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Bayesian Network-based Inferential Analysis of Xigou Reservoir Overtopping Accident

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Abstract: With the development of society and the increasing tension of water resources, the importance of reservoir management has become increasingly prominent. In March 2021, a significant overtop-ping accident occurred at the Xigou Dam, an auxiliary project of the Xiaolangdi Water Conservancy Project (also known as the Xigou Reservoir). The direct cause of the accident was an electrical failure, but it also involved subjective factors such as low risk awareness and weak daily management. This paper extracts 17 scenario nodes from the "Xigou Reservoir Overtopping" accident through scenario analysis and constructs a scenario Bayesian network model by analyzing the progression of the accident. The conditional probability of a node is calculated using the expert scoring method to compute the state probability of the node. Finally, the probabilistic changes in the states of 'water level', 'casualties' and 'economic losses' are analysed by adjusting the prior probabilities of the selected nodes. In the development of this accident, the conditions of equipment maintenance and the implementation of emergency response activities have a significant im-pact on the accident progression. Under conditions of normal equipment maintenance or active emergency response, the probability of the 'water level status' being normal increases by over 20%. Additionally, under normal staff supervision, the probability of the 'water level status' being normal also increases by 14%. The analysis of projected accidents highlights the substantial impact of human factors on these incidents. Therefore, it is crucial to establish robust personnel supervision mechanisms and implement effective equipment maintenance plans to prevent and mitigate risks.

Keywords: Bayesian Network; Scenario Analysis; Reservoir Dam-Break; Scenario Deduction.

1. Introduction

According to statistics, 3,558 dam failures occurred in reservoirs across China from 1954 to 2021, and the average annual dam failure rate far exceeded the internationally recognized acceptable annual dam failure rate of 1 in 10,000[1]. Reservoir dam safety issues are simultaneously affected by a variety of uncertainties such as geology, hydrology, design, construction, and management level. In recent years, with the development of the Internet, the society has become increasingly informed about risky accidents, and the social sensitivity of dam failure accidents has increased significantly. The frequent occurrence of global regional heavy rainfall weather has increased the risk of dam failure. Differences in reservoir management levels also further exacerbate the differences in dam failure risk[2]. In this context, there are higher requirements for reservoir system safety.

Xu Yao et al. analyzed and ranked the dam risk using principal component analysis to facilitate the risk management of reservoir dams by considering three factors: dam failure loss, dam failure probability, and reservoir efficiency[3]. Ding Wei et al. proposed an XGBoost-based prediction method for potential risk assessment of dam facilities with outstanding prediction capability[4]. Pengyuan Lin and Xianqi Tang et al. conducted a dam risk study and a dam leakage risk study based on Bayesian networks, respectively, which solved the problems of uncertainty and correlation of risk factors, and the prediction results had a certain degree of fit with the actual situation[5][6]. Ge Wei et al. used the AHP-BN method to construct a dam failure life loss evaluation model and applied it to examples to verify the effectiveness of the model[9]. Existing studies mainly focus on dam risk assessment and risk prediction, but these studies cannot comprehensively analyze the whole process of accident development, especially the dam failure scenarios under complex conditions such as extreme climate and unexpected situations [10-14]

The scenario is an objective description of the actual situation of unconventional emergencies, serving as the foundation and basis for decision-makers to formulate scientific and efficient response measures. So far, the application of scenario deduction methods has been widespread. Many scholars have applied scenario deduction methods to emergency decision-making in response to emergencies[26-30]. Therefore, this paper focuses on the scenario projection study of dam failure accidents.

The Bayesian network is currently one of the most effective theoretical models in the field of uncertain knowledge representation and reasoning. It is suitable for ex-pressing and analyzing uncertain and probabilistic events and is applied to decision-making that conditionally depends on multiple control factors, allowing for reasoning from incomplete, imprecise, or uncertain knowledge or information. In recent years, there have been many positive developments in the application of Bayesian networks in areas such as event classification and prediction[15-19]. The application of Bayesian networks is also widespread in the research of scenario deduction[20-25].Combining scenario analysis with Bayesian network reasoning helps to conduct a rapid and accurate comprehensive analysis of the accident development process in the face of sudden reservoir emergencies.

In Xiaolangdi Water Conservancy Hub, “Xigou Reservoir Overtopping Accident” is a disaster that has attracted wide attention, which has brought serious losses to Xiaolangdi Hydropower Station and affiliated projects. The accident was complex, starting with the abnormal opening of the working gate of the water supply branch of the irrigation cave, evolving into the damming of the Xigou dam, and ultimately leading to the shutdown of several generating units of the Xiaolangdi hydropower station. This chain reaction revealed weaknesses and potential risks in the management of the reservoir system, and a more advanced and comprehensive safety management approach needs to be sought. This study aims to improve the accuracy and systematic understanding of the Xigou reservoir overtopping accident by introducing a scenario Bayesian network to analyze the accident in terms of extrapolation, and to provide an effective method for risk prevention and response to similar events in the future.

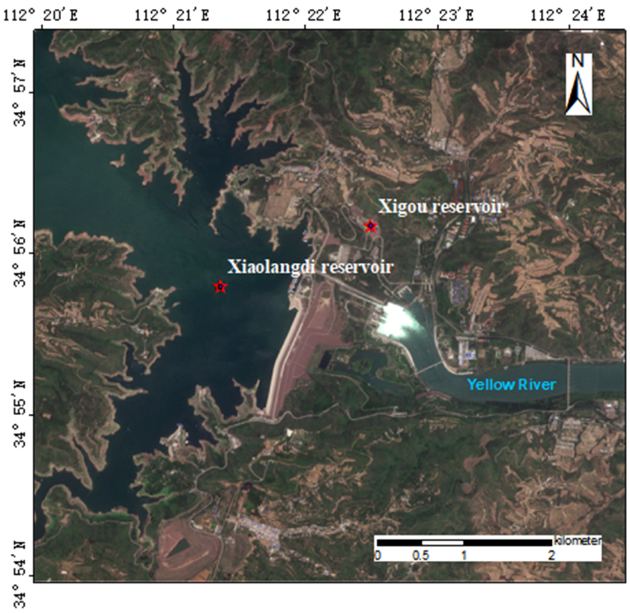


Fig 1. Overview map of study area

2. Study Area and Methods

2.1. Study Area and Datesets

Xigou Dam, an important ancillary project of the Xiaolangdi Hydropower Hub, is located approximately 500 meters northeast of the underground plant of the Xiaolangdi Hydropower Station, about 45 kilometers south of Jiyuan City, Henan Province (see Fig). Its primary function is to protect the underground plant of the Xiaolangdi Hydropower Station from potential natural disasters and to serve as a critical backup water source for the technical water supply of the hydropower station. The Xigou Dam ensures the continuity and stability of hydropower plant operations by drawing water from the Xiaolangdi reservoir through a finely designed system of irrigation caves and water supply branch caves. The dam has a small but significant role in controlling the watershed area, and its normal storage level is maintained at 223 meters with a capacity of 423,800 cubic meters, which provides a solid back-up for the safe operation of the hydropower plant. Xigou Dam has become an integral part of Xiaolangdi Hydraulic Hub since its completion.

The data in this paper are sourced from the investigation report on the Xigou Reservoir overtopping accident issued by the Henan Provincial Emergency Management Department, an analysis of historical data related to reservoir dam failures, and a questionnaire survey of five experts, covering issues such as the conditional probability of accident scenarios occurring.

2.2. Scenario Analysis

At Scenario analysis is a systematic research method that identifies key nodes and potential influencing factors of the event development by envisioning and analyzing various possible development scenarios[7]. First, the research objective is clarified, i.e., to comprehensively understand the dynamic evolution and influencing factors of the Xigou reservoir overtopping accident in order to provide effective decision support and risk management strategies. Next, key event nodes are identified, including the key moments with significant impacts in the development of the event, such as the abnormal opening of the working gate of the water supply branch hole of the irrigation cave, the diffusion of the Xigou dam, and water flow into the Xiaolangdi hydropower station. Various possible development scenarios were then constructed, taking into account possible variables and conditions, including equipment status, maintenance status, and water level changes. Different development paths are envisioned for each constructed scenario, taking into account possible changes, uncertainties, and potential impacts of the event to ensure diversity of scenarios. Finally, each scenario is evaluated to quantitatively and qualitatively analyze its possible impacts on the development of the reservoir overflow event and emergency response, considering possible losses, risks, and countermeasures.

2.3. Bayesian Networks

Bayesian network is a probabilistic graphical model for describing dependencies between random variables. It is based on Bayes' theorem and uses directed acyclic graph (DAG) to represent conditional dependencies between variables for modeling uncertainty and inference processes [8]. A Bayesian network consists of two parts: a topology and a probability distribution. Bayesian networks contain two types of nodes: parent nodes and child nodes. Parent nodes, child nodes plus directed edges connecting the two constitute the basic structure of Bayesian networks, and the directed edges represent the causal relationships between elements.

Probability is categorized into priori probability and conditional probability, and a priori probability calculation is based on prior information, expert opinion, etc. The conditional independence assumption and Markov property can greatly simplify the calculation of joint probability, and the joint probability distribution of Bayesian network can be expressed as the product of marginal probability and conditional probability, which can be obtained:

$$(S_1, S_2, \cdots, S_n) = \prod_1^n P(S_i/Pa(S_i))(i = 1,2,\cdots,n) \quad (1)$$

Where: $\{S= (S_1, S_2, \cdots, S_n)\}$ denotes a set of variables, consisting of nodes S_i of the Bayesian network; Pa (S_i) represent the parent nodes of S_i.

3. Constructing a Scenario-Based Bayesian Network Model for the Xigou Reservoir Overtopping Accident

3.1. Scenario Analysis

Through the research and analysis of the typical cases of reservoir dams in China, as well as the reference to the accident investigation report, 17 scenarios of Bayesian network node variables are extracted and classified into four categories, which are “event state” “disaster-causing factors” “emergency measures” and “consequences of the accident”. Each scenario element is categorized as shown in Table 1.

Table 1. Scenario Element Status of the Xigou Reservoir Overtopping Incident

Element Type	Node	Status	Remarks
Event Status (S)	Water Level Status (S_1)	Normal Water Level (S_{11})	The water level is within the normal operating range, and no abnormal conditions have occurred (before the incident, the Xigou Dam was in an empty reservoir state).
		Critical Water Level (S_{12})	The water level has reached or exceeded the critical level for overtopping, posing a real risk of overtopping. Conventional monitoring systems issue an alarm, indicating that the water level has reached a dangerous level, requiring immediate action.
		Overtopping(S_{13})	The water level has exceeded the overtopping critical level, and overtopping has begun. The rising water level threatens nearby areas, with risks of dam collapse and breach.
	Gate Status (S_2)	Normal Closed (S_{21})	The gate is normally closed, with no abnormalities, ensuring water does not enter the dam.
		Abnormally Open (S_{22})	The gate opens by itself without human intervention, possibly due to electrical failure. Water flows uncontrollably into the dam.
		Manually Closed (S_{23})	After detecting the gate has opened abnormally, emergency measures are taken to close it to prevent more water from entering Xigou Dam and mitigate the accident's impact.
	Powerhouse (S_3)	Low Risk(S_{31})	Water entering the powerhouse is categorized as low or high risk.
		High Risk(S_{32})	
	Power Status (S_4)	Normal(S_{41})	The powerhouse's power status is either normal or lost.
		Power Loss(S_{42})	
Hazard Factors (F)	Gate Hoist Operation (F_1)	Normal Operation(F_{11})	No electrical failures, the gate remains normally closed, and water flows are controlled.
		Minor Fault(F_{12})	Minor electrical issues may cause the gate to open briefly but return to normal, not significantly affecting water flow.
		Major Fault(F_{13})	Serious electrical failure leads to prolonged gate opening, uncontrollable water flow, possibly causing significant damage or danger.
	Monitoring System (F_2)	Normal Monitoring (F_{21})	Video monitoring did not work, and the monitoring system status is categorized as normal or erroneous.
		Erroneous Monitoring (F_{22})	
	Operational Error (F_3)	Yes (F_{31})	Operational errors occurred.
		No (F_{32})	No operational errors occurred.
Hazard Factors (F)	Staff Supervision (F_4)	Strict (F_{41})	Strict supervision means intense, comprehensive monitoring and management of staff.
		Normal (F_{42})	Adequate supervision according to regulations ensures work follows procedures and standards.
		Lax (F_{43})	Supervision is relaxed, lacking clear standards, procedures, or effective implementation.
	Equipment Maintenance (F_5)	Neglected Maintenance(F_{51})	Maintenance was not carried out according to the plan, standards, or requirements.
		Normal Maintenance (F_{52})	Maintenance follows the technical standards, and protocols, ensuring equipment runs well.
Element Type	Node	Status	Remarks
Emergency Measures (M)	Close Gate (M_1)	Deployed (M_{11})	Emergency measures are categorized as deployed or not deployed.
		Not Deployed(M_{12})	
	Flood Discharge (M_2)	Deployed (M_{21})	
		Not Deployed(M_{22})	
	Evacuation (M_3)	Deployed (M_{31})	
		Not Deployed(M_{32})	
	Power Restoration (M_4)	Deployed (M_{41})	
		Not Deployed(M_{42})	
	Reconstruction (M_5)	Deployed (M_{51})	
		Not Deployed(M_{52})	
Accident Consequence (C)	Economic Loss (C_1)	Minor (C_{11})	Direct economic loss below 10 million RMB.
		Moderate (C_{12})	Direct economic loss between 10 and 50 million RMB.
		Major (C_{13})	Direct economic loss between 50 and 100 million.
		Catastrophic (C_{14})	Direct economic loss exceeding 100 million RMB.
	Casualties (C_2)	None (C_{21})	No casualties.
		Minor (C_{22})	Deaths of up to 3 people.
		Moderate (C_{23})	Deaths between 3 and 10 people.
		Major (C_{24})	Deaths between 10 and 30 people.
		Catastrophic (C_{25})	Deaths exceeding 30 people.
	Environmental Damage (C_3)	Yes (C_{31})	Environmental damage occurred.
		No (C_{32})	No environmental damage occurred.

3.2. Bayesian Network Construction

3.2.1. Network Structure

Based on the scenario analysis, a total of 17 main influencing factors and key scenario elements are identified, i.e., the network contains 17 nodes. By analyzing the statistics of the same type of historical accidents, experts' judgments and recommendations and studying the relevant scientific research literature, the causal relationship between the variables of each node is determined, and the construction of the Bayesian network structure is completed, as in Fig.

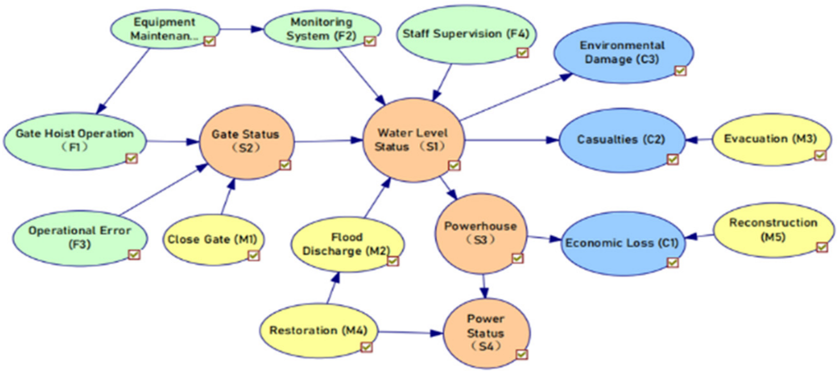


Fig 2. Bayesian network structure of the Xigou Reservoir Overtopping Incident

3.2.2. Determination of Conditional Probabilities of Network Nodes

In order to carry out the scenario projection, the conditional probabilities of the nodes of the Bayesian network are determined by questionnaire. The a priori probabilities of the nodes in the Bayesian network constructed for the “Xigou Reservoir Over-topping Accident” are directly given by experts according to the event itself, as shown in Table 2

Table 2. Bayesian network prior probability table

Node	Status	Prior probability	Explanation
Staff Supervision	1.Strict 2.Normal 3.Lax	(0,0,100)	The accident occurred at 3:35 AM, but the danger was not discovered until after units 3-6 were shut down, leading to a delayed response. Additionally, the investigation identified inadequate maintenance and management of the gate hoist as the direct cause of the accident, and on-site detection methods failed to function. Thus, the status is assessed as "Lax".
Equipment Maintenance	1.Neglected Maintenance 2.Normal Maintenance	(100,0)	The irrigation tunnel's water supply branch gate was poorly maintained and managed, operating with issues for an extended period. Hence, the condition is assessed as "Neglected Maintenance."
Operational Error	1.Yes 2.No	(0,100)	The main cause of the accident was an electrical fault in the programmable controller of the gate control system, with no operational errors. Thus, the status is assessed as "No."
Close Gate	1. Deployed 2. Not Deployed	(0,100)	The first measure after the accident was to close the accident gate of the irrigation hole to stop more water flow into the Xigou Dam and mitigate the impact of the accident. However, due to the failure to detect the danger in time, the favorable time for rescue work was missed. Therefore, the status is assessed as “Not Deployed”.
Power Restoration	1. Deployed 2. Not Deployed	(100,0)	Faced with a total power loss at Xiaolangdi Hydropower Station, restoring power was crucial for normal operations. At 8:42 AM, the diesel generator was started to restore power to the auxiliary plant. Therefore, the status is assessed as "Deployed."
Evacuation	1. Deployed 2. Not Deployed	(100,0)	The scope of influence of the accident is controlled within the management area of the Xiaolangdi Water Conservancy Hub, and there is no threat to the downstream, so there is no need to evacuate people, so the assessment of “Deployed” in this node is closer to reality.
Reconstruction	1. Deployed 2. Not Deployed	(100,0)	Through on-site emergency response, by 2:30 AM on March 2, 2021, Xigou Reservoir had been emptied, and the spillway gate was fully opened. The underground powerhouse was being cleared of sediment and drained, and a restoration plan was formulated to resume operations. Therefore, the status is assessed as "Deployed."

The rest of the node conditional probability through the questionnaire survey collected five experts on the conditional probability of each node of the Bayesian network judgment, and take its average value as the final result. Take the node “monitoring system operation status” as an example, the details are shown in Table 3.

Table 3. Results of conditional probability calculations for the node “Monitoring System”

Monitoring System (F_2)	expert opinion					calculation result
	M_1	M_2	M_3	M_4	M_5	
Normal Monitoring (F_{21})	(0.15, 0.85)	(0.3, 0.7)	(0.25, 0.75)	(0.25, 0.75)	(0.2, 0.8)	(0.23, 0.77)
Erroneous Monitoring (F_{22})	(0.75, 0.25)	(0.6, 0.4)	(0.7, 0.3)	(0.75, 0.25)	(0.8, 0.2)	(0.72, 0.28)

4. Results and Analysis

After constructing the Bayesian network structure and determining the conditional probabilities of the nodes of “Xigou Reservoir Overtopping Accident”, we start to construct the complete Bayesian network of “Xigou Reservoir Overtopping Accident” scenario. In this paper, we use GeNie software to carry out the inference operation of Bayesian network. As shown in Fig, the inference calculates the state probability of each node variable in the Bayesian network of “Xigou Reservoir Overtopping Accident”. The figure shows the probability of the state of each node in the development of the accident, which can be seen to be generally consistent with the reality. In order to clarify the influence of important nodes on the development of the accident, the possible development of the accident is analyzed by changing the prior probabilities of selected nodes, and the probabilities of each state of “Water Level Status”, “Casualties” and “Economic loss” are observed under different conditions. “The probability of each state is observed under different conditions.

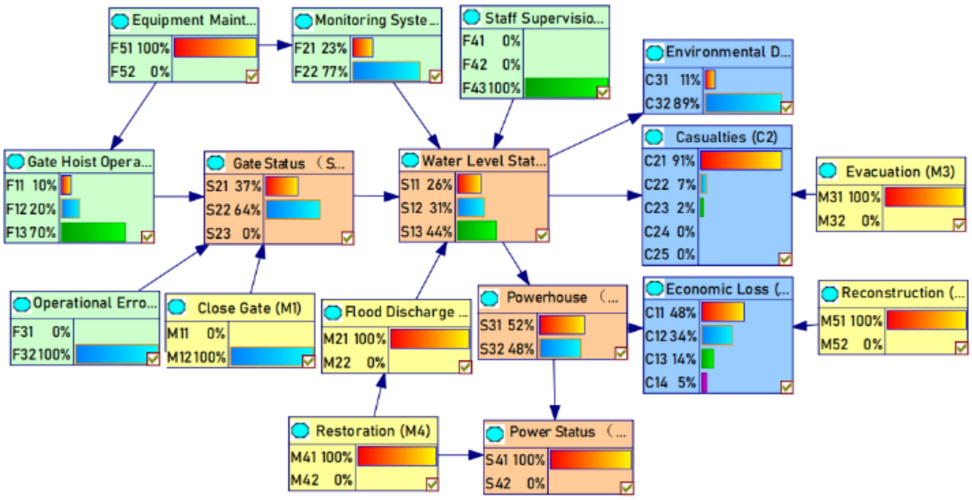
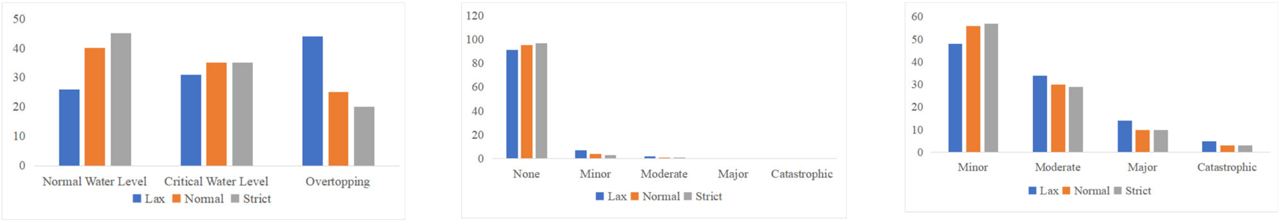


Fig 3. Nodal state probability results for “Xigou Reservoir Overtopping Incident”

4.1. Analysis of Influencing Factors

4.1.1. Influence of Different Staff Supervision Conditions

Only change the a priori probability of the “staff supervision” node, keep the a priori probability of other nodes unchanged, and carry out scenario derivation. When the personnel supervision status is “strict”, “normal” and “lax”, the different probabilities of “water level status”, “casualties” and “economic loss” will be calculated. When the personnel supervision state is “strict”, “normal” and “lax” respectively, the changes of different state probability results of “water level state”, “casualties” and “economic loss” are analyzed. Fig shows that as the staff supervision state gradually strengthens, the probability of the "water level state" being "normal water level" increases, while the probabilities of the "critical water level" state and "overtopping" decrease. The probability of the 'casualties' status being 'none' has increased by 6%, and the probability of the 'economic loss' status being 'minor' has risen by 9%.



(a) Water Level State

(b) Casualties

(c) Economic Loss

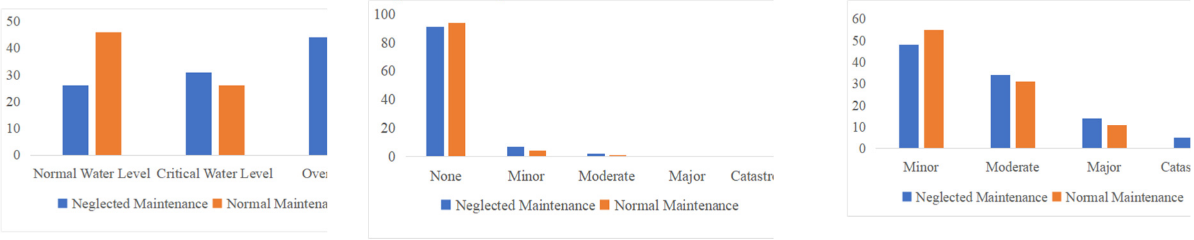
Fig 4. Probability changes at selected nodes under different staff supervision conditions

4.1.2. Impact of Equipment Maintenance Situation

Only change the priori probability of the “equipment maintenance” node, keep priori probability of other nodes unchanged, and carry out scenario derivation. The state probability results of “water level status”, “casualties” and “economic loss” are calculated respectively when the “equipment maintenance” node states are “neglected maintenance” and “normal maintenance” (shown in Fig. It can be observed that the routine maintenance of the equipment has a significant impact on the accident, “normal maintenance” state “normal water level” probability is much higher than the “neglected maintenance” state probability. Similarly, the probability that the 'eco-nomic loss' is 'minor' under 'normal maintenance' has significantly increased from 48% to 55%.

4.1.3. Probability Changes under Normal Management Conditions of Reservoir System

When the status of the node “equipment maintenance” is “normal maintenance” and the status of the node “staff supervision” is “normal”, the probability distribution of each node state is shown in Fig. Under the condition that the states of two nodes are changed to “normal”, the probability of “water level state” is “overtopping” is only 16%.



(a) Water Level State (b) Casualties (c) Economic Loss

Fig 5. Probability changes at selected nodes under different equipment maintenance conditions

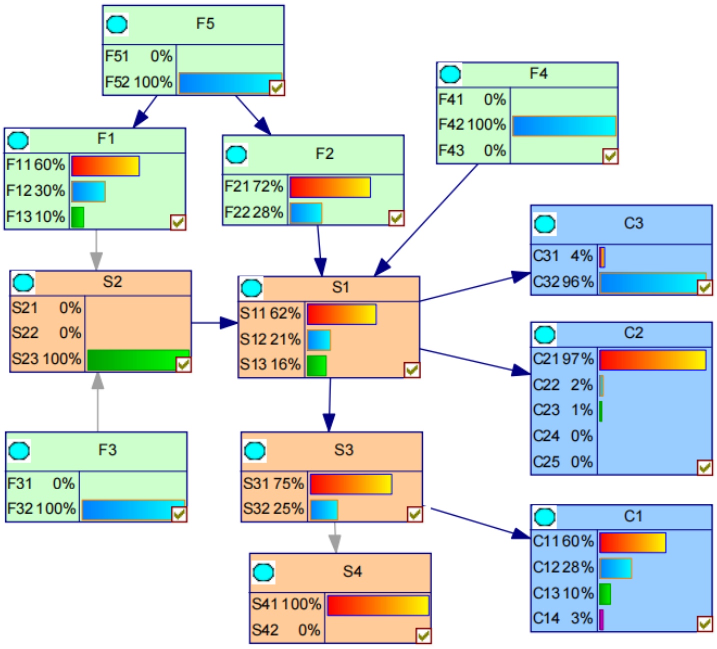
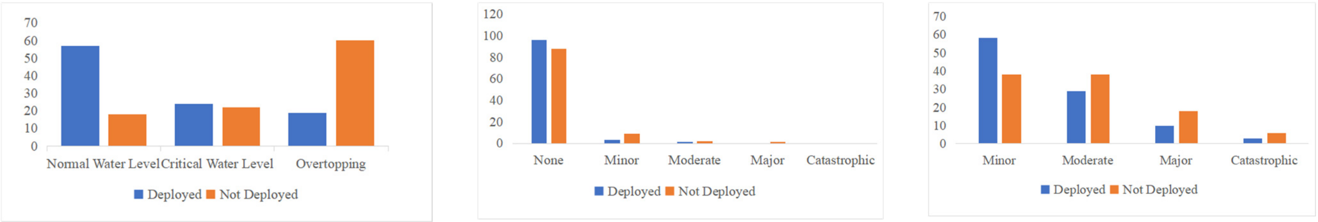


Fig 6. Accident scenario simulation under the conditions of "normal equipment maintenance" and "normal staff supervision"

4.2. Emergency Response Analysis

4.2.1. Change The Priori Probability of the “Emergency Measures” Node Whose Status is “Not Deployed”

Change the priori probability of the node “close gate”, keep the priori probability of other nodes unchanged, and carry out scenarios. When the emergency response activity is “deployed” and “not deployed”, the state probability results of “water level state”, “casualties” and “economic loss” are obtained respectively. As can be seen from Fig, whether or not the emergency measure of “close gate” is activated has a great influence on the development of the incident. The probability of the water level being “normal” increases to 0.57; the probability of “economic loss” increases to 0.57 in the case of “no emergency measures” after the dam overflow accident; the probability of “minor” increases to 0.58.

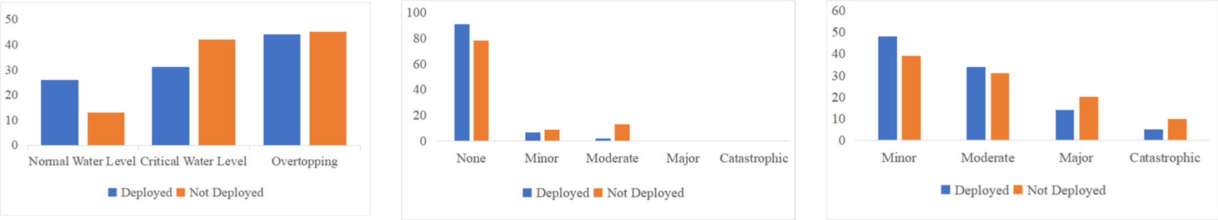


(a) Water Level State (b) Casualties (c) Economic Loss

Fig 7. Probability changes at selected nodes under the condition that all emergency measures are deployed

4.2.2. Changing the Priori Probability of the Emergency Response Node Whose State is “Carry Out”

Change the a priori probability of the node “close the working gate”, keep the a priori probability of other nodes unchanged, and carry out scenarios. When the emergency response activities are “unfolded” and “not unfolded”, the state probabilities of “water level state”, “personnel death” and “economic loss” are obtained, and the results are shown in Fig. The probability of an increase in casualties and economic losses is higher in the absence of emergency measures. The probability of casualties in-creased from 0.09 to 0.22, and the probability that the “economic loss” status was higher than “moderate” increased by 0.11. The change in the probability of the water level state being “overtopping” is small. Considering that the emergency measure of “close gate” was not carried out during the accident, this node had a greater impact on the water level status, so the probability of the water level being “overtopping” did not change significantly.



(a) Water Level State (b) Casualties (c) Economic Loss

Fig 8. Probability changes at selected nodes under the condition that emergency measures are not deployed

5. Conclusion

In this paper, a scenario model of “Xigou Reservoir Overtopping Accident” is established by combining scenario analysis method and Bayesian network, and the whole process of the accident is reviewed and analysed. The probability changes of “water level status”, “casualties” and “economic loss” are analysed under different staff supervision conditions, equipment maintenance situations and emergency response activities. And the following conclusions are drawn:

Seventeen scenario elements representing four types of “Xigou Reservoir Dam Flooding Accident” are proposed and divided into different states. Through the scenario analysis and historical experience, 17 pairs of scenario elements with causal relationship were identified and connected by directed edges. A scenario Bayesian network structure of “Xigou Reservoir Dam Flooding Accident” was constructed. Afterwards, the conditional probabilities of the nodes are determined by the method of expert scoring, and finally the complete Bayesian network of “Xigou Reservoir Damming Accident” is constructed.

According to the accident investigation report of “Xigou Reservoir Damming Accident”, combined with the expert opinion, the prior probability of Bayesian net-work nodes is determined, so as to carry out the scenario projection. Comparing the results with the actual situation, the two are generally consistent, which verifies the reliability and feasibility of the model.

In the development of this accident, the conditions of equipment maintenance and the implementation of emergency response activities have a significant im-pact on the accident progression. Under conditions of normal equipment maintenance or active emergency response, the probability of the 'water level status' being normal increases by over 20%. Additionally, under normal staff supervision, the probability of the 'water level status' being normal also increases by 14%

From the analysis of the projected accidents, it is clear that human factors have a significant impact on the accidents, and that complete personnel supervision mechanisms and reasonable equipment maintenance arrangements are of great significance for risk prevention and avoidance.

The whole process of deduction in this paper mainly relies on sufficient scenario data and expert knowledge, which is more subjective and affects the accuracy of accident deduction. Therefore, it is important to improve the objective data in the accident derivation to improve the accuracy of the model. On the other hand, time is an important influence factor in the development of unexpected accidents, and adding the time factor is more perfect for the accident derivation.

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