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Fault Tree Analysis of Trade-Offs between Environmental Flows and Agricultural Water Productivity in the Lake Urmia Sub-Basin Using Agent-Based Modeling

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Abstract: The recent problems of Lake Urmia (LU) are caused by extensive and complex socio-ecological factors that require a comprehensive approach to consider the relationships between users and identify failure factors at the basin level. For this purpose, an agent-based simulation model of farmers' social interactions and economic interests (ABM) with various support scenarios and random supervision and training by the government agent is developed to evaluate its impact on independent farmers' decision-making in the form of a complex adaptive system. Finally, a fault tree analysis (FTA) is created in the Cara-FaultTree 4.1. software to identify scenarios that lead to the non-development technology in irrigation management (non-DTIM) in the LU sub-basin. The assessment of the impact of government supervision and training revealed that the main causes of non-DTIM in the LU basin are a lack of demands from farmers and low awareness among residents of the basin, with failure probabilities of 0.90 and 0.86, respectively. Ultimately, the failure probability of the main event (non-DTIM) was 0.50. The paths of proper training and farmers' requirements for sustainable agricultural water supply should become more stringent. The results confirm that appropriate measures to strengthen government supervision and training, as well as raise farmers' awareness of the importance of long-term sustainability of water resources, can lead to greater resilience in the DTIM.

Keywords: water resources; demand; risk; resilience; LU

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1. Introduction

The water crisis poses a serious threat to human life. The short-term perspective in managing risks, as well as the lack of transparency and unscientific planning, raise the possibility that the crisis will worsen and expand once it occurs [1,2]. It is, therefore, necessary to assess the catchment areas with a tool so that the right quality of required water can be provided. If financial resources are not made available within the schedule, there will be delays in the implementation of projects in the individual basin areas. The lack of community perspective in regional planning and the lack of codified laws in the watershed as well as the absence of a land-use plan are among the main reasons for the emergence of a critical situation in the basin [3]. With population increase, climate variability, and its numerous problems, watersheds have become less important and are facing various threats. Therefore, the possibility of the occurrence of an undesirable phenomenon (risk) and systematic efforts to determine and manage the threats and hazards through risk identification and analysis are proposed [4]. This objective requires accurate identification of catchment problems and risks. A comprehensive and accurate identification of risks and the determination of the effectiveness of system failure concerning each of these risks may require the provision of accurate and effective solutions to improve the status of the water resources of the basins [5].

In recent years, the LU basin has faced many problems in terms of a lack of water resources and economic and social damage. A comprehensive approach to assessing the performance of catchments can reduce their vulnerability in critical situations and focus on the most vulnerable points [6–8]. The purpose of the risk analysis of the total failure of a watershed is to assess and identify all threat factors regarding the amount of available water; the environmental, economic, and social water quality of the basin; and the impossibility of its provision [9]. On the other hand, the cross-sectional approach to dealing with risks and the lack of transparency in planning increases the risks caused by risks and harbors the possibility of aggravation and expansion of the crisis after it occurs [10]. Accurate knowledge of the basin, the elimination of human and natural destructive factors, and the need to apply novel approaches to risk analysis are the keys to success in improving and preventing possible risks in basins. Compared to water resource use studies with high costs and difficulties, simulation-based modeling offers an alternative method [11]. Many water resource models were proposed to describe population dynamics, which are mainly divided into two types, namely, microscopic and macroscopic models [12]. Microscopic models, including the social force model (SF model) [13], the cellular automata model (CA model) [14,15], and the agent-based model (ABM) [16], can describe individual behavior more accurately and come closer to reality. Among these models, agent-based models have made significant progress in recent years. ABMs have improved the processing speed of computers. ABM can simulate a variety of "agents" that may have rudimentary artificial intelligence to make decisions. Each agent can have a unique set of behavioral rules that allow modeling heterogeneity in the population [17,18].

In recent years, ABM models have been developed for water resources management [19,20]. ABMs have the potential to significantly improve the design of stringent regulations and incentives for water resources management [21]. Nhim et al. [22] concluded that ABM models are a powerful tool for studying how socioeconomic and environmental changes affect the human use of water resources. Pouladi et al. [23] reported that farmers' performance and willingness to engage in LU restoration could be simulated by integrating ABM into the socio-hydrological framework. Ohab-Yazdi and Ahmadi [24] showed that the regional water organization's relevant interactions with other stakeholders led to the control of illegal water extraction and the rise of water levels in aquifers. Anbari et al. [25] concluded that through government-sponsored programs it is possible to offset about 23% of the negative balance of the aquifer within 13 years. Lang and Ertsen [26] investigated the interaction between human and non-human agents in an irrigation system. The results showed that the Irrigation-Related Agent-Based Model (IRABM) offers a new perspective in modeling the human–water system. Okura et al. [27] studied irrigation management using the ABM model and game theory. The results showed that social changes can accelerate farmers' non-cooperative behavior. Shoushtarian et al. [28] developed an ABM model to simulate agricultural water use and socio-hydrological dynamics of California. The results showed that ABM helps to evaluate current water reuse management practices in terms of sustainability of water resources. Streefkerk et al. [29] presented a dynamic adaptive drought modeling model in Kenya that combines socio-hydrological modeling and ABM approaches. The results showed that the absorption of drought adaptation affects soil moisture, groundwater, and drought propagation. Mirzaei et al. [30] concluded that for the implementation of the water–energy–food nexus model in the water-stressed region, the policy of using advanced irrigation technologies under the government's support scenarios is necessary.

Previous studies on water resource utilization mainly focused on farmer behavior and water resource modeling and optimization. There is a knowledge gap regarding the use of information from ABM modeling in decision-making that improves safety. To fill this gap, this study aims to adopt ABM modeling and further develop a fault tree analysis (FTA) method to identify scenarios that lead to non-DTIM in the LU sub-basin. FTA is a decision tree structure based on a graphical method to represent the logical cause of failure [31]. The purpose of the FTA is generally to control risk, the worst-case event is considered the top event, and then the various failures that can lead to the top event are determined through top-down layer-wise logical analysis. These disturbance events are distributed layer by layer in the form of a tree structure. To this end, a case study in the LU sub-basin in the Miandoab Plain was used as an example to demonstrate the methodology. The increase in the area under water cultivation, the decrease in rainfall, the low efficiency of agricultural irrigation, and the lack of an allocation of sufficient water to meet the biological needs of the leading rivers are considered to be the most important factors aggravating the crisis and dryness of LU. In addition, traditional agriculture is one of the reasons for the drying up of LU after the decrease in rainfall. The change from traditional to advanced agriculture is of particular importance due to the drying up of LU. Therefore, risk indicators need to be provided for risk management and improvement of this catchment area. This paradigm can be used for any watershed to identify critical paths and prevent the inappropriate use of water resources. The developed free trade agreement provides water resource managers with a basis for formulating water resource use plans to avoid the catastrophic consequences of water scarcity in catchment areas.

According to the mentioned main goals, in the present study, an ABM simulation model of social interactions and economic interests of farmer agents, along with different scenarios of support policies as well as random supervision and training by the government agent to evaluate its impact on the decision-making of independent farmers in the form of a complex adaptive system, is presented. Next, by using FTA, the scenarios that led to the non-development technology in irrigation management (non-DTIM) in the Lake Urmia basin were identified. In this regard, there are fundamental questions and hypotheses, such as what are the main reasons and factors for solving the non-DTIM in the Lake Urmia basin? The use of ABM and FTA models based on the identification of various factors and their interactions is effective in identifying the reasons for the non-DTIM. The answers to the questions mentioned as the main goals are necessary for the purposeful design of the road map for the DTIM in the LU sub-basin and the achievement of its goals. Regardless of the mentioned cases, the implementation of water consumption management programs is not only accompanied by many uncertainties from the point of view of their effectiveness but will also entail huge costs.

2. Materials and Methods

2.1. LU

The LU basin in northwestern Iran is one of the main basins of Iran, with an area of 51,876 km^2. LU is the largest inland lake in Iran and one of the most valuable aquatic ecosystems in Iran and the world [32]. The downward trend of the water level of LU began in 1995, and in 20 years, the lake level has dropped by more than 8 m. As a result, the remainder of more than 30 billion cubic meters of LU's water volume has been lost due to evaporation and lack of annual rainfall. Due to LU's location in a closed basin, precipitation and runoff are considered sources of water input into the lake, and evaporation is considered water discharge [32].

The two main causes of LU drying are (1) excessive extraction of renewable water resources and unbalanced development in the LU basin (human factors, 69%) and (2) climate change (18%) and persistent drought (natural factors) [33].

Improved living conditions and higher incomes of farmers were the main reasons for the expansion of cultivated area and increase in water consumption in the LU basin due to human factors. The expansion of the cultivated area and increased water consumption created a crisis in LU that is making life more and more difficult for the population living there [33].

2.2. Miandoab Plain

The Miandoab Plain lies in the southern part of LU (Figure 1). The geographical coordinates of Miandoab are 45°43′ N, 36°46′ E, and its altitude is 1292 m above sea level [34]. The average annual rainfall is 296 mm, and the average humidity is 53%. The average annual and minimum temperatures are 11.8 °C and −3 °C, respectively [34]. In the Miandoab Plain, half of the surface flows flow into LU and 20% of the total groundwater. Zarineh Roud and Simineh Roud are the main sources of Miandoab Plain surface water discharged into LU [35]. The Zarineh Roud and Simineh Roud basins comprise the largest sub-basin of the LU basin (34% of the total LU basin area). In recent years, the function of securing the rights of LU has been lost due to the development of exploitation of surface water resources of these rivers.

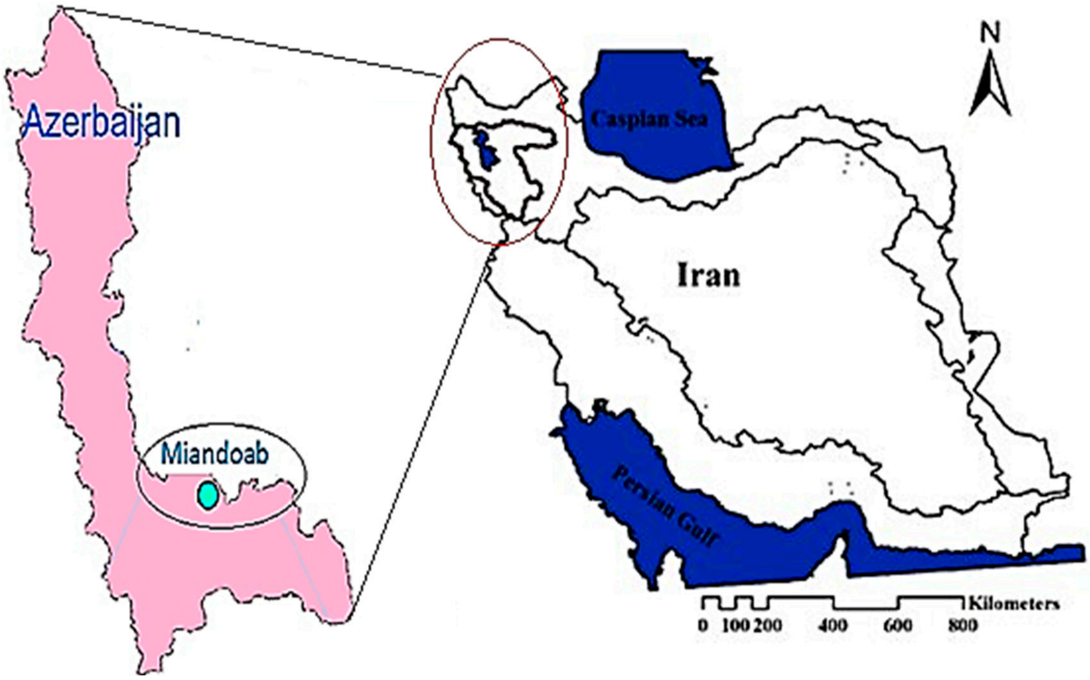


Figure 1. Geographical location of Miandoab Plain (https://www.esri.com/en-us/arcgis/about-arcgis/overview, 8 March 2022).

2.3. Agent-Based Modeling (ABM)

Agent-based models (ABMs) are a popular tool in today's computing environment for simulating the collective outcomes of individual behavior in complex systems. These models are based on the idea that interactions between autonomous and independent agents shape the behavior of a system rather than just focusing on the system's internal variables [36]. ABMs allow for variation and interactions between individual factors to be taken into account by returning the focus to the agents themselves, resulting in a more accurate and realistic representation of the system's behavior. ABMs are particularly useful in modeling complex systems whose behavior is difficult to predict due to the relationships, competition, and interdependencies between their components or between the system and its environment. Using these models, researchers can capture the patterns and structures that emerge from, rather than those that are dictated by, the interactions of individual actors or the emergent properties of the system (Figure 2). Additionally, ABMs enable agents to make decisions by considering the concepts of adaptive learning and intelligence [37].

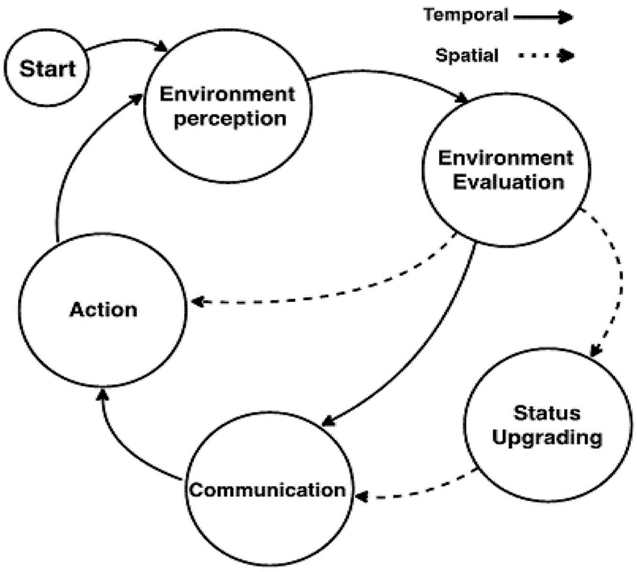


Figure 2. Design of the ABM model.

2.4. Fault Tree Analysis (FTA)

The FTA includes building a fault tree, entering the fault probabilities of the base events, distributing the fault probabilities to determine the probability of the main event, and determining the intersections [38]. When a shear set occurs simultaneously as a group of initiators, the main event occurs. The first step in FTA analysis is to gain a complete and accurate understanding of the system. Accurate and detailed information, including system components, physical and functional interactions between components, and normal and abnormal conditions, can be obtained from various sources, such as reviewing maps, diagrams, instruction manuals, maintenance methods, and interviews with experts. Gates defines the logic in the fault tree and links base events to intermediate and main events (Figure 3). If the main event results from the simultaneous failure of two events or at least one of the events results in the failure of a higher event, AND or OR gates are used [39].

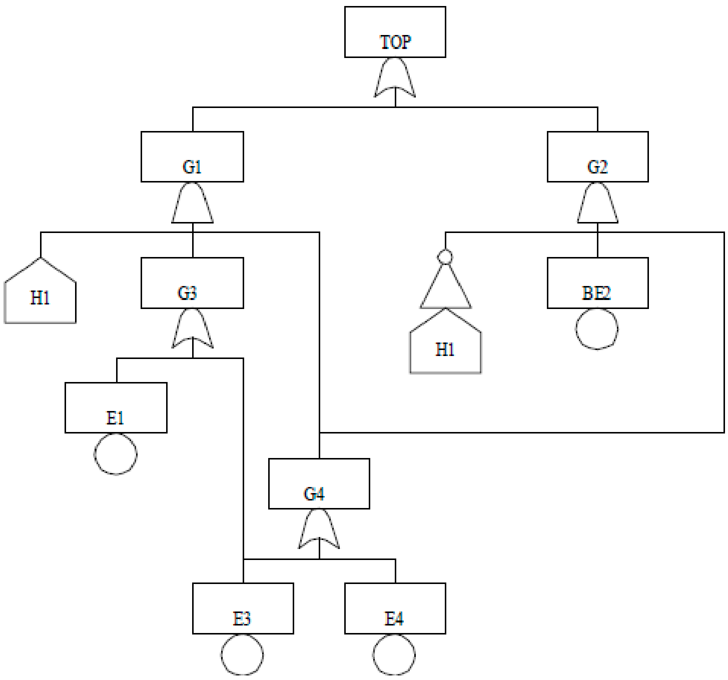


Figure 3. Schematic of FTA.

3. Methodology

3.1. Designed ABM Model

The ABM model aims to replicate farmers' ability to adapt to new DTIM (development technologies in irrigation management). In this model, there are two groups of farmers and government officials. Farmers with low DTIM-WP, regardless of their experience, seek financial benefits and cheaper production and irrigation costs. Looking for long-term strategic goals to maintain the sustainability of water resources on behalf of the government. To encourage farmers to use DTIM, the government offers incentives, in this case, subsidies. It also serves as a tool for tracking farmer productivity and training. Currently, water resources are used by farmers to achieve short-term benefits through irrigation systems and different levels of technology. Farmers adjust the current plan based on a cost–benefit analysis, their desire to increase WP, and their understanding of the importance of DTIM. DTIM charges costs for the initial setup. Government subsidies can be used by any farmer to increase WP. If no farmer makes optimal use of available water resources, long-term access to these resources is at risk. If this is the case, farmers consider this an ad hoc expense. By increasing the allocation of government subsidies, it is possible to motivate farmers to increase their profits. To achieve this, the government can rely on assessment teams equipped with DTIM training to offer help and support to farmers. As part of the government's assessment process, monitoring farmers' behavior is crucial. However, it is important to note that farmers who benefit from the sale of an improved irrigation system may no longer be eligible for certain government programs and future subsidies. The government has the power to strengthen the integrity of farmers through these assessments. Furthermore, to create an effective framework for DTIM in the Moandoab region, government policies are evaluated using the ABM model. For this purpose, NetLogo 6.2.2. is used, a software that simulates various phenomena and has a user-friendly interface. The use of NetLogo 6.2.2., programmed in Java, offers further advantages to the decision model used in this study [40,41].

3.2. Model Description

3.2.1. Farmer Agent

The decision-making power of the government and the changing characteristics and behaviors of a group of farmers are presented in the ABM model as the two most important and powerful players in the use of technology to maximize irrigation management in the LU Basin. ABM helps clarify the complex adaptive system of individual farmers' decisions in response to government policies as well as interactions with other farmers and the environment. The farmer agent receives subsidies from the government (acting as an agent of the Ministry of Water and Agriculture) to increase WP through DTIM. The agent-based adaptability model of farmers in DTIM is schematically shown in Figure 4.

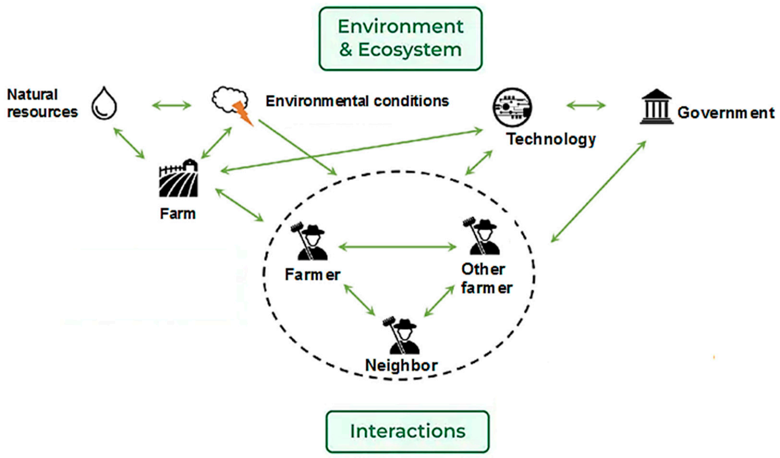


Figure 4. Agents' interactions with the environment and one another at different levels.

The inputs that the proposed framework gathers include job preference, academic education level, age, size of agricultural farm, coordinates, and distances. These data are used to calculate the entrepreneurship index (*entrepre*), which indicates each farmer's potential for developing an irrigation system. The various degrees of the efficacy of the aforementioned elements in determining the *entrepre* index are displayed in Table 1. As model inputs, the amount of farmers' expenses and profits, as well as DTIM costs, have been estimated. Farmers are dispersed throughout the modeling industry. Every farmer has social ties to neighbors with whom they can exchange experiences. They are impacted by government policies in the model environment, which includes education and monitoring programs, government subsidies for irrigation system improvements, and weather- or decision-making-related uncertainties.

Table 1. The effectiveness of the components in calculating the *entrepre* index.

Age (Year)	Education	Occupation	*Entrepre* Index
age < 40 40 < age < 60 age > 60	University education or without education	Without side occupation or unrelated occupation	Normalized innovation index
[1–3]	[1–5]	[1–3]	[0–1]

It is assumed that farmers who do not have the proper level of WP can make decisions for DTIM. One of the considered triggers is the propensity of farmers to DTIM (*prop*).

The minimum value of the prop trigger (*prop*.min) is defined as follows:

$$prop.\text{min} = \frac{(\alpha\ scale) + (\beta\ entrepre)}{(\alpha + \beta)} \tag{1}$$

where α and β express the effect of farm scale and the farmer's entrepreneurship on the initial propensity to DTIM, respectively.

To make decisions, farmers can weigh the costs and benefits of their options, consider past performance, and consider the costs of sustainable water supply (SWS).

In this study, it is assumed that the challenge of SWS in the long term is such that if farmers do not take action to correct the existing process of using water resources, this possibility is seriously threatened. Considering this issue, the non-participation of farmers in upgrading the irrigation system is regarded as a cost. This cost will decrease with the participation of more farmers in improving irrigation productivity (SWR). SWR is calculated as follows:

$$SWR = \frac{6 \times count\ farmers_6}{\sum\limits_{i=1}^{6} irr_{status} \times count\ farmer_{irr_{status}}} \tag{2}$$

Farmers typically leverage their desire for DTIM and honesty when using government subsidies as a trigger for decision-making. Farmers' decisions are influenced by the amount of these stimuli and vice versa. The ABM model then undergoes a sufficient number of iterations in different scenarios and the resulting results of the model are then statistically analyzed. The mean ratio of DTIM, the mean speed of DTIM, the field application efficiency (FAE), and government expenditure (which are taken into account in the number of cases of granting subsidies) are among the results that are considered consistent with the main objectives of the study.

3.2.2. Government Agent

The main goal of the government agent is to improve WP. Assuming that crop yields rise or stay at the same level, the government agent is attempting to persuade the farmer agent to DTIM. The main defenders of the WP in the agriculture sector, incentive policies, have been taken into consideration by the government. One of the policies taken into consideration in this area is providing DTIM with subsidies. Through subsidies, the government hopes to persuade farmers to raise WP. Additionally, the government can lessen DTIM issues and contribute to an increase in WP and crop yield by considering monitoring and training teams. Farmers become more honest and there is less misuse of the facilities provided by the government when it is monitored. Increasing WP in the study area is one of the government's top priorities in this investigation. Consequently, irrigation efficiency is assessed using the FAE index in the manner described as follows:

$$FAE = \frac{\sum_{i=1}^{6} irr_{status=1}\ count\ farmer_{irr_{status}} (r \times eff_{irr_{status}} \times (1-r)\ \rho)}{\sum_{i=1}^{6} irr_{status=1}\ count\ farmer_{irr_{status}}} \quad (3)$$

where $eff_{irr_{status}}$ is the amount of expected WP in different irrigation systems, which is estimated as follows (Table 2) [42].

Table 2. Expected WP in different irrigation systems.

Irrigation System	$eff_{irr_{status}}$	Irr_{status} Amount
Border	30%	1
Furrow	50%	2
Sprinkler	65%	3
Surface drip (tape)	80%	4
Surface drip (tape) (with irrigation management)	90%	5
Subsurface drip irrigation	95%	6

The government's achievement in raising the FAE index's value can be attributed to one of the most important factors. Thus, in the complex socio-environmental system under study, the government's best policies have the potential to either improve this index or accelerate its advancement. The effects of these incentive policies are assessed in the ABM model using various scenarios. To this end, the influence of governmental policies on the outcomes is assessed.

Farmers may be encouraged to make money if government subsidies are increased in proportion. Thus, by taking the assessment teams at various levels with DTIM education into consideration, the government can aid in raising farmers' profits. One aspect of government assessments is keeping an eye on farmers' conduct. Farmers risk losing access to certain government services and the chance to reapply for subsidies if they profit from the sale of their upgraded irrigation system. Evaluations: The government can make farmers more truthful. The government policies are then assessed using the ABM model to provide a framework that works for the management of water resources in the Miandoab region.

The parameters of the ABM model are calibrated using the investigated data and field studies and are presented in Table 3.

Table 3. Range of ABM model parameters.

Parameter	Description	Value
Network-density	Influence of the farmer's neighbors	[0.05, 0.1, 0.2]
α	Farm scale	[0.4, 0.7, 0.9]
β	Farmer's entrepreneurship on the initial propensity to DTIM	[0.4, 0.7, 0.9]
r	Effect of random changes	[0.1, 0.4, 0.7, 0.9]

Table 3. *Cont.*

Parameter	Description	Value
SWS	Sustainable water supply	[1000, 10,000, 50,000]
Seed-ratio	Portion of seed participants of the cooperation	[0.05, 0.1, 0.2]
Seed-owner	Types of earliest participants	[Close owners, Hight *entrepre* and scale, Hight degree, Hight *entrepre*, No other job]
Gov-policy	Subsidy, training, and supervision policy of the government	[Normal, Enlarge, Diminish, Mix of all]
Inspect-owners	Government supervision teams	[4, 8, 16]

3.2.3. Questionnaire Investigation

To define scenarios and identify stakeholders, questionnaires and specialized interviews were employed. The sample size of the interview was 72. Interviews with a range of relevant parties were undertaken in the Miandoab Plain, including farmers, the Ministry of Agriculture (15 agents), managers and specialists of local water organizations (15 agents). The validity of the interview findings was confirmed when the researcher's self-review method and member control were applied to the gathered interviews. ABMs have apparent validity if an expert (group of experts) related to the subject confirms the quality of the simulation results by real-world phenomena. This is performed by taking into account outputs such as the trend of area change under different irrigation methods and the trend of economic profit at micro and macro levels, and it is compared with the actual situation of the studied area according to the opinions of experienced experts. To guarantee the reliability of the interviews, convergent interviews were employed. To achieve this, model attributes and input factors—a variety of social and environmental factors—that influence farmers' adjustment to DTIM were first arranged. Next, every environmental and social component is understood to form the ABM model. Finally, a statistical analysis is used to assess the components and policies that have an impact on the outcomes.

The developed ABM model is applied for 100 years at the time step of a half-crop season. The model considers 42 farmer agents. Drip and sprinkler irrigation are two common examples of both traditional and advanced irrigation techniques that are taken into consideration. The sub-model for figuring out the farmers' economic spending was taken into consideration because of how crucial the economic factor is to the farmer's agent decision-making. The price of planting and harvesting crops, the cost of installing irrigation systems, and the cost of fertilizers and seeds, labor costs for manual labor, water pumps, etc., were computed.

3.3. Compilation of the FTA of LU Sub-Basin

The FTA model was created to quantify and evaluate different scenarios of non-DTIM of LU sub-basin. The probability of failure of basic events is estimated quantitatively and qualitatively based on recorded records. After estimating the failure probability of basic events, AND and OR gates are calculated as follows:

$$P = \prod_{i=1}^{n} P_i \quad (4)$$

$$P = 1 - \prod_{i=1}^{n} (1 - P_i) \quad (5)$$

where P is the probability of each basic event, P_i is the value of the failure probability of the ith basic event, i is the counter, and n is the number of input events connected to the gate.

The impact (contribution) of basic events on the main event is calculated as follows:

$$I_x = \frac{\sum U_x}{U_s} \quad (6)$$

where I_x is the importance of the basic event x in creating the main event, $\sum U_x$ is the sum of the error percentages of the cuts in which the event x is present, and U_s shows the probability of the main event. If the failure probability of the main event is satisfactory, the FTA analysis ends. If the FTA analysis is not satisfactory, it is necessary to reduce the failure probability of the main event and take corrective actions.

A total of 18 parameters were identified as the basic event for non-DTIM risk assessment in the LU sub-basin. Table 4 shows the basic events according to their performance type.

Table 4. Basic events of the FTA of LU basin.

No.	Basic Events	Type	No.	Basic Events	Type
1	Drought	Natural	9	Failure to develop guidelines by the government	Operational
2	Flood	Natural	10	Absence of farmer's demands	Operational
3	Small ownership of agricultural land	Operational	11	Lack of adequate training	Operational
4	Lack of financial resources	Operational	12	Lack of control over the irrigation systems management	Operational
5	Lack of government supervision	Operational	13	Lack of irrigation scheduling	Operational
6	Lack of awareness	Operational	14	Conflict of interest	Operational
7	Inappropriate governance	Operational	15	Insufficient knowledge	Operational
8	Reliable water resources	Operational	16	Improper soil management of agricultural lands	Operational

The flowchart of the study process is presented in Figure 5.

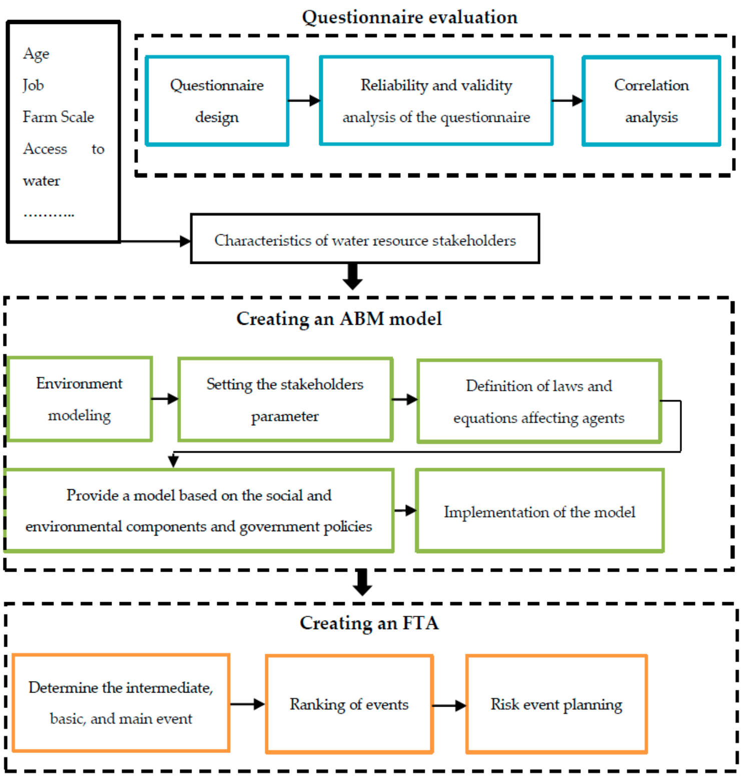


Figure 5. Flowchart of the study process.

4. Results and Discussion

The suggested scenarios, which include 64,800 states, have been combined and run 100 times apiece in the model with 100 time periods to implement the suggested model. By using balanced variance analysis, each of these scenarios was examined. The factors influencing farmers' adaptation to DTIM were examined using balanced variance analysis and Minitab 16.2 software. Tables 5–8 and Figures 6–9 show average WP indicators (SWR, FAE), average propensity threshold (*mean.prop*), and honesty threshold (*mean.honesty*).

Table 5. Balanced variance analysis for *mean.prop*.

Source	DF	SS	MS	F	P
Network-density	2	0.000083	0.000041	1.18	0.308
Random change	3	0.015535	0.005178	147.65	0.000
SWS	2	0.306912	0.153456	4375.59	0.000
Seed-ratio	2	0.000096	0.000048	1.36	0.256
Seed-owner	4	0.000123	0.000031	0.88	0.475
Gov-Subsidy-Policy	3	0.002418	0.000806	22.98	0.000
Inspect-owners	2	0.074007	0.037003	1055.10	0.000
Error	64,781	2.271928	0.000035		
Total	64,799	2.671102			

Note: S = 0.00592207 R–Sq = 14.94% R–Sq(adj) = 14.92%.

Table 6. Balanced variance analysis for *mean.honesty*.

Source	DF	SS	MS	F	P
Network-density	2	9.014	4.507	10,834.69	0.000
Random change	3	0.017	0.006	13.49	0.000
SWS	2	0.032	0.016	38.34	0.000
Seed-ratio	2	0.031	0.015	37.17	0.000
Seed-owner	4	0.001	0.000	0.58	0.677
Gov-Subsidy-Policy	3	0.004	0.001	3.14	0.024
Inspect-owners	2	1164.803	582.401	1,400,027.11	0.000
Error	64,781	26.948	0.000		
Total	64,799	1200.850			

Note: S = 0.0203959 R–Sq = 97.76% R–Sq(adj) = 97.76%.

Table 7. Balanced variance analysis for SWR.

Source	DF	SS	MS	F	P
Network-density	2	0.001113	0.000556	2.23	0.107
Random change	3	0.064029	0.021343	85.61	0.000
SWS	2	0.862558	0.431279	1729.93	0.000
Seed-ratio	2	0.000161	0.00008	0.32	0.725
Seed-owner	4	0.000871	0.000218	0.87	0.479
Gov-Subsidy-Policy	3	0.002044	0.000681	2.73	0.042
Inspect-owners	2	0.718565	0.359282	1441.14	0.000
Error	64,781	16.150154	0.000249		
Total	64,799	17.799494			

Note: S = 0.0157894 R–Sq = 9.27% R–Sq(adj) = 9.24%.

Table 8. Balanced variance analysis for FAE.

Source	DF	SS	MS	F	P
Network-density	2	0.015	0.007	0.32	0.724
Random change	3	744.568	248.189	11046.72	0.000
SWS	2	0.543	0.272	12.09	0.000
Seed-ratio	2	0.177	0.088	3.94	0.020
Seed-owner	4	0.132	0.033	1.47	0.209

Table 8. *Cont.*

Source	DF	SS	MS	F	P
Gov-Subsidy-Policy	3	0.035	0.012	0.51	0.673
Inspect-owners	2	1.972	0.986	43.88	0.000
Error	64,781	1455.451	0.022		
Total	64,799	2202.893			

Note: S = 0.149891 R–Sq = 33.93% R–Sq(adj) = 33.91%.

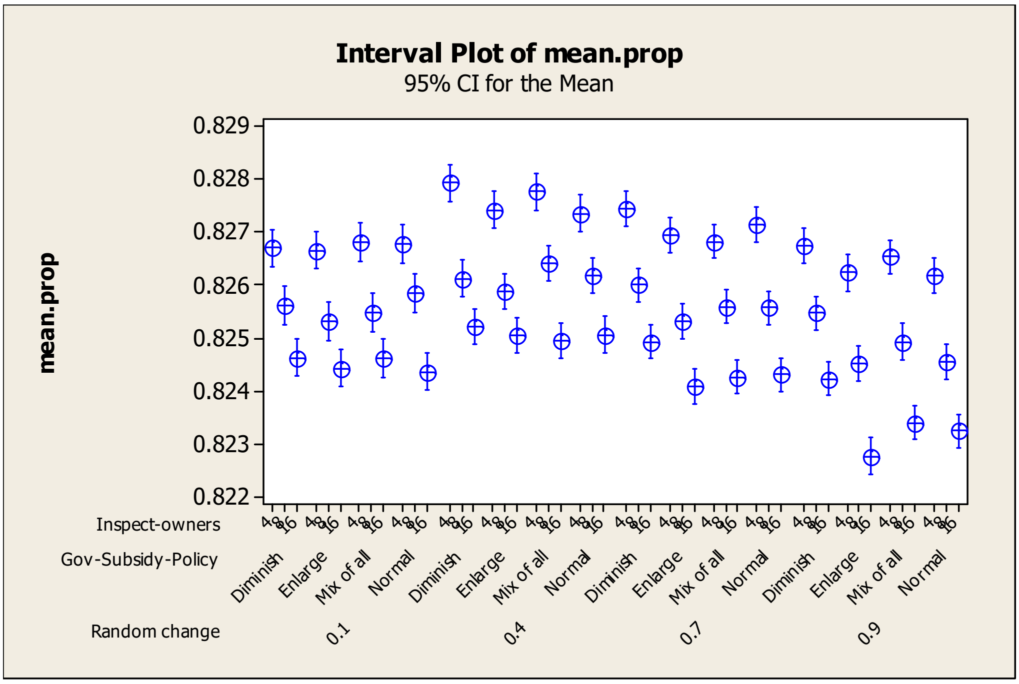


Figure 6. The effect of input indicators on the *mean.prop*.

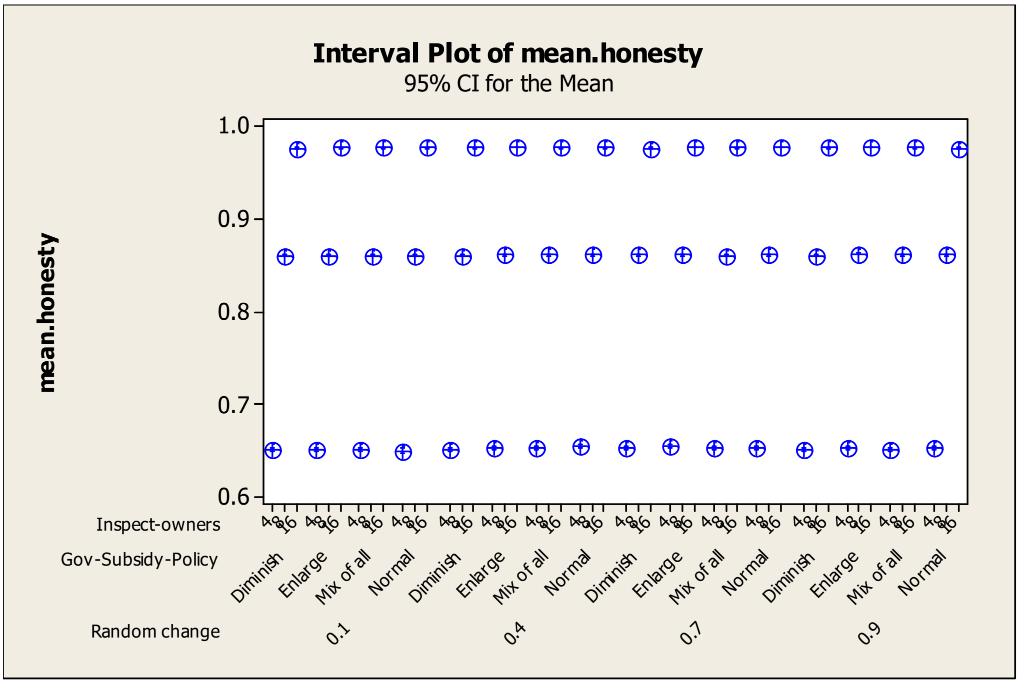


Figure 7. The effect of input indicators on the amount of *mean.honesty*.

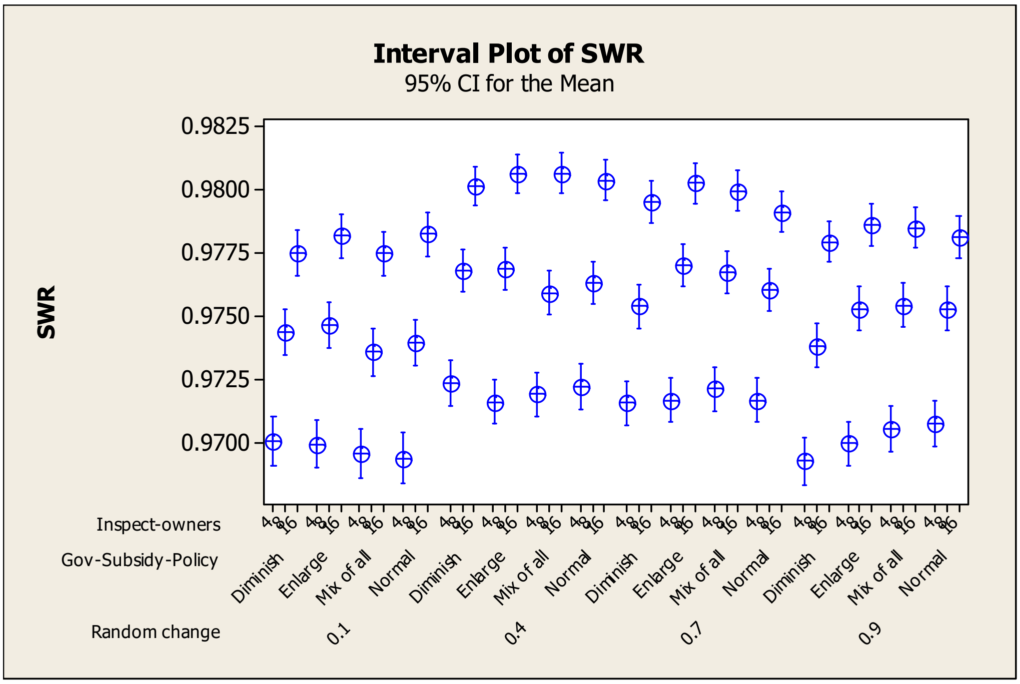


Figure 8. The effect of input parameters on SWR.

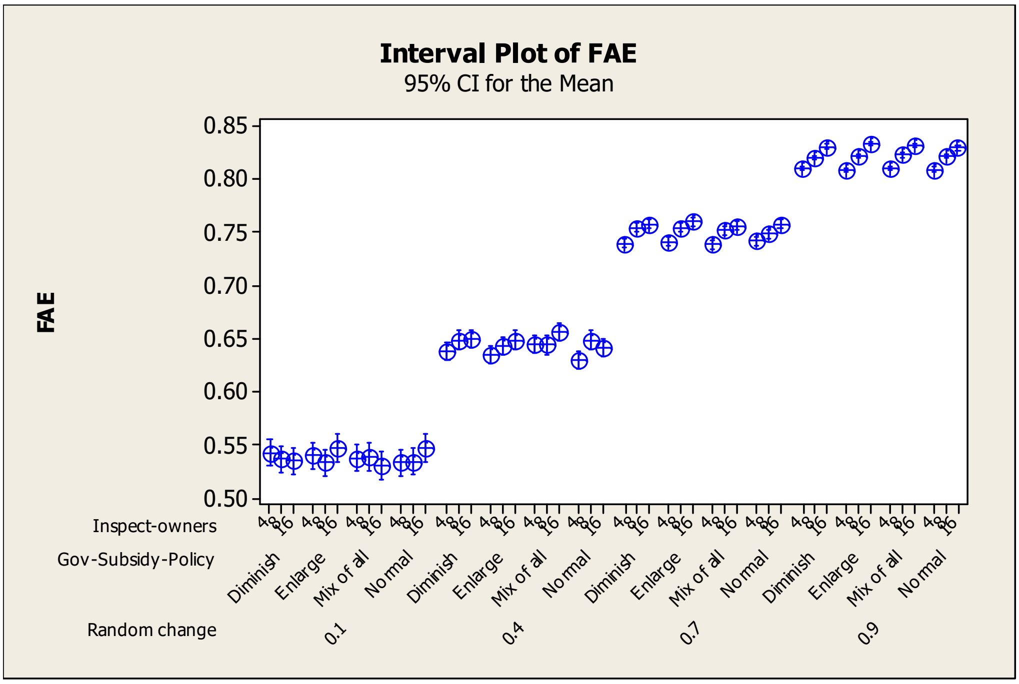


Figure 9. The effect of input indicators on the amount of FAE.

Thus, uncertainty (random change of the system due to climate and agent behavior patterns), SWS, subsidy policy, government supervision, and training are the most effective indicators of the farmer agent's propensity to DTIM (p-value = 0.0 at the confidence level of 95%). The most significant predictors of the farmer agent's inclination to DTIM are SWS, government supervision, and training, with F-values of 4375.59 and 1055.10, respectively. The farmer agent's propensity to DTIM is least affected by the seed-owner and seed-ratio indices. The *mean.prop* index barely changes as a result of the initial population.

As a result, different inputs influence the agents' subjective propensity in the DTIM. The appointment, potential for ideal local management, and involvement of the farmer agent are all facilitated by their involvement in the management of water resources [43–46]. Participation and awareness foster the desire for DTIM. Government subsidies and cost reductions have a significant impact on farmers' adoption of DTIM [47,48].

The most significant parameters on the SWR index are random change (r), SWS, government supervision, and training, with *p*-value = 0.0 at a 95% confidence level. The SWR index is independent of the initial population's seed-ratio, seed-owner, and network-density. The crop yield and WP are greatly influenced by the indicators of SWS, government supervision, and training. The F-values for SWS and government supervision are 1729.93 and 1441.14, respectively. The presence of government supervision and training is crucial for improving WP and taking advantage of government subsidies. This also affects the integrity threshold and the propensity of farmer agents. The effective supervision and management of irrigation systems play a significant role in increasing both the physical and economic WP as well as crop yield, which aligns with the findings of previous studies [49]. Uncertainty, SWS, government supervision, and training are the most effective indicators at the 95% confidence level on FAE (*p*-value = 0.0). Consistent with the findings of the present study, optimal irrigation systems coupled with sufficient government supervision and training will raise FAE and crop yield [50]. The water resource conditions in the LU basin state that the WP can be improved through training and monitoring of the irrigation system [34,51,52]. All inputs and production must be provided continuously, and farmers' representatives must be continuously supersized and trained by the government in the management, maintenance, and operation of field irrigation systems [53].

4.1. Risk of Failure of LU Sub-Basin

In Table 9, the failure probability of the basic events was calculated based on the specific statistics of the LU sub-basin and entered as input into the Cara-FaultTree 4.1. software. In this study, Cara-FaultTree software was used for the complete graphical representation of the overall risk of the basin due to the unique features and simplicity of the environment.

4.2. Measure the Importance of Basic Events

4.2.1. Lack of Accurate Planning in Water Supply and Demand

The average amount of water consumed in the short-term period of the LU basin, in excess of the virtual upper limit of surface water in the agricultural sector, and the amount of surface water consumed in the long-term normal in the agricultural sector are 3600 MCM and 2370 MCM, respectively. The average amount of water consumed in agriculture in the short-term period of the LU basin in excess of the virtual limit of groundwater and the amount of groundwater consumed in agriculture in the long-term in the normal state is 1756 MCM and 1580 MCM, respectively.

The event failure probability value is calculated as follows:

$$\text{P (A24)} = 0.51 \text{ Surface water} \tag{7}$$

$$\text{P (A24)} = 0.11 \text{ Ground water} \tag{8}$$

4.2.2. Unreasonable Economic Value of Water

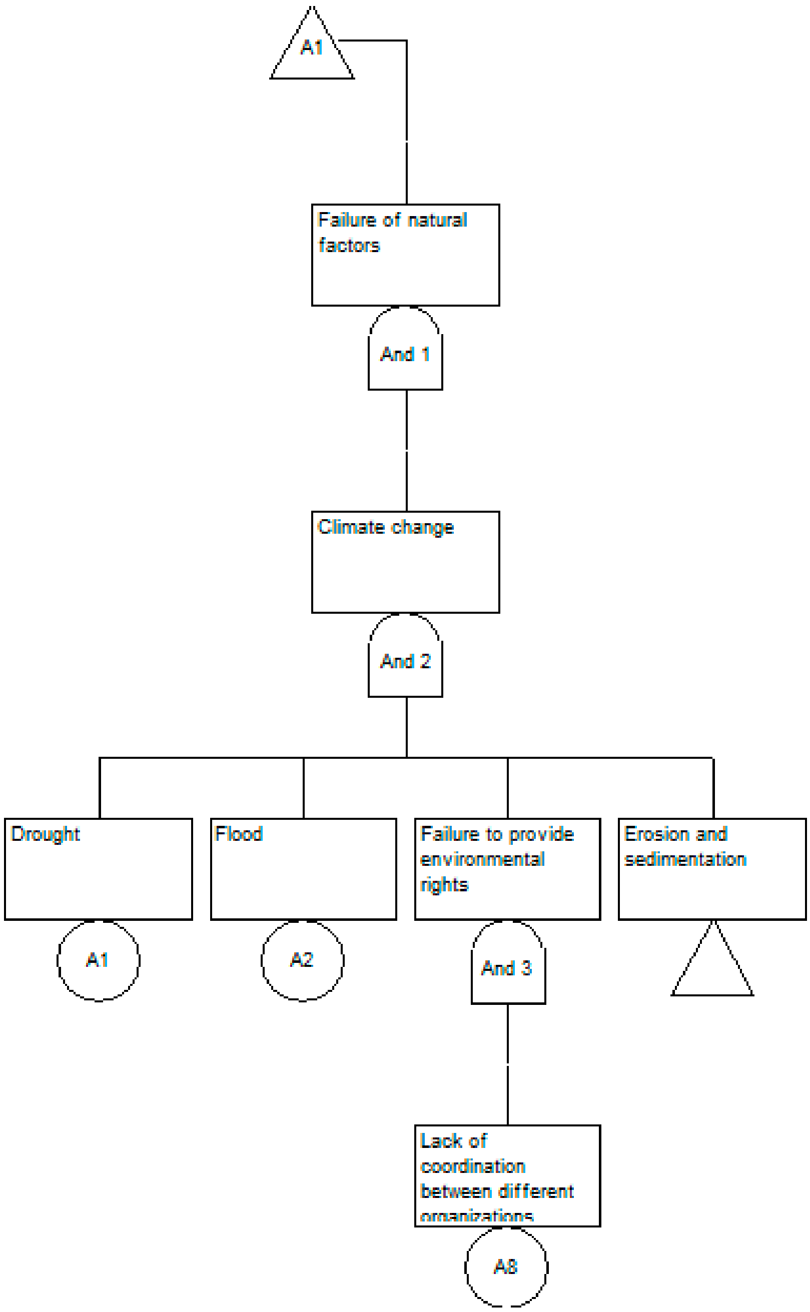
The low economic value of water in the LU basin is caused by the low price of water. The low price of water causes an excessive increase in water in the agricultural sector and leads to economic failure. The probability of an inappropriate water price failure is calculated as follows:

4.2.3. Destructive Water Transfer Systems

Protecting and conserving water in irrigation and drainage networks should be considered one of the cost-effective solutions in water projects. Therefore, the destructive water transfer system may lead to economic failure in the LU basin. The failure caused by this event is similar to the water loss event along the transmission path and is calculated as follows:

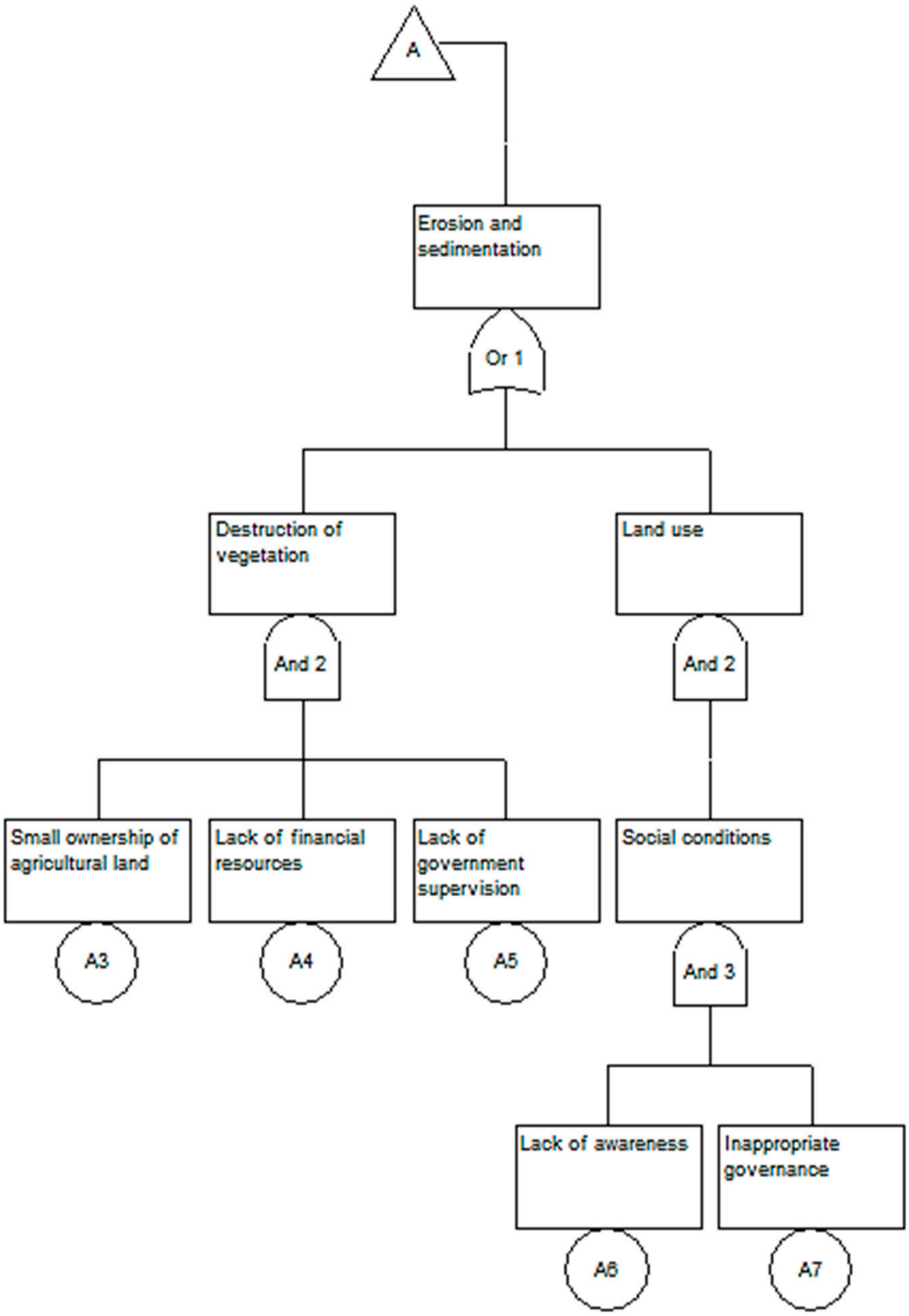
$$P\ (A11) = 0.30 \quad (9)$$

In Figures 10a,b and 11a–d, the probability of the main event is determined based on the probability assigned to the basic events. Indiscriminate water abstraction, dam construction, land-use changes, non-compliance with environmental rights for water, increased CO_2 emissions, low WP, and social and economic conditions are among the important intermediate factors for the failure of the Urmia Lake basin due to human factors. Climate changes (floods, droughts) are important natural factors for reducing water resources in the LU sub-basin.



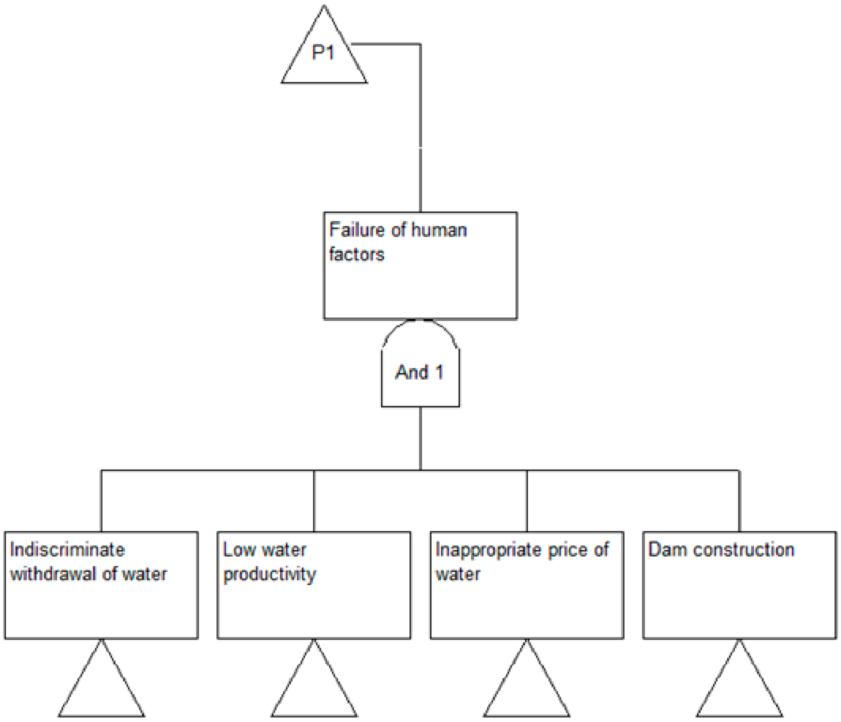
(**a**)

Figure 10. *Cont.*

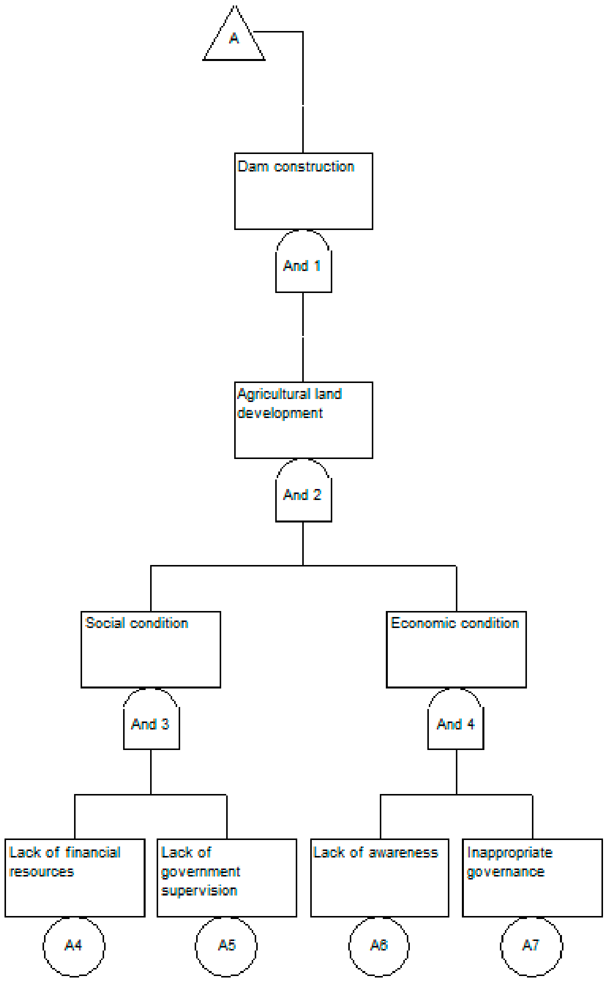


(**b**)

Figure 10. (**a**,**b**) FTA under LU basin failure—caused by natural factors.

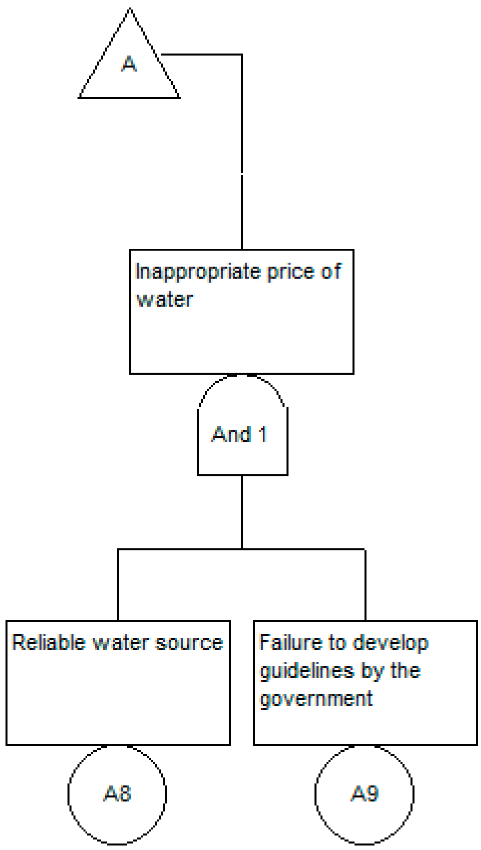


(**a**)

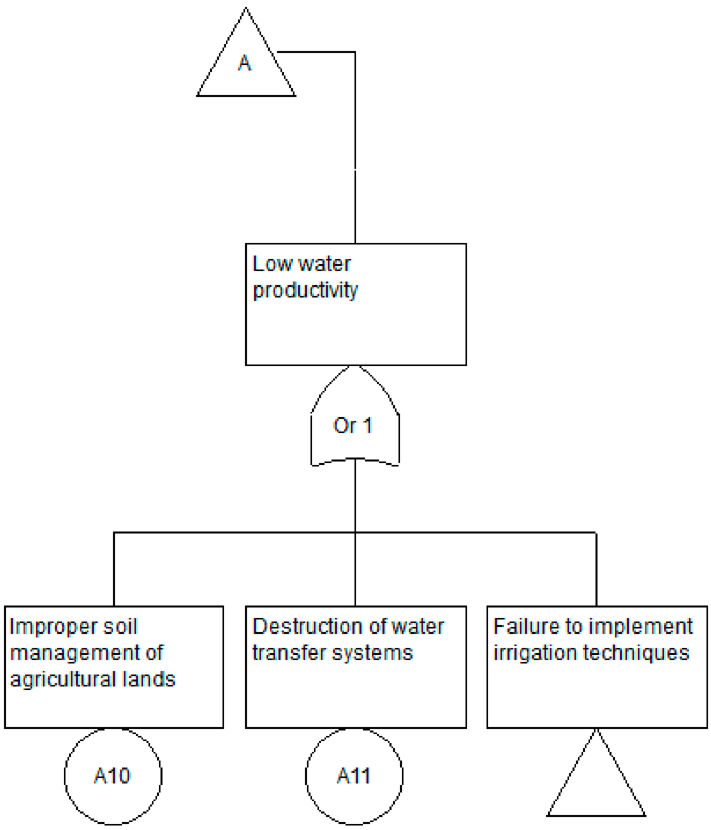


(**b**)

Figure 11. *Cont.*

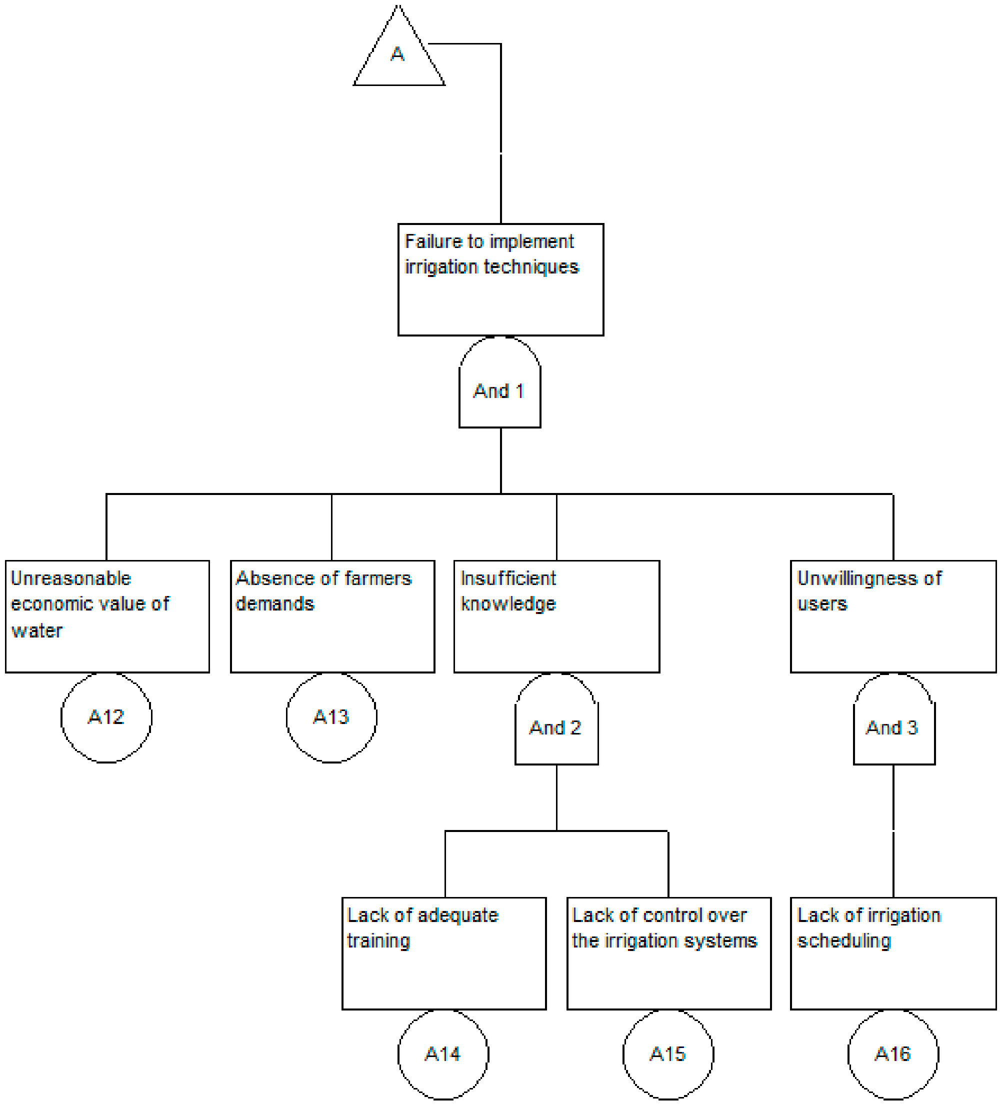


(**c**)



(**d**)

Figure 11. *Cont.*



(**e**)

Figure 11. (**a**–**e**) FTA under LU basin—failure caused by human factors.

In Table 9, the ranking of basic events effective in the non-DTIM of LU sub-basin was calculated.

Table 9. Ranking of basic events effective in non-DTIM in LU sub-basin.

Basic Events	Ix = ∑Ux/Us	Quantitative Rating
CS1 = (A1, A2)	(1/42) × (1/42) = 0.005/0.8 = 0.006	1
CS2 = (A8)	35/42 = 0.83/0.8 = 1.04	7
CS3 = (A3, A4, A5)	(25/42) × (25/42) × (38/42) = 0.32/0.8 = 0.4	2
CS4 = (A6, A7)	(35/42) × (40/42) = 0.79/0.8 = 0.99	6
CS5 = (A8, A9)	(35/42) × (36/42) = 0.71/0.8 = 0.89	5
CS6 = A10	35/42 = 0.83/0.8 = 1.04	8
CS7 = A11	25/42 = 0.60/0.8 = 0.75	4
CS8 = (A3, A12, A13)	(25/42) × (35/42) × (42/42) = 0.50/0.8 = 0.625	3
CS9 = (A14, A15)	(38/42) × (40/42) = 0.86/0.8 = 1.075	9
CS10 = A16	38/42 = 0.9/0.8 = 1.125	10

According to Table 9, the basic events are sorted in descending order by the greatest impact on the vertex event. The higher the value of the Ix index, the more important the basic event is in the vertex event. The results show that the low awareness of the basin residents and the lack of demands of farmers are the most important failure factors in the LU basin, with a failure probability of 0.86 and 0.90, respectively. Finally, the probability of failure of the main event (non-DTIM in the LU sub-basin) was 0.50. The quantity and quality of water resources in the LU can be considered the most important factors affecting the sustainability of its ecological function. However, both factors are influenced by human activities, particularly the increase in cultivated area and the development of irrigation in the upstream sections of this basin. Increasing water use along with the implementation of agricultural development plans will reduce the quantity and quality of water entering the LU basin. In recent years, the lack of environmental protection measures in the LU basin has led to the disappearance of rare species.

In addition, the events of a lack of sufficient training, insufficient knowledge, and management of irrigation systems have a significant impact on the lack of non-DTIM in the LU sub-basin. The participation of users in decision-making and the development of coordination between different organizations in water resources management are the most important parameters in the sustainable management of agricultural water resources. Participatory and centralization events were identified as key components in water resources management, which is consistent with the results of the present study [54–57], Farmers' communities are the first trustees of water resources in the LU sub-basin, which is highly dependent on water resources. The lack of water resources in the LU sub-basin causes the loss of economic activities and disrupts the biological balance. These results are consistent with the studies of [23,58]. These studies also emphasize the participation and role of farmers in the management and exploitation of water resources. Governance and its effectiveness, which correspond to the development and management of surface and underground water resources, were introduced as intermediate events dependent on other events. The results of this study are consistent with the findings of [59,60]. The farming community is the primary manager of water resources in the LU sub-basin, which is highly dependent on water resources. The lack of water resources in the LU sub-basin leads to the loss of economic activities and disrupts the biological balance. These results are consistent with the studies by [58] that emphasize the participation and role of farmers in the management and use of water resources. Governance and its effectiveness corresponding to the development and management of surface and groundwater resources were introduced as intermediate events dependent on other events. The results of this study are consistent with the findings of [59,60].

The government is an influential player in decision-making on LU restoration programs. In addition to government supervision and training, stakeholders must be empowered to implement the prescribed programs (e.g., reducing water consumption) and revitalize LU. However, this local-level approach has not yielded success in structuring the requirements for the implementation of LU restoration programs. In other words, restoring LU is not the concern of stakeholders, and the government is failing to build consensus, achieve user satisfaction and participation, create alternative value for water, and awareness and knowledge of upgrading society and getting to know the real problems and creating solutions for the restoration of LU. Furthermore, farmers, as key beneficiaries, view the restoration of LU as a form of governance and show a desire to achieve this goal. The government's performance in sensitizing the farming community has been weak, and the politically motivated messages tended to play a destructive role. A key factor in the failure was the avoidance of government and stakeholder involvement, as well as inadequate internal and cross-border management in the LU basin caused by centralized legislation, multiple decision-making centers, and inaccurate planning of water supply and demand. The creation of integrated management based on a comprehensive law and plan is the most effective strategy in this area to achieve the sustainable development of the LU basin. Managing the LU basin in an integrated manner that balances regional function and farmers' empowerment can achieve the government's policy objectives.

Due to the lack of "implementation-feedback-learning" mechanisms, the government has not taken advantage of the impending obstacles to learn from and achieve success. In this way, when faced with many problems, instead of finding solutions, it erased them instead of solving them. For example, the strategy to reduce water consumption from dams for use in this sector by 40% was gradually replaced by a 40% reduction in water consumption in the agricultural sector, which has a significantly smaller impact on water supplies than initially expected. Therefore, it is necessary to strengthen and develop educational and promotional activities in the Urmia Lake basin to improve farmers' attitudes and self-efficacy and expand their knowledge and skills in using irrigation systems.

Studies show that there is a positive relationship between extension calls, use of communication channels, social participation, and technical knowledge of farmers and their attitude towards the use of irrigation systems [61,62]. Studies show that there are problems in the LU basin, such as that the government is at the center of the problem, has a technical view, and is satisfied with the cross-sectional results, and that there is no real goal that can be achieved with the government's results consistent with the present study [58,59]. Training farmers in the LU basin about the consequences of lake drying and involving local communities in the restoration process can be successful. To achieve the goals and implement the plans to restore LU, farmers' trust in the government is crucial. Traditional agriculture in the LU basin is not profitable despite the region's high water consumption. Plans to restore LU demonstrate the importance of farmers in the restoration and provide an opportunity for development and sustainable agriculture in the LU basin. By using training tools to improve LU's water resources and revitalize the lake, farmers can contribute to the engagement of surrounding communities. By allocating funds and implementing construction projects and policies, the government has taken measures to revitalize LU. However, to reduce water consumption in LU, experts and advocates must work together to promote local culture, awareness, and engagement. The management and control of the LU basin depend heavily on the residents' awareness of the values of the basin and the threats to its further development [7,59,62]. To prevent the collapse of the LU basin, one of the main objectives is to raise awareness among farmers. To achieve this, the government needs to strengthen its capacity [63].

A similar study concluded that the lack of community perspective in regional planning, the development and lack of codified laws in the basins, the absence of land-use plans, and the lack of sufficient information for the residents of the basin are the most important reasons for social failure. This is consistent with the results of the present study [9].

4.3. Analysis of the Proposed Methods

In socio-ecological systems, there are a variety of complexities, including dynamics, feedback and heterogeneity, and a lack of proper understanding of the complexities in these systems leads to failure in good water governance. However, technical models are needed to understand the behavior of water resources and provide useful information about the current situation. In order to have a correct approach to the process of water governance, a correct understanding of the attitudes, beliefs, and behaviors of the stakeholders is required. One of the approaches that has been widely noticed in recent years for the study of complex systems is the ABM and FTA approaches. These approaches were introduced as effective tools for cooperative management, designing effective strategies, and water resources management policies. By using this approach while modeling the behavior of different stakeholders and the relationships and interactions between them and with the environment and with the dynamic participation of individual, group, and institutional stakeholders in the modeling process, it is possible to make correct decisions with appropriate implementation support. The framework developed in this study is used to understand the characteristics, behaviors, and interactions of effective factors in the process of system changes. In addition, system analysis in such a framework provides a better understanding of the structures of complex systems to support decision-making under conditions of uncertainty in a collaborative process. In the aforementioned cooperative approach, while gaining a more accurate understanding of the components, patterns, and connections of the studied system by attracting the cooperation and willingness of the stakeholders, better solutions can be achieved in the decision-making process. Implementing the developed framework in more case studies with different conditions can lead to the production of more comprehensive guidelines for issues such as cooperative management at the country level while processing the process of stakeholder analysis. This issue will be fruitful in defining the procedures of water governance according to different social, economic, and environmental conditions in the wide area of Iran. Although the majority of water consumption in the catchment area of Lake Urmia is related to the agricultural sector, to complete the developed framework, especially in the areas where the drinking and industrial sectors are influential consumers, their goals, characteristics, and behavioral patterns were evaluated. The relevant factors and interactions should be added to the model.

One of the problems and complexities in modeling social systems is the existence of human agents who potentially have irrational behaviors and complex psychological characteristics—in other words, factors that make quantification, calibration, and validation difficult. Although this issue is a main source of problems in providing simulation outputs, in most cases, the only model that can challenge these conditions is the ABM and FTA models. To develop the presented framework, the integrated exploitation model of surface and underground water can be considered as the environment of the ABM model. The use of more accurate agricultural economic models can have a significant effect in matching the results with the existing reality. In this study, the effects of climate change in the future have been ignored and only sensitivity analysis on climate change has been considered. In future research, the effect of different scenarios of climate change in the process of changing the behavior of the agents and policy-making according to these changes can be considered.

5. Conclusions

The problems of the LU basin are related to extensive and complex factors, which require a comprehensive approach to identify failure factors at the basin level. The search for a general index that covers the general risks of the LU basin to various aspects of water resource scarcity and environmental, economic, and social situations will lead to sufficient knowledge and mastery. Using the ABM model as a basis, farmers' social interactions and financial gains from government subsidies could be simulated. The purpose of the FTA was to set out the sequence of events that could lead to the depletion of water resources in the LU basin. The findings demonstrated that, at a 95% confidence level, random change, SWS, subsidy policy, and government supervision and training are the most reliable measures of farmers' willingness and participation in adapting to the DTIM. A key factor in raising WP is government supervision and training. According to the basic event ranking, the main reasons for failures in the LU basin are low awareness among residents of the basin and lack of demands from farmers, with failure probabilities of 0.86 and 0.90, respectively. In the end, the main event had a probability of failure of 0.50. The inadequate social structure at LU is the main cause of the existing catastrophic situation. The key to maximizing the use of the LU basin's water resources is to demand awareness and participation of the basin residents. Other sub-basins can benefit from an improved situation by mimicking the fault tree structure of the LU basin. As a suggestion for future direction, the methodology used in this study should be extended to other sub-basins of LU over different periods, considering how productivity and development plans may alter the demonstrated risk index.

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