Applied Water Science (2023) 13:125
https://doi.org/10.1007/s13201-023-01925-2

ORIGINAL ARTICLE

Multi-dimensional interest game between reservoir and city stakeholders in the Yellow River Basin: a case study of the lower reaches

Hao Hu[1] · **Guiliang Tian**[1,2,3] · **Zhiqing Dai**[1]

Received: 28 February 2023 / Accepted: 19 April 2023 / Published online: 5 May 2023

Abstract

Reservoirs in sediment-laden rivers can bring multiple benefits, and the calculation and redistribution of these considerable benefits are the premises to ensure the efficient operation of reservoirs. Firstly, the benefits of social economy, ecological environment, flood discharge, and sediment transport under the joint operation of reservoirs are uniformly measured based on the emergy theory. Secondly, the stakeholders are divided into reservoir and city groups. A two-tier gains allocation model is established based on the Nash bargaining model and multi-attribute decision making theory. Finally, taking the lower reaches of the Yellow River, Sanmenxia Reservoir, and Xiaolangdi Reservoir as cases, the multi-dimensional benefits of reservoirs under the two operation modes in the face of typical floods are calculated, and the gains are distributed among stakeholders. The results show that: (1) Although the overall benefit of the system is optimal under one scheduling mode, 7/17 of the stakeholders prefer another mode. (2) Comparing the two operation modes of the reservoir group, it is found that XLD and SMX can improve the overall benefit of 4.12E + 09yuan at the cost of their sediment discharge benefits of 3.08E + 09yuan and 2.82E + 06yuan. (3) After gains distribution, the profit of all stakeholders can be optimized to varying degrees. This study broadens the dimension of benefit accounting under the joint operation of cascade reservoirs and the category of stakeholders in the gain allocation, which is conducive to promoting the ecological protection and sustainable development of sediment-laden rivers.

Keywords Sediment-laden river · Multi-dimensional benefits · Emergy theory · Reservoir group and city group · Two-tier allocation model

Introduction

The Yellow River, which originates in the Tibetan Plateau and flows through nine provinces and autonomous regions, is the mother river of the Chinese nation. Although it is the second-longest river in China, the Yellow River is more famous for its characteristics of less water and more sand, water and sand come from different sources, and the relationship between water and sand is incongruous (Wang et al. 2016). Water resources in the Yellow River basin are incredibly scarce, with the amount of water per capita and per mu being only 23% and 15% of the national average level, which leads to the sharp contradiction between living, production, and ecological water use in the area (Xiang et al. 2017). Relevant studies indicate that the runoff of the Yellow River shows a downward trend under the dual effect of climate change and human activities (Omer et al. 2020). There is no doubt that the contradiction between the supply

---

✉ Guiliang Tian
tianguiliang@hhu.edu.cn

Hao Hu
huhao0912@hhu.edu.cn

Zhiqing Dai
daizhiqing@hhu.edu.cn

[1] Present Address: Business School, Hohai University, Nanjing 211100, China

[2] Present Address: School of Economics and Finance, Hohai University, Nanjing 211100, China

[3] Present Address: Yangtze Institute for Conservation and Development, Nanjing 210098, China

and demand of water resources will be further aggravated by the rapid socioeconomic development and steady population growth in the Yellow River basin (Bai et al. 2019; Zhang et al. 2021a).

In the context of rigid constraints of water resources and frequent extreme weather, cascade reservoirs in the Yellow River play an indispensable role in flood control, water storage and delivery, hydropower generation, water purification, and other aspects, fundamentally ensuring the continuous flow of the river without breaking its banks for many years (Jin et al. 2021; Zhang et al. 2021b). Meanwhile, the water and sediment regulation under the joint operation of cascade reservoirs in the Yellow River effectively controls the sediment deposition, improves the available regulated storage capacity of reservoirs, and fundamentally prevents the lifting of the riverbed of the suspended river on the ground (Jin et al. 2019). Different reservoirs perform multiple tasks in operation, and each task cannot be fully met at the same time because of the apparent conflicts between the functions (Lu et al. 2022).

Under the realistic background of climate change and the reduction of runoff of the Yellow River, river basin management departments and scholars have conducted much research on the multi-objective joint operation of reservoirs (Zhang et al. 2021c). The research results show that the joint operation of cascade reservoirs can improve the comprehensive benefits of a watershed system (Lu et al. 2018), while the reasonable allocation of value-added is the basic premise to maintain the long-range feasibility of the optimal operation of cascade reservoirs (Chen et al. 2020; Wang et al. 2021). Summarize and analyzing the existing literature, it is not difficult to find that the optimization of the operation of reservoirs mainly at the minimum water shortage or the maximum power generation, while the objectives of sediment transport and ecological protection of sandy rivers mostly take the water requirement for sediment transport and ecological base flow as the media, which are transformed into constraints (Li et al. 2022; Lu et al. 2018). Therefore, relevant studies failed to quantify the benefits of sediment transport and the ecological environment, making the benefit accounting under the joint operation of reservoirs not comprehensive enough (Bai et al. 2017; Huang et al. 2019; Jin et al. 2021). More importantly, the joint operation of cascade reservoirs is of far-reaching significance to the ecological protection and social development of cities along the Yellow River. However, the existing research on benefits accounting and gains allocation under the optimized operation of reservoirs is limited to the interior of reservoirs, and there is a lack of analysis on the relationship of interest between reservoirs and cities along the river (Shen et al. 2018a, b; Shen et al. 2018a, b; Xu et al. 2018).

Sediment deposition in sediment-laden rivers will lead to various negative problems, significantly increasing the possibility of severe floods (Chen et al. 2012). Simultaneously, since China has raised the ecological protection and high-quality development of the Yellow River basin into a national strategy, the coordinated development of ecological and economic benefits of the Yellow River basin became an essential foothold for the exploitation of the Yellow River in the future (Xu and Wang 2020). Therefore, multi-dimensional benefits such as sediment reduction and ecological protection should be integrated into the existing optimized operation of reservoirs. In addition, it is essential to further explore the connection of interest between the reservoir group and city group, and reasonably distribute the value-added on this basis.

Aiming at the above problems, this paper established a multi-dimensional benefits accounting model for the joint operation of the cascade reservoirs and a value-added allocation model among multi-stakeholders to improve the existing research. In terms of benefit accounting, this paper introduces the Emergy theory to realize the unified accounting of eco-environmental and economic benefits. Based on obtaining the natural economic value, the Emergy theory converts different categories and incomparable energy or matter into solar emergy for analysis and research (Gan et al. 2023). As a quantitative research method from traditional energy analysis to emerging eco economic systems (Odum 1996), emergy theory has been widely used in water ecological compensation (Guan et al. 2019), ecological environment value assessment (Wu et al. 2019), sustainable development of the city (Li et al. 2021) and so on (Amaral et al. 2016). In terms of gain distribution, this paper establishes a double-layer value-added allocation model under different application modes of the reservoir group based on the differences between the reservoir and city stakeholders, which realizes a win–win situation for all stakeholders.

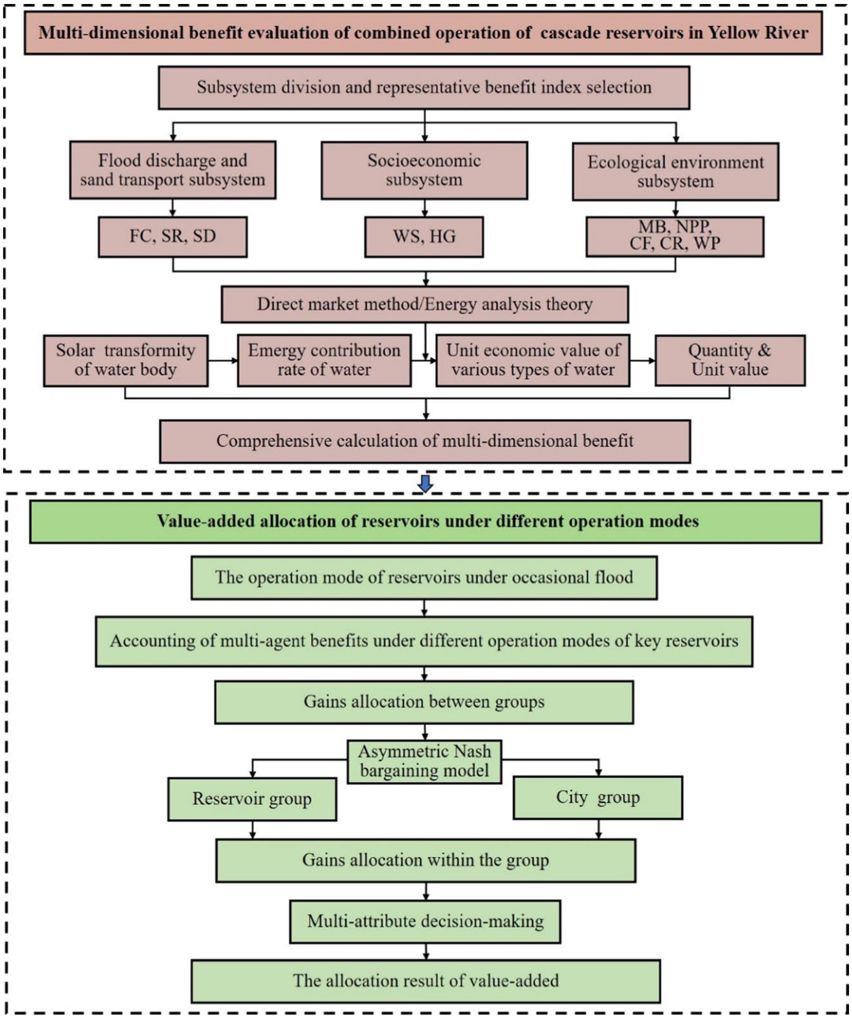
The rest of this paper is structured as follows. The emergy theory and the principles of value-added allocation are briefly described in “Theory” Section. "Methodology" Section proposes the multi-dimensional benefits evaluation model and the distribution model of value-added under the operation of the reservoir group. “Study area and data collection” Section gives the location of the study area and the source of data. In “Results and discussion” Section, the model is applied in the middle and lower reaches of the Yellow River, and the results and discussion are given. “Conclusions” Section further provides the conclusion and future research direction of this study. The research route of this paper is shown in Fig. 1.

Theory

A brief introduction to emergy theory

Emergy theory was proposed by Odum (Odum 1996), a famous American ecosystem scientist. As a new evaluation

Fig. 1 The research flow chart of this study



FC: Flood control; SR: Sediment reduction of the river; SD: Sediment discharge of reservoir; HG: Hydroelectric generation; MB: Maintaining biodiversity; NPP: Net primary productivity; CF: Carbon fixation and oxygen release; CR: Climate regulation; WP: Water purification; WS: Water supply.

theory, Emergy analysis is committed to a unified measurement standard to comprehensively analyze various natural resources in the ecosystem. Emergy theory bridges the ecosystem and the socio-economic system, which converts different types of energy or matter that cannot be compared uniformly into solar emergy. The conversion formula of solar emergy can be expressed as

$$M = \tau \times B \tag{1}$$

where τ means solar transformity of B and B refers to the quality of energy or matter.

In emergy analysis, the emergy-currency ratio (ECR) connects the ecosystem and economic system and realizes the conversion between currency and emergy. ECR indicates the emergy value of a region unit currency, which can be formulated as

$$ECR = \frac{TAE}{GNP} \tag{2}$$

where TAE is the emergy input of the country (region) in a given year and GNP is the corresponding regional gross national product.

The emergy contribution rate of water resources (ECRW) is a crucial parameter of emergy analysis and is a relative index to measure the contribution of water resources to economic production and the ecological cycle. Taking social production as an example, water resources, capital, labour input, and other means of production jointly produce industrial and agricultural products or provide social services. To calculate the emergy value of water resources for specific purposes, extracting the contribution of the emergy value of water resources is essential.

$$ECRW = \frac{EM_{EW}}{EM_{ET}} \quad (3)$$

where EM_{EW} means the emergy input of water resources in a system (sej) and EM_{EI} means the total emergy input of the system (sej).

The energy network analysis of the sediment river system under the joint operation of reservoirs is shown in Fig. 2, and the specific steps of emergy analysis refer to the existing research (Wu et al. 2019).

Principles of value-added allocation

The optimized operation of cascade reservoirs is essentially a Kaldo-Hicks improvement process, and the profit and loss of various stakeholders are different. Therefore, the principle of “who benefits, who compensates” should be followed so that the value-added is shared between the beneficiaries and benefactors. In addition, the allocation of the benefits should follow the principle of “cost–benefit equivalence”, that is, the greater the loss of the stakeholders in the optimized operation of cascade reservoirs, the more value-added share should be allocated. Meanwhile, this paper assumes that the income distribution follows the principle of “social responsibility”, which means that for vulnerable stakeholders (lower GDP), the proportion of its value-added allocation can be appropriately increased.

Methodology

The research methods are mainly divided into two parts. The first part is the calculation of multi-dimensional benefits, and the second part is the income distribution under the joint operation of reservoirs. First, in combination with the inherent characteristics of sandy rivers, this paper mainly selects ten indicators from three dimensions to calculate the multi-dimensional benefits of sandy rivers under the operating conditions of reservoir groups. Secondly, given the individual differences of interest subjects, stakeholders are divided into two categories, as shown in Table 1.

Multi-dimensional benefit accounting

Unit monetary value calculation of various water use

When analyzing the emergy of some benefits of water resources, it is necessary to calculate the solar transformity of various water bodies. The methods to measure the solar transformity of surface water, groundwater, and engineering water in this paper come from existing research (Wu et al. 2019). On this basis, the unit monetary value of various water use is further calculated to quantitatively calculate the benefits of water supply and ecological environment later (Guan et al. 2020; Pulselli et al. 2011).

(a) Industrial water, agricultural water, and *domestic water*

The unit value of industrial, agricultural, and domestic water calculation processes can be summarized in the following four steps.

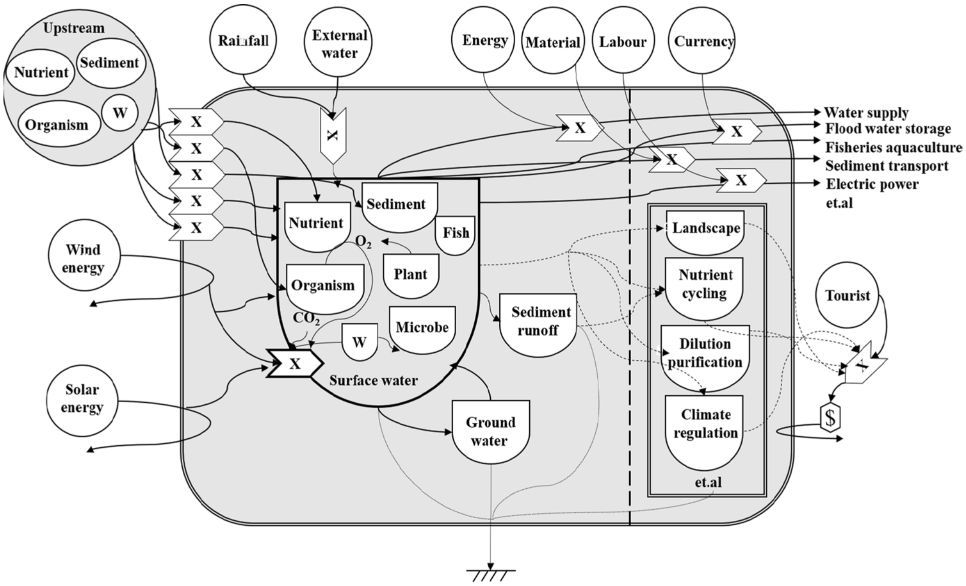


Fig. 2 Energy network diagram of the river from the perspective of multi-dimensional benefits

“X” means the interaction between different substances and energies, and “W” means pollutants.

Table 1 Dimension division and indicators selection of multidimensional benefit accounting

Subsystem	Representative benefit indicators	Stakeholder
Flood control and sand transport subsystem	Flood control E_{FC}	Cities along the Yellow River
	Sediment reduction of the river channel E_{SR}	Cities along the Yellow River
	Sediment discharge of reservoir E_{SD}	Reservoirs
Socioeconomic subsystem	Water supply E_{WS}	Cities along the Yellow River
	Hydroelectric generation E_{HG}	Reservoirs
Ecological environment subsystem	Maintaining biodiversity E_{MB}	Cities along the Yellow River
	Net primary productivity E_{NPP}	Cities along the Yellow River
	Carbon fixation & oxygen release E_{CF}	Cities along the Yellow River
	Climate regulation E_{CR}	Cities along the Yellow River
	Water purification E_{WP}	Cities along the Yellow River

Step 1 Calculate the ECRW of the water body.

$$ECRW_i = \frac{EM_i^{IW}}{EM_i^{IT}} \tag{4}$$

where EM_i^{IW} is the emergy input of water resources of the i - th system in a specific year (sej). EM_i^{IT} is the overall input emergy of the i - th system in this year (sej). i refers to agricultural, industrial, and domestic water-use systems.

Step 2 Calculate the emergy output of water resources in i - th system.

$$EM_i = ECRW_i \times EM_i^{OT} \tag{5}$$

where EM_i^{OT} means the overall emergy output in the i - th system (sej).

Step 3 Calculate the emergy value of unit water.

$$EM_{Pi} = \frac{EM_i}{W_i} \tag{6}$$

where W_i is the consumed water resource in i - th system this year (m^3).

Step 4 Calculate the monetary value of the unit water.

$$E_{Pi} = \frac{EM_{Pi}}{ECR} \tag{7}$$

where ECR is the emergy/currency ratio in the region where i - th system is located (sej/yuan).

(b) Ecological water use

The value of ecological water refers to the ecological protection function of water resources, including the maintenance of biodiversity, net primary productivity, carbon fixation and oxygen release, climate regulation and water purification. Therefore, the monetary value of unit ecological water is expressed as

$$EM_{PE} = \frac{\sum_{i=1}^{5} EM_i}{Q_E} \tag{8}$$

$$E_{PE} = \frac{EM_{PE}}{ECR} \tag{9}$$

where EM_i is the annual benefit of the representative indicators in the subsystem of the ecological environment. Q_E is the annual runoff of the corresponding section (m^3). ECR is the emergy/currency ratio of the city where the hydrology section of the river is located (sej/yuan). EM_{PE} and E_{PE} are the emergy value and monetary value of unit water, respectively (sej/m^3), (yuan/m^3).

Ecological environment subsystem

Based on existing studies (Wu et al. 2019), this paper divides rivers' ecological environmental benefit accounting indicators into the following five categories, as shown in Table 1.

(1) Maintaining biodiversity

Water resources not only provide material needs for organisms but also create suitable living conditions. The benefits of water resources in maintaining biodiversity can be expressed as (Jonsson and Malmqvist 2003)

$$EM_{MB} = N \times R_b \times \tau_b \times ECRW \tag{10}$$

where N is the total biological species in a given area. R_b is the proportion of biological activity area to the global area (%), and τ_b is the solar transformity of global species, $\tau_b = 1.26 \times 10^{25}$ sej/species.

(B) Net primary productivity

Net primary productivity mainly refers to the amount of organic carbon fixed by plants through photosynthesis to remove the part consumed by their own respiration and used for growth and reproduction.

$$EM_{NPP} = A_{npp} \times P_{npp} \times \tau_{npp} \tag{11}$$

where A_{npp} is the area of aquatic plants in regional water (m^2). P_{npp} is the net primary productivity of the unit water area (g/m^2). τ_{npp} is the solar transformity of net primary productivity, $\tau_{npp} = 5.78 \times 10^7$ sej/g.

(C) Carbon fixation and oxygen release

Aquatic plants can absorb carbon dioxide and release oxygen, and the ecological benefits can be expressed as

$$EM_{CF} = \left(\sigma_{co_2} \times P_c \times S_c \times \tau_{co_2} + \sigma_{o_2} \times P_c \times S_c \times \tau_{o_2}\right) \times ECRW \tag{12}$$

where σ_{co_2} and σ_{o_2} are 1.47 and 1.07 respectively. P_c is the average productivity of vegetation (g/hm^2).S_c is vegetation area (hm^2). τ_{co_2} and τ_{co_2} are solar transformity of O_2 and CO_2 respectively, and the corresponding emergy values are 3.78×10^7sej/g and 5.11×10^7sej/g.

(D) Climate regulation

The climate regulation function of river water resources refers to the regulation of water vapour on atmospheric temperature and humidity. The benefits of climate regulation can be transformed into the multiplication of the latent heat, amount of evaporation and solar transformity of steam(Wu et al. 2019).

$$EM_{CR} = \left(2,507.4 - 2.39T_t\right) \times W \times \tau_z \tag{13}$$

where T_t means the average temperature of the given area (°C). τ_z is the solar transformity of steam, τ_z = 12.20 sej/J, and W is the amount of evaporated water (g).

(E) Water purification

Water has a natural ability to purify and precipitate, which can change the concentration of various pollutants (Wu et al. 2019).

$$EM_{WP} = f \times ECRW \times \sum_{p=1}^{n} m_p \times \tau_p \tag{14}$$

where f means the self-purification ratio of the water. m_p is the discharge of p - th pollutant (g), and τ_p is the corresponding solar transformity (sej/g).

(F) Ecological and environmental benefits are related to flow

According to formula (8) and formula (9), the eco-environmental benefits of the river system can be shown as

$$E_{PE} = \frac{EM_{MB} + EM_{NPP} + EM_{CF} + EM_{CR} + EM_{WP}}{Q_E \times ECR} \tag{15}$$

$$E_{Total} = E_{PE,v} \times Q_v \tag{16}$$

where $E_{PE,v}$ is the eco-environmental value of unit water at the v - th river section downstream (yuan/m^3). Q_v is the ecological flow of the v - th river section (m^3).

Flood discharge and sand transport subsystem

(1) Flood control

The losses caused by typical floods under different operation modes of the reservoirs can be expressed as

$$E_{FC} = \sum_{j=1}^{n} A_j \times E_j \times \theta_j \tag{17}$$

where A_j is the inundation area of j - th type land under the given application mode of the reservoirs, and E_j is the value per unit area of j - th type land use. θ_j is the loss rate of inundation of j - th type land. j includes arable land, housing land, etc.

(B) Sediment reduction of the river channel

The indirect method is adopted to calculate the benefit of sediment reduction of the river channel, which is equal to the unit dredging cost multiplied by the sediment dredging volume (Liang et al. 2016).

$$E_{SR} = V_h \times P_h \tag{18}$$

where V_h is the dredging amount of river sediment, P_h is the unit dredging cost, P_h = 4.7 yuan/t.

(C) Sediment discharge of reservoir

Different operation modes of the reservoirs will also affect their own siltation, and the 7 corresponding benefits of reducing siltation are expressed as

$$E_{SD} = \frac{S_d \xi}{D V_c} \tag{19}$$

where S_d is the sediment volume is reduced in the reservoir area (t).D is the sediment density,uniformly taken as 1.2 t/

m^3. V_c is the initial storage capacity of the reservoir (m^3). ξ is the total construction cost of the reservoir (yuan).

Socioeconomic subsystem

(1) Water supply

For the convenience of calculation, the water supply benefits under different operation modes of the reservoir are expressed as

$$E_{WS} = \sum_{h=1}^{H} \sum_{k=1}^{3} E_{Pk}^{h} \times W_{k}^{h} \tag{20}$$

where E_{Pk}^{h} represents the unit price of water delivery to k - th water users in the city h, and W_{k}^{h} represents the amount of water delivery to k - th water users in the city h. k includes industrial, agricultural and domestic water users.

(B) Hydroelectric generation

The power generation benefit of reservoirs in sandy rivers also needs to consider the constraints of the sediment-carrying capacity of generator units. When the sediment concentration in the reservoir is greater than the maximum sediment discharge, the power generation benefit of the reservoir is set to 0. When the sediment concentration in storage is less than the maximum sediment discharge, the calculation formula of power generation benefit is as follows

$$E_{HG} = \begin{cases} \varphi N \min\left(Q_p, Q_{p\max}\right)\Delta H \Delta t, \ Q_s \le Q_{s\max} \\ 0, \ Q_s > Q_{s\max} \end{cases} \tag{21}$$

where φ is the network access price of the reservoir (yuan/kwh); Q_p is the over flow (m^3/s). $Q_{\max}$ is the maximum sediment carrying capacity of the generator set (m^3/s). ΔH is the generating head (m). Δt is the duration of power generation (h). N is the output coefficient of reservoir hydropower station. $Q_{s\max}$ and Q_s are respectively the sediment content of water (kg/m^3) and the maximum sediment volume passing through the turbine (kg/m^3).

The allocation of value-added among the main stakeholders

The optimized operation of key reservoirs in sandy rivers is a Kaldo Hicks improvement process. The profit and loss of each stakeholder are different under different operation modes of reservoirs. Therefore, it is necessary to reasonably allocate the value-added after the optimized operation of reservoirs. To facilitate the dimensionality reduction analysis, this paper divides the distribution of value-added into two levels: the distribution between reservoir-group and city-group and the distribution within the group.

Allocation of gains between the reservoir group and the city group

Nash bargaining solution is an efficient tool to solve the problem of interest negotiation, which is widely used in various fields (Zhao et al. 2021). The equilibrium solution can be expressed as the optimal solution of the following Nash product form.

$$u^* = \max_{u \in \Omega} \left(u_r - d_r\right)^{\alpha} \times \left(u_c - d_c\right)^{1-\alpha} \tag{22}$$

where Ω is the set of valid payment pairs,d_r and d_c are the breaking points of the reservoir group and city group. α and $1 - \alpha$ are the bargaining power of the reservoir group and city group.

Allocation of gains within a group

Multi-attribute decision-making can also solve the distribution problem (Xu et al. 2021). By reasonably selecting indicators and further weighting these indicators, the distribution proportion of each stakeholder can be obtained. Determining the weight of each indicator is the key to the decision-making problem. The product of subjective weight and objective weight is taken as the comprehensive weight in this paper, in which the best worst method (BWM) is selected for the subjective weight. Compared with other subjective methods of weighting, BWM can simplify the decision-making process and ensure the consistency of decision-making (Xu et al. 2021). The entropy weight method is adopted to determine the objective weight. Referring to the principles of value-added allocation proposed in "Principles of value-added allocation" Section, the selection of two groups of value-added allocation indicators is shown in Table 2.

Study area and data collection

Study area

The study area of this paper refer to Sanmenxia reservoir (SMX), Xiaolangdi reservoir (XLD), and the lower reaches of the Yellow River. The lower reaches of the Yellow River from Taohuayu to the Yellow River estuary, with a total length of 786 km and a drainage area of 23,000 km^2. The sediment deposition in the lower reaches of the Yellow River is extremely serious, and the riverbed of some sections is 4–6 m higher than the ground, which makes the Yellow River a world-famous "suspended river". Both banks of the lower Yellow River mainly rely on levees to keep out water, and floods have become the biggest hidden danger threatening the safety of the Huang-Huai-Hai Plain. Cities along the lower reaches of the Yellow River include Luoyang (LY), Jiaozuo (JZ), Zhengzhou (ZZ), Kaifeng (KF), Xinxiang (XX), Puyang (PY), Heze (HZ), Jining (JNI), Tai'an (TA), Liaocheng (LC), Dezhou (DZ), Jinan (JNA), Zibo (ZB), Binzhou (BZ) and Dongying (DY). The length of the river channel in each city is shown in Table 3.

Located in Sanmenxia, SMX is a seasonal regulation reservoir with an effective storage capacity of 439 million m^3. Due to the serious sediment deposition in the reservoir area, the regulation capacity of SMX is very limited. XLD is an incomplete annual regulation reservoir, controlling a drainage area of 69,4000 km^2, accounting for 92.3% of the Yellow River drainage area. The average water level of XLD is 275 m, with a total storage capacity of 12.65 billion m3 and a regulating storage capacity of 5.1 billion m^3. The total installed capacity is 1,800 MW and the average annual power generation is 5.1 billion kwh. The integrated mission of XLD focuses on flood control and sediment reduction while taking into account water supply, irrigation, and power generation. The main hydrological sections of the lower Yellow River include Huayuankou (HYK), Jiahetan (JHT), Gaocun (GC), Sunkou (SK), and Aishan (AS), Luokou (LK), and Lijin (LJ). The specific distribution of critical nodes is shown in Fig. 3.

Data collection

Taking a typical once-every-20-year flood as an example, two different joint application modes of SMX and XLD are set as mode of below the beach and mode of overflow the beach (simply named application mode1 and application mode 2). According to the multi-dimensional benefit accounting method established in this paper, the comprehensive benefit is calculated, and the value-added is further distributed to each stakeholder. Multi-dimensional benefits

Table 2 Indicators selection of intragroup gains distribution

Group	Indicator of distribution					
Cities	Variation of FC	Variation of SR	Variation of ecological environment	Variation of total revenue	Length of channel	GDP per capita
Reservoirs	Variation of SD	Variation HG	Variation of total revenue	Effective storage	Guaranteed output of generator set	–

Table 3 Channel length of cities in the lower Yellow River (unit: km)

City	LY	JZ	ZZ	KF	XX	PY	HZ	JNI	TA	LC	DZ	JNA	ZB	BZ	DY
Length	97	98	160	109.1	165	167.5	185	30.2	36.3	59.51	63.4	183	45.6	94	138

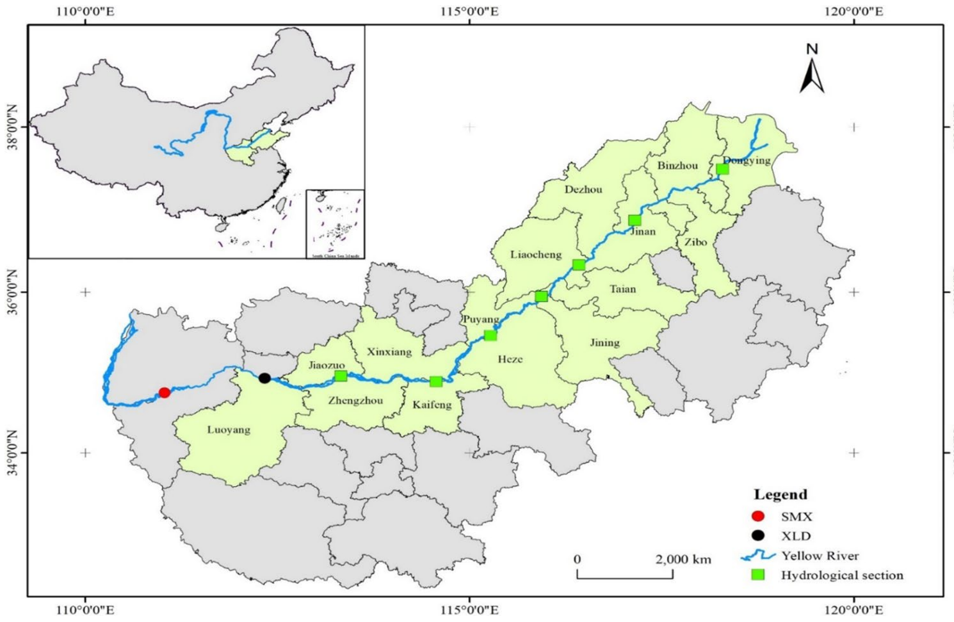


Fig. 3 The study area of the Yellow River

are calculated and distributed based on economic data and water use data in 2016. The data sources mainly include the regional water resources bulletin, statistical yearbook, national economic and social development statistical bulletin. Some data are from the Yellow River water conservancy research institute.

The ECR of each region is obtained according to the annual emergy input and the GNP of each region. Through the classified collection of agricultural, industrial and domestic economic data and water use data in each region, the unit value of various types of water use in the corresponding areas can be calculated. For the value estimation of unit ecological water, the various ecological environment value and ecological flows in each city are approximately estimated based on the monitored runoff, sediment, pollutants, biomass and other data of the main hydrological section of the lower reaches of the Yellow River and the length of the river channel in each city. Relevant data collection and calculation results are shown in Table 4.

Calculate the data in Table 4 according to the steps in "Unit monetary value calculation of various water use" Section, and the unit currency value of various types of water use in each city can be obtained as shown in Table 5. On this basis, the water supply benefit and ecological environment

Table 4 Total eco-environmental emergy and runoff of cities in the lower Yellow River (unit: sej, m^3)

Item City	Maintaining biodiversity	Net primary productivity	Carbon fixation and oxygen release	Climate regulation	Water purification	Sum up	Annual runoff
LY/XLD	1.57E+21	1.22E+19	3.33E+20	2.20E+20	−6.20E+18	2.13E+21	1.62E+10
JZ	–	–	–	–	–	1.55E+21	1.71E+10
ZZ/HYK	8.30E+20	4.90E+18	4.20E+19	1.30E+20	−3.32E+19	9.74E+20	1.79E+10
KF/JHT	7.20E+20	5.30E+18	2.40E+19	1.80E+20	1.01E+19	9.39E+20	1.66E+10
XX	–	–	–	–	–	9.41E+20	1.63E+10
PY	–	–	–	–	–	9.43E+20	1.58E+10
HZ/GC	6.80E+20	6.70E+18	7.00E+18	2.30E+20	2.05E+19	9.44E+20	1.55E+10
JNI/SK	9.40E+20	1.76E+19	1.30E+19	2.30E+20	7.30E+18	1.21E+21	1.44E+10
TA	–	–	–	–	–	8.66E+20	1.39E+10
LC/AS	2.60E+20	3.50E+18	5.20E+19	1.60E+20	4.89E+19	5.24E+20	1.34E+10
DZ	–	–	–	–	–	5.03E+20	1.22E+10
JNA/LK	2.80E+20	3.60E+18	5.60E+19	1.30E+20	1.17E+19	4.81E+20	1.11E+10
ZB	–	–	–	–	–	5.80E+20	1.06E+10
BZ	–	–	–	–	–	8.80E+20	9.17E+09
DY/LJ	9.30E+20	1.14E+19	3.00E+18	1.30E+20	8.40E+18	1.08E+21	8.18E+09

Table 5 ECR and unit value of various types of water in each city (unit: sej/yuan, yuan/m^3)

Item City	ECR	The unit value of industrial water	The unit value of agricultural water	The unit value of domestic water	The unit value of ecological water
LY	3.35E+11	1.78E+01	7.56E+00	2.39E+01	3.91E-01
JZ	3.71E+11	1.23E+01	5.88E+00	2.30E+01	2.45E-01
ZZ	1.64E+11	1.88E+01	7.56E+00	2.71E+01	3.32E-01
KF	3.55E+11	1.67E+01	6.24E+00	2.5.E+01	1.59E-01
XX	3.38E+11	1.68E+01	7.68E+00	2.36E+01	1.70E-01
PY	3.14E+11	1.48E+01	7.78E+00	2.46E+01	1.91E-01
HZ	3.47E+11	1.69E+01	5.77E+00	2.38E+01	1.76E-01
JNI	2.10E+11	1.71E+01	7.83E+00	2.62E+01	4.00E-01
TA	3.46E+11	–	–	–	1.81E-01
LC	3.98E+11	1.51E+01	4.85E+00	2.24E+01	9.87E-02
DZ	2.21E+11	1.76E+01	8.03E+00	2.26E+01	1.86E-01
JNA	9.70E+10	1.96E+01	8.71E+00	2.95E+01	4.47E-01
ZB	3.35E+11	1.65E+01	5.71E+00	2.74E+01	1.63E-01
BZ	3.75E+11	1.41E+01	4.85E+00	2.50E+01	2.56E-01
DY	3.03E+11	1.67E+01	8.09E+00	2.79E+01	4.37E-01

benefit under different operation modes of the reservoir can be further calculated.

Results and discussion

Results

This paper simulates two application modes of SMX and XLD facing typical flood conditions and calculates various benefits in turn: (1) Calculate the corresponding flood loss in combination with the inundation scope and land use type of each city; (2) Calculate the benefit of water supply by collecting the data on all kinds of water use in each city; (3) Combined with the observation data of hydrological stations and the river length, the ecological flow of each city is converted, and further ecological benefits are obtained; (4) Combined with the siltation amount monitored by each hydrological station and the channel length in each city, calculate the river siltation reduction benefit of each city; (5) Calculate the power generation and benefits of SMX and XLD; (6) Calculate the sediment discharge of the reservoir under the two application modes of SMX and XLD, and calculate the corresponding sediment discharge benefits of the reservoir. The calculation results of various benefits for stakeholders under the two application modes of SMX and XLD are shown in Table 6.

Comparing the comprehensive benefits of stakeholders under the two application modes, the selection preferences of each stakeholder are shown in Table 7. The preferences of stakeholders are inconsistent, but the total benefit under mode 1 is more significant than that under mode 2.

Table 6 Profit and loss of each stakeholder under the two application modes (unit: yuan)

Item City	Sediment reduction of the river channel	Ecological environment	Flood control	Water supply	Hydroelectric generation	Sediment discharge of reservoir
LY	−2.62E+09 (−2.61E+09)↑	2.34E+09 (2.38E+09) ↑	−9.88E+06 ↑ (−4.21E+07)	2.64E+07 (2.64E+07)	–	–
JZ	−5.30E+09 (−5.27E+09) ↑	1.49E+09 (1.52E+09) ↑	−4.18E+07 ↑ (−1.01E+08)	3.65E+08 (3.65E+08)	–	–
ZZ	−4.84E+09 ↑ (−5.66E+09)	2.06E+09 (2.09E+09) ↑	−1.50E+08 ↑ (−3.31E+08)	9.49E+08 (9.49E+08)	–	–
KF	−4.54E+08 ↑ (−1.03E+09)	9.59E+08 (9.77E+08) ↑	−1.87E+08 ↑ (−3.73E+08)	1.50E+09 (1.50E+09)	–	–
XX	−3.19E+08 (−3.14E+08) ↑	1.03E+09 (1.04E+09) ↑	−2.12E+08 ↑ (−8.10E+08)	5.58E+08 (5.58E+08)	–	–
PY	−3.23E+08 (−3.18+08) ↑	1.51E+09 ↑ (1.17E+09)	−1.14E+08 ↑ (−6.79E+08)	1.06E+09 (1.06E+09)	–	–
HZ	−7.16E+08 (−6.69E+08) ↑	1.06E+09 (1.08E+09) ↑	−6.76E+07 ↑ (−9.83E+08)	7.27E+08 (7.27E+08)	–	–
JNI	−1.57E+08 (−1.50E+08) ↑	2.33E+09 (2.37E+09) ↑	−8.62E+06 ↑ (−2.05E+07)	9.23E+07 (9.23E+07)	–	–
TA	−2.89E+07 (−2.89E+07)	1.05E+09 (1.07E+09) ↑	−1.24E+07 ↑ (−3.15E+07)	0.00E+00 (0.00E+00)	–	–
LC	−1.10E+08 (−9.43E+07) ↑	5.71E+08 (5.82E+08) ↑	−8.46E+06 ↑ (−3.18E+07)	1.50E+08 (1.50E+08)	–	–
DZ	−1.15E+08 (−8.08E+07) ↑	1.07E+09 (1.09E+09) ↑	−4.61E+07 ↑ (−2.08E+08)	7.05E+08 (7.05E+08)	–	–
JNA	−2.01E+08 (−1.34E+08) ↑	2.55E+09 (2.58E+09) ↑	−6.40E+07 ↑ (−2.66E+08)	5.98E+08 (5.98E+08)	–	–
ZB	−1.79E+07 (−8.57E+06) ↑	9.24E+08 (9.37E+08) ↑	−1.15E+07 ↑ (−1.4E+08)	2.44E+08 (2.44E+08)	–	–
BZ	−3.68E+07 (−1.77E+07) ↑	1.43E+09 (1.47E+09) ↑	−1.79E+07 ↑ (−1.68E+08)	6.85E+08 (6.85E+08)	–	–
DY	−2.70E+07 (−1.30E+07) ↑	2.41E+09 (2.49E+09) ↑	−2.65E+06 ↑ (−6.35E+07)	8.69E+08 (8.69E+08)	–	–
SMX	–	–	–	–	4.72E+08 (4.72E+08)	2.29E+09 ↑ (2.15E+09)
XLD	–	–	–	–	2.87E+07 (3.11E+07) ↑	−7.39E+09 (−4.30E+09) ↑

xxx is the benefit corresponding to application mode 1 and (xxx) is the benefit corresponding to application mode 2.↑ indicating a larger value.

Table 7 Preferences of stakeholders for the two application modes

Stakeholder	LY	JZ	ZZ	KF	XX	PY	HZ	JNI	TA	LC	DZ	JNA	ZB	BZ	DY	SMX	XLD	Overall
Application mode 1		√	√	√	√	√	√				√	√	√	√				√
Application mode 2	√							√	√	√					√	√	√	

"√" indicates the preference of each stakeholder

Therefore, all parties will choose application mode 1 as long as the value-added can be reasonably distributed.

The stakeholders are divided into the reservoir group and the city group, and the benefit distribution among groups is carried out on this basis. The asymmetric Nash bargaining model is adopted to distribute benefits between the two groups here. The breaking point of the city group is 4.24E + 08, which means that the ecological benefits of application mode 1 are reduced compared with mode 2. The breaking point of the reservoir group is 3.09 + 09, which means that the sediment discharge benefits in application mode 1 are lower than that in mode 2. The bargaining power of the main body of the reservoir group is determined by the ratio of the regulation capacity of the leading reservoir group to the average of the regulation capacity of the main reservoirs of the Yellow River. The bargaining power of the city group is given by the ratio of average water consumption in the Yellow River basin to that in the lower reaches. Based on the above, it is necessary to determine the gain to be allocated. The net benefit generated under application mode 1 is 1.04E + 09 yuan more than that under application mode 2, but it is not appropriate to directly configure this part of the gain. As can be seen from Table 7, stakeholders such as XLD, LC and TA prefer to use application mode 2. It is unfair to add the allocation amount of gain to the multi-dimensional benefits corresponding to application mode 2 as the final benefit of stakeholders. Therefore, this paper further adjusts the value added to net gains (1.04E + 09 yuan) plus the profit and loss difference between the two application models of stakeholders who gain more benefits in application mode 2. Then the final value-added is 4.09E + 09 yuan, and the asymmetric Nash bargaining model is established as follows

$$\begin{cases} u^* = \max\limits_{u \in \Omega} \left(u_r - 3.09 \times 10^9\right)^{0.3786} \times \left(u_c - 4.24 \times 10^8\right)^{0.6214} \\ u_r + u_c = 7.06\text{E} + 09 \end{cases}$$

Solving the Nash bargaining solution above, $u_r = 4.63\text{E} + 09$ and $u_c = 2.96\text{E} + 09$ can be obtained. That is, the share of the reservoir group is 1.55E + 09 yuan, and the share of the city group is 2.54E + 09. Based on the above, the value-added is further distributed within groups. For the reservoir group, the distribution indicators selected in this paper include the variation of SD, HG, total revenue, and effective storage, the guaranteed output of the generator set. Since the stakeholders are only XLD and SMX in the reservoir group, the BWM is adopted to determine the weight of indicators. The weight of each indicator is shown in Table 8.

Table 8 Weight of each gain distribution indicator in the reservoir group

Indicator	Variation of SD	Variation of HG	Variation of total revenue	Effective storage	Guaranteed output of generator set
Weight	0.3162	0.2113	0.1261	0.2371	0.1093

For the city group, the entropy weight method and BWM are combined to calculate the weight of each indicator. The selection of the benefit distribution indicators and their corresponding comprehensive weights are shown in Table 9.

According to the relative value and corresponding weight of each decision-making indicator of each stakeholder, the benefit distribution within the group is carried out. The final allocation result is shown in Fig. 4. It can be seen from the figure that among all stakeholders, XLD has the highest gains allocation, accounting for about 36.16% of the total. This is because the generation of value-added under application mode 1 is based on the premise that XLD sacrifices the great benefits of sediment discharge, and XLD has a relatively large regulation capacity for flood compared with SMX, so it should enjoy more benefits. On the contrary, the share of JNI accounts for only 1.12% of the total, because the value of each evaluation indicator of JNI is lower than that of other cities. Specifically, JNI has a smaller range of changes of each benefit under the two application modes and has the shortest channel of the Yellow River in the area are the fundamental reasons for the lowest quota.

Discussion

To better allocate the value-added, it is necessary to compare the profit and loss of each stakeholder under the two scheduling modes. When SMX and XLD are in application mode 1, the profit and loss of each stakeholder are shown in Fig. 5. As seen from the figure, the profits and losses of each stakeholder vary greatly. For the city group, the benefits of

Table 9 Weight of each gain distribution indicator in the city group

Indicator	Variation of FC	Variation of SR	Variation of ecological environment	Variation of total revenue	Length of channel	GDP
Entropy weight method	0.1575	0.1026	0.1997	0.1572	0.1851	0.1978
Best–worst method	0.2913	0.1921	0.2106	0.1142	0.1025	0.0893
Comprehensive weight	0.2828	0.1215	0.2592	0.1106	0.1170	0.1089

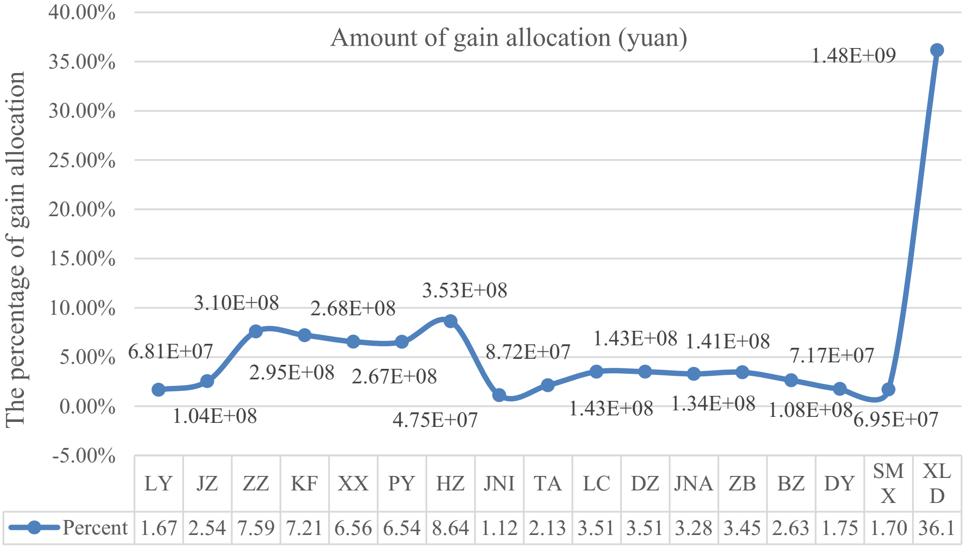


Fig. 4 Distribution of value-added among stakeholders

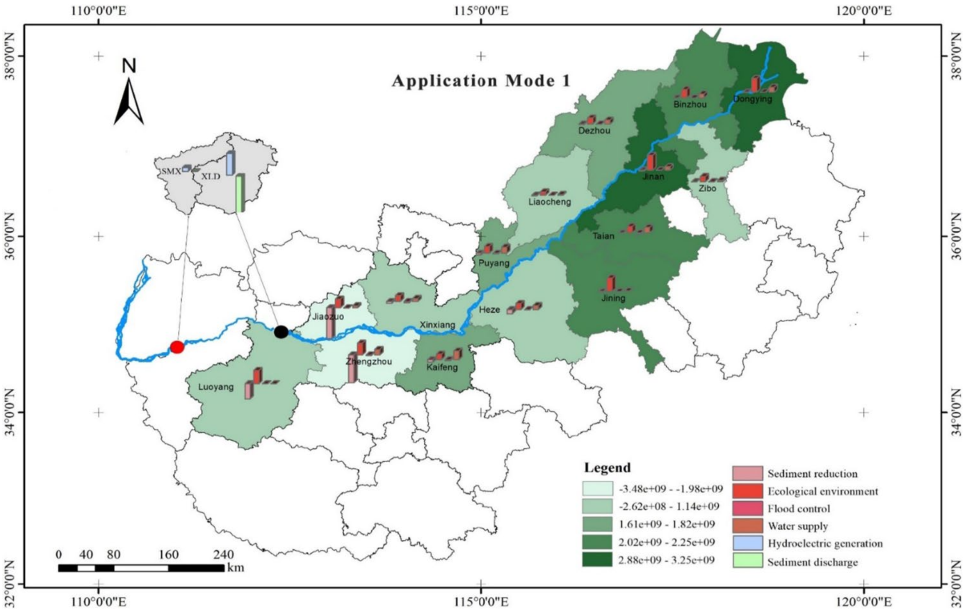


Fig. 5 Profit and loss of each stakeholder under application mode 1

flood control and river channel sedimentation reduction are negative, that is, the flood has brought substantial economic losses and led to serious siltation of the river channel. Furthermore, the negative benefit brought by river sedimentation is much greater than the direct loss brought by flood. Since flooding can ensure water supply and ecological base flow, these two benefits are positive. In general, the comprehensive benefits of cities in Henan province are far lower than those in Shandong province, resulting from the superposition of three main reasons. First, the flood has brought more inundation losses to cities in Henan province. Secondly, the flood has seriously silted the rivers in the Henan section. Finally, the water consumption of cities in Shandong province is greater than that of Henan province. Therefore, the former two bring more negative benefits to Henan province, while the third one brings fewer positive benefits to Henan province. This further makes the comprehensive benefit of DY, Shandong Province, the largest is 3.25E + 09 yuan. However, the comprehensive benefit of JZ in Henan Province is the minimum of − 3.48E + 09 yuan.

As for the reservoirs, since SMX is in the late stage of operation, the sediment in the reservoir area can be discharged by open discharge, so its power generation and sediment discharge benefits are positive, but the benefit value is relatively small. For XLD, its power generation benefit is positive, far more significant than SMX. However, the flood caused a lot of settlement in the internal area of XLD, leading to its overall negative benefits.

When SMX and XLD are in application mode 2, the profit and loss of each stakeholder are shown in Fig. 6. Under this operation mode, the overall trend of multi-dimensional benefits is consistent with operation mode 1, whether for the city group or reservoir group. Although there are minor fluctuations in various benefits, it does not affect the order of magnitude and positive and negative conditions of multi-dimensional benefits. It is worth noting that compared with application mode 1, the flood loss of the city under application mode 2 is increased, and the deposition of some downstream channels has brought more negative benefits. However, the ecological benefits of cities have increased, and the water supply benefits are flat. For the reservoir, the increase of the benefit value of sand discharge in the reservoir under application mode 2 is more significant than the decrease of the benefit value of power generation. The city group is generally more inclined to application mode 1, while the reservoir group is more inclined to application mode 2.

According to the subsystem divided in Table 1, the changes in stakeholders' benefits under the two modes are shown in Figs. 7, 8 and 9. The socio-economic subsystem (Fig. 7) includes the benefits of water supply in cities and the benefits of electricity generation in reservoirs. Under the two application modes, urban water supply can be guaranteed, so the benefits of water supply remain unchanged. Due to the limitation of installed capacity, the power generation benefit of SMX is basically unchanged. The benefit of XLD power generation is far greater than the economic benefit of other stakeholders, and fluctuates under the two modes. The application of mode 1 generates 1.35E + 08 yuan more than that of mode 2. Therefore, the benefits of XLD power generation in the socio-economic subsystem should be focused on in the process of flooding.

Flood control and sand transport subsystem includes flood control, sediment reduction of the river channel, and sediment discharge of the reservoir. Under the two application modes, the benefits of flood control and the benefit of the sediment reduction of the river channel are inconsistent in the direction of change, so the city stakeholders have different preferences in the two application modes (Fig. 8). Under application mode 1, XLD lost 3.08E + 09 yuan more than in application mode 2, and SMX lost 2.82E + 06 yuan more than in application mode 2. Therefore, the reservoir stakeholders are consistent in their preference for application mode 2.

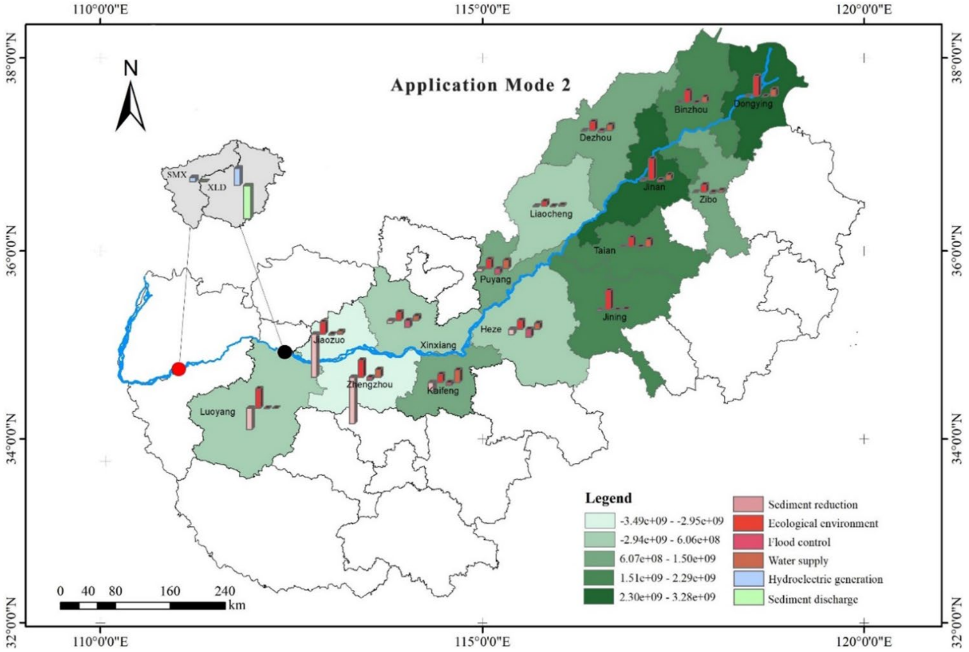


Fig. 6 Profit and loss of each stakeholder under application mode 2

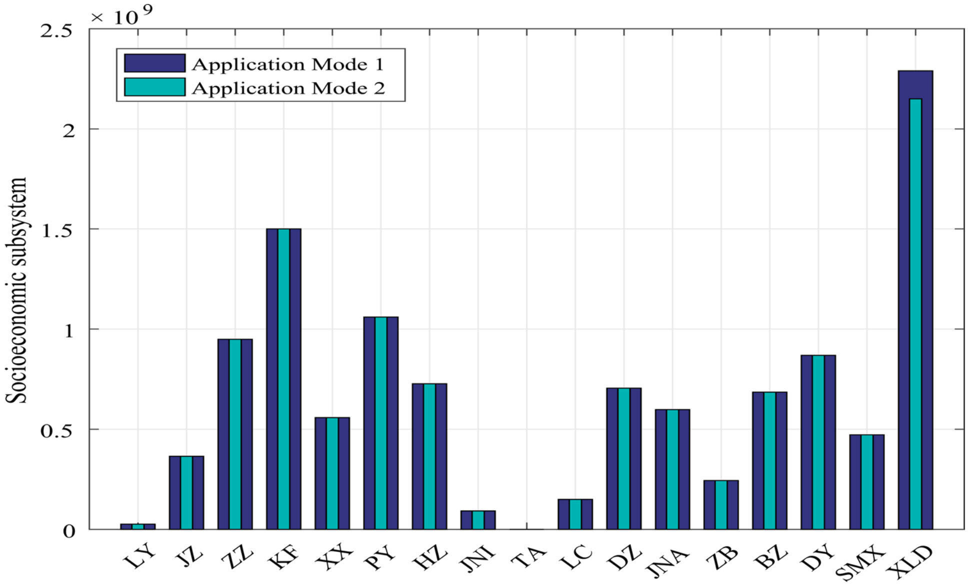


Fig. 7 Benefit change of socio-economic under two application modes

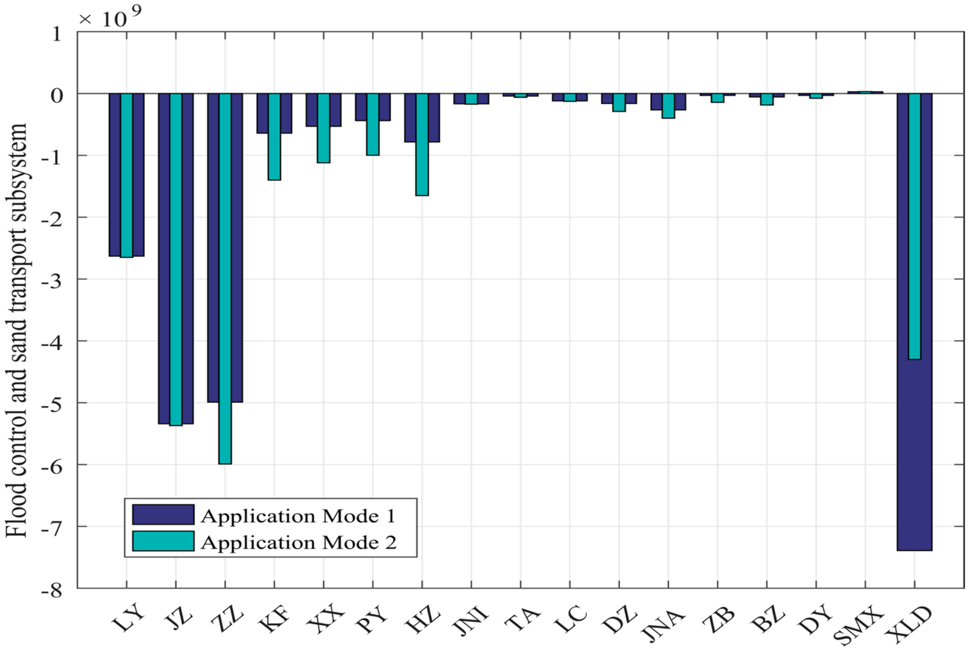
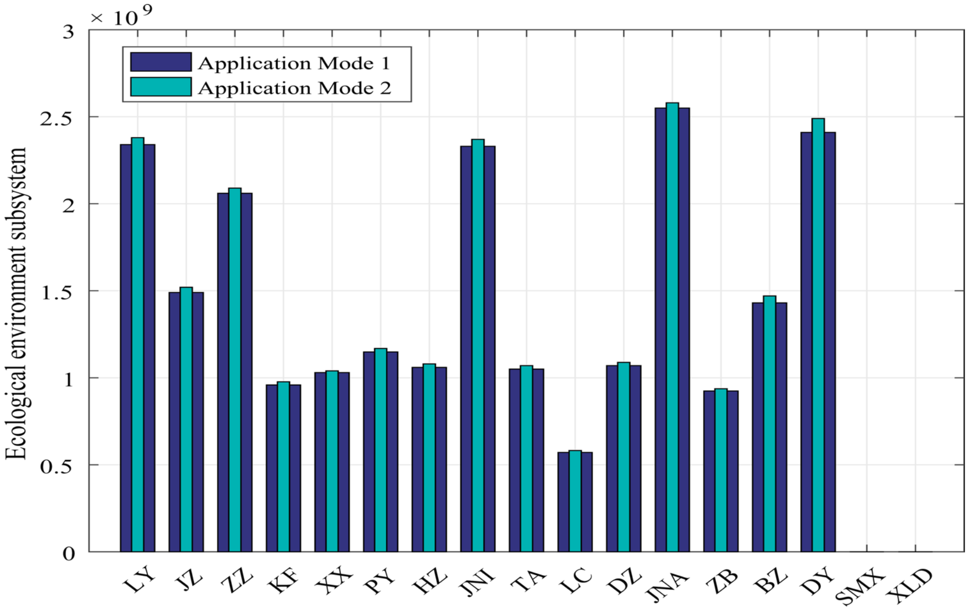


Fig. 8 Benefit change of flood control and sand transport under two application modes

This paper mainly discusses the impact of reservoir operation on the downstream river ecological environment, so it is only directly related to the preferences of city stakeholders. The ecological environment subsystem mainly includes the benefits of the five dimensions in Table 1. As the ecological environment benefit is affected by the discharge, the application mode 2 can bring better ecological flow to the downstream river channel than application mode 1, so the city stakeholders prefer application mode 2.

Analyzing the changes in multi-dimensional benefits of stakeholders under the two application modes is to make a reasonable allocation of gains. This means the question of what to divide and how to divide. As mentioned above, when stakeholders' preferences are inconsistent, they cannot directly add the benefits under the lower state to the quota as their final benefits, which does not meet the principle of fairness. Therefore, adjusting the gain, that is, the added value plus the income difference of individuals with poor system benefits but high individual benefits is necessary. Allocate the revised gain, and take the individual allocation plus the corresponding benefit in the lower state as the final benefit of the stakeholders, which will help the absolute benefit of the stakeholders to be between the corresponding benefits in various states.

Fig. 9 Benefit change of ecological environment under two application modes



Conclusions

The Yellow River is a world-famous river containing sand, with less water and more sand. In particular, the lower reaches of the Yellow River are facing huge flood risks. The scientific regulation of reservoirs can fundamentally ensure the safety of flood control, water supply and the ecological environment of cities along the Yellow River. Reservoirs usually have multiple competing objectives. The priority of various purposes can be weighed by establishing a multidimensional benefit calculation method. This article comprehensively introduces the multi-dimensional advantages of SMX and XLD under different joint application modes. The results show that inundation loss and sediment deposition are the biggest threats facing the lower Yellow River under typical flood conditions. Therefore, the technical innovation of water and sediment regulation should be further strengthened to reduce the adverse effects of sediment deposition in the Yellow River. At the same time, it is necessary to improve the flood control capacity of the lower reaches of the Yellow River by increasing the dam height or speeding up the construction of the planned reservoirs of the Yellow River, to reduce the losses caused by floods.

During the flooding process, reservoir stakeholders and city stakeholders have different preferences for the joint application of reservoirs, so it is necessary to redistribute the interests of stakeholders. In recent years, based on the people-oriented river management concept, the river basin management department has made every effort to ensure that there is no overbank flood in the lower reaches of the Yellow River, which is consistent with the recommendations of this study, that is, it is more reasonable to use application mode 1 in the flooding process, which also requires the downstream cities to make fair compensation for the loss of sediment deposition in the reservoir to ensure the long-term stability of the Yellow River.

The multi-dimensional benefit calculation method and value-added distribution method established in this paper not only achieve a win–win situation for all stakeholders, but also provide direction and guarantee for the optimal joint operation of reservoirs. However, this paper only compares two reservoir group application models. How to find a better reservoir application mode based on the research results of this paper will be the critical problem to be studied in the next step.

Funding The funding was provided by National Key R&D Program of China, (Grant No: 2021YFC3200403), National Natural Science Foundation of China, (Grant No: 61873084)

Data availability Data will be made available on request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Ethical standard This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent Informed consent was obtained from all participants included in the study.

References

Amaral LP, Martins N, Gouveia JB (2016) A review of emergy theory, its application and latest developments. Renew Sustain Energy Rev 54:882–888. https://doi.org/10.1016/j.rser.2015.10.048

Bai T, Kan Y, Chang J, Huang Q, Chang F-J (2017) Fusing feasible search space into PSO for multi-objective cascade reservoir optimization. Appl Soft Comput 51:328–340. https://doi.org/10.1016/j.asoc.2016.12.005

Bai T, Wei J, Chang F-J, Yang W, Huang Q (2019) Optimize multi-objective transformation rules of water-sediment regulation for cascade reservoirs in the upper Yellow River of China. J Hydrol 577:123987. https://doi.org/10.1016/j.jhydrol.2019.123987

Chen Y, Syvitski JPM, Gao S, Overeem I, Kettner AJ (2012) Socio-economic impacts on flooding: a 4000-year history of the Yellow River, China. Ambio 41:682–698. https://doi.org/10.1007/s13280-012-0290-5

Chen Y, Li J, Lu H, Xia J (2020) The dynamic benefit compensation in a multi-reservoir system based on importance analysis. J Clean Prod 249:119402. https://doi.org/10.1016/j.jclepro.2019.119402

Gan L, Wan X, Ma Y, Lev B (2023) Efficiency evaluation for urban industrial metabolism through the methodologies of emergy analysis and dynamic network stochastic block model. Sustain Cities Soc 90:104396. https://doi.org/10.1016/j.scs.2023.104396

Guan X, Hou S, Meng Y, Liu W (2019) Study on the quantification of ecological compensation in a river basin considering different industries based on water pollution loss value. Environ Sci Pollut Res 26:30954–30966. https://doi.org/10.1007/s11356-019-06215-6

Guan X, Jiang P, Meng Y, Qin H, Lv H (2020) Study on production, domestic and ecological benefits of reservoir water supply based on emergy analysis. Processes 8:1435. https://doi.org/10.3390/pr8111435

Huang L, Li X, Fang H, Yin D, Si Y, Wei J, Liu J, Hu X, Zhang L (2019) Balancing social, economic and ecological benefits of reservoir operation during the flood season: a case study of the Three Gorges Project. China J Hydrol 572:422–434. https://doi.org/10.1016/j.jhydrol.2019.03.009

Jin W, Chang J, Wang Y, Bai T (2019) Long-term water-sediment multi-objectives regulation of cascade reservoirs: a case study in the upper Yellow River. China J Hydrol 577:123978. https://doi.org/10.1016/j.jhydrol.2019.123978

Jin W, Wang Y, Chang J, Wang X, Niu C, Wang Yu, Peng S (2021) Multi-objective synergetic reservoir operation in a sediment-laden river. J Hydrol 599:126295. https://doi.org/10.1016/j.jhydrol.2021.126295

Jonsson M, Malmqvist B (2003) Mechanisms behind positive diversity effects on ecosystem functioning: testing the facilitation and interference hypotheses. Oecologia 134:554–559. https://doi.org/10.1007/s00442-002-1148-5

Li J, Sun W, Song H, Li R, Hao J (2021) Toward the construction of a circular economy eco-city: an emergy-based sustainability evaluation of Rizhao city in China. Sustain Cities Soc 71:102956. https://doi.org/10.1016/j.scs.2021.102956

Li F-F, Wang H-R, Qiu J (2022) A MATLAB GUI program for reservoir management to simultaneously optimise sediment release and power generation. J Environ Manage 320:115686. https://doi.org/10.1016/j.jenvman.2022.115686

Liang C, Xin S, Dongsheng W, Xiuying Y, Guodong J (2016) The ecological benefit–loss evaluation in a riverine wetland for hydropower projects—a case study of Xiaolangdi reservoir in the Yellow River. China Ecol Eng 96:34–44. https://doi.org/10.1016/j.ecoleng.2015.12.037

Lu S, Shang Y, Li W, Peng Y, Wu X (2018) Economic benefit analysis of joint operation of cascaded reservoirs. J Clean Prod 179:731–737. https://doi.org/10.1016/j.jclepro.2017.08.140

Lu X, Wang X, Ban X, Singh VP (2022) Considering ecological flow in multi-objective operation of cascade reservoir systems under climate variability with different hydrological periods. J Environ Manag 309:114690. https://doi.org/10.1016/j.jenvman.2022.114690

Odum HT (1996) Environment accounting: emergy and environment decision making. John Wiley, New York

Omer A, Elagib NA, Zhuguo M, Saleem F, Mohammed A (2020) Water scarcity in the Yellow River Basin under future climate change and human activities. Sci Total Environ 749:141446. https://doi.org/10.1016/j.scitotenv.2020.141446

Pulselli FM, Patrizi N, Focardi S (2011) Calculation of the unit emergy value of water in an Italian watershed. Ecol Model 222:2929–2938. https://doi.org/10.1016/j.ecolmodel.2011.04.021

Shen J, Cheng C, Zhang X, Zhou B (2018a) Coordinated operations of multiple-reservoir cascaded hydropower plants with cooperation benefit allocation. Energy 153:509–518. https://doi.org/10.1016/j.energy.2018.04.056

Shen Z, Liu P, Ming B, Feng M, Zhang X, Li H, Xie A (2018b) Deriving optimal operating rules of a multi-reservoir system considering incremental multi-agent benefit allocation. Water Resour Manag 32:3629–3645. https://doi.org/10.1007/s11269-018-2010-9

Wang S, Fu B, Piao S, Lü Y, Ciais P, Feng X, Wang Y (2016) Reduced sediment transport in the Yellow River due to anthropogenic changes. Nat Geosci 9:38–41. https://doi.org/10.1038/ngeo2602

Wang L, Li Y, Wang Y, Guo J, Xia Q, Tu Y, Nie P (2021) Compensation benefits allocation and stability evaluation of cascade hydropower stations based on variation coefficient-shapley value method. J Hydrol 599:126277. https://doi.org/10.1016/j.jhydrol.2021.126277

Wu Z, Di D, Wang H, Wu M, He C (2019) Analysis and emergy assessment of the eco-environmental benefits of rivers. Ecol Indic 106:105472. https://doi.org/10.1016/j.ecolind.2019.105472

Xiang X, Svensson J, Jia S (2017) Will the energy industry drain the water used for agricultural irrigation in the Yellow River basin? Int J Water Resour Dev 33:69–80. https://doi.org/10.1080/07900627.2016.1159543

Xu Y, Wang C (2020) Ecological protection and high-quality development in the Yellow River Basin: framework, path, and countermeasure. Bull Chin Acad Sci Chin Version 35(7):875–883

Xu B, Ma Y, Zhong P, Yu Z, Zhang J, Zhu F (2018) Bargaining model of synergistic revenue allocation for the joint operations of a multi-stakeholder cascade reservoir system. Water Resour Manag 32:4625–4642. https://doi.org/10.1007/s11269-018-2075-5

Xu Y, Zhu X, Wen X, Herrera-Viedma E (2021) Fuzzy best-worst method and its application in initial water rights allocation. Appl Soft Comput 101:107007. https://doi.org/10.1016/j.asoc.2020.107007

Zhang F, Jin G, Liu G (2021) Evaluation of virtual water trade in the Yellow River Delta. China Sci Total Environ 784:147285. https://doi.org/10.1016/j.scitotenv.2021.147285

Zhang J, Shang Y, Liu J, Lu J, Wei S, Wan Z, Luo Q, Chen C, Tong L, Wang Q, Fu J (2021) Optimisation of reservoir operation mode to improve sediment transport capacity of silt-laden rivers. J Hydrol 594:125951. https://doi.org/10.1016/j.jhydrol.2020.125951

Zhang Y, Yu L, Wu S, Wu X, Dai J, Xue W, Yang Q (2021) A framework for adaptive control of multi-reservoir systems under changing environment. J Clean Prod 316:128304. https://doi.org/10.1016/j.jclepro.2021.128304

Zhao L, Yuan L, Yang Y, Xue J, Wang C (2021) A cooperative governance model for SO_2 emission rights futures that accounts for GDP and pollutant removal cost. Sustain Cities Soc 66:102657. https://doi.org/10.1016/j.scs.2020.102657