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Analysis of the time-varying characteristics of the relationships and influence degrees among dam economic life influencing factors

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HIGHLIGHTS

- Economic life of dam was influenced by itself, society, and ecological environment.
- A time-varying analysis model of factors on economic life of dam was constructed.
- Dam economic life was much affected by total reservoir capacity, management level.
- Management measures to extend the economic life of dams were proposed.

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ABSTRACT

As dams age, operating costs increase and associated risks intensify. Addressing the mechanisms influencing dam economic life is crucial for accurate assessment and operation management. Dam economic life is affected by social and ecological environmental factors, whose types, relationships, and influence degree vary over time. In this study, influencing factors were identified across five dimensions: safety, cost, benefit, social impact, and ecological and environmental impact. Using the Random Forest method, the interaction degrees among individual factors were analyzed. Using on Markov theory, the Decision-making Trial and Evaluation Laboratory (DEMATEL) method, and the Interpretative Structural Modeling Method (ISM), a time-varying analysis model was constructed to reveal the mechanisms of these influencing factors. The model was applied to the Luhun Reservoir in Luoyang City, Henan Province, China. Results showed that during the first 20 years of dam operation, factors such as total reservoir capacity and management level considerably affected dam economic life. Over the next 20 years, total reservoir capacity and population protection became the dominant factors. Dam economic life can be extended using management measures, including improving storage capacity utilization, enhancing silt control, and increasing flood control storage capacity.

1. Introduction

As critical national infrastructure, dams are crucial in flood control, power generation, water supply, river salinity regulation, and recharge groundwater (Demirhan et al., 2025; Ge et al., 2021; Zhou et al., 2024). In numerous countries, large scale dam construction projects have been developed (Liu et al., 2024). According to recent data, 94,877 reservoir-types were constructed in China (Ministry of Water Resources of the People's Republic of China., 2023), and 91,804 in the United States (US) (United States Army Corps of Engineers, 2024). In China, above 80 % of reservoirs were built between the 1950s–1970s (28,800 in the 1950s, 19,400 in the 1960s, and 31,300 in the 1970s) (Ge et al., 2025). These reservoirs have been operating for 50–70 years. Similarly, approximately 80 % of reservoirs and dams in the US have been in service 50 years (United States Army Corps of Engineers, 2024). According to relevant standards, the reasonable service life of dams varies between 50 and 100 years, depending on their grade (Ministry of Water Resources of the People's Republic of China., 2014). Owing to historical constraints, reservoirs constructed in China during that period were characterized by low design standards and poor construction quality

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(Zhao et al., 2022; Zhang et al., 2022). In recent years, the frequency of extreme weather events and above-standard has considerably increased. Consequently, dam failures have occurred more frequently, causing severe damage to surrounding and downstream areas (Youssef et al., 2025). Around the Chinese New Year in 2023, the Xinghuo Reservoir (Operated for 55 years, with long-period high water levels, storage exceeding standards, and design flaws) in Hailun Farm, Heilongjiang Province, the Lianfeng Reservoir (Operated for 48 years, with poor construction quality in the risk removal and strengthening process) in Midong District, Urumqi, Xinjiang Uygur Autonomous Region, and the Quting Reservoir (Operated for 53 years, with poor construction quality) in Hongtong County, Shanxi Province, all failure (Sheng et al., 2023). In May 2018, the Shiyue Gou Reservoir (Operated for 9 years) in Xinjiang, China, failed under extreme rainfall, resulting in 20 fatalities (Wu et al., 2020). In May 2020, two dam failures (The Edenville Dam, which operated for 96 years, failed due to persistent rainfall. The Sanford Dam, which operated for 95 years, suffered overtopping failure caused by the Edenville Dam failure, subsequently triggering a cascade of failures) occurred in Michigan, US (Mehta et al., 2020). As operation time increases, numerous of reservoir dams enter the non-economic life phase, marked by reduced operational benefits and safety, including sharply rising operational risks and costs (Willebrand et al., 2024). Hence, developing effective measures to mitigate dam operation risks while maintaining economic efficiency has become a critical issue in the reservoir operation and management.

The service life of an engineering project can be divided into technical and economic life (Xu et al., 2025; Ge et al., 2024). Economic life refers to the acceptable service life that maintains a comprehensive input-output ratio, reflecting economic rationality in engineering use, and is closely related to the operational efficiency of the project (He et al., 2023). In previous studies, we focused on the safety of engineering structures, while the economic efficiency of dam operation in strategies was overlooked, thereby resulting in situations wherein inputs exceed outputs (Ge et al., 2025). The operational risks and costs of numerous dams have increased in recent years, scholars have begun investigating dam economic efficiency from a safety-oriented perspective. Martin (2008) analyzed how maintenance, monitoring and management affect service life and operational economic benefits of concrete and rockfill dams considering physical state changes structures. Dillon and Fishman (2019) examined the effect of agricultural productivity and irrigation efficiency on dam related benefits, such as power generation and flood control, in relation to long-term sustainable operation. Sharafati et al. (2020) proposed a novel random simulation optimization method integrating safety and economic factors using annual operating cost and dam failure probability as optimization objectives for overall dam design. Song et al. (2020) developed a dynamic trade-off model incorporating power generation, fish populations, and project costs using a system dynamics approach to improve dam operation and management, thereby extending dam economic life. To improve the economic efficiency and scientific rationality of dam operation and management, Opgrand et al. (2020) analyzed the costs of restoring downstream ecosystems and compared them to the benefits, further supporting the extension of dam economic life. Kim et al. (2017) comprehensively evaluated the impact of flood damage costs on the economic efficiency of reservoir operation and evaluated dam safety upgrade plans from a flood-damage mitigation perspective, thereby ensuring the economic rationality of dam operation and management inputs and outputs.

The aforementioned studies have provided a foundation for research on the economic viability and service life of reservoir dams and improved continuous dam operational and management systems. However, because input–output activities involved in reservoir operation closely linked to the social and ecological environment, dam economic life is influenced by a wide range of social and ecological factors. Over time, influencing factors, interrelationships, and influence degrees have changed dynamically with societal and the environmental developments. Hence, understanding how these factors affect dam economic life in reservoir dams is crucial for accurate economic life assessment and effective operational management. Additionally, growing attention to operational risks has highlighted the importance of integrating risk management concepts with economic operation management within dam management system. To address this issue, this study identified influencing factors from the perspectives of the dams, society, and ecological environment, focusing on safety, cost, benefits, social impact, and ecological impact. Using the Random Forest method, grade intervals and state transition matrices representing interaction degrees among factors were determined. Based on Markov theory, DEMATEL (Decision-making Trial and Evaluation Laboratory) method, and ISM (Interpretative Structural Modeling Method) method, a time-varying analysis model was developed to capture the aforementioned factors, while corresponding management measures were proposed to ensure the safety and economic efficiency of the reservoir dam operations.

2. Material and methods

2.1. Study area

The Luhun Reservoir is located in Song County, Luoyang City, Henan Province, China, as shown in Fig. 1. It is an earth-rock dam with a height, length, and width of 55, 710, and 8 m, respectively. The reservoir storage capacity is 1.32 billion m^3. It was constructed in 1959 and began operations in 1965. Numerous cities, railways, and cultural relics are located downstream of the Luhun Reservoir, including Yichuan County, Luoyang City, and Gongyi City, with permanent populations of 792,841, 2,550,470, and 800,700, respectively. Owing to its strategic location, the Luhun Reservoir is critical in flood control and disaster mitigation, protecting millions of people downstream.

2.2. Identifying the influencing factors on the economic life of reservoir dams

To develop and utilize water resources effectively and reduce flood disasters, numerous reservoir dams have been constructed worldwide. During their construction and operation, considerable human and material resources were invested. From an ecological perspective, dam construction and operation alter river flow and hydrological conditions, thereby surrounding biodiversity and vegetation coverage (Comino et al., 2020; Xu et al., 2020). Despite these costs, normal dam operation generates considerable benefits (Bell et al., 2025), including hydropower generation, water supply for domestic industrial, and agricultural use, and improved navigation efficiency (Martinez et al., 2025; Moreira et al., 2024). Further, reservoir dams ensure ecological and environmental water requirements, promote vegetation growth, and improve the overall productivity of ecosystems (Chen et al., 2020; Guimaraes et al., 2021). However, dam operation involves inherent risks. During extreme rainfall or flooding, if the inflow exceeds maximum reservoir storage capacity, overtopping may occur, resulting in dam failure (Jibhakate et al., 2024). As the majority of dams are located in mountainous or high-altitude areas, a failure can cause reservoir water to rush rapidly downhill. The resulting conversion of potential energy into immense kinetic energy during flood can result in severe destruction along its path (Al-Gurairy et al., 2024; Yi et al., 2025).

In the construction and operation phases, the positive and negative impacts of reservoir dam operation were closely related to society and the ecological environment, as shown in Fig. 2. In identifying the influencing factors of dam economic life, this study not only focused on the dam but also considered the interrelationships among the dam, society, and ecological environment.

Dam economic life is closely related to the input-output activities during its operation. These activities focus on ensuring dam safety, wherein safety implies that the dam remains structurally intact and operational. In this study, the influencing factors of the dam economic

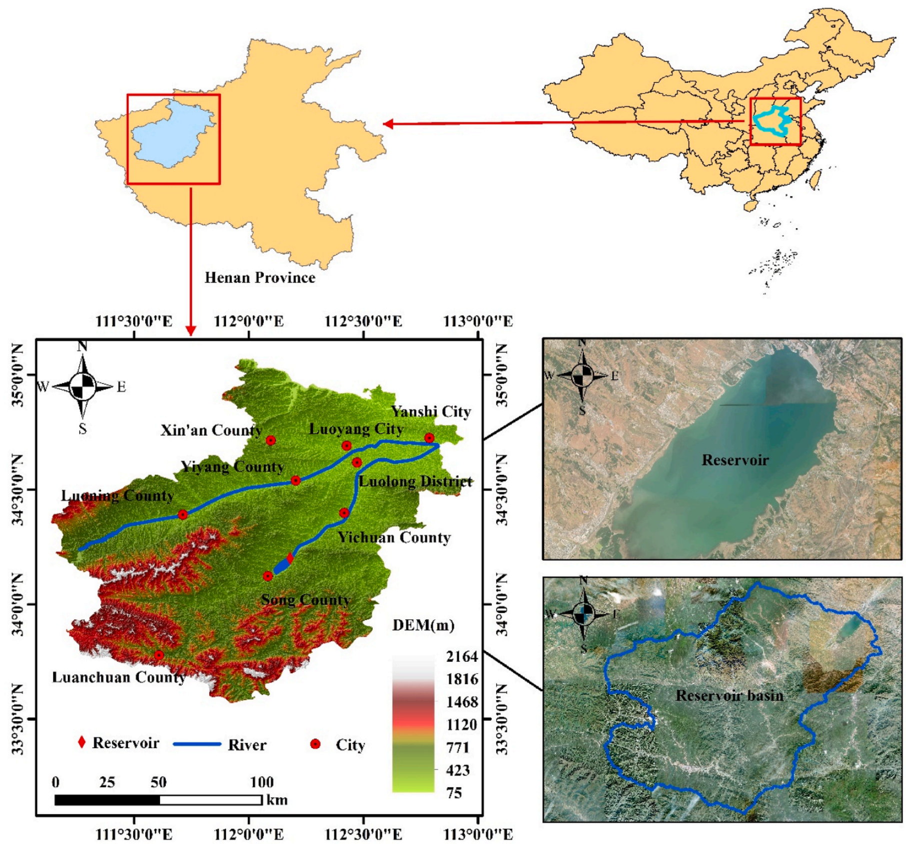

Fig. 1. The location of Luhun Reservoir and the distribution of surrounding city.

life were identified and analyzed comprehensively consider the relationships among dams, society, and ecological environment. Factors were classified into five aspects: safety, cost, benefit, social impact, and environmental impact, as shown in Fig. 3.

Prior studies have paid considerable attention to dam safety issues (Nourani et al., 2024). To enhance dam managements and operational safety, researchers have summarized and analyzed the causes and forms of dam failures based on past failure cases. Dam failure modes are classified into two types: overtopping and structural failure (Khursheed et al., 2025; Khan et al., 2025). Overtopping failure occurs frequently in earth-rock dams (Li et al., 2024). When excessive floods cause inflows to exceed outflows, the reservoir water level rises rapidly, surpassing dam crest elevation. When this happens, floodwater erodes the crest and downstream slope materials, gradually forming a failure that penetrates the dam body and result in large-scale damage. Overtopping failures in earth-rock dams generally manifest as either progressive or instantaneous damage (Chen et al., 2019). Conversely, gravity dams, constructed with high-strength concrete, may experience instantaneous failure when excessive water pressure causes instability and overturning. From the aforementioned analysis, factors such as dam type (Zuo et al., 2024), height (Rif'atin et al., 2024), total reservoir capacity (Fluixa-Sanmartin et al., 2019), flood control capacity (Zhou et al., 2020), and dam body materials (Zhao et al., 2024) considerably impact overall dam safety during overtopping events. Regarding structural failure modes, the strength of dam material is critical the higher the material strength, the greater the structural stability, and lower the risk of seepage and landslide failure. Although routine hazard mitigation and reinforcement can improve safety, accumulated structural deterioration over time reduces the effectiveness of these measures, thereby resulting in a gradual decrease in overall dam safety.

In the cost aspect, during dam, economic and material inputs comprise two components: daily operation and management costs, removal danger and strengthening costs (Petheram and McMahon, 2019; Kandulu et al., 2024). According to the 《Regulation for economic evaluation of water conservancy construction projects》 (SL72-2013), daily operation and management costs refer to the expenses required to ensure normal reservoir dam operation. These include material costs, fuel and power expenses, employee salaries, management fees, reservoir area funds, fixed asset insurance premiums, and depreciation costs (Ministry of Water Resources of the People's Republic of China., 2013). Because reservoir dams vary in type and scale (dam height and storage capacity), the manpower and material resources required for safe operation also differ. Generally, larger projects demand greater management efforts, and incur higher daily operational and management costs. As a dam ages, structural hazards inevitably develop. Ensuring safe operation requires detailed hazard mitigation plans and allocation of human and material resources for remediation. Further, dam operation inherently involves considerable risk, which is determined by its probability and consequences. Probability is closely related to dam safety, while consequences depend on the level of socio-economic development in the surrounding and downstream areas (Goel and Srinivas, 2025).

In the benefit aspects, with the continuous progress and development of society, reservoir dams have been increasingly utilized for multiple purposes such as power generation, agricultural irrigation, and aquaculture, resulting in diversification of their benefits (Pabon et al., 2025; Morovati et al., 2024). Coupled with the rapid urbanization and growing demand for water consumption in daily life and industrial production, dams are critical in supplying water for domestic and productive uses. To improve the overall efficiency of power grids, numerous pumped-storage power stations have been constructed. Further, the construction of reservoir dams raises water levels, improves navigation conditions, and increases transportation efficiency. As societal needs continue to expand, the benefits derived from reservoir dams have been

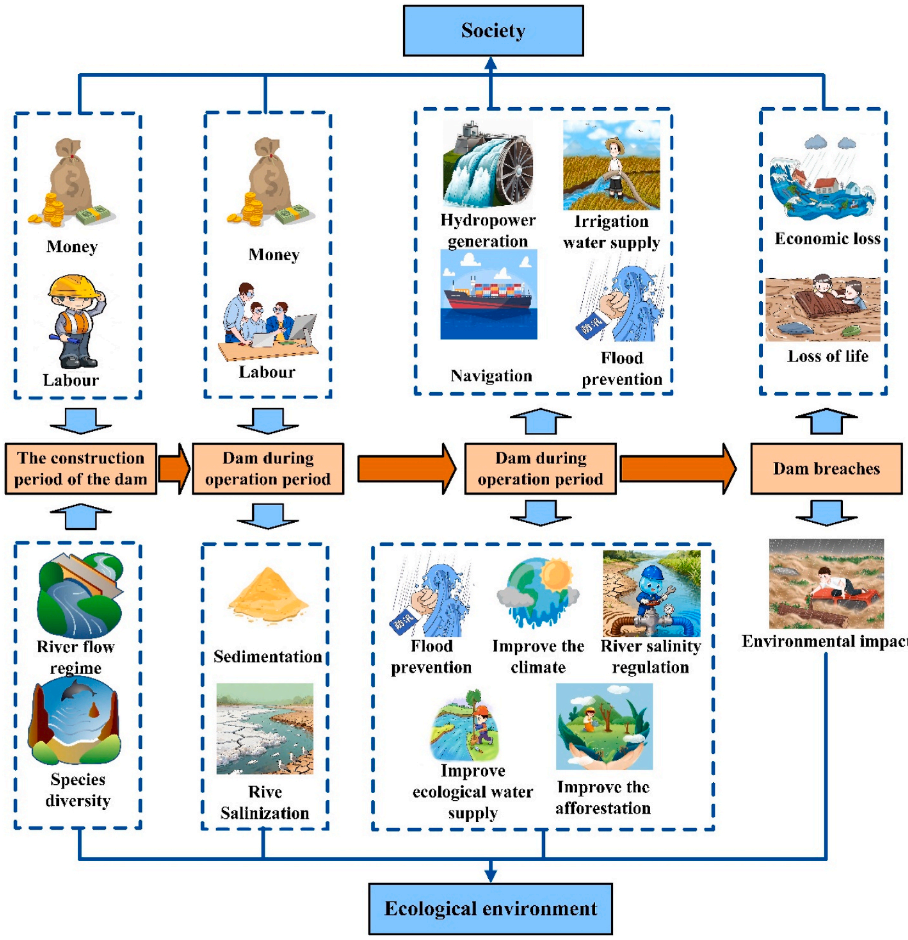

Fig. 2. The relationship between reservoir dams and society and the ecological environment.

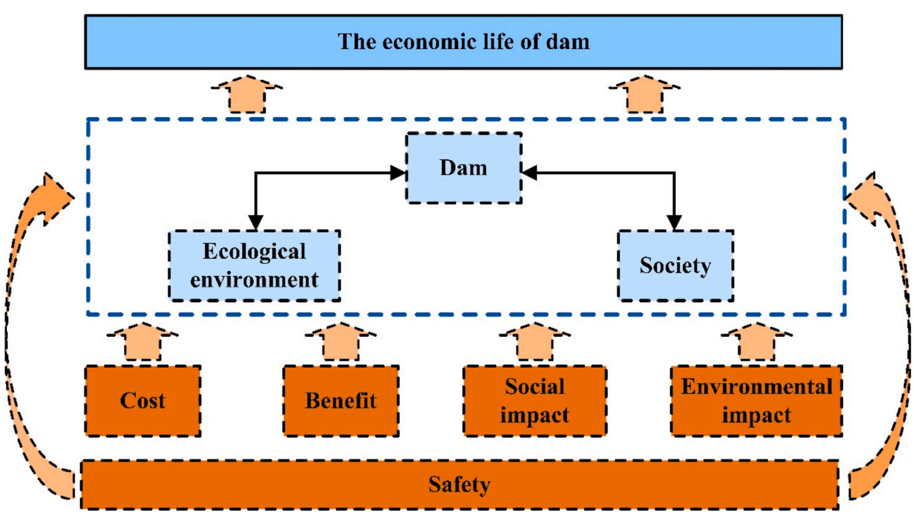

Fig. 3. The identification process of influencing factors on the economic life of reservoir dams.

further developed and gradually optimized. However, the sedimentation severely impacts the development of the dam's benefits, thereby affecting the reservoir dam economic life. Firstly, sedimentation reduces reservoir capacity and diminishes the dam's water storage volume, thereby diminishing its benefits for power generation, irrigation and water supply (Liu et al., 2025). Simultaneously, the long-term sedimentation within the dam reservoir area reduces the permeability of the reservoir bed, thereby affecting the dam's ability to recharge groundwater (Rahmati et al., 2020). Moreover, for artificially replenished reservoirs in arid and semi-arid regions, reduced permeability at the reservoir bed will increase the water detention of the reservoir, thereby exacerbating evaporation losses to some extent and consequently diminishing the volume of artificially recharged water (Sedlacek et al., 2022). Therefore, the impact of sediment deposition cannot be ignored in the daily operation and management of dams.

In the social impact aspects, the construction and operation of a reservoir dam inevitably affect the surrounding society. For example, rising water levels caused by dam construction may submerge residential areas, resulting in large-scale resettlement before the reservoir is filled, and inundate nearby farmland under normal operating conditions. Conversely, dam construction can effectively prevent flood disasters and protect the lives and properties of residents in surrounding and downstream areas. Hence, both the negative and positive impacts of the dam construction are closely associated with the population, arable land, and socio-economic development of the affect regions.

Reservoir dam construction alters natural hydrological conditions of the original river, disrupts existing ecological balance, and negatively impacts ecological environment (Zhang et al., 2021). However, as the reservoir dam gradually integrates with its surroundings, it generates positive environmental impacts. By retaining floodwaters, the dam helps maintain the relative stability of ecosystems inside and outside the river channels, thereby preventing severe ecological damage that uncontrolled floods cause. Further, the reservoir water storage capacity enables pollutant settlement, thereby reducing contamination in downstream river environments. The abundant water stored in the reservoir ensures adequate ecological and environmental flows for surrounding and downstream regions, supporting steady development of the ecosystems. Furthermore, the improvement of ecological conditions and continuous enhancement of biodiversity contribute to advancing current carbon governance efforts for the dam and surrounding society.

Based on the aforementioned analysis, the influencing factors were identified and analyzed. The results are shown in Fig. 4.

2.3. Calculating the influence relationship and degree of influence factors

Different methods can be utilized to analyze the influence degree among individual factors, including Pearson's Correlation Coefficient (Dorado et al., 2022), Linear Regression Analysis (Zeinalnezhad et al., 2020), Principal Component Analysis (Szymanska-Pulikowska et al., 2023), and Random Forest (Fikru and Brodmann, 2025). Random Forest, proposed by Leo Breiman and Adele Cutler, is an efficient learning algorithm based on the classification and regression tree model. In this approach, numerous subsets are randomly extracted from the original data set, while feature subsets are randomly selected during the training of each tree to construct numerous decision trees. The model structure is shown in Fig. 5. The Pearson Correlation Coefficient Method, Linear Regression Analysis, and Principal Component Analysis primarily have the advantage of handling linear relationships and are less accurate in their computational results when dealing with non-linear associations. Compared to the above methods, the Random Forest algorithm effectively captures the complex nonlinear relationships among factors influencing the economic life of reservoir dams. By integrating multiple decision trees, it reduces the risk of overfitting and enhances model stability. This approach yields superior fitting capabilities and robustness (Suarez-Fernandez et al., 2025). Furthermore, model accuracy can be improved by adjusting the number of decision trees, making the calculation both flexible and efficient.

In the aforementioned analysis, numerous factors influence the

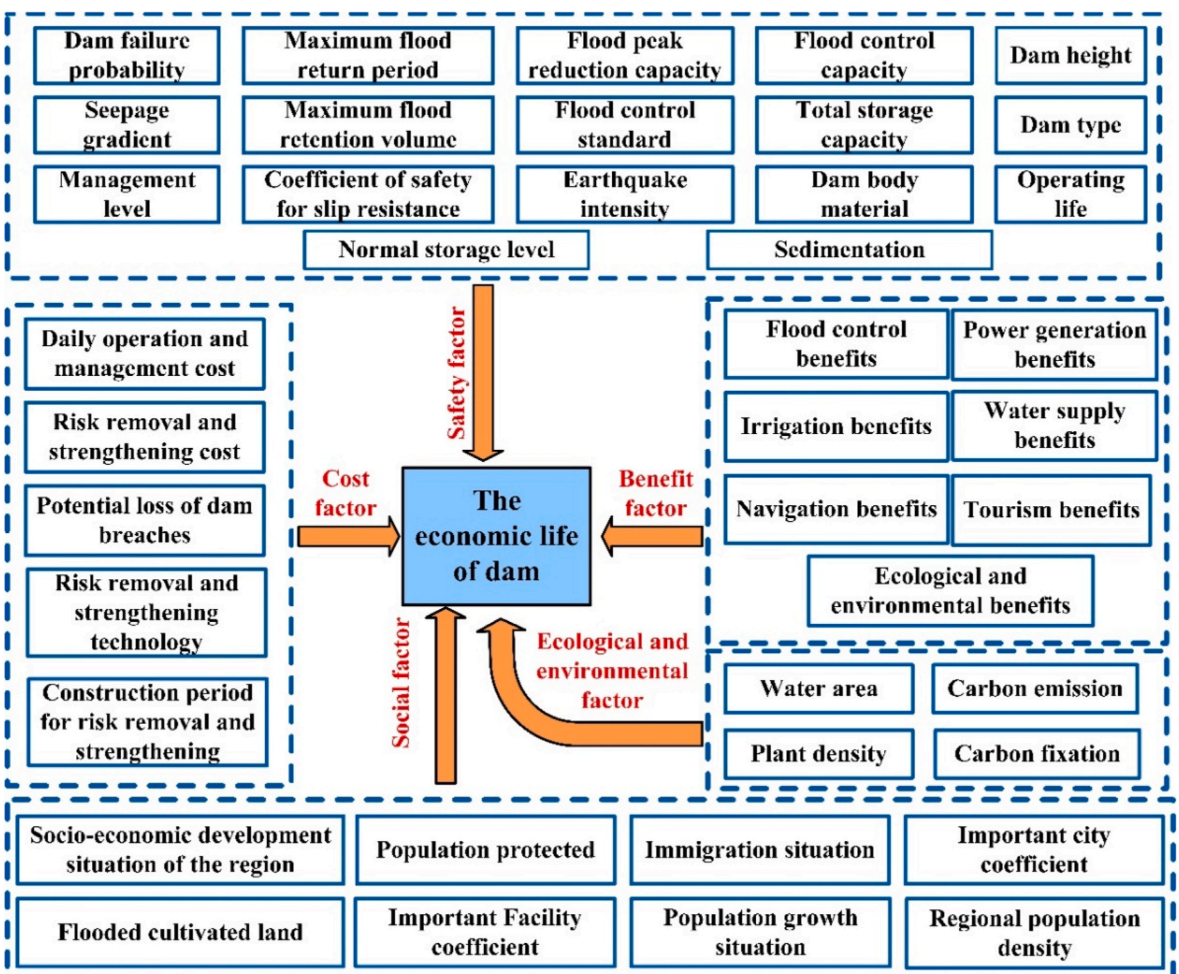

Fig. 4. The identification results of influencing factors of the economic life in reservoir dams.

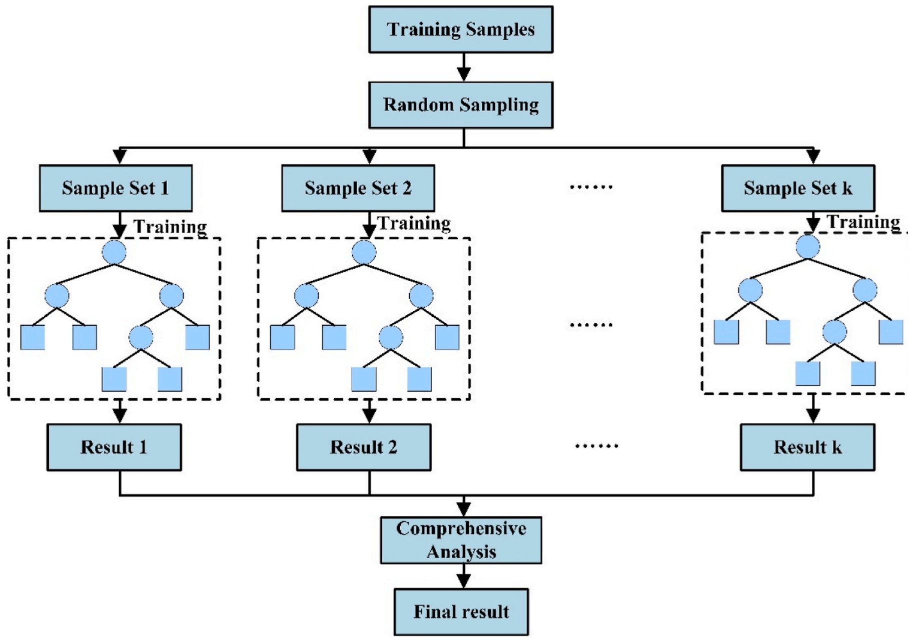

Fig. 5. The structure of the Random Forest model.

economic life of reservoir dams, while their relationships remain complex. Hence, clarifying these relationships within the overall structure is critical. DEMATEL method and ISM model were introduced and combined in this study to analyze the relationships and mutual influence degrees among the influencing factors of reservoir dam economic life. The ISM model, proposed by John N. Warfield, integrates qualitative and quantitative analysis to transform abstract ideas into intuitive models with clear structural hierarchies, thereby revealing the hierarchical relationship among system elements (Trivedi et al., 2021). The DEMATEL method, developed by A. Gabus and E. Fontela at Battelle Laboratories (US), applies graph theory and matrix tools to identify interactions and causal relationships among system factors (Kang et al., 2025). It is characterized by structural intuitiveness, high model reliability, and the capacity to analyze large datasets and determine relationships among complex system factors. Consequently, it provides a simple and effective method for clarifying the degree of interaction among complex system and determining the influence of each factor within the overall system (Li and Fei, 2025).

As operating time progresses, the state of each factor changes with environmental conditions, resulting in corresponding variations in interrelationships and influence degrees. To address this issues, Markov theory was incorporated and coupled with the DEMATEL method and ISM model to analyze the time-varying patterns of the influencing factors. Proposed by Russian mathematician A.A. Markov, this theory is a critical approach for investigating the state space of discrete-time dynamic systems. Its core principle is that the future state of a system depends only on its current state and is independent of past states. Given the state of the process at time t_0, the conditional distribution of the process at time $t > t_0$ is independent of all states prior to time t_0 (Wu et al., 2025). Its calculation is expressed in Eq. (1) as follows:

$$P\{X(t_n) \le x_n | X(t_1) = x_1, X(t_2) = x_2, \cdots, X(t_{n-1}) = x_{n-1}\} = P\{X(t_n) \le x_n | X(t_{n-1}) = x_{n-1}\} \tag{1}$$

2.4. Model for analyzing time-varying relationships and mutual influence degrees among influencing factors of reservoir dam economic life

Given the numerous and complex factors influencing dam economic life, each factor may be affected by multiple others. To address this, the random forest algorithm was introduced to analyze and quantify the mutual influence degrees among factors based on engineering data. The preliminary influence relationships were then determined from the final results. A total of 1200 reservoirs across China were selected as samples for this study. The distribution of the selected samples is shown in Fig. 6 and Table 1.

To convert qualitative relationships into quantitative ones, the mutual influence degrees among factors calculated using the random forest algorithm were subjected to distribution fitting to determine their distribution patterns. The fitting performance was assess using three parameters: Akaike information criterion (AIC), Bayesian information criterion (BIC), and Mean square error (MSE). MSE is a commonly used indicator for measuring the deviation between predicted and actual values, reflecting the average prediction error of the model. A smaller MSE value indicates a higher prediction accuracy. The calculation formula is expressed in Eq. (2).

$$MSE = \frac{1}{n}\sum_{i=1}^{n} (y_i - \widehat{y}_i)^2 \tag{2}$$

where n represents the sample size; y_i the i-th true value; $\widehat{y}_i$ the i-th predicted value.

Qualitatively, the mutual influence degree among factors can be categorized as no influence, slightly, generally, comparatively strong, or extremely strong. Among these, no influence corresponds with a quantitative value 0. In this study, only four levels-slightly, generally, comparatively strong, and extremely strong were considered in the calculation. To ensure uniform interval distribution, the data were divided into four equal intervals based on the distribution fitting results and probability distribution functions. The corresponding quartiles were then calculated to characterize the data distribution and dispersion. The process is shown in Fig. 7.

The state transition probability matrix is a key component of Markov theory and critical link between static and dynamic analysis. It describes the transition probabilities between discrete states, indicating the likelihood of a system moving from its current state to its next, as expressed in Eq. (3). Based on the calculated influence degrees among factors and their corresponding grade intervals, the state transition probability matrix elements can be determined, as expressed in Eq. (4).

$$P_{i-j} = \begin{bmatrix} p_{i-j-1} & p_{i-j-2} & \cdots & p_{i-j-n} \end{bmatrix} \tag{3}$$

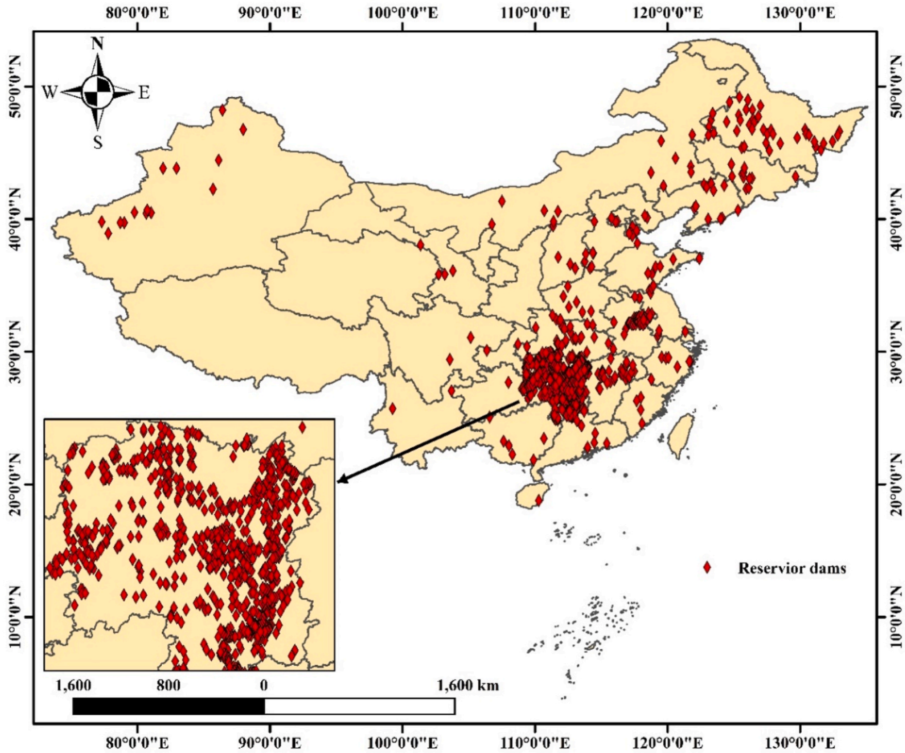

Fig. 6. The location of the samples selected by the study.

Table 1
The situation of the samples selected by the study.

Total sample size	1200 dams	
Dam type characteristics (According to building materials)	Earth dam	289 dams
	Rockfill dam	321 dams
	Concrete dam	308 dams
	Stone masonry dam	282 dams
Engineering scale characteristics	Large (I) type	78 dams
	Large (II) type	149 dams
	Medium	281 dams
	Small (I) type	489 dams
	Small (II) type	203 dams

$$p_{i-j-k} = \frac{N_{i-j-k}}{Z_{i-j}} \left(0 \le p_{i-j-k} \le 1, \sum\nolimits_{k=1}^{n} p_{i-j-k} = 1 \right) \tag{4}$$

where $P_{i\text{-}j}$ represents the state transition probability matrix for the influence degree of factors i on factor j; $p_{i\text{-}j\text{-}n}$ the probability that the influence degree of i on j transitions to grade n; $N_{i\text{-}j\text{-}k}$ the number of occurrences wherein the influence degree of i on j falls within grade k; $Z_{i\text{-}j}$ the total sample size of the calculated influence degree between i on j.

By integrating the Random Forest algorithm with the determined grade intervals, the influence degree grade among each factor pair was determined, while a direct influence matrix D_t was constructed, as expressed in Eq. (5).

$$D_t = D_0 \cdot P^t = \begin{bmatrix} {d_{11}}^0 & {d_{12}}^0 & \cdots & {d_{1n}}^0 \\ d_{21}^0 & d_{22}^0 & \cdots & d_{2n}^0 \\ \vdots & \vdots & \ddots & \vdots \\ d_{n1}^0 & d_{n2}^0 & \cdots & d_{n3}^0 \end{bmatrix} \cdot \begin{bmatrix} P_{1-1} & P_{1-2} & \cdots & P_{1-n} \\ P_{1-2} & P_{2-2} & \cdots & P_{2-n} \\ \vdots & \vdots & \ddots & \vdots \\ P_{n-1} & P_{n-2} & \cdots & P_{n-n} \end{bmatrix}^t \tag{5}$$

where D_t represents the direct influence matrix among factors at time t; D_0 the direct influence matrix among factors at the initial moment, determined based on actual project conditions; d_{ij}^0 the influence degree of i on j at the initial moment; $P_{i\text{-}j}$ the state transition probability matrix for the influence degree of i on j.

To eliminate the effect of differing numerical ranges on the overall model results, the direct influence matrix between factors in the system was normalized, as expressed in Eq. (6).

$$G_t = \frac{D_t}{max \sum_{j=1}^{n} d_{ij}^t} = \frac{\{D_0 \cdot P^t\}}{max \sum_{j=1}^{n} d_{ij}^t} \tag{6}$$

where G_t represents the normalized matrix of the direct influence matrix among factors at time t.

The comprehensive impact matrix is used in system analysis to assess the impact of multiple factors on multiple objectives, reflecting the combined effects of interactions among system elements. Based on the normalized direct influence matrix, the comprehensive influence matrix can be calculated as expressed in Eq. (7).

$$T_t = \lim_{n \to \infty} \left(G_t + G_t^2 + G_t^3 + \cdots + G_t^n \right) = G_t (I - G_t)^{-1} \tag{7}$$

where T_t represents the comprehensive influence matrix among factors at time t; I the unit matrix.

In the comprehensive influence matrix T_t, each element t_{ij} ($i, j = 1, 2, 3, \ldots, n$) represents both the influence degree of i on j and vice versa. The sum of all elements in i-th row of T_t represents the total influence of i on all other factors in the system (except itself), denoted as $E_{i\text{-}t}$. Similarly,

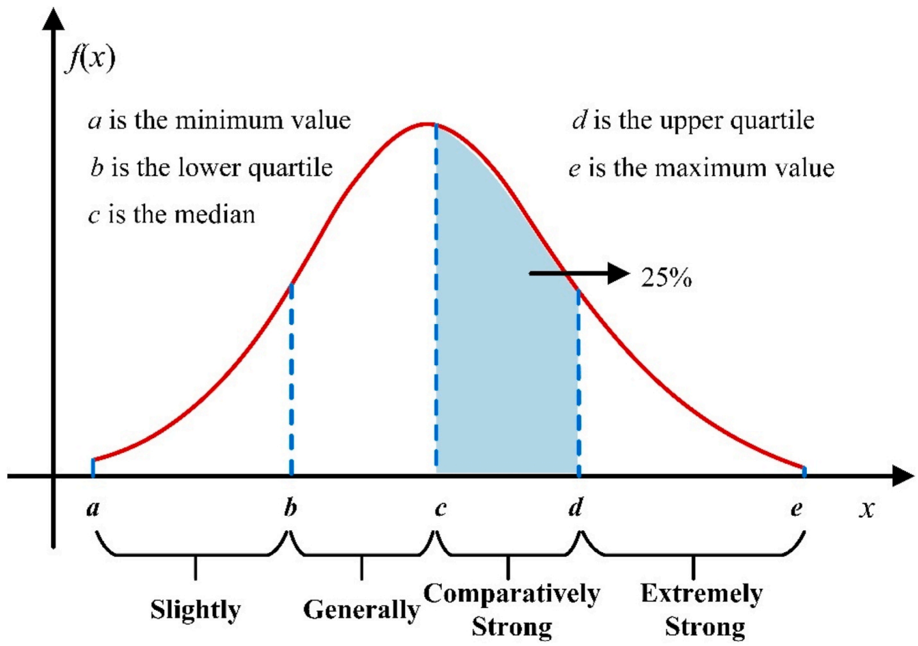

Fig. 7. Determining the influence degree interval.

the sum of all elements in the j-th column of T_t represents the total degree to which j is influenced by other factors (except itself), denoted as $A_{j\text{-}t}$. The calculation is expressed in Eq. (8) as follows:

$$E_{i-t} = \sum_{j=1}^{n} t_{ij-t} \qquad A_{j-t} = \sum_{i=1}^{n} t_{ij-t} \tag{8}$$

The degree of centrality represents the sum of the influence a factor exerts on other factors and the influence it receives, indicating its overall importance in the system. Its calculation was shown in Eq (9). The degree of causality represents the difference between the influence exerted and that received, indicating whether the factor primarily acts as a cause or an effect. The calculation of the degree of causality was shown in Eq. (9).

$$C_{i-t} = E_{i-t} + A_{i-t} \qquad Y_{i-t} = E_{i-t} - A_{i-t} \tag{9}$$

where $C_{i\text{-}t}$ represents the degree of centrality of i at time t; $Y_{i\text{-}t}$ the degree of causality of i at time t.

To clarify the varying roles of different factors over time, the relative importance of each factor at different times points was calculated based on the degree of centrality for each factor across the system. The calculation formula was shown in Eq. (10).

$$W_{i-t} = \frac{C_{i-t}}{\sum_{i=1}^{n} C_{i-t}} \tag{10}$$

where $W_{i\text{-}t}$ represents the relative importance of i in the system at time t. A larger value indicates a higher importance of the factor within the system and a greater overall influence.

The comprehensive influence matrix T_t captures the mutual influence among factors but excludes the self-influence of each. To comprehensively assess the influence relationship within the system, the overall influence matrix of factors was derived from the comprehensive influence matrix, as expressed in Eq. (11).

$$H_t = T_t + I \tag{11}$$

where H_t represents the overall influence matrix of factors in the system at time t.

The accessibility matrix represents the interaction paths among influencing factors, thereby reflecting their mutual accessibility. The overall influence matrix includes the self-influence and inter-factor interactions, which encompasses all relationships within the system. Based on the calculation results of the overall influence matrix, the accessibility matrix M_t, was constructed, as shown in Eq. (12).

$$m_{ij-t} = \begin{cases} 1 & h_{ij-t} \geq \lambda \\ 0 & h_{ij-t} < \lambda \end{cases} \tag{12}$$

where: $m_{ij\text{-}t}$ represents the element in the i-th row and j-th column of M_t, representing the influence relationship between i and j at time t. When $m_{ij\text{-}t} = 1$, an influence relationship exists between i and j at time t; when $m_{ij\text{-}t} = 0$, no such relationship exists.λ represents the threshold for converting the overall influence matrix into an accessible matrix. When the influence degree of i on j exceeds λ, it exerts a reactive influence. λ was determined by comprehensively evaluating all elements of the overall influence matrix. In related studies, λ is determined by calculating the average value of all elements in the overall influence matrix.

Based on the constructed accessibility matrix, the accessibility set and precedence set of each factor at different times were determined. The accessibility set $R(i)$ comprises the influencing factors corresponding to the columns wherein the element value in the row of i equal 1, while the precedence set $Q(i)$ comprises the influencing factors corresponding to the row wherein the element value in the column i equal 1. First, the accessibility and precedence set of all factors were identified. As expressed in Eq. (13), factor satisfying the specified conditions were determined and ground to form the highest-level factor set. The rows and columns corresponding to these were then removed from the accessibility matrix to obtain a new matrix. This procedure was repeated iteratively to identify the second-level factor set until all hierarchical levels were determined. Based on the constructed accessibility matrix, the interaction paths among factors are analyzed to clarify the hierarchical structure of each factor and their influence relationships.

$$R(i)_t = R(i)_t \cap Q(i)_t \tag{13}$$

where $R(i)_t$ represents the accessibility set of i at time t; $Q(i)_t$ the precedence set of *i* at time *t*.

The overall calculation process of the time-varying analysis model for the mutual influence relationships and influence degrees among factors affecting reservoir dam economic life is illustrated in Fig. 8.

3. Results

3.1. Analyzing the influence relationship and influence degree among individual factors

Based on the identified influencing factors of dam economic life, engineering data were collected and analyzed using Random Forest algorithm to examine the influence relationships and influence degrees among factors. The calculated influence degree among individual factors is illustrated in Fig. 9.

3.2. The results of fitting the distribution function of the influence degree between single factors, the influence grade interval, and the transfer matrix

Based on the calculated influence degrees among single factors in the sample, their distributions were fitted, and their corresponding distribution functions determined using the MSE (the smaller the MSE mean square error, the better the fit), as shown in Fig. 10. Majority of the results followed a normal distribution, while some conformed to a Weibull distribution. According to the distribution fitting results, the data were divided into four equal intervals using probability distribution functions and calculated quartiles, thereby transforming the qualitative description of influence degrees into a quantitative one. The classification results of the influence degree grades-slightly, generally, comparatively strong, or extremely strong (excluding no influence, corresponding to 0)—are presented in Table 2.

3.3. Analysis results of time-varying characteristics of mutual influence relationships and influence degrees of factors affecting Luhun Reservoir economic life

Based on the identified influencing factors of dam economic life, relevant data for each factor were collected according to the actual conditions of the Luhun Reservoir. The Random Forest algorithm was then applied to analyze the mutual influence relationships and influence degrees among factors during the reservoir operation. The results are illustrated in Fig. 11.

Using the calculated influence degrees among individual factors, classified influence degree grades from the data sample, and state

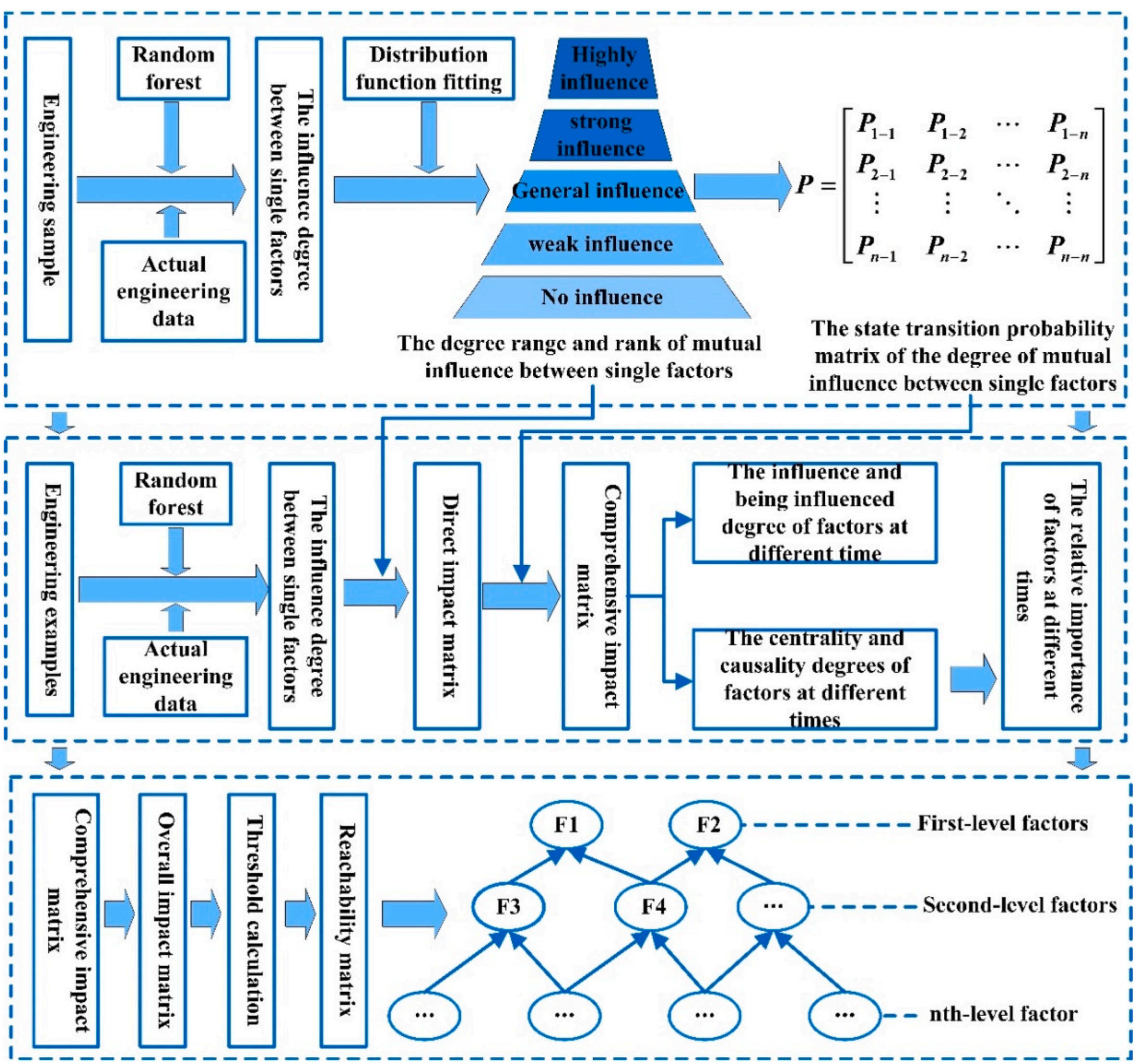

Fig. 8. The overall calculation process of the time-varying analysis model for the mutual influence relationship and influence degree of influencing factors on the economic life of reservoir dams.

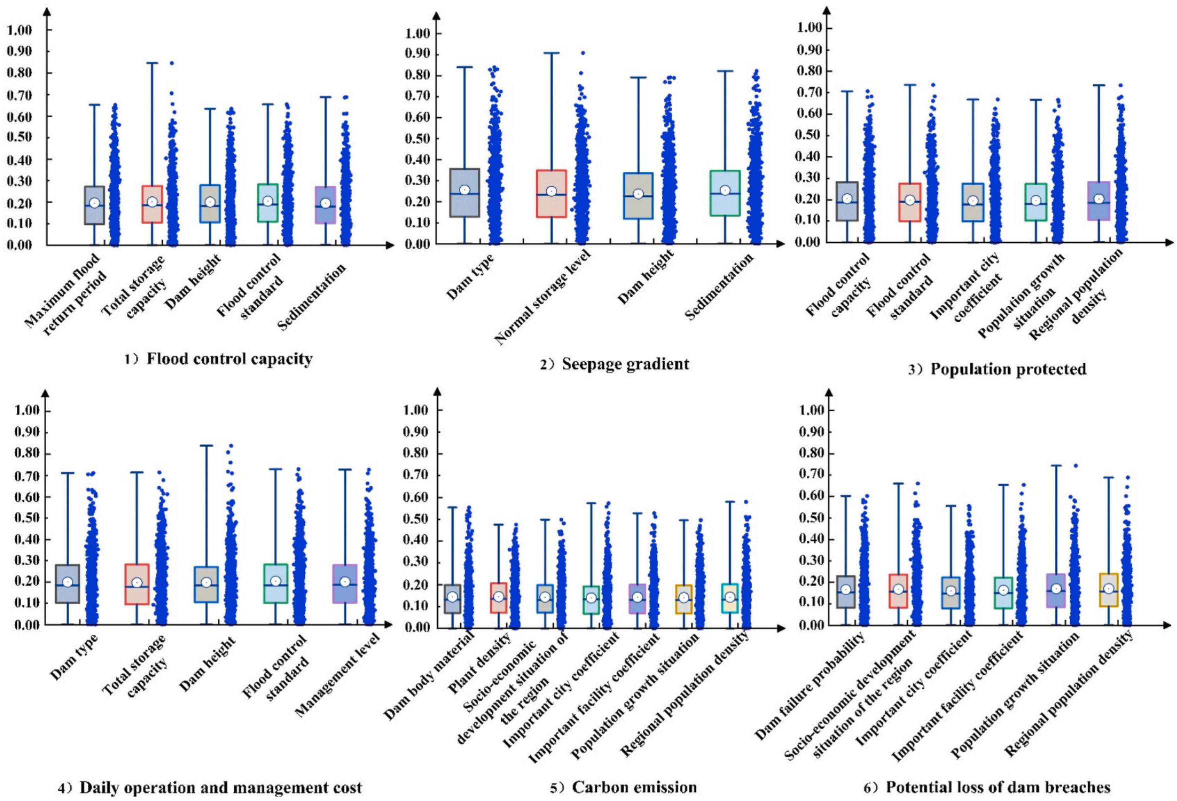

Fig. 9. The calculation results of the influence degree between single factors.

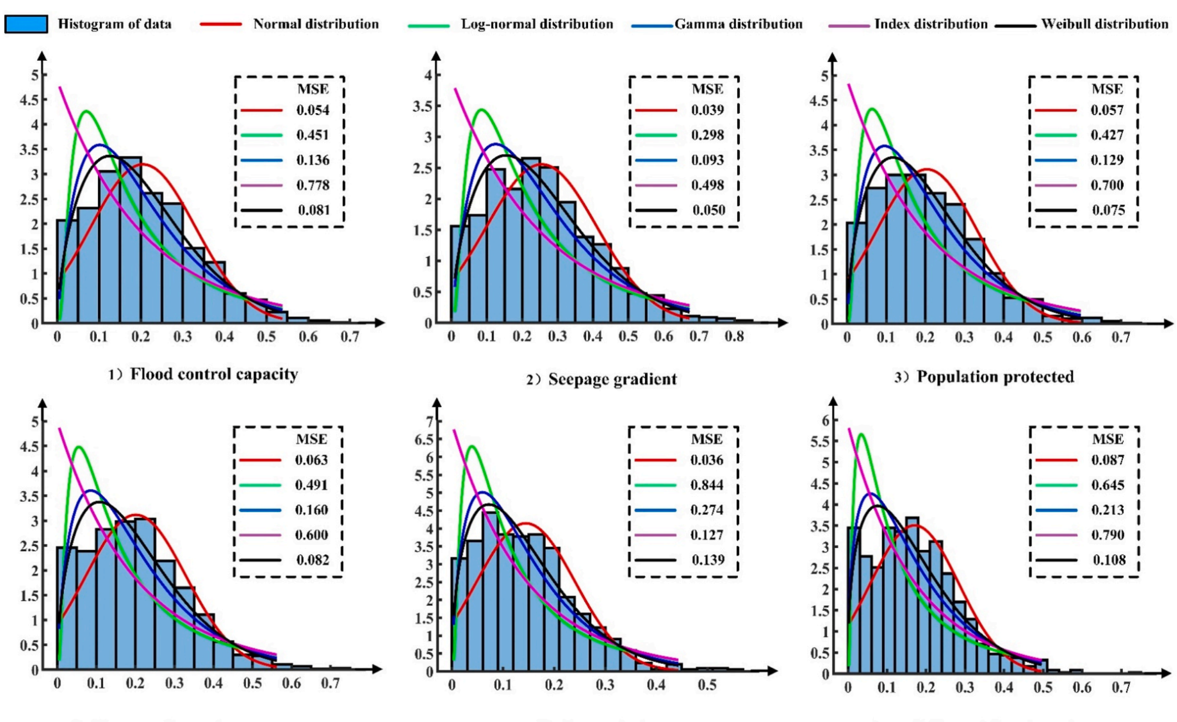

Fig. 10. The distribution function fitting results.

transition probability matrix among factors, a direct influence matrix for reservoir dam economic life at different operation stages was constructed. Eqs. (6)–(10) were applied to compute the influence degree, influenced degree, and relative importance of each factor across different years (with the current year denoted as Year 1). The results are presented in Table 3, while the variations in the relative importance for selected factors are shown in Figs. 12 and 13.

Where 0* represents a value that is very small, approaching 0, but

Table 2
The classification results of the influence degree grade between various factors in the sample.

The influence relationship between factors	Influence degree			
	Slightly	Generally	Comparatively strong	Extremely strong
Maximum flood return period→Dam failure probability	(0, 0.035]	(0.035, 0.066]	(0.066, 0.098]	(0.098, 0.296]
Seepage gradient→Dam failure probability	(0, 0.036]	(0.036, 0.067]	(0.067, 0.097]	(0.097, 0.276]
Dam type→Dam failure probability	(0, 0.035]	(0.035, 0.065]	(0.065, 0.095]	(0.095, 0.268]
Dam type→Seepage gradient	(0, 0.148]	(0.148, 0.257]	(0.257, 0.365]	(0.365, 0.840]
Total storage capacity→Normal storage level	(0, 0.149]	(0.149, 0.252]	(0.252, 0.356]	(0.356, 0.824]
Dam height→Total storage capacity	(0, 0.153]	(0.154, 0.257]	(0.257, 0.362]	(0.362, 0.821]
Maximum flood return period→Flood control standard	(0, 0.001]	(0.001, 0.081]	(0.081, 0.156]	(0.156, 1]
Dam type→Dam body material	(0, 0.014]	(0.014, 0.048]	(0.048, 0.118]	(0.118, 1]
Total storage capacity→Flooded cultivated land	(0, 0.331]	(0.331, 0.492]	(0.492, 0.654]	(0.654, 0.999]

not directly equal to 0.

As presented in Table 3, t_1 represents twenty years ago (relative to the present time); t_2 ten years ago; t_3 five years ago; t_4 the present time; t_5 five years later; t_6 ten years later; t_7 twenty years later. The factor numbers correspond to those shown in Fig. 11.

Based on the comprehensive influence matrices of factors affecting reservoir dam economic life at different times, and using Eq. (11)–(13), an accessibility matrix was developed to characterize the inter-factor influence relationships and determine the hierarchy structure. the resulting hierarchical structures and variations in the influence relationships among factors across different years are shown in Fig. 14.

4. Discussion

(1) As shown in Fig. 13, during the operation of the Luhun Reservoir, from twenty years ago to two years later, factors such as total reservoir capacity and management level were critical within the overall system and considerably impacted the dam operational economic life. From two years later to twenty years later, the importance of total reservoir capacity and population protection increased, exerting a greater influence on the dam economic life. In practical terms, the total storage capacity is closely related to the effectiveness, costs, and associated social and environmental impacts of the dam. The management level directly affects the overall operating costs, while population protection determines the social benefits and flood control performance during operation—both of which considerably influence dam economic life.

As illustrated in Fig. 12, the relative importance of flood control benefits increased over time, driven primarily by the influence of population protection and total reservoir capacity. Based on the final model results, in the subsequent operational stages of the Luhun Reservoir, management strategies must improve the utilization efficiency of total storage capacity, enhance sediment control, and increase the flood control storage capacity of the reservoir dam. These measures would expand the downstream protection range, thereby extending reservoir dam economic life.

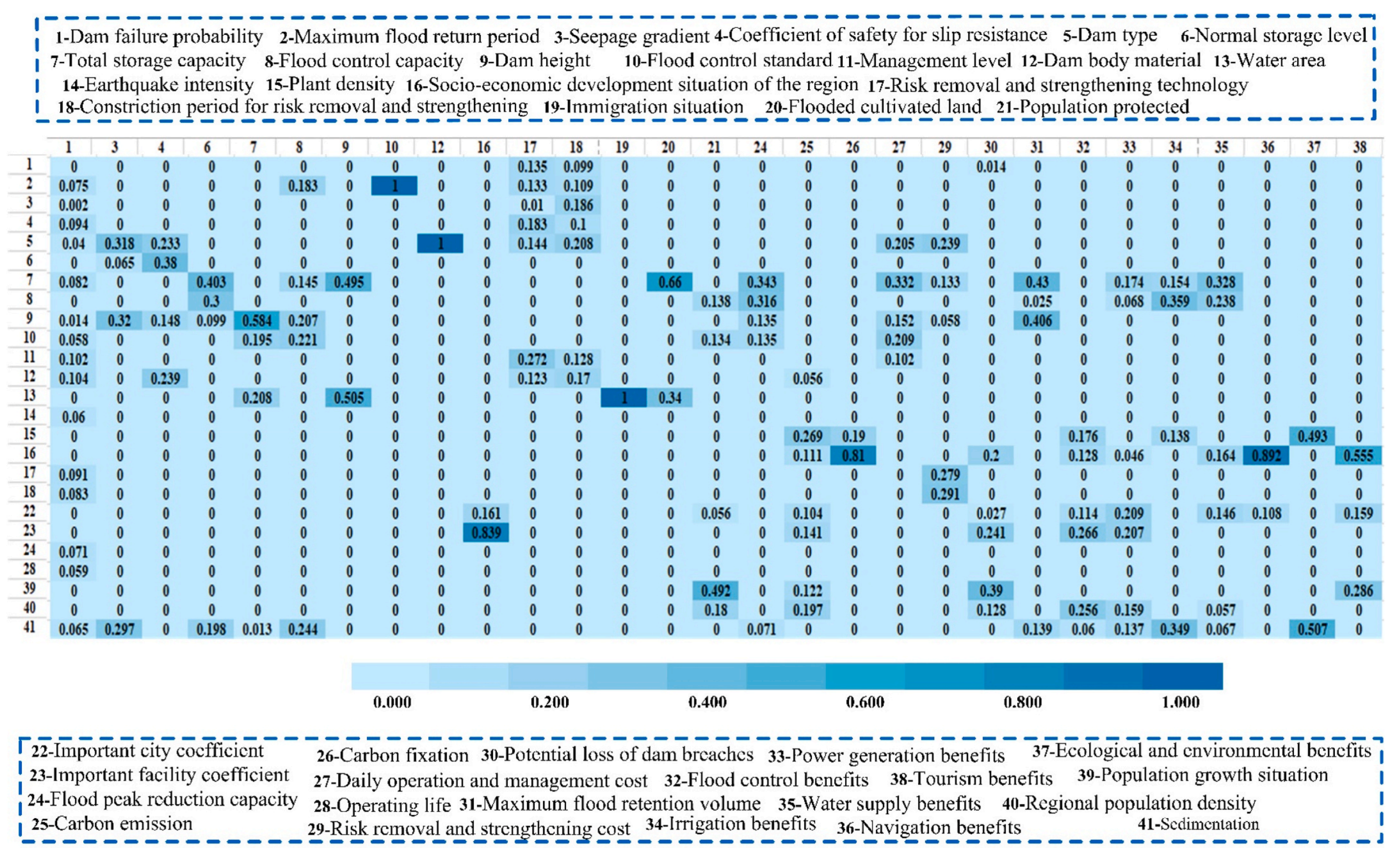

Fig. 11. The influence degree between single influencing factors for the economic life in Luhun Reservoir.

Table 3
The calculation results of the relative importance of various factors in different years.

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
t_1	0.02	0.044	0.018	0.037	0.06	0.021	0.062	0.039	0.051	0.018	0.059
t_2	0.016	0.038	0.023	0.041	0.052	0.026	0.067	0.038	0.055	0.018	0.078
t_3	0.014	0.038	0.024	0.042	0.049	0.027	0.067	0.038	0.055	0.017	0.084
t_4	0.014	0.031	0.024	0.034	0.037	0.021	0.067	0.037	0.048	0.017	0.071
t_5	0.038	0.004	0.012	0.004	0.004	0.002	0.124	0.057	0.036	0.020	0.014
t_6	0.082	0*	0.003	0*	0*	0*	0.197	0.071	0.040	0.020	0.002
t_7	0.168	0*	0*	0*	0*	0*	0.286	0.051	0.027	0.01	0*

	F12	F13	F14	F15	F16	F17	F18	F19	F20	F21	F22
t_1	0.041	0.021	0.002	0.026	0.045	0.022	0.039	0*	0.010	0.006	0.027
t_2	0.035	0.022	0.003	0.023	0.032	0.034	0.040	0*	0.010	0.006	0.023
t_3	0.034	0.021	0.004	0.023	0.029	0.039	0.041	0*	0.010	0.006	0.022
t_4	0.031	0.022	0.003	0.022	0.035	0.039	0.044	0.006	0.008	0.019	0.028
t_5	0.013	0.013	0*	0.011	0.054	0.019	0.021	0.011	0.001	0.103	0.044
t_6	0.003	0.004	0*	0.002	0.038	0.004	0.005	0.004	0*	0.148	0.039
t_7	0*	0*	0*	0*	0.013	0*	0*	0*	0*	0.143	0.025

	F23	F24	F25	F26	F27	F28	F29	F30	F31	F32	F33
t_1	0.030	0.030	0.015	0.010	0.014	0.004	0.023	0.01	0.018	0.039	0.005
t_2	0.025	0.030	0.017	0.010	0.012	0.004	0.027	0.014	0.017	0.031	0.007
t_3	0.024	0.028	0.018	0.010	0.011	0.004	0.028	0.017	0.017	0.030	0.009
t_4	0.024	0.022	0.026	0.008	0.017	0.003	0.022	0.029	0.017	0.027	0.022
t_5	0.011	0.002	0.029	0.001	0.05	0*	0.002	0.038	0.007	0.033	0.064
t_6	0.002	0*	0.008	0*	0.059	0*	0*	0.009	0.001	0.058	0.047
t_7	0*	0*	0.001	0*	0.036	0*	0*	0*	0*	0.083	0.012

	F34	F35	F36	F37	F38	F39	F40	F41
t_1	0.014	0.040	0.022	0.009	0.019	0.011	0.011	0.008
t_2	0.016	0.039	0.013	0.007	0.015	0.011	0.013	0.010
t_3	0.015	0.038	0.01	0.007	0.013	0.011	0.014	0.011
t_4	0.011	0.037	0.008	0.006	0.01	0.015	0.020	0.017
t_5	0.001	0.029	0.001	0.001	0.001	0.018	0.039	0.068
t_6	0*	0.004	0*	0*	0*	0.005	0.033	0.111
t_7	0*	0*	0*	0*	0*	0*	0.014	0.130

(2) As shown in Fig. 14, the hierarchical relationships among factors influencing the Luhun Reservoir operational economic life change continuously over time. However, regardless of the variations in other hierarchical levels, the first-level factors remain constant. These include immigration situation, flooded cultivated land, population protected, carbon emissions, carbon fixation, daily operational management costs, risk removal and strengthening costs, potential loss of dam failure, flood control benefits, power generation benefits, irrigation benefits, water supply benefits, navigation benefits, ecological environment benefits, and tourism benefits. Factors at other hierarchical levels affect Luhun Reservoir dam economic life indirectly through their influence on these first-level factors, which collectively encompass both dam-related aspects and its broader social and environmental impacts. Consequently, when evaluating the Luhun Reservoir dam economic life, these first-level factors can be directly adopted as evaluation indicators to develop a comprehensive indicator system for assessment.

(3) Compared to existing studies, this study identified the influencing factors of reservoir dam economic life across three dimensions-dams, society, and ecological environment and from five perspectives: safety, cost, benefits, social impact, and ecological environmental impact. Using the Random Forest method, the mutual influence degrees among influencing factors were analyzed. Based on different confidence levels, corresponding grade intervals and state transition matrices were determined, enabling the conversion between qualitative and quantitative analyses. By integrating Markov theory with the DEMATEL, and ISM methods, a comprehensive model was developed to elucidate the influence paths, mutual influence degrees, and relative importance of factors affecting reservoir dam economic life at different operational stages under varying risk. Based on the final analysis results, targeted management measures were proposed to enhance the safety and economic efficiency of reservoir dam operations. The proposed model aims to improve the reservoir dam risk management framework and provide a new approach for optimizing dam operation and management.

(4) In this study, based on the actual development situation of China, the influencing factors of reservoir dam economic life were identified across three domains dams, society, and ecological environment, and analyzed from five aspects: safety, cost, benefits, social impact, and ecological impact. Numerous, reservoirs in China were selected as samples. As shown in Fig. 8, the majority of the samples were located near the Luhun Reservoir, exhibiting minor differences in surrounding social development and ecological conditions. However, variations in national contexts and projects specific conditions may shift the focus of affected objects during dam operation. Hence, when identifying influencing factors, analyzing their relationships, and determining their degrees of influence, it is crucial to select scientific and reasonable factors based on actual project conditions, national laws, regulations, and standards, including establishing an analysis system for reservoir dam economic life mechanism that corresponds with the development conditions and strategic needs of the country.

5. Conclusion

This study identified the influencing factors of reservoir dam economic life across three domains - dams, society, and ecological environment and from five aspect: safety, cost, revenue, social impact, and ecological environment impact. The Random Forest method was utilized to analyze degrees of influence among these factors. Based on different confidence levels, the corresponding grade intervals and state transition

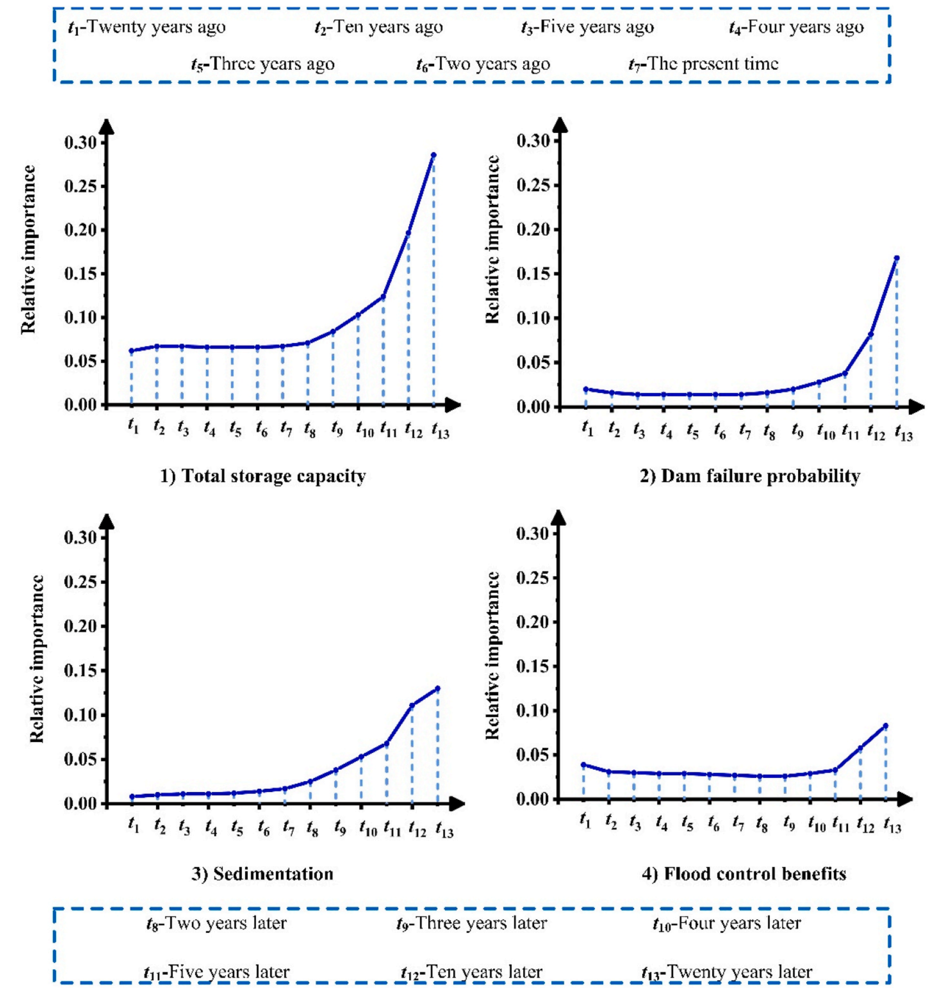

Fig. 12. The change of relative importance of factors over time.

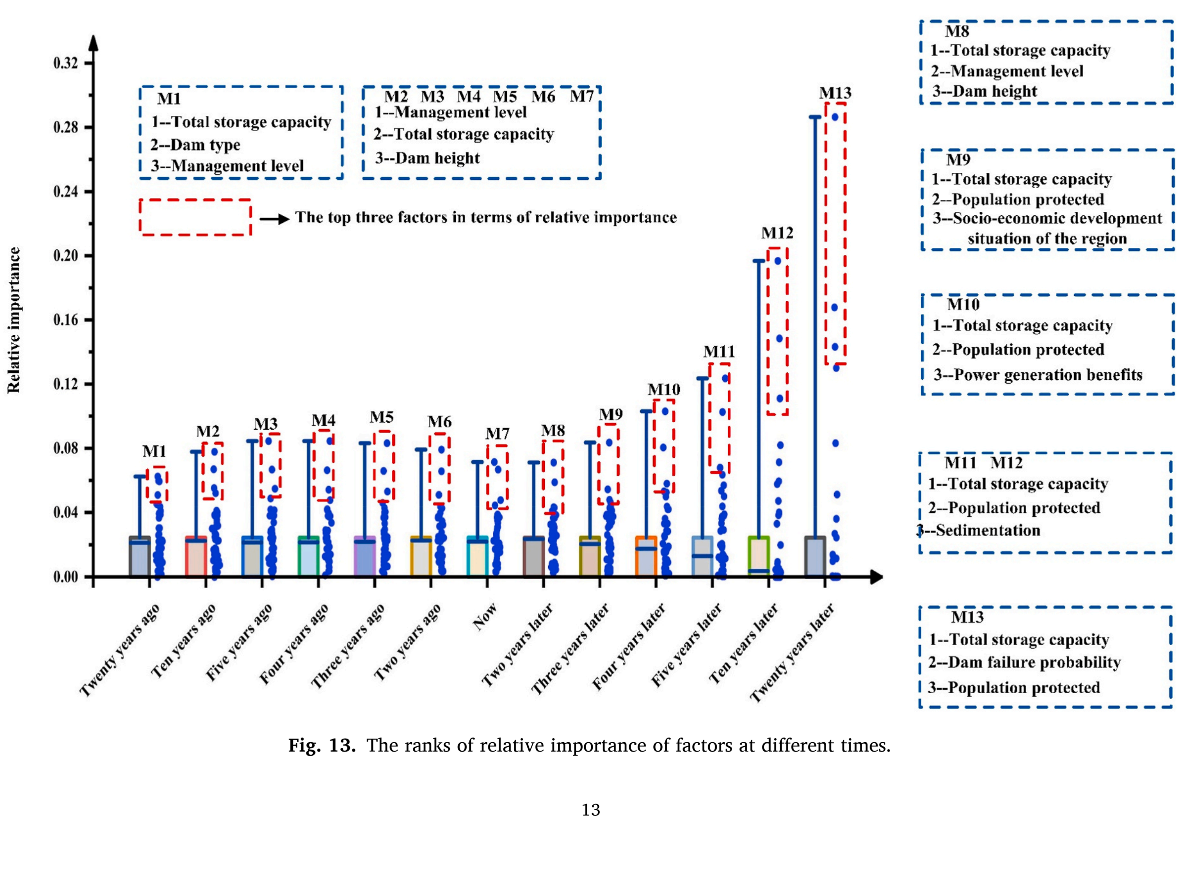

Fig. 13. The ranks of relative importance of factors at different times.

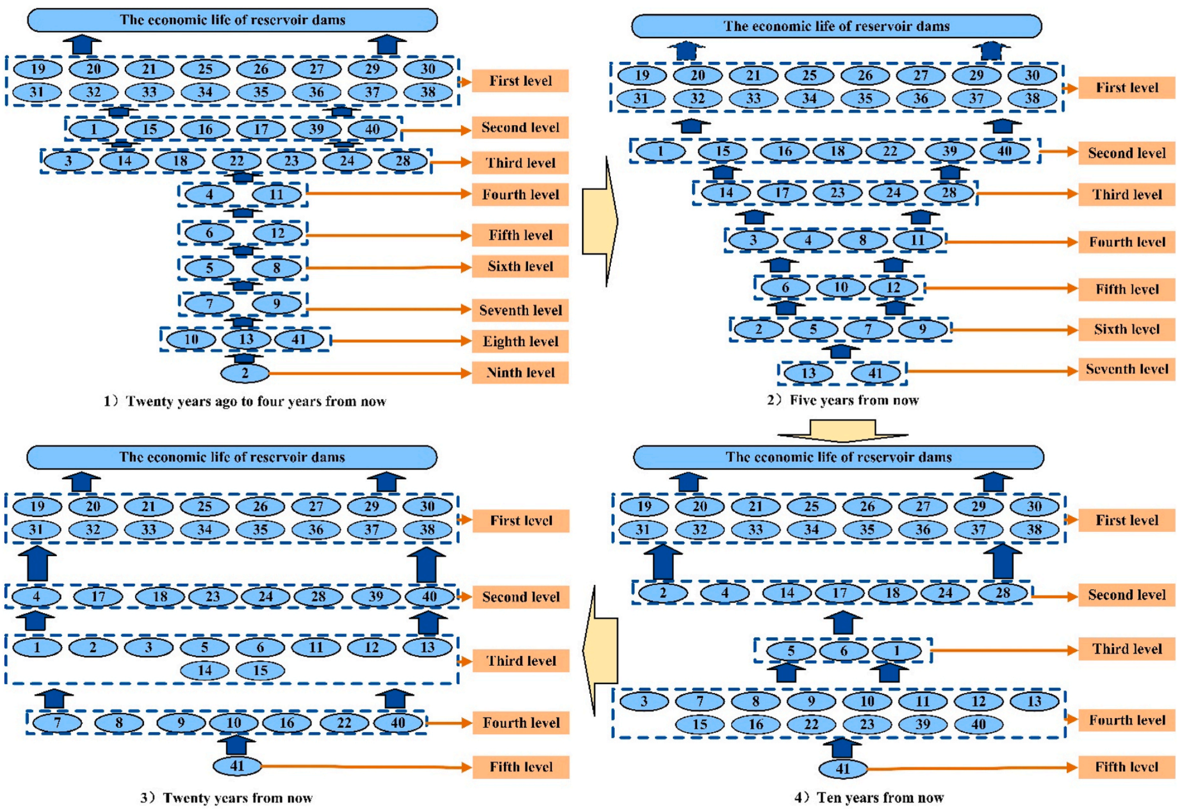

Fig. 14. The hierarchy and influence relations of various factors in different years.

matrices of mutual influence were established. By integrating Markov theory, DEMATEL method, and ISM approach, a time-varying analysis model of influencing factors was developed to clarify their influence paths, mutual relationships, and relative importance at different risk stages of dam operation. The model was then applied to the Luhun Reservoir in Henan Province to analyze the time-varying characteristics of the mechanisms affecting its economic life. During the Luhun Reservoir operation, from twenty years ago to two years later, factors such as total reservoir capacity and management standards were critical in the overall system, considerably affecting the reservoir dam economic life. From two years to twenty years hence, the relative importance of factors such as total reservoir capacity and population protection remains high, continuing to exert strong influence on the dam economic life. Based on the results of the model, in the subsequent operational phase of the Luhun Reservoir, management measures must improve the utilization efficiency of the total reservoir capacity of the dam, intensify sedimentation control efforts, and enhance the flood control reservoir capacity of the dam. These measures will strengthen downstream populations protection and extend dam's economic life.

CRediT authorship contribution statement

Heqiang Sun: Writing – review & editing, Formal analysis, Conceptualization. **Wei Ge:** Writing – original draft, Formal analysis, Conceptualization. **Fuheng Ma:** Methodology, Investigation. **Zongkun Li:** Writing – review & editing, Methodology. **Yadong Zhang:** Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization. **Menglu Xia:** Validation, Supervision. **Jianyou Wang:** Methodology, Investigation, Funding acquisition. **Pieter van Gelder:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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