISO (www.iso.org/sdgs)	Failure in desalination plants caused by environmental (e,g, red tide) phenomenon
	BE8	Yilmaz and Harmancioglu 2010)	Failure in meeting future agricultural demand
	BE9	Yilmaz and Harmancioglu (2010)	Shortage in industrial water supply
	BE10	Yilmaz and Harmancioglu (2010)	Shortage in domestic water supply
	BE11	Kefayati et al. (2018)	Relative water stress
	BE12	Yilmaz and Harmancioglu (2010)	Lack of aquifer recharge
Economic	BE13	Ghachlou et al. (2019)	Shortage of financial resources
	BE14	Yilmaz and Harmancioglu (2010)	Decline in benefit-cost ratio (B/C)

2.6.2 FTA Technique

Regarding to the impact of water on political, cultural, social, economic, and environmental aspects, water resources planning is a key element to achieve sustainable development. Therefore, the top event was first determined in the FTA structure, then BEs and intermediate events were identified based on water resources planning results. As shown in Fig. 3, the top event termed as “the failure of water resources development plans” considering sustainable development criteria subdivided into three intermediate events including social, economic, and environmental &water resources failures.

2.7 The Determination of Failure Probability of the BEs

Computing the failure probability of the BEs requires a profound and accurate understanding of them. The method of computing BEs was as follows:

Employment decrease:

Population growth has led to a growing demand for domestic and industrial water that may result in changing under study dams’ purposes. Domestic and industrial water supply enjoy a high priority than agricultural sector. Therefore, not only the amount of water allocated to agricultural demands but also cultivation area will be declined by changing the dams’ purposes. This issue will lead to have less employment rate in agricultural sector. However, the employment rate of 2 to 3 persons per liter per second in conventional farming can increase to 20 to 30 in the greenhouse farming in agriculture sector. Therefore, the water requirement of cultivated area in modern and traditional agriculture in each scenario was obtained using Vensim model. Then the employment rate in future (N_{EF}) and current situation (NEC) were calculated to determine the failure probability of a WRDP using Eq. 6.

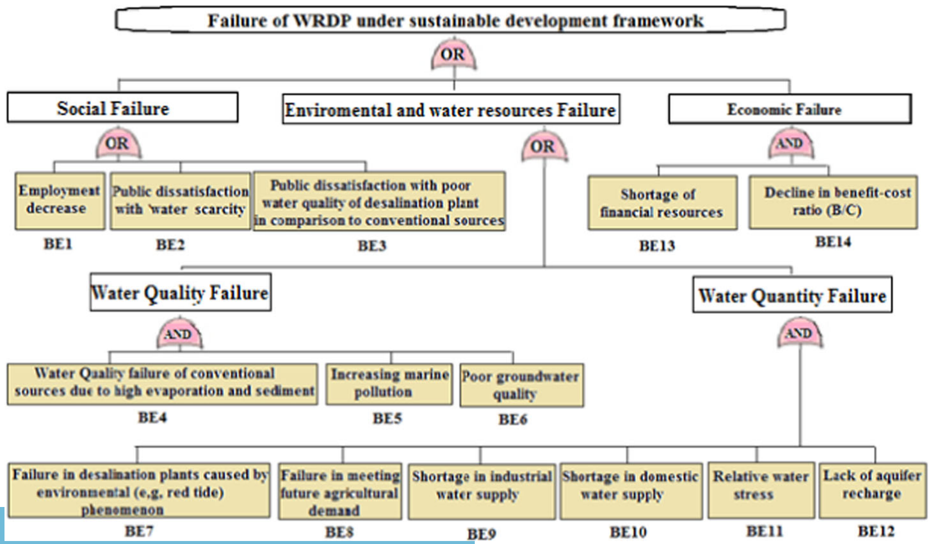

Fig. 3 The FTA Structure for risk assessment of WRDPs in Open FTA Software

$$PBE1 = \frac{NEC - NEF}{NEC} \tag{6}$$

Public dissatisfaction of water scarcity:

Eq. 7 was used to calculate the failure probability of public dissatisfaction due to shortage in agricultural, domestic, and industrial water supply.

$$PBE2 = \frac{TD - TS}{TD} \tag{7}$$

Where P_{BE2} is the failure probability of "public dissatisfaction of water shortage", TD is the total demands and TS is the total volume of supplied water.

Public dissatisfaction with poor water quality of desalination plants in comparison to conventional sources:

In some areas, the quality of surface water resources is better than the water quality provided by desalination plants. Consequently, the more demands provided by the desalination plants, the more people will be dissatisfied. The failure probability of this index can be estimated from the ratio of the consumed volume of desalination plants (CV_{DP}) to the total volume of supplied demands.

$$PBE3 = \frac{CVDP}{TS} \tag{8}$$

Water Quality failure of conventional sources due to high evaporation and sediment:

Storing surface water in the area with high annual sediment and evaporation will reduce the water quality in the reservoirs. The failure probability of this BE (P_{BE4}) can be calculated using Eq. 9:

$$PBE4 = \frac{AAS + AAE}{TVR} \tag{9}$$

Where A_{AS} is the average annual sediment volume, A_{AE} is the average annual evaporation from the reservoir, and TV_R is the total annual water regulation volume modeled by Vensim.

Increasing marine pollution:

Sea is polluted by effluent of the DPs and other sources of contamination. According to the studies, the average effluent produced in the desalination plants is 75% of water withdrawal of the desalination plant (IV_{DP})(Iran's National Water & Wastewater Engineering Company, 2018). Thus in this study, the effluent production rate (WP_C) was considered 0.75. The failure probability of this index can be obtained using Eq. 11 after estimating the effluent (GW) in each plan.

$$GW = WP_C \times IV_{DP} \tag{10}$$

$$PBE5 = \frac{GW}{GW_{max}} \tag{11}$$

Where P_{BE5} denotes the failure probability of the basic event of "increased marine pollution", GW_{max} is the highest amount of effluent in each scenario.

Poor groundwater quality:

The groundwater resources in the study area has a very poor quality due to excessive water withdrawal. Therefore, the improvement of aquifer's quality is highly dependent on the groundwater resources withdrawal. The groundwater resources withdrawal obtained from Vensim is another factor influencing the selection of water resource development best plan. The failure probability due to the poor groundwater quality was obtained from the ratio of groundwater withdrawal to the total available water using Eq. 12:

$$PBE6 = \frac{GWw}{TS} \tag{12}$$

Failure in desalination plants caused by environmental phenomenon:

The red tide phenomenon leads to the failing of the operation of desalination system, blocking filters and reducing the production volume of the desalination plant. According to the studies, the water production in the desalination plants decreases to 40% of products of desalination plant as the result of the phenomenon. Therefore, in this study, the reduction rate of water in the desalination plants (CR_{wp}) was considered 0.4. This phenomenon occurs in the studied area every 6 months so, its occurrence probability (P_O) was considered 0.5. The failure probability of this BE and the annual water production in the desalination plant (VR_{WP}) were obtained by the following Equations:

$$PO \times CRwp \times IVDP = VR_{WP} \tag{13}$$

$$PBE7 = \frac{VRWP}{VRWP\ max} \tag{14}$$

Where $VR_{WP\ max}$ is the maximum reduced water production in desalination plants.

Failure in meeting future agricultural demand:

In order to calculate the failure due to shortage of agricultural water for the existing cultivation area, it was necessary to estimate the volume of supplied water for agricultural demand (SW_{AD}) using Vensim model. The failure probability of this BE was calculated using the total existing agricultural demand (TA_{CAD}) applying Eq. 15:

$$PBE8 = \frac{TACAD - SWAD}{TACAD} \tag{15}$$

Shortage in industrial water supply:

Vensim model was used to estimate the amount of supply (AS_{ID}) for the total amount of industrial demand (TA_{ID}) and the failure probability of this event was calculated by Eq. 16.

$$PBE9 = \frac{TAID - ASID}{TAID} \tag{16}$$

Shortage in domestic water supply:

The failure probability of this index can be calculated using the amount of supplied domestic water (AS_{DD}) and the total amount of domestic demand (TA_{DD}) based on the following formula:

$$PBE10 = \frac{TADD - ASDD}{TADD} \tag{17}$$

Relative water stress:

This index is derived from the ratio of the consumed volume of conventional resources to the total available water resources. Therefore, the volume of water withdrawal in the dams (V_{DW}) and the volume of groundwater withdrawals (V_{GWW}) estimated by Vensim model were used to estimate the index. Then, the failure probability was calculated using the annual average volumes of dam inflow (AV_{DI}) and the annual available groundwater (A_{PGW}), based on Eq. 18:

$$PBE11 = \frac{VDW + VGWW}{AVDI + \ APGW} \tag{18}$$

Lack of aquifer recharge:

$$PBE12 = \frac{DAR - SAR}{DAR} \tag{19}$$

Where S_{AR} presents the supplied quantity of aquifer's artificial recharge, D_{AR} is the volume of demand for aquifer's recharge.

Shortage of financial resources:

To calculate the financial shortage index (FS), first, the present value of the project cost (PV_C) was calculated in a base year considering appropriate rate of return, then multiplied by the financial shortage rate (C_{FS}). According to references, only 40% of the total infrastructures budget was allocated by government in 2017. Therefore, the shortage of financial supply rate and economical rate of return were considered 0.6 and 12%, respectively. The failure probability was estimated as follow

$$FS = C_{FS} \times PV_C \tag{20}$$

$$PBE13 = \frac{FS}{FSmax} \tag{21}$$

Where FS_{max} is the maximum financial shortage in the Scenarios.

Decline in Benefit- cost ratio (B/C):

The present value of costs and benefits of each scenario was obtained in the base year (by not taking into account the spent expenses of the under operation and construction projects). Then the B/C economic index (EI) was calculated for each Scenario. The failure probability of the index was determined by Eq. 22:

$$PBE14 = 1 - \frac{EI}{EImax} \tag{22}$$

Where EI_{max} is the maximum (B/C) among the scenarios.

3 Results and Discussion

3.1 Water Resource Planning

Vensim model was utilized for water resources modeling in the different Scenarios. Data of the current condition of water supply was applied in order to verify the model. Figure 4 illustrates the current water resource scheme of the region in the Vensim software. The Jegin dam operation data inventory was selected for validation of the model.

The model uses the demands in the year of 2046 in all scenarios. The results obtained for the water resource development plans are presented in Table 2. The Scenarios are differed based on scheme of the projects and the policies used in operation of the system. For instance, the volume of water supply from the conventional resources is high in the Scenarios that the priority is to supply water from the dams. However, reliability of water supply in each sector was set to be similar in all Scenarios. The minimum required reliability was considered 100%, 92%, and 80% for domestic, industry, and agricultural demands, respectively.

3.2 The Failure Probability of the Basic Events

The failure probability of the BEs has been computed applying Eqs. 6 to 22 based on Vensim model outputs, existing studies, reliable references, and experts' judgments. The failure probability of BEs shown in Table 3 was entered as inputs to the fault tree in order to estimate the top event probability. The failure probabilities of indices 9 and 10 that attributed to shortage of industrial and domestic supply, were obtained 0.08 and 0, respectively for all scenarios except scenario S_0. In the Scenario S_0 (existing situation) there is no compensation plan to fulfil the shortages.

3.3 The Results of Risk Assessment

3.3.1 Crisp FTA

The failure probability of the BEs was considered as inputs of Open FTA software. The failure probability of the top event was crisply calculated corresponding to the feature of each Scenario. The results obtained for the failure probability of the top event and intermediate events were used to rank the Scenarios based on the non-fuzzy fault tree as presented in Table 4.

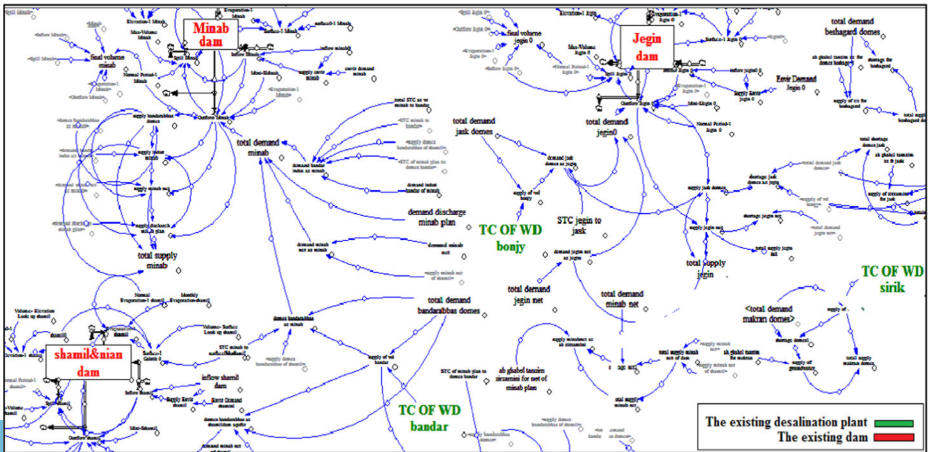

Fig. 4 Schematic of current demand and supply system for a part of the region

Table 2 Water resources planning results for different scenarios (Values in MCM)

Scenarios	Total demand	Total supply	Agricultural supply	Total supply from desalination plants	Discharge into sea	Evaporation
S0	327.7	244.6	108.5	9.8	90.2	91.2
S1	385.2	354.6	154.4	132.1	98.0	95.6
S2	420.4	382.8	182.6	160.2	98.0	95.6
S3	382.5	352.5	152.3	117.1	89.1	93.9
S4	417.7	380.7	180.4	145.3	89.1	93.9
S5	401.4	364.0	163.8	140.5	110.9	115.6
S6	441.6	396.2	196.0	172.6	110.9	115.6
S7	397.4	360.9	160.6	121.5	95.1	110.6
S8	437.6	393.0	192.8	153.6	95.1	110.6
S9	399.6	362.6	162.4	140.9	104.7	114.7
S10	441.6	396.2	196.0	172.6	104.7	114.7
S11	397.4	360.9	160.6	121.5	95.1	110.6
S12	437.6	360.9	160.6	153.6	95.1	110.6
S13	386.4	351.9	151.7	140.5	142.8	95.9
S14	441.6	396.0	195.8	184.6	142.8	95.9
S15	382.4	348.7	148.5	121.5	95.1	110.6
S16	437.6	392.9	192.6	165.6	95.1	110.6
S17	384.6	350.5	150.3	140.9	104.7	114.7
S18	439.8	394.6	194.4	185.1	104.7	114.7
S19	382.4	348.7	148.5	121.5	95.1	110.6
S20	437.6	364.7	164.5	165.6	95.1	110.6

Overall, the results indicate that all of the sub-Scenarios of S_1 to S_4 in the first Scenario were less likely to be failed comparing to sub-Scenarios of S_5 to S_{20} in the second Scenario considering the differences in the three intermediate events. However, the sub-Scenario of 1–4 (particularly S_4) in the first Scenario were selected as the top rank of the Scenarios with the

Table 3 Failure probability of the basic events in different Scenarios

	BE1	BE2	BE3	BE4	BE5	BE6	BE7	BE8	BE9	BE10	BE11	BE12	BE13	BE14
S0	0.22	0.34	0.04	0.13	0.05	0.54	0.05	0.35	0.77	0.77	0.54	0.32	0.00	1.00
S1	0.22	0.17	0.28	0.14	0.86	0.37	0.86	0.35	0.08	0.00	0.49	0.31	0.24	0.24
S2	0.00	0.10	0.34	0.14	1.00	0.34	1.00	0.18	0.08	0.00	0.49	0.31	0.26	0.10
S3	0.22	0.17	0.24	0.12	0.69	0.37	0.69	0.35	0.08	0.00	0.52	0.32	0.21	0.15
S4	0.00	0.10	0.30	0.12	0.83	0.34	0.83	0.18	0.08	0.00	0.52	0.32	0.23	0.00
S5	0.25	0.19	0.26	0.15	0.69	0.34	0.69	0.40	0.08	0.00	0.43	0.30	0.98	0.78
S6	0.00	0.11	0.33	0.15	0.84	0.30	0.84	0.20	0.08	0.00	0.43	0.30	1.00	0.73
S7	0.25	0.19	0.21	0.11	0.69	0.35	0.69	0.40	0.08	0.00	0.46	0.31	0.98	0.79
S8	0.00	0.11	0.28	0.11	0.85	0.31	0.85	0.20	0.08	0.00	0.46	0.31	1.00	0.73
S9	0.25	0.19	0.26	0.12	0.69	0.33	0.69	0.40	0.08	0.00	0.43	0.31	0.81	0.74
S10	0.00	0.11	0.33	0.12	0.84	0.30	0.84	0.20	0.08	0.00	0.43	0.31	0.83	0.67
S11	0.25	0.19	0.21	0.11	0.69		0.69	0.40	0.08	0.00	0.46	0.32	0.81	0.74
S12	0.00	0.09	0.28	0.11	0.85	0.31	0.85	0.16	0.08	0.00	0.46	0.32	0.83	0.67
S13	0.35	0.22	0.27	0.10	0.69	0.35	0.69	0.48	0.08	0.00	0.41	0.30	0.81	0.74
S14	0.00	0.11	0.37	0.10	0.90	0.30	0.90	0.20	0.08	0.00	0.41	0.30	0.83	0.68
S15	0.35	0.22	0.21	0.11	0.69	0.36	0.69	0.48	0.08	0.00	0.44	0.31	0.95	0.77
S16	0.00	0.11	0.32	0.11	0.90	0.31	0.90	0.20	0.08	0.00	0.44	0.31	0.98	0.70
S17	0.35	0.22	0.28	0.12	0.69	0.35	0.69	0.48	0.08	0.00	0.40	0.31	0.79	0.78
S18	0.00	0.11	0.37	0.12	0.90	0.30	0.90	0.20	0.08	0.00	0.40	0.31	0.82	0.70
S19	0.35	0.22	0.21	0.11	0.69	0.36	0.69	0.48	0.08	0.00	0.44	0.32	0.78	0.73
S20	0.00	0.11	0.32	0.11	0.90	0.31	0.90	0.20	0.08	0.00	0.44	0.32	0.81	0.64

Table 4 The failure probability of the top event based on the failure probability of three intermediate events and Scenarios ranking in the non-fuzzy fault tree

Scenario	Probability of social failure	Probability of economic failure	Probability of environmental and water resources failure	risk	rank
S0	0.495	0.000	0.004	0.497	3
S1	0.526	0.057	0.043	0.572	5
S2	0.393	0.025	0.046	0.435	2
S3	0.500	0.032	0.032	0.531	4
S4	**0.359**	**0.000**	**0.035**	**0.382**	**1**
S5	0.543	0.763	0.035	0.896	19
S6	0.391	0.727	0.038	0.840	16
S7	0.511	0.766	0.027	0.889	18
S8	0.349	0.729	0.030	0.829	14
S9	0.547	0.602	0.027	0.825	12
S10	0.395	0.560	0.030	0.742	9
S11	0.511	0.599	0.027	0.810	10
S12	0.349	0.563	0.030	0.724	7
S13	**0.622**	**0.737**	**0.024**	**0.903**	**21**
S14	0.424	0.687	0.028	0.825	13
S15	0.594	0.740	0.028	0.898	20
S16	0.382	0.690	0.032	0.814	11
S17	0.626	0.576	0.028	0.846	17
S18	0.430	0.525	0.032	0.738	8
S19	0.594	0.573	0.028	0.832	15
S20	0.382	0.523	0.032	0.714	6

failure probability of the top event of 38%. Figure 5 demonstrates a schematic of demands and water resources supplies in the top ranked sub-Scenario of S_4.

3.3.2 The Results of FFTA

The fuzzy sets of the BEs were estimated for four fuzzy mods and then they were used as inputs for fuzzy fault tree. A code was developed for fuzzy fault tree in Excel that computes the

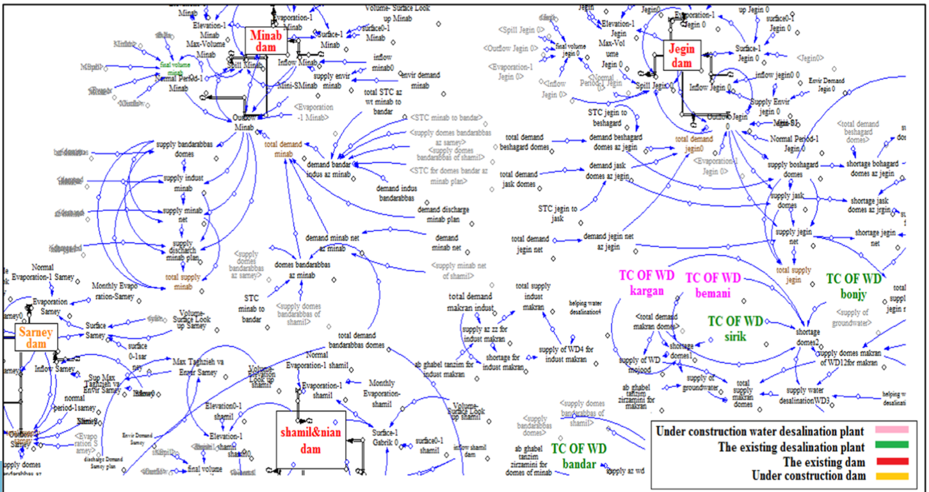

Fig. 5 Schematic of demands and supplies in the sub-Scenario of S_4

fuzzy set and the defuzzification values of the failure probability of the top event for all Scenarios. The results that presented in Tables 5 and 6 show the ranking of Scenarios for different fuzzification coefficient sensitivity analysis modes.

As shown in Table 6, the defuzzification failure probability of the top event were almost equal as results of the triangular fuzzy set and symmetric expansion of crisp numbers in the first and second modes of sensitivity analysis (5% higher or lower, 10% higher or lower). Whereas the results in the third and fourth modes (10% higher and 5% lower and 5% higher and 10% lower) were higher and lower than the first two modes, respectively.

Therefore, the ranking of the scenarios based on all four modes was almost the same. In other words, considering uncertainties based on different Fuzzification coefficients, Sub-Scenario 1–4 (S4) and sub-Scenario 2–3-1 (S13) were selected as the best Scenario and worst Scenarios, respectively. In all modes of sensitivity analysis, the Scenario pertaining to the existing condition was ranked as third. Figure 6 presents the probability of fuzzy failure of the top event in the best (S4) and worst (S13) sub-Scenarios for different fuzzification modes.

3.4 Ranking BEs

The BEs have been ranked based on their contribution to the top event. Therefore, two indices of BI in non-fuzzy approach (Eq. 3) and FIM in fuzzy approach (Eq. 5) were used in order to rank the BEs. The importance of the BEs were investigated in the best and worst sub-Scenarios and the Scenario pertaining to the existing condition.

According to the results shown in Table 7, the BEs ranking showed that the B/C reduction, shortage of financial resources, employment rate decline, and public dissatisfaction scores 1 to 5 ranks, respectively in the worst sub-Scenario (S13). The economic failure factors are the main reasons for failure of the top event in the Sub-Scenario. However, these factors draw

Table 5 Failure probability of the top event in FFTA for different fuzzification coefficients

Sub-senario	10%higher&lower Fuzzy value	5%higher&lower Fuzzy value	10%higher&5%lower Fuzzy value	5%higher&10%lower Fuzzy value
S0	(0.46,0.50,0.54)	(0.48,0.50,0.52)	(0.48,0.50,0.54)	(0.46,0.50,0.52)
S1	(0.52,0.57,0.62)	(0.55,0.57,0.60)	(0.55,0.57,0.62)	(0.52,0.57,0.60)
S2	(0.39,0.44,0.48)	(0.41,0.44,0.46)	(0.41,0.44,0.48)	(0.39,0.44,0.46)
S3	(0.49,0.53,0.58)	(0.51,0.53,0.60)	(0.51,0.53,0.58)	(0.49,0.53,0.60)
S4	(0.34,0.38,0.42)	(0.36,0.38,0.40)	(0.36,0.38,0.42)	(0.34,0.38,0.40)
S5	(0.81,0.90,0.97)	(0.86,0.90,0.93)	(0.86,0.90,0.97)	(0.81,0.90,0.93)
S6	(0.74,0.84,0.93)	(0.79,0.84,0.89)	(0.79,0.84,0.93)	(0.74,0.84,0.89)
S7	(0.80,0.89,0.97)	(0.85,0.89,0.93)	(0.85,0.89,0.97)	(0.80,0.89,0.93)
S8	(0.73,0.83,0.93)	(0.78,0.83,0.88)	(0.78,0.83,0.93)	(0.73,0.83,0.88)
S9	(0.75,0.83,0.89)	(0.79,0.83,0.86)	(0.79,0.83,0.89)	(0.75,0.83,0.86)
S10	(0.67,0.74,0.82)	(0.70,0.74,0.78)	(0.70,0.74,0.82)	(0.67,0.74,0.78)
S11	(0.73,0.81,0.85)	(0.77,0.81,0.85)	(0.77,0.81,0.88)	(0.73,0.81,0.85)
S12	(0.64,0.72,0.81)	(0.68,0.72,0.77)	(0.68,0.72,0.81)	(0.64,0.72,0.77)
S13	(0.85,0.90,0.95)	(0.87,0.90,0.93)	(0.87,0.90,0.95)	(0.85,0.90,0.93)
S14	(0.73,0.83,0.87)	(0.78,0.83,0.87)	(0.78,0.83,0.91)	(0.73,0.83,0.87)
S15	(0.82,0.90,0.96)	(0.86,0.90,0.93)	(0.86,0.90,0.96)	(0.82,0.90,0.93)
S16	(0.72,0.81,0.91)	(0.77,0.81,0.86)	(0.77,0.81,0.91)	(0.72,0.81,0.86)
S17	(0.78,0.85,0.90)	(0.81,0.85,0.88)	(0.81,0.85,0.90)	(0.78,0.85,0.88)
S18	(0.66,0.74,0.82)	(0.70,0.74,0.78)	(0.70,0.74,0.82)	(0.66,0.74,0.78)
S19	(0.76,0.83,0.89)	(0.80,0.83,0.86)	(0.80,0.83,0.89)	(0.76,0.83,0.86)
S20	(0.63,0.72,0.80)	(0.67,0.72,0.76)	(0.67,0.72,0.80)	(0.63,0.72,0.76)

Table 6 Ranking of Scenarios based on failure probability of the top event for different fuzzification coefficients

	5% higher&lower		10% higher&lower		10%higher&5%lower		5%higher&10%lower	
Sub-senario	defuzzifiion value	rank	defuzzifiion value	rank	defuzzifiion value	rank	Defuzzifiion value	rank
S0	0.496	3	0.496	3	0.503	3	0.493	3
S1	0.572	5	0.572	5	0.580	5	0.568	5
S2	0.435	2	0.435	2	0.443	2	0.431	2
S3	0.531	4	0.531	4	0.538	4	0.527	4
S4	**0.382**	**1**	**0.382**	**1**	**0.389**	**1**	**0.379**	**1**
S5	0.894	19	0.895	19	0.907	19	0.888	19
S6	0.839	16	0.840	16	0.855	17	0.832	16
S7	0.888	18	0.889	18	0.901	18	0.881	18
S8	0.829	14	0.829	14	0.846	15	0.820	14
S9	0.824	13	0.824	12	0.835	12	0.818	13
S10	0.741	9	0.742	9	0.755	9	0.734	9
S11	0.809	10	0.809	10	0.821	10	0.803	10
S12	0.723	7	0.724	7	0.738	7	0.716	7
S13	**0.899**	**21**	**0.903**	**21**	**0.908**	**21**	**0.897**	**21**
S14	0.819	12	0.825	13	0.839	13	0.817	12
S15	0.896	20	0.897	20	0.907	20	0.891	20
S16	0.814	11	0.814	11	0.829	11	0.806	11
S17	0.844	17	0.845	17	0.854	16	0.840	17
S18	0.737	8	0.738	8	0.750	8	0.731	8
S19	0.831	15	0.831	15	0.841	14	0.826	15
S20	0.714	6	0.714	6	0.728	6	0.707	6

particular attention for risk management. Strategies such as raising revenues from water tariff and finding alternate financial sources can help to reduce the risk of the plan.

Table 8 shows the results of the BEs ranking for the Scenario pertaining to the existing condition (S0). In both fuzzy and non-fuzzy approaches, the failure of the social indices enjoys the highest importance. Order of importance of social indices are public dissatisfaction yielded from water shortage, low employment rate, and public dissatisfaction for poor water quality of

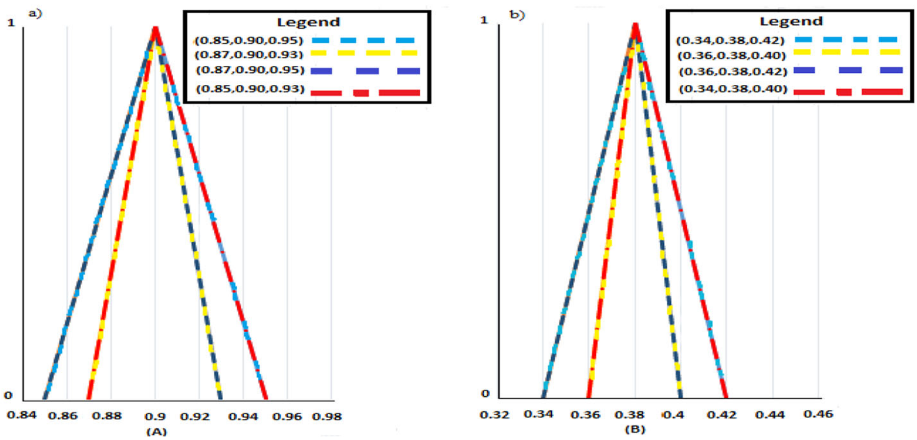

Fig. 6 Fuzzy failure probability for different fuzzification coefficients (the first to fourth modes presented in colors light blue, yellow, dark blue and red, respectively)9(**a**) the best sub-Scenario (S4), 9(**b**) the worst sub-Scenario (S13)

Table 7 Ranking of BEs for the worst sub-Scenario (S13) based on BI and FIM index

Basic event	1	2	3	4	5	6	7	8	9	10	11	12	13	14
BI	0.15	0.12	0.13	0.02	0	0.01	0	0	0	0	0	0	0.29	0.35
Rank	3	5	4	6	8	7	9	10	11	12	13	14	2	1
FIM	0.23	0.19	0.21	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.38	0.47
Rank	3	5	4	6	8	7	10	11	12	9	13	14	2	1

desalination plants respectively. The economic, environmental, and water resources indices have less contribution in the failure of the top event. Therefore, special attention should be paid to social failure factors in formulating risk management strategies.

Since the sub-Scenario of S4 that elected as the best scenario, has high risk, risk mitigation plan should be provided in risk management strategies. The results of ranking the events are shown in Table 9 for the best sub-Scenario both in fuzzy and non-fuzzy approaches. The BEs of the social failure were the most effective factors in the failure of the top event. The BEs include public dissatisfaction as a result of poor water quality of desalination plants compared to conventional resources and public dissatisfaction due to water shortage and low employment rate. The events pertaining to failure of conventional resources due to poor water quality because of high evaporation and sediment in the reservoirs and low economic index are in the fourth and fifth ranks.

4 Conclusion

In this study, a holistic approach was presented to assess the reliability and risk of WRDPs. A new framework was used for risk assessment of WRDPs in terms of sustainable development criteria applying the FTA technique. The technique was applied for a case study in south of Iran, where water supply is crucial issue for future development plans. The failure of WRDPs was selected as an undesired event in the presented FTA. All determining factors in the occurrence of the top event were identified based on the 14 indices approved by authorities, and various researchers in the fault tree structure. The FFTA was used to consider the uncertainties in the analysis. In this way, the failure probability of the BEs was first estimated based on the recorded data. Then, the percentage of lower and upper limits was used for fuzzification of the BEs failure.

In both approaches FTA and FFTA, the sub-Scenario of S4 (including the existing and under construction projects and auxiliary desalination plants) was selected as the best Scenario representing the failure probability of 38% for the top event. Also, the sub-Scenario of S13 including the existing and under construction projects and under study plan for water transfer

Table 8 Ranking of BEs for the existing condition Scenario (S0) based on BI and FIM index

Basic event	1	2	3	4	5	6	7	8	9	10	11	12	13	14
BI	0.65	0.75	0.52	0.01	0.04	0.003	0.004	0.00	0.00	0.00	0.00	0.00	0	0
Rank	2	1	3	5	4	7	6	8	9	10	11	12	13	14
FIM	0.87	0.99	0.70	0.02	0.05	0.004	0.01	0.001	0.00	0.002	0.001	0.001	0	0
Rank	2	1	3	5	4	7	6	10	12	8	11	9	13	14

Table 9 Ranking of BEs for the best Scenario (S4) based on BI and FIM index

Basic event	1	2	3	4	5	6	7	8	9	10	11	12	13	14
BI	0.618	0.674	0.885	0.183	0.028	0.067	0	0	0	0.001	0	0	0	0.143
Rank	3	2	1	4	7	6	9	10	11	8	12	13	14	5
FIM	0.83	0.90	0.99	0.25	0.38	0.09	0	0	0	0.00	0	0	0	0.19
Rank	3	2	1	4	7	6	9	10	11	8	12	13	14	5

from Jegin dam to Bandar Abbas city and developing Gabrik dam and Auxiliary desalination plants, was identified as the worst Scenario with failure probability of 90%.

The main outcome of the paper was the ranking of Scenarios through risk based analysis of criteria. All the required indices were quantified and some of their necessary parameters were extracted by experts' judgments. The result of ranking assists managers and decision makers to implement the best development plans and mitigate the possible risks of the plan by improving effective indices in the top event failure. The probabilistic approach with fuzzy logic in the proposed method enjoys the great advantages comparing to MCDM methods. The key issue in evaluating WRDPs is to identify the decisive factors in plans failure and risk based decision-making. Therefore, the BEs can be prioritized and their pairwise or multiple relationship be considered using logical gates in FTA. The formulas were used to quantity the failure of the events in the paper can be improved by profound understanding the events. Moreover, the occurrence of each BE was individually investigated, whereas examining two or more related threats can possibly increase the probability of the top event occurrence. Therefore, it is recommended to model these threats by dependent probabilistic approach.

Compliance with Ethical Standards

Conflict of Interest None.

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