

## Article

# Dam Failure Consequence Assessment: An Empirical Study from China

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## Abstract

Dam failure can trigger cascading consequences involving human safety, economic losses, social disruption, and environmental damage. Accurate assessment of these consequences remains challenging due to uncertainties associated with indicator selection, expert judgment, and consequence classification. To address these issues, this study develops an integrated model for evaluating dam failure consequences under uncertainty. A multidimensional evaluation index system consisting of life loss, economic loss, social impact, and environmental impact is established based on existing studies and expert knowledge. The hesitant cloud model is combined with an improved entropy weight method to represent the hesitancy in expert evaluations and to improve the rationality of indicator weight determination. Furthermore, set pair analysis is introduced to evaluate the uncertain relationships between assessment indicators and consequence levels. The proposed model is applied to a reservoir case in China to verify its applicability. The results indicate that the first cumulative membership value, obtained by cumulatively summing the dam failure consequence grades from “slight” to extremely severe”, that exceeds the confidence level  $\lambda$  is 0.7799, corresponding to the severe consequence level. This result is consistent with the comprehensive evaluation obtained using the cloud matter element method. Compared with the traditional method, the generalized set pair potential avoids the case where the opposition degree ( $c$ ) equals 0. The proposed approach improves the representation of uncertainty and reduces the influence of unclear boundaries among evaluation levels. This study provides a practical decision support tool for dam failure consequence assessment and reservoir risk management.

**Keywords:** dam failure consequence; hesitation cloud model; set pair analysis; entropy weight method; risk assessment



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## 1. Introduction

The reservoir dam is an essential hydraulic infrastructure that plays an irreplaceable role in flood control, water storage, irrigation, hydropower generation, and regional water resource regulation [1,2]. However, due to long-term exposure to external environmental factors such as water erosion, fluctuations in reservoir water pressure, geological evolution, and extreme climatic events, dam structures are susceptible to various defects, including seepage, settlement, cracking, and deformation [3]. Once such defects accumulate

beyond the structural bearing capacity, dam failure incidents may occur, resulting in severe casualties, property losses, and ecological damage [4].

Historical dam failure events have demonstrated that such disasters are characterized by sudden occurrence, extensive impact range, and complex cascading disaster chains. For instance, the collapse of the Banqiao Reservoir in Henan Province, China, in 1975 caused massive casualties, enormous economic losses, and severe regional social disruption and ecological deterioration [5]. Similar catastrophic events have also occurred internationally, such as the Vajont Dam disaster in Italy and the Teton Dam failure in the United States [6,7]. The Vajont Dam disaster demonstrated that even when the dam structure remains largely intact, reservoir-induced landslides can generate catastrophic overtopping waves, resulting in severe loss of life. In contrast, the Teton Dam failure was caused by internal erosion during the initial filling stage, leading to extensive downstream flooding and substantial economic losses. With the increasing frequency of extreme rainfall events worldwide and the aging of many existing reservoirs, dam failure risks have become increasingly complex. Therefore, comprehensive evaluation of dam failure loss consequences is of great theoretical significance and practical value for risk identification, disaster prevention, emergency management, and the protection of human lives and property.

Numerous studies on dam failure consequence assessment have primarily focused on direct economic losses and loss of life, while relatively limited attention has been paid to social and environmental consequences [8]. In recent years, researchers have recognized that dam failures may trigger cascading impacts on infrastructure, public services, ecosystems, and regional socioeconomic development, highlighting the necessity of a more comprehensive consequence assessment framework [4]. In addition, uncertainty remains one of the major challenges in dam failure consequence assessment. Uncertainties arise from multiple sources, including indicator selection, data acquisition, determination of grading criteria, and the choice of evaluation methods, all of which may affect the reliability and robustness of assessment results [9]. Consequently, considerable efforts have been devoted to developing uncertainty-based assessment methods, such as fuzzy theory, cloud models, Bayesian networks, and set pair analysis, to improve the objectivity and reliability of dam failure consequence evaluation under uncertain conditions [2,10]. Nevertheless, effectively integrating multiple sources of uncertainty into a comprehensive consequence assessment framework remains an important research challenge.

To address the limitations of existing studies, this study develops an integrated model for evaluating the consequences of dam failures in reservoirs, considering uncertainty. A comprehensive evaluation index system is established, which provides a broader understanding of dam failure consequences beyond casualties and direct economic damage. To improve the reliability of the evaluation process, the hesitant cloud model is combined with the improved entropy weight method to describe uncertainty in expert judgments and obtain more reasonable indicator weights. Set pair analysis is further introduced to handle the uncertain relationships between evaluation indicators and consequence levels. The proposed model is applied to a reservoir case in China to verify its applicability. The main contribution of this study is the integration of multidimensional consequence assessment and uncertainty analysis, providing a practical approach for reservoir risk evaluation and decision-making.

The cloud model, developed by Chinese academician Li Deyi, is a mathematical framework that quantifies fuzziness and uncertainty into numerical values for the purpose of analysis and processing [11]. The model effectively accommodates both quantitative and qualitative data, thereby enhancing the precision and reliability of data processing and decision-making. The cloud model has been extensively applied in information processing [12], decision analysis [13] and intelligent control [14]. The assessment of

dam failures inherently involves fuzziness and randomness, which previous research has frequently neglected. The cloud model presents a valuable opportunity to address these issues and can be utilized to evaluate dam failures [15]. Set pair analysis theory is a method for dealing with uncertain problems [16], first proposed by Professor Zhao Keqin in 1989. The fundamental concept of this theory is to construct a set pair by combining two interrelated sets and to quantify their relationship through three components: identity, discrepancy, and opposition [17]. Set pair analysis theory reveals the dialectical unity between certainty and uncertainty by describing their interrelationship, which is consistent with the principles of natural dialectics and human cognitive thinking patterns. It provides an effective way to address uncertainty problems and has been widely applied in many fields [18–20].

Therefore, this study develops an evaluation index system to assess the losses associated with dam failures, combining a hesitant cloud model with the traditional entropy weighting method. Furthermore, a set pair analysis model is conducted to evaluate dam failures. A case study of a reservoir in China is used to validate the proposed approach. The main contributions of this study are summarized as follows: (1) An improved cloud entropy weight–set pair analysis framework is proposed to evaluate dam breach consequences under uncertain conditions. (2) A hesitant cloud model is incorporated to better characterize the fuzziness, randomness, and hesitation inherent in expert evaluations. (3) An improved entropy weight method is adopted to enhance the objectivity of indicator weight determination. (4) A comprehensive evaluation system integrating life loss, economic loss, social impact, and environmental impact is established to provide a more holistic assessment of dam breach consequences.

The remainder of this study is organized as follows: Section 2 provides a background study on static indicators, dynamic indicators, and evaluation methods for dam failure loss consequences. Section 3 interprets the research methodologies. Section 4 conducts validation and analysis based on a case study to evaluate the effectiveness of the improved cloud–entropy weight–set pair analysis method in the comprehensive assessment of dam breach loss consequences. Further discussions and conclusions are presented in Sections 5 and 6.

## 2. Literature Review

Dam failures represent significant and catastrophic events that highlight the importance of robust risk management practices. Particularly, assessing losses resulting from dam failures is a critical aspect of risk management. In the planning and design of hydraulic engineering projects, evaluating potential losses associated with dam failures aids in predicting impacts. Researchers have dedicated substantial efforts to the assessment of dam failures, focusing on three areas.

### 2.1. Static Indicators

Static indicators include both direct and indirect losses associated with dam failures, such as mortality rates, vulnerable populations, the extent of inundation, inundation depth, and the value of the dam. Statistical methods are employed to quantify these indicators, drawing on actual dam failure data [21]. The Brown and Graham method was introduced to create a calculation model emphasizing at-risk populations and warning times based on historical dam failure cases [22]. Subsequently, the DeKay and McClelland method was developed, which integrated considerations of flood severity from dam breaks, alongside factors such as at-risk populations and warning times. Empirical formulas for calculations were subsequently derived through parameter calibration [23]. Based on these methods, Graham [24] examined the factor of at-risk populations and provided mortality rates under various conditions based on historical dam failure data. This approach aims to enhance

the assessment model by incorporating the vulnerability of specific populations in the event of a dam failure. Müller et al. [25] further refined Graham's methodology by including additional factors that influence loss of life, leading to revised calculation outcomes. Castillo-Rodríguez et al. [26] utilized mathematical and statistical analyses to assess the extent and depth of flooding downstream of a dam failure, significantly improving the accuracy of evaluations regarding loss of life and economic impacts. Day [27] built on earlier research by thoroughly investigating the effects of governmental emergency response plans and other variables on loss of life resulting from dam failures. This research refined assessment models, further enhancing the accuracy of evaluations concerning a dam failure on human lives and socioeconomic conditions. Existing static indicator-based methods provide a simple and intuitive approach for assessing dam failure consequences by using historical statistical data and clearly defined evaluation factors. These methods are easy to implement and have practical value in preliminary risk assessment. However, they mainly depend on historical failure cases and empirical relationships, which limits their ability to reflect dynamic disaster evolution processes and uncertainties caused by complex interactions among different influencing factors.

## 2.2. Dynamic Indicators

Dynamic indicators integrate factors such as dam safety coefficients, the extent of downstream flood inundation, and flood duration into assessments of dam failures. Analyzing these indicators presents challenges that require the application of computer models and algorithms for effective simulation and prediction [28]. Berning et al. [29] expanded the analysis of economic losses resulting from a dam failure by incorporating additional factors, including inundation duration, warning time, river flow velocity, and water depth. Haque [30] proposed an innovative method for calculating the probability distribution of the time required to restore a damaged ecosystem, based on ecosystem duration and recovery rate, thereby enhancing the assessment of environmental risks. This approach integrates assessments of ecosystem recovery time with probability theory, facilitating a comprehensive analysis of environmental risk. Dynamic indicator-based methods improve the understanding of dam failure consequences by considering time-dependent factors and disaster evolution characteristics. They can provide more detailed information regarding flood propagation processes and environmental responses. Nevertheless, these methods usually require sufficient monitoring data, accurate model parameters, and complex numerical simulations, which may restrict their application when data availability is limited.

## 2.3. Evaluation Methods

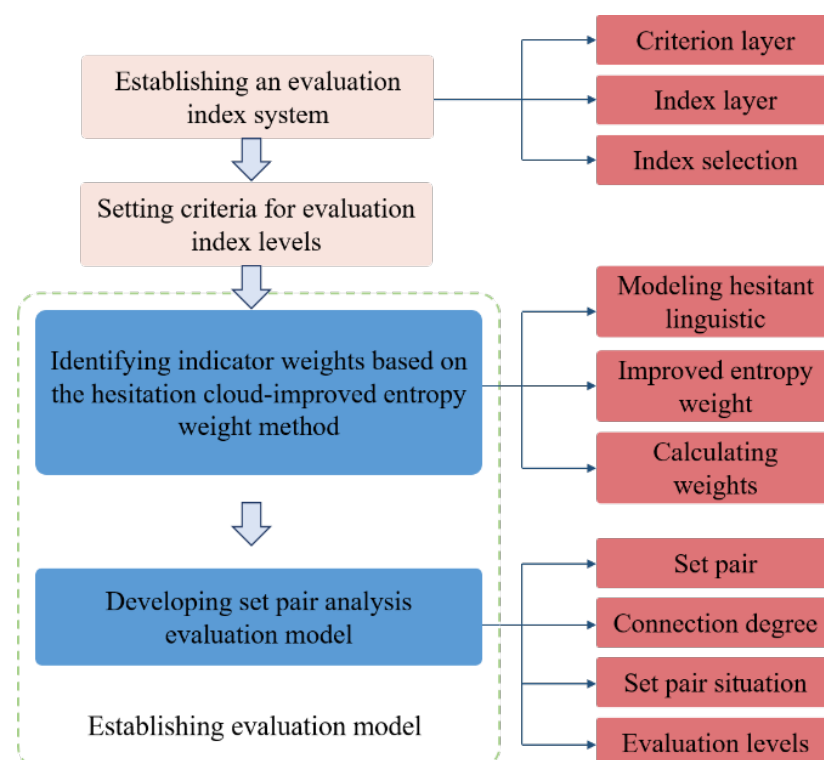
Hydrological and hydrodynamic models are employed to simulate the flooding process resulting from a dam failure, thereby forecasting the flood's impact on downstream areas in terms of extent, water depth, and flow velocity [31–33]. The magnitude of flood disasters and the corresponding economic losses in downstream regions are assessed through numerical simulation methods based on statistical data and historical records. Dutta et al. [34] underscored the significance of incorporating cascading economic impacts in loss assessments. They developed an innovative unit loss model that integrates physically based distributed hydrological models with distributed flood loss estimation models. Similarly, Kirchherr and Charles [35] introduced a “matrix framework” approach, which conceptualizes the complexity and multidimensionality of the social impacts of dams as an interconnected system. In addition, Manzano et al. [36] examined groundwater contamination resulting from a tailings dam breach in Spain, highlighting the environmental consequences of dam failures. Comprehensive evaluation methods provide an effective

way to integrate multiple factors and evaluate dam failure consequences from a systematic perspective. Compared with single-factor analysis, these approaches can better describe the combined effects of social, economic, and environmental impacts. However, uncertainties associated with expert cognition, indicator weighting, and unclear boundaries between consequence levels remain challenging and may influence the reliability of evaluation results.

A comprehensive review of existing studies reveals several limitations in current dam breach consequence evaluation research. First, most evaluation systems primarily focus on life loss and direct economic damage, while insufficient attention has been paid to social impacts and ecological losses. Second, existing weighting methods often struggle to balance subjectivity and objectivity effectively. Third, conventional evaluation models cannot simultaneously address fuzziness, randomness, and hesitation in dam breach consequence assessment. Finally, the stability and reliability of evaluation results require further improvement. Therefore, there is a pressing need for a robust evaluation model that effectively addresses the consequences of dam failures and resolves issues such as uncertainty in the evaluation process, inter-indicator correlations, and dimensional inconsistencies. Such a model would offer a comprehensive understanding of the impacts of dam destruction on the lives, economy, society, and environment of the entire region, thereby providing valuable insights for the development of effective emergency response and risk management strategies.

### 3. Methodology

This study develops a comprehensive evaluation index system for assessing dam failure losses, drawing from the existing literature. Subsequently, it outlines the specific implementation process of the enhanced “hesitant cloud–entropy weighted–set pair analysis method”, which encompasses data processing, weight calculation, and result analysis. Finally, through practical case studies, we validate and evaluate the effectiveness of the “hesitant cloud–entropy weighted–set pair analysis method” in the comprehensive assessment of dam failures. The evaluation process for dam failures in reservoirs is illustrated in Figure 1.



**Figure 1.** The evaluation process for dam failures in reservoirs.

### 3.1. Evaluation Index System

#### 3.1.1. Criterion Layer

Based on existing research and engineering practices, this study sets the criteria layer for the dam breach assessment system, including life loss, economic loss, social impact, and environmental impact [37].

Resulting life loss refers to fatalities and injuries occurring within downstream inundation areas following a dam failure, primarily caused by flood hydrodynamic forces, submergence, and adverse environmental conditions such as low temperature exposure. Economic loss denotes the direct and indirect economic consequences induced by a dam failure. Direct losses include the destruction of residential and industrial buildings, agricultural land, forest resources, and wildlife habitats, as well as damage to critical infrastructure, such as water supply systems, hydropower facilities, transportation networks, and other public utilities. Indirect losses are associated with the disruption of regional economic activities, impairment of employment and industrial production, and subsequent long-term economic downturn. Social impact refers to the systemic and multifaceted consequences of a dam failure on social systems, encompassing human casualties, property loss, degradation of social stability, and erosion of public trust in governmental institutions. Such impacts are typically extensive and persistent, exerting long-term influences on community resilience and societal development. Environmental impact denotes irreversible or long-term alterations to the natural environment caused by a dam failure, including river water quality deterioration, soil erosion, ecosystem degradation, and biodiversity loss. These impacts may not only undermine local ecological integrity and ecosystem services but also generate cascading and long-lasting adverse effects on broader environmental systems.

#### 3.1.2. Index Layer

To conduct a comprehensive and precise assessment of the impacts following a dam breach, it is crucial to offer a more refined categorization of evaluation indicators. This study synthesizes the selection of evaluation indicators from recent research by systematically organizing and analyzing the literature. Table 1 presents the primary dam breach evaluation indices in reservoirs.

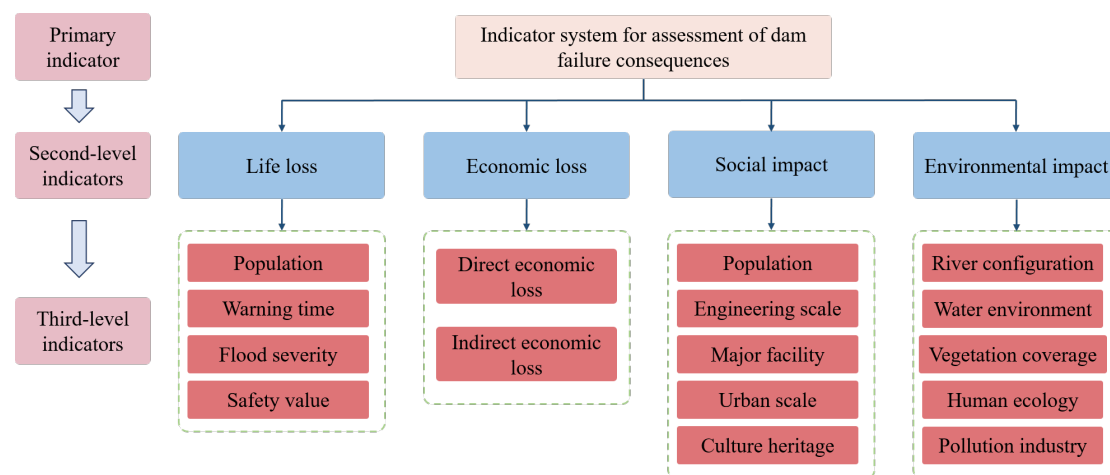
**Table 1.** Primary reservoir dam failure evaluation indices.

| Criterion Layer      | Index Layers and Related References                                                                                                                                    |
|----------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Life loss            | Population [38], warning time [39], flood severity degree [40], safety value [41], population composition at risk [42], and time of dam failure [43].                  |
| Economic loss        | Direct economic loss [44] and indirect economic loss [45].                                                                                                             |
| Social impact        | Population [46], engineering scale [37], major facility [47], urban scale [48], culture heritage [49], economic aggregate [50], and political impact [51].             |
| Environmental impact | Vegetation coverage [52], river configuration [53], biodiversity [54], human ecology [55], pollution industry [56], water environment [51], and soil environment [57]. |

To guarantee the scientific assessment of evaluation indices, this study engaged twenty experts from diverse departments and disciplines to participate in the index selection process. These twenty experts were mainly responsible for screening and optimizing the evaluation indicators to ensure the completeness and applicability of the proposed indicator system. They were from the transport management department (two experts from the provincial Flood Prevention Office, three experts from the Hydraulic Bureau),

universities (two experts from Hohai University, three experts from Fuzhou University), hydraulic engineering design units (three senior engineers from the Fujian Hydraulic and Hydropower Survey and Design Institute, three senior engineers from the Fuzhou Hydraulic and Hydropower Planning and Design Institute), and hydraulic engineering construction units (two engineers from Fujian Hydraulic and Hydropower Engineering Bureau Co., Ltd., two engineers from China Communications Hydraulic and Hydropower Construction Co., Ltd.).

The experts analyzed, scored, and compared the primary indices in the context of index selection, offering insights and recommendations. Twenty participants were surveyed using expert consultation questionnaires, all of which were returned. Subsequently, after eliminating incomplete and duplicate responses, a total of 18 valid questionnaires were retained. Given the diverse professional backgrounds of the experts, average scores were computed for each index. Through an iterative process of refinement and modification, the initial pool of 22 indices was reduced to a final set of 16 evaluation indices. The assessment indicator system for dam failure consequences in reservoirs was then established, as illustrated in Figure 2.



**Figure 2.** The assessment indicator system for dam failure consequences in reservoirs.

The comprehensive evaluation indicators for dam failures in reservoirs are vast and intricate. They encompass quantitative metrics and a substantial array of qualitative metrics. It is paramount for each indicator to be subjected to meticulous scrutiny, whereby its significance, inherent attributes, and determination methodologies are comprehensively comprehended. This ensures that the evaluation process is rigorous, holistic, and grounded in a deep understanding of the nuances.

#### (1) Life loss.

This study focuses on reservoirs with downstream population exposure, including those whose downstream inundation areas contain urban, rural, or mountainous communities. Therefore, life loss is considered the primary concern in the consequence assessment. The life loss resulting from a dam failure includes the fatalities sustained by individuals located downstream of a dam failure. These casualties are caused by factors such as powerful water flows, widespread flooding, and unfavorable weather conditions. Population refers to individuals who are trapped in floodwaters when the depth of flooding exceeds a critical threshold during hydrological disasters. Warning time is the duration between the issuance of official evacuation alerts and the arrival of floodwaters in a specific location, typically denoted as WT. Flood severity is the extent of the damage caused to populations, crops, infrastructure, and grassland vegetation downstream of a reservoir due to a dam

failure event. It is commonly assessed using two parameters, namely, flood depth ( $D$ ) and flow velocity ( $V$ ), calculated using the formula  $Flood\ Severity = Depth(D) \times Velocity(V)$ . Safety value represents the perceptions and understanding of residents in areas at risk of dam failures, particularly in relation to risk assessment. These values are closely associated with the potential losses resulting from such events.

## (2) Economic loss.

The economic loss resulting from a dam failure includes both direct and indirect components. Direct loss represents the quantifiable economic value lost due to the impacts of flooding and inundation caused by a dam failure, including the structural integrity of the dam and the economic resources in downstream flood-prone areas. Indirect loss encompasses the economic impacts and consequences that arise from a series of chain reactions triggered by a dam failure. They are generally not direct physical damages but rather arise from the economic effects and repercussions of the breach. Empirical coefficient methods are frequently used to calculate indirect economic loss, based on both domestic and international research findings. The method involves determining the ratio between indirect and direct economic loss across various industries by analyzing empirical data from representative regions. Subsequently, Formula (1) can be employed to calculate indirect economic losses, as shown below:

$$E_i = kE_d \quad (1)$$

where:

$E_i$  denotes the indirect economic loss resulting from the flood;

$E_d$  signifies the direct economic loss attributed to the flood;

“ $k$ ” represents the conversion coefficient, which quantifies the ratio of indirect economic losses to direct economic losses caused by floods, derived from empirical research and data analysis. Previous studies have estimated indirect economic losses using empirical coefficient methods. In one study, indirect economic loss was estimated using a conversion coefficient “ $k$ ” of 0.63 according to the Chinese water conservancy industry guideline SL/Z 720–2015 Guidelines for Preparing Emergency Plans for Reservoir Dam Safety Management [58], which recommends adopting  $k = 0.63$  when detailed post-disaster investigation data are unavailable. Therefore, indirect economic loss was calculated as 0.63 times the direct economic loss in this study.

## (3) Social impact.

The social impact of a dam failure encompasses a wide array of effects on various aspects of society. When a dam failure transpires in densely populated regions, the magnitude of its social impact is typically amplified. The assessment of the population during a dam failure is similar to the methods used to estimate potential life loss, involving the number of people living within the hazard zone. Engineering scale serves as a direct indicator of size and significance, which is directly related to the severity and destructiveness of the flooding, thereby determining its social impact. Major facilities encompass essential systems integral to daily life and the normal functioning of urban areas, along with industrial, mining, and military installations. Urban scale refers to the size and importance of the towns affected by a breach and plays a significant role in determining the prioritization of, and investment in, post-disaster rescue and reconstruction efforts. Furthermore, it affects the recovery and development of socioeconomics in the aftermath of such disasters. Cultural heritage encompasses both tangible and intangible cultural assets that have been preserved and inherited throughout human cultural evolution and hold significant historical, cultural, artistic, and other values. All these indicators are qualitative in nature.

## (4) Environmental impact.

The environmental impact of a dam failure encompasses the irreversible damage or alterations to the surrounding ecosystem. River configuration includes the alterations downstream of a dam collapse, where significant sediment transport can reshape the river. The water environment refers to qualitative indicators reflecting changes in river water quality caused by the influx of debris, harmful substances, and construction waste during floods. Vegetation coverage serves as a metric representing the extent of reduction in downstream agricultural, forest, and grassland areas due to flood impacts, indicating the degree of surface vegetation affected. Human ecology evaluative indicators assess the damage floods inflict on ecological landscapes, cultural parks, tourist attractions, and other vulnerable areas. The pollution industry is measured using evaluative indicators reflecting the degree of contamination resulting from floods that damage industrial facilities containing pollutants, causing their dispersion into the environment.

### 3.2. Criteria for Evaluation Index Levels

This study adopts a combined approach of the standard method and reference method to establish grading criteria for evaluating dam failure consequences. Based on relevant regulations, technical standards, previous studies, and historical dam failure cases, the consequence levels are divided into five categories: slight, average, moderate, severe, and extremely severe. The threshold values of quantitative indicators were determined according to existing classification standards and empirical research. Specifically, the population at risk was classified according to the potential exposure scale of downstream residents under different dam failure scenarios, while economic loss levels were determined based on disaster loss classification criteria and previous consequence assessment studies. Indicators such as flood severity and vegetation coverage were categorized using commonly adopted evaluation ranges in flood risk and ecological impact assessments. For qualitative indicators, including engineering scale, major facilities, urban scale, cultural heritage, and environmental conditions, numerical values were assigned through standardized scoring methods and expert knowledge to allow unified calculation with quantitative indicators. Among them, engineering scale represents the importance and size of hydraulic structures, where Level 1 indicates the largest and most important projects and Level 5 represents relatively small-scale projects. It should be noted that the population at risk appears in both life loss and social impact assessments because it reflects different dimensions: in life loss evaluation, it represents potential casualties and human safety risks, whereas in social impact evaluation, it describes the influence scope and social disruption caused by a dam failure. In this study, the five consequence levels for a dam breach were established based on relevant standards and regulations, previous studies, and expert judgment. The classification criteria for each evaluation indicator were derived from previous research findings and statistical analyses of historical dam failure data. Specific evaluation criteria are presented in Tables 2–5.

**Table 2.** Classification criteria for life loss evaluation indicators.

| Indicator                  | Impact Severity Level          |                                        |                                           |                                         |                               |
|----------------------------|--------------------------------|----------------------------------------|-------------------------------------------|-----------------------------------------|-------------------------------|
|                            | Slight                         | Average                                | Moderate                                  | Severe                                  | Extremely Severe              |
| Population at risk/million | [0, 0.1)                       | [0.1, 1)                               | [1, 10)                                   | [10–100)                                | [100–1000)                    |
| Warning time               | Full warning<br>$W_T \geq 1.0$ | Major warning<br>$0.75 < W_T \leq 1.0$ | Moderate warning<br>$0.5 < W_T \leq 0.75$ | Fewer warnings<br>$0.25 < W_T \leq 0.5$ | No warning<br>$W_T \leq 0.25$ |
| Flood severity             | Extremely low<br>[0, 0.5)      | Low<br>[0.5, 4.6)                      | Moderate<br>[4.6, 12)                     | High<br>[12, 15)                        | Extremely high<br>[15, 100)   |

Table 2. Cont.

| Indicator     | Impact Severity Level       |                   |                     |                   |                              |
|---------------|-----------------------------|-------------------|---------------------|-------------------|------------------------------|
|               | Slight                      | Average           | Moderate            | Severe            | Extremely Severe             |
| Safety values | Extremely clear<br>[0, 0.5) | Clear<br>[25, 45) | Average<br>[45, 65) | Vague<br>[65, 85) | Extremely vague<br>[85, 100) |

Table 3. Classification criteria for economic loss evaluation indicators.

| Indicator                   | Impact Severity Level |          |          |          |                  |
|-----------------------------|-----------------------|----------|----------|----------|------------------|
|                             | Slight                | Average  | Moderate | Severe   | Extremely Severe |
| Economic losses/billion CNY | [0, 0.5)              | [25, 45) | [45, 65) | [65, 85) | [85, 100)        |

Table 4. Classification criteria for social impact evaluation indicators.

| Indicator                  | Impact Severity Level                                      |                                                                 |                                                                                    |                                                                |                                                      |
|----------------------------|------------------------------------------------------------|-----------------------------------------------------------------|------------------------------------------------------------------------------------|----------------------------------------------------------------|------------------------------------------------------|
|                            | Slight                                                     | Average                                                         | Moderate                                                                           | Severe                                                         | Extremely Severe                                     |
| Population at risk/million | [0, 0.1)                                                   | [0.1, 1)                                                        | [1, 10)                                                                            | [10–100)                                                       | [100–1000)                                           |
| Engineering scale          | Level 5                                                    | Level 4                                                         | Level 3                                                                            | Level 2                                                        | Level 1                                              |
| Major facilities           | General facilities                                         | County-level major facilities                                   | City-level major facilities                                                        | Provincial-level major facilities                              | National-level major facilities                      |
| Urban scale                | Scattered households                                       | Country                                                         | Town                                                                               | County-level city and prefecture-level city                    | Municipality and provincial capital city             |
| Culture heritage           | General protection of cultural relics and natural heritage | County-level protection of cultural relics and natural heritage | City-level and provincial-level protection of cultural relics and natural heritage | National-level protection of cultural relics and rare wildlife | World heritage cultural sites and endangered species |

Table 5. Classification criteria for environmental impact evaluation indicators.

| Indicator                         | Impact Severity Level                                                                   |                                                                                             |                                                                                             |                                                                                          |                                                                                              |
|-----------------------------------|-----------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------|
|                                   | Slight                                                                                  | Average                                                                                     | Moderate                                                                                    | Severe                                                                                   | Extremely Severe                                                                             |
| Vegetation coverage               | Minimal damage, with no substantial economic impact on forest regions<br>[0, 0.2)       | Minimal damage, with partial substantial economic forest regions<br>[0.2, 0.4)              | Severe damage, with no substantial economic impact on forest regions<br>[0.4, 0.6)          | Severe damage, with partial substantial economic forest regions<br>[0.6, 0.8)            | Severe damage, with all substantial economic forest regions<br>[0.8, 1)                      |
| River configuration               | Grade 5 river has suffered minor damage<br>[0, 20)                                      | Grade 4 river has sustained some damage<br>[20, 40)                                         | Grade 3 river has sustained some damage<br>[40, 60)                                         | Grade 2 river has sustained severe damage<br>[60, 80)                                    | Grade 1 river has sustained severe damage<br>[80, 100)                                       |
| Water environment                 | Agricultural water use areas and general landscape-required waters<br>[0, 20)           | Industrial water use areas and recreational waters without direct human contact<br>[20, 40) | Secondary zone of the centralized drinking water surface source protection area<br>[40, 60) | Primary zone of centralized drinking water surface source protection area<br>[60, 80)    | Headwater or national nature reserve<br>[80, 100)                                            |
| Humanistic ecological environment | Natural landscapes or county cultural landscapes have sustained minor damage<br>[0, 20) | Municipal cultural landscapes or tangible cultural heritage have been damaged<br>[20, 40)   | Provincial cultural landscapes or tangible cultural heritage have been damaged<br>[40, 60)  | National cultural landscapes or tangible cultural heritage have been damaged<br>[60, 80) | World-class cultural landscapes or tangible cultural heritage have been damaged<br>[80, 100) |
| Pollution industry                | Near-zero pollution industry<br>[0, 20)                                                 | Small-scale chemical or pesticide factory<br>[20, 40)                                       | Medium-scale chemical or pesticide factory<br>[40, 60)                                      | Large-scale chemical or pesticide factory<br>[60, 80)                                    | Industries such as nuclear power plants that cause devastating pollution<br>[80, 100)        |

### 3.3. Evaluation Model

#### 3.3.1. Identifying Indicator Weights Based on the Hesitation Cloud-Improved Entropy Weight Method

##### (1) Modeling hesitant linguistics.

When utilizing expert experiential knowledge to assess the significance of evaluation indicators, experts may occasionally exhibit uncertainty regarding the importance of specific indicators. Given that human subjective judgments inherently contain a degree of ambiguity, imposing rigid criteria on these judgments can overlook this intrinsic uncertainty, thereby increasing the likelihood of evaluative errors. To more accurately characterize the ambiguity and hesitance associated with the expert weighting process, this study incorporates the theory of hesitation clouds into the research on weight allocation. In assessing indicators, domain experts typically use linguistic terms to convey their subjective perceptions. These linguistic expressions encompass not only fuzzy uncertainty but also random uncertainty.

The qualitative concept  $l$ , articulated using linguistic terminology, can be represented as  $l(Ex, En, He)$  through a normal cloud model. Arithmetic operations, such as addition, subtraction, multiplication, and division on cloud models, are explicitly defined in terms of these three parameters. The calculation formulas for cloud models involving addition and multiplication are presented below:

$$l_1 + l_2 = \begin{pmatrix} Ex_1 \\ En_1 \\ He_1 \end{pmatrix} + \begin{pmatrix} Ex_2 \\ En_2 \\ He_2 \end{pmatrix} = \begin{pmatrix} Ex_1 + Ex_2 \\ \sqrt{En_1^2 + En_2^2} \\ \sqrt{He_1^2 + He_2^2} \end{pmatrix} \quad (2)$$

$$l_1 \times l_2 = \begin{pmatrix} Ex_1 \\ En_1 \\ He_1 \end{pmatrix} \times \begin{pmatrix} Ex_2 \\ En_2 \\ He_2 \end{pmatrix} = \begin{pmatrix} Ex_1 \times Ex_2 \\ |Ex_1 \times Ex_2| \times \sqrt{\left(\frac{En_1}{Ex_1}\right)^2 + \left(\frac{En_2}{Ex_2}\right)^2} \\ |Ex_1 \times Ex_2| \times \sqrt{\left(\frac{He_1}{Ex_1}\right)^2 + \left(\frac{He_2}{Ex_2}\right)^2} \end{pmatrix} \quad (3)$$

When  $l_i(Ex_i, En_i, He_i), i = 1, 2, \dots, n$ , the formula for calculating the comprehensive cloud model  $l_s$  for an  $n$ -term normal cloud model in the domain  $U$  is:

$$l_s = \begin{pmatrix} \frac{\sum_{i=1}^n Ex_i}{n} \\ \frac{\max_i(Ex_i + 3En_i) - \min_j(Ex_j - 3En_j)}{6} \\ \frac{\sum_{i=1}^n He_i}{n} \end{pmatrix} \quad (4)$$

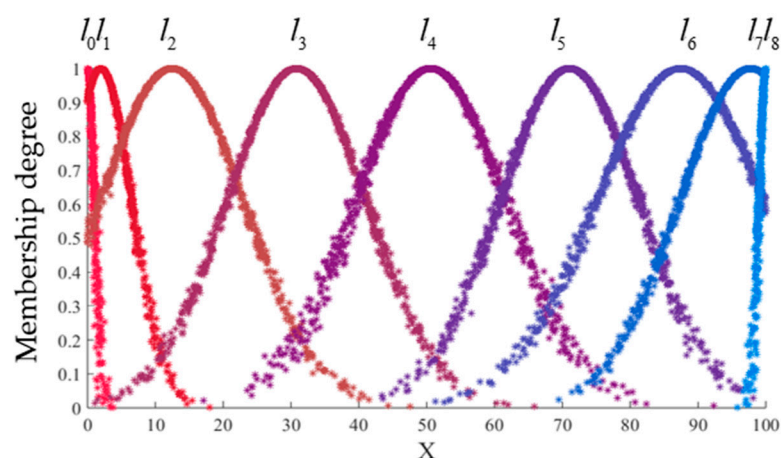
To address situations in which domain experts are uncertain about the significance of specific indicators in practical scenarios, or when they prefer to use a broader and more diverse range of evaluative language to express their subjective perspectives, this study employs a hesitant fuzzy linguistic term set.

In the context of weight allocation for  $n$  evaluation criteria denoted as  $A = (a_1, a_2, \dots, a_n)$ , assuming  $q$  domain experts participate in assessing the importance of these criteria, denoted as expert set  $E = (e_1, e_2, \dots, e_q)$ , let  $H_L = \{l_i, \dots, l_{i+k}\}, i \geq 0, k \geq 0, i + k \leq m$ , be a hesitant fuzzy linguistic term set defined on  $L = \{l_0, \dots, l_m\}$ . Therefore,  $H_L^{ik}$  represents the hesitant fuzzy linguistic term set for the expert  $e_i$  assessment of the importance of criterion  $k$ , where  $i \in \{1, 2, \dots, q\}, k \in \{1, 2, \dots, n\}$ .

The comprehensive language term set  $L = \{l_0, \dots, l_m\}$  employed in this study is derived from the linguistic term cloud models developed by [59], utilizing interval survey and membership function fitting methods, as illustrated in Table 6. Based on the data presented in Table 6, the cloud diagram of the complete language term set  $L$  is depicted in Figure 3.

**Table 6.** The complete linguistic term set  $L$  for defining a normal cloud model.

| Linguistic Term          | Cloud Model          |
|--------------------------|----------------------|
| None ( $l_0$ )           | (0.00, 1.00, 0.20)   |
| Extremely low ( $l_1$ )  | (1.97, 4.57, 0.22)   |
| Low ( $l_2$ )            | (12.46, 10.62, 0.34) |
| Slightly low ( $l_3$ )   | (30.83, 10.30, 0.33) |
| Moderate ( $l_4$ )       | (50.58, 11.09, 0.56) |
| Slightly high ( $l_5$ )  | (71.05, 10.27, 0.41) |
| High ( $l_6$ )           | (87.43, 12.42, 0.41) |
| Very high ( $l_7$ )      | (97.75, 10.54, 0.27) |
| Extremely high ( $l_8$ ) | (100.00, 1.00, 0.20) |



**Figure 3.** The cloud diagram of the complete linguistic term set  $L$ .

## (2) Improved entropy weight.

Previous research on cloud models has typically placed greater emphasis on the computation of expectations while underutilizing entropy and hyper-entropy. Nevertheless, entropy and hyper-entropy in cloud models serve as effective measures of numerical divergence and randomness, thereby accurately reflecting consensus regarding risk factors. Consequently, this study integrates the entropy weight method to address discrepancies among indicators. Building upon traditional entropy weight approaches, an enhanced model for indicator weighting was developed. The revised cloud entropy weight formula is presented in Equation (5).

$$\omega = \begin{cases} \frac{Ex_j}{\ln(1 + En_j) + 1} \cdot \frac{1}{\sum_{j=1}^n \frac{Ex_j}{\ln(1 + En_j) + 1}} & (En_j \neq 0) \\ \frac{Ex_j}{\sum_{j=1}^n Ex_j} & (En_j = 0) \end{cases} \quad (5)$$

## (3) Calculating weights.

This study integrates the hesitant cloud model with an enhanced entropy method to simultaneously address the fuzziness, randomness, and hesitancy inherent in subjective evaluations during expert decision-making processes. This approach more precisely represents the objective reality of human decision-making. The main steps involved in the improved weight calculation model, which is based on the hesitant cloud and enhanced entropy method, are outlined as follows:

(1) Experts define the complete set  $L$  of linguistic terms within the domain utilizing the normal cloud model. They assess the significance of evaluation criteria and derive the information decision matrix  $M_i, i \in \{1, 2, \dots, q\}$  from each expert.

(2) The outcomes of expert  $e_i$ 's assessment of the significance of evaluation criterion  $c_k$  are denoted as  $M_{ik}$ . The degrees of importance determined by  $q$  experts concerning evaluation criterion  $c_k$  are represented by  $q$  hesitant fuzzy linguistic term sets  $H_L^{1k}, H_L^{2k}, \dots, H_L^{qk}$ .

(3) After calculating the decision results of each expert, the hesitant fuzzy linguistic term sets are converted into comprehensive cloud models  $c_1, c_2, \dots, c_q$ , and then these comprehensive cloud models are converted into average cloud models  $CM_k, k \in 1, 2, \dots, n$ , where  $CM_k$  presents the importance levels of various evaluation criteria reflected from the parameters of the cloud models.

(4) Utilizing the cloud model representations of the importance levels associated with each evaluation criterion, we calculate the weights of these criteria.

### 3.3.2. Set Pair Analysis Evaluation Model

#### (1) Set pair.

Set pair analysis theory effectively addresses the challenges associated with fuzzy uncertainty, resulting in more efficient solutions to practical problems. This approach accurately captures the interrelationships and mutual constraints among various entities, thereby more faithfully representing real-world situations. Furthermore, it is straightforward to compute, easy to understand and apply, and well suited for diverse scenarios across various fields.

#### (2) Connection degree.

Set pair  $H = (A, B)$  has  $N$  characteristics, of which  $S$  characteristics are shared between set  $A$  and set  $B$ , representing identity.  $P$  characteristics are opposite, and the remaining  $F$  characteristics are neither the same nor opposite, representing the difference. The degree of interrelationship between the two sets is represented by the connection degree, as shown in Equation (6).

$$\mu = \frac{S}{N} + \frac{F}{N}i + \frac{P}{N}j = a + bi + cj \quad (6)$$

where  $\mu$  denotes connectivity;  $N$  represents the total number of characteristics in sets  $A$  and  $B$ , and  $F = N - S - P$ ; and  $i$  is the difference coefficient,  $i \in [-1, 1]$ , while  $j$ , the opposition coefficient, is fixed at  $-1$ . The parameters  $a, b, c$  signify similarity, difference, and opposition within sets  $A$  and  $B$ , respectively,  $a, b, c \in [0, 1]$ , and they satisfy the normalization condition  $a + b + c = 1$ .

The indicators for life losses, economic losses, social impact, environmental impact, and comprehensive evaluation of consequences are all characterized as "the smaller the better" cost-type indicators. Consequently, by comparing and analyzing the indicator values  $x_k$  of the two sets that form the pair and the standard values  $s_{k-1} \sim s_k$  corresponding to the evaluation grades, we can draw the following conclusions.

(1) When  $x_k$  is within the range of  $s_{k-1} \sim s_k$ , it is considered identical, and at this time,  $a = 1$ .

(2) When  $x_k$  is within the adjacent range of  $s_{k-1} \sim s_k$ , if  $x_k < s_{k-1}$ , it is considered an excellent difference, and the value is denoted as  $b_1$ ; if  $x_k > s_k$ , it is considered an inferior difference, and the value is denoted as  $b_2$ .

(3) When  $x_k$  is within the spaced range of  $s_{k-1} \sim s_k$ , if  $x_k < s_{k-2}$ , it is considered excellent opposition, and the value is denoted as  $c_1$ ; if  $x_k > s_{k+1}$ , it is considered inferior opposition, and the value is denoted as  $c_2$ .

Consequently, there are five evaluation levels (slight, average, moderate, severe, extremely severe), and the formulas for calculating the connectivity of the indicator pairs corresponding to each evaluation level can be established. Detailed derivations are provided in Table S1.

### (3) Set pair situation.

A set pair situation is a mathematical theory that deals with the interactions between certainty and uncertainty in systems. Its main mathematical tool is the connection degree, which is used to evaluate the magnitude of identity, difference, and opposition. In traditional set pair analysis, the set pair potential is calculated as the ratio of identity degree  $a$  to opposition degree  $c$ , as shown in Formula (7).

$$SHI(H) = \frac{a}{c}, c \neq 0 \quad (7)$$

However, when utilized in real engineering projects, the following limitations are encountered.

(1) In practical applications, there are instances where  $c = 0$ , but the formula is unable to calculate the set pair situation in such cases.

(2) Traditional calculation methods may yield results that are incongruent with actual situations. For instance, if the two connection degrees are  $\mu_1 = 0.15 + 0.84i + 0.01j$  and  $\mu_2 = 0.90 + 0.01i + 0.09j$ , according to traditional formulas, the result is  $SHI(H)_1 = 15 > SHI(H)_2 = 10$ . Consequently, the former is categorized as a slight identity situation, while the latter is identified as a strong identity situation, which contradicts actual findings.

To address these issues, scholars conducted research and introduced the concept of a generalized set pair situation based on the traditional set pair situation. The ratio of the relative identity degree  $e^a$  and relative opposition degree  $e^c$  is defined as the generalized set pair situation, as shown in Formula (8).

$$SHI(H)_G = \frac{e^a}{e^c} \quad (8)$$

### (4) Evaluation levels.

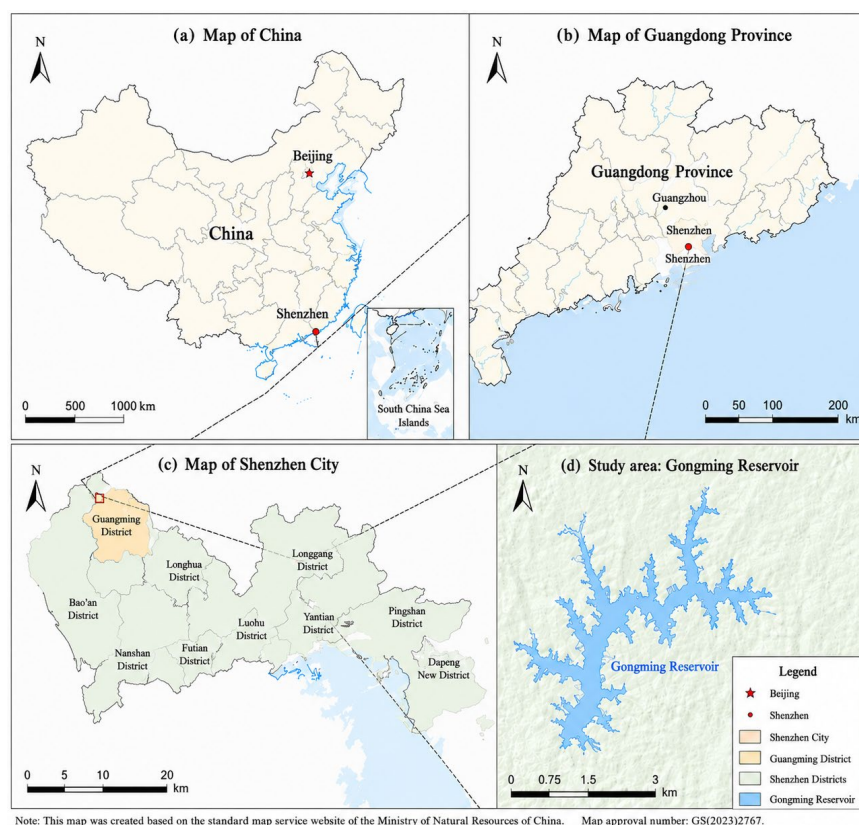
After calculating  $SHI(H)_G$  using Formula (8), it is normalized to ascertain the membership degree  $\mu_i$  of the evaluated object relative to a specific evaluation level  $S_i$ . In this context,  $\max\{\mu_i\}$  denotes the comprehensive evaluation level associated with the consequences stemming from dam failure losses. The aggregate of the membership degrees across all evaluation levels for the evaluated object totals 1. This normalization process is implemented when the following conditions are met:

$$i_0 = \min \left\{ i \mid \sum_{i=1}^n \mu_i > \lambda, 1 \leq i \leq n \right\} \quad (9)$$

If the conditions are met, the evaluated object is assigned to level  $i_0$ . The confidence criterion is determined by the “strength” perspective, where higher levels occupy a larger proportion. Typically, a confidence value  $\lambda$  ranging between 0.5 and 0.7 is chosen [60]. A higher  $\lambda$  value signifies a more conservative evaluation outcome. This study adopted a  $\lambda$  value of 0.6 based on the experts’ recommendations.

#### 4. Study Case

The GM (Gongming) Reservoir is located in Shenzhen City, Guangdong Province, southern China, within the Pearl River Delta region. The GM Reservoir was selected because it represents a typical urban reservoir with high population exposure, important water supply functions, and complex downstream environments. This reservoir comprises three key components: the expansion of an existing reservoir, a cross-border water source connection project, and a water supply and distribution system. It plays a crucial role in flood control and serves as a strategic reserve for water storage in Shenzhen, primarily ensuring reliable water supply services to major water treatment facilities in the Bao'an and Guang Ming New Districts in western Shenzhen, thereby safeguarding the city's water resource security. Following the expansion, the normal storage level of the GM Reservoir is 59.7 m, with a check flood level of 60.58 m. The normal storage capacity is 142 million cubic meters, while the total storage capacity is 148 million cubic meters. The catchment area covers 11.77 square kilometers, extending approximately 4.2 km from north to south and about 2.1 km from east to west. The dam has a top length of 895 m and reaches a maximum height of 54 m; it is classified as a homogeneous earth dam. The regional location and a downstream schematic diagram of the reservoir are shown in Figures 4 and 5.



**Figure 4.** Regional location map of the GM Reservoir.

##### 4.1. The Values of Evaluation Indicators

To ensure the reliability and consistency of the evaluation results, the indicator values used in this study were determined through a combination of multiple data sources and validation methods. Quantitative indicators, such as population at risk, economic losses, reservoir characteristics, and flood-related parameters, were obtained from reservoir design documents, engineering investigation reports, official statistical data, and the relevant literature [61,62]. For qualitative indicators involving social and environmental impacts, expert assessments were conducted based on predefined evaluation criteria to reduce

subjective uncertainty. In addition, the average values of multiple evaluation results were adopted to minimize individual differences and improve data comparability. The final evaluation values of each indicator are presented in Table 7.



**Figure 5.** Downstream schematic diagram of the Shenzhen GM Reservoir.

**Table 7.** Evaluation indicator values of the Shenzhen GM Reservoir.

| Second-Level Indices | Third-Level Indexes               | Specific Description                                                                                                                                                            | Value  |
|----------------------|-----------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------|
| Life loss            | Population at risk                | 9310 persons in district I, 27,930 persons in district II                                                                                                                       | 37,240 |
|                      | Warning time                      | Partial warning                                                                                                                                                                 | 0.6/50 |
|                      | Flood severity                    | $S = D \times V$                                                                                                                                                                | 10.8   |
|                      | Safety values                     | Public awareness regarding the severity of the consequences of dam failure remains largely inadequate                                                                           | 75     |
| Economic loss        | Direct economic losses            | This primarily encompasses losses resulting from the submergence or destruction of reservoirs, highways, and industrial zones, as well as agricultural and ancillary industries | 26.65  |
|                      | Indirect economic                 | Indirect economic losses are derived by multiplying direct economic losses by a factor of 0.63                                                                                  | 16.79  |
| Social impact        | Population at risk                | 9310 persons in district I, 27,930 persons in district II                                                                                                                       | 37,240 |
|                      | Engineering scale                 | Level 2                                                                                                                                                                         | 69     |
|                      | Major facilities                  | Provincial-level major facilities                                                                                                                                               | 84     |
|                      | Urban scale                       | Prefecture-level city                                                                                                                                                           | 75     |
|                      | Culture heritage                  | Provincial level protects cultural relics and natural heritage                                                                                                                  | 60     |
| Environmental impact | River configuration               | Major rivers suffer damage                                                                                                                                                      | 78     |
|                      | Water environment                 | Downstream water quality is at Level III                                                                                                                                        | 55     |
|                      | Vegetation Coverage               | Large areas of surface forests and grasslands are damaged                                                                                                                       | 0.5    |
|                      | Humanistic ecological environment | Municipal cultural landscapes have been damaged                                                                                                                                 | 36     |
|                      | Pollution industry                | General chemical factory                                                                                                                                                        | 40     |

Note: Quantitative values were obtained from engineering documents and statistical data or calculated according to the corresponding evaluation criteria, while qualitative indicators were converted into numerical scores based on expert assessments and classification standards. For flood severity,  $S = D \times V$ , where  $S$ ,  $D$ , and  $V$  represent flood severity, flood depth, and flow velocity, respectively. The coefficient 0.63 denotes the conversion coefficient used to estimate indirect economic losses from direct economic losses.

#### 4.2. Determining the Weight of Indicators

Ten experts were selected from the previously invited group of twenty experts to assess the significance of each indicator level in relation to the higher-level indicators and to assign scores accordingly. The four secondary-level indicators are  $B = \{\beta_1, \beta_2, \beta_3, \beta_4\}$ , including life loss  $\beta_1$ , economic loss  $\beta_2$ , social impact  $\beta_3$ , and environmental impact  $\beta_4$ . The third-level indicators are  $B_1 = \{\beta_{11}, \beta_{12}, \beta_{13}, \beta_{14}\}$ ,  $B_3 = \{\beta_{31}, \beta_{32}, \beta_{33}, \beta_{34}, \beta_{35}\}$ , and

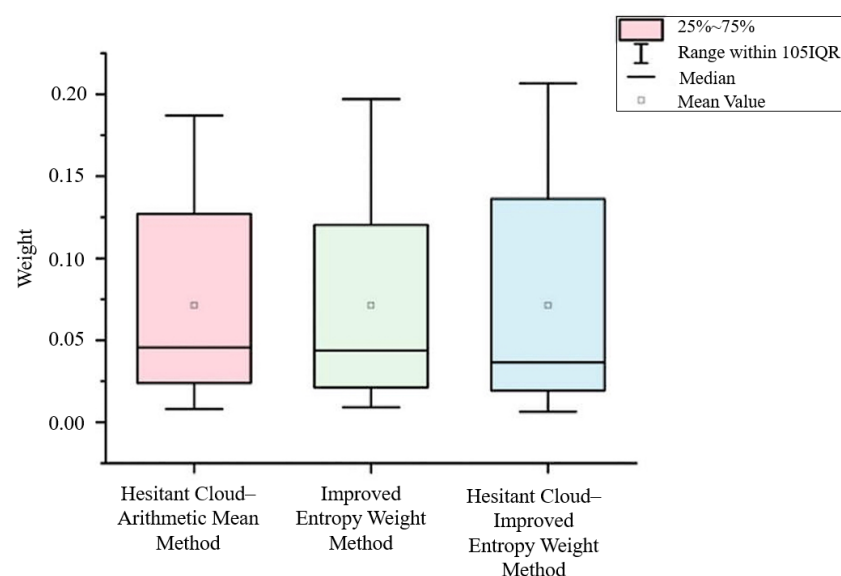
$B_4 = \{\beta_{41}, \beta_{42}, \beta_{43}, \beta_{44}, \beta_{45}\}$ . It should be noted that this study employs conversion coefficients to calculate and assess the lower-level indicators of economic loss, thereby eliminating the necessity for weight analysis of direct and indirect economic losses. The 20 experts articulated their subjective judgments through linguistic expressions, which were subsequently transformed into a decision matrix utilizing the hesitant fuzzy linguistic term set.

Statistical analysis of the experts' scores reveals that each expert employed two to three evaluation terms in their assessments, indicating some uncertainty regarding certain indicators. This aligns with human thinking patterns and is close to reality. Utilizing Formula (4), the integrated cloud model for each expert's judgment of each evaluation indicator represented by hesitant fuzzy language terms and the average integrated cloud model for each indicator are calculated.

Formula (5) and the average comprehensive cloud model parameters derived from the previous calculations are utilized to ascertain the final weight  $\omega$ . Additionally, we compare  $\omega$  with the results obtained from the other two weight calculation methods. The first method directly applies the improved entropy weight technique to the precise scores provided by the experts, yielding weight  $\hat{\omega}_1$  without employing the hesitant cloud approach. The second method calculates the average comprehensive cloud model of the expert scores utilizing the hesitant cloud approach and subsequently computes the arithmetic mean of the expected values, normalizing them to derive weight  $\hat{\omega}_2$ . The results are shown in Table 8, and a graphical statistical analysis of the weights established by the three methods is presented, with the specific analysis shown in Figure 6.

The pink, green, and light blue boxes illustrated in Figure 5 represent the distribution ranges of the results calculated by different evaluation models. The box represents the interquartile range (IQR, 25–75%), the horizontal line inside the box indicates the median value, and the square marker represents the mean value. The whiskers indicate values within 1.5 times the IQR. No abnormal values were detected in this analysis. The weight determination method employed in this study results in a different weight distribution compared to the other two methods, reducing the risk of weight concentration that could lead to misjudgment and thus enhancing accuracy.

From Table 8, the weights of the sub-indicators for the comprehensive evaluation of dam failure loss consequences are derived, as shown in Table 9. The third-level indicators are normalized to obtain the weight of each indicator for the corresponding second-level indicators. The results are shown in Tables 10–12.



**Figure 6.** Box plot of evaluation indicator weights.

**Table 8.** Summary table of evaluation indicator weights.

| Primary Evaluation Indicator             | Second-Level Indicators $\beta_i$ | $\hat{\omega}_1$ | $\hat{\omega}_2$ | $\omega$ | Third-Level Indicators $\beta_{ij}$            | $\hat{\omega}_1$ | $\hat{\omega}_2$ | $\omega$ |
|------------------------------------------|-----------------------------------|------------------|------------------|----------|------------------------------------------------|------------------|------------------|----------|
| Comprehensive evaluation of dam failures | Life loss $\beta_1$               | 0.5571           | 0.5484           | 0.6226   | Population at risk $\beta_{11}$                | 0.1483           | 0.1561           | 0.1721   |
|                                          |                                   |                  |                  |          | Warning time $\beta_{12}$                      | 0.1504           | 0.1582           | 0.1746   |
|                                          |                                   |                  |                  |          | Flood severity $\beta_{13}$                    | 0.1270           | 0.1203           | 0.1362   |
|                                          |                                   |                  |                  |          | Safety values $\beta_{14}$                     | 0.1314           | 0.1138           | 0.1396   |
|                                          | Economic loss $\beta_2$           | 0.1251           | 0.1345           | 0.1066   | Direct economic losses $\beta_{21}$            | -                | -                | -        |
|                                          |                                   |                  |                  |          | Indirect economic losses $\beta_{22}$          | -                | -                | -        |
|                                          | Social impact $\beta_3$           | 0.1588           | 0.1539           | 0.1353   | Population at risk $\beta_{31}$                | 0.0387           | 0.0409           | 0.0346   |
|                                          |                                   |                  |                  |          | Engineering scale $\beta_{32}$                 | 0.0248           | 0.0228           | 0.0200   |
|                                          |                                   |                  |                  |          | Major facilities $\beta_{33}$                  | 0.0239           | 0.0213           | 0.0193   |
|                                          |                                   |                  |                  |          | Urban scale $\beta_{34}$                       | 0.0325           | 0.0283           | 0.0267   |
|                                          |                                   |                  |                  |          | Culture heritage $\beta_{35}$                  | 0.0389           | 0.0406           | 0.0347   |
|                                          | Environmental impact $\beta_4$    | 0.1590           | 0.1632           | 0.1355   | River configuration $\beta_{41}$               | 0.0128           | 0.0138           | 0.0100   |
|                                          |                                   |                  |                  |          | Water environment $\beta_{42}$                 | 0.0525           | 0.0469           | 0.0383   |
|                                          |                                   |                  |                  |          | Vegetation coverage $\beta_{43}$               | 0.0138           | 0.0150           | 0.0101   |
|                                          |                                   |                  |                  |          | Humanistic ecological environment $\beta_{44}$ | 0.0081           | 0.0092           | 0.0065   |
|                                          |                                   |                  |                  |          | Pollution industry $\beta_{45}$                | 0.0717           | 0.0783           | 0.0706   |

**Table 9.** Weights of sub-indicators for the comprehensive evaluation of dam failures.

| Indicators | Life Loss | Economic Loss | Social Impacts | Environmental Impacts |
|------------|-----------|---------------|----------------|-----------------------|
| Weight     | 0.6226    | 0.1066        | 0.1353         | 0.1632                |

**Table 10.** Weights of sub-indicators for life loss.

| Indicators | Population at Risk | Warning Time | Flood Severity | Safety Values |
|------------|--------------------|--------------|----------------|---------------|
| Weight     | 0.2765             | 0.2805       | 0.2188         | 0.2242        |

**Table 11.** Weights of sub-indicators for social impact.

| Indicators | Population at Risk | Engineering Scale | Major Facilities | Urban Scale | Culture Heritage |
|------------|--------------------|-------------------|------------------|-------------|------------------|
| Weight     | 0.2558             | 0.1478            | 0.1426           | 0.1973      | 0.2565           |

**Table 12.** Weights of sub-indicators for environmental impact.

| Indicators | River Configuration | Water Environment | Vegetation Coverage | Humanistic Ecological Environment | Pollution Industry |
|------------|---------------------|-------------------|---------------------|-----------------------------------|--------------------|
| Weight     | 0.0738              | 0.2827            | 0.0745              | 0.0480                            | 0.5210             |

As shown in Table 9, life loss has the largest weight (0.6226), indicating that human safety is the dominant consideration in the comprehensive consequence assessment. This is consistent with the primary objective of dam safety management, which prioritizes the protection of human life. In comparison, economic, social, and environmental impacts receive relatively lower weights, although they remain important components of the evaluation framework. In Table 10, the weights of the four sub-indicators are relatively balanced. Among them, warning time has the highest weight, highlighting the importance of a timely emergency response. As shown in Table 11, population at risk and cultural heritage receive relatively higher weights, suggesting that human exposure and the protection of valuable

social assets play a more significant role in evaluating social impacts than engineering scale in the case study. Table 12 indicates that the pollution industry indicator has the largest weight, suggesting that industrial pollution is the dominant contributor to environmental consequences following dam failures in the study area.

#### 4.3. Calculation of Connection Degree

Utilizing Formulas (4)–(8), the connection degree between the evaluation indicators for life losses, economic losses, social impacts, and environmental impacts and the five evaluation levels (slight, average, moderate, severe, extremely severe) is calculated. It is important to note that economic losses can be quantified directly for scoring purposes; thus, the degree of connection between direct economic losses and the evaluation levels is computed accordingly. The results are as shown in Table S2.

By multiplying the weight vector ( $W = [\omega_1, \omega_2, \dots, \omega_n]$ ) of the evaluation indicators by the connectivity matrix, one obtains the comprehensive connection degree matrix  $A = W \cdot \mu$ . We integrate the calculated comprehensive connection degree of life losses, social impacts, and environmental impacts evaluations with their respective individual connection degree to the overall connection degree of economic losses. By employing the same methodology and corresponding weights, the comprehensive connection degree matrix  $A$  for the comprehensive evaluation of the dam failure loss consequences is derived as follows:

$$A = W \cdot \mu = \begin{bmatrix} 0.2434 + 0.0000i^+ + 0.2949i^- + 0.0000j^+ + 0.4617j^- \\ 0.4566 + 0.0000i^+ + 0.3948i^- + 0.0000j^+ + 0.1485j^- \\ 0.8152 + 0.0075i^+ + 0.0950i^- + 0.0000j^+ + 0.0823j^- \\ 0.7302 + 0.1818i^+ + 0.0840i^- + 0.0040j^+ + 0.0000j^- \\ 0.6711 + 0.2353i^+ + 0.0000i^- + 0.0936j^+ + 0.0000j^- \end{bmatrix}$$

In summary, based on the calculated connection degree matrices for life loss, economic loss, social impact, and environmental impact, along with the comprehensive evaluation of dam failures, utilizing the definitions and principles of generalized set pair theory, we computed the generalized set pair potentials across five distinct levels. The results were subsequently normalized, and confidence intervals were calculated to derive the final evaluation outcomes. Furthermore, this study contrasted these findings with those obtained through traditional set pair situation calculation methods. Detailed results are presented in Tables 13–17.

**Table 13.** Evaluation results and comparison of life loss.

| Evaluation Indicator                           | Slight | Average | Moderate      | Severe           | Extremely Severe |
|------------------------------------------------|--------|---------|---------------|------------------|------------------|
| $SHI(H)_G$<br>(Generalized set pair situation) | 0.8081 | 1.5296  | 2.5226        | 2.2238           | 1.8006           |
| $\mu_i$<br>Confidence interval                 | 0.0910 | 0.1722  | 0.2839        | 0.2503<br>0.7974 | 0.2027           |
| $SHI(H)$<br>(Traditional set pair situation)   | 0.5219 | 10.4781 | Indeterminate | Indeterminate    | 7.6194           |

Tables 13–16 summarize the evaluation results for the four consequence categories. The results show that the consequences of life loss, economic loss, and social impact are generally at relatively high levels, whereas the environmental impact is comparatively lower. This indicates that the potential consequences of a dam failure are dominated by risks to human safety, property, and social activities, while environmental impacts, although

important, contribute relatively less to the overall consequence assessment in this case. These findings provide the basis for the comprehensive evaluation presented in Table 17.

**Table 14.** Evaluation results and comparison of economic loss.

| Evaluation Indicator                           | Slight | Average | Moderate | Severe        | Extremely Severe |
|------------------------------------------------|--------|---------|----------|---------------|------------------|
| $SHI(H)_G$<br>(Generalized set pair situation) | 0.3688 | 0.3771  | 0.4720   | 1.2362        | 2.7183           |
| $\mu_i$<br>Confidence interval                 | 0.0713 | 0.0729  | 0.0913   | 0.2390        | 0.5255<br>1.0000 |
| $SHI(H)$<br>(Traditional set pair situation)   | 0.0002 | 0.0021  | 0.0269   | Indeterminate | Indeterminate    |

**Table 15.** Evaluation results and comparison of social impact.

| Evaluation Indicator                           | Slight | Average | Moderate      | Severe           | Extremely Severe |
|------------------------------------------------|--------|---------|---------------|------------------|------------------|
| $SHI(H)_G$<br>(Generalized set pair situation) | 0.8418 | 1.3576  | 2.3167        | 2.5396           | 1.8537           |
| $\mu_i$<br>Confidence interval                 | 0.0945 | 0.1524  | 0.2600        | 0.2851<br>0.7920 | 0.2081           |
| $SHI(H)$<br>(Traditional set pair situation)   | 0.6153 | 4.0938  | Indeterminate | Indeterminate    | 19.3284          |

**Table 16.** Evaluation results and comparison of environmental impact.

| Evaluation Indicator                           | Slight | Average | Moderate         | Severe  | Extremely Severe |
|------------------------------------------------|--------|---------|------------------|---------|------------------|
| $SHI(H)_G$<br>(Generalized set pair situation) | 1.3832 | 2.1875  | 2.4835           | 1.8047  | 1.1693           |
| $\mu_i$<br>Confidence interval                 | 0.1532 | 0.2423  | 0.2751<br>0.6706 | 0.1999  | 0.1295           |
| $SHI(H)$<br>(Traditional set pair situation)   | 3.5357 | 35.1810 | Indeterminate    | 21.2444 | 1.6279           |

**Table 17.** Evaluation results of the comprehensive evaluation for dam failures.

| Evaluation Indicator                           | Slight | Average | Moderate | Severe           | Extremely Severe |
|------------------------------------------------|--------|---------|----------|------------------|------------------|
| $SHI(H)_G$<br>(Generalized set pair situation) | 0.8038 | 1.3608  | 2.0813   | 2.0674           | 1.7816           |
| $\mu_i$<br>Confidence interval                 | 0.0993 | 0.1681  | 0.2571   | 0.2554<br>0.7799 | 0.2201           |

Based on the obtained connection degree results and the established confidence criterion, the consequence level of the case reservoir was determined. The comprehensive evaluation result obtained using the hesitant cloud entropy weighting method combined with improved set pair analysis indicates that the dam failure consequence level is classified as “severe”. This result reflects the combined influence of multiple dimensions rather than being dominated by a single factor. Specifically, the evaluation results of different consequence dimensions show that life loss and environmental impact are both classified as “severe”, while economic loss reaches the “extremely severe” level and social impact is evaluated as “moderate”. The high severity of life loss is mainly associated with the exposed downstream population and limited warning conditions during potential dam

failure events. The extremely severe economic consequences indicate that damage to reservoirs, infrastructure, and related economic activities may result in substantial direct and indirect losses. Although social impact presents a relatively lower consequence level, factors such as urban development, important facilities, and cultural resources still contribute to the overall risk. In addition, environmental impacts caused by river system disturbance, water quality degradation, and ecological damage further increase the complexity of dam failure consequences.

Compared with the traditional set pair situation method, the improved generalized set pair situation adopted in this study provides a more stable evaluation process. Traditional approaches may generate uncertain or invalid results under specific connection degree conditions, limiting their applicability in complex risk assessment problems. The generalized set pair situation avoids this limitation by improving the characterization of identity, difference, and opposition relationships among evaluation levels. Therefore, the proposed evaluation model can better distinguish consequence levels and provide clearer information for decision-making in reservoir safety management.

## 5. Discussion

### 5.1. Influence Mechanism of Dam Failure Consequences

Dam failure disasters are characterized by multi-factor interactions and cascading evolution processes. Their consequences are not only determined by the hydraulic characteristics of flood propagation but are also influenced by the combined effects of population distribution, social resilience, infrastructure exposure, and ecological vulnerability. Traditional dam failure risk assessments have primarily focused on casualties and direct economic losses. However, with increasing urbanization and stronger interactions among socioeconomic systems, the consequences of dam failures have gradually evolved from single-dimensional physical damage into compound impacts involving social, economic, and ecological systems. Particularly for reservoirs located in highly urbanized regions, dense population distribution, interconnected critical infrastructure, and environmental sensitivity may further amplify the severity and spatial extent of disaster consequences. Therefore, establishing a comprehensive evaluation model incorporating life loss, economic loss, social impact, and environmental impact is essential for revealing the formation mechanism of dam failure consequences from a systematic perspective and improving risk identification under complex disaster scenarios.

### 5.2. Uncertainty Characterization in Consequence Evaluation

Consequence evaluation of dam failures involves multiple sources of uncertainty, including incomplete indicator information, inconsistency in expert cognition, and ambiguous boundaries among different risk levels. Due to the low-frequency, high-impact, and complex evolutionary characteristics of dam failure events, deterministic evaluation approaches may have limitations in accurately representing actual risk states. During the comprehensive assessment process, experts may have difficulty providing completely precise judgments, while differences in information contained within indicators can also influence the rationality of weight allocation.

Compared with traditional evaluation methods, the proposed hesitant cloud-improved entropy weight-set pair analysis model provides a more comprehensive representation of uncertainty in the evaluation process. Conventional entropy weight methods mainly depend on information differences among indicators and may ignore the hesitation existing in expert judgments, while traditional cloud models have a limited ability to distinguish the relative importance of different indicators. By integrating hesitant cloud theory and improved entropy weighting, the proposed method maintains expert judgment informa-

tion while obtaining a clearer distribution of indicator weights. Furthermore, compared with conventional set pair analysis, the improved model better describes the uncertain relationships between evaluation objects and consequence levels, reducing the influence of unclear classification boundaries. Therefore, the proposed model provides more distinguishable evaluation results and improves the reliability of decision-making for complex dam failure scenarios.

### 5.3. Implications for Reservoir Safety Management

Modern reservoir safety management is gradually shifting from traditional structural reliability assessment to comprehensive risk-based management. Focusing solely on dam structural stability is insufficient to address the challenges associated with complex disaster environments. Effective dam failure risk prevention requires integrated consideration of pre-disaster risk identification, emergency response during disasters, and post-disaster recovery capacity. A comprehensive consequence evaluation model can provide decision support for identifying critical risk factors, thereby facilitating the optimization of monitoring and early-warning systems, emergency resource allocation, and regional disaster prevention strategies. Moreover, considering the significant differences among reservoirs with various geographical conditions and engineering scales, future research should incorporate real-time monitoring information, hydrodynamic simulation data, and multi-case validation to further enhance the applicability and robustness of evaluation models in practical reservoir management.

## 6. Conclusions

This study proposed a comprehensive evaluation model for assessing dam failure consequences by integrating a hesitant cloud-improved entropy weight method and set pair analysis. The main conclusions are summarized as follows:

- (1) A multidimensional evaluation index system for dam failure consequences was established based on existing studies and expert knowledge. The system consists of four dimensions, including life loss, economic loss, social impact, and environmental impact, with 16 detailed indicators. Compared with traditional evaluation systems mainly focusing on casualties and economic losses, the proposed model provides a more comprehensive representation of dam failure consequences.
- (2) The hesitant cloud model was combined with the improved entropy weight method to optimize indicator weight determination. This approach considers the uncertainty and hesitation existing in expert judgments while improving the differentiation among indicator weights. Furthermore, the set pair analysis model was introduced to handle uncertainty relationships between evaluation objects and consequence levels, improving the reliability of the evaluation process.
- (3) The proposed model was validated through a reservoir case study. The results demonstrate that the method can effectively integrate multiple consequence factors and provide clearer evaluation information for decision-makers. In addition, the model has potential applications in reservoir risk assessment, emergency management, and the planning stage of hydraulic infrastructure, such as site selection and risk comparison of dry reservoirs.

Compared with existing dam breach consequence assessment methods, the proposed framework provides a more comprehensive treatment of uncertainty by integrating the hesitant cloud model with the improved entropy weight method and set pair analysis. The proposed approach enhances the objectivity of weight determination, improves the representation of uncertain information, and provides a practical tool for comprehensive dam breach consequence assessment.

However, several limitations remain. The current evaluation system mainly considers relatively stable indicators related to life loss, economic loss, social impact, and environmental impact, while dynamic factors such as extreme rainfall conditions, real-time reservoir operation status, emergency response capacity, and human behavior characteristics have not been fully incorporated. These factors may influence the evolution and final consequences of dam failure events. Future studies could further expand the indicator system by integrating additional environmental, climatic, and management-related factors. Furthermore, with the development of artificial intelligence and monitoring technologies, machine learning approaches combined with real-time data collection could be introduced to establish an intelligent evaluation system, allowing automatic risk assessment and dynamic decision support for reservoir safety management.

**Supplementary Materials:** The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/w18151844/s1>. Table S1: Calculation formula for the connection degree between evaluation indicators and corresponding evaluation grades; Table S2: Connection degree calculation results for each evaluation indicator.

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