

# Multi - objective collaborative governance model for watershed water environment

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**Abstract.** Due to the conflicting objectives and lack of coordination among multiple stakeholders in watershed management, an integrated model for hydrodynamic-water quality coupling and multi-objective collaborative governance in the Huai River Basin needs to be developed. The model uses the control unit as a carrier, integrating DEM (Digital Elevation Model), land use data, water quality monitoring information, and pollution discharge records to simulate the pollutant transport process and the effectiveness of countermeasures. Furthermore, the NSGA-II algorithm is improved to solve for the Pareto sets corresponding to the four objectives: environment, economy, ecology, and coordination. Validation using main stream data from 2018 to 2024 shows high accuracy in fitting the baseline operating conditions. Results indicate that the environmental priority scheme can optimize the compliance rate from 76% to over 90%. In the collaborative scenario, the government and enterprises share responsibilities more effectively, and the coordination index and satisfaction are also strengthened. Sensitivity analysis can further identify high- load and drought- prone risk sections, providing a basis for differentiated investment and robust governance.

## 1 Introduction

In recent years, watershed management has shifted from a single objective to a multi-objective collaborative transformation. Li et al. [1] created a multi-level multi-objective regulation model to achieve coordination of agricultural and ecological water use; Zhang et al. [2] gave a framework for water environment- economy collaborative improvement under the background of "dual carbon"; Yuan et al. [3] explored the distribution of benefits of cross-border watershed alliances based on fuzzy multi-weight; Liu et al. [4] showed that administrative barriers and uneven interests would affect the efficiency of collaboration; Zhao et al. [5] demonstrated the hierarchical coupling phenomenon in environmental protection supervision from the perspective of multi-agent; Wan et al. [6] examined the feasibility of multi-objective collaboration in reservoir scheduling; Lu et al. [7] gave a collaborative evaluation model of water conservancy project supply chain; Fu et al. [8] and Yang et al. [9] respectively used game theory and robust improvement to explore the uncertainties of cross-border water resource allocation; Zhang et al. [10] shaped a five-element coupling improvement method of water-energy-economy-carbon-ecology. While progress has been made in research on multi-objective and multi-stakeholder collaboration, regional adaptability and operability still need to be improved. Based on this, this paper develops a watershed multi-objective collaborative governance model that takes into account the environment, economy, and collaborative performance, and also presents a comprehensive decision-making framework that can be generalized.

## 2 Study Area, Data and Indicator System

### 2.1 Study on the general situation of the watershed and the characteristics of water environment problems

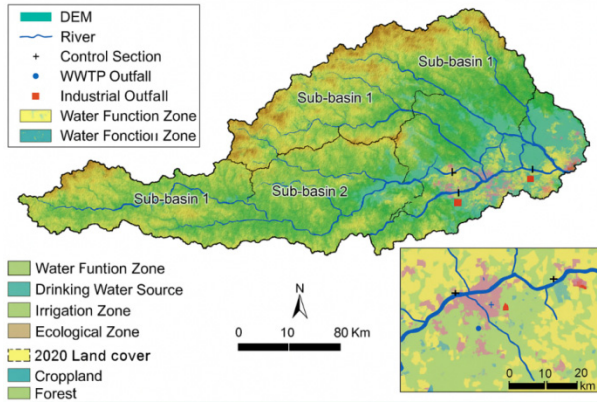
The Huai River Basin is located in the Qinling-Huai River climate transition zone, covering an area of approximately 270,000 km<sup>2</sup>. It transitions from hills to plains from west to east, with a dense, feather-like river system. The average annual precipitation is 885–920 mm, with 50%–75% occurring from June to September, resulting in significant differences between wet and dry seasons and frequent floods and droughts. The basin's functional zones encompass drinking water sources, industrial water supply, agricultural irrigation, and ecological protection; multi-objective management requires consideration of both water quality and water supply reliability. COD, NH<sub>3</sub><sup>-</sup> - N, and TP have consistently exceeded standards in some tributaries and main streams.  $t$  The pollutant concentrations  $k$  at the upstream cross-sections during the monitoring period  $m$  are denoted as [value missing  $C_k^{(m)}$ ], and the multi-year average is defined as [value missing].

$$\bar{C}_k^{(m)} = \frac{1}{N_m} \sum_{t=1}^{N_m} C_k^{(m)}(t) \quad (1)$$

Wherein,  $\bar{C}_k^{(m)}$  represents the average concentration  $m$

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of pollutants at the cross section  $k$  over many years,  $N_m$  refers to  $m$  the number of effective detection stages at the cross section,  $C_k^{(m)}(t)$  and is  $t$  the concentration value actually measured at the first stage. According to Equation (1),  $COD_{Cr}$  river sections with higher average concentrations of  $NH_3-N$  and TP can be identified, thus providing a quantitative basis for subsequent red line limits and collaborative governance scenarios. Figure 1 illustrates the location of the study basin and a schematic diagram of its water function zoning.



**Figure 1.** Schematic diagram of the location of the study watershed and the division of water function zones

## 2.2 Data Sources and Monitoring Network Construction

To support the parameterization and validation of the collaborative governance model, this study integrates multi-source data from 2018 to 2024, including flow rate and water level, rainfall, water quality (monthly average DO,  $COD_{Cr}$ ,  $NH_3-N$ , TP), sewage discharge records, and land use. The water quality of the Huai River has improved from "slightly polluted" to "good" in recent years, with approximately 84% of national monitoring sections achieving excellent or good water quality in 2023, and maintaining a high level in 2024. All observation sequences  $x(t)$  are uniformly aggregated to the scheduling period  $m$  as representative values.

$$X_m = \frac{1}{n_m} \sum_{t \in m} x(t) \quad (2)$$

Wherein,  $X_m$  represents  $m$  the representative value during the scheduling period, such as monthly average flow or monthly average concentration;  $n_m$  represents the number of observations during the scheduling period;  $m$   $x(t)$  and is the  $t$  original observation value. The monitoring network follows the principle of "mainstream control — tributary representative — functional zone outlet — downstream response of sewage outlets," encompassing the upper, middle, and lower reaches, as well as major inflow and outflow sections into the lake and reservoir. Table 1 summarizes the water quality characteristics of typical sections of the Huai River main stream from 2018 to 2024, reflecting  $COD_{Cr}$ , the differences in DO,  $NH_3-N$ , TP, and compliance rates between

the upper and lower reaches, and also demonstrating the trend of improvement from slight pollution to better conditions in recent years.

**Table 1.** Statistical data on water quality at some national control sections of the Huai River main stream (multi-year average from 2018 to 2024).

Section ID	River Name	DO <sub>mean</sub> (mg/L)	COD <sub>Cr</sub> mean (mg/L)	NH <sub>3</sub> -N <sub>mean</sub> (mg/L)	TP <sub>mean</sub> (mg/L)	Attainment Rate (%)
H01	Wangjiaba	7.8	16.9	0.32	0.07	90
H02	Fuyang	7.0	19.8	0.68	0.13	76
H03	Huainan	7.2	18.7	0.59	0.11	80
H04	Bengbu	6.9	20.2	0.71	0.14	74
H05	Lutaizi	7.4	17.5	0.48	0.09	82

Table 1 shows that the water quality at Wangjiaba in the upper reaches is excellent, with high dissolved oxygen (DO) and low levels of  $COD_{Cr}$  and nutrients, achieving a compliance rate of approximately 90%. In the middle reaches, from Fuyang to Bengbu, the water quality is affected by urban industrial activities, resulting in increases in  $COD_{Cr}$ ,  $NH_3-N$ , and TP, and a decrease in the compliance rate to 74%-80%. In the lower reaches, the water quality at Lutaizi has significantly improved after treatment, with all indicators approaching the average level of the entire basin.

## 2.3 Construction of a Multi-Objective Collaborative Governance Indicator System

Based on the practices of ecological compensation and collaborative governance in the Huai River Basin, a four-category indicator system is constructed: water environment quality, governance cost, eco-social benefits, and collaborative performance. The former includes  $COD_{Cr}$ , the exceedance and compliance rates of  $NH_3-N$  and TP; from a cost perspective, it involves annual investment and unit cost reduction; at the eco-social level, it relates to ecosystem services and satisfaction indices; and in terms of collaboration, it quantifies cross-boundary assessments, inter-departmental joint actions, and consistency of implementation. All indicators  $x_{i,d}$  are dimensionless, and benefit-related indicators are linearly normalized.

$$z_{i,d} = \frac{x_{i,d} - x_i^{\min}}{x_i^{\max} - x_i^{\min}} \quad (3)$$

Where  $z_{i,d}$  represents the dimensionless  $d$  value of  $x_{i,d}$  the  $i$ -th  $i$  indicator in the given scenario; refers to the original indicator value before dimensionless processing; and and represent  $x_i^{\min}$  the  $x_i^{\max}$  minimum and maximum values of this indicator across all scenarios or historical samples, respectively. After standardizing the indicators, a weight vector is used  $w = (w_1, \dots, w_n)$  to form a comprehensive goal achievement index:

$$I_d = \sum_{i=1}^n w_i z_{i,d} \quad (4)$$

Where  $I_d$  is the comprehensive evaluation value of the scenario  $d$ ;  $n$  is the number of indicators included in the evaluation;  $w_i$  is  $i$  the weight of the  $i$ -th indicator, satisfying the condition  $\sum_{i=1}^n w_i = 1$ . The weights can be obtained through a combination of the analytic hierarchy process (AHP) and the entropy weight method, along with expert judgment, and are systematically perturbed in the sensitivity analysis. Table 2 provides examples of indicators and threshold ranges to connect regulatory red lines with optimization model objectives:

### 2.4 Weight elicitation, uncertainty treatment, and Pareto-solution stability

To reduce potential subjectivity in weighting, we explicitly document the expert panel and propagate weight uncertainty to the Pareto-solution selection step. An expert panel was convened following a stakeholder-balanced principle (watershed regulators, municipal water-environment agencies, WWTP/industrial practitioners, and academic researchers; total  $n = [N_{exp}]$ ). Experts completed two Delphi rounds to score pairwise comparisons for the AHP layer; the consistency ratio (CR) was required to be  $<0.10$ , otherwise the matrix was revised. Entropy weights were computed from the normalized indicator matrix across all scenarios/solutions, and the final weight was obtained by a convex combination:

$$w_i = \lambda w_i^{AHP} + (1 - \lambda) w_i^{ENT}, \lambda = [\lambda], \quad (5)$$

where  $\lambda$  was determined by expert consensus and cross-validated by historical governance priorities. To test robustness, we performed Monte Carlo perturbation on the final weights: each  $w_i$  was perturbed within  $\pm[\delta]\%$  while preserving the simplex constraint  $\sum_{i=1}^m w_i = 1, w_i \geq 0$ , and  $[N_{MC}]$  resamples were generated. For each resample, the TOPSIS-based scheme selection was repeated and the selection frequency of each Pareto solution was recorded. We report (i) the probability of selecting the same solution as the baseline weights, (ii) the rank stability measured by Kendall's  $\tau$  between baseline and perturbed rankings, and (iii) the variability of the chosen solution's objective vector. Solutions with high selection frequency and low rank variability are treated as stable recommendations, while solutions that are highly weight-sensitive are marked for negotiation-sensitive decision support.

**Table 2.** Multi-objective collaborative governance indicators and threshold ranges.

Indicat or ID	Indicator Name	Target Value	Red-line Limit	Warnin g low	Warnin g high	Initial Weight
QW1	COD_Cr exceedance ratio (%)	0	20	5	15	0.25
QW2	NH <sub>3</sub> -N exceedance ratio (%)	0	20	5	15	0.20

Indicat or ID	Indicator Name	Target Value	Red-line Limit	Warnin g low	Warnin g high	Initial Weight
EC1	Annual total management cost (10 <sup>8</sup> CNY)	8	15	10	13	0.20
ES1	Ecological service index (0–1)	0.80	0.60	0.70	0.75	0.15
CG1	Collaborative governance index (0–1)	0.85	0.50	0.65	0.75	0.20

Among them, Target Value is the management expectation value, Red-line Limit represents the legal or planned red line, Warning\_low / Warning\_high is used to set the warning range, and Initial Weight is the initial weight.

### 2.5 Control Unit Partitioning and Boundary Condition Setting

To achieve operable spatial collaborative governance, the control unit delineation comprehensively considers DEM (Digital Elevation Model), river network, land use, and administrative boundaries: hydrological response units are generated based on a 30-meter DEM, and river channels are superimposed to ensure clear outlets. Functional zones are delineated according to land use and sewage outlets, and finally, administrative boundaries and water function zones are used to tailor these zones to obtain manageable units. Each unit serves as a decision-making scale for multi-objective optimization, and its emissions and measure configurations are adjusted at this scale. The steady-state mass conservation of its control section can be expressed as:

$$Q_{in,u} C_{in,u} + \sum_{p \in P_u} L_{p,u} = Q_{out,u} C_{out,u} \quad (6)$$

Wherein,  $Q_{in,u}$  represents the upstream inflow flow rate into unit  $u$ ,  $C_{in,u}$  represents the corresponding inflow pollutant concentration,  $P_u$  represents  $u$  the combination of point sources and equivalent area sources within the unit, is  $L_{p,u}$  the pollution load of  $Q_{out,u}$  the source term,  $p$  is the flow rate at the unit outlet section,  $C_{out,u}$  and is the pollutant concentration at the outlet section.

### 2.6 Validation of control-unit delineation and enhanced inter-unit boundary conditions

Because the Huai River Basin contains extensive plain river-network areas where micro-topography is subtle, we tested whether a 30 m DEM is sufficient for hydro-response unit (HRU) segmentation. Specifically, the HRUs derived from the 30 m DEM were compared against a higher-resolution elevation product ( $[DEM_{ref}]$ , spatial resolution  $[r_{ref}]m$ ) on representative plain sub-basins. Three criteria were used: (1) outlet matching accuracy (distance between delineated outlets and the mapped channel confluence/outlet), (2) area-overlap consistency (Jaccard index) of HRU polygons, and (3) drainage-density and flow-accumulation pattern similarity. If the outlet error exceeded  $[\varepsilon_{out}]m$  or the overlap dropped

below  $[J_{\min}]$ , adjacent HRUs were merged along the river network and administrative boundaries to avoid over-fragmentation in flat terrain.

In addition, Equation (5) adopts a control-section mass balance. To mitigate the potential bias caused by simplified unit-to-unit boundary conditions, we introduced an explicit lateral exchange term between hydraulically connected adjacent units:

$$Q_{u,in} C_{u,in} + L_u - Q_{u,out} C_{u,out} + \sum_{v \in N(u)} E_{uv} (C_v - C_u) = 0, \quad (7)$$

Where  $N(u)$  denotes neighboring units connected by channels/canals/floodplains, and  $E_{uv}$  is an exchange coefficient estimated from connectivity type and typical lateral flow magnitude. This term allows bank-side return flows, canal diversions, and local floodplain exchanges to be represented in a parsimonious way without requiring a full 2D model, thereby improving applicability in dense plain networks.

### 3 Multi-objective collaborative governance model and solution method for watershed water environment

#### 3.1 Overall Framework and Stakeholder Collaborative Governance Mechanism for Multi-Objective Collaborative Governance

The data and control unit framework in Chapter 2, an integrated framework of "hydrology-water quality- measures-multi-stakeholder decision-making" is constructed, linking physical and institutional processes. As shown in Figure 2, the system comprises a data layer, a hydrological-water quality simulation layer, a multi-objective optimization layer, and a collaborative decision-making layer, respectively outputting flow, concentration, and load reduction, and generating governance solutions under red lines, budgets, and collaborative rules. To measure the cost-responsibility matching among multiple stakeholders, a collaborative index is introduced.

$$J_{\text{coop}} = 1 - \frac{1}{2|S|} \sum_{s \in S} |r_s - c_s| \quad (8)$$

Among them,  $J_{\text{coop}}$  is the collaborative governance index, whose value ranges from  $[0,1]$  1 to 1. The closer the value is to 1, the more consistent the cost sharing and emission reduction responsibilities are;  $S$  is the base number of participating entities, which includes watershed management agencies, local governments, enterprises, and the public/NGOs, etc.;  $r_s$  is  $S$  the proportion of responsibility borne by the entities in the reduction of target pollutants;  $c_s$  and is  $S$  the proportion of costs actually borne by the entities.

#### 3.2 Bargaining-consistent collaborative index and operationalization for public/NGO responsibilities

Equation (6) implicitly assumes a linear penalty for the deviation between responsibility shares and cost shares.

However, real-world bargaining is often nonlinear: small deviations may be tolerated, whereas large deviations can trigger breakdowns or renegotiation. We therefore generalize the penalty to a flexible form:

$$\text{CoopIndex} = 1 - \frac{1}{N} \sum_{k=1}^N \phi(d) (|r_k - c_k|), \quad (9)$$

With  $\phi(d) = d^\beta, \beta \geq 1$ , or a piecewise specification

$$\phi(d) = \begin{cases} 0, & d \leq d_0, \\ \left(\frac{d-d_0}{1-d_0}\right)^\beta, & d > d_0, \end{cases} \quad (10)$$

where  $\beta$  and  $d_0$  reflect negotiation sensitivity and tolerance. Parameters were calibrated (or scenario-tested) using historical eco-compensation agreements and recorded negotiation outcomes (e.g., whether agreements were reached within a fixed number of rounds), and sensitivity analysis over  $\beta \in [\beta_{\min}, \beta_{\max}]$  was conducted to examine whether the ranking of Pareto solutions changes under different bargaining behaviors.

For non-entity institutions such as the public/NGOs, "responsibility" is not a direct emission-reduction fraction. We operationalize  $r_{\text{public/NGO}}$  through a contribution-to-outcome mapping: (i) define measurable participation variables (e.g., environmental reporting frequency, volunteer monitoring hours, community co-funding amount, and education/outreach coverage); (ii) convert them to a normalized contribution score  $S_{\text{public}}$  via entropy/AHP within the socio-ecological benefit layer; (iii) translate  $S_{\text{public}}$  into an equivalent responsibility share  $r_{\text{public}} = \eta S_{\text{public}}$ , where  $\eta$  is determined so that  $\sum_{k=1}^N r_k = 1$  and the marginal effect of public participation on load reduction (captured by the response function in Eq. (8)) is consistent with empirical studies or local pilot data. This makes the collaborative index computable and comparable across entity and non-entity stakeholders.

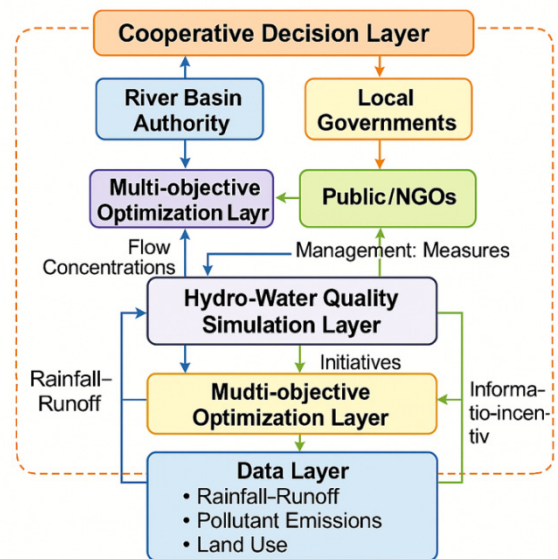


Figure 2. Overall Framework Diagram for Multi-Objective Collaborative Governance of Watershed Water Environment

### 3.3 Hydrodynamic-Water Quality Coupled Model and Pollution Load Estimation

The hydrodynamic-water quality coupling module uses a control unit to discretize the river network, combining one-dimensional hydrodynamic equations with convection-dispersion-reaction water quality equations; it constructs a one-dimensional river network on the main stream and major tributaries, and describes  $k$  the spatiotemporal evolution of pollutants using the following equation:

$$A \frac{\partial C_k}{\partial t} + \frac{\partial(QC_k)}{\partial x} = \frac{\partial}{\partial x} \left( AD_k \frac{\partial C_k}{\partial x} \right) - Ak_k C_k + AS_k(x,t) \quad (11)$$

Wherein,  $A$  represents the cross-sectional area;  $C_k$  represents  $k$  the dissolved concentration of pollutants;  $t$  indicates time;  $Q$  is the cross-sectional flow rate, which is the same as the flow sequence in Chapter 2;  $x$  is the river channel coordinate;  $D_k$  represents  $k$  the longitudinal dispersion coefficient of pollutants;  $k_k$  represents the first-order decay (or comprehensive reaction) coefficient;  $S_k(x,t)$  is the external inflow portion per unit volume of water caused by both point and non-point sources. Point source loads are calculated according to the discharge log, corresponding to time steps daily or monthly, while non-point source loads are estimated based on land use and rainfall-runoff coefficients, and input into the river according to the control unit. Hydrodynamic and water quality parameters are determined using observational data from 2018-2024, and evaluated using a combination of NSE and RMSE, and a multi-section overall exploration is conducted (Table 3).

**Table 3.** Calibration results of key parameters of the hydrodynamic-water quality model. (main stream of the Huai River)

Parameter Type	Symbol	Initial Value	Optimal Value	95% CI Lower	95% CI Upper
Main channel Manning's n	nm	0.030	0.028	0.026	0.030
Floodplain Manning's n	nf	0.050	0.047	0.044	0.050
Dispersion coefficient (COD)	DCOD (m <sup>2</sup> /s)	200	260	210	320
Dispersion coefficient (NH <sub>3</sub> -N)	DNH <sub>3</sub> (m <sup>2</sup> /s)	180	230	190	290
First-order decay (COD)	kCOD (d <sup>-1</sup> )	0.15	0.18	0.14	0.22
First-order decay (NH <sub>3</sub> -N)	kNH <sub>3</sub> (d <sup>-1</sup> )	0.20	0.24	0.18	0.28
First-order decay (TP)	kTP (d <sup>-1</sup> )	0.05	0.06	0.04	0.08

### 3.4 Response Function and Scenario Parameterization of Governance Measures

From the perspective of the control unit, governance methods encompass many types, such as improving standards for urban wastewater treatment plants, reducing industrial emissions, adopting agricultural non-point source pollution control (BMPs) (best practices), carrying out river ecological

restoration, and implementing water allocation. To uniformly illustrate the impact of different measures on the load within the improvement model, this study transforms the measure intensity variable into a load reduction coefficient within the control unit. A saturated response function is introduced to analyze the relationship between any type of measure  $j$  and pollutants  $k$ .

$$\eta_{j,k}(u_{j,k}) = 1 - \exp(-a_{j,k}u_{j,k}) \quad (12)$$

Among them,  $\eta_{j,k}(u_{j,k})$  is the reduction rate of  $j$  pollutants targeted by the measure  $k$ , and its value is within the range of [0,1];  $u_{j,k}$  is the intensity or scale variable of the implementation of the measure in a specific control unit. The improvement of urban sewage standards can be reflected by the improvement level of the effluent standards of sewage treatment plants, and agricultural BMPs can be represented by the treatment area or coverage ratio;  $a_{j,k}$  is the response coefficient that reflects the marginal reduction efficiency, which can be obtained through engineering experience or regression analysis. The original load is calculated according to  $L_k^{raw}$  the source and sink terms in input formula (7).

$S_k(x,t)$  To implement  $L_k = L_k^{raw}(1 - \eta_{j,k})$  this, the combined impact of the set of measures on river water quality can be clearly demonstrated. When parametrically processing the scenario, it is necessary to first determine the maximum intensity that each type of measure can achieve and its corresponding investment cost curve. Then, these parameters should be  $u_{j,k}$  used as decision variables and combined with control units and pollutant types to carry out multi-objective improvement work.

### 3.5 Construction of Multi-Objective Optimization Model

Based on the aforementioned indicator system and response function, a multi-objective collaborative governance model for watershed water environment is constructed. For a given decision vector  $\mathbf{X}$  (including the intensity of measures and scheduling parameters for each unit), four categories of objectives—environmental, economic, ecological, and collaborative—are defined and combined to form a multi-objective vector.

$$\mathbf{F}(\mathbf{x}) = (f_{env}(\mathbf{x}), f_{cost}(\mathbf{x}), f_{eco}(\mathbf{x}), f_{coop}(\mathbf{x})) \quad (13)$$

Among them,  $f_{env}(\mathbf{x})$  represents the weighted sum of the duration of pollutant exceedance or the gap in compliance at key control sections, which should be minimized;  $f_{cost}(\mathbf{x})$  represents the total life-cycle cost after discounting various engineering investments and operation and maintenance costs to present value, which should also be minimized;  $f_{eco}(\mathbf{x})$  represents the negative value of the ecosystem service index or its opposite, with the aim of turning "improving ecosystem services" into a "reduction" problem;  $f_{coop}(\mathbf{x})$  represents the

negative value of synergistic performance, which is related to the value in equation (6)  $J_{coop}$ , so that the greater the synergy, the smaller the target value.

### 3.6 Collaborative Governance Strategy Solution Algorithm and Scheme Selection Rules

To solve the constrained multi-objective problem, an improved NSGA-II was adopted. The decision vector  $\mathbf{x}$  is encoded using a three-dimensional chromosome model of "control unit – measure type – intensity," with continuous variables represented by real numbers and start/stop states by integers/binaries. Crossover and mutation updates the scheme while ensuring feasibility, and the hydrodynamic-water quality model is called in each generation to calculate spatiotemporal concentrations and synergy indices (Figure 3). To improve the interpretability of the Pareto set, a comprehensive fitness function is introduced:

$$F^*(\mathbf{x}) = \sum_q \lambda_q \phi_q(\mathbf{x}) + \lambda_p P(\mathbf{x}) \quad (14)$$

Among them,  $F^*(\mathbf{x})$  the comprehensive fitness function used for subsequent ranking and TOPSIS normalization is  $\phi_q(\mathbf{x})$  the index value obtained after interval normalization  $\lambda_p$  of the four objectives of environment, cost, ecology and synergy;  $[0,1]$  is the weight coefficient;  $P(\mathbf{x})$  is the constraint violation penalty term, which will take a positive value if the scheme violates the water quality red line or budget limit, otherwise it will be zero;  $\lambda_p$  is the penalty coefficient, which is used to make infeasible schemes move away from the frontier.

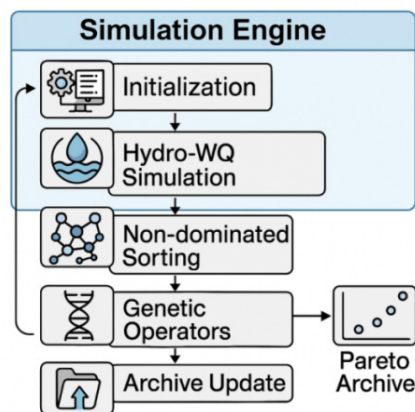


Figure 3. Solution process and information interaction diagram of the multi-objective collaborative governance model

## 4 Model Application and Result Analysis

### 4.1 Simulation of Baseline Operating Conditions and Model Validation

Based on the hydrodynamic-water quality coupling model mentioned above, the runoff and sewage discharge records from 2018 to 2020 were selected as the reference for the

baseline operating condition, and the measures were maintained at the "current level". According to Equation (7),  $COD_{Cr}$  the monthly simulated values of  $NH_3-N$  in the Huaihe River main stream were obtained step by step from the control unit level and compared with the detection data. The calibrated model was independently validated in 2021-2022 to test its portability in different hydrological years. In Figure 4, the observation and simulation time series of Wangjiaba, Bengbu sections  $COD_{Cr}$  and  $NH_3-N$  were compared, and the river sections with high risk during the high water period were also marked with a profile along the route.

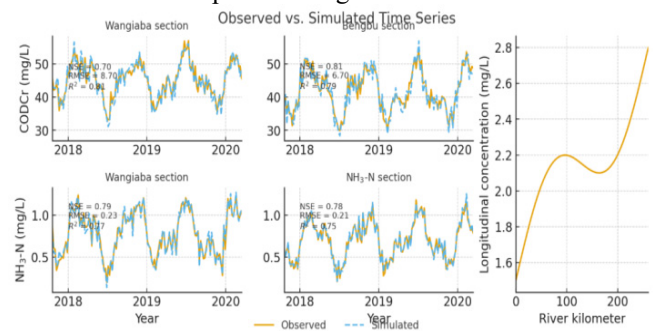


Figure 4. Comparison curves of observed and simulated values for a typical cross-section under baseline conditions.

### 4.2 Results of Multi-Objective Optimization and Pareto Front Analysis

Based on the multi-objective model in Chapter 3 and NSGA-II, climate and pollution scenarios from 2019 to 2022 were selected as representative years. Through 200 generations of evolution, more than 1,000 non-dominated solutions were obtained. Each generation calls the hydrodynamic-water quality model to calculate the compliance rate and the duration of exceedances, and then adds investment and operating costs, thus forming a vector containing four objectives. The Pareto set includes "environment-first," "economic-first," and "compromise" schemes. Table 4 summarizes six typical schemes, where P0 serves as the reference standard, and the others are the improved results. When moving from P5 to P1, water quality and ecological indicators improve, but the unit improvement cost increases. Figure 5 displays P1-P5 and the entire Pareto solution set in the same graph, using different colors to divide the three regions, which more intuitively shows the coordination relationship between cost, benefit, and ecology.

Table 4. Representative Governance Schemes under Pareto Front

Scheme ID	Type	Water Quality Attainment (%)	Exceedance Reduction (%)	Total Cost (10 <sup>8</sup> CNY)	Cost per 1% Improvement (10 <sup>8</sup> CNY)	Ecological Index (0 – 1)
P0	Baseline	76	0	0.0	–	0.62
P1	Env-priority	92	78	13.5	0.17	0.86
P2	Env-biased	89	70	11.2	0.16	0.83
P3	Balanced	87	64	9.8	0.15	0.81
P4	Econ-biased	84	55	7.4	0.13	0.77
P5	Econ-priority	82	49	6.0	0.12	0.74

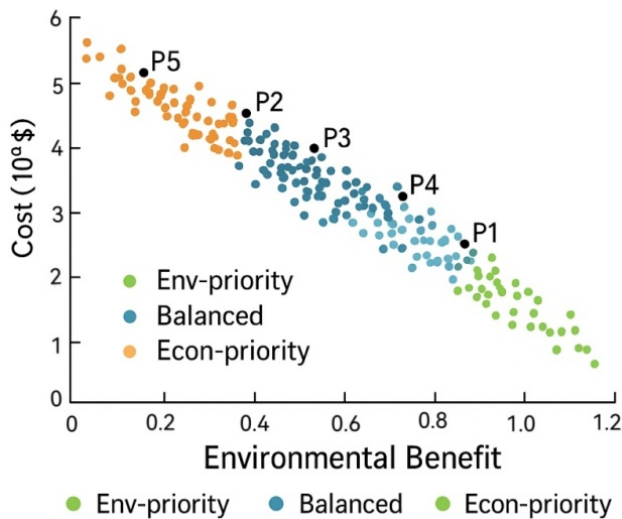


Figure 5. Scatter plot of Pareto frontier for multi-objective collaborative governance

### 4.3 Comparison and Contribution Decomposition of Multi-Agent Collaborative Scenarios

Building upon multi-objective improvements, a collaborative governance mechanism was added, setting up S1 (government-guided, enterprise-passive emission reduction), S2 (government- enterprise-public incentive collaboration), and S3 (cross- administrative region joint governance). The combination of measures under each scenario was re-solved, and the government and enterprise investment, emission reduction contributions, and benefits were calculated. Table 5 shows that when transitioning from S1 to S2 and S3, the enterprise's emission reduction contribution, collaboration index, and public satisfaction all significantly improved. Figure 6 illustrates the comprehensive situation of the three scenarios in terms of EnvBenefit, CoopIndex, and Satisfaction, using grouped bar charts to compare the investment and reduction amounts of the government and enterprises, thus demonstrating the differences in burden and benefits under different mechanisms.

Table 5. Stakeholder Contributions under Different Cooperation Scenarios.

Scenario-Actor	Investment (10 <sup>8</sup> CNY)	Emission Reduction (kt/a)	Env Benefit Index (0-1)	Coop Index (0-1)	Public Satisfaction (0-100)
S1-Government	7.5	18.2	0.78	0.68	71
S1-Enterprises	3.1	9.4	0.72	0.63	65
S2-Government	6.2	17.0	0.81	0.81	82
S2-Enterprises	5.4	15.3	0.84	0.83	80
S3-Government	6.8	18.9	0.86	0.88	85
S3-Enterprises	4.7	14.6	0.83	0.86	79

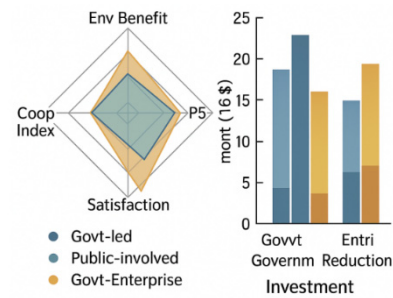


Figure 6. Radar/Bar Chart of Comprehensive Performance in Multi-Agent Collaborative Governance Scenario

### 4.4 Sensitivity and Uncertainty Analysis and Management Implications

To examine the robustness of optimal and synergistic solutions, scenarios such as H-Load, L-Load, H-Cost, L-Cost, Dry, and Wet should be established based on load intensity, measure costs, discount rates, and hydrological year patterns. The hydrodynamic-water quality model should then be re-run. Environmental, economic, and ecological indicators under scenarios P3 and S3 are assessed, and robustness and risk are calculated. Table 6 shows that drought years combined with high loads are the most unfavorable, with robustness dropping to between 0.75 and 0.78 and risk reaching 3 to 4. Low loads and abundant water years are more stable. Therefore, management implications are proposed, including strengthening upstream sensitive units, reserving drought redundancy, and reducing inefficient measures.

Table 6. Key Objective Responses under Sensitivity and Uncertainty Scenarios.

Scenario ID	Δ Env Objective (%)	Δ Cost Objective (%)	Δ Ecological Index	Robustness Index (0-1)	Risk Level (1-5)
Normal	0	0	0.00	1.00	1
H-Load	+18	+4	-0.06	0.78	3
L-Load	-12	-3	+0.04	0.86	2
H-Cost	+3	+15	-0.01	0.82	3
Dry	+10	+5	-0.05	0.75	4
Wet	-6	+2	+0.02	0.88	2

## 5 Conclusion and Outlook

This study focuses on the water environment improvement needs of the Huai River Basin, creating a governance model that incorporates data, hydrodynamic-water quality simulation, multi-objective improvement, and collaborative decision-making to connect flow changes, pollution transport, response measures, and multi-stakeholder game theory. Benchmark simulation results from monitoring and discharge records conducted between 2018 and 2024 show good fit for CODCr and NH<sub>3</sub>-N, with NSE and R<sup>2</sup> both within reasonable ranges. Multi-objective evolution yielded a Pareto scheme encompassing "environmental priority – economic priority," where approximately a 20% cost increment can improve compliance rates by more than 10%. Collaborative scenarios demonstrate that joint assessment and incentives can improve the synergy index, satisfaction, and sensitivity analysis of enterprise emission reduction contributions. This analysis

identifies key units and robust measures during drought years and high-load periods, providing quantitative support for the "red line + collaboration + risk" governance path.

Research and Demonstration on Key Technologies for Precise Perception and Intelligent Supervision of Safe Operation of Small Hydropower Plant Clusters under Centralized Control (2024YFC3213400), Research on Ecologically Constrained Assessment Methods for Hydropower Resources (Y124011)

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