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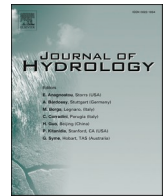
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Research papers

Economic life evaluation of reservoir dams based on comprehensive costs and benefits analysis considering potential dam breach: A case study of the Luhun reservoir in China

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ABSTRACT

The scientific evaluation of a dam's economic life is necessary to determine its management strategy rationally. However, most studies have mainly focused on analyzing the current economic characteristics of reservoir dams without considering their long-term development trend. And they have failed to incorporate the potential loss caused by dam breaches as one of the operating costs for dams. Consequently, this results in the inability to scientifically calculate the economic life of reservoir dam operations. Therefore, this study analyzed the factors influencing the economic life of reservoir dams in term of safety, costs, benefits and society, and established an economic life evaluation indicator system for reservoir dams. Based on the analyses of costs and benefits of reservoir dams, an economic life evaluation model for reservoir dams was constructed by comprehensively considering the impact of potential dam breaches and the social impact of reservoir dams on the production and lives of local residents. Moreover, based on economic theory, the economics of various types of management measures for reservoir dams and their impact on the economic life of dams were analyzed. The proposed model was applied to the Luhun Reservoir in Henan Province, China, to quantify the comprehensive costs and benefits of its operation for each year after 1990 s, analyze the trend of its "cost-benefit" relationship, and calculate its expected economic life. The results showed that when considering its own risks and social impacts, the expected economic life of the Luhun Reservoir was 74 years. The Luhun Reservoir is expected to operate up to its non-economic life span till 2039. Finally, suggestions for expanding the economic life of dams were proposed. Potential dam breach losses can significantly reduce the economic life of reservoir dams. And risk management measures for reservoir dams should be particularly strengthened during daily operations and management.

1. Introduction

As an important part of infrastructure, dams facilitate social and economic development as well as disaster prevention and mitigation (Ge et al., 2022; Wang et al., 2023; Wu et al., 2021). However, owing to historical conditions, many dams in developing countries suffer from problems such as poor construction quality and low flood protection standards (Zhao et al., 2022; Zhang et al., 2022a; Xu et al., 2024). With the passage of operating time, an increasing number of dams are exceeding their operating economic life, with gradually decreasing

operational safety and economy (Wang et al., 2022; Ge et al., 2020a). Meanwhile, the safety and life of a dam are reduced by the influence of external factors (such as critical factors: sedimentation) during its operation. Sedimentation is a significant challenge for reservoir dams. Sedimentation can reduce the capacity of a reservoir, rendering it less flood-resistant and affecting the safety and life of the dam (Schleiss et al., 2016). In addition, the frequency of extreme meteorological events has increased in recent years, with a gradual increase in the frequency of floods that have exceeded the design standards of dams (Macias-Tapia et al., 2021; Chen et al., 2023). Owing to a combination of factors (poor

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construction, low flood protection standards and floods that have exceeded the design standards of dams), dams have breached, causing severe damage to the area around the dam and downstream (Li et al., 2021; Ge et al., 2020b). In May 2018, 20 people were killed and eight disappeared when the Sheyuegou Reservoir in Xinjiang, China, overtopped and breached owing to exceptionally heavy rainfall (Ge et al., 2021; Wu et al., 2020). In May 2020, two dams in the US state of Michigan were breached, necessitating the emergency evacuation of tens of thousands of people in the surrounding area (Mehta et al., 2020). Thus, we are facing multiple challenges of many dams gradually entering the non-economic life span, reduced safety and economy, and serious losses caused by dam breaches, which necessitates focusing on engineering measures to reinforce and improve the operational safety of dams. Consequently, the downgrading or removal of dams that are technically infeasible in terms of reinforcement, have a high social and environmental impact, and are outside the economic life span is an effective and reasonable management measure to eliminate safety hazards. Therefore, a scientific and accurate evaluation of the economic life of reservoir dams and clarification of the safety trends and economic changes in the operation of reservoir dams are crucial for the operation and management of reservoir dams.

In the study of dam operation management systems, an economic analysis of dams based on the relationship between operational costs and benefits is often employed to guide the determination of dam operation management measures. Strzepak et al. (2008) used a computable general equilibrium (CGE) model to compare the Egyptian economy with and without the Aswan Dam, analyzed the socio-economic impact of the construction of the Aswan Dam on Egyptian society, and proposed relevant management measures for the operation of the Aswan Dam. Zamarron-Mieza et al. (2017) analyzed the “cost-benefit” relationship and the potential risks associated with dam management strategies such as maintenance, downgrade, or removal. Consequently, they systematically proposed a multi-criteria approach to decision-making for the management of aging dams. Niu et al. (2021) analyzed the costs and benefits of dam sedimentation management and discussed the economic feasibility of various management options, which provided theoretical guidance for dam sedimentation management. Klein et al. (2022) classified the different types of small hydropower and the various economic indicators used to evaluate hydropower projects. Consequently, they assessed the economics and feasibility of small hydropower development by analyzing the operating costs and benefits of small hydropower in many countries. Nikafkar et al. (2023) studied the economic value of sediments within reservoirs through a cost-benefit analysis and provided an economical and reasonable direction for the management of sediments within reservoirs. Considering the environmental impact of hydropower projects, Hatamkhani et al. (2023) created a comprehensive simulation model to optimize hydropower decisions based on a cost-benefit analysis of hydropower development. However, these studies did not consider the risks to dams and their changing trends over time when analyzing their operational economics. Consequently, they reported an inaccurate evaluation of the operational economics of dams.

Meanwhile, with the development of socio-economic and environmental protection concepts, certain studies have analyzed the economics of dam operation with a comprehensive consideration of its important role in the socio-economic and ecological environment. Brown et al. (2009) integrated biophysical, socio-economic, and geopolitical perspectives into the ‘cost-benefit’ analysis of dam construction. Consequently, they established integrative dam evaluation models (IDAM) to be used in guided dam construction and operational management decisions. Considering the complex relationships between the different stakeholders (environmental, economic, and social) involved in dams at different geographical scales, Song et al. (2021) analyzed the “cost-benefit” of various operation and management options for dams by combining integrated system dynamics modeling (SDM) and role-play simulation (RPS). The results provided a scientific and rational

reference for dam operation decisions. To promote ecosystem conservation and restoration, Saad et al. (2021) quantified Payment for Ecosystem Services (PES) in dam operation and management and analyzed the benefit relationships between the inputs and outputs of dam operation and protected ecosystem restoration. Focusing on the environmental and economic impacts, Nhiakao et al. (2022) evaluated the operation of the Nam Che 1 Hydropower Project using a cost-benefit analysis approach. Sasthav et al. (2022) developed a design model for hydropower development by comprehensively considering multiple objectives of hydropower economics, impacts on ecosystems, etc. Moreover, based on the impact of internal dam sediments on dam operations and the environmental damage caused by the corresponding treatment measures, Shelley et al. (2022) evaluated the economic, social, and environmental impacts of different treatment options in the context of several dam sediment treatment cases in the USA. The results provided a reference for the sustainable management of dams. However, these studies have mainly focused on the judgment of the current economic status of the dam in operation without analyzing and considering the economic changes in the process of its operation. Thus, they cannot accurately assess the changing trend of the dam itself to formulate corresponding management measures to ensure the safety and economy of the dam in long-term operation.

Therefore, this study aimed to analyze the economic characteristics of dams and evaluate their economic life in a scientific and reasonable manner to ensure the economic safety of their long-term operation. The factors influencing the economic life of dams including dam operation safety, cost, benefit, and socio-economic aspects were analyzed. Consequently, an economic life evaluation indicator system for dams was established. By incorporating the theory of dam risk management, the comprehensive costs and benefits of dam operation under the effect of potential dam breach risk were quantified. Based on the change in dam operation time, the trends in the comprehensive costs and benefits of reservoir dam operation over time were analyzed. A dam economic life evaluation model was established to comprehensively consider the social impact of reservoir dams on local production and life. Furthermore, appropriate management measures were formulated to ensure the safety and economy of dam operations and realize the sustainable development of the dam itself, the socio-economic environment, and the ecological environment.

2. Material and method

2.1. Study area

The Lulun Reservoir is a large (1)-type reservoir that is mainly used for flood control and has multiple functions, such as water supply, power generation, irrigation, and tourism. It is an earth and rock dam with a height, length, and width of 55, 710, and 8 m, respectively. The design flood protection standard for this reservoir is 1000 years. The check flood standard for this reservoir is 10,000 years (In the relevant Chinese standards, the flood criteria used for the design of permanent hydraulic structures are divided into two cases: normal application and extraordinary application. These cases are referred to as the design standard and the check standard, respectively. Usually, the normal application of the flood was used to determine the design flood level of a water conservancy and hydropower hub project, the design flood flow, and other hydraulic building design parameters. And this standard flood was called the design flood. The norms provide for floods in a short period of time exceeding the design standard, the main hydraulic buildings are not allowed to be destroyed. They only allow some minor building damage or failure. This situation is known as the extraordinary application conditions or standards, and in accordance with this standard determined by the flood, it is known as the check flood.). The total storage capacity of the reservoir is 1.32 billion m³. The watershed area controlled by this reservoir is 3,492 km². The Lulun Reservoir is located in the middle reaches of the Yi River, a tributary of the Yellow River, in

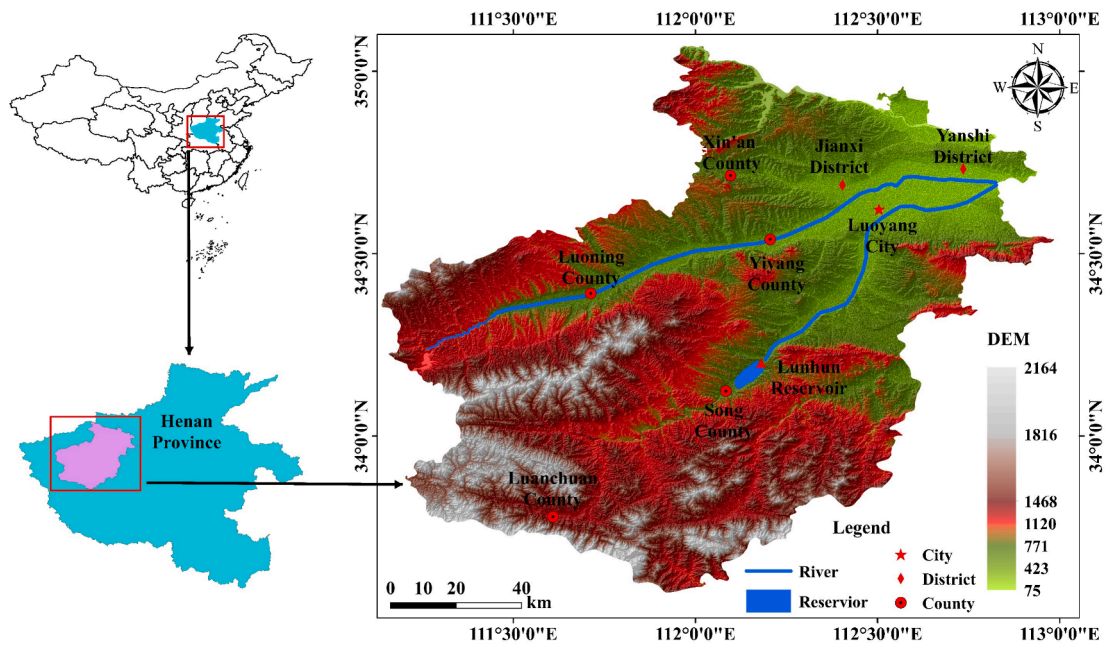


Fig. 1. The geographical location of the Luhun Reservoir.

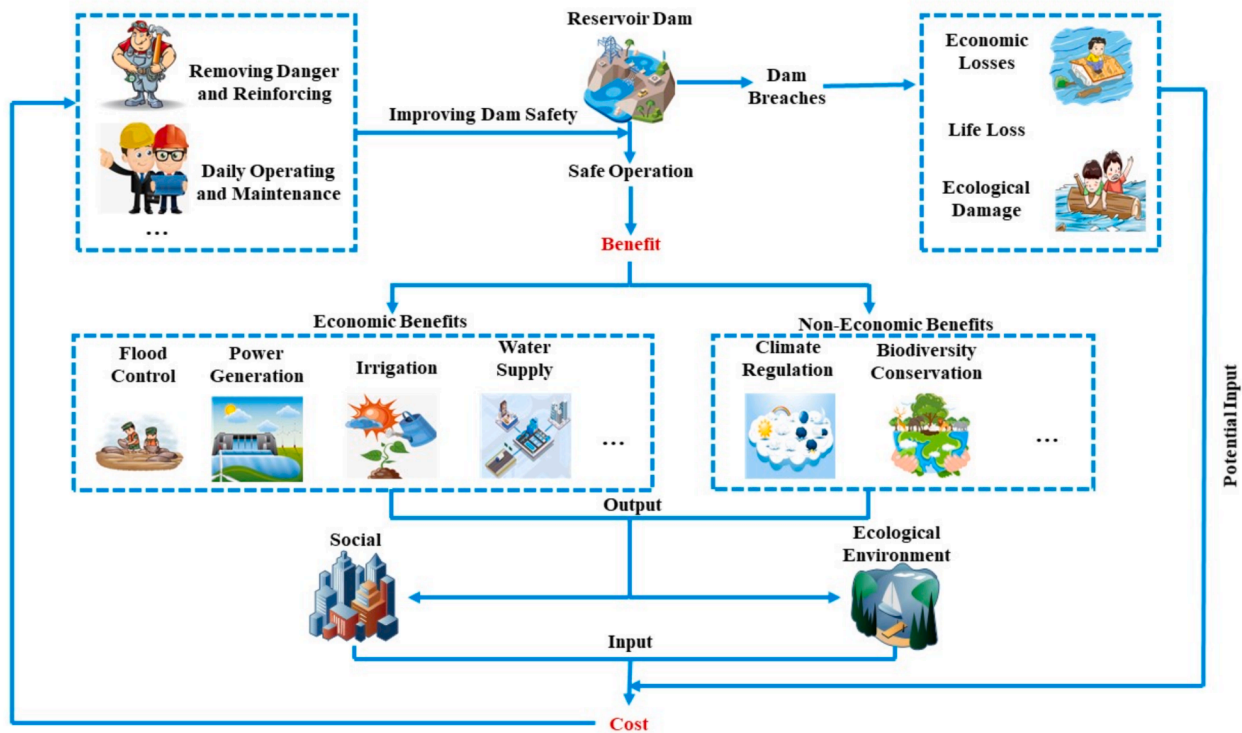


Fig. 2. The relationship between dams, society and the ecological environment.

Song County, Luoyang City, Henan Province, China. It is located at an important location with several important cities, railways, and cultural monuments downstream, protecting the lives and property of millions of people and facilitating flood prevention and mitigation. The geographical location of the Luhun Reservoir is shown in Fig. 1. It was constructed in 1959 and began operations in 1965 (It has been in operation for 48 years). The total investment in the construction of Luhun Reservoir was \$23.38 million (Ge et al., 2022; Zhang et al., 2022b). In 1990, the value of fixed assets of the Luhun Reservoir was assessed and confirmed by the

Henan River Accountant's Office to be \$187.09 million, of which \$175.72 million was for common works and the remaining \$11.36 million was for special works of the reservoir power station (Ge et al., 2022; Zhang et al., 2022b).

2.2. Analysis of indicators for evaluating the economic life of dams

2.2.1. Constructing systems of evaluation indicators

In contrast to the technical life of a building in terms of safety and

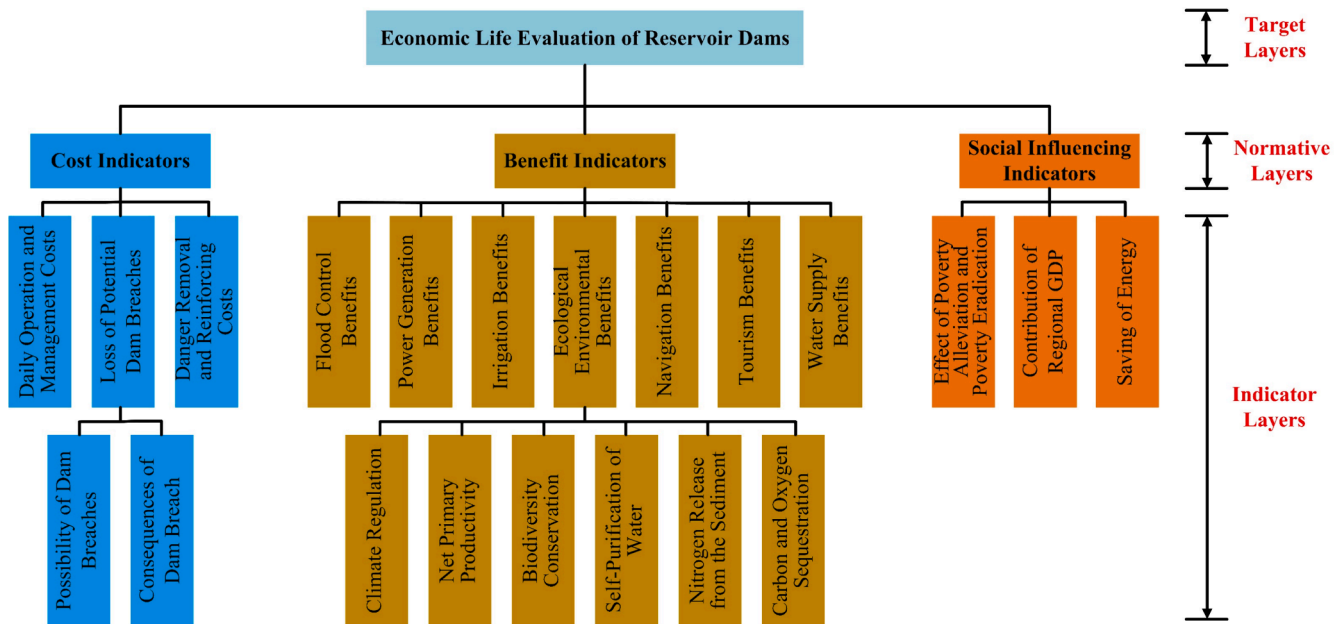


Fig. 3. The economic life evaluation indicator system for reservoir dams.

functionality, the economic life of a building is defined as the number of service years that satisfy the expectations of its economic rationality in terms of an acceptable ratio of combined inputs to outputs (Zhang et al., 2017; Yeter et al., 2022). According to Wu et al. (2012) and Gu et al. (2018), the concept of considering socio-economic benefits, dam safety, the environment, and ecology, as well as the minimization of the negative impact on the environment and ecology or mutual harmonious coexistence, was proposed in the comprehensive evaluation of the service status of dams. In this study, we primarily considered the safety, costs, benefits, and social impacts of dams when analyzing the factors influencing their economic life. The relationships among dams, society, and the ecological environment are shown in Fig. 2.

(1) Safety factors.

The reasons for safety issues in dams can be summarized in two aspects: a) irrational design, irregular construction, and insufficient management inputs, the safety of dams has become problematic, and b) poor working conditions of dams over a long period of time (Pisaniello et al., 2017; Xiang et al., 2015; Yang et al., 2014). For example, natural disasters, such as earthquakes, floods, and landslides, are frequent in areas where dams are located.

However, it is no longer of engineering significance in dam economic life evaluation to conduct operational economics studies on dams with significant safety problems. Therefore, the premise for conducting an economic life study is that the dam can be safely operated under normal technical maintenance conditions.

(2) Comprehensive cost factors during dam operation

The operational costs of a reservoir dam are generally defined as deterministic economic inputs during operation (such as daily operation and management costs, danger removal and reinforcing costs). According to the concept of risk management for reservoir dams, while they function and provide great benefits, they also pose significant risks. This risk is a burden that the society must bear to maintain and develop (Rinzin et al., 2023; Cipollini et al., 2023; Lin et al., 2019). In addition, because of the combined effect of the general deterioration of dams and extreme weather factors, dam breaches occur occasionally, causing severe damage to the areas around and downstream of the dams (Tang et al., 2023; Schmitz et al., 2023). Therefore, when conducting an economic life evaluation study of dams, the loss from dam breaches under the conditions of continuous social and economic development must be considered.

(3) Comprehensive benefit factor during dam operation

Dams, as crucial components of water conservancy engineering systems, serve as important centers for the regulation and control of water resources, as well as a powerful guarantee for the full exploitation of water resources. Dams must be used comprehensively, and the allocation of water resources must be rationalized to maintain a healthy socio-economic and ecological environment. According to the different functions played by dams, they provide various benefits during their operation, including flood control, power generation, irrigation, water supply, navigation, tourism, and ecological and environmental benefits.

(4) Social impact factors.

Social impact assessment of engineering projects is the process of analyzing and evaluating the contribution and impact of projects on the achievement of various national and local social development objectives (Da Silva et al., 2021). In the case of the economic life evaluation of dams, the social impact factor focuses on analyzing the extent to which the social objectives of the dam will be achieved once it is built, and the importance of the dam to the local area (Aledo et al., 2021). The content of social impact evaluation research at the international level has expanded from the traditional, narrow definition to include people-centric evaluation. This has been greatly enriched at both the temporal and spatial levels. Therefore, based on the characteristics of dams, this study identified the social influences on the economic life evaluation of dams in terms of individuals and families, political and social structures, the direct influence of dams, public resources, and social adaptability (Fung et al., 2019).

Thus, based on the above analysis of the impact factors on a dam's economic life, this study established an economic life evaluation index system for dams on the premise of comprehensively considering both technical (dam operational benefits should be greater than operational cost inputs) and social impact factors. The economic life evaluation index system for dams is illustrated in Fig. 3.

2.2.2. Quantifying economic life evaluation indicators for reservoir dams

The quantification of indicators is the basis for constructing a dam economic life evaluation model, and its accuracy directly affects the scientific nature of the dam economic life evaluation results.

(1) Cost indicators.

In this study, the cost indicators primarily included daily operation and management costs, danger removal and reinforcing costs, and the

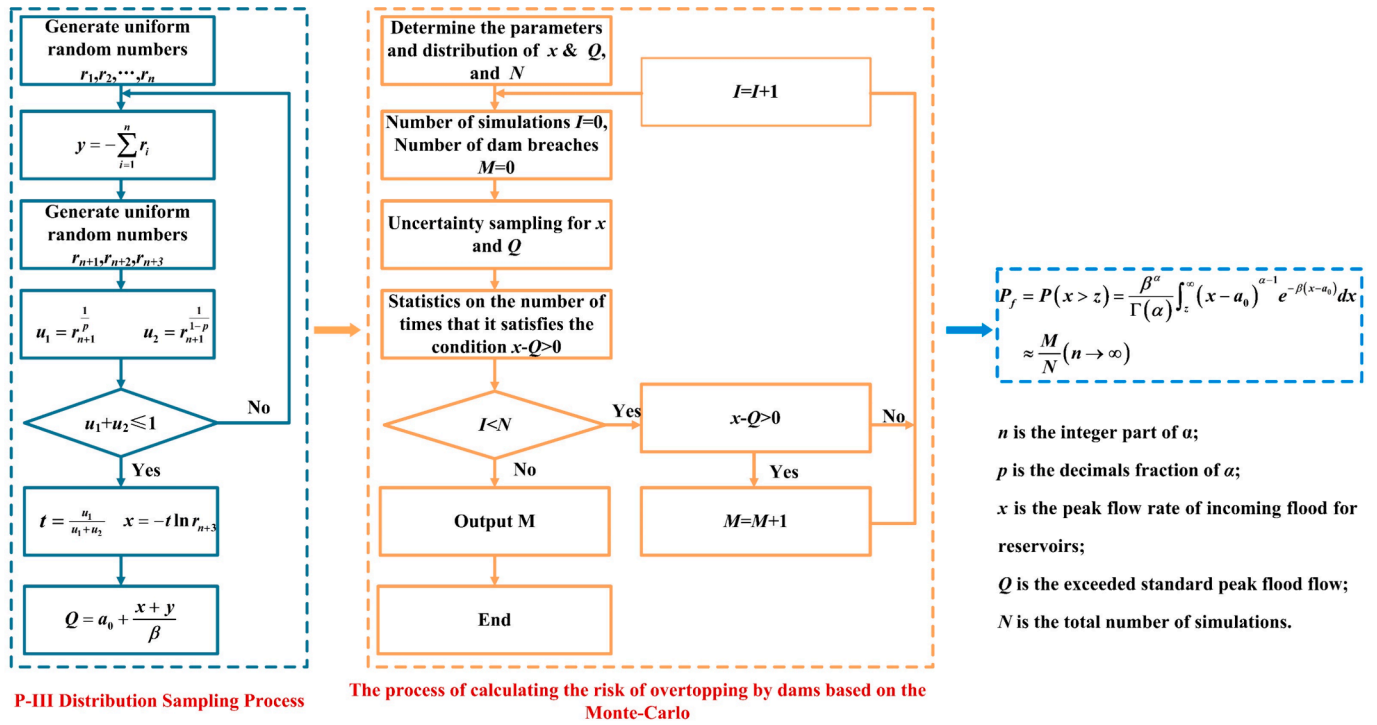


Fig. 4. The calculation process of possibility for dam breaches.

loss of potential dam breaches.

1) Daily operation and management costs.

Daily operation and management costs are the costs incurred to ensure the normal operation of dams. In China, the relevant standards (Ministry of Water Resources of the People's Republic of China., 2013) have divided the daily operation and management costs of dams as follows: material costs, fuel and power costs, staff salaries, fixed asset depreciation, management costs, fixed asset insurance, other costs, etc., and have assigned the corresponding quantification methods. Therefore, in this study, these costs were quantified by considering the actual operating conditions of the dams. Finally, the daily operation and management costs of the dams were comprehensively calculated. The calculation formula for the daily O&M costs is expressed as Eq (1).

$$V_D = \sum_{i=1}^7 v_i \tag{1}$$

where V_D is the daily operation and management costs, and v_i is the material cost, fuel and power costs, staff salaries, fixed asset depreciation, management costs, fixed asset insurance, and other costs ($i = 1, 2, \dots, 7$).

2) Danger removal and reinforcing costs.

Danger removal and reinforcing are engineering measures to improve the safety of dams and ensure their safe operation using existing technical means (Su et al., 2015). In general, the danger removal and reinforcement costs of dams can be calculated using a multi-year averaging method. In China, according to relevant standards (Ministry of Water Resources of the People's Republic of China., 2013), the danger removal and reinforcing costs were calculated at 1 % of the dam's fixed assets. Considering that danger removal and reinforcing costs will gradually increase over time, the quantitative values of danger removal and reinforcing costs in this study were taken as the largest of the two calculated values. The formula for danger removal and reinforcing costs is shown in Eq (2).

$$V_R = \max \left[1\%A, \frac{1}{n} (v_1 + v_2 + \dots + v_m) \right] \tag{2}$$

where V_R is the danger removal and reinforcing costs, A is the fixed assets of the dam, and v_m is the cost of removing danger and reinforcing for the m^{th} time in n years.

3) Loss of potential dam breaches.

Dam risk is associated with the probability of dam breaches, which is related to the safety of the dam, and the downstream impacts of dam breaches, which are related to the levels of social and economic development downstream (Liao et al., 2022; Yang et al., 2022; Zhang et al., 2022). When conducting the economic life evaluation of a dam, the loss from a potential dam breach must be quantified as a cost indicator. According to this definition, the calculation formula is expressed as Eq (3):

$$V_L = P_f \times L \tag{3}$$

where V_L is the loss owing to potential dam breaches, P_f is the possibility of dam breaches, and L is the impact of the downstream dam breach.

a) Possibility of dam breaches.

The reasons for dam breaches can generally be divided into overtopping damage caused by flooding and structural damage caused by seepage, pipe surges, etc. In addition, earthquakes, wars, and other factors can cause dam breaches as well (Guan et al., 2023; Eldeeb et al., 2023). In dam economic life evaluation studies, the safe operation of dams under normal technical maintenance conditions is the premise for conducting this study. Therefore, the structural damage caused by the dam's safety and quality problems was not considered in this study for dam breach probability analysis. In addition, according to relevant studies (Zhao et al., 2020), the most prevalent reason for earth-rock dam breaches is the overtopping of the dam caused by excessive flooding or insufficient capacity of the dam to release flood water. Therefore, the primary factors affecting overtopping dam breaches were considered in this study.

Overtopping by floods is a phenomenon wherein the highest water level in front of a dam exceeds the top elevation of the dam or the top elevation of the dam's wave wall during flooding. In this study, if we set X as the highest water level in front of the dam, and Z as the crest elevation, the probability of overtopping by a flood can be expressed as P

($X > Z$).

The occurrence of overtopping by floods is mainly impacted by several factors, such as floods that have exceeded the design standards of dams, flood discharge capacity, wind and wave factors, and reservoir capacity. Because flood overtopping is a hydrological event, hydrological uncertainty is the focus of this study. The risk of breaches caused by a flood that exceeded the design standards of dams was explored. In China, according to relevant studies (Jia et al., 2023; He et al., 2021), the flood frequency distribution has followed a P-III type probability distribution, and its probability density function is expressed as Eq (4).

$$f(x) = \frac{\beta^\alpha}{\Gamma(\alpha)}(x - a_0)^{\alpha-1} e^{-\beta(x-a_0)}$$

$$\alpha = \frac{4}{C_s^2}$$

$$\beta = \frac{2}{\bar{x}C_v C_s}$$

$$a_0 = \bar{x} \left(1 - \frac{2C_v}{C_s}\right)$$
(4)

where \bar{x} , C_v , and C_s are the mean, coefficient of variation, and coefficient of deviation of the flood flow x , respectively; they were primarily derived from the statistical regularity.

Flood flow was simulated using the acceptance-rejection sampling method. If the excess standard flood flow is expressed in terms of z , the probability of overtopping by a flood is calculated as shown in Eq (5).

$$P_f = P(x > z) = \frac{\beta^\alpha}{\Gamma(\alpha)} \int_z^\infty (x - a_0)^{\alpha-1} e^{-\beta(x-a_0)} dx$$
(5)

Based on the above analysis, the Monte-Carlo method was used to calculate the risk of flood overtopping. This method involves the use of the probability of an event occurring over several trials to estimate the probability of an event occurring. Therefore, each variable was sampled several times. When the number of samples is sufficiently large, according to the large number theorem, the frequency at this point is close to the probability, and is used as the value of the corresponding risk probability (Ardeshirtanha and Sharafati., 2020). The calculation process is illustrated in Fig. 4.

b) Calculation of flood inundation losses based on dam breaches flood simulation

The Luhun Reservoir, which is the subject of this study, is an earth-rock dam. According to relevant studies (Peter et al., 2018; Wang et al., 2018), the forms of dam breaches in earth-rock dams are progressive, with most being horizontally localized breaches. However, no authoritative method exists for estimating the height of a vertical breakage. In this study, the most unfavorable case of complete dam breaches (breaches to the bottom of the dam) was considered for safety concerns. Therefore, the dam breach conditions were set as follows: overtopping by floods, gradual breaches, partial horizontal breaches, and vertical breaches extending to the bottom of the dam. In this study, it was assumed that the dam breaches developed from the centerline of the dam axis, with the breach width being 1/2 the length of the main dam. The starting water level was the calibrated flood level. Other parameters (the reservoir capacity and water level, and reservoir discharge flow rate and water level, etc.) were set according to relevant studies (Li et al., 2023; Ma et al., 2019). Water quantity data, such as water depth, time of arrival, and inundation area of each area downstream of the dam site, were available. The inundation loss caused by the dam-breach flood was calculated by superimposing land types on the inundation area.

(2) Benefit indicators.

In this study, the benefit indicators mainly included flood control, power generation, irrigation, water supply, navigation, tourism, and ecological and environmental benefits.

1) Flood control benefits.

Flood control benefits are typically divided into economic and non-

economic benefits (Xu et al., 2023; Ding et al., 2023). This study primarily focused on the economic characterization of dam operations based on a cost-benefit relationship. Therefore, the economic benefits of flood control were mainly considered when quantifying the flood control benefits. The non-economic benefits of flood control, such as the protection of people's lives, were considered as social impact factors.

The methods for calculating quantitative analysis of flood control benefits include the flood loss frequency, actual typical year series, and simulation curve methods (Chen et al., 2023; Li et al., 2023). The calculation process for the actual typical year-series method is as follows: a) An actual year-series is selected with complete, representative flood information and a certain length. b) The value of loss by flood for each year is determined with and without flood protection projects. c) The difference between the average losses is used as the average multi-year loss by a flood, that is, the flood control benefit. The calculation formula for the flood control benefits is expressed as Eq (6).

$$V_f = \sum_{i=1}^{n-1} [(L_i + L_{i+1})/2](P_i - P_{i+1}) - \sum_{i=1}^{n-1} [(M_i + M_{i+1})/2](P_i - P_{i+1})$$
(6)

where V_f is the flood control benefits, P_i and P_{i+1} are the flood frequency values of the two adjacent, L_i and L_{i+1} are the values of loss by flood corresponding to the adjacent frequencies in the absence of flood control projects. And M_i and M_{i+1} are the values of loss by flood corresponding to the adjacent frequencies in the presence of flood control projects.

2) Power generation benefits.

Hydroelectricity is the process of converting the potential energy of high-level water into the kinetic energy of a turbine and then converting the kinetic energy into electrical energy through a generator. Hydroelectric projects, such as dams, generate electricity from rivers. The benefits of electricity generation can be expressed as the product of the price and amount of electricity generated annually. The formula for calculating the power generation benefits of the dam is expressed as Eq (7).

$$V_e = P_e Q_e$$
(7)

where V_e is the power generation benefit of the dams, P_e is the price of electricity in the local area, and Q_e is the annual power generation from the dam, which decreases each year owing to changes in hydrological characteristics and reservoir sedimentation, kW-h.

3) Irrigation benefits.

Natural river ecosystems have a limited function in irrigating farmlands. However, dam construction has increased the irrigation capacity of rivers, expanded the irrigation area, and increased the irrigation guarantee rate, thereby guaranteeing water for agriculture. The irrigation benefits of reservoir dams are mainly reflected in the fact that irrigation promotes crop growth and increases crop yields. Thus, the irrigation benefits of dams can be expressed in terms of the value added to the production value of the arable land that is guaranteed to be irrigated. The calculation formula for the irrigation benefit for dams is expressed as Eq (8).

$$V_i = \alpha \sum_{i=1}^n P_i \Delta Y_i S_i$$
(8)

where V_i is the irrigation benefit of dams, P_i is the price of irrigated crop i in the current year, ΔY_i is the incremental increase in production of an irrigated crop i through comparisons before with after irrigation, S_i is the planted area of an irrigated crop i , and α is the distribution coefficient for irrigation benefits.

4) Water supply benefits.

To adapt to social and economic development and safeguard the quality of life of people, engineering measures such as impounding, storing, diverting and lifting water have been used to provide river water to various water users. In China, the water charges collected from residents by water management authorities are mainly determined based on

the price of water and the amount of water consumed by residents (Liu et al., 2021). The water supply benefits from dams supplying water to users can be expressed as the product of the price and volume of water supplied. The formula for calculating the water supply benefits of the dam is expressed as Eq (9).

$$V_w = P_w Q_w \tag{9}$$

where V_w is the water supply benefit of the dams, P_w is the price of water used by residents who were supplied by the dams, Q_w is the average water supply from the dam over multiple years.

5) Navigation benefits.

By increasing the water level of the river, the navigability of the river was improved by the dam. Thus, the shipping capacity increases. Moreover, the shipping costs are reduced. Thus, the navigation benefits of dams can be expressed as the product of the improved channel length and the unit cost of transport saved. The formula for calculating the navigation benefits of a dam is expressed as Eq (10).

$$V_n = \beta P_n D Q_n \tag{10}$$

where V_n is the navigation benefits of dams, P_n is the unit cost of transport saved, D is the improved channel length, Q_n is the average volume of goods transported per year, and β is the distribution coefficient for the additional navigation benefits from improved water conditions.

6) Tourism benefits.

Tourism benefits are incremental regional tourism benefits resulting from the construction of reservoir dams, which improve the natural landscape of the reservoir area and increase the cultural and recreational value of the river. Therefore, the tourism benefits of a reservoir dam can be expressed as the product of the average tourism cost per traveler in the local area and the annual increase in tourism. The formula for calculating the tourism benefits of a dam is expressed as Eq (11).

$$V_t = P_t Q_t \tag{11}$$

where V_t is the tourism benefit of dams, P_t is the average tourism cost (The tourism cost here is the average amount spent by tourists-the amount actually spent by tourists) per traveler in the local area, and Q_t is the annual increase in tourism.

7) Ecological environmental benefits.

Dams negatively impact the original ecosystem and change the surrounding ecosystem during the early stages of construction. However, dams gradually integrate into the surrounding ecological environment over time. The regulation and storage of water resources by dams have induced many ecological benefits, such as climate regulation, net primary productivity, biodiversity conservation, self-purification of water, nitrogen release from the sediment, and carbon and oxygen sequestration. Existing studies have expressed (Wu et al., 2019; Wu et al., 2022) the ecological and environmental benefits of reservoir dams in terms of energy and converted them to money using the local energy-to-money ratio. The formula for ecological and environmental benefits of a dam is expressed as Eq (12).

$$E_{PE} = \left(\sum_{i=1}^n EM_i / Q_E \right) / EDR \tag{12}$$

$$V_E = (Q_{E1} + Q_{E2}) E_{PE}$$

where V_E is the ecological and environmental benefits of dams, E_{PE} is the ecological and environmental value of a unit volume of water in dams, EM_i is the energy of various ecological and environmental benefits (climate regulation, net primary productivity, biodiversity conservation, self-purification of water bodies, nitrogen release from the sediment, as well as carbon and oxygen sequestration), $i=(1,2,\dots,n, n \leq 7)$ (In the process of calculating the economic value of ecological water supply, we first calculated the energy values generated by reservoir dams in the processes of climate regulation, net primary productivity, biodiversity conservation, self-purification of water bodies, release of nitrogen from sediments, and sequestration of carbon and oxygen with the use of energy value theory. Then, based on the average annual flow rate of the dam and the energy value currency conversion coefficient, the economic value generated by the unit water volume of the dam in the ecological environment was calculated. Thus, for the value of “n” in the Eq (12), the maximum value is 7), Q_E is the average flow of dams per year; EDR is the local energy-to-money ratio, Q_{E1} is the amount of ecological water storage, and Q_{E2} is the amount of environmental water demand.

(3) Social impact indicators.

In this study, the social impact indicators mainly include: the effect of poverty alleviation and poverty eradication, the contribution of regional GDP, and energy saving.

1) Effect of poverty eradication by poverty alleviation

The impact of reservoir dams on poverty eradication is primarily related to the poverty eradication rate of the local communities near the dams. Therefore, in this study, the poverty eradication rate was directly used to express the impact of reservoir dams on poverty eradication. The formula to calculate impact of poverty eradication on poverty alleviation is expressed as Eq (13).

$$f_e = \frac{N_e}{N_a} \times 100\% \tag{13}$$

where f_e is the poverty eradication rate of the local community near the dam, N_e is the number of people whose poverty was eradicated in the community near the dam, and N_a is the number of people whose poverty was alleviated in the community near the dam.

2) Contribution of regional GDP.

The local economy is boosted during the operation of the dam, and thus the local GDP increases. Therefore, the impact of dams on local GDP, that is, their contribution to regional GDP, was expressed in this study using the proportion of dam-led GDP to total local GDP. The calculation formula for the dam’s contribution to the regional GDP is expressed as Eq (14).

$$P_{GDP} = \frac{GDP_D}{GDP_L} \times 100\% \tag{14}$$

where P_{GDP} is the contribution of a dam to regional GDP, GDP_D is the GDP driven by dams, and GDP_L is the total local GDP.

3) Saving of energy.

Dams increase the local electricity supply by generating electricity, which reduces the consumption of fossil fuels, particularly coal. Therefore, the annual electricity production of the dam power station can be converted into a total coal amount of E/Q (E is the annual electricity production of the dam power station; Q is the electricity generated from 1 t of standard coal (Dou et al., 2023)). The formula for calculating the energy savings of the dam is expressed as Eq (15).

$$C_s = \frac{Q_e}{Q} \tag{15}$$

where C_s is the dam’s energy savings and Q_e is the annual electricity

Table 1

The scoring criteria of social impact evaluation comprehensive coefficient of dams.

Score range of φ	The qualitative description of the social impacts caused by dams
(-1.0, -0.5)	Serious negative impact on social and environmental
(-0.5, 0)	Not fully performing its intended function and had negative impacts on the environment
(0, 0.5)	Largely fulfilled its intended function and had some positive social impact
(0.5, 1.0)	Fully integrated into local production and life, with a high level of popular acceptance

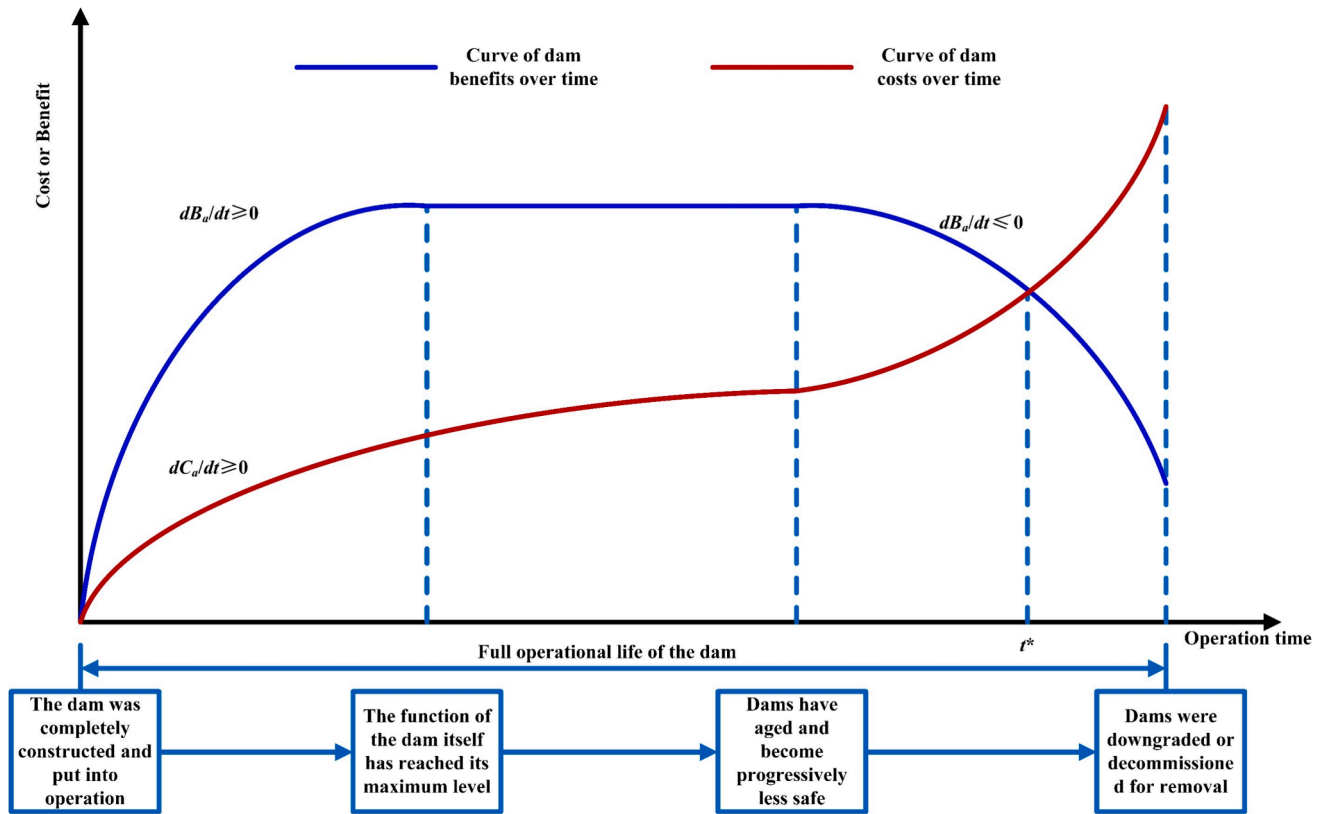


Fig. 5. Curves of dam costs and benefits over time.

production of the dam power station.

Because of the different dimensions of the social impact indicators as mentioned above, it is difficult to carry out comprehensive calculations and analyses directly during the evaluation process. Based on the results of the quantitative analyses of the evaluation indicators above, the social impact of the dam was qualitatively evaluated (Kirchherr and Charles, 2016).

According to the approach of Wu et al., (2012) to environmental assessment in an integrated assessment model of the service status of dams, a comprehensive social impact evaluation coefficient was introduced in this study to evaluate the social impacts (which may be positive or negative) of dams on local production and life. The social impact evaluation comprehensive coefficient of a dam is expressed as φ , and $\varphi \in (-1.0, 1.0)$. The scoring criteria for the comprehensive social impact evaluation coefficient of the dams are listed in Table 1. A positive value represents a positive social impact of dams in the local area whereas a negative value represents a negative social impact of dams in the local area, with higher values indicating higher levels of impact.

2.2.3. Calculating the relative importance of evaluation indicators

In the economic life evaluation of dams, each evaluation indicator has a different degree of influence. Consequently, the relative importance of each evaluation indicator must be calculated. Therefore, based on a comparative analysis of various weight-solving methods, such as AHP (Tansar et al., 2023), Entropy Method (Ghodusinejad et al., 2023), Cloud Model (Guo et al., 2020), etc. to improve the scientific accuracy of the evaluation results, the cloud model was used to calculate the weights of the dam economic life evaluation indicators in this study. This method adequately considers the uncertainty of expert scoring, such as vagueness and randomness, which can reduce the superimposed influence of expert scoring uncertainty on the results and help solve the problem of weight distribution decentralization (Peng et al., 2021).

The Cloud Model is a mathematical model for the uncertainty

transformation between quantitative values and qualitative concepts, pioneered by the famous Chinese scholar and academician Li Deyi (Zhang et al., 2023). Compared to the traditional weight calculation method, this model can intuitively reflect the randomness and ambiguity of objects in the objective world and simultaneously combine the two to form a mapping relationship between quantification and qualification. In the process of weight calculation, it overcomes the disadvantage of lack of objectivity when evaluation linguistic data, and is able to deal well with the problem of human ambiguity and uncertainty. This method of converting qualitative concepts into specific quantitative values largely compensates for the shortcomings of traditional fuzzy functions (Guo et al., 2020; Yin et al., 2022).

2.3. Evaluation models of the economic life of dams

Dam economic life evaluation is an analysis of the costs and benefits of dam operation, with the premise of considering the safe operation of dams, specifying the economic characteristics of dam operation, and determining the number of operating years for which the dam meets economic rationality. According to Marchioni et al. (2023), Cost-Benefit analysis (CBA) is an economic decision-making method that evaluates the economic reasonableness of an object by comparing the relationships between all cost and benefit data for that object. It quantifies all the costs and benefits of the analyzed projects individually, which can accurately and visually reflect the costs and benefits of the projects and help in their analysis and decision-making. Therefore, based on the theory of cost-benefit analysis, the trends in the annual operating costs and operating benefits of reservoir dams over time were analyzed in this study by comprehensively considering the social impact factors of reservoir dams. Consequently, an economic life evaluation model for reservoir dams was established.

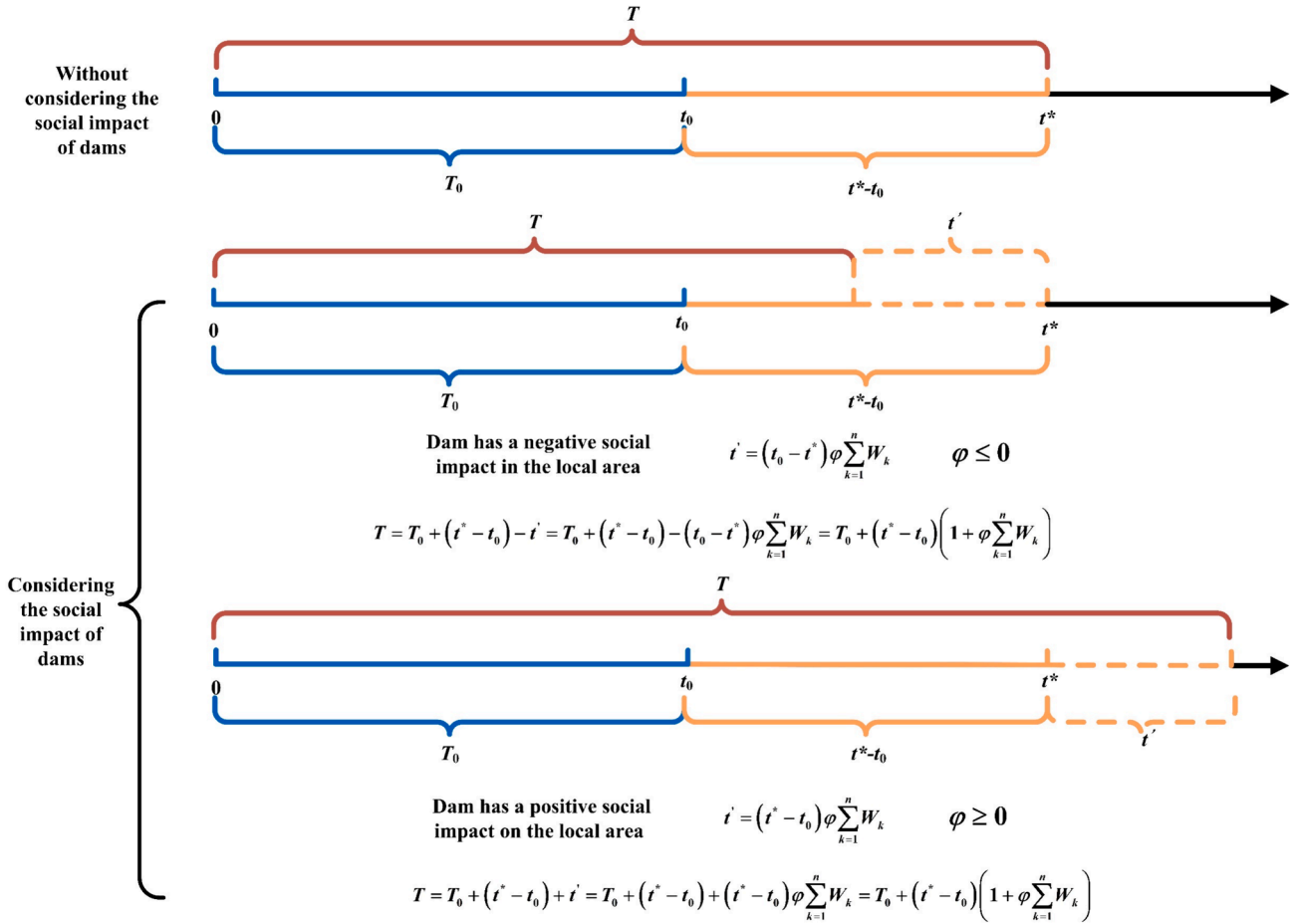


Fig. 6. Economic life evaluation of dams when no repair measures were taken.

2.3.1. Calculating the comprehensive cost and comprehensive benefit of the dam's operation

(1) Analysis of the comprehensive costs of dam operation

In general, dams receive more attention from society in the early years of operation, with higher investments in management and maintenance, and their economic benefits are more significant. The benefits of dams gradually level off over time. However, with an increase in operating costs each year, operating economics begin to decline. Meanwhile, the probability of dam breaches increases, and the economic losses caused by dam breaches also increase. The annual operating cost of dams is influenced by multiple factors, random in nature, and tends to increase over time, that is, $dC_a / dt \geq 0$. The annual operating costs of the dams are shown in Fig. 5. Since the time the dam was constructed and put into service, we have divided the process of changing the costs as well as the benefits of operating the dam into three stages. The first stage is the period from the start of the dam's operation to its operational stabilization (full functioning). During this period, the cost of the reservoir dam increases, as do the benefits. In the second phase, dam operation is stable until the dam ages and becomes less safe. During this period, the dam operation is stable, and its costs and benefits are stable. During the third stage, as the dam ages, its safety decreases until it reaches retirement. During this period, due to the aging of the dam, its functionality becomes limited, and the benefits it provides gradually diminish. In order to ensure its safe operation, increased investments are required, leading to a significant increase in operating costs for the dam.

Based on the quantitative results of the cost indicators and the calculation results of the relative importance of the indicators, the annual comprehensive operating costs of the dams can be calculated quantitatively. The calculation formula for comprehensive costs of dam

operation is expressed as Eq (16).

$$C_a = W_D V_D + W_R V_R + W_L V_L \tag{16}$$

where C_a is the comprehensive cost of dam operation, V_D is the daily operating and maintenance cost, V_R is the removal of danger and reinforcing costs, V_L is the loss of

potential dam breaches, W_D is the weight of the daily operating and maintenance cost indicator, W_R is the weight of removing danger and reinforcing costs indicator, and W_L is the weight of loss of potential dam breach indicator.

(2) Analysis of the comprehensive benefits of dam operation

Dams significantly alter the natural hydrological characteristics of rivers, particularly the annual flow regulation. These factors affect the service value of the river itself at every moment. In addition, with population growth and economic development, the demand for water is increasing, inevitably leading to an absolute decrease in the natural runoff from rivers. If the random effects of human and natural factors are ignored, the benefits generated by a dam will gradually increase as it performs its own functions after being in service for some time. However, dam performance decreases over time. After the benefit of the dams reaches its maximum, the annual benefit of their operation is reduced from year to year; that is, $dB_a / dt \leq 0$. The annual operating benefits of the dams are shown in Fig. 5.

Based on the quantitative results of the benefit indicators and the calculation results of the relative importance of the indicators, the annual comprehensive operating benefits of the dams can be calculated quantitatively. The calculation formula for the comprehensive benefits of the dam operation is expressed as Eq (17).

$$B_a = W_f V_f + W_e V_e + W_w V_w + W_i V_i + W_n V_n + W_t V_t + W_E V_E \quad (17)$$

where B_a is the comprehensive benefit of the dam's operation, V_f is the flood control benefit, V_e is the power generation benefit of dams, V_i is the irrigation benefit of dams, V_w is the water supply benefit of dams, V_n is the navigation benefit of dams, V_t is the tourism benefit of dams, V_E is the ecological and environmental benefit of dams, W_f is the weight of the flood control benefit indicator, W_e is the weight of the power generation benefit indicator, W_w is the weight of the water supply benefit indicator, W_i is the weight of the irrigation benefit indicator, W_n is the weight of the navigation benefit indicator, W_t is the weight of the tourism benefit indicator, and W_E is the weight of the ecological and environmental benefit indicator.

2.3.2. Calculation principle for dam economic life evaluation models

The construction and operation of dams require significant investment; however, the benefits generated by dams are also enormous. In general, engineering projects can recover investment costs after a period of operation. There is a relatively minimal engineering significance in conducting economic life evaluation studies on dams that have been in operation for a short period and have yielded stable returns. The economic life evaluation model in this study was primarily aimed at dams with aging engineering facilities and reduced operational returns. Therefore, the original investment in the dam was not considered in this study for conducting the 'cost-benefit' analysis.

Based on the annual trends of the comprehensive operating cost and the comprehensive operating benefit (calculated from the moment of decrease in the operating benefit), the tipping point t^* at which the annual comprehensive operating cost of the dam is equal to the comprehensive operating benefit can be determined. The calculation principle is illustrated in Fig. 5.

When $t \leq t^*$ (t is the time of dam operation), the comprehensive operating benefit of the dam exceeds the comprehensive operating cost of the dam, which indicates that the dam can continue to generate benefits and that it is within its economic life span at this time. When $t > t^*$ (t is the time of dam operation), the comprehensive operating benefits of a dam are less than the comprehensive operating costs of the dam, and the dam has been operated beyond its economic life span. At this time, the dam may require repairs to extend its economic life, or risk degradation and removal. Thus, this study analyzing the actual engineering situation to evaluate the economic life of a dam under these two situations. The two situations are as follows: a) economic life evaluation of dams when no repair measures were taken; b) economic life evaluation of dams when repair measures were taken.

(1) Economic life evaluation of dams when no repair measures were taken.

When $t = t^*$ (t is the duration of dam operation), the comprehensive operating costs and benefits of the dam are equal. If the economic lives of reservoir dams without rehabilitation measures were to be calculated, the social impacts of reservoir dams must be considered comprehensively. If the dam has a positive social impact on the local area, the actual economic life of the dam is longer than the calculated expected economic life (a lifetime that satisfies the economic rationality obtained by analyzing only the relationship between the comprehensive operating cost and benefit of the dam). Whereas, if the dam has a negative social impact within the local area, the actual economic life of the dam is shorter than the calculated expected economic life. The results are presented in Fig. 6.

According to the above analysis, the economic life of reservoir dams without repair measures can be calculated using Eq (18).

$$T = T_0 + (t^* - t_0) \left(1 + \varphi \sum_{k=1}^n W_k \right) \quad (18)$$

where T is the actual economic life of dams, T_0 is the operation time of dams, t_0 is T is the starting time of the study calculation, t^* is the tipping

point (at which the annual comprehensive operating cost of the dam is equal to the comprehensive operating benefit), W_k is the weight of the k_{th} indicator from the social impact factor, $k=(1,2,\dots,n)$, φ is the comprehensive coefficient for the social impact assessment of dams, and $\varphi \in (-1.0, 1.0)$.

(2) Economic life evaluation of dams when repair measures for dams were taken.

When $t = t^*$ (t is the time of dam operation), suppose that the dam is rehabilitated to extend its life, and additional capital investment F_1 (it is a one-time input at a point in time that does not require consideration of the effect of the bank's discount rate) is required at this time. Following rehabilitation, dam operating costs are likely to decrease, or operating benefits may increase. In this study, the increase in benefits is denoted as B_1 and the net benefits are denoted as A . At this point, the tipping point at which the operating costs of the dams are equal to their operating benefits is removed, and the new tipping point is marked as $t = t_1^*$. Consequently, the time interval between the two tipping points is $\Delta t = t_1^* - t^*$, that is, the economic life was extended by repair measures.

Based on the above analysis, the different "cost-benefit" changes that may be introduced by different repair measures were analyzed in this study. The three main situations are as follows: a) reduced costs and unchanged benefits unchanged costs and increased benefits, reduced costs and increased benefits.

1) Reduced costs and unchanged benefits.

The structure of the dams was rehabilitated through measures such as the removal of dangers and strengthening. At this time, the operational benefits of the dams were unchanged. Daily operation and management costs and the loss of potential dam breaches can be reduced. In this situation, the one-off investment F_1 is the dam's removal of dangers and strengthening costs.

2) Unchanged costs and increased benefits.

Dredging of reservoirs can effectively increase the storage capacity of the reservoir's active storage, which also helps to increase the storage capacity for power generation and irrigation. However, the maintenance of power generation and irrigation infrastructure can improve water utilization efficiency. Both of these measures have no impact on the operating costs of dams, but can improve the benefits of dams. In this situation, the one-off investment, F_1 is the cost of dredging or maintaining of other facilities.

3) Reduced costs and increased benefits.

By combining these two situations, dams can be rehabilitated by taking measures to reduce the annual operating costs of the dam while increasing the operating benefits. In this situation, the one-off investment F_1 is the total cost of the various restoration measures for the dams.

Based on the cost-benefit analysis, the relationship between the extended economic life Δt and the payback life of the one-time capital investment F_1 must be considered. If the former is greater than or equal to the latter, the selected rehabilitation measure is likely to be reasonable; otherwise, it is not. The payback life reflects the effectiveness of dam rehabilitation to a certain extent. However, because of the influence of economic indicators, the calculation results of payback life are uncertain and are less applied in the engineering field. Therefore, in this study, the economic internal rate of return ($EIRR$) and economic net present value rate ($ENPVR$), which are two indicators of the national economic evaluation system, were used to evaluate the rehabilitation measures of the dams economically. The calculation formulae for $EIRR$ and $ENPVR$ are expressed as Eq (19) and Eq (20), respectively.

$$\sum_{t=1}^n (B - C)_t (1 + EIRR)^{-t} = 0 \quad (19)$$

$$ENPVR = \frac{\sum_{t=1}^n (B - C)(1 + i)^{-t}}{I_p} \quad (20)$$

where B is annual benefits, C is annual costs, $(B-C)_t$ is the net benefits in t_{th} year, I_p is the present value of investments, n is the number of years in

Table 2
The daily operating and maintenance costs of Luhun Reservoir.

	Material Costs	Fuel and Power costs	Staff Salaries	Fixed Asset Depreciation
Value (\$)	251896.41	175718.74	415620.75	4902834.87
	Management Costs	Fixed Asset Insurance	Other Costs	Total
Value (\$)	623431.12	175718.74	3440976.74	9986197.37

calculation, and i is social discount rate.

The $EIRR$ reflects the contribution of water construction projects to the national economy. Here, $EIRR \geq I$ indicate that a water construction project is economically sound and feasible. The $ENPVR$ reflects the net contribution of a project unit of investment to the national economy. Further, $ENPVR \geq 0$ indicates that the project is economically viable. The higher value of this variable, the more economically viable the project.

Based on the above analysis, if rehabilitation measures are planned for the dam, the formula for calculating the economic life of the reservoir dam at this time is expressed as Eq (21).

$$T = T_0 + (t_1^* - t_0) \tag{21}$$

where T is the actual economic life of the dam, T_0 is the operation time of the dams, t_0 is the starting time of the study calculation, and t_1^* is the new tipping point (after rehabilitation measures were implemented on the dam).

3. Results

3.1. Quantitative results of the indicators

The Luhun Reservoir was completed and began operation in 1965,

with irrigation and power generation components operating in 1974 and 1977, respectively. In this study, owing to the lack of data on the previous operation of the dam, we used 1990 as the starting point for the quantitative analysis of the ‘cost-benefit’ relationship for the Luhun Reservoir.

3.1.1. Quantitative results of cost indicators

In this study, the cost indicators primarily included daily operation and management costs, danger removal and reinforcing costs, and the loss of potential dam breaches.

(1) Daily operation and management costs.

Based on the actual situation of the project, the daily operation and management costs of the Luhun Reservoir were calculated using Eq (1). The calculation results are listed in Table 2 (Ge et al., 2022; Zhang et al., 2022).

(2) Danger removal and reinforcing costs.

According to statistics, the government invested \$2.71 million and \$13.65 million from September 2001 to the end of June 2006 for danger removal and reinforcing of Luhun Reservoir, respectively. According to Eq (2), the average annual cost of danger removal and reinforcing of the Luhun Reservoir was calculated to be \$2.73 million.

(3) Loss of potential dam breaches.

1) Possibility of dam breaches.

Based on the actual flood measurement data of the Luohe River Basin over many years, a P-III type frequency curve was fitted to determine the hydrological statistical parameters, as shown in Fig. 7. We conducted 200,000 Monte Carlo simulations using MATLAB and statistically counted the number of $X > Z$. The results of the Monte Carlo simulations are presented in Fig. 8. The final calculation results for the dam breach probability were $P_f = 1.05 \times 10^{-4}$.

2) Calculation of flood inundation losses.

According to the results of the dam breach flood simulation, the breach of the dam reached its maximum after 1 h and the maximum flow rate of the dam breach floods was $57734.36 \text{ m}^3/\text{s}$. The floods caused by dam breaches have spread downstream from Song County, passing

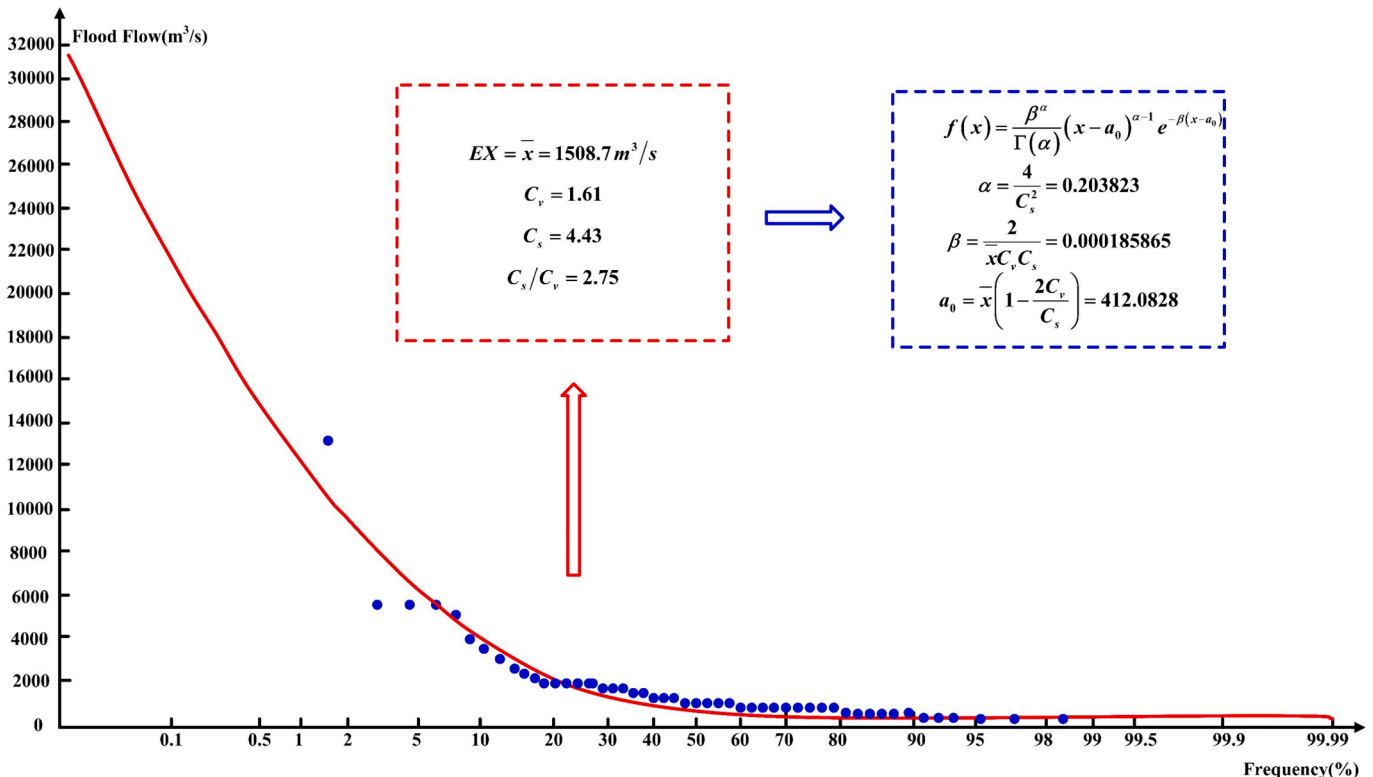


Fig. 7. Flood flow and frequency curves.

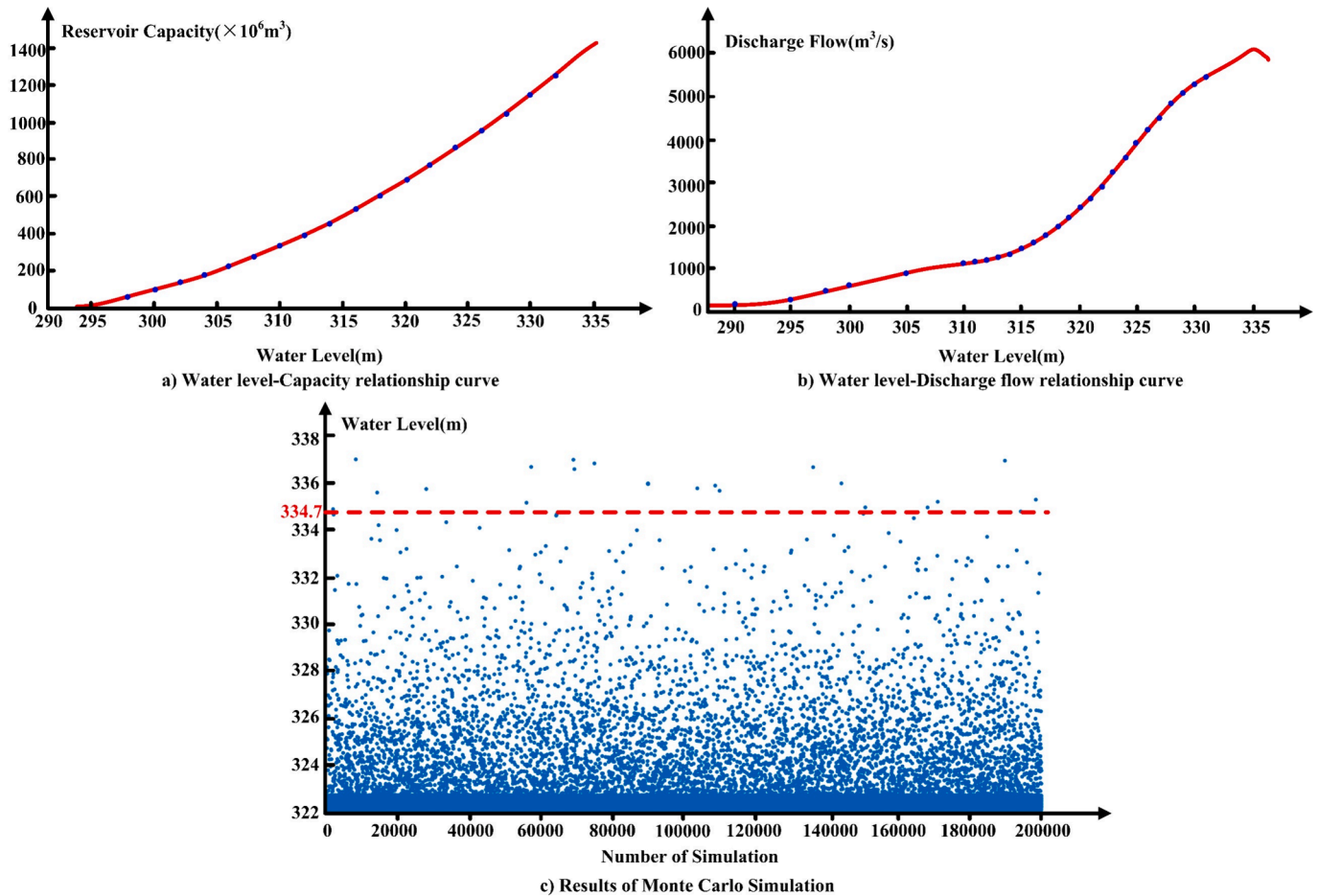


Fig. 8. The results of Monte Carlo simulation.

through Yichuan County, Luolong District and Yanshi City in a total of 4 areas covering an area of approximately 291 km². The flood inundation scenario is shown in Fig. 9.

In this study, the results of the dam-breach flood simulation were overlaid with a land-use-type layer, as shown in Fig. 10. The dam-breach flood inundation was counted, as shown in Table 3.

Based on the statistical results of the area inundated by the dam-breach flood, the losses of each type of property were calculated. Table 4 presents the results of the study.

Thus, using Eq (3), the loss of potential dam breaches at the Luhun Reservoir in this study was calculated to be 166.3 million yuan.

3.1.2. Quantitative results of benefit indicators

According to the statistical analysis of the actual losses in the river downstream of the Luhun Reservoir in recent years, the flood of 2003 is more representative. Data on the losses from this flood are more comprehensive and closer to reality. Therefore, the average multi-year flood control benefit of the Luhun Reservoir was calculated by combining Eq (6). Table 5 presents the results.

According to Eq (7) – (11), the annual benefits of Luhun Reservoir in terms of power generation, irrigation, water supply, navigation, and tourism in the starting year were calculated by combining the operations of the Luhun Reservoir. Table 6 presents the results.

Using Eq (14), the ecological and environmental benefits of the Luhun Reservoir were calculated. Table 7 presents the results.

3.1.3. Determination of the social impact comprehensive evaluation coefficient

The Luhun Reservoir is a large (1) type reservoir with an annual

regulating function, and offers great flood control benefits through its joint operation with two other large reservoirs. Moreover, it is closely linked to the local production and life of the people. Based on the calculations and analyses of the three social impact evaluation indicators, the social impact comprehensive evaluation coefficient of the Luhun Reservoir was taken as 1 in this study after consulting the local people and experts with certain knowledge of the project and combining it with the actual local situation.

3.2. Evaluation results of dam economic life

Based on the calculation results of the relative importance of the evaluation indicators, the comprehensive costs and benefits of the operation of the Luhun Reservoir dam were calculated using Eq (16) and (17). Considering the effect of inflation, the costs and benefits after the 1990 s were discounted to 1990 s levels at the prevailing social discount rate. Table 8 presents the results of the study.

Based on the above data, the relationship between comprehensive cost and benefit over time was fitted to obtain a “cost-benefit” relationship curve over time for the Luhun Reservoir. The tipping point was identified as, $t^*=2031$ (when potential dam breach losses were not considered, $t^*=2103$). The comprehensive cost change curve was $B(t) = 1.444t^3 + 323.1t^2 - 11420t + 33340000$ and the comprehensive benefit change curve was $C(t) = -28.26t^3 + 4238t^2 - 232700t + 39420000$, as shown in Fig. 11.

Based on the tipping point t^* , the social impact comprehensive evaluation coefficient for the Luhun Reservoir must be further analyzed to determine its final economic life, as shown in Eq (22).

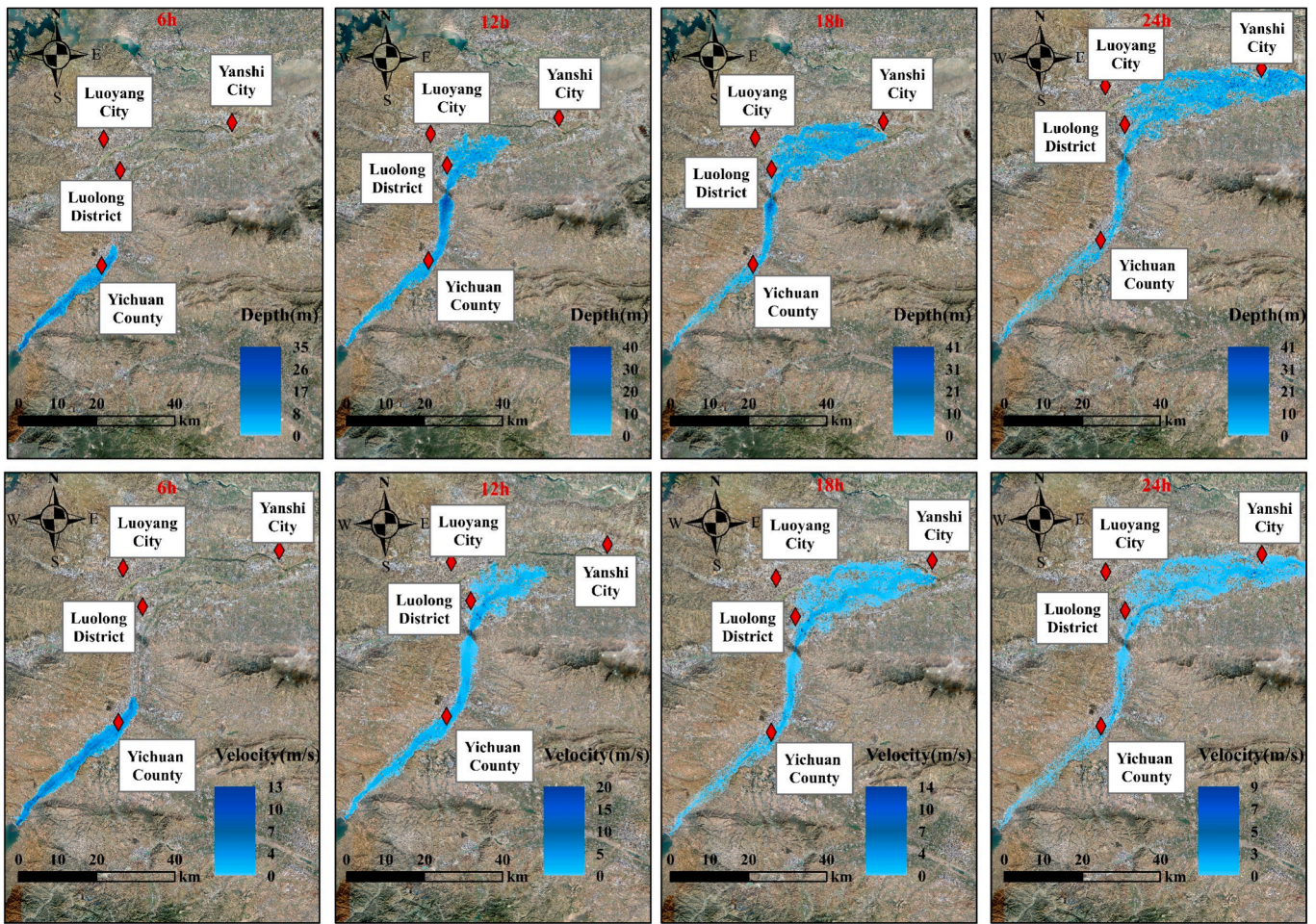


Fig. 9. Flood inundation situation(Depth(6 h, 12 h, 18 h, 24 h), Velocity(6 h, 12 h, 18 h, 24 h)).

$$T = T_0 + (t^* - t_0) \left(1 + \varphi \sum_{k=1}^n W_k \right) \quad (22)$$

$$= 25 + (2031 - 1990)(1 + 1 \times 0.199) = 74.16$$

According to the above analysis and calculations, the Luhun Reservoir currently operates within its life span and can be maintained in smooth operation while satisfying the safety and economic conditions. Based on the ‘cost-benefit’ relationship, the economic life of the Luhun Reservoir was calculated to be 74.16 years. It is expected to move beyond its economic life span into the non-economic operating range by 2039 s.

4. Discussion

The quantified results of the cost-benefit indicators during the operation of the Luhun Reservoir indicated that the loss of potential dam breaches and flood control benefits each accounted for more than 50 % of the comprehensive operating costs and benefits, which have a significant impact on the results of the dam economic life evaluation. In general, reservoirs with greater flood control benefits cause greater losses in the event of dam breaches. Therefore, in the case of large reservoirs wherein flood control is the primary objective, the most effective means of improving their economic life involves reducing the possibility of dam breaches by implementing reasonable control measures in a timely manner from a safety perspective. In addition, the irrigation benefits of the Leuven Reservoir accounted for 20 % of its comprehensive operating benefits. The reservoir’s irrigation infrastructure was completed and opened to water in 1974. Therefore, the maintenance of

irrigation facilities and reasonable increases in the amount of water supplied by reservoirs for downstream agricultural irrigation could also be effective in increasing the economic life of reservoirs.

According to Fig. 11, the Luhun Reservoir is expected to reach its tipping point by 2031 s. At this time, the comprehensive operation costs of the dam are going to equal to its comprehensive operation benefits. In engineering communities, it is generally accepted that dams have a design life of 50 to 100 years. In this study, the economic life span of the Luhun Reservoir was calculated to be 74 years by comprehensively considering the economics of the reservoir’s operation and its positive social impact on local production and life. The reservoir is expected to operate into the non-economic life interval until the 2039 s. According to the analysis in Fig. 11, reservoir dredging measures can increase the reservoir storage capacity in combination with the actual engineering situation of Luhun Reservoir. However, as the benefits of power generation at Luhun Reservoir are a relatively small part of the total benefits, it is not obvious that the operational life of dams can be improved through improvements in the power generation conditions. With increased water storage in reservoir dams, measures to enhance irrigation benefits can also be undertaken. However, the primary factor limiting irrigation benefits is the level of irrigation facilities when the amount of water used for irrigation is certain. Therefore, we must focus on the maintenance of irrigation facilities while increasing the reservoir storage capacity to effectively extend the economic life of Luhun Reservoir.

Compared to existing methods for analyzing the economic life of dams, this study considered the loss of potential dam breaches under conditions of sustained social and economic development, and

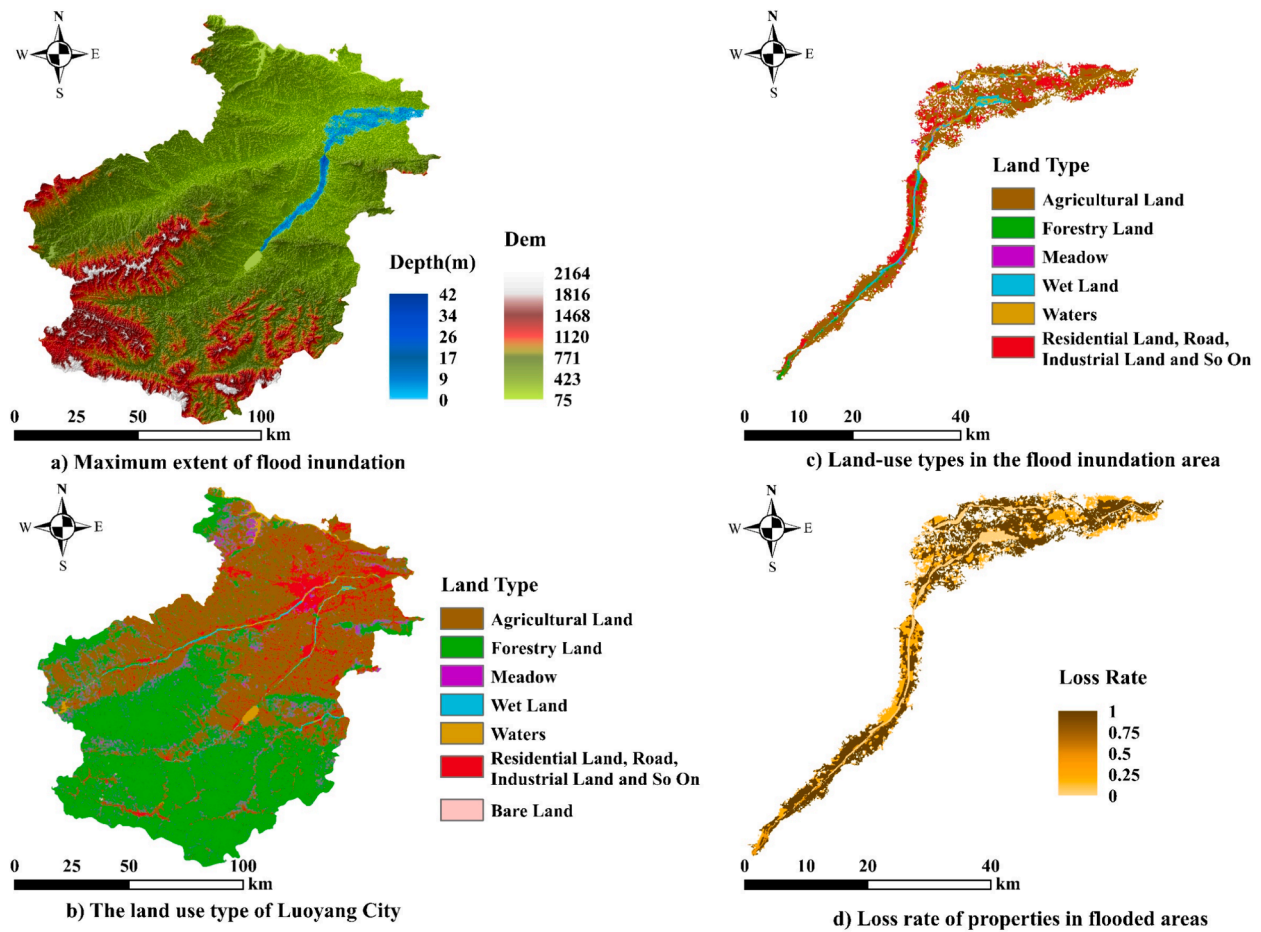


Fig. 10. The Land use types and loss rate of properties in the flood inundation area.

Table 3
The flood inundation of dam breaches.

Area	Town	Village	Covering an area (km ²)	Population	Cultivated Land (km ²)	Road(km)	Bridge	Railway(km)
Song County	2	26	24	35,627	268.58	13	9	0
Yichuan County	8	75	154	206,938	1174.01	78	48	0
Luolong District	11	138	175	279,080	1154.95	65	40	31
Yanshi City	12	138	250	312,989	1737.97	64	40	22

Table 4
The losses of each type by property.

	Residents' property	Cultivated Land	Woodland, Grassland	Transport interruption losses and repair costs	Fixed assets	Medical, Schools, Commercial	Total
The losses of property (\$ million)	14312.79	1040.82	752.34	356.07	6288.28	396.12	23146.42

Table 5
Average multi-year flood control benefit of the Luhun Reservoir.

Area	Song County	Yichuan County	Luolong District	Yanshi City	Gongyi City	Total
Flood Control Benefit (\$)	2087421.20	13220334.27	1728384.75	5843387.75	556645.65	23436173.62

Table 6

Annual benefits of power generation, irrigation, water supply, navigation and tourism of Lulun Reservoir.

Benefit	Power Generation Benefits	Irrigation Benefits	Water Supply Benefits	Navigation Benefits	Tourism Benefits
Value (\$)	1279199.54	1322033.43	91846.53	0	695807.07

quantified the 'cost-benefit' relationship under the impact of uncertainty. In this study, a comprehensive social impact evaluation coefficient was introduced to comprehensively analyze the social impact of dams on local production and life, making the final evaluation results more comprehensive and scientific. In addition, an operational economic evaluation and economic life calculation method were proposed

for dams rehabilitated with various rehabilitation measures, thus improving the usefulness and completeness of the model. The evaluation model aimed to improve the risk management system for reservoir dams and provide new ideas for the operation and management of reservoir dams. However, owing to the differences in the social situation of each country, the evaluation indicators and certain parameters must be adjusted according to the laws, regulations, and standards of each country in the process of applying the model. And the establishment of a system of indicators and a model for evaluating the economic life of reservoir dams must satisfy the needs of the country's own strategy. In this study, the accuracy of the economic life evaluation was strongly affected by the results of the quantification of the comprehensive costs and benefits of the operation. In this case, the loss of potential dam breaches depends on whether a dam breach occurs and also on the year in which the breach occurs and the economic situation of the inundated

Table 7

Ecological and environmental benefits of Lulun Reservoir.

	Climate Regulation	Net Primary Productivity	Biodiversity Conservation	Self-Purification of Water	Nitrogen Release from the Sediment	Carbon and Oxygen Sequestration
Value	$0.84 \times 10^{19} sej$	$7.45 \times 10^{17} sej$	$3.66 \times 10^{19} sej$	$-4.32 \times 10^{17} sej$	$5.11 \times 10^{19} sej$	$6.63 \times 10^{17} sej$
	The total of ecological and environmental benefits	Energy-to-money ratio	Average flow of dams per year	Value of water resources in the ecological and environmental	Amount of environmental water demand	Ecological and environmental benefits
Value	$9.61 \times 10^{19} sej$	$2.41 \times 10^{12} sej/\$$	$10.25 \times 10^8 m^3$	$0.04 \$/m^3$	$4619.28 \times 10^4 m^3$	$\$ 1847548.67$

Table 8

Comprehensive costs and comprehensive benefits of the Lulun Reservoir by year.

Year	1990	1995	2000	2005	2010	2015	2020
Comprehensive costs (\$ million)	33.27	33.33	33.40	33.48	33.61	33.76	33.92
Comprehensive benefits (\$ million)	35.81	35.49	35.27	35.08	34.96	34.85	34.74

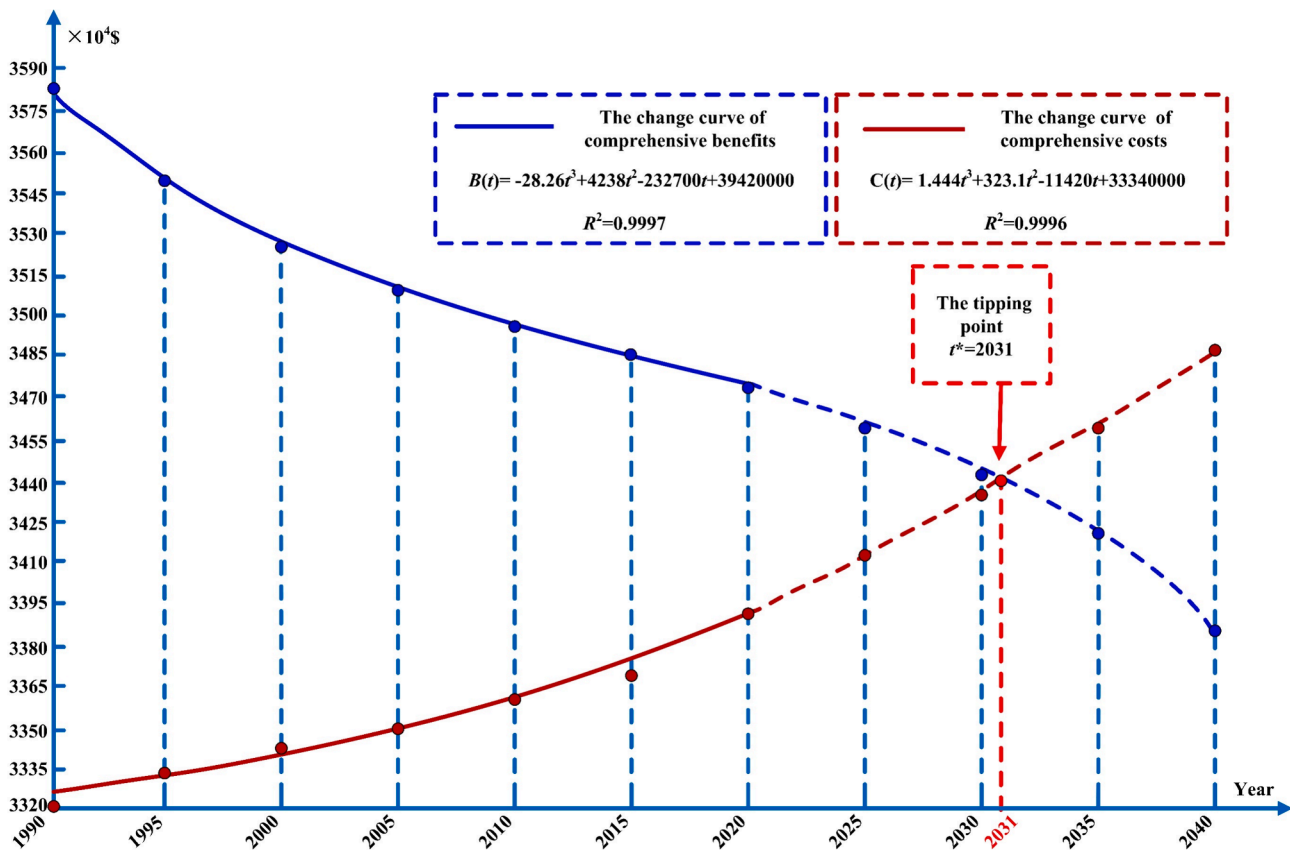


Fig. 11. The change curve of comprehensive costs and comprehensive benefits for Lulun Reservoir.

area, which is highly uncertain. To ensure the accuracy of the assessment results, the effects of the structural nature of the dam and changes in the surrounding environment over time on the quantitative results should be considered. In addition, owing to the paucity of academic research on dam economic life spans, there is no uniformity in the analysis of the social impacts on economic life spans.

5. Conclusion

Based on the analysis of the impact factors on a dam's economic life, an economic life evaluation indicator system was established in this study considering the impact of potential losses caused by dam breaches. A quantitative method for three types of evaluation indicators, such as cost, benefit, and social impact was proposed. A comprehensive social impact evaluation factor was introduced to consider the social impact of dams on local production and life. Based on cost-benefit theory and economics, the changes characteristic of "cost-benefit" for dams over time were analyzed. A dam economic life evaluation model was constructed. The model was applied to the Luhun Reservoir in Henan Province and was calculated to have an economic life of 74 years based on the quantification of the combined costs and benefits of the Luhun Reservoir and a comprehensive analysis of its social impact factors. According to the calculation analysis, we can extend the economic life of the Luhun Reservoir by maintaining the dam structure or rehabilitating irrigation engineering facilities. However, the accuracy of the model's evaluation results was largely affected by the quantitative results of operating costs and operating benefits, which will be further improved and enhanced in future research and practice.

CRedit authorship contribution statement

Wei Ge: Writing – review & editing, Formal analysis, Conceptualization. **Heqiang Sun:** Writing – original draft, Formal analysis, Conceptualization. **Laihong Jing:** Supervision. **Zongkun Li:** Writing – review & editing, Methodology. **Yongchuang Li:** Methodology, Investigation. **Bo Cao:** Validation. **Te Wang:** Methodology. **Yutie Jiao:** Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization. **Hua Zhang:** 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.

Data availability

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

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