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An Intuitionistic Fuzzy Based Decision-Making Method for River Operation Management: Practice from China

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Abstract: River course is the path of carrying river flow and the blood of modern economic and social development. River operation management has attracted great attention from governments and water conservancy circles all over the world. In China, the river operation management mode refers to the combination of two dimensions: The organization method of river operation management and the bearing and use method of river maintenance fund. Based on the practice of China, we used a two-dimensional matrix method to construct a feasible mode set, including 12 modes, according to the various organization methods of river operation management and the bearing and use methods of river maintenance fund over the years in China. We also compared and analyzed the advantages, disadvantages, and applicable conditions of these 12 river operation management modes. In particular, we investigated the main rivers of 19 provinces and municipalities in China, identified the main factors of the river operation management mode, further identified 5 key indexes, and constructed a decision-making index system for the river operation management mode. We used the intuitionistic fuzzy hybrid average (IFHA) and intuitionistic fuzzy weighted average (IFWA) operators to construct a set of river operation management mode selection method based on intuitionistic fuzzy decision-making. A case study was conducted to select the operation management mode for the Heilongjiang section of Songhua River, using the method put forward in this paper. This study can promote water resource management research and prepare for a possible future sustainability emergency.

Keywords: river course; operation management mode; intuitionistic fuzzy decision-making; Songhua River

1. Introduction

Rivers, the path through which water flows, also include lakes, artificial waterways, flood discharge areas, flood storage areas, flood detention areas, etc. in China. The main task of river management is to ensure the safety of flood discharge and give full play to the comprehensive benefits of the river, specifically for river regulation and the maintenance of embankments on both sides of the river [1]. In China, the river operation management mode mainly refers to the organization method of river operation management and the bearing and use method of the river maintenance fund. Since China's reform and opening up, Chinese provincial governments and water conservancy departments have constantly overcome the tendency of "more efforts on construction and less on

operation management", strengthened river management, and continuously rationalized and improved the river management system in light of their own reality under the spiritual guidance of gradually transferring the focus of water resources work to management. After more than 10 years of hard work, the framework of the three-level river management system (city, county or district, township) has been basically formed in the important areas along the big rivers in China. However, China's river management is still in the process of exploration and practice, and different management systems play a very different role in its operation. Because river management involves many departments, such as the water conservancy and municipal department, there inevitably exist such phenomena as unclear property rights, unclear responsibilities, and imperfect self-restraint mechanisms in the course of its operation management. Since the management system is not smooth, the functions of departments overlap, and the process of water management and water law enforcement involves a wide range, resulting in management disorder [2]. With the rapid development of social economy and the acceleration of urbanization, rivers have been polluted to varying degrees and the water ecological environment has deteriorated [3]. At present, river course management belongs to a pure public welfare project, and there is no operation fund. The operation management of a river course can only rely on the government's financial supply. The financial situation of provincial and municipal governments is different, and the degree of financial supply to rivers is also different. That is to say, the social and flood control benefits of rivers cannot be brought into full play in economically backward areas. Therefore, it is very important to select an appropriate operation management mode for a particular river course in order to strengthen the river operation management, effectively maintain an ecological balance, and improve the standards of flood control and waterlogging control.

At present, there are some studies in various countries all over the world in the area of the river operation management system. According to the management mode of urban river way operation commonly used in northwest China, Ding [4] established a suitable optimization index system and model, which provides direction guidance and theoretical support for river regulation planning. Zhang et al. [5] provided an efficient way to restore and manage lakes at their suitable size by river regulation and water transfer projects, which are important to facilitate sustainable development in arid regions. Rivers' regulation in China has transformed from urban and big rivers to medium-sized and small rivers. Zhu et al. [6] proposed a river regulation model based on the concept of natural-friendly rivers. At present, scholars have done a lot of research on the operation management of river embankment engineering. Some scholars have analyzed river embankment engineering from the management point of view. Based on the analysis of the existing improper management, the maintenance and management measures of river embankment engineering have been put forward [7–11]. Other scholars started with the reform of the management system of river embankment projects. Among them, Li and Liu [12] put forward the reform measures of the river management system based on an analysis of the obstacles to the operation of the current grass-roots river management system. Zhang [13] put forward the reform measures of "separation of management and maintenance" to the grass-roots river management system. Gu [14], aiming at the drawbacks of the existing grass-roots river management system, put forward reform measures, including reforming the management method and implementing a "separation of management and maintenance".

Water resources management is closely related to river operation management. Sustainable water resources management can promote river operation management. Diffuse pollution caused by rainfall events potentially affects the water quality in rivers; therefore, Kozak [15] investigated it with a quali-quantitative approach in order to improve water quality planning and management recovery strategies. The results indicate that diffuse pollution has to be considered to establish future decision-making strategies to water resources management. New Zealand is one of the first countries in the world that has enshrined the concept of watershed management in law, through institutional arrangements and the Resource Management Act of 1991—a law constructed on a watershed management legacy that began in 1941. Pyle et al. [16] outlined the development of New Zealand's Resource Management Act (as it applies to water management) and the lessons that have

been learned in its implementation. Veale and Cooke [17] summarized the lessons learnt in the Grand River watershed and contends that integrated watershed management, although difficult to implement, provides a useful framework for practical application and positive results. Developing and implementing integrated watershed management plans is essential to ensure a healthy future of a water course. The Yaqui River Basin (YRB) is in the semiarid state of Sonora in northwest Mexico. The flow in this watershed is controlled by three reservoirs: Angostura, Novillo, and Oviachic. A daily reservoir operation model was developed for this system to assist local reservoir operators in the decision-making process [18]. Water management in complex situations such as these needs alternative strategies. However, it is difficult to decide which strategies will be the most effective [19]. Zhang et al. [20] provided an efficient conceptual framework, by combining the analytic hierarchy process (AHP) and fuzzy technique for order preference by similarity to an ideal solution (TOPSIS) technique, to evaluate the water management practices in the mining industry and tested it in 16 mines located in the Bowen Basin in Queensland, Australia. Cuvelier and Greenfield [21] conducted an assessment of the progress in Manitoba since the early 1990s (Mitchell and Shrubsole, 1994) regarding integrated watershed management plans, and explained the current conditions, including the structural framework, governance, public consultations, and First Nations participation, along with examples of experiences, successes, failures, and lessons learnt. Michigan's current water management system is highly decentralized and based more on jurisdictional than watershed boundaries. Kraff and Steinman [22] studied alternative water resource management approaches from both environmental and economic perspectives. In order to be able to efficiently address the environment problem of water basins, Galvis et al. [23] adopted an integrated approach, the three-step strategic approach (3-SSA), consisting of the following steps: (1) Minimization and prevention, (2) treatment for reuse, and (3) stimulated natural self-purification. The eWater Cooperative Research Centre of Australia developed a river system modelling software called eWater Source, which can be used to assist water managers and river operators in the planning and operating of river systems [24].

The continuous exploration of river course management around the world has greatly enriched the theory and practice of river course management, and river basin management has become an effective mode in the national and regional rivers' operation management. The basin of the Seine River is an extremely important economic region for France and Europe. In Raso's study, he presents the setting of an optimal and centralized solution to the problem of reservoir operation on the Upper Seine-Aube river system, which was found by applying the stochastic dual dynamic programming (SDDP) procedure [25]. The Tennessee River Basin management mode in the United States, the Thames River Basin management mode in Britain, and the Murray-Darling River Basin management mode in Australia are all classical and representative. Tennessee River is the eighth largest river in the United States. It is 1043 km long and runs through seven states. In order to solve the problems of navigation and flood control, vegetation restoration and land reclamation, assist industrial and agricultural development and power generation, and improve the local environment and people's living standards, the Tennessee Valley Authority (TVA) was established by the United States Congress in 1933 through the Tennessee Valley Authority Act to carry out comprehensive development and management of the Tennessee Valley [26]. In order to solve pollution and protect the ecological environment of the river basin, the Thames River Water Authority was established in 1974. The Thames River Water Authority is located in London [27]. It consists of six departments: Water Resources Planning Office, Water Resources Management Office, Water Quality Department, Farmland Drainage Department, Fisheries and Tourism Department, and Administration Department. It carries out unified planning and management of the Thames River Basin. The Murray River is the largest river in Australia, with a length of 2500 km. The Darling River is the largest tributary of the Murray River, accounting for about 20% of the total flow of the Murray River. The management model of the Murray-Darling Basin is a measure to solve the environmental, social, cultural, and management problems it faces [28]. Its goal is to promote and coordinate effective planning and management so as to realize the equal, efficient, and sustainable utilization of water, soil, and environmental resources in the Murray-Darling Basin.

In contrast, research on the river course management mode in China started relatively late. In recent years, some related measures have been gradually carried out, with the central government giving river operation management more attention, in order to ensure normal river operation management. In order to ensure a good ecological environment of the river courses, the Chinese government issued opinions on the comprehensive implementation of “The River Chief System” in 2016 [29]. The implementation of “The River Chief System” has effectively changed the level of river protection and river operation management. Tinghu district of Yancheng city, Jiangsu Province, takes the opportunity of implementing “The River Chief System” in an all-round way, makes every effort to carry out river regulation, improves the long-term management mechanism of the water environment, and promotes river operation management [30]. Specifically, relevant studies have been carried out in some areas of China. Beginning in 2014, Heilongjiang Province, with the support of the central government, has comprehensively renovated the “Three Rivers” in northeast China, including the Songhua River, which has an important impact on ensuring the economic and social development of the “Three Rivers” basin. However, the provincial government departments are concerned regarding how to effectively organize river operation management after river regulation, that is, what kind of river operation management mode should be adopted [31]. Liu pointed out the problems existing in the management of the Yellow River, and proposed that a management system combining river course management with administrative region management should be established [32]. According to Yuan’s research [33], river management belongs to the social pure public welfare undertakings. River management must perform certain administrative powers, and should give the river management units clear legal status, management authority, and management means. Based on an analysis of the current situation regarding the water supply, electricity demand, flood control, ice control, and ecology, a multi-objective optimal operation model for the cascade reservoirs in the upper and middle reaches of the Yellow River was constructed to reveal the relationships between power generation and other objectives [34]. Zhang [35] studied the three major river courses of the Pearl River, Liao River, and Yangtze River, and concluded that river management should set up a river course management system according to local conditions, improve the supporting legal system, enhance the role and status of river course management agencies, and build a platform mechanism for multi-party participation. All in all, the relevant studies are not systematic, which were aimed at the deficiencies existing in the management mechanism.

According to China’s practice, there are many feasible river operation management modes, but it is a problem that needs further study regarding how to choose the most appropriate one from several river operation management modes. In the modern decision-making process, aggregation operators are regarded as a useful tool for the assessment of the given alternatives and whose target is to integrate all the given individual evaluation values into a collective one [36]. The design optimization of the river operation management mode is a decision-making problem affected by many factors. Some achievements have been made in relevant research. Chen et al. [37] proposed a spatial assessment framework for flood risk evaluation of Australian coal mines coupling geographic information system (GIS), remote sensing (RS), and analytical hierarchy process (AHP). Liu et al. [38] developed an integrated framework to estimate the spatial likelihood of flood hazards by coupling the weighted naive Bayes (WNB), geographic information system, and remote sensing. Liu et al. [39] further addressed the decision method and procedure for a project delivery system (PDS) decision by using the fuzzy ordered weighted geometric averaging (FOWGA) operator and demonstrated the mode selection method as well. The results demonstrated that the method can overcome the current drawback of subjectivity of the project delivery decision method, better solve the decision-making information loss problem during the assembling process. Jian and Zhang [40] established a decision-making model of the general contracting mode for water conservancy projects based on the IFWA operator, but it used the analytic hierarchy process to determine the weight of indexes. However, experts’ opinions have a greater subjective impact, and the IFWA operator could easily cause a loss of decision-making information in the process of data aggregation. Liu et al. [41] established a comprehensive scheme-ranking model

based on an intuitionistic fuzzy hybrid average (IFHA) operator and intuitionistic fuzzy weighted average (IFWA) operator, and then demonstrated the feasibility, objectivity, and scientific nature of the decision model by a practical case analysis of a hydropower station.

The comprehensive literature analysis shows that scholars have mainly focused on the deficiencies of existing river management systems or mechanisms, the ecological management of water resources, and the river course management mode. To our knowledge, there is a relative lack of research on the existing river operation management modes, and the decision-making of river operation management is relatively complex. This article investigated the main rivers in 19 provinces and municipalities in China, constructed a feasible mode set including 12 modes, and a decision-making index system of the river operation management mode, and then proposed an intuitionistic fuzzy decision-making method with an IFHA operator and IFWA operator to select a suitable river operation management mode, thus aiming to provide more reliable references for the decision-making of the river operation management mode in the future.

2. Methodology

Based on the research and analysis of the river operation management modes in various provinces and municipalities in China, this paper defines the concept of the river operation management mode, that is, the river operation and management mode as a combination of two dimensions: The organization method of river operation management and the bearing and use method of the river maintenance fund. To address the research gap identified in the literature, this study aimed to provide an effective decision-making method for the river operation management mode. For example, the Anhui section of the Yangtze River is under the direct management of Anhui Provincial River Administration Bureau. However, due to the particularity of some river sections, the city-level direct management is more appropriate, and unclear property rights and responsibilities exist, so the current river operation management mode is not suitable. Therefore, a set of appropriate river operation management modes should be designed by comprehensively considering various factors.

After investigating the main rivers in 19 provinces and municipalities in China (in Appendix A), we summarized four kinds of organization methods of river operation management and seven kinds of bearing and use methods of the river maintenance fund. By using the two-dimensional matrix method, a set of 28 modes of river operation management was constructed. According to the principle that the main responsibility body of the river operation management mode is consistent with the main body user of the river maintenance fund, the infeasible mode set of river operation management modes were deleted, and the feasible mode set of 12 modes were obtained.

Then, based on the results of the survey, we analyzed the management system of the main river provinces in China, summarized the important factors of the river operation management mode, and constructed the selection index system, including five key indexes. Furthermore, an intuitionistic fuzzy decision-making model of the river operation management mode was constructed, and the selection steps based on the combination of IFHA operator and IFWA operator were designed.

Further, a case study was conducted by taking the Heilongjiang section of the Songhua River as an example. The IFHA operator was used to determine the weights of indexes and aggregate the judgement information of invited experts. The IFWA operator was used to aggregate the judgement information of indexes, and the comprehensive index values of alternative modes of river operation management were obtained, and then the decision was made. The technical roadmap of this research is shown in Figure 1. The detailed research process is described in the following subsections.

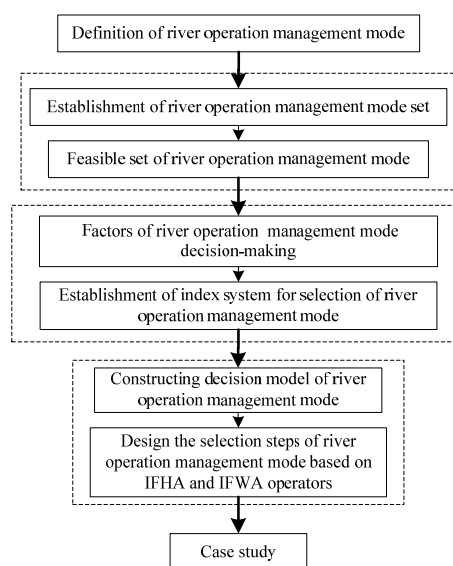


Figure 1. Technical roadmap of this research.

2.1. Feasible Set Construction of River Operation Management Mode

2.1.1. Basic Units and Modes of River Operation Management

- (1) Basic units of river operation management. In China, the basic units for river operation management are determined by administrative divisions. Generally, county administrative divisions are taken as the basic unit, and urban administrative divisions are taken as the unit for urban inland river course. For the case where the scope of river embankment protection is divided into administrative divisions or above the county level, the water administrative department of the government at a higher level shall be in charge of the embankment protection.
- (2) Basic mode of river operation management. The practice of river operation management in China shows that there are two main factors affecting its performance: One is the organizational method of river operation management, i.e., the combination way of management organizations at different management levels, such as through the combination of administrative subordinate relationship, contract relationship, supervision relationship, or through loose consultation and guidance relationship. The other is the fund of river operation management, including the cost of flood control, annual repair, and special maintenance.

2.1.2. Organizational Method of River Operation Management

According to the management practice of the main rivers from 19 provinces and municipalities in China (including Liaoning Province, Anhui Province, Hubei Province, Hunan Province, Zhejiang Province, Shandong Province, Sichuan Province, Shaanxi Province, Fujian Province, Jiangxi Province, Jiangsu Province, Gansu Province, Guangxi Province, Guizhou Province, Guangdong Province, Hebei Province, Chongqing, Tianjin, and Ningxia), river operation management is divided into provincial, county (city), and township levels. Four kinds of management organization method emerge: A1 “vertical” management method, A2 “Provincial and county-level grading” management method, A3 “Completely grading” management method, and A4 “riverside” management method. Comparisons among these four types of the river management method, organization structure, responsible subjects, and relevant management units are shown in Table 1.

Table 1. Comparisons of organization modes of river embankment operation management.

Types	Organization Structure	Responsible Subject	Administrative Responsibility of County or City-Level Governments	Provincial Government Management	Representative Provinces
A1	<pre> graph TD A[Provincial water administration department] -- Subordination --> B[Provincial river management agency] B -- Subordination --> C[XX river management agency] </pre>	Provincial river management agencies	Assist provincial river management agencies	Direct management and payment of all maintenance funds	29 reaches of Yangtze River and Huai River in Anhui province
A2	<pre> graph TD A[Provincial river management agency] -- Guidance, supervision --> D[Country-level river management agency] B[County-level water administration department] -- Subordination --> D </pre>	County -level river management agencies	Bear the responsibility of the main body of river management and the main maintenance funds	Coordinating, supervising and appropriately subsidizing maintenance funds	Part of the Yangtze River and Huai River in Anhui province, Jiangxi province
A3	<pre> graph TD A[County-level water administration department] -- Subordination --> C[Country-level river management agency] B[Township government management agency] --> C C --> D[XX river management agency] </pre>	Township or county-level river management agencies	Township assistance to county-level river management agencies	Direct management and payment of all maintenance funds	Tai'an and Panshan in Liaoning province
A4	<pre> graph TD A[City-level water administration department] -- Subordination --> B[City-level river management agency] B --> C[.....] B --> D[.....] </pre>	City-level river agencies	Bear the responsibility of the main body of river management and the main maintenance funds	Coordinating, supervising and appropriately subsidizing maintenance funds	Nanjing, Wuhan, etc.

2.1.3. Bearing and Use Method of River Maintenance Fund

According to China's river management regulations and other relevant policies, as well as the management practice of the main rivers from 19 provinces and municipalities in China, there are seven kinds of bearing and use methods of the river maintenance fund. Comparisons among these seven types of bearing and use methods of the river maintenance fund, funding source, subject of funds use, scope of application, funds spending, and representative provinces are shown in Table 2.

Table 2. Comparisons of bearing and use methods of the river maintenance fund.

Types	Funding Source	Subject of Funds Use	Scope of Application	Funds Spending	Representative Provinces
B1	Provincial government finance	Provincial river management agencies	Across administrative divisions or mainly in agriculture	Low management cost, small risk	29 reaches of Yangtze River and Huai River in Anhui province
B2	Provincial government finance	County-level government finance	Across administrative divisions or mainly in agriculture	Easy management, low cost	Jiangxi province
B3	Provincial government finance	Provincial and county-level river management agencies	Across administrative divisions or mainly in agriculture.	County-level river management agencies are responsible for the project application and implementation; provincial river management agencies are responsible for project approval and supervision	Guangdong province
B4	County-level government finance	County-level government finance	Economically developed areas, industrial areas or cities	Easy management, low cost	22 reaches of Yangtze River and Huai River in Anhui province
B5	Provincial and county-level government finance	County-level government finance	Economically developed areas, industrial areas or cities	Easy management, low cost	Before the reform of Yangtze and Huai Rivers in Anhui province
B6	Provincial and county-level government finance	Provincial and county-level river management agencies	Economically developed areas, agricultural areas, industrial areas or cities	County-level river management agencies are responsible for the project application and implementation; provincial river management agencies are responsible for project approval and supervision	Guangxi zhuang autonomous region and Heilongjiang province
B7	City-level government finance	City-level river management agencies	Riverside	Easy management, low risk	Nanjing, Wuhan, Wuhu, etc.

2.1.4. Feasible Set of River Operation Management Mode

According to the definition of the river operation management mode, four kinds of organization methods of river operation management (A) and seven kinds of bearing and use methods of the river maintenance fund (B) were combined to obtain 28 kinds of river operation management modes, namely the A×B matrix, as shown in Table 3.

Table 3. A × B matrix.

A\B	B1	B2	B3	B4	B5	B6	B7
A1	M11	M12	M13	M14	M15	M16	M17
A2	M21	M22	M23	M24	M25	M26	M27
A3	M31	M32	M33	M34	M35	M36	M37
A4	M41	M42	M43	M44	M45	M46	M47

Note: The River operation management mode is the combination of A and B, i.e., M11 is the combination of A1 and B1.

According to the principle that the main responsibility body of the river operation management mode is consistent with the main user of the river maintenance fund, M12 and M13 modes are provincial

vertical management, and the provincial finance department bears all the maintenance funds. There is no need for county-level river management agencies to participate in the use of funds, so these two modes cannot exist. Then, 16 similar infeasible modes were deleted, and the feasible set of river operation management modes was finally obtained, that is, 12 kinds of river operation management modes (with purple), as shown in Table 4.

Table 4. Feasible set of river operation management modes.

	B1	B2	B3	B4	B5	B6	B7
A1	M11	M12	M13	M14	M15	M16	M17
A2	M21	M22	M23	M24	M25	M26	M27
A3	M31	M32	M33	M34	M35	M36	M37
A4	M41	M42	M43	M44	M45	M46	M47

Different river operation management modes have their own characteristics, and the advantages and disadvantages of each mode are also different from different perspectives. This is mainly due to the different interests and responsibilities of the relevant subjects in different operation management modes. We should analyze and optimize the river operation management mode on the basis of objectivity as far as possible. The characteristics of the feasible river operation management modes are shown in Appendix B.

2.2. Factors of River Operation Management Mode Selection

A river course is a system from upstream to downstream. Generally, although the reach is managed by the city and country as a unit, it is necessary for the national and provincial water administration departments to make a unified planning and design of its management mode. On the premise of guaranteeing the overall operation safety of the river course, we should promote the balanced economic and social development of the river basin.

There are many factors affecting the selection of the river operation management mode, since the river operation management involves a wide range of aspects and is easily affected by the external environment. Based on the survey and summary of the management system of the main rivers in China (including 19 provinces, such as Liaoning Province and Anhui Province), we obtained comparisons of the organization modes of river embankment operation management (Table 1), comparisons of the bearing and use methods of the river maintenance fund (Table 2), and comparisons of the river operation management modes' advantages, disadvantages, and applicable conditions (Appendix B.).

By comparing the characteristics of these 12 kinds of river operation management modes, we obtained five important indexes, including the scope of river embankment protection objects, the importance of river embankment protection objects, the economic development level of river embankment protection areas, the construction foundation of the river operation management team, and the safety of river maintenance funds [1,2,4,6,13]. Combining the actual situation of the embankment project operation, the selection index system of the river operation management mode was determined as shown in Table 5.

Table 5. Index system for the selection of the river operation management mode.

Index	Index Description
the scope of river embankment protection objects (Y_1)	Generally speaking, the objects of river embankment protection are county-level, city-level inland and cross-administrative divisions. The scope of river embankment protection objects determines the choice of management organization method.
the importance of river embankment protection objects (Y_2)	The selection of river operation management mode is usually influenced by the importance of river protection object. The river operation management mode responsible by provincial river management department should be selected for the important river protection object.
the economic development level of river embankment protection areas (Y_3)	The more developed the river protection subject's regional economy is, the less the corresponding government financial pressure is. Generally, the protected areas of rivers are mainly agricultural and industrial areas or cities.
the construction foundation of river operation management team (Y_4)	To a certain extent, the construction foundation of county-level river management team will determine whether it will become the main responsibility body of river operation management.
the safety of river maintenance funds (Y_5)	When the provincial government allocates river maintenance funds to the county-level government, which often means the risk of using funds is high, the river operation management mode with stricter supervision of funds should be chosen.

2.3. Decision-Making Model of the River Operation Management Mode

Generally, fuzzy sets are used to reflect expert opinions, but the value of the membership function is only a single value. In practice, it cannot express the three judgment attitudes at the same time: Support (affirmation), opposition (negation), and hesitation (uncertainty) [34]. Owing to the increasing complexity and uncertainty of the economic and social environment, people often hesitate to some extent or have a lack of knowledge in the process of cognition, which results in three aspects: Affirmation, negation, or hesitation between affirmation and negation. For example, in various electoral voting events, abstention often occurs in addition to support and opposition.

The introduction of an intuitionistic fuzzy hybrid average (IFHA) operator can not only reflect the membership degree, non-membership degree, and hesitation degree of experts' opinions but also give them different weights according to the experience level of experts, thus avoiding the loss of decision information. Moreover, it weakens the influence of overly optimistic and pessimistic experts' opinions on the decision results by making the weights of the data positions orderly. It provides a decision-making model with a less subjective influence and more accurate output results. Thus, the intuitionistic fuzzy weighted average (IFWA) operator was used to aggregate the indexes' values of each alternative, and we obtained the comprehensive indexes' ranking of each alternative.

2.3.1. Overview of the Intuitionistic Fuzzy Hybrid Average (IFHA) Operator

(1) Aggregation processes of the intuitionistic fuzzy hybrid average operators (IFHA) [42]:

The intuitionistic fuzzy hybrid average (IFHA) operator is a mapping. $IFHA: \Theta^n \rightarrow \Theta$, such that:

$$IFHA_{\omega, w}(\alpha_1, \alpha_2, \dots, \alpha_n) = w_1 \dot{\alpha}_{\sigma(1)} \oplus w_2 \dot{\alpha}_{\sigma(2)} \oplus \dots \oplus w_n \dot{\alpha}_{\sigma(n)}, \quad (1)$$

where $w = (w_1, w_2, \dots, w_n)^T$ is the weighted vector of the IFHA operator, i.e., location weight. $w_j \in [0, 1] (j = 1, 2, \dots, n)$ $\sum_{j=1}^n w_j = 1$. $\dot{\alpha}_j = n\omega_j \alpha_j (j = 1, 2, \dots, n)$, $(\dot{\alpha}_{\sigma(1)}, \dot{\alpha}_{\sigma(2)}, \dots, \dot{\alpha}_{\sigma(n)})$ is a permutation of the weighted intuitionistic fuzzy array $(\dot{\alpha}_1, \dot{\alpha}_2, \dots, \dot{\alpha}_n)$, such that $\dot{\alpha}_{\sigma(j)} \geq \dot{\alpha}_{\sigma(j+1)} (j = 1, 2, \dots, n-1)$;

$\omega = (\omega_1, \omega_2, \dots, \omega_n)^T$ is the weight vector of $\alpha_j (j = 1, 2, \dots, n)$, $\omega_j \in [0, 1] (j = 1, 2, \dots, n)$, $\sum_{j=1}^n \omega_j = 1$; and n is the balance coefficient (at this point, if vector $(\omega_1, \omega_2, \dots, \omega_n)^T$ approaches $(1/n, 1/n, \dots, 1/n)^T$, then, $(n\omega_1\alpha_1, n\omega_2\alpha_2, \dots, n\omega_n\alpha_n)^T$ approaches $(\alpha_1, \alpha_2, \dots, \alpha_n)^T$).

Set $\dot{\alpha}_{\sigma(j)} = (\mu_{\dot{\alpha}_{\sigma(j)}}, \nu_{\dot{\alpha}_{\sigma(j)}})(j = 1, 2, \dots, n)$, then:

$$IFHA_{\omega, w}(\alpha_1, \alpha_2, \dots, \alpha_n) = \left(1 - \prod_{j=1}^n (1 - \mu_{\dot{\alpha}_{\sigma(j)}})^{w_j}, \prod_{j=1}^n \nu_{\dot{\alpha}_{\sigma(j)}}^{w_j} \right). \quad (2)$$

- (2) Determining the position weight. Using the normal distribution weighting method [43,44], we can get $W = (w_1, w_2, \dots, w_n)$, as shown in Equation (3):

$$w_i = \frac{\frac{1}{\sqrt{2\pi\sigma_n^2}} e^{-\left[\frac{(i-\mu_n)^2}{2\sigma_n^2}\right]}}{\sum_{j=1}^n e^{-\left[\frac{(j-\mu_n)^2}{2\sigma_n^2}\right]}} (i = 1, 2, \dots, n), \quad (3)$$

where $\mu_n = \frac{1}{n} \frac{n(1+n)}{2} = \frac{1+n}{2}$, $\sigma_n = \sqrt{\frac{1}{n} \sum_{j=1}^n (j - \mu_n)^2}$, i is the sort of data location.

2.3.2. Overview of the Intuitionistic Fuzzy Weighted Average (IFWA) Operator

- (1) Aggregation processes of the intuitionistic fuzzy weighted average operators (IFWA) [42]:

The intuitionistic fuzzy weighted average (IFWA) operator is also a mapping. IFWA: $\Theta^n \rightarrow \Theta$, such that:

$$IFWA_{\omega}(\alpha_1, \alpha_2, \dots, \alpha_n) = w_1\alpha_1 \oplus w_2\alpha_2 \oplus \dots \oplus w_n\alpha_n, \quad (4)$$

where $\omega = (\omega_1, \omega_2, \dots, \omega_n)^T$ is the weighted vector of $\alpha_j (j = 1, 2, \dots, n)$, $\omega_j \in [0, 1] (j = 1, 2, \dots, n)$, $\sum_{j=1}^n \omega_j = 1$.

Set $\alpha_j = (\mu_{\alpha_j}, \nu_{\alpha_j})(j = 1, 2, \dots, n)$, then:

$$IFWA_{\omega}(\alpha_1, \alpha_2, \dots, \alpha_n) = \left(1 - \prod_{j=1}^n (1 - \mu_{\alpha_j})^{\omega_j}, \prod_{j=1}^n \nu_{\alpha_j}^{\omega_j} \right). \quad (5)$$

- (2) Sorting and optimizing the integration results of IFWA operators. For any intuitionistic fuzzy number $\alpha = (\mu_{\alpha}, \nu_{\alpha})$, it can be evaluated by the score function s [45]:

$$s(\alpha) = \mu_{\alpha} - \nu_{\alpha}, \quad (6)$$

where $s(\alpha)$ is the score of α , $s(\alpha) \in [-1, 1]$.

Equation (6) shows that the score value of the intuitionistic fuzzy number α is directly related to the difference between its membership degree μ_{α} and non-membership degree ν_{α} . That is, the greater the difference between μ_{α} and ν_{α} , the greater the score value of α is, and the larger the intuitionistic fuzzy number α is. In particular, if $s(\alpha) = 1$, then α takes the maximum of $(1, 0)$, if $s(\alpha) = -1$, then α takes the maximum of $(0, 1)$.

Set $\alpha = (\mu_{\alpha}, \nu_{\alpha})$, $\alpha_1 = (\mu_{\alpha_1}, \nu_{\alpha_1})$ and $\alpha_2 = (\mu_{\alpha_2}, \nu_{\alpha_2})$, and they are intuitionistic fuzzy numbers, which satisfies:

$$\alpha_1 \oplus \alpha_2 = (\mu_{\alpha_1} + \mu_{\alpha_2} - \mu_{\alpha_1}\mu_{\alpha_2}, \nu_{\alpha_1}\nu_{\alpha_2}), \quad (7)$$

$$\lambda\alpha = (1 - (1 - \mu_\alpha)^\lambda, \nu_\alpha^\lambda), \lambda > 0. \quad (8)$$

2.3.3. Selection Steps of the River Operation Management Mode based on the Combination of the Intuitionistic Fuzzy Hybrid Average (IFHA) and Intuitionistic Fuzzy Weighted Average (IFWA) Operators

- (1) According to experts' knowledge structure and engineering practice experience, several experts are invited and given different opinions weight. Invite experts to judge the impact of each index on the selection of the river operation management mode, and then obtain the intuitionistic fuzzy judgment information of the experts.
- (2) Use the normal distribution weighting method to determine the position weights of the expert opinions in the process of aggregation.
- (3) Use the IFHA operator to aggregate experts' opinions and get the group's intuitionistic fuzzy judgment information about the impact of each index on the selection of the river operation management mode.
- (4) From the group's intuitionistic fuzzy judgment information, obtain the score function value of each index, and then determine the weight of each index according to the score function value.
- (5) Invite experts to give intuitionistic fuzzy judgment information of the river operation management modes to meet each selection index.
- (6) Use the IFHA operator to aggregate experts' opinions and obtain the group's intuitionistic fuzzy judgment information about the satisfaction degree of each alternative river operation management mode to the selected index system.
- (7) Use the IFWA operator to aggregate the intuitionistic fuzzy judgment information of each alternative, and obtain the comprehensive index value of each alternative.
- (8) According to the comprehensive index of each alternative, obtain its score function value, and then rank the alternatives to determine the final scheme.

3. Case study

Songhua River is one of the seven major rivers in China located between east longitude $119^{\circ}52' \sim 132^{\circ}31'$ and northern latitude $41^{\circ}42' \sim 51^{\circ}38'$, with the east–west width being 920 km, north–south length being 1070 km, and the total area of the basin is 561,200 km², which flows through the Heilongjiang Province, the Inner Mongolia Autonomous Region, and Jilin Province. The main stream of Songhua River crosses the Songnen Plain and the Sanjiang Plain. It is an important industrial base and grain production base in China, as well as an area where floods and droughts frequently occur.

The Heilongjiang section of the Songhua River main stream begins at the Sancha estuary of Zhaoyuan County. It covers 17 cities (counties), 8 farms, and 3 forestry bureaus, such as Harbin, Jiamusi, Zhaoyuan, and Zhaodong. Finally, it flows into Heilongjiang through Tongjiang, with a total length of 939 km. The main characteristics of the river are shown in Table 6.

According to the characteristics of the Heilongjiang section of Songhua River in Table 7, it can be divided into the Harbin-Jiamusi section and other county sections. This paper only shows the calculation process of the river operation management mode decision-making by taking the Harbin-Jiamusi section as an example.

Table 6. Characteristics of the Heilongjiang section of Songhua River's main stream.

Index	Index Description
the scope of river embankment protection objects (Y_1)	Covers 17 cities(counties); Between Harbin and Jiamusi are Grade 1 embankment with a length of 151 km; In other counties are Grade 2 and below embankment with a length of 796 km.
the importance of river embankment protection objects (Y_2)	Protects 7.23 million people, 24,000 km ² of protected area and 14,647 km ² of farmland; The average benefit of flood control for multi-year is 76 million yuan.
the economic development level of river embankment protection areas (Y_3)	In Harbin and Jiamusi, the economy is more developed; The other counties are predominantly agrarian regions.
the construction foundation of river operation management team (Y_4)	The construction foundation of river operation management team is good, but the county is poor.
the safety of river maintenance funds (Y_5)	The security of funds for operation maintenance of county rivers is low.

Table 7. Experts' judgment information on the importance of different indexes.

Index	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
Y_1	(0.7, 0.2)	(0.8, 0.1)	(0.8, 0.1)	(0.8, 0.1)	(0.6, 0.3)
Y_2	(0.8, 0.1)	(0.4, 0.1)	(0.9, 0.1)	(0.7, 0.2)	(0.8, 0.1)
Y_3	(0.7, 0.1)	(0.6, 0.2)	(0.7, 0.2)	(0.5, 0.3)	(0.6, 0.2)
Y_4	(0.6, 0.1)	(0.5, 0.3)	(0.7, 0.2)	(0.5, 0.1)	(0.5, 0.3)
Y_5	(0.6, 0.2)	(0.4, 0.3)	(0.8, 0.1)	(0.6, 0.2)	(0.4, 0.3)

3.1. Determining Index Weight based on the Intuitionistic Fuzzy Hybrid Average (IFHA) Operator

We invited five experts to evaluate the impact of each index on the selection of the operation management mode of river embankment projects, and gave them intuitionistic fuzzy judgment information, as shown in Table 7. The weight vector of five experts' opinion was $Z = (0.15, 0.20, 0.30, 0.25, 0.10)$.

Then, the position weight of expert judgment information was determined. By the normal distribution weighting method, the location weight vector was determined as $W = (0.112, 0.236, 0.304, 0.236, 0.112)$. Because of the large number of indexes, the process of weight determination was introduced only by taking index Y_1 as an example.

The intuitionistic fuzzy array of five experts' judgment on the importance of index Y_1 was obtained as follows:

$$\alpha_{Y_1} = [(0.7, 0.2), (0.8, 0.1), (0.8, 0.1), (0.8, 0.1), (0.6, 0.3)].$$

According to Equation (1), the weighted intuitionistic fuzzy array can be given as follows:

$$\dot{\alpha}_{Y_1} = [(0.595, 0.299), (0.8, 0.1), (0.911, 0.032), (0.866, 0.056), (0.368, 0.548)].$$

According to Equation (6), the score function values were 0.296, 0.700, 0.879, 0.810, and −0.180, respectively.

The intuitionistic fuzzy numbers in $\dot{\alpha}_{Y_1}$ were sorted according to the value of the score function, and the ordered weighted fuzzy array was obtained as follows:

$$\dot{\alpha}_{\sigma(Y_1)} = [(0.911, 0.032), (0.866, 0.056), (0.8, 0.1), (0.595, 0.299), (0.368, 0.548)].$$

According to Equation (2), the comprehensive index of Y_1 based on the IFHA operator was calculated as (0.777, 0.120), and its score function was 0.657.

Similarly, the values of each index score function based on the IFHA operator were 0.657, 0.604, 0.413, 0.406, and 0.313, respectively. After normalization, the index weight vector $W' = (0.275, 0.252,$

0.173, 0.170, 0.130) was obtained. It can be seen that, judging by the experts, indexes Y_1 and Y_2 have a greater impact on the selection of the river operation management mode, while Y_5 has the least impact, which is consistent with the actual situation. The scope of river embankment protection objects determines the support degree of provincial and county-level finance, that is, the bearing and use method of the river maintenance fund. The importance of a river embankment protection object determines whether it is supervised directly by provincial river management agencies or cooperatively by provincial and county river management agencies, that is, the organization method of river operation management. Y_1 and Y_2 fundamentally determine which type of operation management mode the river is suitable for. Since a series of supervisory measures have been implemented in all parts of China for the use of river maintenance funds, various river operation management modes have less discrimination and weight on Y_5 .

3.2. Aggregation of Expert Judgment Information based on the Intuitionistic Fuzzy Hybrid Average (IFHA) Operator

By the same five experts, the evaluation information of the M11, M22, M23, M24, M25, M26, M32, M33, M34, M35, M36, and M47 modes satisfying the above indexes were given respectively. Based on the IFHA operator, we aggregated the judgement information of each expert, and then obtained the fuzzy judgement information of the corresponding indexes of each alternative mode. Due to the large amount of data, this paper introduced the process of expert judgment information aggregation based on the IFHA operator, taking the M11 mode as an example, which meets the degree of the Y_1 index. The judgment information is shown in Table 8.

Table 8. Experts' judgment information on the satisfaction degree of M11 mode to index Y_1 .

Mode	Y_1				
	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
M11	(0.810, 0.120)	(0.800, 0.260)	(0.870, 0.280)	(0.820, 0.290)	(0.820, 0.270)

Based on Equation (1), it can be found that:

$$\dot{\alpha}_{M11} = [(0.712, 0.204), (0.800, 0.260), (0.953, 0.148), (0.883, 0.213), (0.576, 0.520)].$$

The corresponding score function values were 0.508, 0.540, 0.805, 0.670, and 0.056. We ranked the intuitionistic fuzzy numbers in $\dot{\alpha}_{M11}$, according to the value of the score function, and obtained an orderly weighted intuitionistic fuzzy array:

$$\dot{\alpha}_{\sigma(M11)} = [(0.953, 0.148), (0.883, 0.213), (0.800, 0.260), (0.712, 0.204), (0.576, 0.520)].$$

With the location weight unchanged, we used Equation (2) to calculate the comprehensive index value (0.822, 0.238) of the degree to which the M11 mode satisfies the Y_1 based on the IFHA operator. Similarly, the aggregation judgment information that the alternative modes based on the IFHA operator satisfy the degree of each index was obtained, as shown in Table 9.

It can be seen that the aggregation process based on the IFHA operator not only considers the differences of experts' abilities and experiences, and gives the corresponding weights to different experts' opinions, but also considers the subjective preferences of each expert when facing the same decision-making problem. At the same time, we used the location weights to orderly weigh, which weakened the influence of experts' subjective preferences on the decision-making results, fully reflecting the fairness of the decision-making model.

Table 9. Expert judgment information aggregation based on the intuitionistic fuzzy hybrid average (IFHA) operator.

Mode	Y_1	Y_2	Y_3	Y_4	Y_5
M11	(0.822, 0.238)	(0.804, 0.118)	(0.527, 0.318)	(0.700, 0.192)	(0.579, 0.190)
M22	(0.563, 0.229)	(0.558, 0.230)	(0.403, 0.463)	(0.448, 0.414)	(0.517, 0.180)
M23	(0.567, 0.233)	(0.517, 0.190)	(0.417, 0.416)	(0.487, 0.377)	(0.578, 0.179)
M24	(0.351, 0.389)	(0.330, 0.260)	(0.564, 0.232)	(0.337, 0.478)	(0.469, 0.204)
M25	(0.352, 0.407)	(0.387, 0.241)	(0.503, 0.355)	(0.356, 0.527)	(0.447, 0.305)
M26	(0.444, 0.285)	(0.404, 0.185)	(0.500, 0.342)	(0.300, 0.448)	(0.490, 0.240)
M32	(0.520, 0.197)	(0.512, 0.269)	(0.483, 0.298)	(0.442, 0.396)	(0.442, 0.374)
M33	(0.569, 0.179)	(0.531, 0.289)	(0.383, 0.400)	(0.508, 0.383)	(0.383, 0.216)
M34	(0.396, 0.312)	(0.433, 0.246)	(0.575, 0.251)	(0.478, 0.292)	(0.526, 0.215)
M35	(0.360, 0.410)	(0.442, 0.288)	(0.485, 0.285)	(0.297, 0.553)	(0.404, 0.400)
M36	(0.501, 0.281)	(0.516, 0.272)	(0.449, 0.195)	(0.275, 0.511)	(0.450, 0.256)
M47	(0.381, 0.457)	(0.501, 0.229)	(0.534, 0.332)	(0.467, 0.258)	(0.455, 0.159)

3.3. Aggregation of the Indexes Judgment Information based on Intuitionistic Fuzzy Weighted Average (IFWA) Operator

Experts aggregated by IFHA operators fully considered and weakened the influence of experts' own differences and subjective preferences on the judgment information that each alternative mode meets the characteristics of the indexes. Therefore, we used the IFWA operator to aggregate the judgment information of each index, and obtained the final comprehensive index of each alternative mode to select the most suitable river operation management mode. The index weight vector was $W' = (0.275, 0.252, 0.173, 0.170, 0.130)$. According to Equation (5), we aggregated the data in Table 10 and obtained the final comprehensive index values of each alternative mode, as shown in Table 10.

Table 10. Comprehensive index value of various alternative modes.

Mode	Comprehensive Index	Score Function Value
M11	(0.736, 0.196)	0.540
M22	(0.512, 0.278)	0.235
M23	(0.519, 0.257)	0.263
M24	(0.403, 0.306)	0.097
M25	(0.403, 0.351)	0.052
M26	(0.429, 0.279)	0.150
M32	(0.489, 0.280)	0.209
M33	(0.498, 0.271)	0.227
M34	(0.471, 0.267)	0.205
M35	(0.401, 0.369)	0.031
M36	(0.456, 0.286)	0.170
M47	(0.465, 0.287)	0.177

4. Results and Discussion

4.1. Results

According to the final score function value of each alternative mode, M11 is the optimal mode. It can be seen that the most suitable operation management mode of the river course between Harbin and Jiamusi in Heilongjiang Province of Songhua River's main stream is the M11 mode, which is the combination of A1 ("vertical" management method) and B1 (the provincial government shall fully bear the cost of embankment maintenance, and the provincial river management agencies shall be responsible for the use of funds). The river course of the Harbin-Jiamusi section of Heilongjiang Province in the main stream of Songhua River is a Grade 1 embankment with a length of 151 km. The objects of river embankment protection are two cities, Harbin and Jiamusi. The river course from

Harbin to Jiamusi city protects a large population and large area of farmland in Heilongjiang Province, and the multi-year average flood control benefit is high. It is very important for Heilongjiang Province, thus the “vertical” management organization method should be chosen. On the other hand, Harbin and Jiamusi have developed an economy and good foundation for river management team construction, and the provincial government fully bears the cost of river maintenance, which is used by provincial river management agencies.

Similarly, according to the same method, the above mentioned process of calculation and decision-making was carried out in other county sections of Heilongjiang Province of Songhua River’s main stream. According to the final score function value of each alternative mode, the M23 is the optimal mode, that is, the combination mode of A2 (“provincial and county-level grading” management method) and B3 (the provincial government shall fully bear the cost of embankment maintenance, and the provincial and county river management agencies shall jointly be responsible for the use of funds).

Therefore, it is suggested that the M11 + M23 operation management mode is adopted in the Heilongjiang section of Songhua River. The M11 mode should be used in the Harbin-Jiamusi section, and the M23 model used in other county sections.

4.2. Discussion

The feasible set of river operation management modes constructed in this paper was based on the practical experience and institutional framework of the main rivers in China. When making decisions on the operation management mode of a certain section of river, it is necessary to judge one by one according to the index system, and then choose the appropriate mode from the feasible set of river operation management modes, which is very time consuming and complex. The next step of this research is to classify and simplify the currently feasible river operation management modes, and to establish the corresponding relationship between the river and the operation management modes. Furthermore, how to optimize the decision-making steps, and quickly design the operation management mode of any river section needs future study.

In this study, we invited five experts to evaluate the impact of each index on the selection of the operation management mode of river embankment projects. Naturally, there was some uncertainty about the preference weights, even though they were from experts. Therefore, it is important to perform a sensitivity analysis on the preference weights and provide measures for assessing the sensitivity of strategy ranking outcomes to changes in these weights [46,47]. China’s sustainability programs have achieved a range of water management objectives, such as improving water quality; and reducing river sedimentation, soil water retention, and flood mitigation; and water conservation and supply [48]. However, in the face of China’s abundant water resources, there is a lack of research on river operation management, thus this study can promote relevant research and prepare for a possible future sustainability emergency.

At present, China is vigorously implementing The River Chief System, aiming at protecting water resources, preventing water pollution, improving the water environment, and restoring water ecology. A four-level river chief system at the province, municipality, county, and township levels has been established in an all-round way, and a mechanism for river and lake management and protection with clear responsibilities, orderly coordination, strict supervision, and strong protection has been established. With the institutional change of China’s river management departments and the optimization of the river operation management mode, a new river operation management mode may gradually emerge. The emergence of a new river operation management mode will not only enrich the index system of river operation management mode selection but also expand the feasible set of river operation management modes, which will have a sustainable development effect on future water resource management research.

5. Conclusions

River operation management is not only a problem of management organization or organization structure but also involves the bear and use of the maintenance fund of river embankment. Therefore, this paper defined the river operation management mode as a combination of two dimensions: The organization method of river operation management and the bearing and use method of the river maintenance fund.

According to the management practice of large rivers in various parts of China, this study proposed four kinds of river operation management methods and seven kinds of bearing and use methods of the river maintenance fund. In theory, we obtained 28 kinds of river operation management modes. In light of the principle that the main responsibility body of the river operation management mode is consistent with the main user of the river maintenance fund, we deleted the infeasible modes and obtained a feasible mode set of 12 modes.

All kinds of operation management modes have their own characteristics, and they have different advantages and disadvantages when observing different modes from different perspectives. According to the actual situation of river operation management, we constructed the index system of river operation management mode selection. The decision-making model based on the intuitionistic fuzzy mixed average operator not only subdivides the river operation management mode but also establishes an index system suitable for the selection of river operation management mode. We also considered the importance difference of expert opinions in the decision-making process, weakened the influence of the subjective preferences of experts by using position weights, aggregated the complete decision-making information, and fully ensured the fairness of the decision-making process and the rationality of the output results. Finally, taking the Heilongjiang section of the Songhua River as an example, we designed the M11 mode in the Harbin-Jiamusi section, and the M23 model in other county sections, thus the M11 + M23 operation management mode in the Heilongjiang section of Songhua River. The decision-making model based on intuitionistic fuzzy operator is a very suitable tool for river operation management, which can provide a better selection method for the relevant departments of river operation management.

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Table A3. Comparisons of river operation management modes' disadvantages

[illegible]

Table A4. Comparisons of river operation management modes' applicable conditions.

[illegible]

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