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Combined with social network analysis and bioengineering, this paper explores the regional cooperative governance strategy of inter-governmental coordination of cross-domain ecological environment

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SUMMARY: *This paper proposes a cross-domain inter-government collaborative governance framework for ecological environment combining social network analysis and bioengineering, aiming to identify regional ecological risk transmission, inter-government cooperation structure and the embedding mechanism of bioremediation technology. In this study, the local government, watershed management agencies, ecological and environmental departments, and restoration implementation agents were modeled as collaborative network nodes, and the behaviors of joint monitoring, data sharing, ecological compensation, and project co-construction were transformed into relational weights, and the governance suitability was evaluated by combining plant remediation, microbial remediation, constructed wetlands, and ecological buffer zone construction. On this basis, two kinds of strategies of government-led collaborative governance and evolutionary cooperative governance supported by bioengineering are constructed. Based on the scenario simulation of typical cross-domain watershed regional data, the results show that the comprehensive risk index can be reduced to 0.31, the inter-government collaborative network density can be increased to 0.76, and the proportion of cooperative subjects can reach 88.6%. Its long-term governance effect is better than that of conventional zoning governance and government-led collaborative governance.*

KEYWORDS: *Social network analysis; Bioengineering; Cross-domain ecological environment governance; Inter-government coordination in governance*

1 Introduction

Cross-domain ecological and environmental governance is related to regional development security, resource carrying capacity and public governance resilience. With the rapid development of basin economic belts, urban agglomerations and cross-administrative industrial corridors, problems such as water pollution transmission, air pollution diffusion, soil heavy metal migration, and ecological corridor fragmentation are no longer limited to a single administrative district. The lagging industrial emissions, land use adjustment or ecological restoration in a certain region may be transmitted to adjacent regions through the river system, wind field, transportation network and industrial chain, thus forming a governance pattern of multi-subject, multi-scale and multi-responsibility boundaries. Chaffin

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et al. [1] pointed out that there is a tight coupling relationship between environmental governance network and geographical space, and rapid environmental change requires governance research to pay attention to spatial dependence, organizational relationship and institutional adaptability at the same time. This judgment shows that the cross-domain ecological environment problem is not a simple pollution control problem, but a composite governance problem embedded in government relations, resource flows and ecological processes.

Existing research on ecological and environmental governance has gradually shifted from single-point governance to collaborative governance. However, in actual operation, inter-government collaboration still faces obstacles such as division of responsibility, information hysteresis, uneven interests and differences in governance objectives. Huber et al. [2] found through the study of social-ecological network adaptation that whether the connection structure between governance subjects matches the ecosystem boundary will directly affect the governance effectiveness. McIlwain et al. [3] further pointed out that there are obvious structural power differences in polycentric water governance networks, and some key subjects have more coordination resources and agenda-setting capabilities, while marginal subjects are often difficult to fully participate in decision-making. It can be seen that cross-domain inter-government collaborative governance can not stay at the policy initiative level, but also need to use measurable network analysis methods to identify the structure of inter-government relationship, synergy strength, core nodes and potential fracture points.

Social network analysis provides a clear quantitative tool for the above problems. Indicators such as centrality, density, structural holes, agglomerated subgroups, and network connectivity can reveal the cooperative relationships among local governments, environmental protection departments, watershed management agencies, scientific research organizations, and business subjects. Fried et al. [4] proposed that network tools can help identify synergy gaps, but their application needs to be combined with specific governance scenarios and institutional design principles. In their study on sea level rise governance, Pozzi et al. [5] found that emerging policy subsystems often rely on cross-sectoral connectivity and continuous interaction in polycentric networks. Koebele et al. [6] emphasized that collaborative water governance should not only expand participation, but also pay attention to fairness and representation. Therefore, this paper uses the social network analysis method to describe the inter-government collaborative relationship, not only examining "who cooperates with whom", but also focusing on whether the cooperative relationship is stable, whether the information flow is smooth, and whether the responsibility sharing is balanced.

At the same time, cross-domain ecological environmental governance also needs the support of operational ecological restoration technology. Traditional inter-government collaborative research mainly focuses on system coordination and policy implementation, and the discussion on the embedding mechanism of bioengineering technology in regional cooperative governance is insufficient. McNaught[7] pointed out in the Climate and Disaster Resilience Development Review that collaborative governance at the local level needs to integrate risk identification, ecological restoration and community action into the same policy framework. According to Battisti et al. [8], whether natural base solutions can work in the long term depends on the stability of collaborative governance arrangements. Holscher et al. [9] further proposed that nature-based solutions in urban governance need to form sustainable capacity through co-production mechanism. This extends to cross-domain ecological and environmental governance. Bioengineering methods such as bioremediation, phytoremediation, microbial degradation, ecological buffer zone construction and wetland reconstruction should not be regarded as engineering projects in a single region, but should be embedded in regional collaboration networks and become important technical variables of inter-government governance strategies. Table 1 summarizes the main research implications involved in the introduction of this paper and their supporting relationships for the model construction of this paper.

Table 1: Implications of related studies for the research design of this paper

Research focus	Representative viewpoint	Implications for this study
Environmental governance networks and spatial relations	Environmental change requires simultaneous attention to governance networks and geographical processes [1]	Defines cross-domain ecological environmental issues as governance objects shaped by both spatial diffusion and intergovernmental interaction
Social-ecological network fit	The degree of fit between network structure and ecological boundaries affects governance outcomes [2]	Uses social network analysis to identify whether intergovernmental collaboration relationships fit the scope of pollution diffusion and ecological restoration
Polycentric governance power structure	Power differences exist between core and peripheral actors in governance networks [3]	Identifies key governmental nodes and weak links in collaboration through centrality and structural hole indicators
Application of collaborative network tools	Network tools can reveal collaboration gaps but should serve governance design [4]	Translates network identification results into the basis for hierarchical collaboration, responsibility sharing, and strategy selection
Governance of nature-based solutions	The sustainability of nature-based solutions depends on stable collaborative arrangements [8]	Incorporates bioengineering remediation measures into the regional cooperative governance strategy system

In the field of bioengineering, Kuppan et al. [16] systematically reviewed the application of sustainable bioremediation technology in pollution control, and pointed out that microorganisms, plants and ecological materials can provide solutions with lower disturbance for waste and pollution management. Biermann and Havlick[17] discussed the relationship between ecological restoration, genetics and environmental governance, suggesting that technological governance is not simply an engineering choice, but also involves ecological ethics, institutional boundaries and public responsibility. Ayilara and Babalola[18] emphasized that microorganisms play an important role in the bioremediation of environmental wastes. Bhowmick et al. [19] explained from the perspective of potential functional microorganisms that the effect of pollution remediation was closely related to the adaptability of microbial communities, pollutant types and environmental conditions. The above studies provide a technical basis for the introduction of bioengineering governance variables in this paper, and also show that cross-domain collaborative governance needs to combine "institutional network" with "ecological restoration process".

Based on this, this paper focuses on the regional cooperative governance of inter-governmental coordination of cross-domain ecological environment, and tries to construct a governance model combining social network analysis and bioengineering. This paper focuses on three issues: first, how to define the spatial scope, time scale and subject boundary of cross-domain ecological environmental governance; Secondly, whether the inter-government collaborative relationship can be identified, measured and evaluated by social network analysis method; Thirdly, how to embed bioengineering technology into regional cooperative governance strategies and promote the transformation from government-led collaborative governance to evolutionary cooperative governance. The follow-up structure of this paper is as follows: in the second part, the method and architecture of inter-governmental collaborative governance model of cross-domain ecological environment are constructed, and the spatio-temporal scale definition, inter-governmental collaborative relationship identification model and regional cooperative governance strategy decision-making mechanism are explained respectively. The third part designs governance scenarios based on typical cross-domain ecological environment regional data. Section 4 analyzes and discusses the model results. Section 5 summarizes the research conclusions and proposes future optimization directions.

2 Method and architecture of inter-government collaborative governance model for cross-domain ecological environment

Cross-domain inter-government collaborative governance of ecological environment is not a passive disposal of pollution events by a single government department, but a dynamic system composed of ecological environment status, administrative subject relationship, bioengineering repair capability and regional cooperation strategy. Referring to the idea of social-environmental system modeling, this paper abstracts the process of cross-domain ecological environmental governance as a cyclic structure of "environmental risk identification, inter-government relationship measurement, bioengineering adaptation, and collaborative strategy feedback". Regional governments at all levels, river basin management agencies, environmental protection departments, agricultural and rural departments, scientific research institutions and ecological restoration enterprises are regarded as nodes in the governance network, and inter-regional joint monitoring, data sharing, policy consultation, project co-construction and funding coordination are regarded as relationship edges between nodes. The ecological environmental risk was comprehensively characterized by pollution load, diffusion direction, ecological sensitivity and restoration difficulty. In this paper, the state of the inter-governmental collaborative governance system of cross-domain ecological environment at time step t is expressed as follows.

$$\mathrm{G_t} = \langle \mathrm{E_t}, \mathrm{N_t}, \mathrm{B_t}, \mathrm{S_t} \rangle \tag{1}$$

where, $\mathrm{E_t}$ represents the state of regional ecological environment, including variables such as water quality, atmosphere, soil and ecological patch stability. $\mathrm{N_t}$ represents the state of inter-government collaborative network, including network density, node centrality, cross-domain connection strength and structural hole location. $\mathrm{B_t}$ represents the state of bioengineering support, including microbial remediation, plant remediation, ecological wetland construction and biological buffer zone construction capacity; $\mathrm{S_t}$ represents the state of governance strategies, including a combination of strategies such as government leadership, joint negotiation, project co-construction and evolutionary cooperation. This expression can simultaneously retain three types of information: ecological process, governance relationship and technical intervention, and avoid simplifying cross-domain environmental governance to a single pollution index change. In order to describe the change of governance states, this paper defines the set of regional cooperative governance states as follows.

$$\mathrm{Q} = \{\mathrm{q}_1, \mathrm{q}_2, \mathrm{q}_3, \mathrm{q}_4, \mathrm{q}_5\} \tag{2}$$

Among them, q_1 represents low risk stable coordination, q_2 represents mild risk routine coordination, q_3 represents moderate risk strengthening coordination, q_4 represents high risk joint control, and q_5 represents severe risk emergency linkage. The governance state is determined by the current ecological environment state, inter-government coordination network and governance actions, and its state transition function can be expressed as follows.

$$\mathrm{T}(\mathrm{A}_\mathrm{t}, \mathrm{G}_\mathrm{t}, \mathrm{q}_\mathrm{t}) \to \mathrm{q}_{\mathrm{t}+1}, \quad \mathrm{q}_\mathrm{t}, \mathrm{q}_{\mathrm{t}+1} \in \mathrm{Q} \tag{3}$$

where, A_t is the set of actions taken by each governance subject within time step t, including joint law enforcement, pollution source emission limitation, ecological compensation, bioremediation project investment and cross-domain data sharing. If the inter-government collaboration intensity is high, and the bioengineering remediation measures have a good match with the pollution type, the system status may transfer from the high risk level to the low risk level. If the collaborative network is loose, the responsibility division is fuzzy, or the repair measures lag behind, the governance state may remain unchanged, or even evolve to a higher risk level. To facilitate the correspondence between model states and governance responses, this paper classifies governance levels according to comprehensive risk index, inter-government collaboration status and bioengineering adaptation status, as detailed in Table 2.

Table 2: Classification table of cross-domain ecological environment governance status

Comprehensive risk index	Intergovernmental collaboration status	Bioengineering adaptation status	Governance status level	Strategic implication
0.00–0.20	Stable network connections and sufficient information sharing	Mature remediation measures and evident ecological restoration	(q1) Low-risk stable collaboration	Maintain routine monitoring and collaborative assessment
0.21–0.40	Local cooperation exists, with relatively timely cross-regional response	Remediation measures are basically adaptive	(q2) Mild-risk routine collaboration	Strengthen joint inspections in key areas
0.41–0.60	Some entities have insufficient connections, and collaboration efficiency declines	Remediation measures show certain delays	(q3) Moderate-risk strengthened collaboration	Initiate cross-regional consultation and joint governance
0.61–0.80	Dispersed network structure and poor responsibility transmission	Insufficient matching of remediation technologies	(q4) High-risk joint control	Establish binding collaboration and project co-construction mechanisms
0.81–1.00	Obvious collaboration breakdown and ecological risk spillover	Insufficient remediation capacity or implementation failure	(q5) Severe-risk emergency coordination	Activate cross-regional emergency response and special rectificatio

In the running process of the model, the comprehensive risk index is not simply determined by pollution concentration, but calculated by environmental pressure, spatial spillover, inter-government coordination capacity and bioengineering support capacity. For regional unit i, its comprehensive risk index can be expressed as follows.

$$R_{i,t} = \alpha P_{i,t} + \beta O_{i,t} - \gamma C_{i,t} - \delta B_{i,t} \tag{4}$$

where $P_{i,t}$ represents the pollution pressure of regional unit i at time step t; $O_{i,t}$ represents the cross-domain spillover influence; $C_{i,t}$ represents the inter-government coordination capability; $B_{i,t}$ represents the bioengineering repair support capability; α,β,γ,δ are the weight parameters. This formula reflects the basic judgment of this model: ecological risk not only comes from pollution itself, but also from cross-domain transmission. Risk reduction depends not only on administrative regulation, but also on the quality of collaborative network and the adaptation degree of repair technology. Figure 1 shows the overall operation process of the model.

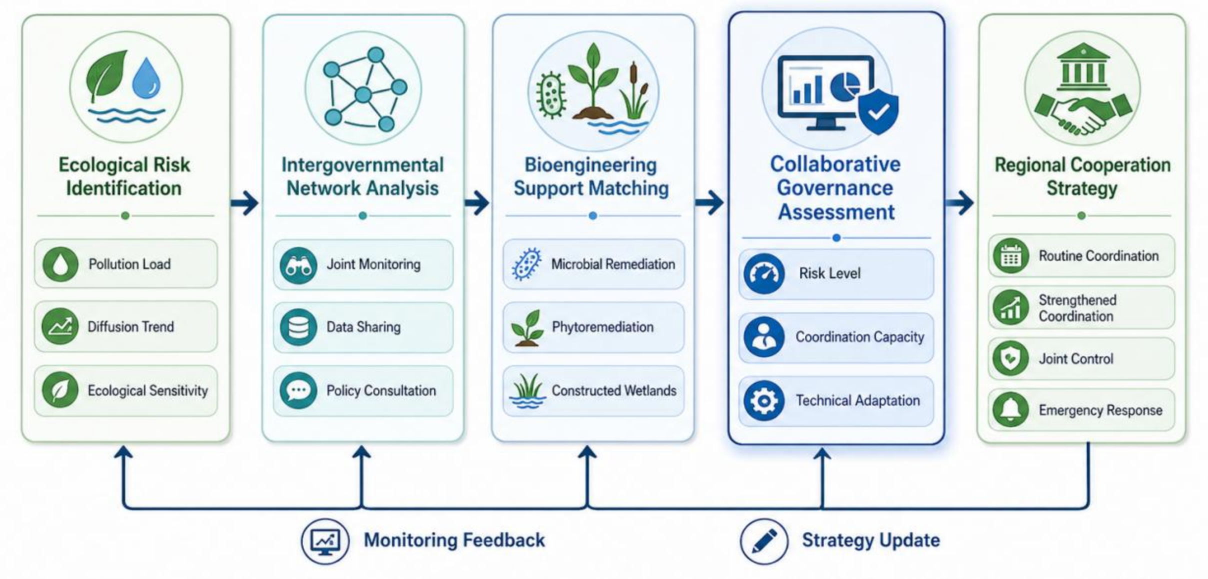

Figure 1: Operation process of inter-government collaborative governance model for cross-domain ecological environment

2.1 Spatial and temporal scale definition of cross-domain ecological environmental governance

Cross-domain ecological environmental governance has obvious time accumulation and space conduction. In this paper, discrete time steps are used to describe the governance process, and one time step is set to one month to adapt to the basic cycle of ecological environment monitoring, government meetings and consultation, and governance project scheduling. For pollution emergencies, the time step can be shortened to one week. For long-term governance matters such as wetland restoration, phytoremediation, and bio-buffer zone construction, multiple time steps can be combined into quarterly or annual observation Windows. The adjustability of the time scale enables the model to serve both short-term risk warning and long-term collaborative governance assessment.

In spatial scale, this paper does not take a single administrative region as the only unit of analysis, but divides the study area into several cross-domain governance units:

$$U = \{u_1, u_2, \dots, u_m\} \tag{5}$$

Each governance unit is jointly determined by administrative boundaries, watershed boundaries, ecological corridors, pollution source distribution, and bioremediation suitable areas. Adjacent governance units may be linked through river systems, atmospheric flow fields, industrial transfer, and policy collaboration. In order to characterize the cross-domain influence strength between units, the spatial correlation strength is defined as follows.

$$L_{ij,t} = \lambda W_{ij,t}^{h} + \mu W_{ij,t}^{a} + \nu W_{ij,t}^{g} \tag{6}$$

where $W_{ij,t}^{h}$ represent the hydrological connection strength, $W_{ij,t}^{a}$ represent the atmospheric transmission influence, $W_{ij,t}^{g}$ represent the inter-government governance connection strength. λ,μ,ν are the weights of different spatial relations. If the two regions are in the downstream-upstream relationship of the same basin, and there is a normalized joint governance mechanism, their spatial correlation strength is high. If the administration is adjacent but lacks ecological transmission and policy interaction, the spatial correlation strength is low.

2.2 The inter-government collaborative relationship identification model based on social network analysis

The inter-government collaborative relationship identification model based on social network analysis is used to measure the cooperation intensity, structure position and collaboration gap between administrative subjects in cross-domain ecological environmental governance. Different from judging governance responsibility solely based on administrative level, social network analysis can transform joint law enforcement, information sharing, policy consultation, ecological compensation, project co-construction and biological engineering collaborative repair and other behaviors into computable relationship networks, so as to identify the core nodes, edge nodes and cross-domain connection channels in regional cooperative governance. The basic function of the model is to transform the scattered inter-government interaction records into the governance network structure, which provides the basis for subsequent policy decisions. In this paper, the inter-government collaborative network of cross-domain ecological environment is expressed as follows.

$$N_t = (V_t, E_t, W_t) \tag{7}$$

where, V_t represents the set of subjects involved in governance within time step t, including provincial governments, city and county governments, ecological and environmental departments, watershed management agencies and bioengineering implementation units. E_t represents the set of cooperative relations formed between agents. W_t represents the set of relationship weights, which is used to describe the strength of collaborative ties. If there is joint monitoring, data exchange, ecological restoration co-construction or pollution emergency linkage between the subjects, it is considered that there is an effective connection between them. To avoid misjudging sporadic meetings or formal documents as stable collaborative relationships, this paper defines collaborative relationships as those in which at least two types of substantive interactions occur in the same governance cycle.

The weight of inter-government collaborative relationship is calculated by policy interaction intensity, data sharing frequency, joint governance project and bioengineering collaboration degree, and its expression is as follows.

$$w_{ij,t} = \theta_1 M_{ij,t} + \theta_2 D_{ij,t} + \theta_3 P_{ij,t} + \theta_4 B_{ij,t} \tag{8}$$

Where, $w_{ij,t}$ denotes the collaborative weight of agent i and agent j at time step t. $M_{ij,t}$

denotes the strength of policy consultation and joint law enforcement; $D_{ij,t}$ denotes the monitoring data sharing frequency; $P_{ij,t}$ denotes the co-construction degree of cross-domain governance projects; $B_{ij,t}$ denotes the degree of bioengineering collaborative repair; $\theta_1, \theta_2, \theta_3, \theta_4$ are the weight coefficients. Compared with the general collaborative governance model, this paper included the degree of bioengineering collaboration into the weight calculation, in order to reflect the technical support role of microbial remediation, plant remediation, constructed wetland construction and ecological buffer zone management on cross-domain cooperation. After obtaining the relationship weights, the inter-government collaborative relationship matrix can be constructed as follows.

$$A_t = [a_{ij,t}]_{n \times n}, \quad a_{ij,t} = \begin{cases} w_{ij,t}, w_{ij,t} \geq \tau \\ 0, w_{ij,t} < \tau \end{cases} \tag{9}$$

where, τ is the effective threshold of collaborative relationship. When $w_{ij,t}$ is lower than the threshold, it means that the relationship between the subjects is weak, and it is difficult to form a stable cross-domain governance role. When $w_{ij,t}$ reaches the threshold, then it is included in the effective cooperative network. This processing can reduce the interference of low intensity and low persistence interaction on network structure judgment, and make the model identification results closer to the actual governance operation state. In order to further judge the overall coordination level of the network, this paper selects network density, node centrality and cross-domain bridging ability as the main indicators. Network density is used to describe the overall degree of connectivity between inter-government subjects, and is calculated as follows.

$$\mathrm{Den}_t = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} I\,(a_{ij,t} > 0)}{n(n-1)} \tag{10}$$

where, $I(a_{ij,t} > 0)$ is the indicator function, which takes 1 if there is an effective synergistic relationship between subject i and subject j, and 0 otherwise. The higher the network density, the more fully the connection between the cross-domain governance subjects, the smoother the information flow and resource allocation. If the network density is low, it indicates that regional governance still has problems such as department segmentation, administrative boundary obstruction or idle coordination mechanism.

Node centrality is used to identify subjects that assume key coordination functions in cross-domain ecological environmental governance. If a government or department maintains a high intensity of contact with multiple regions, and can continuously organize joint monitoring, pollution tracking and bioengineering remediation projects, the node has a high centrality in the network. Cross-domain bridging capability is then used to identify subjects that connect different watersheds, different urban agglomerations, or different ecological functional zones. Although not necessarily at the highest administrative level, this type of agent may play an important role in information transmission, technology diffusion and dispute coordination.

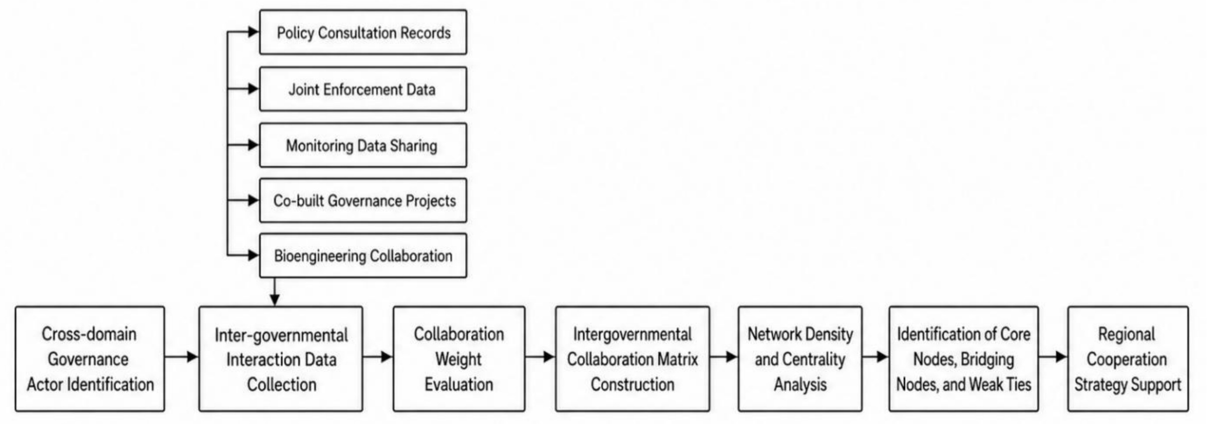

Figure 2: Inter-government collaborative relationship identification process based on social network analysis

As shown in Figure 2, the model starts from the identification of cross-domain governance subjects, and after the collection of inter-government interaction data, the calculation of relationship weights and the construction of collaborative relationship matrices, the governance network that can be used for analysis is formed. The model output includes core coordinating agents, edge participating agents, cross-domain bridging nodes, and collaborative weak relations. If a region is in a key position on the pollution spilt path, but its network centrality and bridging capacity are low, it means that there may be insufficient governance responsibility or insufficient collaborative participation in the region. If a subject has both high centrality and strong bioengineering collaboration connection, it can be set as the lead node of the regional ecological restoration project.

2.3 Decision-making mechanism of regional cooperative governance strategy

The regional cooperative governance strategy decision-making mechanism is used to transform the ecological risk level, inter-government collaborative network structure and bioengineering adaptation results obtained in the previous article into executable governance actions. Cross-domain ecological environmental problems have obvious externalities. Pollution control, ecological restoration or industrial adjustment in one region will affect the environmental quality and governance cost of adjacent regions. Therefore, when formulating actions, each governance body should not only rely on the short-term benefits of its own jurisdiction, but also consider the overall ecological objectives of the region, the stability of inter-government relations and the long-term effects of bioengineering restoration. In this paper, the set of alternative actions of regional governance agent i at time step t is expressed as follows.

$$\mathrm{A_{i,t}} = \{\mathrm{a^r_{i,t}}, \mathrm{a^m_{i,t}}, \mathrm{a^c_{i,t}}, \mathrm{a^b_{i,t}}\} \tag{11}$$

where, $\mathrm{a^r_{i,t}}$ represent pollution source constraint actions, $\mathrm{a^m_{i,t}}$ represent joint monitoring actions, $\mathrm{a^c_{i,t}}$ represent cross-domain negotiation actions, and $\mathrm{a^b_{i,t}}$ represent bioengineering repair actions. Different agents select action combinations according to ecological risk status, collaborative network location and their own resource conditions. If the regional risk level is high and the cross-regional spilt influence is obvious, the governance mechanism emphasizes more on government leadership and forced coordination. If the risk is in the controllable range and there is a stable cooperation foundation between the subjects, the evolutionary cooperation mechanism can be introduced to form stable cooperation among the government, scientific research institutions and repair enterprises in the long-term interaction. Figure 3 shows the overall structure of the decision-making mechanism of regional cooperative governance strategy in this paper. This structure brings administrative coordination, bioengineering and network collaboration into the same governance decision-making framework to avoid the disconnection of the three elements in the strategy design.

Figure 3: Structure of decision-making mechanism for regional cooperative governance strategy

Under this mechanism, the government-led strategy emphasizes centralized judgment of risk status by core governance subjects, and promotes collaborative execution through administrative coordination, joint law enforcement and project scheduling. Evolutionary cooperative governance strategy emphasizes that agents adjust their actions according to benefits, punishments, behaviors of neighboring agents and ecological restoration performance in long-term interaction. The two types of strategies are not mutually exclusive, but switch dynamically according to the risk level and collaborative maturity.

2.3.1 Government-led collaborative governance strategy

The government-led collaborative governance strategy is suitable for the governance context of high ecological risk, obvious pollution spillover, or unstable formation of inter-government collaborative network. The strategy sets up a core governance body with overall rights, which can be the provincial ecological and environmental authorities, watershed management agencies or cross-regional joint conference offices. According to the comprehensive risk index, the inter-government collaborative network measurement results and the bioengineering adaptation status, the core agent issues governance tasks to the relevant regional governments and supervises the implementation of actions.The core objectives of the government-led strategy can be expressed as follows.

$$\max \mathrm{Z_t} = \eta_1 \Delta \mathrm{E_t} + \eta_2 \Delta \mathrm{C_t} + \eta_3 \Delta \mathrm{B_t} - \eta_4 \mathrm{K_t} \tag{12}$$

where, $\mathrm{Z_t}$ represents the comprehensive governance utility at time step t; $\Delta\mathrm{E_t}$ represents the improvement of ecological environment; $\Delta\mathrm{C_t}$ represents the improvement range of inter-government coordination capability; $\Delta\mathrm{B_t}$ represents the improvement of bioengineering repair performance; $\mathrm{K_t}$ represents the governance cost; $\eta_1, \eta_2, \eta_3, \eta_4$ are the weight coefficients. This objective function reflects the basic direction of the government-led strategy, which is to enhance environmental improvement, collaborative efficiency and restoration performance under the condition of controlling the cost of governance.

In the specific operation, the core governance subject divides the governance tasks into three categories according to the risk level: conventional coordination, strengthened management and control, and emergency linkage. For mild risk areas, focus on promoting monitoring data sharing and joint inspection; For medium-high risk areas, cross-domain law enforcement, pollution source emission limitation, ecological compensation and bioremediation engineering should be configured. For severe risk regions, cross-regional emergency response is initiated and relevant subjects are required to perform governance actions synchronously. Its action constraint can be expressed as follows.

$$\sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{x_{i,t}}\, \mathrm{g_{i,t}} \geq \mathrm{G_t^{min}} \mathrm{i} = 1 \tag{13}$$

where, $\mathrm{x_{i,t}}$ represent whether subject i participates in the government-led collaborative action, participation is 1, otherwise it is 0; $\mathrm{g_{i,t}}$ denotes the governance contribution ability of subject i; $\mathrm{G_t^{min}}$ represents the minimum required governance intensity at the current risk level. If the actual governance intensity is lower than the threshold, it means that the current collaborative investment is insufficient, and administrative constraints need to be improved or cross-domain resource allocation needs to be increased.

The advantages of the government-led strategy lie in its fast response speed, clear responsibility boundary, and strong action consistency, especially in situations such as pollution transboundary transfer, sudden water quality abnormality, and ecological restoration project delay. However, this strategy may also suffer from strong administrative dependence, insufficient local initiative, and limited long-term cooperation flexibility. Therefore, after the ecological risk tends to be stable, it is necessary to gradually introduce the evolutionary cooperation mechanism, so that each agent can form self-restraint and cooperation profit expectation in continuous interaction.

2.3.2 Evolutionary cooperative governance Strategy supported by bioengineering

The evolutionary cooperative governance strategy supported by bioengineering emphasizes that each governance agent adjusts its own strategy according to benefits, costs, punishments and the behaviors of neighboring agents in the long-term collaboration. Different from the government-led strategy, this mechanism does not completely rely on administrative orders from higher levels, but uses bioengineering restoration projects as cooperation carriers connecting different regions, so as to form stable interactions between upstream and downstream, pollution export sites and ecological bearing sites, and government departments and technical institutions. In evolutionary cooperative governance, the comprehensive benefit of agent i is composed of ecological improvement benefit, collaborative network benefit, bioengineering performance benefit and governance cost.

$$U_{i,t} = \rho_1 e_{i,t} + \rho_2 c_{i,t} + \rho_3 b_{i,t} - \rho_4 k_{i,t} - \rho_5 p_{i,t} \tag{14}$$

where $U_{i,t}$ denotes the governance gain of agent i at time step t; $e_{i,t}$ represents the benefit of ecological quality improvement in the region; $c_{i,t}$ represents the resource and information benefits brought by inter-government collaboration; $b_{i,t}$ denotes the bioengineering remediation performance gain; $k_{i,t}$ denotes the governance input cost; $p_{i,t}$ denotes the penalty cost caused by insufficient coordination or pollution spillover; $\rho_1, \rho_2, \rho_3, \rho_4, \rho_5$ are the payoff weights. If the subject participates in the joint restoration and achieves better ecological performance, its income will increase. If the subject reduces the input or shifts the pollution pressure, the penalty cost increases.

The cooperative tendency of agents is not fixed, but adjusted according to historical payoffs and the performance of neighboring agents. In this paper, the probability that agent i chooses cooperative governance at the next time step is expressed as follows.

$$P_{i,t+1} = P_{i,t} + \omega(U_{i,t} - \overline{U}_{N_i,t})(1 - P_{i,t}) \tag{15}$$

where $P_{i,t}$ denotes the cooperation probability of agent i at time step t. $\overline{U}_{N_i,t}$ denotes the average payoff of its neighboring cooperative agents; Let ω denote the policy learning rate. When the agent's own profit is higher than the average level of neighboring agents, the probability of continued cooperation increases. When the revenue is lower than the average level of neighboring agents, agents may reduce their input or re-choose governance strategies. This setting reflects the demonstration effect and competition effect in cross-domain governance.

Bioengineering factors play a key regulatory role in this strategy. If a remediation technology has high adaptability to local pollution types, ecological conditions and treatment cycles, the benefits of cooperation are easier to be observed and shared, and the cooperative relationship between subjects is more stable. Bioengineering fitness can be expressed as follows.

$$H_{i,t} = \frac{r_{i,t} \cdot s_{i,t}}{k_{i,t} + 1} \tag{16}$$

where, $H_{i,t}$ denotes the bioengineering fitness of subject i; $r_{i,t}$ denotes pollution reduction rate or ecological restoration rate; $s_{i,t}$ denotes the technology suitability score; $k_{i,t}$ denotes the unit governance cost. A higher fitness indicates that the technology has stronger governance value in the current region and can be used as a preferred choice for cross-domain joint projects. Figure 4 shows the applicable relationship of the two types of strategies under different governance situations. The horizontal axis represents the inter-government collaborative maturity, and the vertical axis represents the bioengineering fitness. Different quadrants correspond to different governance strategy choices.

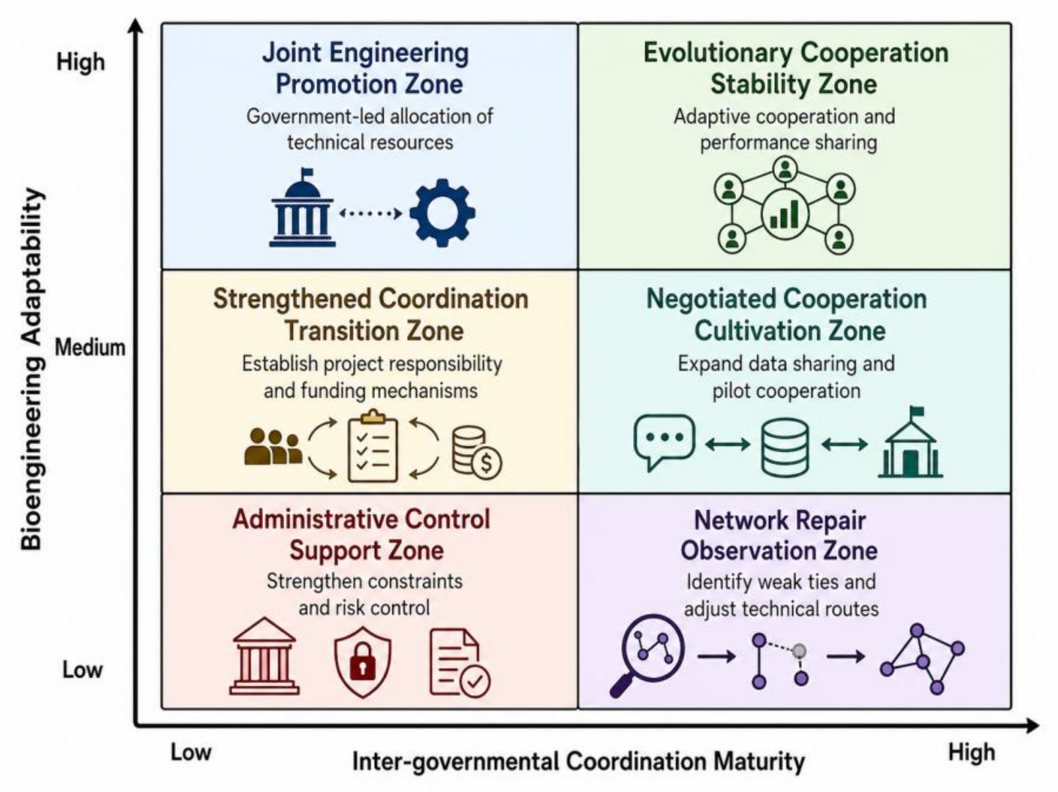

Figure 4: Strategy selection under inter-government collaborative maturity and bioengineering suitability

As can be seen from Figure 4, when the maturity of inter-government collaboration is low and the suitability of bioengineering is insufficient, regional governance needs to rely on government-led strategies to carry out risk coverage. When the suitability of bioengineering is high but the inter-government collaboration is still insufficient, the government should take the lead to promote the construction of joint projects to improve the efficiency of technical resource allocation. When the inter-government collaboration maturity and bioengineering suitability are both high, the evolutionary cooperation strategy is more applicable, and each agent can form stable cooperation through project revenue sharing, ecological compensation and performance feedback.

Therefore, the decision-making mechanism of regional cooperative governance strategy in this paper is not simply to choose a certain governance mode, but to dynamically match according to ecological risk, collaborative network and bioengineering conditions. The government-led strategy focuses on risk pressure reduction and responsibility integration, and the evolutionary cooperation strategy focuses on long-term repair, profit feedback and subject self-adjustment. After the combination of the two, the inter-government collaborative governance of cross-domain ecological environment can change from temporary linkage to structured cooperation, and from administrative task assignment to networked, technological and sustainable regional co-governance.

3 Governance scenario design based on typical cross-domain ecological environment regional data

This paper takes a watershed cross-domain ecological environment region as a prototype, constructs a simulation sample of governance scenarios, and sets up data structures around three types of variables: environmental monitoring, inter-government collaboration, and bioengineering restoration. The study area consisted of agricultural counties in the upper reaches, industrial parks in the middle reaches, central urban areas in the lower reaches and ecological buffer zones along the river, involving 4 prefecture-level cities, 12 counties and 3 types of major ecological sensitive units. The total area of the region is about 18,600 km², the main stream length is about 312 km, and the proportion of transboundary river reaches is 41.7%. The upstream region is mainly responsible for the reduction of farmland runoff and aquaculture wastewater, the middle reaches are concentrated in chemical, building materials and equipment manufacturing enterprises, and the downstream urban areas are facing the pressure of domestic sewage inflow, shoreline hardening and wetland degradation. Because the direction of pollution transmission is not consistent with the administrative boundary, the independent governance of a single region is prone to the problems of "insufficient upstream emission reduction, pressure on downstream governance" and "cross-border spillovers of ecological restoration benefits".

This paper constructs monthly scenario panel data from January 2021 to December 2023, forming a total of 36 time steps. The data include water quality monitoring, atmospheric monitoring, soil and ecological monitoring, inter-government collaborative records, and bioengineering restoration project data. Among them, the 2021-2022 data is used for parameter calibration, and the 2023 data is used for governance scenario validation. The specific variables and statistical characteristics are shown in Table 3. It can be seen from Table 3 that the total phosphorus, chemical oxygen demand, PM2.5 and the coverage rate of ecological buffer zone in the study area all show obvious cross-domain differences, indicating that there are simultaneously problems of pollution pressure, ecological vulnerability and unbalanced repair capacity in the region.

Table 3: Statistical characteristics of typical cross-domain ecological environmental governance data

Variable type	Indicator name	Mean	Standard deviation	Maximum	Minimum
Water environment	Ammonia nitrogen concentration (mg/L)	1.18	0.42	2.36	0.46
Water environment	Total phosphorus concentration (mg/L)	0.23	0.09	0.51	0.08
Water environment	Chemical oxygen demand (mg/L)	24.7	7.8	46.3	12.5
Atmospheric environment	PM2.5 concentration (μg/m³)	42.6	13.4	78.9	18.7
Soil ecology	Heavy metal composite index	0.47	0.16	0.82	0.19
Ecological restoration	Phytoremediation coverage rate (%)	36.8	11.6	61.2	18.5
Intergovernmental collaboration	Monthly average joint law-enforcement actions	5.4	2.1	11.0	2.0
Intergovernmental collaboration	Monthly average data-sharing activities	8.7	3.5	17.0	3.0

In order to ensure that data of different dimensions can enter the same model, monitoring variables and governance variables are standardized in this paper. The positive indicators are transformed using Equation (17), and the reverse indicators such as pollution concentration and risk index are processed in reverse:

$$\mathrm{X'}_{\mathrm{i,t}} = \frac{\mathrm{X}_{\mathrm{i,t}} - \mathrm{X}_{\mathrm{i}}^{\mathrm{min}}}{\mathrm{X}_{\mathrm{i}}^{\mathrm{max}} - \mathrm{X}_{\mathrm{i}}^{\mathrm{min}}} \tag{17}$$

where $\mathrm{X}_{\mathrm{i,t}}$ represents the original value of index i at time step t, $\mathrm{X'}_{\mathrm{i,t}}$ represents the normalized result, and $\mathrm{X}_{\mathrm{i}}^{\mathrm{max}}$ and $\mathrm{X}_{\mathrm{i}}^{\mathrm{min}}$ represent the maximum and minimum values of this index during the sample period, respectively. For a small number of missing monitoring values, this paper adopts the smoothing completion method of adjacent months:

$$\widehat{\mathrm{X}}_{\mathrm{i,t}} = \frac{\mathrm{X}_{\mathrm{i,t-1}} + \mathrm{X}_{\mathrm{i,t+1}}}{2} \tag{18}$$

where, $\widehat{\mathrm{X}}_{\mathrm{i,t}}$ are the estimated values after completion. The proportion of missing values in the sample was 2.8%, mainly concentrated in the months of individual soil sampling and the months of bioengineering project records updating lag, and the data after completion could maintain the continuity of time series.

In terms of scenario design, this paper sets up three types of governance scenarios: conventional zoning governance, government-led collaborative governance, and evolutionary cooperative governance supported by bioengineering. The parameter Settings for the three categories of scenarios are shown in Table 4. It can be seen from Table 4 that government-led collaborative governance increases the initial collaborative density from 0.34 to 0.52, and increases the intensity of joint law enforcement from 5 times per month to 12 times per month. The cooperative governance of bioengineering evolution further improves the frequency of data sharing and the input index of bioengineering, so that phytoremediation, microbial remediation and wetland purification projects can participate in long-term collaborative adjustment.

Table 4: Parameter setting of cross-domain ecological environment governance scenario

Parameter name	Conventional partitioned governance	Government-led collaborative governance	Bioengineering-based evolutionary cooperative governance
Number of participating governance entities	12	12	12
Initial intergovernmental collaboration density	0.34	0.52	0.52
Monthly average joint law-enforcement actions	5	12	9
Monthly average data-sharing activities	6	12	18
Bioengineering investment index	0.28	0.46	0.73
Target phytoremediation coverage rate (%)	42	55	68
Target load reduction rate of constructed wetlands (%)	18	29	41
Ecological compensation response coefficient	0.22	0.48	0.71
Strategy update cycle (months)	6	3	1
Target comprehensive risk index	≤0.60	≤0.45	≤0.35
Simulation period (months)	36	36	36

4 Results and discussion

Based on the three types of governance scenarios set in Section 3, this paper inputs environmental stress, spatial spilover, inter-government collaborative capacity, and bioengineering remediation capacity into the comprehensive risk index model, and updates the governance status according to monthly time steps. The simulation period is 36 months, each type of scenario is repeated 12 times, and the mean value is taken as the analysis result. The three scenarios are conventional zoning governance, government-led collaborative governance and bioengineering evolution cooperative governance. The evaluation indicators include comprehensive risk index, inter-government collaborative network density, proportion of cooperative subjects, pollution reduction rate and ecological restoration performance. The lower the comprehensive risk index is, the smaller the regional ecological environment risk is. The higher the density of inter-government collaborative network and the proportion of cooperative subjects, the more stable the connection between cross-domain governance subjects.

As shown in Figure 5, the three types of governance scenarios can all reduce the regional comprehensive risk index, but there are obvious differences in the decline amplitude and stability. Under the conventional zoning governance, the composite risk index decreased from 0.72 at the beginning to 0.58 at the 36th month. Although the risk was alleviated, the decline speed was slow, and the improvement rate became flat after the 18th month. The government-led collaborative governance declined faster, falling to 0.53 in the 12th month and 0.42 in the 36th month, indicating that unified coordination, joint law enforcement and centralized scheduling can quickly reduce cross-domain ecological risks. The comprehensive risk index finally dropped to 0.31, which was significantly lower than the other two scenarios, indicating that the governance effect could continue to accumulate after the joint action of bioremediation projects, ecological compensation and inter-government collaborative networks.

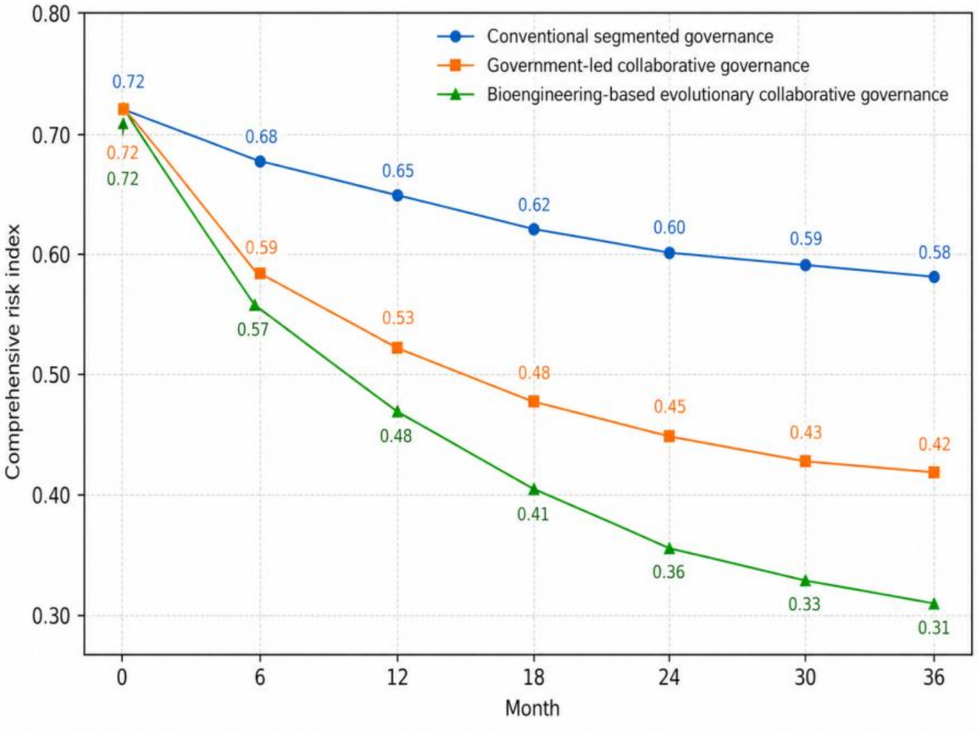

Figure 5: Changes in comprehensive risk index under different governance scenarios

Figure 5 reflects that conventional zoning governance mainly relies on the internal rectification of each administrative region, which is difficult to block the transboundary transmission of pollution in time. Government-led collaborative governance has a strong advantage in the early stage, because the core governance subjects can quickly integrate monitoring data, law enforcement resources and project funds. However, the decline in this scenario weakens after the 24th month, indicating that the marginal effect of governance will gradually decrease in the later period by relying solely on administrative push. In the early stage, there was little gap between the bioengineering evolutionary cooperative governance and the government-led governance. However, with the gradual play of plant remediation, microbial remediation and constructed wetland projects, the risk index continued to decline in the later stage, reflecting the composite advantages of technical remediation and collaborative network evolution.

The inter-government collaborative network indicators further illustrate the structural differences across governance scenarios. As shown in Figure 6, the network density of conventional partition governance only increases from 0.34 to 0.39, and the proportion of cooperative subjects increases from 50.0% to 56.7%, which indicates that low-frequency cooperation is still the main part between subjects, and the cross-domain governance connection is weak. Government-led collaborative governance increased the network density to 0.64, and the proportion of cooperative subjects reached 81.4%, indicating that administrative coordination can rapidly expand the coverage of cooperation. The network density of bioengineering evolution cooperative governance reaches 0.76, the proportion of cooperative subjects reaches 88.6%, and the average centrality of core nodes reaches 0.72, which indicates that the co-construction of bioengineering projects not only improves the synergy intensity, but also enhances the opportunity for marginal areas to participate in cross-domain governance.

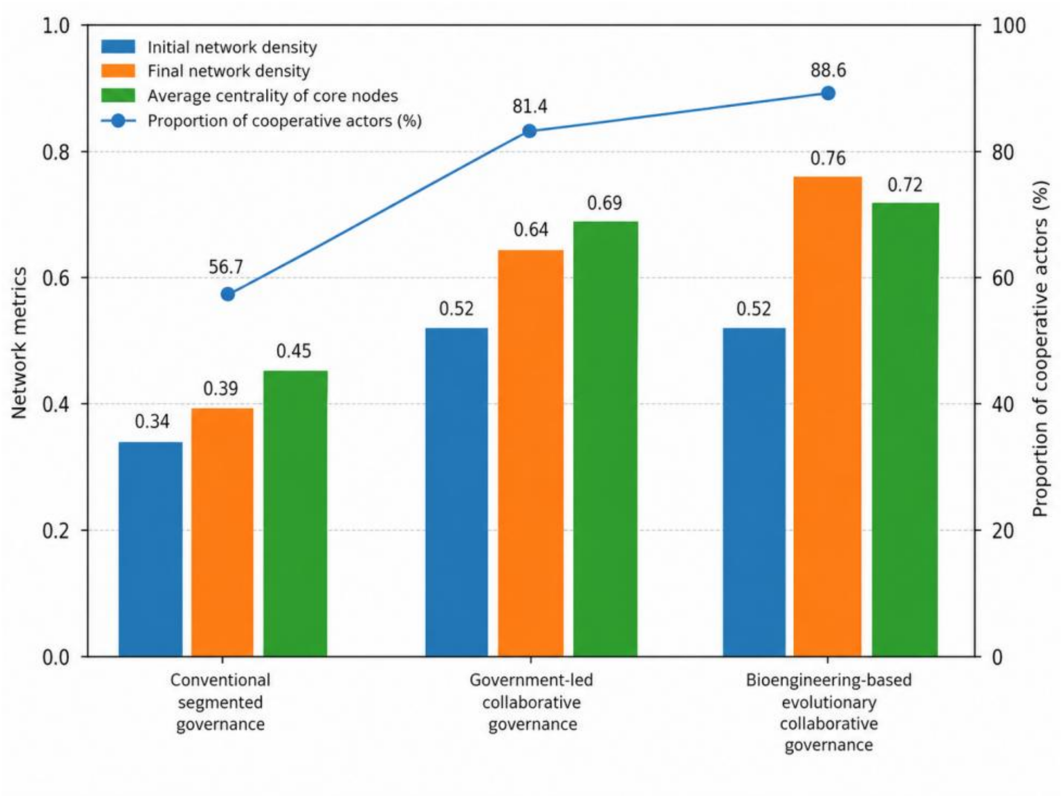

Figure 6: Comparison of inter-government collaborative network indicators

It can be seen from Figure 6 that although government-led collaborative governance can improve network density, its network structure is strongly dependent on the core coordination subject. Some local governments may return to the state of low cost and low input governance if the superior department's dispatch intensity declines. The advantage of cooperative governance of bioengineering evolution lies in embedding inter-government cooperation into specific ecological restoration projects. In the upstream region, pollution reduction and plant remediation were used to reduce the risk of spilover. In the midstream region, microbial remediation and enterprise emission reduction were used to reduce pollution load. In the downstream region, wetland construction and ecological buffer zone restoration were used to improve the carrying capacity. In the process of project co-construction, income distribution and later maintenance, the cooperative relationship is more stable.

From the perspective of environmental improvement indicators, the three types of governance scenarios also show obvious differences in pollution reduction and ecological restoration. As shown in Figure 7, under conventional zoning management, the reduction rate of chemical oxygen demand is 18.6%, the reduction rate of total phosphorus is 15.4%, the reduction rate of PM2.5 is 11.8%, and the reduction rate of constructed wetland load is 18.0%. The government-led collaborative governance increased to 31.2%, 27.8%, 23.5% and 29.0%, respectively, indicating that centralized law enforcement and unified scheduling had a strong control effect on short-period pollution indicators. The improvement rate of bioengineering evolutionary cooperative governance was even higher, with the reduction rate of chemical oxygen demand (COD) reaching 38.5%, total phosphorus (TP) reaching 35.7%, constructed wetland load reduction rate reaching 41.0%, and phytoremediation coverage rate increasing to 68.4%, slightly higher than the target value of 68% set by the scenario.

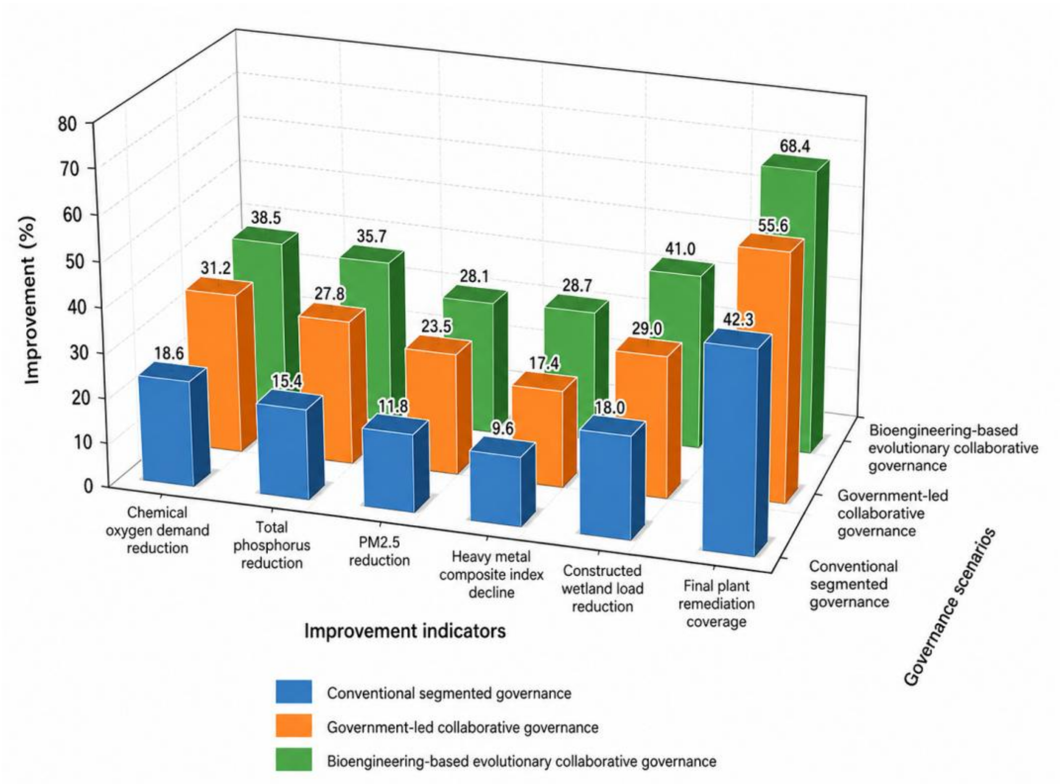

Figure 7: Improvement of environmental indicators under different governance scenarios

Figure 7 shows that the government-led collaborative governance has significantly improved the indicators that can be regulated, enforced and short-term interfered, such as chemical oxygen demand, total phosphorus and PM2.5. Bioengineering evolutionary cooperative management has more advantages in wetland purification, plant remediation and soil risk reduction. This shows that cross-domain ecological environmental governance cannot only rely on administrative control, but also need to embed bioengineering technology into the regional cooperation process. For water pollution, constructed wetlands and microbial remediation can be used to improve pollution degradation ability. For the risk of heavy metals in soil, the migration risk can be reduced by phytoremediation and ecological isolation zones. For ecological buffer degradation, regional ecological resilience can be enhanced through continuous shoreline restoration and vegetation restoration.

The comprehensive results show that conventional zoning governance can maintain the basic governance order, but it is difficult to effectively deal with the transboundary pollution transmission and the spillovers of ecological restoration benefits. Government-led collaborative governance has strong short-term control ability, and is suitable for high risk, dispersed responsibility or sudden pollution situations. The cooperative governance of bioengineering evolution performs better in the long-term operation, and the reason is that the mechanism improves the ecological restoration performance and the inter-government cooperation structure at the same time, so that the temporary linkage between governance subjects turns to sustainable cooperation. Therefore, a more reasonable path for inter-government collaborative governance of cross-domain ecological environment is to strengthen government leadership and unified scheduling in the stage of high risk, and gradually improve the co-construction, ecological compensation and collaborative network adaptive ability of bioengineering projects after the risk stabilizes, so as to form a regional cooperative governance mechanism with both short-term pressure drop effect and long-term repair ability.

5 Conclusion

Cross-domain ecological environmental problems have obvious spatial spiltionality and subject relevance, and it is difficult for a single region, single department or single engineering measure to effectively deal with pollution transmission, ecological restoration lag and governance responsibility dispersion. Focusing on the fusion application of social network analysis and bioengineering, this paper constructed a cross-domain inter-government collaborative governance model of ecological environment, which included ecological risk identification, inter-government collaborative relationship measurement, bioengineering adaptation and regional cooperation strategy into a unified analysis framework. The research shows that the social network analysis method can reveal the collaboration intensity, core nodes and weak connections between government subjects, and make the cross-domain governance relationship turn from empirical judgment to structural identification. Bioengineering technology provides a sustainable repair carrier for regional cooperation, which can improve the quality of ecological environment through plant remediation, microbial remediation, constructed wetlands and ecological buffer zone construction. The scenario simulation results show that conventional zoning governance has a limited role in reducing comprehensive risk, government-led collaborative governance has a strong short-term control effect, and evolutionary cooperative governance supported by bioengineering performs better in risk pressure drop, network stability and ecological restoration performance. This paper proposed that the inter-governmental collaborative governance of cross-domain ecological environment should strengthen government coordination, joint law enforcement and data sharing in the high-risk stage, promote the joint construction of bioengineering projects, ecological compensation and cooperation benefit feedback after the risk has stabilized, and form a regional governance mechanism with administrative constraints, technical repair and network coordination. Follow-up studies can further introduce longer period of measured data, and carry out comparative verification combined with different river basins, urban agglomerations and ecological functional areas, so as to improve the applicability and policy interpretation power of the model.

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References

[1] Chaffin B C, Floyd T M, Anzollitto P. Environmental governance networks and geography: A research agenda at the confluence of critical concepts for navigating rapid environmental change[J]. Annals of the American Association of Geographers, 2024, 114(8): 1718-1730.

[2] Huber M N, Angst M, Fischer M. The link between social-ecological network fit and outcomes: a rare empirical assessment of a prominent hypothesis[J]. Society & Natural Resources, 2024, 37(7): 1090-1107.

[3] McIlwain L, Baird J, Baldwin C, et al. Structural power dynamics in polycentric water governance networks[J]. Society & Natural Resources, 2024, 37(3): 402-427.

[4] Fried H, Hamilton M, Berardo R, et al. Engaged Network Tools to Close Collaborative Gaps: Uses, Limitations, and Design Principles[J]. Society & Natural Resources, 2024, 37(9): 1397-1416.

[5] Pozzi T, Zufall E, Gmoser-Daskalakis K, et al. Nascent policy subsystems in polycentric governance networks: The case of sea-level rise governance in the San Francisco Bay Area[J]. Policy Studies Journal, 2024, 52(3): 561-581.

[6] Koebele E A, Méndez-Barrientos L E, Nadeau N, et al. Beyond engagement: Enhancing equity in collaborative water governance[J]. Wiley Interdisciplinary Reviews: Water, 2024, 11(2): e1687.

[7] McNaught R. The application of collaborative governance in local level climate and disaster resilient development–A global review[J]. Environmental Science & Policy, 2024, 151: 103627.

[8] Battisti L, Cuomo F, Manganelli A. Collaborative governance arrangements: what makes nature-based solutions endure?[J]. Territory, Politics, Governance, 2025, 13(10):

1421-1441.

[9] Hölscher K, Frantzeskaki N, Kindlon D, et al. Embedding co-production of nature-based solutions in urban governance: emerging co-production capacities in three European cities[J]. Environmental Science & Policy, 2024, 152: 103652.

[10] Swette B, Huntsinger L, Lambin E F. Collaboration in a polarized context: lessons from public forest governance in the American West[J]. Ecology and Society, 2023, 28(1).

[11] Alblas E, van Zeben J. Collaborative agri-environmental governance in the Netherlands: a novel institutional arrangement to bridge social-ecological dynamics[J]. Ecology and Society, 2023, 28(1).

[12] Barraclough A D, Cusens J, Måren I E. Mapping stakeholder networks for the co-production of multiple ecosystem services: A novel mixed-methods approach[J]. Ecosystem Services, 2022, 56: 101461.

[13] Kiss B, Sekulova F, Hörschelmann K, et al. Citizen participation in the governance of nature-based solutions[J]. Environmental Policy and Governance, 2022, 32(3): 247-272.

[14] Hofstad H, Sørensen E, Torfing J, et al. Designing and leading collaborative urban climate governance: Comparative experiences of co-creation from Copenhagen and Oslo[J]. Environmental Policy and Governance, 2022, 32(3): 203-216.

[15] Kauark-Fontes B, Marchetti L, Salbitano F. Integration of nature-based solutions (NBS) in local policy and planning toward transformative change. Evidence from Barcelona, Lisbon, and Turin[J]. Ecology and Society, 2023, 28(2).

[16] Kuppan N, Padman M, Mahadeva M, et al. A comprehensive review of sustainable bioremediation techniques: Eco friendly solutions for waste and pollution management[J]. Waste management bulletin, 2024, 2(3): 154-171.

[17] Biermann C, Havlick D. Ecological restoration, genetics, genomics, and environmental governance[J]. Environment and Society, 2024, 15(1): 142-159.

[18] Ayilara M S, Babalola O O. Bioremediation of environmental wastes: the role of microorganisms[J]. Frontiers in Agronomy, 2023, 5: 1183691.

[19] Bhowmick K, Roy D, Rana D, et al. Potential microbes in bioremediation: a review[J]. Materials Today Sustainability, 2024, 28: 101032.

[20] Maglione G, Zinno P, Tropea A, et al. Microbes' role in environmental pollution and remediation: a bioeconomy focus approach[J]. AIMS microbiology, 2024, 10(3): 723.

[21] Lavanya M B, Viswanath D S, Sivapullaiah P V. Phytoremediation: An eco-friendly approach for remediation of heavy metal-contaminated soils-A comprehensive review[J]. Environmental Nanotechnology, Monitoring & Management, 2024, 22: 100975.

[22] Islam M M, Saxena N, Sharma D. Phytoremediation as a green and sustainable prospective method for heavy metal contamination: a review[J]. Rsc Sustainability,

2024, 2(5): 1269-1288.

[23] Sharma M, Rawat S, Rautela A. Phytoremediation in sustainable wastewater management: an eco-friendly review of current techniques and future prospects[J]. AQUA—Water Infrastructure, Ecosystems and Society, 2024, 73(9): 1946-1975.

[24] Matheson S, Fleck R, Irga P J, et al. Phytoremediation for the indoor environment: a state-of-the-art review[J]. Reviews in Environmental Science and Bio/Technology, 2023, 22(1): 249-280.