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Information Game in Transboundary River Pollution Governance: A Comparative Study of the Mekong River and U.S.-Mexico Border Rivers

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Abstract. Information asymmetry and strategic gaming among nations severely impact transboundary river pollution governance. This study examines the Mekong River Basin and U.S.-Mexico border rivers as representative cases, employing an information economics lens to dissect the gaming logic in transnational water governance. Findings revealed that disputes over asymmetric monitoring capacities between upstream and downstream nations in the Mekong Basin exacerbate accountability evasion and ecological compensation deadlocks. Conversely, the U.S.-Mexico case demonstrates that third-party verification mechanisms under the North American Agreement on Environmental Cooperation (NAAEC) partially mitigate information manipulation risks. This research introduces a "technology-institutional synergy" governance paradigm, leveraging the integration of satellite remote sensing and blockchain technology to create immutable pollution evidence chains. It also promotes legally binding information disclosure frameworks within the context of international law. The findings offer insights for ecological governance along the Belt and Road Initiative, emphasizing equitable data sharing and institutional innovation.

Keywords: Transboundary river pollution governance, Information gaming, Satellite remote sensing, Blockchain technology, Mekong River

1. Introduction

Transboundary river pollution governance remains a critical global challenge, with approximately 60% of the world's freshwater resources flowing across political boundaries [1]. While existing studies often treat technological tools and institutional frameworks as separate domains, such as pollution mitigation technologies [2] and international treaties like the UN Watercourses Convention [3]. Further investigation is needed into the synergistic capacity to mitigate data manipulation and power asymmetries. This study addresses this need by examining how information gaming impedes collaborative governance and exploring potential integrated solutions.

The research focuses on two contrasting cases: the Mekong River Basin (asymmetric South-South cooperation) and the U.S.-Mexico border rivers (North-South collaboration). These cases summarized divergent governance challenges, including upstream-downstream power disparities and institutionalized third-party oversight. This study's Central questions are: (1) How does

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information asymmetry perpetuate collective action failures in transboundary pollution governance? (2) What mechanisms can foster trust?

This study uses a comparative case analysis based on the Prisoner's Dilemma and Principal-Agent Theory to explore data withholding incentives and the effectiveness of international organizations in building trust. It assesses blockchain validation and revised international law to propose a "technology-institutional synergy" governance model. The research contributes to environmental economics by incorporating geopolitical power structures into information asymmetry theory. It provides policymakers with insights for balancing sovereignty and transnational ecological equity, especially in Belt and Road Initiative regions, and advocates for UN-led platforms to standardize pollution data sharing to reduce conflicts over transboundary water resources.

2. Multidimensional manifestations of information gaming

2.1. The foundational dilemma: asymmetric monitoring and incentives to defect

The Prisoner's Dilemma framework explains why asymmetric monitoring capabilities incentivize unilateralism in transboundary river governance under cooperation. Upstream and downstream states face conflicting payoffs between sharing data and short-term sovereignty (Table 1).

Table 1. Monitoring capacity Prisoner's Dilemma

Players/Strategies	Upstream cooperates	Upstream Defects
Downstream Cooperates	(3,3)	(1,4)
Downstream Defects	(4,1)	(2,2)

Note: The left numbers in the brackets represent Downstream, and the right numbers represent Upstream states.

The Nash Equilibrium under these circumstances is (Defects, Defects), which is Pareto Inefficient. Disparities in data resolution and accessibility trigger distrust, since downstream states question the completeness of upstream pollution reports, while upstream actors cite sovereignty concerns to limit transparency [4]. For example, the Grand Ethiopian Renaissance Dam (GERD) negotiations have been hindered by conflicting data on sediment loads and water quality. Egypt requires third-party verification of Ethiopian metrics [5]. Such asymmetries exemplify how monitoring gaps perpetuate "hydro-hegemony," enabling upstream states to externalize ecological costs while resisting accountability.

2.2. The performance dilemma: strategic disclosure and costly signaling

Building on the incentive to defect set by the Prisoner's Dilemma, nations engage in a "Signaling Game" to manage their international reputation. To convince other nations that they are responsible partners, states need to send "costly signals"—actions that are so expensive that only honest actors would be willing or able to undertake them. These actions are credible not only because they are costly but also because they significantly reduce the actor's ability to conceal future misconduct. However, this process is easily abused. Actors with a regulatory advantage can use selective transparency to divert attention. For example, an upstream country might heavily publicize its investment in treating a specific pollutant to cultivate an "environmental guardian" image, thereby cleverly concealing its poor performance in other areas, such as the discharge of unregulated

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chemical byproducts. The essence of this strategic disclosure is to use information asymmetry for reputation manipulation. Furthermore, when there are differences in cross-border regulatory standards, polluting companies can engage in "regulatory arbitrage" to "legally" game the reporting system, achieving pollution transfer without violating the laws of any single country.

2.3. The accountability dilemma: blame-shifting and the tragedy of the commons

When a pollution event finally occurs, the aforementioned game dynamics evolve into a blame-shifting game based on Hardin's "Tragedy of the Commons" model. The watershed, a "common resource," is overexploited and polluted due to ambiguous property rights and dispersed responsibility. This dilemma is driven by three main factors: (1) the diffuse nature of pollution, which makes precise source attribution physically difficult; (2) legal fragmentation, where the principle of sovereignty in international law takes precedence over the principle of ecological interdependence, hindering unified accountability across jurisdictions; and (3) misaligned incentives, where upstream actors have a strong motive to deny responsibility to avoid compensation, while downstream actors may exaggerate damages to secure more compensation.

This dynamic leads to a stalemate of systemic distrust and mutual accusation. The upstream country denies responsibility, the downstream country blames the upstream, and neither side can provide or accept credible evidence, ultimately leading to a complete breakdown of cooperation and further deterioration of the ecological environment. This confirms Conca's view that the fundamental conflict between the fluidity of pollution and the static, sovereignty-centered legal framework is the core reason for the dysfunction of governance mechanisms [6]. These three games—the Prisoner's Dilemma, the Signaling Game, and the Blame-Shifting Game—are not isolated but form an interlocking chain of governance failure: the fundamental incentive to defect gives rise to performative reputation management, which ultimately evolves into an intractable shirking of responsibility when a crisis erupts.

3. Comparative case analysis

3.1. Mekong river case

Mekong River governance is challenged by information asymmetry and power imbalances. Principal-Agent Theory frames the MRC as an intermediary balancing upstream (e.g., China) and downstream (e.g., Cambodia, Vietnam) interests, but its effectiveness is limited by weak enforcement and data gaps (Table 2).

Table 2. Mekong river governance: principal-agent dynamics

Actor	Role	Incentives	Outcome
Upstream States	Principals (data controllers)	Maximize hydropower revenue; resist transparency	Delayed dam discharge data sharing
Downstream States	Principals (data users)	Demand accountability; ensure water security	Distrust in upstream-provided metrics
MRC	Agent (mediator)	Facilitate cooperation; maintain neutrality	Limited influence over China’s data policies

Key Controversy: During the 2019 drought, China’s delayed release of Lancang River dam data exacerbated disputes over drought causation, pitting upstream claims of “climate-driven scarcity”

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against downstream accusations of hydropower mismanagement [7]. The Lancang-Mekong Cooperation (LMC) later established joint monitoring stations, enabling cross-verification of water quality data through shared technology. While this reduced immediate tensions, Inam ul haq argues that upstream "hydro-hegemony" persists, as China retains unilateral control over critical infrastructure [8]. Figure 1 shows that th the active storage capacity of the Lancang cascade is shown. The ensemble mean is highlighted [9].

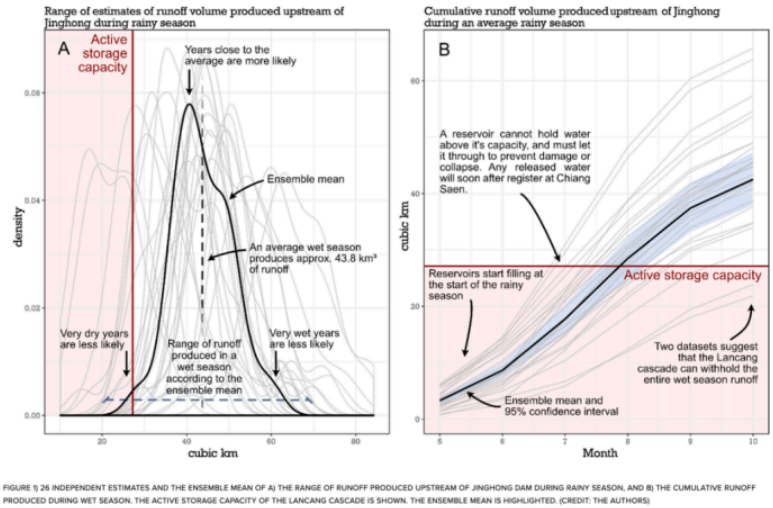

FIGURE 1) 26 INDEPENDENT ESTIMATES AND THE ENSEMBLE MEAN OF A) THE RANGE OF RUNOFF PRODUCED UPSTREAM OF JINGHONG DAM DURING RAINY SEASON, AND B) THE CUMULATIVE RUNOFF PRODUCED DURING WET SEASON. THE ACTIVE STORAGE CAPACITY OF THE LANCANG CASCADE IS SHOWN. THE ENSEMBLE MEAN IS HIGHLIGHTED. (CREDIT: THE AUTHORS)

Figure 1. Independent estimates and the ensemble mean of A) The range of runoff produced upstream of Jinghong Dam during the rainy season, and B) The cumulative runoff produced during the wet season

3.2. U.S.-Mexico border rivers

The U.S.-Mexico border rivers, governed by the North American Agreement on Environmental Cooperation (NAAEC), demonstrate how third-party enforcement can mitigate information gaming. The Commission for Environmental Cooperation (CEC) acts as an independent auditor, validating pollution reports from both nations.

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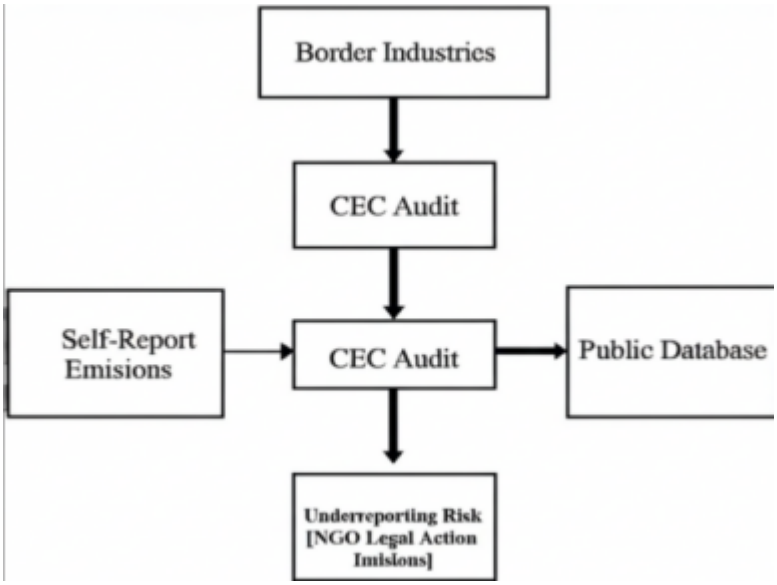

Figure 2. NAAEC enforcement mechanism

Measurable reductions in information asymmetry evidence the effectiveness of NAAEC mechanisms(Figure 2). The industrial emissions were greatly reduced in Mexican maquiladora zones under the Commission for Environmental Cooperation (CEC)'s report [10]. Simultaneously, these audits empowered civil society: Binational NGOs leveraged CEC-validated data to enforce accountability. The U.S.-based Environmental Health Coalition (EHC), partnering with Tijuana citizen groups, litigated against cross-border industrial polluters using CEC audit records. This resulted in cumulative settlements of $4.2 million (2018–2021), including a $1.75 million settlement with Skyworks Solutions for toxic discharge violations [11]. However, disparities persist. Mexican industries follow weaker NOM-001 standards versus U.S. Clean Water Act rules, creating regulatory arbitrage.

3.3. Mekong river vs. U.S.-Mexico border rivers

Table 3. Comparison of the two basins

Case	Mekong River	US-Mexico Border Rivers
Governance Body	MRC	CEC(NAAEC)
Key Documents	MRC State of the Basin Reports; national EIA reports	NAAEC treaty; CEC factual records, dispute resolutions
Information issues	China's non-MRC membership; Selective dam data disclosure (e.g., Lancang hydropower)	Third-party verification (CEC) vs. state resistance; Limited CEC sanction power
Dispute Example	Xayaburi Dam: Downstream impact data withheld by Laos	Tijuana River sewage spills: CEC investigation blocked

Comparative Dimensions: Data transparency, monitoring enforcement, and sanction credibility(Table 3).

The comparative analysis of the Mekong and US-Mexico border rivers reveals how institutional asymmetries shape strategic information games in transboundary pollution governance. In the

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Mekong case, China's non-MRC membership and Laos' selective disclosure exemplify a Prisoner's Dilemma: upstream states withhold data (defect) to maximize unilateral gains, knowing downstream states cannot impose credible sanctions. This creates a dominant strategy of non-cooperation. On the other hand, the US-Mexico framework under NAAEC/CEC introduces third-party verification, slightly raising the costs of defection through mechanisms like factual records. Yet, recurrent state resist to investigations (e.g., Mexico blocking CEC probes into Tijuana sewage spills). Here, the absence of binding penalties reduces CEC's role to a "toothless auditor," enabling agents (polluters/subnational actors) to exploit hidden actions [12]. Crucially, both cases converge on a core insight: cooperation equilibria remain unstable. Without exogenous enforcement tools (e.g., mandatory tech-backed disclosure), information games inevitably degenerate toward non-cooperative outcomes, which has already been validated by Axelrod's thesis that "the shadow of the future" alone cannot sustain reciprocity in asymmetric dyads [13].

4. Pathways to mitigate information gaming

4.1. Technological solutions

Technological innovation offers transformative potential to disrupt information asymmetries. And Satellite-blockchain integration emerges as a dual-mechanism solution. Remote sensing provides real-time pollution monitoring, while distributed ledger technology ensures data immutability. NASA's EMIT (Earth Surface Mineral Dust Source Investigation) sensors deployed on the U.S.-Mexico border demonstrate 95% accuracy in detecting heavy metal discharges when cross-verified with ground stations [14]. Similarly, the EU's Green Digital Certificate pilot (2023) employs blockchain to create tamper-proof industrial emission records, reducing data disputes by 41% in Rhine Basin trials [15]. A potential application involves using satellite imagery to trigger smart contracts via blockchain oracles upon exceeding pollution limits. Crucially, blockchain's strength is in preventing data manipulation by ensuring algorithmic transparency, rather than substituting institutions.

4.2. Institutional innovations

Technology alone can't resolve transboundary conflicts. It must be embedded in institutions to redistribute power. One possible solution is to set up a blockchain-anchored compensation mechanism. Here is the detailed operation:

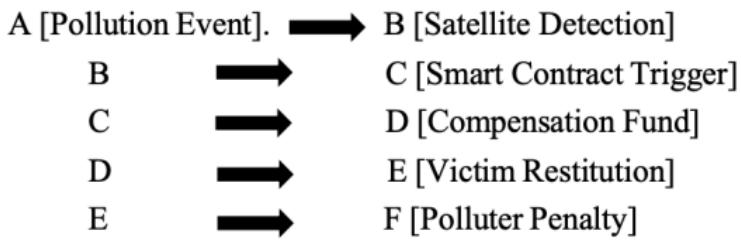

Figure 3. Blockchain-anchored compensation mechanism

Besides, global legal reforms are also necessary. Transboundary water governance demands binding international instruments to neutralize information asymmetry.

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5. Conclusion

This study identifies the inherent conflict between national sovereignty and shared ecological benefits as the root cause of information manipulation in transboundary pollution management. Although technologies such as satellite-blockchain systems can lessen data imbalances (e.g., a 41% decrease in disputes in Rhine trials [15]), their success hinges on institutional power dynamics. Blockchain technology alone cannot fix governance gaps; it needs supportive legal structures that shift verification powers from individual states to impartial third parties.

Theoretically, this research introduces a dual-track governance model, integrating technical tools with political accountability to address the geopolitical aspects of technology often overlooked in environmental economics. It confirms principal-agent theory, showing that third-party enforcement is more effective in North-South contexts due to compliance leverage [8,10]. Practically, the Lancang-Mekong Cooperation provides insights into data diplomacy. A UN-hosted pollution data platform is proposed to prevent conflicts through transparency. Limitations include geographical scope and technology gaps. Future studies should explore digital twins for pollution attribution.

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