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Multi-objective optimal allocation of sediment resources based on the subjective trade-off rate method

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A B S T R A C T

The rational utilization of the characteristics of sediment resources to achieve the optimal allocation of sediment resources is a key problem that must be solved urgently for ecological governance. On the basis of determining the allocation mode of sediment resources, this study established the multi-objective optimal allocation model of sediment resources, which aimed at the maximum ecological, economic, and social benefits and used the ε-constraint method and Kuhn–Tucker condition to obtain the non-inferior solution. Moreover, the optimal equilibrium solution of the model was obtained by using the subjective trade-off method from the perspective of preference. The Weishan and Bojili irrigation areas in China were then chosen as a case study to verify the feasibility and validity of the model. Results corroborate that, compared with the present situation, the proportions of sediment transport into the field in Weishan and Bojili irrigation areas are significantly increased and that the proportions of the main and branch canal sediment detention in the two irrigation areas are reduced. Compared with the results of the non-inferior solution, ecological and social benefits have been improved, and economic benefit has been decreased. The coordinated optimization of ecological, economic, and social benefits has been realized, instead of blindly pursuing economic benefit.

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1. Introduction

Rivers and lakes are important for the early utilization of water resources, while reservoirs reflect the complex needs of modern human beings. Given the natural erosion and human activities, sediment siltation problem in rivers, lakes and reservoirs has become increasingly prominent. For instance, the Yellow River is the second largest river in China. With the inharmonious relationship between water and sediment and rapid increase in the utilization of hydropower resources, significant changes have taken place in the spatial distribution of sediments in the Yellow River in different periods, resulting in serious sediment disasters and ecological deterioration problems (Hu et al., 2010a). Sediment disasters have seriously affected the production and life of people, as well as the functions of rivers, lakes, and reservoirs (Rashid et al., 2015). Through turning disaster into wealth, making full use of the resource characteristics of sediments has become a potential way to solve the above problems. Disasters caused by sediments have been known. However, the resource characteristics of sediments have been accepted by the public only in recent years. Along the Yellow River, sediment resources are used for flood control and dike reinforcement, soil improvement of waterlogged saline–alkali land, building materials, and other approaches, which provide significant ecological, economic, and social benefits (Chen et al., 2017). The main sediment treatment is centralized desilting through the desilting basin for a considerable time. However, with the long-term utilization, dredging sediment accumulates on both sides of desilting basin and channels. This buildup reduces the capacity of water and sediment transport in channels, increases the burden of drainage channels and dredging cost, and causes the desertification of land. The fundamental cause for these problems is the failure to optimize the allocation of sediment resources. Hu et al. (2010a) put forward the relevant definition of sediment resource allocation: based on related rules and criteria, through some measures and approaches or modes, the available sediment

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resources should be allocated rationally in different areas or allocation units in the basin. Therefore, identifying suitable resource allocation approaches for different characteristics of sediments to maximize the benefits or minimize disaster loss and realizing the optimal allocation of sediment resources are urgent problems for sediment managers.

The rational allocation of sediment resources focuses on allocation result and effect evaluation. It reflects relatively fair and satisfactory allocation schemes, which can solve a series of complex relationships including the coordination of upper, lower reaches and different benefits. Generally speaking, the result of rational allocation is not necessarily the best for a certain allocation unit, but the overall benefit is the best for the entire sediment resource allocation system. The optimal allocation of sediment resources focuses on the allocation process and technical method, which is the means to determine rational allocation schemes. The general optimization problem is described and realized mathematically. With the improvement of the optimization method, the result of optimal allocation will gradually "approach" the requirement of rational allocation.

The optimal allocation of sediment resources is different from the traditional allocation method that only focuses on short-term resource optimization and efficiency improvement. It pays attention to the resilience of the ecosystem or social system and the capacity for long-term development. By establishing a multi-objective optimal allocation model, the optimal allocation scheme with rational modes and amount for sediment resources with different types is put forward to balance the conflicting relationship of ecological, economic, and social benefits.

The problem of sediment in China is prominent, and the theory of sediment resource utilization and its allocation is a new concept that has emerged. Previously, experts and scholars have studied the optimal problems of sediment resources. Hu et al. (2010a,c), (2010b) carried on systematic research on the optimal allocation problem of sediment resources, put forward the overall framework, theory and scheme of sediment resource allocation, and adopted the analytic hierarchy process to construct the model. It has laid the foundation for allocation of sediment resources. Star et al. (2017) allocated the investments of sediment management in river basin and presented an alternative approach to effective prioritization of sediment reductions considering the influence of siltation on ecology. Underwood et al. (2015) provided a basic framework for systematic and cost-effective sediment resource management, including operational integrated sediment production, detectable and adjustable management, and regional sediment supply and allocation plans. Research on the optimization of sediment resources focuses on the construction of an optimal allocation model by the analytical hierarchy process (AHP) (Hu et al., 2010a; Chen et al., 2017; Zhao and Hu, 2012); allocation techniques and evaluation (Lu et al., 2012); joint regulation of water and sediment (Yang et al., 2017; Kong et al., 2015; Miao et al., 2016; Rashid et al., 2015; Hajiabadi and Zarghami, 2014); benefit analysis of soil and water conservation (Adeogun et al., 2018; Mtibaa et al., 2018); effective analysis of sediment siltation (Hou and Wang, 2017; Smetanová et al., 2017); sediment dredging and management (Zheng et al., 2019); analysis of organic content in sediment; and approaches to sediment utilization (Mymrin et al., 2016; Benzerzour et al., 2017; Cappuyns et al., 2015; Mattei et al., 2017; Wang et al., 2018). However, studies on the optimal allocation of sediment resources are limited. The related models are also based on AHP to construct a general objective function by expanding the objective architecture, solved by the simplex method. The results are evaluated by the AHP or fuzzy comprehensive evaluation method, which cannot satisfy the complex relationship between sediment and water resource system. Moreover, research on ecological, economic, and social levels is few. Hou and Wang (2017) calculated the comprehensive benefits of sediment utilization in the Xixiayuan reservoir of the Yellow River with a volume of 2000 m^3. With such a massive volume, directly measuring different benefits brought about by the different allocation approaches of sediment allocation is difficult.

Ecological, economic, and social benefits are the three main objectives in the optimal allocation of sediment resources, which cannot be measured in a unified unit. The key is to find a suitable solution. Many studies have been conducted on the solutions of multi-objective optimization problems, including two types: (1) solution methods of converting multiple objectives into a single objective, including ideal point method, multiplication–division method, and geometric mean method (Chen and Kuo, 2018; Ren et al., 2017) (2) and solution methods based on Pareto-optimal solutions. One solution is realized by intelligent algorithms, including Nondominated Sorting Genetic Algorithm II (NSGA-II) and Multi-objective Genetic Algorithm (MOGA) (Bai et al., 2015; Lewis and Randall, 2017; Mahmoudsoltani et al., 2018; Xiong et al., 2018; Dong et al., 2016). The other is the non-inferior solution generation technology, including weight method and constraint method (Peng et al., 2014; Stidsen et al., 2014; Jing et al., 2018; Kaddani et al., 2017). The first type of solution method depends on transforming modes from multiple objectives into a single objective, which has certain subjectivity, whereas the other is almost an optimal solution under the preference of Pareto. As many Pareto-optimal solutions and different solutions cannot be directly compared, decision makers must change their preferences to determine the best strategy. The difficulty is to establish a measurement standard to reflect the new preferences of decision makers. Therefore, identifying new preferences and determining further comparison rules to determine the optimal equilibrium solution and achieve cooperative optimization among the objectives are crucial to the multi-objective optimal allocation model of sediment resources.

In sum, the key to sediment treatment and utilization is to establish the optimal allocation mode and allocation model of sediment resources. In view of the existing problems, we aim to study the construction and solution method of the optimal allocation model. In comparison with the existing research, there are three contributions of this study. 1) A multi-objective optimal allocation model of sediment resources is constructed, and its non-inferior solutions are obtained by the ε-constraint method. 2) The optimal equilibrium solution of the developed model is determined by using the subjective trade-off rate method from the perspective of preference. 3) The proposed model is applied to two irrigation areas in China, the corresponding optimal allocation scheme of sediment resources is put forward, and the ecological, economic, and social benefits brought about by sediment resources are analyzed. The developed model and method can be used to help decision maker identify a desired plan for allocating sediment resources.

2. Model formulation

2.1. Problem description

To detail the characteristics of sediment resources, this study considers the optimal allocation problem of sediment resources from the perspective of sediment utilization rather than sediment treatment. Sediment utilization can be divided into natural utilization and artificial utilization and can be subdivided into many approaches. Natural utilization refers to sediment utilization in natural ways through the energy of the river itself, and artificial utilization refers to sediment utilization through artificial measures, restricted by the present technical level and economic conditions. In the present study, the modes of sediment allocation are artificial utilization. Sediments with different particle levels are distributed to different parts; coarse sediment is used in the sludge soil dredged area and dike construction, and fine sediment is used as building materials or transported to the field to reduce artificial soil desertification and the siltation of the drainage system (Haimann et al., 2018). The decision is described as follows. For n allocation unites, each unite has seven allocation modes and each allocation mode is constrained by certain constraint conditions. As an entire system, these allocation unites have three objectives including ecological, economic and social benefits and are centralized allocated. Sediment allocation has seven modes as follows:

(1) Allocation mode 1: desilting basin sediment detention. Sediment in the flow is guided and deposited in accordance with the wishes of people through this mode to reduce the siltation of canals and the cost of sediment treatment.
(2) Allocation mode 2: main canal sediment detention. The balance mechanism of erosion and deposition in the main canal should be realized as far as possible through this sediment regulation and control.
(3) Allocation mode 3: branch canal sediment detention. A small amount of siltation is allowed in branch and below canals. Through the multi-stage dispersion of sediments, the capacity of water and sediment transport are improved, the pressure of sediment desilting at the head of canal is reduced, and sediment allocation is optimized.
(4) Allocation mode 4: sediment transport into the field (muddy irrigation). Muddy irrigation is a method of transporting fine sediment into the field after coarse sediment is deposited in the desilting basin. The sand-bearing flow does not pass through the desilting basin, but through water conveyance canals into the field in sequence. Its remarkable feature is that the treatment and utilization of sediment can be transformed from point to surface, that is, the siltation of canals can be reduced, fine sediment with more organic content can be brought into the field, nutrient composition and fertility of the field can be improved, and the quality of crops can be improved. The range of sediment utilization has been expanded and it has remarkable ecological, economic, and social benefits.
(5) Allocation mode 5: sediment retrogradation. Sediment is discharged into the drainage channels by using abandoned irrigation water. Excessive sediment in irrigation operation should be avoided as much as possible to maintain the capacity of water storage and drainage and reduce the salinization of land.
(6) Allocation mode 6: strengthening dike by machinery siltation. Sediment is used as material for dikes. While strengthening a dike, a large amount of dredging sediment is rationally arranged, which saves the cost from other materials and has remarkable effect on ecological, economic, and social benefits.
(7) Allocation mode 7: redundant sediment. Redundant sediment siltation in the river is used for the outside river. If it is not used, it will have an ecological impact. By using it as building materials, income will be increased and ecological deterioration can be alleviated.

The comprehensive department manager of a river or lake, as the decision maker of optimal allocation of sediment resources, pursues the optimization of the three objectives. First, determining the decision variables of sediment resource allocation that affect objective benefits and constraint conditions that decision variables must meet is necessary. Thereafter, the multi-objective optimal allocation model of sediment resources is constructed, and an appropriate method is selected to find the values of decision variables satisfying constraint conditions as the optimal equilibrium solution. Lastly, the optimal allocation scheme of sediment resources with different types is put forward to realize the coordinated development of the objective benefits.

2.2. Determining objective functions

The modes of sediment allocation are taken as the decision variables of the model, which are as follows:

x_{ab}: Sediment allocation decision variable, which means that the sediment amount in allocation unit a and allocation mode b (10^4 t), $\mathbf{X} = (X_1, X_2, \cdots, X_n)$ is allocation matrix; $X_a = (x_{a1}, x_{a2}, \cdots, x_{a7})^T$ is the column vector in allocation unit a;

$N = \{1, 2, \cdots, n\}$: Allocation unit set;

n: Number of allocation units;

$a \in N$: Allocation unit, which means the administrative areas along the same river or lake;

$M = \{1, 2, \cdots, 7\}$: Allocation mode set;

$b \in M$: Allocation mode.

Table 1 shows the modes of sediment allocation and allocation units.

The objective functions are analyzed as follows.

2.2.1. Ecological benefit objective

Ecological benefit is reflected in sediment resource utilization in the river and utilization outside the river by improving water ecology of the river. A series of ecological problems will occur if sediment problems are not addressed. This study uses the indices including soil desertification, farmland occupation, biodiversity, and river health to measure ecological benefit (Xiao et al., 2017). As the data of ecological benefit indicator are difficult to collect and the AHP is a simple and effective method for the sustainable development assessment, the relationship between ecological benefit and decision variables is established by the AHP (Akhoundi and Nazif, 2018). The objective function of ecological benefits can be expressed as follows:

$$f_1(X) = \max \sum_{b=1}^{7} \delta_b x_b' \tag{1}$$

$x_b' = \sum_{a=1}^{n} x_{ab}$: Sediment amount of allocation mode b in each unit (10^4t), which makes distinguishing the influence of different allocation modes on ecological benefit easy;

δ_b: Weighting coefficient of allocation mode index.

The weighting coefficient of allocation mode index δ_b is determined by the AHP. Table 2 shows the ecological benefit hierarchy of sediment resource allocation, including objective layer A, benefit index layer B, and allocation mode layer C. The investigation and statistics result of the priority evaluation of the ecological benefit hierarchy analysis of sediment resource allocation can be taken from issuing the expert questionnaire. After determining the evaluation of allocation mode layer C on benefit index layer B and benefit index layer B on objective layer A, the weighting coefficient δ_b of allocation mode layer C to objective layer A is determined, and the objective function of ecological benefit (1) can be determined.

Here, the physical meaning of the weighting coefficient is not to reflect the proportion of sediments in various allocation modes but to reflect the contribution of various allocation modes to the

Table 1
Modes of sediment allocation and allocation units.

Allocation modes (10^4 t)	Allocation units						
	Unit 1	Unit 2	Unit 3	⋯	Unit a	⋯	Unit n
Desilting basinsediment detention	x_{11}	x_{21}	x_{31}	⋯	x_{a1}	⋯	x_{n1}
Main canal sediment detention	x_{12}	x_{22}	x_{32}		x_{a2}		x_{n2}
Branch canal sediment detention	x_{13}	x_{23}	x_{33}		x_{a3}		x_{n3}
Sediment transport into the field	x_{14}	x_{24}	x_{34}		x_{a4}		x_{n4}
Sediment retrogradation	x_{15}	x_{25}	x_{35}		x_{a5}		x_{n5}
Strengthening dike by machinery siltation	x_{16}	x_{26}	x_{36}		x_{a6}		x_{n6}
Redundant sediment	x_{17}	x_{27}	x_{37}		x_{a7}		x_{n7}

Table 2
Ecological benefit hierarchy of sediment resource allocation.

Hierarchy	Analytical structure						
Objective layer A	Ecological benefit						
Benefit index layer B	Soil desertification		Farmland occupation		Biodiversity	River health	
Allocation mode layer C	Desilting basin sediment detention	Main canal sediment detention	Branch canal sediment detention	Sediment transport into the field	Sediment retrogradation	Strengthening dike by machinery siltation	Redundant sediment
Weighting coefficient	δ_1	δ_2	δ_3	δ_4	δ_5	δ_6	δ_7

ecological benefit objective of sediment resource allocation. As the objective function is constrained by the constraint conditions, the weighting coefficient can only make a rational contribution within the range of constraint conditions.

2.2.2. Economic benefit objective

Economic benefit (10^4 Yuan) is reflected in the benefit brought by using redundant sediments to make products needed by other industries or living departments. For the convenience of analysis, this study only calculates the benefit of redundant sediment as building materials:

$$f_2(X) = \max\sum_{a=1}^{n}\left(r_{a7}x_{a7} - \sum_{b=1}^{7}c_{ab}x_{ab}\right) \tag{2}$$

r_{a7}: Unit income of sediment treatment and utilization (Yuan/t);
x_{a7}: Sediment amount in the allocation of building materials (10^4 t);
c_{ab}: Unit cost of sediment treatment and utilization (Yuan/t).

2.2.3. Social benefit objective

Social benefit is reflected in the improvement of water quality which can enable flood control and mitigate disasters. The value of flood disaster reduction is used to represent social benefit, which is measured by the market value method (Huang et al., 2016). The value of social benefit E_w can be expressed as follows:

$$E_w = \sum_{a=1}^{n} W_a \cdot p_w \tag{3}$$

W_a: Increased available water through sediment treatment and utilization in unit a (m^3);
p_w: Water price (Yuan/m^3). Referring to the water market, the general value is 0.3 Yuan/m^3.

According to the calculated value of social benefit and the historical statistical data of sediment allocation variables, to simplify calculation, the regression model of social benefit about sediment allocation variable x_{ab} is fitted by the multivariate linear regression method. Therefore, the objective function of social benefit (10^4 Yuan) can be expressed as follows:

$$f_3(X) = \max E_w(X) = \alpha + \sum_{a=1}^{n}\beta_a\sum_{b=1}^{7}x_{ab} \tag{4}$$

$x_a = \sum_{b=1}^{7}x_{ab}$: Sediment amount allocated in unit a (10^4 t);
α,β_a: Regression coefficient.

2.3. Determining constraint conditions

Let the constraint conditions of the optimal allocation model of sediment resources be $g_{la}(X) \le 0, l = 1, 2\cdots, s, a \in N$, l is the serial number of constraints, s is the number of constraints in each allocation unite. The constraint conditions are defined as follows: each unite has seven decision variables (Table 1) and s constraints. According to the principles of the optimal allocation of sediment resources, balance mechanism of erosion and deposition, and the actual requirements of sediment allocation balance, through decomposing the relationships between each constraints and decision variables, we can determine the constraint relationships that general model needs to satisfy (Zhou and Wang, 2010; Chen et al., 2017).

(A) The constraint of desilting capacity $g_{1a}(X) \le 0$: the role of desilting basin is to regulate sediment peaks and the content of coarse particles, to intercept harmful coarse sediment, and to create conditions for the remote transportation of fine sediment. The appropriate allocation amount of desilting basin sediment detention x_{a1} can reduce the siltation of the lower canals; hence, the range of decision variable x_{a1} is defined.

(B) The constraint of main canal sediment detention capacity $g_{2a}(X)\leq 0$: the main effect is to achieve the balance of erosion and deposition in the main canal as far as possible through the appropriate allocation amount of main canal sediment detention x_{a2} and to improve the capacity of water and sediment transport; hence, the range of decision variable x_{a2} is defined.
(C) The constraint of branch canal sediment detention capacity $g_{3a}(X)\leq 0$: maintaining the balance of erosion and deposition from the main canal to the final canal is difficult. Therefore, a small amount of siltation in branch canals should be allowed, and the balance of erosion and deposition in the main canal should be guaranteed. On the basis of siltation over the years, the range of decision variable x_{a3} is determined.
(D) The constraint of capacity of sediment transport into the field $g_{4a}(X)\leq 0$, $g_{5a}(X)\leq 0$: the majority of fine sediment should be transported into the field as far as possible; hence, the range of decision variable x_{a4} and its relationship with $x_{a1}, x_{a2}, x_{a3}, x_{a5}, x_{a6}, x_{a7}$ are determined.
(E) The constraint of sediment and water retrogradation capacity $g_{6a}(X)\leq 0$: the main effect is to maintain the flood control and waterlogging capacity of drainage channels by strictly controlling receding water and sediment; hence, the range of decision variable x_{a5} is defined.
(F) The constraint of capacity of strengthening dike by machinery siltation $g_{7a}(X)\leq 0$: as an important measure for sediment utilization, it relies heavily on the artificial mechanical measures including dredging and extracting hyper-concentrated flow to the dike to strengthen it. This constraint is restricted by the economic input; hence, the range of decision variable x_{a6} is determined.
(G) The constraint of capacity of redundant sediment utilization $g_{8a}(X)\leq 0$: as the process of building materials by using redundant sediment in river is restricted by the existing technical level and economic input, making full use of sediment to produce more building materials is impossible. Counting the annual processing and utilization capacity of redundant sediment for building materials and the range of decision variable x_{a7} is determined.
(H) The constraint of total sediment amount $g_{9a}(X)\leq 0$: the optimal allocation of sediment resources is carried out under the condition of a certain amount of sediment. According to the sediment budget, the total sediment amount is equal to the sum of sediment amount of the allocation modes in each allocation unit; hence, the range of decision variable x_a is determined.

Furthermore, $g_{la}(X)\leq 0$ are the general forms of the constraint conditions. For the problem in this study, they can be expressed in the following specific forms: $\underline{B}_{la}\leq\sum_{b=1}^{7}A_{lab}x_{ab}\leq\overline{B}_{la}$, x_{a1} is sediment coefficient, $\underline{B}_{la}$ and $\overline{B}_{la}$ are the minimum and maximum sediment resource constraints in each allocation unite. Specially, $g_{1a}(X)\leq 0$ consist of $x_{a1}\leq\overline{B}_{1a}$ and $-x_{a1}\leq-\underline{B}_{1a}$, which can be expressed as $\underline{B}_{1a}\leq x_{a1}\leq\overline{B}_{1a}$. $g_{2a}(X)\leq 0$ and $g_{3a}(X)\leq 0$ are represented in the same way;

$g_{4a}(X)\leq 0$ are expressed as $\sum_{b=1}^{7}A_{4ab}x_{ab}\leq\overline{B}_{4a}$;

$g_{5a}(X)\leq 0$, $g_{6a}(X)\leq 0$, $g_{7a}(X)\leq 0$ and $g_{8a}(X)\leq 0$ can be expressed as $\underline{B}_{5a}\leq x_{a4}\leq\overline{B}_{5a}$, $\underline{B}_{6a}\leq x_{a5}\leq\overline{B}_{6a}$, $\underline{B}_{7a}\leq x_{a6}\leq\overline{B}_{7a}$ and $\underline{B}_{8a}\leq x_{a7}\leq\overline{B}_{8a}$, respectively.

$g_{9a}(X)\leq 0$ are expressed as $\sum_{b=1}^{7}x_{ab}\leq\overline{B}_{9a}$.

The values of the parameters in each constraint are calculated in the empirical analysis.

3. Solution process

3.1. Pareto-optimal solutions of multi-objective optimization

According to the above analysis, the multi-objective optimal allocation model of sediment resources for comprehensive department manager can be expressed as follows:

$$\max_{X\in\Omega} f(X)=\{f_1(X),f_2(X),f_3(X)\} \tag{5}$$

$\Omega=\{X|g_{la}(X)\leq 0, x_{ab}\geq 0, l=1,2,\cdots,s, a=1,2,\cdots n, b=1,2,\cdots,7\}$ is the decision space for the optimal allocation model of sediment resources, which reflects the preference of comprehensive department manager. For convenience, the maximization problem is transformed into the minimization problem, and $f_1(X), f_2(X), f_3(X)$ are determined by formulas (1), (2), and (4), respectively.

Pareto-optimal solutions (or non-inferior solutions) of the model (5) are under a special preference Ω_p. Moreover, none of these solutions can make any of the objectives better under the condition that the other objectives are invariant. That is to say, the objective vectors corresponding to different solutions cannot be compared further as the alternatives in the Pareto-optimal solutions set cannot be ranked, which reflect the decision maker's behavior preference with no difference in a wide range of choices (Tamilselvi et al., 2018).

Decision maker can give a new preference to reduce the original Pareto-optimal solutions set. Haimes and Hall (1974) put forward the surrogate worth trade-off method. This method requires the decision maker to rank satisfaction or dissatisfaction. Consequently, elaborating the degree of preference or the rank in practice is difficult for decision maker; the non-inferior solutions should only be generated by the ε-constraint method (Hall and Haimes, 1976; Singh et al., 2017).

In the present study, the subjective trade-off rate method is used to solve the model, and another form of preference is given from the trade-off rate (Wang et al., 1996). In the past, few achievements in the application of the subjective trade-off rate method have emerged. The subjective trade-off rate method, through dialogue between the decision maker and the analyzer or mathematical model, connects the decision maker's preference with the non-inferior solutions, and forms the new preference in the objective function space and then transits to the decision space. This method creates convenience for the decision maker to arbitrarily give the trade-off rate between any two objectives, and the non-inferior solutions are not restricted by the ε-constraint problem. Therefore, this method can effectively determine the optimal equilibrium solution in the optimal allocation process of sediment resources, which provides a new idea for solving multi-objective optimization problems.

3.2. Solution of multi-objective optimal allocation model based on the subjective trade-off rate method

At a certain objective level (corresponding to a Pareto-optimal solution), on the basis of the subjective trade-off rate method, the steps for solving the model (5) are summarized as follows (Wang et al., 1996):

Step 1 Finding non-inferior solution X^0 of the model (5), which is transformed into the minimization problem of the multi-objective optimal allocation of sediment resources $\Omega_p - \min_{X\in\Omega} f(X)$ and setting $y^0=f(X^0)$, $y^0\in Y$. $Y=f(X)$ is the objective space. The process is as follows:

Selecting the ecological benefit of the model (5) as the basic objective function; the other two objectives are replaced into corresponding ε-constraint:

$$\min_{X\in\Omega} -f_1(X)$$

Subject to:

$$\begin{cases} g_{la}(X) \le 0, l = 1, 2, \cdots, s \\ f_2(X) \ge \varepsilon_2^0 \\ f_3(X) \ge \varepsilon_3^0 \end{cases} \tag{6}$$

ε_2^0: Minimum tolerable level of objective$f_2(X)$;
ε_3^0: Minimum tolerable level of objective$f_3(X)$.

Constructing the Lagrange function of the model (6):

$$L(X) = -f_1(X) + \sum_{a=1}^{n}\sum_{l=1}^{s}\mu_{la}g_{la}(X) - \lambda_2\left[f_2(X) - \varepsilon_2^0\right] - \lambda_3\left[f_3(X) - \varepsilon_3^0\right] - \mu_{ab}x_{ab} \tag{7}$$

μ_{la},λ_2,λ_3,μ_{ab}: The generalized Lagrange multiplier.

Let X^* be the minimum point of the model (6), according to the Kuhn-Tucker condition:

$$\begin{cases} \nabla f_1(X^*) - \sum_{a=1}^{n}\sum_{l=1}^{s}\mu_{la}\nabla g_{la}(X^*) + \lambda_2\nabla f_2(X^*) + \lambda_3\nabla f_3(X^*) + \mu_{ab}x_{ab} = 0 \\ \mu_{la}g_{la}(X^*) = 0, l = 1, 2, \cdots, s \\ \lambda_2\left[f_2(X^*) - \varepsilon_2^0\right] = 0 \\ \lambda_3\left[f_3(X^*) - \varepsilon_3^0\right] = 0 \\ \mu_{ab}x_{ab}^* = 0 \\ \mu_{la}, \lambda_2, \lambda_3, \mu_{ab} \ge 0 \end{cases} \tag{8}$$

Solving Eq. (8) and selecting a solutionX^0 as the non-inferior solution of the model (5).

Step 2 Asking the decision maker to make his/her subjective trade-off rate λ_{ij}^0 between objective i and objective j at the levely^0.

If one unit will be increased in the objective j, then how many units, the decision maker thinks it is worth, will be reduced in the objective i. For the minimum problems, believing that the decision maker will think that the more the objective is reduced, the better has a reason. However, when objective i is reduced too little, the decision maker could not accept. The minimum trade-off rate that the decision maker can accept is called the subjective trade-off rate, expressed asλ_{ij}^0:

$$\lambda_{ij}^0 = \min\left\{\lambda > 0 \left| \begin{array}{c} If\ -y_i^0 + y_i^1 \ge \lambda\left(-y_j^1 + y_j^0\right), -y_k^1 \le -y_k^0, \\ k\in\{\overline{1,m}\}\backslash\{i,j\}, y^1 \ne y^0, \\ \text{Sediment resource allocation decision maker thinks} \\ y^1 \text{ is better than } y^0 \end{array}\right.\right\} \tag{9}$$

m: The number of objectives in model (5). Therefore, taking $m = 3$; $i, j = 1,2,3$.

In the practical application, the following consistency conditions should be satisfied: (1)$\lambda_{ij}^0 > 0$, for any $i,j\in\{\overline{1,m}\}$; (2)$\lambda_{ij}^0 = \lambda_{ik}^0\lambda_{kj}^0$, for any$i,j,k\in\{\overline{1,m}\}$.

Step 3 Constructing the parameter linear programming of sediment resource allocation:

$$P_i^0(\varepsilon_j) : \begin{cases} v_i(\varepsilon_j) = \min_{X\in\Omega_i(\varepsilon_j)} -f_i(X) \\ \Omega_i(\varepsilon_j) = \left\{X\in\Omega \middle| -f_j(X) \le -y_j^0 + \varepsilon_j, -f_k(X) \le -y_k^0, k\in\{\overline{1,m}\}\backslash\{i,j\}\right\} \end{cases} \tag{10}$$

Solving it and obtaining the objective trade-off rate $\overline{\lambda}_{ij}^0$. $\overline{\lambda}_{ij}^0$ is expressed as follows:

$$\overline{\lambda}_{ij}^0 = -\frac{dv_i(\varepsilon_j)}{d(\varepsilon_j)}|\varepsilon_j = 0 \tag{11}$$

According to formulas (1), (2), and (4), $v_i(\varepsilon_j)$ is a convex function; ε_j is the parameter variable.

Step 4 Comparing λ_{ij}^0 and $\overline{\lambda}_{ij}^0$ and judging the effectiveness of the subjective trade-off rate.

(1) If $\lambda_{ij}^0 > \overline{\lambda}_{ij}^0$, then there are no improved Pareto-optimal solutions thany^0 under the subjective trade-off rate for the problem $\Omega_p - \min_{X\in\Omega} f(X)$; (2) If $\lambda_{ij}^0 = \overline{\lambda}_{ij}^0$, then no answer; (3) If $\lambda_{ij}^0 < \overline{\lambda}_{ij}^0$, then turn to step 5.

Step 5 Choosing $\overline{\varepsilon_j} > 0$, so that when $0 < \varepsilon_j < \overline{\varepsilon_j}$, there is

$$v_i(\varepsilon_j) - v_i(0) < -\lambda_{ij}^0\varepsilon_j \tag{12}$$

Step 6 Solving the parameter linear programming $P_i^0(\varepsilon_j)(0 < \varepsilon_j < \overline{\varepsilon_j})$, and let the solution be $\overline{X}$.

Step 7 Testing whether $\overline{X}$ is the non-inferior solution of the problem $\Omega_p - \min_{X\in\Omega} f(X)$:

(1) If “No,” then return to step 6;

(2) If "Yes," then $\overline{X}$ is the optimal solution of the problem. If the decision maker accept $\overline{X}$ as the final decision, then the result does not need to be improved and the process is completed, or turn to step 8.

Step 8 Set $X^0 = \overline{X}$, and return to step 1.

The solution process of the model (5) based on the subjective trade-off rate method is shown in Fig. 1.

4. Case study

The Weishan irrigation area (36°07′-37°02′N, 115°28′-116°27′E) was selected as unit 1. As the largest irrigation area in the lower Yellow River, Weishan irrigation area is located at Liaocheng City in the western part of Shandong Province, China. It undertakes the water supply task for agricultural irrigation with 36×10^4 ha, industrial and urban construction of Liaocheng City, and inter-basin water transfer task. The Bojili irrigation area (36°55′–38°10′N, 118°07′–119°10′E) was selected as Unit 2. As one of the largest irrigation areas in Shandong Province, Bojili irrigation area is located on the left bank of the lower Yellow River and the westernmost part of Binzhou City, Shandong Province, China (Fig. 2). It undertakes the agricultural production and water supply tasks for 1.2 million people in urban and rural areas of Binzhou City. The two irrigation areas have played a great role in local development, but they both have very prominent problems of sediment siltation, which have been paid great attention at the national level. This also added to our interests to choose them as our case study area since the conditions of water and sediment are similar.

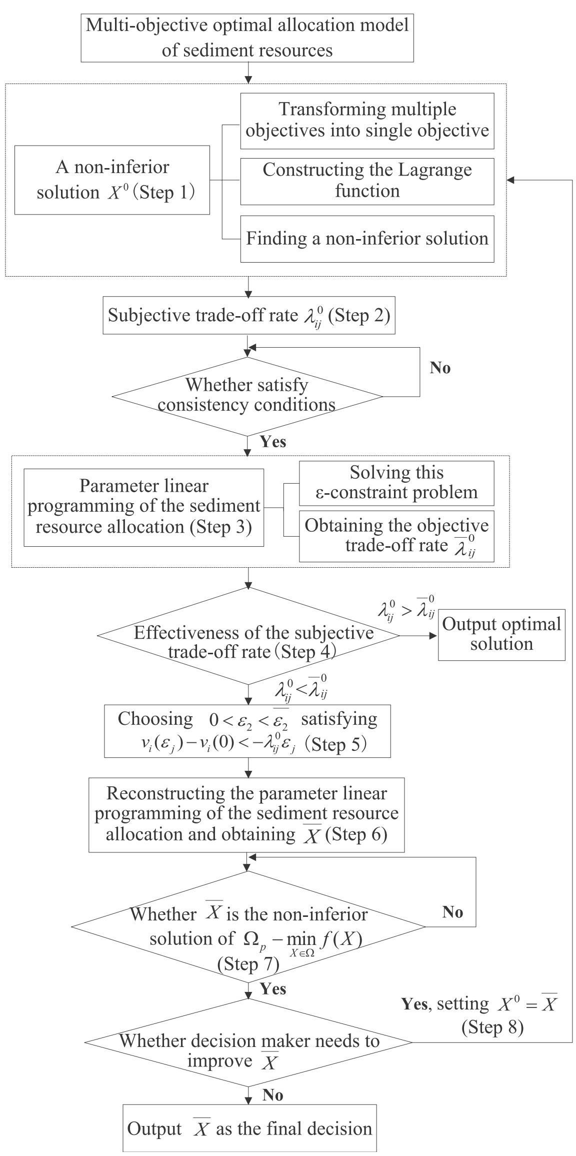

Fig. 1. The flowchart of the solution process based on the subjective trade-off rate method.

The objective functions and constraint conditions are constructed according to sediment siltation and distribution data collected from the research unites in the past years, the statistical yearbook of the research units and the China Statistical Yearbook, the government portal, the potential and capacity of sediment allocation, and economic input analysis. The main results are as follows:

(1) Objective functions

According to the result of expert investigation, the fitting result of the model and historical statistics (Jiang and Cao, 2012), the objective functions are determined as follows:

$$f_1(X) = 0.0745x_1' + 0.1023x_2' + 0.1232x_3' + 0.3041x_4' + 0.0723x_5' + 0.2557x_6' + 0.0681x_7' \tag{13}$$

$$f_2(X) = 50x_7' - 1.698x_1' - 1.23x_2' - 0.755x_3' - 0.8x_4' - 4x_5' - 15x_6' \tag{14}$$

$$f_3(X) = 31038.54 + 2.54x_1 + 30.38x_2 \tag{15}$$

$x_b' = x_{1b} + x_{2b}$: Sediment amount of the allocation mode b in the two units (10^4 t);
$x_1 = \sum_{b=1}^{7} x_{1b}$: Sediment amount allocated in unite 1 (10^4 t);
$x_2 = \sum_{b=1}^{7} x_{2b}$: Sediment amount allocated in unite 2 (10^4 t).

The details of the calculation process of parameters are provided in the Supporting Information.

(2) Constraint conditions

Combined with Section 2.3 and the actual situation, constraint conditions are analyzed as follows.

(A) Constraint of desilting capacity

Coarse sediment larger than the critical particle size must be disposed of by the desilting basin. The critical particle size in irrigation areas of Shandong Province is determined to be 0.037 mm, the proportion of coarse sediment larger than the critical particle in Shandong Province is calculated to be 30.6%–42.2% (Zhou and Wang, 2010), and the appropriate desilting proportion of the desilting basin should be within that range. The maximum value of sediment diversion capacity in the Weishan irrigation area and the Bojili irrigation area is 3178×10^4t and 1099×10^4t, respectively; hence, the corresponding constraints $g_{1a}(X) \le 0$ are as follows:

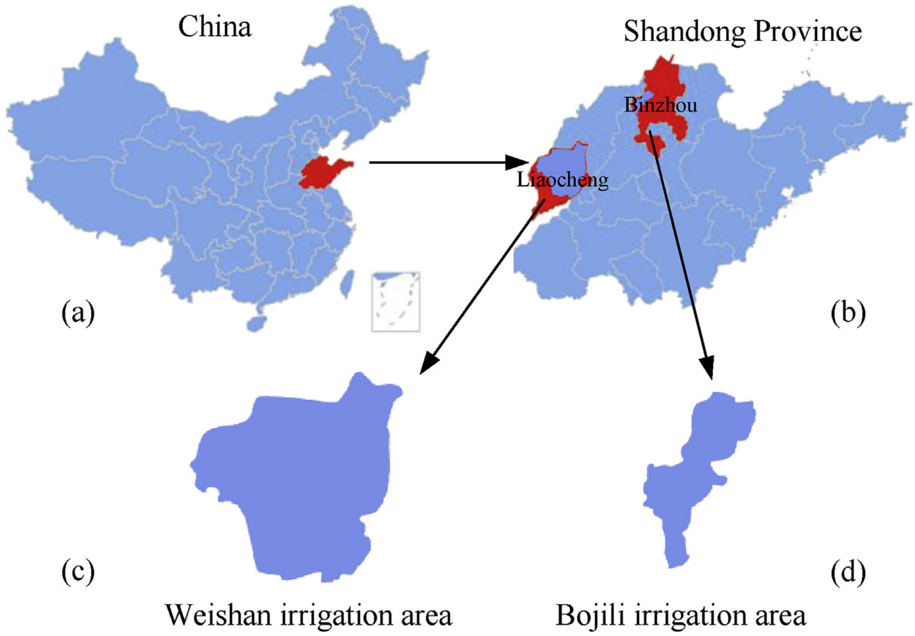

Fig. 2. Study area (a) the location of Shandong Province in China, (b) the location of Liaocheng City and Binzhou City, (c) Weishan irrigation area, (d) Bojili irrigation area.

$$972 \le x_{11} \le 1341$$

$$336 \le x_{21} \le 463 \quad (16)$$

(B) Constraint of main canal sediment detention capacity

According to the historic summary, by building a desilting strip canal at the head of the canals to deal with harmful coarse sediment and improving the capacity of sediment transportation in canals by taking engineering measures (e.g., reforming the section shape of the main canal and lining the canal) and non-engineering measures (e.g., water and sediment regulation and water saving), the balance of erosion and deposition in the main canal can be basically realized; hence, let $\underline{B}_{2a} = \overline{B}_{2a} = 0$. The corresponding constraints $g_{2a}(X) \le 0$ should be expressed as follows:

$$x_{12} = 0, x_{22} = 0 \quad (17)$$

(C) Constraint of branch canal sediment detention capacity

According to the needs of maintaining the balance of erosion and deposition from main canal to final canal, having high engineering support standards and management techniques is necessary, but they are difficult to achieve at present and for a long time to come. The siltation data of the irrigation areas classify the allowable proportion of the sediment detention in branch canals in the Weishan irrigation area and the Bojili irrigation area as 5.67%–44% and 20%–25%, respectively (Zhou and Wang, 2010). The corresponding constraints $g_{3a}(X) \le 0$ are as follows:

$$180 \le x_{13} \le 1398$$

$$219 \le x_{23} \le 274 \quad (18)$$

(D) Constraint of capacity of sediment transport into the field

More sediment should be transported into the field through rational allocation. The amount of sediment in branch canals and below should be more than that in the desilting basin, the main canal and that which retreated into the drainage channels. The dispersion coefficient is required to be not less than 1, and the meaning of the dispersion coefficient can be found in the research of Wang et al. (2010). The corresponding constraints $g_{4a}(X) \le 0$ should be as follows:

$$\frac{x_{13} + x_{14} + x_{16} + x_{17}}{x_{11} + x_{12} + x_{15}} \ge 1, \frac{x_{23} + x_{24} + x_{26} + x_{27}}{x_{21} + x_{22} + x_{25}} \ge 1 \quad (19)$$

Settling the desilting basin between sediment transportation canals and the main canal in the upper reaches, the desilting basin and sediment transportation canals are concentrated to intercept coarse sediment, and the remaining 40% fine sediment is silted in the main canal and the field. The best way to accommodate this part of the sediment is transportation into the field. The corresponding constraints $g_{5a}(X) \le 0$ are as follows:

$$317 \le x_{14} \le 1271$$

$$110 \le x_{24} \le 440 \quad (20)$$

(E) Constraint of sediment and water retrogradation capacity

The statistics of the average minimum and maximum sediment content in the lower reaches of the Yellow River and the regulations categorize the allowable proportions of the sediment retrogradation in Weishan irrigation area and Bojili irrigation area as 1.87%–4.51% and 1%–3.77%, respectively (Zhou and Wang, 2010). The corresponding constraints $g_{6a}(X) \le 0$ are as follows:

$$59 \le x_{15} \le 143$$

$$11 \le x_{25} \le 41 \tag{21}$$

(F) Constraint of capacity of strengthening dike by machinery siltation

The capacity of strengthening dike by machinery siltation is bound by the existing level of economic input. Given that the two units adopted the method of dredging instead of sinking to clear sediment in the desilting basin, machinery siltation method for sediment utilization has not been used in the two unites. The sediment utilization capacity of this mode is determined to 0; hence, let $\underline{B}_{7a} = \overline{B}_{7a} = 0$. The corresponding constraints $g_{7a}(X) \le 0$ should be expressed as follows

$$x_{16} = 0, x_{26} = 0 \tag{22}$$

(G) Constraint of capacity of redundant sediment utilization

Brick factories are built near the canals and the desilting basin, and the redundant sediment of $200 \times 10^4\,\mathrm{m}^3$ and $4 \times 10^4\,\mathrm{m}^3$, respectively, could be used in Weishan irrigation area and Bojili irrigation area. Therefore, the capacity of building materials processing and utilization are about 260×10^4t in Weishan irrigation area and 5×10^4t in Bojili irrigation area (the density of sediment is calculated as 1.3 t/m^3). The corresponding constraints $g_{8a}(X) \le 0$ are as follows:

$$0 \le x_{17} \le 260, 0 \le x_{27} \le 5 \tag{23}$$

(H) Constraint of total sediment amount

By counting the amount of sediment diversion in different historical stages, the capacity of sediment diversion in Weishan irrigation area and Bojili irrigation area are less than 3178×10^4t and 1099×10^4t respectively. The corresponding constraints $g_{9a}(X) \le 0$ are as follows:

$$\sum_{b=1}^{7} x_{1b} \le 3178, \sum_{b=1}^{7} x_{2b} \le 1099 \tag{24}$$

In sum, the multi-objective optimal allocation model of sediment resources is expressed as follows:

$$\min_{X \in \Omega} -f(X) = \{-f_1(X), -f_2(X), -f_3(X)\}$$

Subject to:

$$\begin{cases} 972 \le x_{11} \le 1341 \\ 336 \le x_{21} \le 463 \\ x_{12} = 0, x_{22} = 0 \\ 180 \le x_{13} \le 1398 \\ 219 \le x_{23} \le 274 \\ \dfrac{x_{13}+x_{14}+x_{16}+x_{17}}{x_{11}+x_{12}+x_{15}} \ge 1, \dfrac{x_{23}+x_{24}+x_{26}+x_{27}}{x_{21}+x_{22}+x_{25}} \ge 1 \\ 317 \le x_{14} \le 1271 \\ 110 \le x_{24} \le 440 \\ 59 \le x_{15} \le 143 \\ 11 \le x_{25} \le 41 \\ x_{16} = 0, x_{26} = 0 \\ 0 \le x_{17} \le 260, 0 \le x_{27} \le 5 \\ \sum_{b=1}^{7} x_{1b} \le 3178, \sum_{b=1}^{7} x_{2b} \le 1099 \end{cases} \tag{25}$$

For the expression of$f_1(X)f_2(X)f_3(X)$, see Eqs. (13–15).

5. Result analysis and discussion

5.1. Analysis of the model solution

The model (25) is solved based on Section 3.2.

(1) According to the Kuhn-Tucker condition of the model (25) or Eq. (8), a non-inferior solution $X^0 = (X_1^0, X_2^0)$ is selected, of which the specific values are as follows:

$$X_1^0 = \left(x_{11}^0, x_{12}^0, x_{13}^0, x_{14}^0, x_{15}^0, x_{16}^0, x_{17}^0\right) = (972, 0, 609, 422, 59, 0, 260)^T$$

$$X_2^0 = \left(x_{21}^0, x_{22}^0, x_{23}^0, x_{24}^0, x_{25}^0, x_{26}^0, x_{27}^0\right) = (336, 0, 219, 127, 11, 0, 5)^T$$

Then we get $f_1(X^0) = 390$,$f_2(X^0) = 9690$ and $f_3(X^0) = 58200$. The details of the calculation process of the non-inferior solution are provided in the Supporting Information.

(2) The optimal allocation of sediment resources is to maximize economic benefit and to pay more attention to the coordinated development of ecological and social benefits. Under the preference for sustainable utilization of water and sediment resources, decision maker is willing to sacrifice economic benefit in exchange for greater improvement in ecological and social benefits. According to Eq. (9) and the consistency conditions, the subjective trade-off rate of the first objective to the second objective under the objective level $y^0 = f(X^0)$ is $\lambda_{12}^0 = 0.1984$.
(3) The objective trade-off rate is obtained by Eqs. (10) and (11): $\overline{\lambda}_{12}^0 = 0.3801$.
(4) As $\lambda_{12}^0 < \overline{\lambda}_{12}^0$, the subjective trade-off rate is effective. Thereafter, turn to step 5.
(5) According to the actual needs and situation of the irrigation areas, choosing $\varepsilon_2 = 1576.472$. Then $v_1(\varepsilon_2) = -748$, $v_1(0) = -f_1(X^0) = -390$.

(6) Solving the parameter linear programming of sediment resources allocation $P_1^0(\varepsilon_2)(0<\varepsilon_2<\overline{\varepsilon_2})$, and the optimal solution is as follows:

$$\overline{X}=(\overline{x}_{11},\overline{x}_{12},\overline{x}_{13},\overline{x}_{14},\overline{x}_{15},\overline{x}_{16},\overline{x}_{17},\overline{x}_{21},\overline{x}_{22},\overline{x}_{23},\overline{x}_{24},\overline{x}_{25},\overline{x}_{26},\overline{x}_{27})$$

$$=(972,0,531,1271,143,0,260,337,0,274,440,414,0,5)$$

(7) Through testing, $\overline{X}$ is the non-inferior solution of the model (25), so$\overline{X}$ is the optimal solution of the model (25) under the given subjective trade-off rate λ_{12}^0 at the objective level y^0. Improving the result is unnecessary. Therefore, the optimal equilibrium solution of the model (25) is $X^*=\overline{X}, f_1(X^*)=748$, $f_2(X^*)=8319$ and $f_3(X^*)=72495$. Ecological, economic, and social benefits are, respectively, 748, 8319×10^4 Yuan, and $72{,}495\times10^4$ Yuan. The amount of desilting basin sediment detention, main canal sediment detention, branch canal sediment detention, sediment transport into the field, sediment retrogradation, strengthening dike by machinery siltation, and redundant sediment are, respectively, 972×10^4 t, 0×10^4 t, 531×10^4 t, 1271×10^4 t, 143×10^4 t, 0×10^4 t, 260×10^4 t in the Weishan irrigation area and 337×10^4 t, 0×10^4 t, 274×10^4 t, 440×10^4 t, 41×10^4 t, 0×10^4 t, 5×10^4 t in the Bojili irrigation area.

Fig. 3 depicts the Pareto front of the developed model (25), and the optimal equilibrium solution of subjective trade-off rate method is also given. Fig. 3 (a) presents a 3-dimensional plot with three objectives, Fig. 3 (b) presents a 2-dimensional view of social-economic, Fig. 3 (c) presents a 2-dimensional view of economic-ecological, and Fig. 3 (d) presents a 2-dimensional view of social-ecological.

Fig. 4 depicts the comparative results between optimal allocation and present situation of the Weishan and Bojili irrigation areas.

On the basis of the above analysis, Table 3 demonstrates the comparative analysis results of the subjective trade-off rate method and non-inferior solution, and the comparative results between optimal allocation and present situation.

5.2. Result comparison and optimal allocation measures

(1) According to Table 3, the ecological, economic, and social benefits obtained from the subjective trade-off rate method are 748, 8319×10^4 Yuan and $72{,}495\times10^4$ Yuan, respectively. The ecological, economic, and social benefits under the non-inferior method are 390, 9690×10^4 Yuan, $58{,}200\times10^4$ Yuan, respectively, which are shown in the last three lines of Table 3. The model of this study has obtained the intuitive optimization results of ecological, economic, and social benefits. According to Fig. 3, compared with the non-inferior solution, the decision maker pays more attention to the improvement of ecological level or ecological objective by weighing the gain and loss of the objectives, which improves ecological and social benefits. A small part of the economic benefits are lost, solving the conflict among different objectives. Coordinated development has been achieved, rather than blindly pursuing the maximization of economic benefit.

Hu et al. (2010a), Chen et al. (2017), Zhao and Hu (2012) and Zhou and Wang (2010) constructed the optimal allocation models

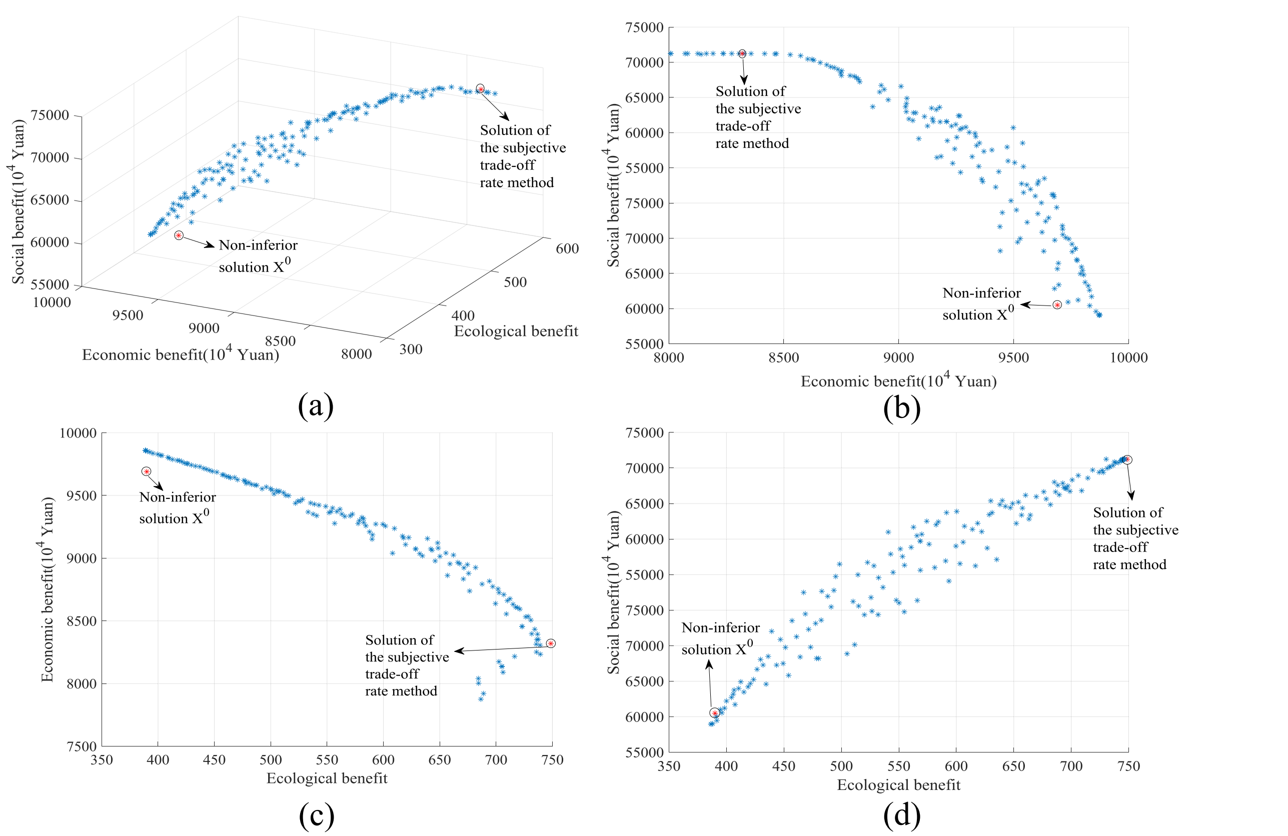

Fig. 3. Pareto front (PF) of the multi-objective optimal allocation model of sediment resources obtained by NSGA-II (a) PF with three objectives, (b) PF with social and economic, (c) PF with economic and ecological, (d) PF with social and ecological.

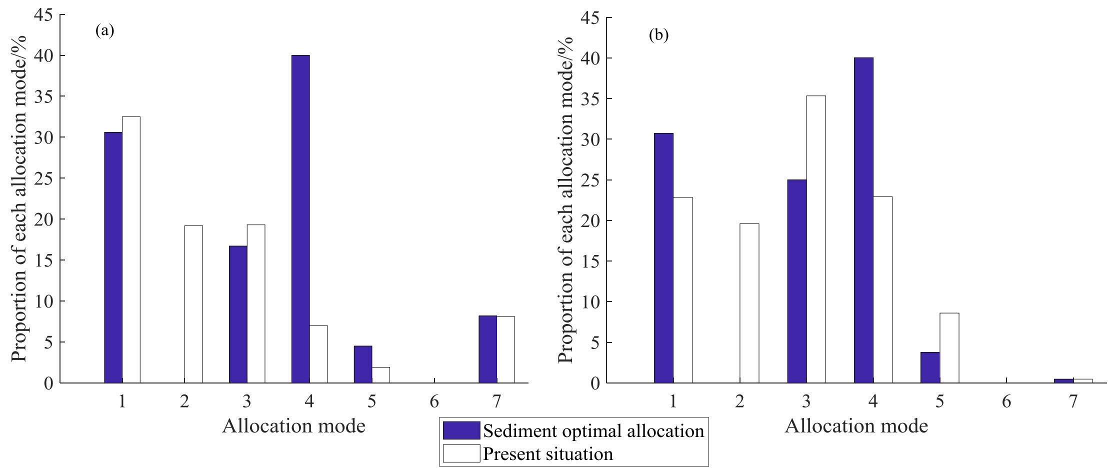

Fig. 4. Comparative results between optimal allocation and present situation (a) Weishan irrigation area, (b) Bojili irrigation area (Allocation modes 1 to 7 are, respectively, desilting basin sediment detention, main canal sediment detention, branch canal sediment detention, sediment transport into the field, sediment retrogradation, strengthening dike by machinery siltation, and redundant sediment).

Table 3
Comparative analysis results.

Item	Non-inferior solution		Subjective trade-off rate method		Allocation proportion of present situation	
	Weishan	Bojili	Weishan	Bojili	Weishan	Bojili
Desilting basin sediment detention (10^4 t)	972	336	972 (30.60%)	337 (30.72%)	32.50%	22.86%
Main canal sediment detention (10^4 t)	0	0	0 (0%)	0 (0%)	19.20%	19.60%
Branch canal sediment detention (10^4 t)	609	219	531 (16.71%)	274 (24.99%)	19.30%	35.34%
Sediment transport into the field (10^4 t)	422	127	1271 (39.99%)	440 (40.04%)	7%	22.92%
Sediment retrogradation (10^4 t)	59	11	143 (4.51%)	41 (3.76%)	1.90%	8.60%
Strengthening dyke (104 t)	0	0	0 (0%)	0 (0%)	0%	0%
Building materials (10^4 t)	260	5	260 (8.18%)	5.2 (0.47%)	8.10%	0.47%
Ecological benefit	390		748			
Economic benefit (10^4 Yuan)	9690		8319			
Social benefit (10^4 Yuan)	58,200		72,495			

Note: the proportion of the amount of each allocation mode is reported in parentheses.

of sediment resources; however, our results are different from theirs. They established a comprehensive single-objective evaluation function on technology and economy (Hu et al., 2010a; Chen et al., 2017) or on ecological, social, and economic benefits (Zhao and Hu, 2012; Zhou and Wang, 2010) by using the AHP. According to different conditions of water and sediment, different values are given to the parameters in the constraint conditions, and the allocation schemes under different values are calculated. The AHP or fuzzy evaluation method is used to evaluate the allocation schemes. Table 4 shows a detailed hierarchical analysis of their research.

They use AHP to determine β_d, and sediment amount in each allocation mode is calculated according to β_d from large to small (Hu et al., 2010a; Chen et al., 2017) or simplex method (Zhou and Wang, 2010), and the optimal allocation schemes of sediment resources are obtained when the comprehensive objective evaluation functions are the largest. The effect of sediment treatment and utilization can only be compared from the size of the comprehensive objective evaluation function; however, the conflict and contradiction among different objectives cannot be solved.

Table 4
Analytical hierarchy content for sediment resource allocation.

Item	Content
Comprehensive objective function	$F(x) = \max\sum_{d=1}^{n_1}\beta_d X_d$ $F(x)$: Comprehensive objective function; β_d: weight coefficient of allocation mode; X_d: sediment allocation mode variable; $d = 1, 2, \cdots, n_1$: allocation mode; n_1: number of allocation modes
Sub-objective	Technical, economic sub-objectives (Hu et al., 2010a; Chen et al., 2017); ecological, social and economic benefits sub-objectives (Zhao and Hu, 2012; Zhou and Wang, 2010)
Constraint condition	$\sum_{d=1}^{n_1} A_{ld}X_d \le B_l(l = 1, 2, \cdots, s)B_l$: Constraint amount of sediment resources for each constraint condition; A_{ld}: water and sediment coefficient for each constraint condition; s: the number of constraint conditions
Allocation mode	Allocation modes are determined according to different ways of sediment treatment and utilization
Allocation model	Multi-objective analytical hierarchy optimal allocation model (The hydro-sediment dynamic model provides ranges for the parameters in constraint conditions)
Allocation evaluation	Evaluation object: sediment allocation schemes under various water and sediment conditions: Evaluation index: technical and economic indicators (Hu et al., 2010a; Chen et al., 2017); sediment dispersion coefficient (Zhao and Hu, 2012)
Allocation method	Simplex method, AHP or fuzzy evaluation method

Given the lack of intuitive expressions of ecological, economic, and social benefits brought by different allocation modes of sediment resources, for decision maker to fully calculate the effects of different allocation schemes on different benefits and to balance the optimal allocation scheme for the coordinated development of objective benefits is unfavorable. In this study, a multi-objective optimal allocation model of sediment resources is established, and the relationship between the modes of sediment allocation and the objective benefits are determined. The subjective trade-off rate method is used to weigh the conflict among different benefits, which is of certain reference value to the practical application of the irrigation areas.

(2) According to Table 3, the third and fourth columns are the optimal allocation of sediment resources calculated by the subjective trade-off rate method, depicting the amount of desilting basin sediment detention, main canal sediment detention, branch canal sediment detention, sediment transport into the field, sediment retrogradation, strengthening dike by machinery siltation, and redundant sediment utilization are, respectively, 972×10^4 t, 0×10^4 t, 531×10^4 t, 1271×10^4 t, 143×10^4 t, 0×10^4 t, 260×10^4 t in the Weishan irrigation area and 337×10^4 t, 0×10^4 t, 274×10^4 t, 440×10^4 t, 41×10^4 t, 0×10^4 t, 5×10^4 t in the Bojili irrigation area. The first and second columns are the allocation amount of sediment resources by the method of non-inferior solution, revealing the amount of desilting basin sediment detention, main canal sediment detention, branch canal sediment detention, sediment transport into the field, sediment retrogradation, strengthening dike by machinery siltation, and redundant sediment are, respectively, 972×10^4 t, 0×10^4 t, 609×10^4 t, 422×10^4 t, 59×10^4 t, 0×10^4 t, 260×10^4 t in the Weishan irrigation area and 336×10^4 t, 0×10^4 t, 219×10^4 t, 127×10^4 t, 11×10^4 t, 0×10^4 t, 5×10^4 t in the Bojili irrigation area.

These two methods make the redundant sediment fully used as building materials. However, as the comprehensive department manager pays more attention to ecological benefit at the new preference, compared with the non-inferior solution, the amount of sediment transported into the field is increased in these two irrigation areas, branch canal sediment detention is decreased in the Weishan irrigation area and a small part of that is increased in the Bojili irrigation area determined by the subjective trade-off rate method. Moreover, under the condition of maintaining the capacity of water storage and drainage of drainage channels, the amount of sediment retrogradation has been improved to a certain extent. The optimal allocation of sediment resources in the two irrigation areas under the new preference has improved ecological and social benefits.

(3) According to Table 3 and Fig. 4, compared with the present situation, the dispersity of sediment in the two irrigation areas is more obvious, the proportions of sediment transport into the field are increased significantly and the siltation proportions in branch canals are relatively reduced. The proportions of main canal sediment detention are also reduced. In addition, for the Bojili irrigation area, the proportion of desilting basin sediment detention is increased relatively. The distribution of sediment siltation is too concentrated and the actual siltation level of the main canal is far from the requirement of erosion and deposition balance.

The cause of the above problems is the lag of relevant planning, policy and management, which makes the management of dredging and mining lack of order, purpose and effectiveness, resulting in the contradiction between insufficient volume of desilting basin and land used for dredging sediment. To a certain extent, the allocation and utilization of sediment resources are restricted. Therefore, the key to solve the sediment problems in these two irrigation areas is to improve sediment management system and continue to use the optimal measures of sediment allocation, so as to reduce the siltation in canals, improve the sediment transportation capacity, and achieve a large proportion of sediment transportation into the field.

(1) Make sediment transported from the point (desilting basin), through the line (main canal) to the surface (from branch canals to the field), so most sediment can be transported to the middle and lower reaches, branch canals and the field of the irrigation areas. Moreover, line the sediment transportation canals, build and rebuild the hydraulic structures, improve the long-distance transportation capacity and the dispersity of sediment, and realize the muddy water irrigation.
(2) On the basis of the development and utilization of sediment resources, start from the improvement of basic facilities including electricity, transportation, water conservancy and communications; sandy highlands with high standards should be vigorously built and traditional farmland should be thoroughly changed. The desilting regions should be built as the deep processing base of agricultural and sideline products or building materials base. Make waste profitable and transform the disaster into resources.
(3) Implement timely water diversion, centralized diversion and short-term diversion, and make full use of water resources in order to save water and reduce the siltation. Simultaneously, pay attention to preventing soil desertification, improve the utilization efficiency of water resources and irrigation guarantee rate and promote the balanced development of the irrigation areas.

In addition, for Bojili irrigation area, it is necessary to change the function of the desilting basin from more desilting to the interception of coarse sediment as far as possible in order to make most of the fine sediment transported into the lower branch canals, and avoid the excessive use of the desilting basin. The operation of reservoir sediment interception and implementation of engineering reconstruction centered on water saving and efficiency enhancement create conditions to alleviate the siltation and make sediment transported into the field as much as possible. In the Weishan irrigation area, the operation way of sediment transport channel of desilting basin is reformed, and the lining engineering is basically in place. These optimal measures have reduced the siltation in desilting basin.

6. Conclusion

The multi-objective method is used in this study to construct the optimal allocation model of sediment resources, which is solved by the subjective trade-off rate method from the perspective of preference. On the basis of determining ecological, economic, and social benefits, the constraint conditions of sediment resource allocation are established from the aspects of optimal allocation principles of sediment resources, balance mechanism of erosion and deposition, and allocation balance relation. The subjective trade-off rate method is used and the optimal equilibrium solution is obtained to analyze the alternative trade-off relationship among different objectives in the model, which reflect the preference of the decision maker. Thereafter, the model is applied to two irrigation areas and the optimal scheme of different allocation modes put forward in this paper achieves the coordinated development of ecological, economic, and social benefits. The model and the solution method can provide references for sediment resource allocation and enrich the research on sediment resources.

The optimal allocation of sediment resources is a very difficult and complex problem. In the future, the developed model in this study can be improved through considering the combination of sediment regulation technology, long-distance sediment transportation technology, and coordinative dispatch of water and sediments. In addition, the construction of nonlinear dynamic programming mathematical models of sediment resources should be explored.

Acknowledgments

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Appendix A. Supplementary data

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