Deduction of sudden rainstorm scenarios: Integrating decision makers' emotions, dynamic Bayesian network and DS evidence theory

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Deduction of sudden rainstorm scenarios: Integrating decision makers' emotions, dynamic Bayesian network and DS evidence theory

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Abstract: Event scenarios serve as the basis for emergency decision-making after sudden disasters, and the accuracy of scenario deduction directly determines the effectiveness of emergency management implementation. On July 20, 2021 an exceptionally heavy rainstorm disaster occurred in Zhengzhou, Henan Province, China causing serious urban waterlogging, river floods, flash floods and landslides, and resulting in major casualties and property losses:14.79 million people affected, 398 people killed or missing (380 people in Zhengzhou) and a direct economic loss of 120.06 billion RMB. In order to investigate the complex evolution process of this disaster, a dynamic Bayesian network, evidence theory and emotion update mechanism are integrated to develop an efficient and effective scenario deduction model, with an emphasis on combining subjective and objective factors. In this model, more attention is given to subjective factors such as decision makers' emotions. The elements of scenario deduction are classified into the situation status, meteorological factor, emergency activities, decision makers' emotions and emergency goals, the coupling relationship between the elements are comprehensively analyzed, and the influence of these elements on the evolution mechanism of the rainstorm disaster is investigated, so as to facilitate targeted emergency management measures for the rescue operations. The empirical results show that the proposed dynamic Bayesian network can effectively simulate the dynamic change process of scenario deduction, the improved Dempster-Shafer (DS) evidence theory can reduce the subjectivity of the model in dealing with the uncertainty of the evolution process, and the emotion update mechanism can adequately quantify and decrease the influence caused by the emotional changes of decision-makers. The model may better replicate actual events, and it may apply to the scenario deduction of other disasters, making an impact on the study of sudden catastrophes.

Keyword: dynamic Bayesian Network, Scenario Deduction, Scenario Element, Improved DS Evidence Theory, Sentiment Update Mechanism

1. Introduction

Major public emergencies such as earthquakes, floods, terrorist attacks and infectious diseases are occurring more and more frequently around the world. These unconventional events damage the security and stability, threaten human health and life, and cause significant impacts on global economic development. According to incomplete statistics, In the past 40 years, the heavy and natural disasters occurred more than 40 times in China (Zhou et al. 2015), and human tragedies have been staged at an average frequency of at least twice a year. In order to effectively respond to such events, China has successively promulgated and implemented emergency plans for various kinds of disasters, e.g. “People's Republic of China Flood prevention” and "Overall Emergency Plan for National Urban Public Incidents”. In view of the characteristics of major natural disasters including low frequency and high harm, long impact cycle, wide spread, and often cascading disasters, a series of reliable and effective emergency response plans have been approved by the country. Accordingly, many research supports are required to implement these preventative and rescue, and it is determined that the emergency disaster scenario deduction is a core field of emergency managements. Such a scenario deduction system is critical for optimizing the utility value of emergency management implementation. Therefore, in recent years, scholars in the field of scenario deduction have contributed widely through their researches.

Hallegatte et al. (2016) studied the impact of climate change on future hazard amplitudes and probabilities by quantifying climate change. Li et al. (2015) analyzed the evolution of the secondary disaster dammed lake event caused by the earthquake through system dynamics simulation. Barredo and Engelen (2010) made progress towards exploring the variation and growth in exposure using a combined model of flood risk and land use. Robioson et al. (2018) investigated the relationship between the scenario unit and the intensity of destruction in the Nepal earthquake, and provided a reference for the formulation of emergency plans. Rawluk, Ford and Williams (2018) proposed a scenario planning model that considers the value of citizens in response to the Australian forest fire incident, making the scenario management more humane. Wang et al. (2021) adopted evidence theory and meta-model studied the scenario deduction of urban flood disasters. Li, Chen and Liu (2019) developed a new method based on ontology cluster for the evolution reasoning of emergency scenarios, and extended the sematic web rule language to realize scenario deduction, which can apply Bayesian network to perform conditional probability reasoning.
However, existing studies on emergency scenario deduction insufficiently considered the influence of subjective factors in evolution of the development of events， for example, Zhang, Hao and Zhang (2020), Qie and Rong (2020), Xu et al.(2022), Song et al. (2022), etc, only based on the four factors of the situational state, emergency objectives, emergency response measures, and external environmental impact to carry out scenario deduction of sudden disasters. For sudden natural disasters, uncertainty is one of the main characteristics, but there is little research on how to quantify the subjective factors that are inevitable in dealing with uncertain events. Hence, this existing gap in research on the emergency scenario deduction models becomes an imminent issue to be probed. Thankfully, the Dempster-Shafer (DS) evidence theory provides a technique tool to deal with uncertainty due to subject bias in decision making, and the Dempster Rule of Combination has been utilized to decrease the effect of biasness in the present study.

Further, this paper takes the coupling relationship between the evolution of the "7.20" heavy rainstorm scenario in Henan and emergency management measures as a breakthrough point, condensing the key situational units in the disaster, and analyzes the scenario status, meteorological factor, emergency activities, decision-makers emotions, and emergency goals. These elements are the main nodes in the dynamic Bayesian network. The node probability does not directly depend on the expert setting, but mainly uses fuzzy sets and improved DS evidence theory to obtain the prior probability and conditional probability of the node. We employ the emotion update mechanism to quantitative research on subjective factors in emergency management, comprehensively analyze the influence of subjective and objective factors on the evolution mechanism of rainstorm disasters, construct a universal dynamic deduction model, enhance application value of the research.

2. Construction of sudden rainstorm scenario based on dynamic Bayesian network

The dynamic Bayesian network is an extension of the Bayesian network in the time dimension. Based on the dynamic Bayesian network, a scenario deduction model for sudden rainstorms can be constructed, which can not only accurately locate the evolution path of the scenario, but also effectively solve the evolution of the emergency scenario.

In this paper, the "7.20" Henan Zhengzhou Extraordinary heavy rainstorm is used as an example to carry out a scenario deduction. The basic steps are: 1) based on the actual situation of this heavy rain and similar cases, determine the key scenario elements of the event; 2) to synthesize previous researches on the scenario relationship, the relationship between the key scenario elements by a dynamic Bayesian network; 3) in order to ensure the matching of node probability with the actual situation, the improved evidence theory is employed to integrate the multivariate uncertainty information of seven experts, and then the prior probability, conditional probability and state probability of node variables are calculated， which in applications describes dynamical updates of the scenario.

2.1 Event Overview

On July 20, 2021 an exceptionally heavy rainstorm disaster occurred in Zhengzhou, Henan Province, China causing serious urban waterlogging, river floods, flash floods and landslides, and resulting in major casualties and property losses. After the rainstorm, the national and local governments have actively taken measures, however, the amount of water is still increasing, and the development of the rainstorm event and the emergency measures taken by the government are shown in Figure 1.

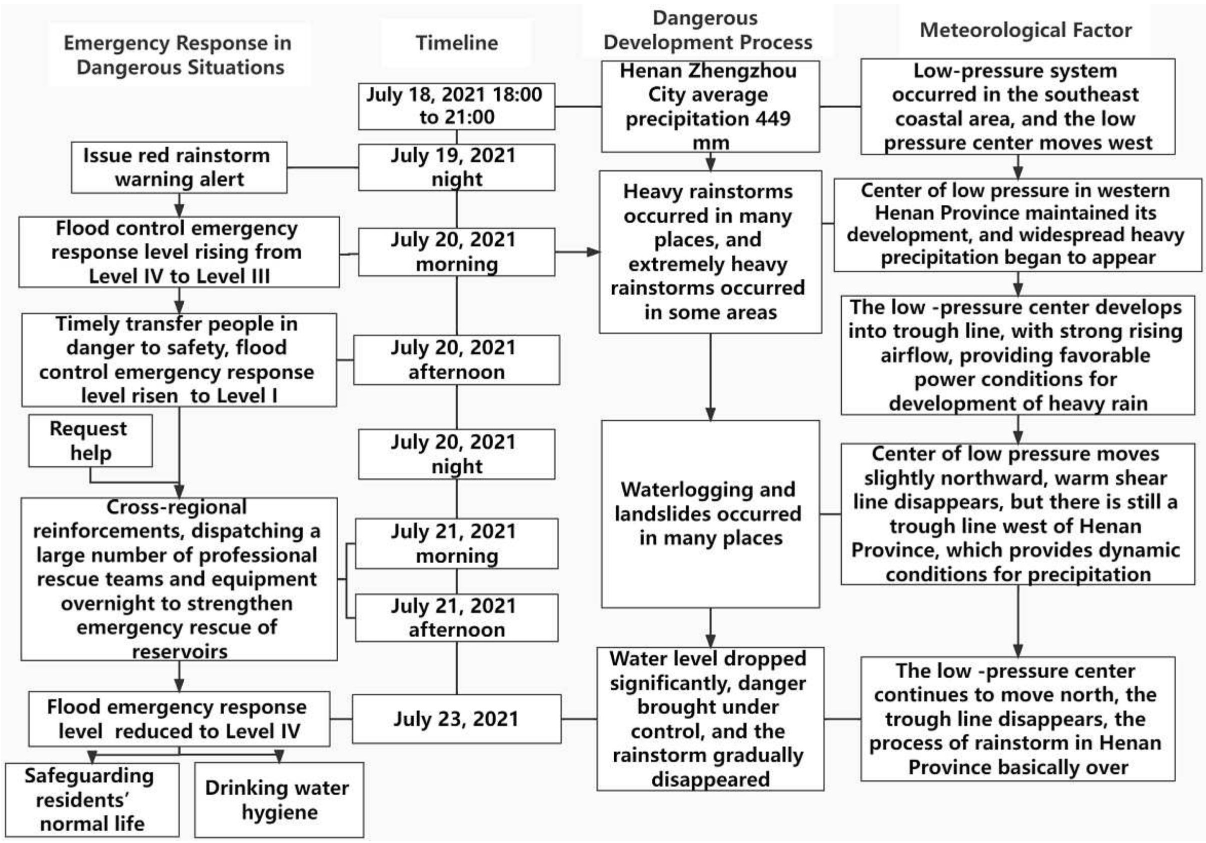

Figure 1. "7.20" heavy rainstorm event process and emergency response

2.2 Scenario element determination

Defining the scenario elements is the basis and premise of scenario deduction. Scholars in different fields have different ways dividing the scenario elements of emergencies (Zhang, Feng 2020). In the "7.20" heavy rainstorm event, different emergency response activities such as those conducted by the emergency rescue department and the Henan Meteorological Bureau, the emotional preferences of all subjective factors in the emergency activities, and the evolution of the event itself affected the development direction of the event.

Therefore, four elements of scenario state (S), meteorological factor (M), emergency action (A), decision maker's emotion (E) and emergency target (T) are selected as the knowledge elements of the "7·20" rainstorm disaster scenario. Since the government emergency management has the greatest effect on reducing the number of casualties and property losses (Liu et al. 2016), according to the actual situation of the "7.20" heavy rainstorm event and the emergency activities of various governmental departments, we will define the different developments of events as different scenarios, and scenario deduction is used to analyze the possible scenario elements in the development process and the degree of correlation between them, so as to facilitate timely adjustments to emergency management measures. The specific scenario description is as follows.

(1) After analyzing the causes of the heavy rain in Henan, the Central Meteorological Observatory concluded that the atmospheric circulation situation was stable, the terrain precipitation effect was significant, and the convective "train effect" was obvious (M1), which caused the rainstorm, and then the precipitation intensity increased and the maintenance time was extended, resulting in extreme precipitation in the local area, that is, the initial scenario of the event S1. In response to scenario S1, the government launched a flood prevention emergency plan, organized an emergency rescue team to garrison the key safety points, increased the intensity of inspection (A1) and other measures, if the response measures are effective, it will not cause panic among the people, ensure the normal life of the people and be prepared to deal with heavy rainstorms (T1). Because extreme weather did not improve in a short period of time and the government did not make timely emergency measures, the scenario evolved into S2.

(2) As the low-pressure center in western Henan Province continued to develop, large-scale heavy precipitation (M2) began to appear. The government has raised the emergency response level of flood control from Level IV to Level III, ordered each household to repair the house, restricted the travel of non-essential personnel, and cleaned the water outlet (A2) in time. If the response measures are effective (T2), will improve for scenario S3. If the response is not timely or appropriate in some aspects, the surface water will not be discharged in time. Coupled with the development of a trough line in the low-pressure center in western Henan Province, there is a strong updraft (M3) that worsens the scenario to S4, . The center of the low pressure moves slightly northward, and the warm shear line disappears, but there is still a groove line west of Henan Province (M4), finally triggering scenario S6.

(3) For the deteriorated scenario S4, the government and relevant governmental offices should strengthen inspections on rivers, reservoirs, geological disasters, urban infrastructure, etc., and force all factories with hidden dangers (such as enterprises that may enter water and enterprises with hot furnaces) to stop work and stop production (A4).

If the government's emergency measures are appropriate and all levels of society actively cooperate with the governmental instructions (T5), secondary disasters, namely Scenario S5, will not be triggered, and the normal operation of emergency infrastructure can also be guaranteed (T4). The best evolution direction is the Occurrence Scenario S9.

(4) In response to small floods caused by heavy rain (S6), the government and relevant departments have arranged for professionals to provide on-site guidance on reservoir dangers, excavate drainage channels as soon as possible to lower the water level, add hydrological stations, and strengthen supervision and early warning (A6), etc. If the emergency management is effective, it can ensure that the danger of the reservoir is controlled and the number of casualties is reduced (T6). Otherwise, Scenario S7 will be triggered. At this time, the government must start a wider drainage project, expand the emergency drainage channel, transfer personnel from dangerous areas, increase emergency equipment and medical team (A7), etc. This can strive to control the number of casualties and property losses in the shortest possible time.

(5) The low-pressure 低气压 center in Henan Province continued to move north, and the trough line disappeared (M5), and the water in the ground area in some areas was significantly reduced. The gradual disappearance of floods is scenario S10, and there is still a risk of landslides in areas close to the mountains, which is scenario S8.

If the emergency department accelerates the transfer of personnel in the disaster area and increases high-tech rescue equipment (A8), under the premise of timely supply of medical supplies, search and rescue efficiency would be boosted, and the number of casualties does not increase (T8), heavy rainfall was also nearing completion, and the scenario was finally completely controlled, and the heavy rain disappeared, known as scenario S11.

During the implementation of emergency activities, there will be many subjective factors that affect the success of emergency goals and the evolution of scenarios, that is, the knowledge element (E1, E2, ..., E8) of decision makers' emotional preference considered in this paper, which includes The emotions of the government officials when formulating measures, emotions of the public towards sudden rainstorms, emotions of leaders directing emergency activities on the spot, emotions of the implementers of emergency activities, etc. Studies have pointed out that the decision-making process can be affected by both expected emotions and immediate emotions (Loewenstein et al.2001). Hence, this paper collectively refers to all subjective factors as decision-makers emotion, as one of the situational elements, to analyze its impact on the evolution of the event situation. In order to clearly illustrate the research ideas of this paper, a situational knowledge meta-structure composed of 11 situational states, 5 meteorological factors, 8 emergency activities, 8 emergency goals and 8 decision-maker emotions is constructed. We summarize these concepts in Table 1.

Table 1. Scenario element information table

Scenario status	Decision maker sentiment	Meteorological factors	Emergency activities	Contingency targets
S1 rainstorm	**E1** optimistic/ pessimistic	**M1** low-pressure system appeared along the southeast coast, the center of low-pressure	**A1** activate the flood prevention emergency plan; organize emergency rescue teams to garrison key safety points and	**T1** the normal living order of the people, and make all the preparations for the deterioration of heavy rains

		moved westward	increase the intensity of inspections; each site is equippe with sufficient special flood prevention materials and equipment	
S2 Precipitation continues to increase	**E2** optimistic/ pessimistic	**M2** low-pressure center in the western part of Henan Province maintained development, and the western and central parts were controlled by the system, and large-scale heavy precipitation began to appear	**A2** improve the level of flood prevention emergency response; organize the maintenance of houses; restrict people's travel; clean up the water outlet in time; and do a good job in popularizing flood prevention emergency measures	**T2** ensure that all the water outlets are unblocked, and all the rest are protected at home except for the necessary travel personnel
S3 the ground area is reduced by water	**E3** optimistic/ pessimistic	/	**A3** vigorous dredging of drainag channels, all personnel involved flood control	**T3** water in the ground area is accelerating and decreasing
		S9 all stagnant water is discharged		
S4 the weather continued to deteriorate and heavy rainstorms occurred	**E4** optimistic/ pessimistic	**M3** the low-pressure center developed into a trough line with strong updraft, providing favorable dynamic conditions for the development of heavy rain	**A4** strengthen inspections and inspections of rivers, reservoirs, geological disasters, urban infrastructure, etc.; force all factories with hidden dangers (enterprises that may have water inlets and hot furnaces, etc.) to stop work and production	**T4** ensure that all hidden factories are shut down, avoid other accidents such as explosions, and ensure that all infrastructure is operating normally
S5 secondary disasters occur	**E4** optimistic/ pessimistic	/	**A5** enterprises continue to close down and add infrastructure	**T5** the whole society is subordinate to the unified organization of the state
		S9 all stagnant water is discharged		
S6 heavy rains trigger small floods	**E6** optimistic/ pessimistic	**M4** the center of the low pressure moves slightly northward, and the warm shear line disappears, but a trough line still exists west of Henan Province	A6 arrange professional personnel to guide the dangerous situation of the reservoir on the spot; excavate the drainage trough as soon as possible to reduce the water level, add hydrological stations,	**T6** ensures reservoir danger is under control and casualties continue to decrease

			and strengthen supervision and early warning	
S7 heavy rains triggered large flooding	**E7** optimistic pessimistic		**A7** extensive excavation of emergency drainage channels; transfer of personnel in hazardous areas; and increase of emergency equipment and medical teams	**T7** ensure that the water level is controlled, all personnel in the danger area are evacuated, and there is no increase in the number of casualties
			S10 the flood disappeared	
S8 floods trigger landslides	**E8** optimistic/ pessimistic	**M4** the center of the low pressure moves slightly northward, and the warm shear line disappears, but a trough line still exists west of Henan Province	**A8** accelerate the transfer of personnel from disaster areas, add high-tech rescue equipment	**T8** the supply of medical supplies is timely, the efficiency of search and rescue is guaranteed, and the number of casualties is no longer increasing
S11 the danger was completely controlled and the rainstorm disappeared				

2.3 Build a scenario deduction path

After determining the scenario elements, it should focus on the actual situation of the rainstorm event, learn from scholars' research on similar cases, and use directed edges to represent the relationship between scenario elements to construct an initial dynamic Bayesian network for scenario deduction. In the evolution of sudden rainstorm disasters, the development direction of the event is often affected by the interaction between various scenario units. Each development state has a "natural extreme value". The appearance of the extreme value means that one scenario is about to end, and the next scenarios begin to form. For all scenarios (S1, S2, ..., S8) in the evolution of the rainstorm event, the effect of accompanying meteorological factors (M1, M2, ..., M5), the mood of decision makers (E1, E2, ..., E8), and emergency activities (A1, A2, ..., A8). The degree of effectiveness of implementation determines the degree to which emergency objectives (T1, T2, ..., T8) are achieved, thus producing varying degrees of destructive effects on the current scenario, directly intervening and controlling the evolution of the next scenario. At the same time, the emotions of decision makers (E1, E2, ..., E8), emergency goals of the previous scenario (T1, T2, ..., T8) and context itself (S1, S2, ..., S8) are affected. Afterwards, it will in turn provide feedback on emergency activities (A1, A2, ..., A8). All scenarios are generated from this, and the dynamic Bayesian scenario deduction path diagram of the event is shown in Figure 2. In Figure 2, due to the rapid development of torrential rain, it is difficult to control, and emergency resources cannot be supplied in time in the short term. As a result, some emergency rescue activities often cannot be effectively controlled the deterioration of the situation, leading to two possible evolution paths of optimistic and pessimistic accident scenarios.

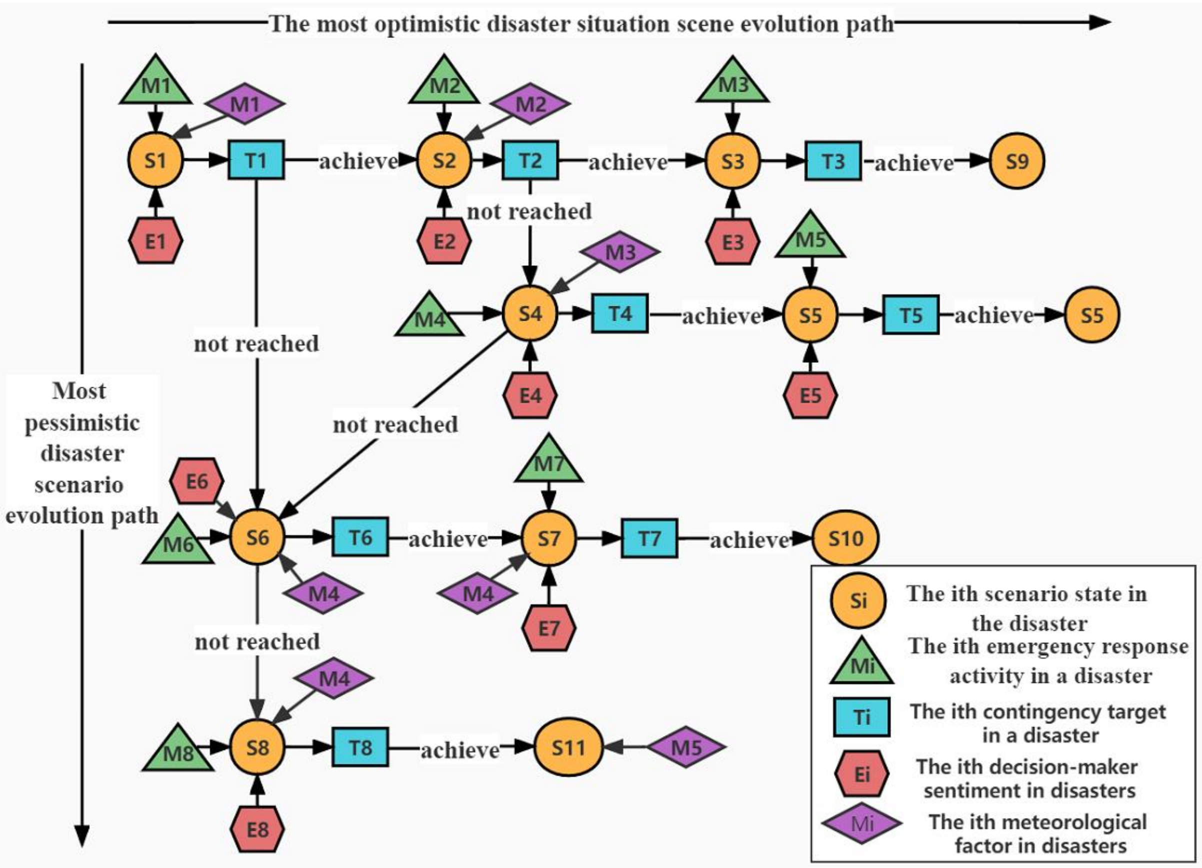

Figure 2. Schematic diagram of the dynamic Bayesian scenario deduction path for the "7.20" heavy rainstorm event

3. Scenario probability calculation and deduction

3.1 Determining probabilities using the emotional renewal mechanism probability

Compared with decision-making in general scenarios, decision-making in emergencies will inevitably be affected by personal emotions, external public opinion, evolution of disaster situations, etc. Hence, the impact of optimistic or pessimistic decision-making on scenario evolution is crucial. Accordingly, the consideration of the dynamic changes of decision makers' emotions cannot be ignored. Therefore, all subjective factors in heavy rain events are collectively referred to as decision makers' emotions (E1, E2, ..., E8), and they are analyzed as one of the elements of heavy rain scenarios. Its relationship with other situational units establishes an emotion update mechanism to dynamically adjust the emotional (E) probability of decision makers. Taking the emotional changes of decision makers as the breakthrough point, the dynamic reference point ($\overline{L}_1^i$、$\overline{L}_2^i$) under the influence of emotions is determined according to the degree of loss caused by the scenario (casualties and property damage are mainly considered in the article). We then calculate the profit and loss value of the current scenario loss relative to the reference point （t_{1j}^i、t_{2j}^i）,obtain the current scenario value from the profit and loss value, and compute the casualty and property loss scenario value （v_{1j}^i、v_{2j}^i） according to different weights to get the comprehensive value of the scene (v_j^i). Next, the scenario value evaluation value ($\overline{eva}^i$) for the current stage is calculated using the standard evaluation values obtained from the original data (eva_j^i). Finally, the emotional value of the next stage

(em^{i+1}) is obtained by the functional relationship between the sentiment value of the current stage (em^{i}) and the evaluation value of the situational value ($\overline{eva}^{i}$). The specific calculation steps are as follows.
First, referring to the method of determining budget levels in the literature (Li et al. 2017), an $\emptyset$ budget level for losses caused by sudden rainstorms is proposed. Based on Formula (1), the dynamic reference points for casualties and property losses in scenario S1 are calculated respectively. When facing with the decision-making problem of emergencies, because it is difficult to obtain all the current information of the event required for decision-making in a relatively short period of time, this paper uses the form of intuitionistic fuzzy numbers to represent the casualties, and casualties. Information on property damage is provided in Table 2.

$$\bar{L}_q^i \begin{cases} \min_j L_{qj}^i + \frac{2\emptyset-1}{2\emptyset}(\max_j L_{qj}^i - \min_j L_{qj}^i), em^i < \frac{1}{\emptyset}; \\ \min_j L_{qj}^i + \frac{2\emptyset-3}{2\emptyset}(\max_j L_{qj}^i - \min_j L_{qj}^i), \frac{1}{\emptyset} \le em^i < \frac{2}{\emptyset}; \\ \cdots \\ \min_j L_{qj}^i + \frac{3}{2\emptyset}(\max_j L_{qj}^i - \min_j L_{qj}^i), \frac{\emptyset-2}{\emptyset} \le em^i < \frac{\emptyset-1}{\emptyset}; \\ \min_j L_{qj}^i + \frac{1}{2\emptyset}(\max_j L_{qj}^i - \min_j L_{qj}^i), \frac{\emptyset-1}{\emptyset} \le em^i; \end{cases} \quad (1)$$

Among them, $\bar{L}_q^i (q = 1,2)$ represents the dynamic reference point of casualties and property losses in Scenario S1, i represents the ith stage in the evolution of contingencies.

Table 2. Information on casualties and property damage in the "7.20" heavy rainstorm event

scenarios	Casualties/person		Property damage / 100 million yuan	
	The number intervals	The corresponding intuitive fuzzy numbe	The number intervals	The corresponding intuitive fuzzy numbe
S1	[2,4]	[0.995,0.000]	[1,5]	[0.997,0]
S2	[5,10]	[0.980,0.008]	[10,20]	[0.987,0.006]
S4	[11,30]	[0.930,0.023]	[30,100]	[0.934,0.019]
S6	[31,80]	[0.804,0.073]	[150,400]	[0.734,0.100]
S7	[81,180]	[0.553,0.198]	[500,800]	[0.467,0.333]
S8	[181,400]	[0.000,0.450]	[900,1500]	[0.000`,0.600]

Then, according to the intuitionistic fuzzy number and dynamic reference point in Table 4, two kinds of profit and loss values of S1 are obtained. The formula is

$$t_{1j}^i = D(\bar{L}_1^i, l_{1j}^i), t_{2j}^i = D(\bar{L}_2^i, l_{2j}^i) \quad (2)$$

In the formula, $l_{qj}^i (q = 1,2)$ represents the intuitionistic fuzzy numbers （l_{1j}^i、l_{2j}^i） corresponding to the number of casualties and property losses in scenario Si, $D(a, b)$ represents the distance between the intuitionistic fuzzy numbers a and b. If $\mathrm{a} = (\mu_1, \upsilon_1), \mathrm{b} = (\mu_2, \upsilon_2)$

$$D(a, b) = \left(1 - max(L, H), \quad min(L.H)\right) \quad (3)$$

In the formula, $L = min(\mu_1, \mu_2)/max(\mu_1, \mu_2), H = min(1 - \upsilon_1, 1 - \upsilon_1)/max(1 - \upsilon, 1 - \upsilon_1)$.

Then the foreground values of $\bar{l}_{1j}^i$ and $\bar{l}_{2j}^i$ caused by scenario S1 are

$$v_{1j}^i = \begin{cases} {t_{1j}^i}^{\alpha}, \bar{L}_1^i > l_{1j}^i; \\ -\lambda(t_{1j}^i)^{\beta}, \bar{L}_1^i \le l_{1j}^i. \end{cases}$$

$$v_{2j}^i = \begin{cases} {t_{2j}^i}^{\alpha}, \bar{L}_2^i > l_{2j}^i; \\ -\lambda(t_{2j}^i)^{\beta}, \bar{L}_2^i \le l_{2j}^i. \end{cases} \qquad (4)$$

Then we fuse the two foreground values to get the comprehensive value v_j^i of the scenario S1:

$$v_j^i = \sum_{q=1}^{2} \eta_q v_{qj}^i \,; i = 1,2,\ldots,n, j = 1,2,\ldots,k. \qquad (5)$$

Calculated according to the comprehensive value, the evaluation value of scenario S1 is

$$\overline{eva}^i = \frac{1}{k}\sum_{j=1}^{k} eva_j^i \,, i = 1,2,\ldots,n. \qquad (6)$$

In the formula, $eva_j^i = (v_j^i - \min_j v_j^i)/(\max_j v_j^i - \min_j v_j^i), i = 1,2,\ldots,n, j = 1,2,\ldots,k.$

Finally, after judging the probability of the current scenario value evaluation value ($\overline{eva}^i$) and the standard evaluation value (eva_j^i), the sentiment value of the next stage (em^{i+1}) is calculated. If $em^{i+1} > em^i$, it indicates that the mood of the decision maker is more optimistic in the next stage, and by taking this value as an optimistic probability in the E2 prior probability, we obtain the corresponding pessimistic probability using $p = 1 - em^{i+1}$, where

$$em^{i+1} = \begin{cases} em^i + \theta|S(\overline{eva}^i)|, p(\overline{eva}^i > ewa^i) \ge 0.5; \\ em^i, p(\overline{eva}^i = ewa^i) \ge 0.5; \\ em^i - \theta|S(\overline{eva}^i)|, p(\overline{eva}^i > ewa^i) < 0.5. \end{cases}$$

(7)

In Formula (7), $p = min\left\{max\left\{\frac{1-v_1-\mu_2}{\pi_1+\pi_2}, 0\right\}, 1\right\}$, $\pi_i = 1 - \mu_i - v_i$, $S(a)=\mu_1 - v_1$.

In addition, according to the meaning of the parameters and referring to the relevant literature(Wang, Nie and Zhao 2020) , all parameters of the calculation process are set as: $\emptyset = 5$, $\alpha = 0.89, \beta = 0.92, \lambda = 2.22, em^1 = 0.5$, $ewa^1 = ewa^2 = \cdots = ewa^8 = (0.5,0.5), (\eta_1, \eta_2) = (0.8,0.2)$. Bring the information of scenario S1 into Equations (1)~(7) to obtain $em^2 = 0.652$ for scenario S2, that is, $p(E2 = P) = 0.652$. By analogy, the scenario value of all scenarios is finally obtained as shown in Table 3, and the emotional probability of decision makers for each scenario is calculated, as shown in Table 4.

Table 3. v_{1j}, v_{2j}, v_j calculation results

Stage scenarios	v_{1j}	v_{2j}	v_j
S1	[0.048,0.000]	[0.105,0.000]	[0.059,0.000]
S2	[0.049,0.018]	[0.107,0.014]	[0.061,0.017]
S4	[0.055,0.050]	[0.122,0.043]	[0.069,0.049]
S6	[0.028,0.157]	[0.080,0.210]	[0.038,0.166]

S7	[0.335,0.392]	[0.017,0.624]	[0.281,0.430]
S8	[0.491,0.000]	[0.634,0.000]	[0.524,0.000]

Table 4. Prior Probabilities of Decision Maker Sentiment

Node name	Optimistic probability value
E1	0.500
E2	0.652
E4	0.416
E6	0.691
E7	0.387
E8	0.238

3.2 Improve the DS evidence theory to determine node condition probabilities

By organizing and analyzing previous literature research, historical data and materials of previous heavy rain disasters, we determine the prior probability and conditional probability of each scenario node when heavy rain occurs.

Due to the lack of data, for example, there is no specific record of the emotions of decision makers in the rainstorm event, there is no complete record of the emergency activities of the government and relevant departments, and there is no unified standard for the measures taken by different provinces to deal with sudden rainstorms. Therefore, this paper adopts a combination of data and expert scoring methods to determine node probabilities.

In order to improve the objectivity of the node probability estimation, the node probability is obtained by using the improved DS evidence theory by incorporating fuzzy set theory and the decision makers' evaluation results of seven experts. We will regard the factors to be examined and the concepts describing the uncertainty of these factors as a fuzzy set, establishes a membership function, and describe the degree of fuzziness of the factors to be examined (Zhang et al. 2015), thereby reducing the subjectivity of expert scoring.

Based on some of the collected data, this study invited seven domain experts to evaluate the scenario element table, and then we assigned the variable value level of each scenario node (as shown in Table 5) and the degree of uncertainty of this level. Further, we used Gaussian After normalizing the grades, the probability value of each expert's score is obtained by the membership function. This article divides each node in the scenario element table into two levels: danger and safety, when the expert scores the node, the corresponding target score interval is [0.5,1], [0,0.5) (out of 1), according to the Gaussian membership function, the center of the membership function corresponding to the two levels of each node is 0.75 and 0.25 (Jia, Chen and Ke, 2020), which is

$$y = e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (8)$$

Table 5. Network node variable types and value sets

Optimistic probability value	Node variable type	The node takes the set of values

Scenario State(S)	Boolean variables	{true（T），false（F）}
Meteorological factors(M)	Boolean variables	{true（T），false（F）}
Decision maker sentiment(E)	Boolean variables	{optimism（P），gloomy（N）}
Emergency activities(A)	Boolean variables	{effective（T），void（F）}
Contingency targets(T)	Boolean variables	{attain（T），miss（F）}

DS evidence theory has strong multi-source uncertain information fusion ability (Song et al. 2020), this article uses matrix analysis to improve data fusion of the theory of DS evidence (Xi et al. 2009). In order to reduce the problem of computational complexity when the membership matrix is substituted for data fusion in DS evidence theory, and in this paper, the matrix analysis is employed to integrate expert opinions by combining two evidences and recursive calculation.

$$C = \begin{bmatrix} C_1 \\ C_2 \\ \vdots \\ C_7 \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \\ \vdots & \vdots \\ c_{71} & c_{72} \end{bmatrix} \quad (9)$$

Then the outer product operation is used, multiplying the transpose C_i^T of ith row with jth row C_j to get a new matrix B. The sum of all the elements of the main diagonal in matrix B is the numerator of $q(B)$ (see Formula (11)), and the sum of all non-dominant diagonal elements is the degree of conflict K after fusion.

$$B = C_i^T \times C_j = \begin{pmatrix} C_{i1} \\ C_{i2} \end{pmatrix} \begin{pmatrix} C_{j1} & C_{j2} \end{pmatrix} = \begin{bmatrix} C_{i1} \times C_{j1} & C_{i1} \times C_{j2} \\ C_{i2} \times C_{j1} & C_{i2} \times C_{j2} \end{bmatrix} \quad (10)$$

Finally, the weight allocation improved DS evidence theory synthesis algorithm is used to calculate the probability values of the two levels after the fusion, and the improved synthesis formula is (Jia, Chen and Ke, 2020)

$$m(B) = \begin{cases} 0, B = \emptyset \\ \dfrac{\sum_{A_i \cap B_j \cap C_k \cap \ldots = B} m_1(A_i) m_2(B_j) m_3(C_k) \ldots}{1-K} + f(B), \quad B \neq \emptyset \end{cases} \quad (11)$$

where $f(B) = K\,q(B)$ is a probability allocation function for evidence conflicts, that is, assign the degree of conflict (K) between the evidences to each element in the matrix B. Therefore, this probability allocation function is satisfied $\sum_{B \subset \theta} f(B) = K$, let $q(\mathrm{B}) = \frac{\sum_{i=1}^{n} m_i(B)}{n}$.

Combine the decision maker sentiment probability value calculated in 2.1the prior probability and conditional probability of all node variables are finally obtained, as shown in Table 6. As "meteorological factors" data is obtained from weather forecast information, the evidence of initial meteorological factors is all set to true (T) in the dynamic Bayesian network, so the probability impact of them is no longer considered in Table 6.

Table 6. Prior probability and conditional probability table of node variables

Node	Prior probability	conditional probability	
S1	P(A1=T) =0.92	P (S1=T|A1=T, E1=P) =0.60	P (S1=T|A1=F, E1=P) =0.42

	P(E1=P) =0.50	P (S1=T|A1=T, E1=N) =0.51	P (S1=T|A1=F, E1=N) =0.37
T1		P(T1=T|S1=T) =0.75	P(T1=T|S1=F) =0.43
S2	P(A2=T) =0.79 P(E2=P) =0.50	P(S2=T|T1=T, A2=T,E2=P)=0.66 P(S2=T|T1=T, A2=T,E2=N)=0.62 P(S2=T|T1=T, A2=F,E2=P)=0.78 P(S2=T|T1=T, A2=F,E2=N)=0.53	P(S2=T|T1=F, A2=T,E2=P)=0.92 P(S2=T|T1=F, A2=T,E2=N)=0.82 P(S2=T|T1=F, A2=F,E2=P)=0.52 P(S2=T|T1=F, A2=F,E2=N)=0.44
T2		P(T2=T|S2=T) =0.79	P(T2=T|S2=F) =0.36
S3	P(A3=T) =0.74 P(E3=P) =0.80	P(S3=T|T1=T, A3=T,E3=P)=0.87 P(S3=T|T1=T, A3=T,E3=N)=0.80 P(S3=T|T1=T, A3=F,E3=P)=0.72 P(S3=T|T1=T, A3=F,E3=N)=0.67	P(S3=T|T1=F, A3=T,E3=P)=0.24 P(S3=T|T1=F, A3=T,E3=N)=0.30 P(S3=T|T1=F, A3=F,E3=P)=0.19 P(S3=T|T1=F, A3=F,E3=N)=0.28
T3		P(T3=T|S3=T) =0.87	P(T3=T|S3=F) =0.22
S4	P(A4=T) =0.86 P(E4=P) =0.50	P(S4=T|T2=T, A4=T,E4=P)=0.80 P(S4=T|T2=T, A4=T,E4=N)=0.72 P(S4=T|T2=T, A4=F,E4=P)=0.68 P(S4=T|T2=T, A4=F,E4=N)=0.54	P(S4=T|T2=F, A4=T, E4=P)=0.31P(S4=T|T2=F,A4=T, E4=N)=0.39 P(S4=T|T2=F, A4=F, E4=P)=0.23 P(S4=T|T2=F, A4=F, E4=N)=0.29
T4		P(T4=T|S4=T) =0.84	P(T4=T|S4=F) =0.46
S5	P(A5=T) =0.81 P(E5=P) =0.74	P(S5=T|T4=T, A5=T,E5=P)=0.88 P(S5=T|T4=T, A5=T,E5=N)=0.78 P(S5=T|T4=T, A5=F,E5=P)=0.69 P(S5=T|T4=T, A5=F,E5=N)=0.70	P(S5=T|T4=F, A5=T, E5=P)=0.69 P(S5=T|T4=F, A5=T, E5=N)=0.72 P(S5=T|T4=F, A5=F, E5=P)=0.44 P(S5=T|T4=F, A5=F, E5=N)=0.58
T5		P(T5=T|S5=T) =0.93	P(T5=T|S5=F) =0.54
S9		P(S9=T|T3=T, T5=T)=0.90 P(S9=T|T3=T, T5=F)=0.37	P(S1=T|T3=F, T5=T)=0.68 P(S1=T|T3=F, T5=F)=0.71
S6	P(A6=T) =0.90 P(E6=P) =0.50	P(S6=T|T1=T, A6=T,E6=P)=0.87 P(S6=T|T1=T, A6=T,E6=N)=0.94 P(S6=T|T1=T, A6=F,E6=P)=0.81 P(S6=T|T1=T, A6=F,E6=N)=0.88	P(S6=T|T1=F, A6=T,E6=P)=0.57 P(S6=T|T1=F, A6=T,E6=N)=0.69 P(S6=T|T1=F, A6=F,E6=P)=0.32 P(S6=T|T1=F, A6=F,E6=N)=0.43
T6		P(T6=T|S6=T) =0.89	P(T6=T|S6=F) =0.39
S7	P(A7=T) =0.93 P(E7=P) =0.50	P(S7=T|T6=T, A7=T,E7=P)=0.81 P(S7=T|T6=T, A7=T,E7=N)=0.88 P(S7=T|T6=T, A7=F,E7=P)=0.85 P(S7=T|T6=T, A7=F,E7=N)=0.91	P(S7=T|T6=F, A7=T, E7=P)=0.61 P(S7=T|T6=F, A7=T, E7=N)=0.69 P(S7=T|T6=F, A7=F, E7=P)=0.34 P(S7=T|T6=F, A7=F, E7=N)=0.41
T7		P(T7=T|S7=T) =0.91	P(T7=T|S7=F) =0.48
S10		P(S10=T|T7=T) =0.53	P(S10=T|T7=F) =0.16
S8	P(A8=T) =0.95	P(S8=T|T6=T, A8=T, E8=P)=0.68	P(S8=T|T6=F, A8=T, E8=P)=0.73

<table>
<tr><td></td><td>P(E8=P) =0.50</td><td>P(S8=T|T6=T, A8=T, E8=N)=0.74</td><td>P(S8=T|T6=F, A8=T, E8=N)=0.78</td></tr>
<tr><td></td><td></td><td>P(S8=T|T6=T, A8=F, E8=P)=0.86</td><td>P(S8=T|T6=F, A8=F, E8=P)=0.80</td></tr>
<tr><td></td><td></td><td>P(S8=T|T6=T, A8=F, E8=N)=0.90</td><td>P(S8=T|T6=F, A8=F, E8=N)=0.83</td></tr>
<tr><td>T8</td><td></td><td>P(T8=T|S8=T) =0.96</td><td>P(T8=T|S8=F) =0.63</td></tr>
<tr><td>S11</td><td></td><td>P(S11=T|T8=T) =0.38</td><td>P(S11=T|T8=F) =0.12</td></tr>
</table>

3.3 Calculation of node state probability in rainstorm scenario

The prior probability and conditional probability in Table 8 are put into Formula (12), and the state probability of each node variable is calculated sequentially from S1. For example, the state probability of S1 is computed as:

$$P(S1=T)=P(S1=T|A1=T,E1=P)P(A1=T)P(E1=P)+P(S1=T|A1=T,E1=N)P(A1=T)P(E1=N)+P(S1=T|A1=F,E1=P)P(A1=F)P(E1=P)+P(S1=T|A1=F,E1=N)P(A1=F)P(E1=N)=0.6\times0.92\times0.5+0.51\times0.92\times0.5+0.42\times0.08\times0.5+0.37\times0.08\times0.5=0.5422.$$

The state probability of all remaining nodes are calculated using the following formula, and the result is shown in Figure 3.

$$P(S1,S2\ldots,Sn)=P(Sn|S1,S2,\ldots,Sn-1)\ldots P(S2|S1)P(S1)=\prod_1^n P\big(Si\big|P(\prod Si)\big),i=1,2,\ldots,n \qquad (12)$$

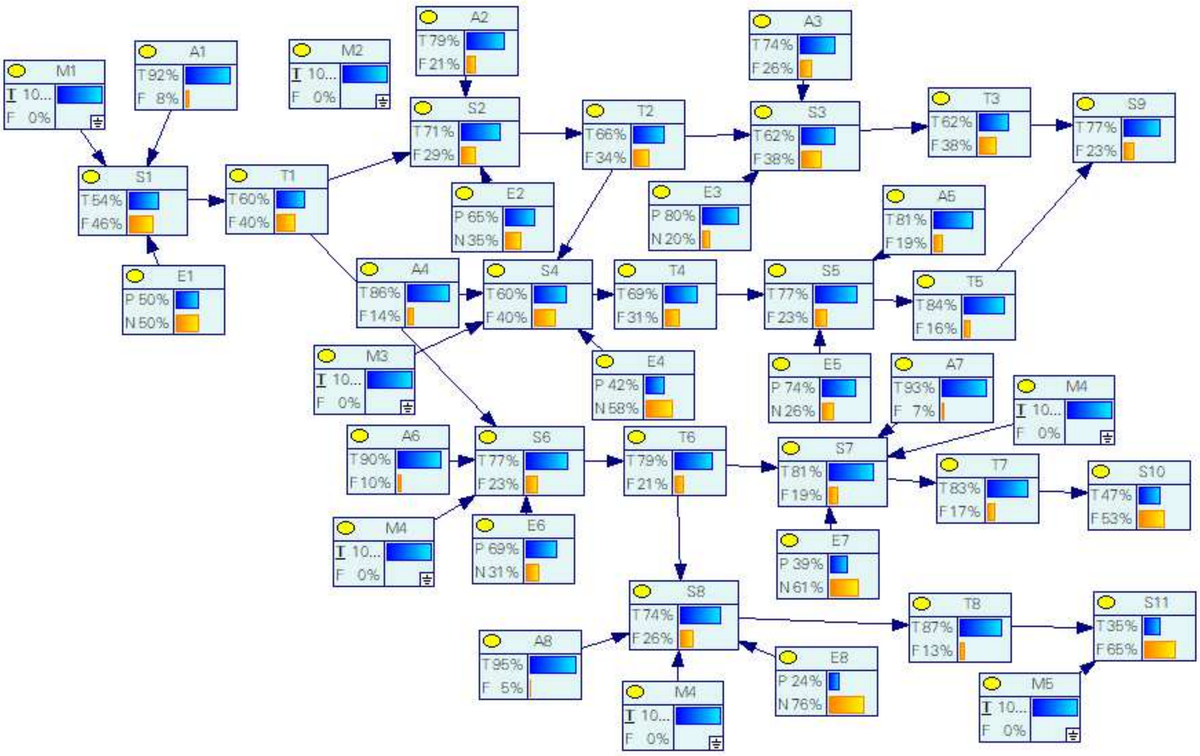

Figure 3. Bayesian network structure for scenario deduction of "7.20" rainstorm event

3.4 Analysis of results

(1) The probabilistic deduction of the above dynamic Bayesian network graph shows that when the heavy rain occurred, the government did not take effective emergency actions in time, the probability of a heavy rain (S2), the probability of a small flood caused by heavy rain (S6). Both the probability of large-scale floods caused by heavy rain (S7) and the probability of landslides due to floods (S8) exceeded 0.7. It can be seen that if the emergency rescue and other measures are not taken timely after a heavy rain disaster, the probability of scenario deterioration increases dramatically. Disasters are difficult to control, and the losses incurred are unpredictable.

Therefore, in the stage of disaster prevention, the organizers or officials should take the initiative to improve their risk awareness and emergency mutation ability, increase monitoring of the main factors that may cause the water level to rise, and conduct more afforestation activities on a daily basis to reduce the probability of soil erosion caused by heavy rains. They need to have a hands-on attitude toward relevant issues. For the disaster response stage, it is necessary to improve the professional capabilities in flood control and flood relief emergency personnel distribution, carry out more training and more reforms, and strengthen the maintenance and improvement of emergency equipment (such as pumping and drainage equipment, high-precision detection instruments, rescue materials, etc). Work closely with the communities to develop preventive plans and rescue strategies. For the disaster recovery stage, under the premise of ensuring that residents' lives return to normal, enhancing the risk awareness and self-rescue and mutual rescue capabilities of the whole society is the core of the work, and it must be carried out effectively to the end.

(2) According to relevant reports, most of the emergency targets in this rainstorm disaster had not been reached. In order to improve the matching degree between the model and the facts, the evidences of T2, T3, T5, and T7 were set to be not reached (F). The simulation results show that the rainstorm will evolve to the stage of large floods (S7) and landslides (S8) with greater probability, which is consistent with the real disaster results and this proves the feasibility and effectiveness of the proposed method. In the actual application process of the model, changing the completion of emergency activities and dealing with subjective factors can affect the probability of achieving the emergency goal, and in turn affect the evolution path of the disaster. In this way, the staff will be able to intuitively recognize their own operations when taking countermeasures, so as to adjust the relevant countermeasures in real time and grasp the evolution of the incident in advance.

(3) This paper simplifies the extraction of scenario elements in the process of "7.20" heavy rainstorm event scenario deduction. In the real disaster handling process, there are many factors that make it difficult to predict the development trend of rainstorm. Therefore, in practical applications, more relevant factors should be identified based on the above methods, and more real-time disaster information should be integrated into the scenario deduction, so as to improve the ability of the whole society to respond to emergencies and minimize losses.

3.5 Comparative analysis

(1) To our best of knowledge, at present, there is no relevant research on the "7.20" heavy rainstorm except a few isolated studies in Chinese, such as Zhang et al. (2022), Cai et al. (2022), Wang et al. (2022), Bu He et al. (2022), etc. Their studies only focused on the economic impact and reflection of this rainstorm event after the disaster, without paying attention to the impact of various variables

on the development trend of the disaster situation in the process of the interpretation of the disaster scenario. Therefore, the research in this paper is an expansion of the field of rainstorm research in Henan and has certain research value.

(2) As typical representatives of the traditional scenario elements in scenario deduction, meteorological factors, emergency activities and emergency goals are used by many scholars to carry out scenario deduction research on different sudden disasters (Zhang, Hao and Zhang 2020, Qie and Rong 2020, Xu et al. 2022, Song et al. 2022, etc.). In the field of disaster scenario deduction research, the "decision-maker sentiment" is firstly included as a scenario element. Therefore, for the comparison purpose, nodes relevant to "decision-makers emotions" in the dynamic Bayesian scenario deduction path diagram are dropped, and at the same time, it is ensured that the model method and other node-related data are consistent with the above for comparative experiments. The final result is shown in Figure 4.

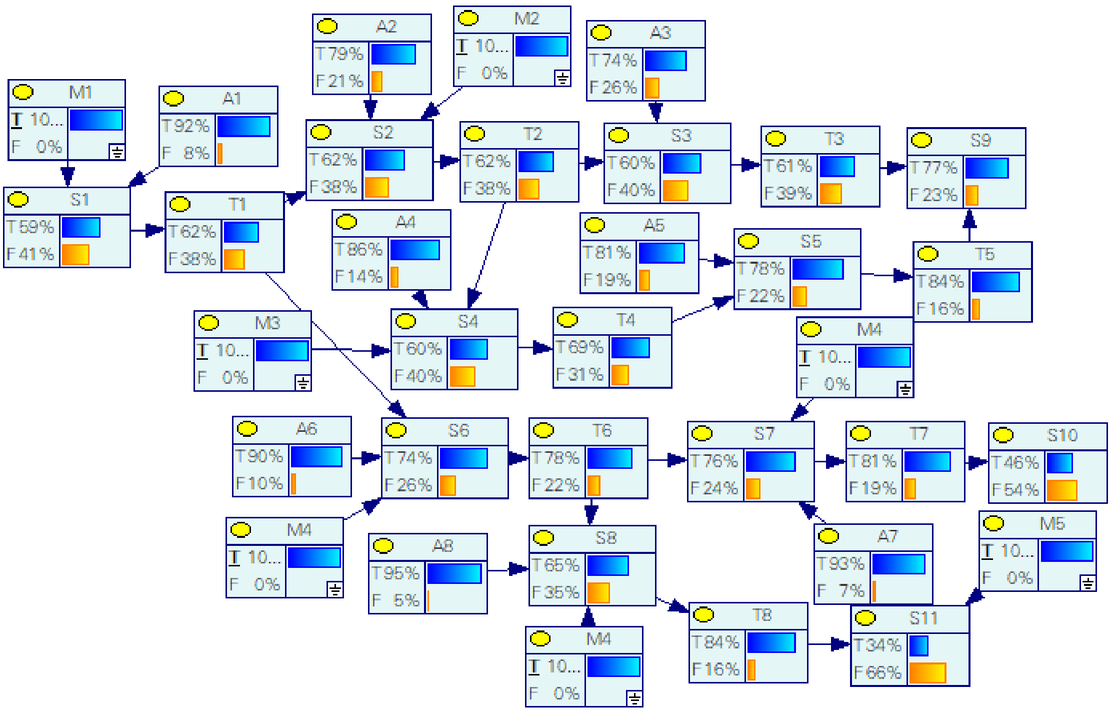

Figure 4. A diagram of a Bayesian network that does not take into account the sentiment of decision makers

By comparing the probabilities of nodes in Figure 3 and Figure 4, it is seen that the probability of multiple key scenarios with a probability of more than 0.7 in Figure 3 decreased in Figure 4. The probability of a heavy rain (S2) has decreased 9%, the probability of a small flood caused by heavy rain (S6) has decreased 3%, the probability of large-scale floods caused by heavy rain (S7) has decreased 5%, the probability of landslides due to floods (S8) has decreased 9%, and the probabilities of other nodes also vary slightly. Overall, without considering the influence of the subjective element of "decision-maker sentiment", the sudden rainstorm scenario is in a more positive direction, this can easily lead to over-optimism among policymakers about the current situation of disasters. As a result, the intensity of the emergency response activities (A) taken is insufficient to affect the evolution of the next scenario, and this continues to be a vicious circle until it affects the entire evolution of the disaster. Therefore, in the face of sudden disasters, by combining subjective and objective elements, we would be able to more accurately grasp the process of disaster development, and decision makers can take timely and appropriate measures to minimize losses.

4 Conclusion

(1) In this study, targeting the dynamical evolutional process of sudden heavy rainstorms, a framework has been developed for selecting situational states, meteorological factor, emergency activities, decision makers' emotions and emergency targets at different stages as network nodes. The relationship between major disaster scenario units and the scenario evolution mechanism are analyzed: Based on the dynamic Bayesian network, using the improved Dempster Rule of Combination and sentiment update mechanism, the initial network of scenario evolution is determined, the state probability of each scenario is updated using an expert evaluation method, and the potential development paths of the rainstorm are explored. In this way, the feasibility of emergency activities and the rescue operations of emergency goals are accessed before putting into use. Particularly early actions and effective measures are determined as critical strategies for prevention and rescue operations. To validation of the proposed model, the Henan rainstorm event is used to explain the effectiveness, feasibility, easiness to apply, and interpretability of the parameters in the model.

(2) The sudden rainstorm emergency scenario deduction method based on the dynamic Bayesian network and considering the emotions of the decision makers, integrated with quantitative elements, can be implemented for better analyzing the uncertainty, complexity and derivative problems of emergency response strategies and rescue operations in the rainstorm environment. Combined analysis with qualitative elements provides a new idea for improving the traditional scenario analysis methods, it is hoped that it will play a greater value in the future.

(3) The traditional expert scoring method is still used to determine the probability of nodes in dynamic Bayesian networks in this paper. The use of fuzzy set theory and improved DS evidence theory reduces the subjectivity in the experts' scoring results. Disaster risk reduction demands multisectoral, inclusive and accessible actions at all levels to provide effective support. Disaster risk reduction is interdisciplinary, and it requires the improvement of the availability of knowledge, which can promote researchers to consider the broader impact of risk assessment during the deduction of disaster scenarios. Several ways could be used to extend our model in the future. For example, we can extend our model with Choquet fuzzy integral operators to synthesize scenario elements attribute values. In the future research, we can also consider more expert opinions and historical data to identify key paths for cascading disasters and disaster scenario deduction.

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