

Tripartite Evolutionary Game on Transboundary Pollution with Eco-compensation and Regulation

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Abstract:

Transboundary watershed pollution presents a classic collective action problem. Upstream and downstream governments often face coordination difficulties because abatement costs are local while benefits largely flow downstream. Eco-compensation mechanisms are widely adopted to internalize externalities, yet their effectiveness depends on compliance and oversight costs. Stringent regulation involves higher monitoring and enforcement expenses, while routine supervision maintains basic checks. To address this, we construct a tripartite evolutionary game model including upstream, downstream, and a superior regulator. Compensation is conditional on upstream performance and regulatory evaluations. We analyse strategy evolution under stringent and routine supervision using replicator dynamics. Our results reveal that moderate compensation effectively incentivizes upstream proactive governance, while too low or too high undermines the mechanism: low compensation fails to cover costs and discourages effort, while high compensation reduces downstream willingness to pay, weakening overall cooperation. The interaction between compensation level and regulatory intensity is crucial. Stringent supervision strengthens enforcement via penalties, but its long-term sustainability hinges on whether regulatory benefits—such as water quality improvement and credibility—outweigh enforcement costs. Furthermore, when synergistic gains from collaboration (environmental, economic, reputational) cover compensation outlays and institutional costs, the system tends to converge to a stable equilibrium of “active governance—compensation compliance—routine supervision.” This equilibrium ensures stable cooperation without excessive regulatory burden. This mature state avoids permanent stringent oversight while maintaining accountability through periodic monitoring. The study offers practical insights for optimizing compensation and sustaining transboundary cooperation.

Keywords:

Transboundary Watershed, Eco-compensation, Regulatory Supervision, Tripartite Evolutionary Game, Collaborative Governance

1. Introduction

Transboundary watershed pollution control is a quintessential collective action problem in regional environmental governance. Pollutants flowing downstream create

a spatial mismatch: upstream abatement costs are locally incurred, yet environmental benefits—improved water quality, reduced health risks, and secure water supply—spill over to downstream jurisdiction [1]. Under fiscal pressure, divergent performance evaluations, and development-oriented incentives, local governments often under-invest in pollution control, delay promised compensation, or shift responsibility to neighbours [2]. In China, this problem is exacerbated by administrative boundaries that fragment natural river systems, turning integrated watersheds into pieces of fragmented governance and magnifying cross-border externalities.

To internalize these externalities, ecological compensation has been widely adopted [3]. The core logic is that downstream beneficiaries compensate upstream protectors for the opportunity costs of conservation and pollution abatement. With major water diversion projects such as the South-to-North Water Transfer, China's watershed compensation schemes have evolved from pilot experiments to formal institutions [4-5]. However, compensation cannot be treated as unconditional fiscal transfers. Engel et al. and Wunder emphasize that effective payments for environmental services must be contingent on verifiable environmental performance; otherwise, guaranteed payments may weaken upstream effort [6], while unenforceable commitments by downstream parties can cause agreements to break down [7]. Thus, it is crucial to link compensation with performance monitoring, regulatory verification, and a well-designed penalty system, and to explore theoretically how multiple agents adjust their strategies over the long run. Yi et al. [8] and Lu et al. [9] respectively constructed differential game models for watershed ecological compensation and multi-regional coalitions; Chen and Ren further compared transboundary water pollution control strategies under different management scenarios [10].

Existing studies follow three main analytical routes. Cooperative game models focus on fair cost-sharing among riparians, starting with Ambec and Sprumont's "sharing a river" framework [11], later extended to polluted rivers by Ni and Wang [12], to river networks, and to permission structures [13]. These models explain how to allocate costs once cooperation is formed, but they say little about how cooperation emerges, how compensation is enforced, or when supervision should exit. Differential game models incorporate pollution stocks, investment dynamics, and long-term welfare, providing optimal paths under full rationality and perfect foresight [14]. Yet they are less suited to capturing the bounded rationality, learning, and gradual adjustment that characterize local government behavior. In contrast, evolutionary game theory assumes bounded rationality and uses replicator dynamics to model strategy adaptation through payoff comparisons and imitation [15]. This approach has been increasingly applied to watershed compensation and transboundary pollution [16]. Nevertheless, most evolutionary studies treat compensation as an exogenous lump-sum transfer, rarely linking it to performance and regulatory intensity; they often fail to distinguish between stringent and routine supervision, and the feasible interval of compensation—along with its interaction with penalties and synergy gains—remains underexplored.

To fill research gaps, we build a tripartite evolutionary game model with an upstream government, a downstream government, and a superior regulator—who, in China's hierarchical system, possesses monitoring, coordination, and sanction powers—to study the regulation–compensation–coordination mix. Eco-compensation is conditional on upstream performance and regulatory verification, and we distinguish stringent versus routine supervision. Using payoff matrices, replicator

dynamics, and simulations, we examine the feasible compensation interval, the expansion effect of penalties, and the transition from stringent to routine supervision. Results show that a feasible interval exists only when total synergy gains and loss avoidance exceed costs and opportunistic profits. Penalties widen this interval, but only if stringent supervision yields net benefits to the regulator. When synergy gains cover all costs, the system converges to a mature cooperative state [17].

Our contributions are threefold: first, we unify compensation, penalties, and synergy gains in a tripartite evolutionary framework; second, we derive an analytical expression for the feasible compensation interval, avoiding the incentive distortions of unconditional payments; third, we distinguish mature coordination from stringent coordination and reveal the sustainability condition for strict oversight. The remainder of the paper is organized as follows: Section 2 presents the model and payoff matrix; Section 3 derives replicator dynamics and stability conditions; Section 4 reports numerical simulations; Section 5 concludes with policy implications.

2. Model Assumptions and Payoff Matrix

The model incorporates three participants: the upstream government U , the downstream government D , and the higher-level regulatory authority G . The probability that the upstream government chooses active governance is x , and the probability of choosing passive governance is $1-x$. The probability that the downstream government chooses to fulfill ecological compensation is y , and the probability of choosing to refuse ecological compensation is $1-y$. The probability that the higher-level regulatory authority chooses strict regulation is z , and the probability of choosing routine regulation is $1-z$. As shown in Table 1.

It is necessary to clarify that “routine regulation” in this paper does not imply a complete absence of supervision. Instead, it refers to maintaining fundamental water quality monitoring, governance performance verification, and information disclosure mechanisms. “Strict regulation” builds upon routine regulation by incorporating high-frequency inspections, special inspections, and punitive enforcement. Therefore, even if the regulatory authority opts for routine regulation, ecological compensation can still be paid conditionally based on the baseline evaluation results.

Table 1. Three stakeholder parties and strategy settings.

Stakeholder	Strategy I	Strategy II	Probability
Upstream government U	Active governance	Passive governance	$x, 1-x$
Downstream government D	Fulfill compensation	Refuse compensation	$y, 1-y$
Superior regulatory agency G	Strict supervision	Routine supervision	$z, 1-z$

The assumptions are grounded in watershed compensation practices and prior studies: upstream bears pollution control costs, downstream benefits from improved water quality via payments; payments should hinge on verifiable performance, not unconditional transfers; and superior oversight is essential for upstream–downstream cooperation. Accordingly, we make the following assumptions:

Assumption 1: Active upstream governance incurs cost C_U and yields benefit B_U . If downstream compensates and upstream passes assessment, upstream receives; synergy adds S_U . This follows PES logic (protector costs, beneficiaries pay by performance) and water-quality-based compensation in projects like South-to-North Water Diversio [18].

Assumption 2 Passive upstream governance yields short-term opportunistic benefits H_U , but incurs environmental and reputational losses L_U , and is penalty F_U under strict supervision. In practice, upstream regions often relax governance for short-term gains, transferring pollution downstream. Empirical work confirms that opportunity costs shape upstream behavior and that penalties deter passivity.

Assumption 3: Downstream compliance cost C_D ; compensation E is paid only if upstream actively governs and passes verification; otherwise, no transfer occurs. Fulfillment yields water quality benefits B_D and synergy benefits S_D ; refusal gives short-term gain H_D , but incurs penalty F_D under strict supervision. Willingness to pay depends on water quality gains.

Assumption 4: Strict supervision cost C_G , yields performance benefit B_G , additional reputation M_G , and synergy performance S_G , when formed. Routine supervision avoids high costs but incurs loss L_G when synergy fails. This aligns with China's basin compensation institutions, where central/ basin agencies coordinate and incentivize through assessment [19].

Assumption 5: The penalty parameters F_U and F_D are losses to violators but enforcement utility to the regulator—enhancing authority, reducing accountability risk, and improving enforcement, not merely fiscal revenue. This reflects the "deterrence" rather than "revenue" rationale in environmental regulation [20].

The main parameters and definitions are shown in Table 2.

Table 2. Main Parameters and Definitions.

Parameter	Definition
(C_U, C_D, C_G)	Governance cost (U) ; participation cost (D) ; supervision cost (G)
E	Ecological compensation amount
(B_U, B_D, B_G)	Governance benefit (U) ; water quality benefit (D) ; performance benefit (G)
S_U, S_D, S_G	Synergy benefits (U, D, G)
H_U, H_D	Opportunistic benefits: passive governance (U) , refusal (D)
L_U, L_D, L_G	Losses: environmental (U) , welfare (D) , performance (G)
F_U, F_D	Penalties for passive governance (U) and refusal (D) under strict supervision
M_G	Additional performance/reputation benefit from strict supervision (G)

The payoff matrix is presented under two scenarios based on the superior regulator's strategy: strict supervision and routine supervision. In each cell, the triplet denotes the payoffs for the upstream government, downstream government, and superior regulatory agency, respectively. Payoff matrix under strict supervision are shown in Table 3. Payoff matrix under routine supervision are shown in Table 4.

Table 3. Payoff matrix under strict supervision.

Upstream/Downstream	Fulfill compensation	Refuse compensation
Active governance	$U : B_U + S_U + E - C_U$ $D : B_D + S_D - E - C_D$ $G : B_G + S_G + M_G - C_G$	$U : B_U - C_U$ $D : B_D + H_D - F_D$ $G : B_G + M_G - C_G$

Passive governance	$U : H_U - L_U - F_U$ $D : -L_D - C_D$ $G : -L_G - C_G + F_U$	$U : B_U + S_U + E - C_U$ $D : B_D + S_D - E - C_D$ $G : B_G + S_G$
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Table 4. Payoff matrix under routine supervision.

Upstream/Downstream	Fulfill compensation	Refuse compensation
Active governance	$U : H_U - L_U - F_U$ $D : H_D - L_D - F_D$ $G : -L_G - C_G + F_U + F_D$	$U : B_U - C_U$ $D : B_D + H_D$ $G : B_G$
Passive governance	$U : H_U - L_U$ $D : -L_D - C_D$ $G : -L_G$	$U : H_U - L_U$ $D : H_D - L_D$ $G : -L_G$

3. Replicator Dynamics and Stability Analysis

3.1. Expected Payoffs and Replicator Dynamics Equations

To facilitate the derivation of the replicator dynamics equations from the payoff matrix, let π_U^A and π_U^N denote the expected payoffs for the upstream government when choosing active governance and passive governance, respectively; let π_D^P and π_D^R denote the expected payoffs for the downstream government when choosing to fulfill ecological compensation and to refuse ecological compensation, respectively; and let π_G^S and π_G^L denote the expected payoffs for the superior regulatory agency when choosing strict supervision and routine supervision, respectively.

For the upstream government, when it adopts active governance, its payoff depends on whether the downstream fulfills ecological compensation; when it adopts passive governance, its payoff mainly depends on whether it is penalized under strict supervision. Therefore:

$$\begin{aligned}\pi_U^A &= y(B_U + S_U + E - C_U) + (1 - y)(B_U - C_U), \\ \pi_U^N &= z(H_U - L_U - F_U) + (1 - z)(H_U - L_U).\end{aligned}\quad (1)$$

For the downstream government, when it fulfills ecological compensation, it needs to pay the compensation amount and bear the mechanism participation cost; when it refuses compensation, it can obtain short-term opportunistic benefits, but incurs a penalty under strict supervision. Therefore:

$$\begin{aligned}\pi_D^P &= x(B_D + S_D - E - C_D) + (1 - x)(-L_D - C_D), \\ \pi_D^R &= xz(B_D + H_D - F_D) + x(1 - z)(B_D + H_D) \\ &\quad + (1 - x)z(H_D - L_D) - (1 - x)(1 - z)(H_D - L_D).\end{aligned}\quad (2)$$

For the superior regulatory agency, the payoff under strict supervision is obtained by weighting the payoffs across the four combinations of upstream and downstream strategies; under routine supervision, it neither bears the high-intensity supervision cost nor obtains the penalty enforcement utility. From the payoff matrix, we have:

$$\begin{aligned}\pi_G^S &= xy(B_G + S_G + M_G - C_G) + x(1-y)(B_G + M_G - C_G + F_D) \\ &\quad + (1-x)y(-L_G - C_G + F_U) + (1-x)(1-y)(-L_G - C_G + F_U + F_D), \\ \pi_G^L &= xy(B_G + S_G) + x(1-y)B_G + (1-x)y(-L_G) + (1-x)(1-y)(-L_G).\end{aligned}\quad (3)$$

From the above expected payoffs, the payoff differences between the two alternative strategies for each of the three parties are obtained as follows:

$$\begin{aligned}\Delta_U &= \pi_U^A - \pi_U^N = B_U - C_U - H_U + L_U + y(S_U + E) + zF_U, \\ \Delta_D &= \pi_D^P - \pi_D^R = x(S_D - E) - C_D - H_D + zF_D, \\ \Delta_G &= \pi_G^S - \pi_G^L \\ &= xy(M_G - C_G) + x(1-y)(M_G - C_G + F_D) \\ &\quad + (1-x)y(F_U - C_G) + (1-x)(1-y)(F_U + F_D - C_G) \\ &= F_U + F_D - C_G + x(M_G - F_U) - yF_D.\end{aligned}\quad (4)$$

It is evident that B_G, S_G, L_G are performance terms that are either jointly gained or jointly borne under both strict and routine supervision; they cancel out in the strategy payoff differential and therefore do not directly determine the evolutionary direction of the regulatory strategy. Whether the regulatory agency chooses strict supervision mainly depends on the additional performance/reputation benefit M_G , the supervision cost C_G , and the penalty enforcement utilities F_U and D_U .

Similarly, Δ_D does not contain B_D or L_D . This is because, under the setting of this paper, the basic water quality improvement benefits or pollution losses are primarily determined by the upstream governance status. For a given upstream strategy, the downstream's choice to fulfill or refuse compensation does not change its underlying environmental benefits; thus, B_D or L_D appear in both downstream strategy payoffs and cancel out in the payoff difference. What actually changes are the synergy benefits, compensation payment, mechanism participation cost, opportunistic benefits, and regulatory penalties. Therefore, whether the downstream fulfills the compensation mainly depends on variables such as S_D, E, C_D, H_D, F_D . This specification captures the possible free-rider motivation of the downstream in transboundary watershed governance.

$$\begin{aligned}\dot{x} &= x(1-x)\Delta_U, \\ \dot{y} &= y(1-y)\Delta_D, \\ \dot{z} &= z(1-z)\Delta_G.\end{aligned}\quad (5)$$

Let

$$C_U + H_U - L_U - B_U - S_U < E < S_D - C_D - H_D, M_G < C_G \quad (6)$$

Then $\Delta_U = a + yb + zF_U$, $\Delta_D = xc + d + zF_D$, The Jacobian matrix of the system is

$$J = \begin{pmatrix} (1-2x)\Delta_U & x(1-x)(S_U + E) & x(1-x)F_U \\ y(1-y)(S_D - E) & (1-2y)\Delta_D & y(1-y)F_D \\ z(1-z)(M_G - F_U) & -z(1-z)F_D & (1-2z)\Delta_G \end{pmatrix}.\quad (7)$$

3.2. Boundary Equilibrium Points and Stability Conditions

At a boundary equilibrium, a variable at 0 yields an eigenvalue equal to its strategy payoff differential; at 1, the eigenvalue is the negative of that differential. If all three eigenvalues are negative, the equilibrium is locally asymptotically stable, corresponding to a specific strategy combination. Since our model is an asymmetric multi-population game with three heterogeneous agents, we avoid the ESS terminology from symmetric games and use “locally asymptotically stable” instead. Local stability only ensures convergence within a neighborhood, not global attraction. When the initial state is far from the equilibrium or parameters near the compensation boundary, the system may drift to other boundary equilibria or exhibit prolonged periodic/quasi-periodic fluctuations. Hence, the subsequent simulations examine evolutionary paths under varied initial conditions and parameter changes to test robustness. The eigenvalues for the eight boundary equilibria under general parameters are shown in Table 5.

Table 5. Eigenvalues of boundary equilibrium points under general parameter settings.

Equilibrium point	λ_x	λ_y	λ_z
$E_1(0,0,0)$	a	d	$F_U + F_D - C_G$
$E_2(1,0,0)$	$-a$	$c + d$	$M_G + F_D - C_G$
$E_3(0,1,0)$	$a + b$	$-d$	$F_U - C_G$
$E_4(0,0,1)$	$a + F_U$	$d + F_D$	$-(F_U + F_D - C_G)$
$E_5(1,1,0)$	$-(a + b)$	$-(c + d)$	$M_G - C_G$
$E_6(1,0,1)$	$-(a + F_U)$	$c + d + F_D$	$-(M_G + F_D - C_G)$
$E_7(0,1,1)$	$a + b + F_U$	$-(d + F_D)$	$-(F_U - C_G)$
$E_8(1,1,1)$	$-(a + b + F_U)$	$-(c + d + F_D)$	$-(M_G - C_G)$

Proposition 1 (Mature Synergistic State).

$$C_U + H_U - L_U - B_U - S_U < E < S_D - C_D - H_D, \quad M_G < C_G \quad (8)$$

$E_5(1,1,0)$ is a locally asymptotically stable equilibrium. Under this condition, the system stabilizes at “upstream active governance, downstream fulfills ecological compensation, and superior routine supervision.”

Proof: From Table 5, the three eigenvalues of $E_5(1,1,0)$ are $-(a + b)$, $-(c + d)$, and $M_G - C_G$. When $a + b > 0$, $c + d > 0$, and $M_G < C_G$, all three eigenvalues are negative; hence $E_5(1,1,0)$ is locally asymptotically stable. Substituting $a = B_U - C_U - H_U + L_U$, $b = S_U + E$, $c = S_D - E$, $d = -C_D - H_D$ yields the above conditions.

Proposition 1 indicates that there exists an effective interval for the ecological compensation amount. If the compensation is below the lower bound, it is insufficient to incentivize upstream active governance; if it exceeds the upper bound, it compresses the downstream net benefit from fulfilling the agreement.

Proposition 2 (Strong-Supervision Synergistic State).

$$C_U + H_U - L_U - F_U - B_U - S_U < E < S_D - C_D - H_D + F_D, \quad M_G > C_G \quad (9)$$

$E_8(1,1,1)$ is a locally asymptotically stable equilibrium. Compared with Proposition 1, strict supervision penalties reduce the lower bound of compensation required to motivate upstream active governance and raise the upper bound that downstream can

afford, thereby expanding the effective interval of the ecological compensation mechanism. However, whether strict supervision can be sustained in the long run depends on whether M_G exceeds C_G . In policy terms, $M_G > C_G$ implies that the additional performance, reputation, and accountability benefits from strict supervision are sufficient to cover the supervision cost, so the regulator has incentive to maintain high-intensity supervision. If $M_G < C_G$, then after the synergistic mechanism is basically established, the regulator is more likely to switch from strict to routine supervision.

Proof: From Table 5, the three eigenvalues of $E_8(1,1,1)$ are $-(a+b+F_U)$, $-(c+d+F_D)$, and $-(M_G-C_G)$. When $a+b+F_U > 0$, $c+d+F_D > 0$, and $M_G > C_G$, all three eigenvalues are negative; hence $E_8(1,1,1)$ is locally asymptotically stable. Substituting a, b, c, d yields the stability conditions in Proposition 2.

Proposition 3 (Existence Condition of the Effective Compensation Interval)

In the mature synergistic state, the effective interval for ecological compensation exists if and only if

$$C_U + H_U - L_U - B_U - S_U < S_D - C_D - H_D \Leftrightarrow B_U + S_U + L_U + S_D > C_U + H_U + C_D + H_D \quad (10)$$

This condition indicates that the combined benefits from upstream–downstream synergistic governance and the loss-avoidance effect must outweigh the sum of governance costs, mechanism participation costs, and opportunistic benefits. Otherwise, regardless of the ecological compensation amount, it is difficult to simultaneously satisfy the upstream incentive compatibility and downstream participation constraints.

Moreover, from Propositions 1 and 2, it follows that strict supervision lowers the lower bound of the effective compensation interval and raises the upper bound by F_D , thereby expanding the interval width by $F_U + F_D$. This implies that regulatory penalties not only alter short-term behavior but also expand the feasible scope of the compensation mechanism by reshaping the incentive compatibility boundaries.

In addition to the eight boundary equilibrium points, the system may also possess interior equilibrium points. An interior equilibrium requires that the payoff differentials for the three parties vanish simultaneously,

$$\Delta_U = 0, \Delta_D = 0, \Delta_G = 0 \quad (11)$$

jointly hold. Expanding the payoff differentials yields

$$\begin{cases} a + y^*(S_U + E) + z^*F_U = 0, \\ x^*(S_D - E) - C_D - H_D + z^*F_D = 0, \\ F_U + F_D - C_G + x^*(M_G - F_U) - y^*F_D = 0. \end{cases} \quad (12)$$

Therefore, the existence of an interior equilibrium point is not guaranteed; it depends on whether the above linear system has a unique solution satisfying $0 < x^* < 1, 0 < y^* < 1, 0 < z^* < 1$. If the solution falls outside the unit cube, this mixed state does not carry an interpretable probabilistic meaning. If the solution lies in the interior, its local stability must be assessed by the eigenvalues of $J(x^*, y^*, z^*)$; it is locally

asymptotically stable only if all eigenvalues have negative real parts. Under the baseline parameter values, the interior equilibrium point is approximately

$$(x^*, y^*, z^*) \approx (0.554, 0.613, 0.119)$$

$$\lambda(J^*) \approx \{-0.575, 0.287 \pm 0.675i\}. \quad (12)$$

Since there exist conjugate complex eigenvalues with positive real parts, this interior equilibrium is not locally asymptotically stable; it can be regarded as a threshold mixed state separating different evolutionary regions. This result also implies that near conditions of insufficient compensation, excessive compensation, or critical regulatory parameters, the system may exhibit rotational dynamics away from the interior point, leading to phased oscillations or long-term fluctuations in the evolutionary patterns. This paper focuses on boundary stable states with clear policy implications, while in the numerical simulations we examine the applicability of the boundary stability conclusions through different initial states and long-run average checks.

4. Numerical Simulation and Result Analysis

4.1. Parameter Settings and Stability Verification

To verify the theoretical results, baseline parameters are set as in Table 6. These parameters are designed for mechanism testing, not watershed-specific estimation, following three principles: (i) upstream active governance has a substantial cost, creating a positive compensation incentive threshold; (ii) the compensation amount is tested at low, moderate, and high levels; and (iii) supervision cost distinguishes sustainable from unsustainable strict supervision.

The replicator dynamics are solved numerically in Python over $t \in [0, 200]$, with initial state $(x_0, y_0, z_0) = (0.3, 0.3, 0.1)$. The fourth-order Runge–Kutta method with step $\Delta t = 0.05$ is used. To avoid misinterpreting transients, outcomes are assessed by the average strategy probabilities over the last 20% of the period $t \in [160, 200]$, rather than terminal values. Trajectory figures show only $t \in [0, 30]$ for readability, while stability checks and summary tables are based on full-length simulations.

Table 6. Baseline simulation parameters.

Parameter	C_U	C_D	C_G	E	B_U	B_D	B_G	S_U	S_D
Value	6.0	0.8	3.5	1.8	3.0	5.0	3.0	1.5	3.5
Parameter	S_G	H_U	H_D	L_U	L_D	L_G	F_U	F_D	M_G
Value	1.2	1.5	0.5	2.0	4.0	3.5	4.0	3.0	1.0

Baseline compensation interval, Substituting the baseline parameters yields:

$$E_{\min} = C_U + H_U - L_U - B_U - S_U = 1.0,$$

$$E_{\max} = S_D - C_D - H_D = 2.2. \quad (14)$$

This interval defines the feasible range for mature synergy under routine supervision: the lower bound reflects upstream incentive constraint, and the upper bound reflects downstream participation constraint. If $E < E_{\min}$, upstream lacks incentive to invest; if $E > E_{\max}$, downstream tends to refuse compensation.

Substituting the baseline parameters into the eigenvalue expressions of each boundary equilibrium point and determining their signs, the results show that E_2 and E_3 have positive eigenvalues and are unstable points; E_1, E_4, E_6, E_7 and E_8 all have both positive and negative eigenvalues, thus being saddle points; only $E_5(1,1,0)$ has all three eigenvalues negative (-0.80, -0.40, -2.50), so it is identified as a locally asymptotically stable equilibrium point. This indicates that under the baseline parameters, the system will tend toward the mature cooperative state of "upstream active governance—downstream fulfillment of compensation—superior routine supervision."

4.2. Comparison of Long-Run Averages Across Scenarios

To compare evolutionary outcomes under different institutional settings, we simulate five scenarios: baseline, low compensation, high compensation, sustainable strict supervision, and extended penalties. All simulations use the full replicator dynamics. The long-run state is evaluated by averages over $t \in [160, 200]$. In particular, $\bar{Q}$ is the time average of $\bar{Q} = \overline{x(t)y(t)}$, not $\overline{x(t)y(t)}$. Results are given in Table 7.

Table 7. Long-run averages (last 20% period) across main scenarios.

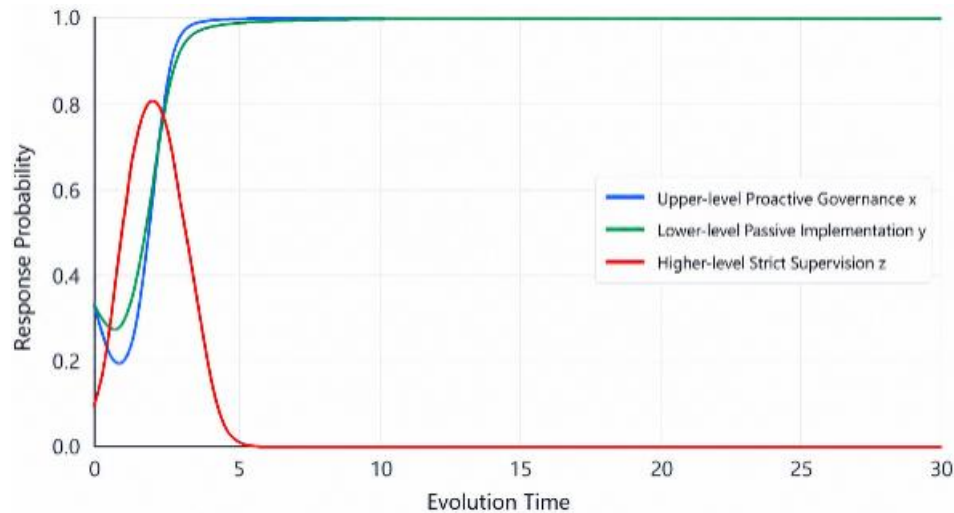
Scenario	Parameter	$\bar{x}$	$\bar{y}$	$\bar{z}$	$\bar{Q}$	Outcome description
Baseline	$E = 1.8$	0.999	0.999	0.001	0.998	Mature synergy
Low compensation	$E = 0.5$	0.625	0.921	0.217	0.623	Insufficient upstream incentive
High compensation	$E = 3.0$	0.828	0.592	0.311	0.581	Insufficient downstream compliance
Low compensation + strict supervision	$E = 0.5, F_U = 6.0, C_G = 0.5$	0.999	0.999	0.999	0.998	Downstream constraint expanded
High compensation + strict supervision	$E = 3.0, F_D = 5.0, C_G = 0.5$	0.999	0.999	0.999	0.998	Upstream constraint expanded
Low supervision cost	$C_G = 0.5$	0.999	0.999	0.999	0.998	Strict supervision sustained

Table 7 shows that in the baseline scenario $\bar{x}$, $\bar{y}$, and $\bar{Q}$ are all close to 1, while $\bar{z}$ is close to 0, indicating that the system converges to the mature synergistic state. In the low-compensation and high-compensation scenarios, the values of $\bar{Q}$ are 0.623 and 0.581, respectively, both substantially lower than that of the baseline, suggesting that when compensation deviates from the reasonable interval, the system may fail to converge to the mature equilibrium and instead exhibit periodic or quasi-periodic strategy adjustments. Furthermore, when the supervision cost is reduced to $C_G = 0.5$ and either F_U or F_D is increased accordingly, both the low- and high-compensation scenarios can regain a high level of synergy. This indicates that the conclusion that regulatory penalties expand the effective compensation interval requires the sustainability of strict supervision as a prerequisite. Under the baseline parameters

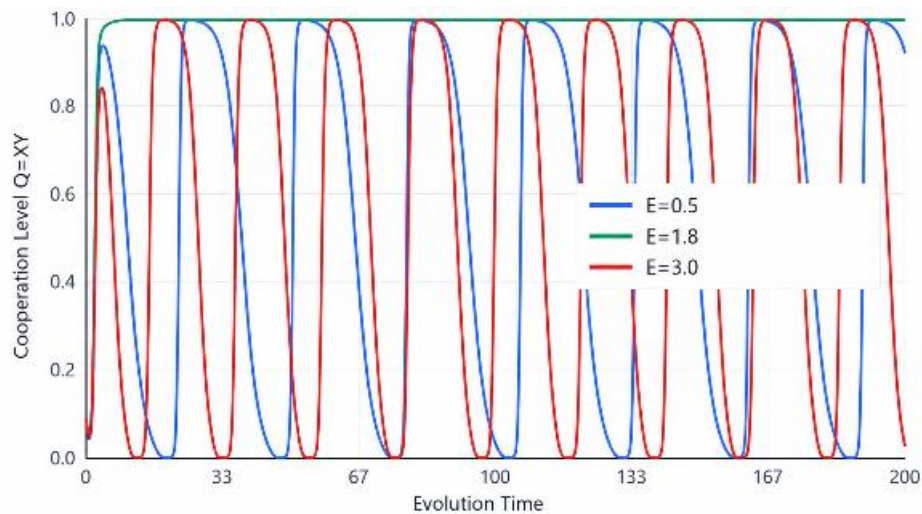
where $C_G > M_G$, penalties primarily serve to provide constraints and accelerate convergence during the mechanism-formation phase.

4.3. Dynamics and Compensation Sensitivity

The baseline scenario converges quickly, so the left panel of Figure 1 shows only $t \in [0, 30]$. The compensation sensitivity plots present the full $t \in [0, 200]$ trajectories to reveal long-term fluctuations under low and high compensation.



(a) $E = 1.8$



(b) $E = 0.5, 1.8, 3.0$

Figure 1. Simulation of Baseline Scenario and Eco-compensation.

Figure 1 shows that under the baseline parameters, the probability of upstream active governance and the probability of downstream compensation fulfillment both rise rapidly and converge toward 1, while the probability of strict supervision first increases briefly and then declines toward 0. The long-run average outcomes are close to the equilibrium, indicating that $E_5(1,1,0)$ strict supervision primarily plays a role in identification, constraint, and correction during the initial phase of mechanism formation. The level of synergistic governance is defined as $Q = xy$, representing the simultaneous occurrence of upstream active governance and downstream compensation fulfillment. When $E = 1.8$, the compensation amount lies

within the reasonable interval $1.0 < E < 2.2$, and $\bar{Q}$ remains at a high level in the long run. In contrast, when $E = 0.5$ or $E = 3.0$, the system exhibits notable fluctuations. The long-run averages are lower than those of the baseline scenario. This indicates that low compensation is insufficient to consistently incentivize upstream active governance, while high compensation compresses the downstream net benefit from fulfilling the agreement; both are detrimental to stable synergy.

It should be noted that the early fluctuations in the low- and high-compensation scenarios do not indicate computational errors, but rather result from bounded-rational agents adjusting their strategies in response to relative payoffs. When parameters lie outside the effective compensation interval or near the theoretical boundaries, the repelling dynamics near the interior mixed state cause the system to undergo pronounced strategy adjustments before gradually entering the neighborhood of a boundary equilibrium or settling into sustained fluctuations. Therefore, this paper combines graphical visualization with the last-20% period averages to avoid judging regime stability based solely on short-run trajectories.

4.4. Compensation Range and Regulatory Penalty Sensitivity

Figure 2, Figure 3, Figure 4 examines the reasonable compensation interval for ecological compensation from a continuous-parameter perspective. Figure 2 presents simulation results based on the full three-party model, with the vertical axis showing $t \in [160, 200]$ over $t \in [160, 200]$, and the vertical dashed lines marking the theoretical boundaries $E_{\min} = 1.0$ and $E_{\max} = 2.2$. It can be observed that within the reasonable interval the system more readily sustains a high level of synergy; outside this interval, the values do not mechanically drop to zero, but may instead exhibit non-zero long-run means after prolonged fluctuations, which is consistent with the low-compensation and high-compensation scenarios reported in Table 7. Figure 4 and Figure 5 illustrate, under the baseline regulatory cost, the joint effects of E and F_D on the long-term compliance probability y and the long-term collaborative governance level $\bar{Q} = \bar{x}(t)y(t)$, respectively. These two quantities differ in meaning: y reflects the downstream party's willingness to comply, whereas $\bar{Q}$ simultaneously requires active upstream governance and downstream compliance, thus better representing the overall level of collaborative governance. The black boundary lines in the figures denote the theoretical upper bound of compliance under sustainable stringent regulation, serving as a theoretical reference for the expansion effect of penalties in the complete three-party system. Non-zero long-run averages may still occur in the low- or high-compensation regions, because in these regions the system exhibits long-term fluctuations or periodically approaches cooperative states; the mean over the last 20% of the time horizon retains such dynamic information rather than simply being treated as zero. Since $C_G > M_G$ under the baseline parameters, stringent regulation is difficult to sustain over the long term, and the effect of penalties on long-term compliance also depends on whether the regulator consistently chooses stringent oversight. The low compensation + stringent regulation and high compensation + stringent regulation scenarios in Table 7 further demonstrate that when $C_G > M_G$, the role of penalties in extending the effective compensation interval can be more fully manifested.

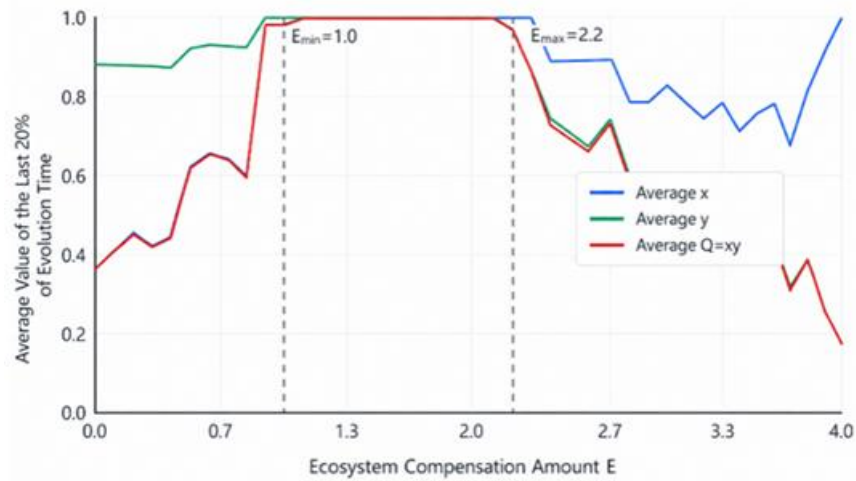


Figure 2. Complete Three-Party Model $E \in [0, 4]$.

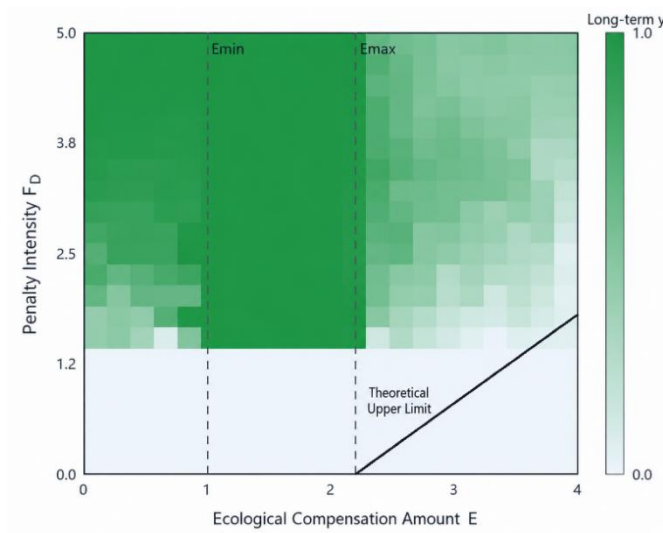


Figure 3. Baseline supervision cost $\bar{y}$.

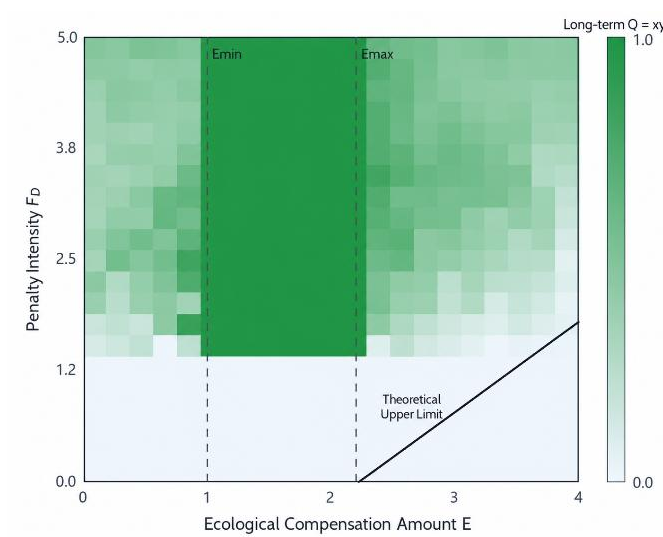


Figure 4. Amount of ecological compensation E .

4.5. Sensitivity of Regulatory Constraints and Collaborative Benefits

Figure 5 shows the effects of varying the penalty for downstream refusal to compensate F_D , while keeping all other parameters at their baseline values. The results indicate that a higher penalty intensity can restrain downstream refusal behavior during the stringent regulation phase and accelerate the increase in compliance probability; however, once the system transitions to routine regulation, long-term compliance still relies on reasonable compensation standards and collaborative benefits. Figure 6 demonstrates that when $C_G < M_G$, stringent regulation is more likely to persist over the long term, whereas when $C_G > M_G$, stringent regulation eventually ceases to be sustained. In particular, when $C_G = M_G = 1.0$, the eigenvalue associated with the regulatory direction $\lambda_z = M_G - C_G = 0$, equals zero, implying that the stringent regulation direction is at a critical state; linearized stability analysis is no longer conclusive, and small perturbations, initial conditions, and higher-order nonlinear terms may all influence the subsequent evolutionary path. The curves in the figure reflect only the evolutionary trends under the specific initial conditions considered.

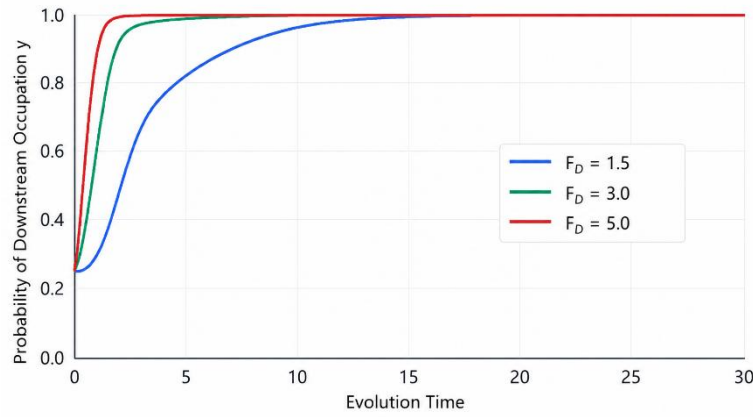


Figure 5. Penalty Intensity Simulation $F_D = 1.5, 3.0, 5.0$.

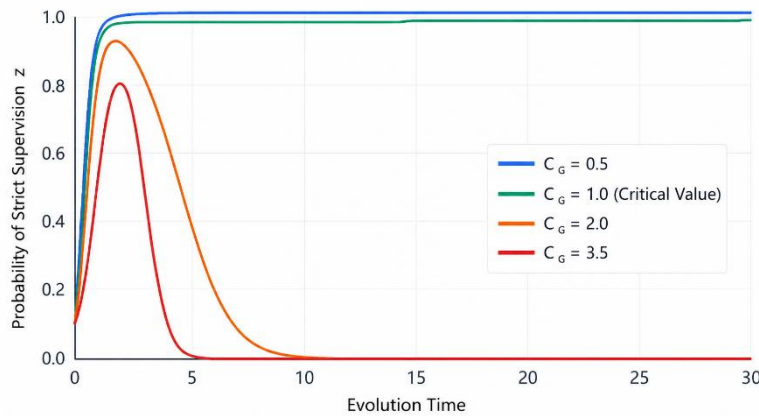


Figure 6. Regulatory Cost Simulation $C_G = 0.5, 1.0, 2.0, 3.5$.

Figure 7 adjusts the downstream collaborative benefit S_D around the baseline values and displays the full evolutionary trajectories over $t \in [0, 200]$. Under $E = 1.8, C_D = 0.8, H_D = 0.5$, and the downstream compliance constraint can be written as $E < S_D - C_D - H_D$, $S_D > E + C_D + H_D = 3.1$. Therefore, when $S_D = 2.5$, the condition is not

satisfied, and the collaborative governance level tends to exhibit long-term fluctuations; when $S_D = 3.5$ or $S_D = 4.5$, the condition is met, and the system more readily enters a mature collaborative state. Figure 8 shows that, for the four sets of initial states chosen in this study, differences in initial willingness mainly affect the convergence speed and early-stage paths, without altering the long-term evolutionary direction under the conditions that ensure stability. This result serves to illustrate that the baseline findings are somewhat robust to initial states, but it does not constitute a rigorous proof of global stability.

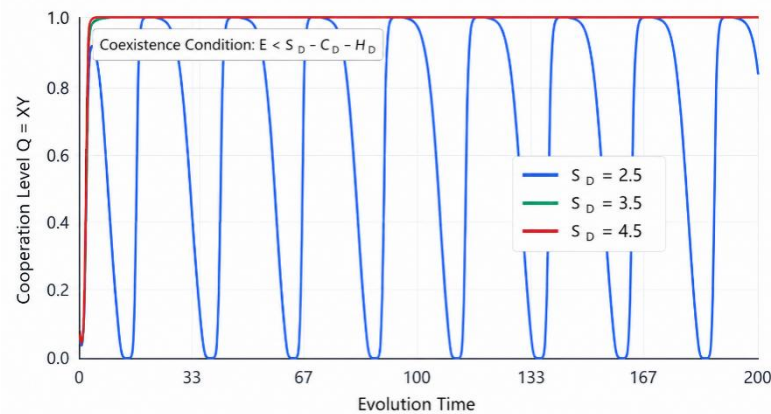


Figure 7. Synergy Benefit Simulation $S_D = 2.5, 3.5, 4.5$.

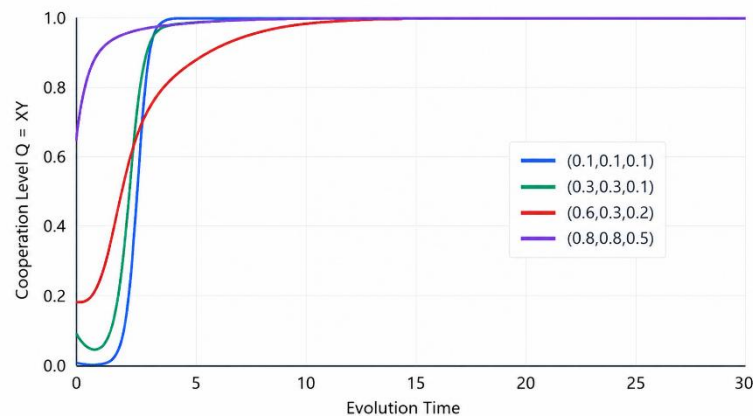


Figure 8. Initial State Simulation.

4.6. Phase Trajectory Analysis

Figure 9 presents the differences in $x-y$ phase trajectories under varying ecological compensation levels. The dots denote the initial states, the arrows indicate the direction of evolution, the asterisks mark the mean points over the interval $t \in [160, 200]$, and $(1,1)$ represents the mature collaborative state. When the ecological compensation deviates from the reasonable interval, the system does not necessarily converge to the mature collaborative equilibrium but may instead exhibit periodic or quasi-periodic strategic adjustments, reflecting the dynamic instability arising from an imbalanced governance mechanism in transboundary watershed systems.

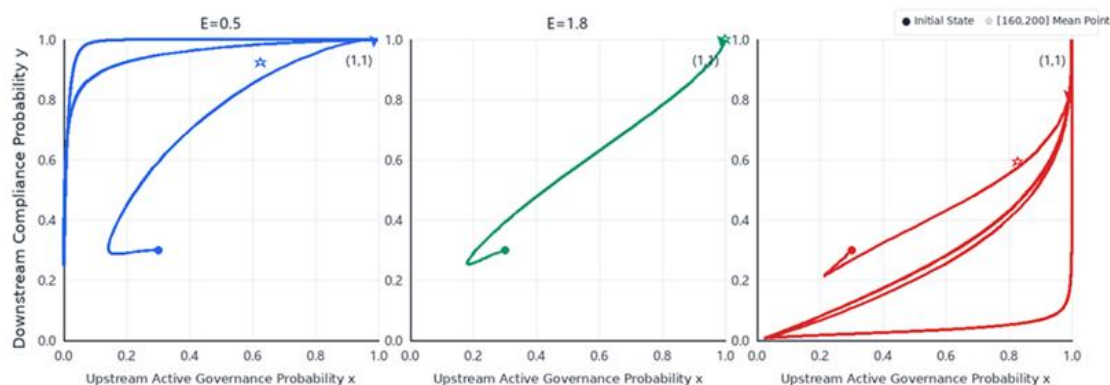


Figure 9: Mean points for $E = 0.5, 1.8, 3.0$ and $t \in [160, 200]$

5. Conclusions

This paper develops a three-party evolutionary game model comprising the upstream government, the downstream government, and a superior regulatory agency, focusing on the issues of insufficient ecological compensation compliance, misalignment of costs and benefits between upstream and downstream parties, and the regulator's choice of regulatory intensity in the collaborative governance of transboundary watershed pollution in China. Ecological compensation is modeled as conditional compensation linked to upstream governance performance and regulatory assessment. Two institutional scenarios—stringent regulation and routine regulation—are respectively characterized. The evolutionary dynamics of the system are examined through expected payoff derivation, replicator dynamic equations, local stability analysis of equilibrium points, and numerical simulations. The findings are as follows. First, under the model specification and baseline parameter settings, there exists a reasonable compensation interval $1.0 < E < 2.2$. When the compensation falls below this interval, the upstream party lacks sufficient incentives for active governance; when it exceeds this interval, the downstream party's net benefit from compliance declines. Although the specific boundaries of this interval depend on parameter values, the general logic that “too low or too high compensation hinders collaboration” is robust. Second, the effective compensation interval does not naturally exist; its emergence presupposes that the combined benefits from collaborative governance and loss-aversion effects are sufficient to cover governance costs, participation costs, and opportunistic gains of both upstream and downstream parties. Third, regulatory penalties can lower the minimum compensation required for upstream governance and raise the maximum compensation bearable by the downstream party; however, this expansion effect hinges critically on the sustainability of stringent regulation. When stringent regulation cannot be sustained over the long term, penalties mainly exert phased constraining and accelerating effects. Fourth, collaborative benefits and initial willingness primarily affect the speed of evolution, whereas institutional parameters—such as compensation standards, penalty intensity, and regulatory costs—determine whether the system can stably converge to a mature collaborative state.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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