

Governing Transboundary Risks of Atmospheric Water Resource Manipulation: Exploratory Evidence for Climate Governance

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Abstract

Deliberate atmospheric intervention is becoming part of the climate adaptation toolkit, yet its cross-border consequences fall outside existing climate governance frameworks. Drawing on 42 transboundary corridor pairs (2000–2023), this paper provides exploratory evidence of an association between upstream atmospheric water resource manipulation (AWRM) programme intensity and downstream infrastructure economic exposure. Fixed-effects panel estimates place this association broadly in the range of 7–12% per standard deviation, amplified in hydrologically stressed corridors. A stylised game-theoretic framework illustrates why non-cooperative equilibria generate inefficient outcomes when upstream states internalise only a fraction of corridor-wide costs. These are risk signals rather than verified causal estimates. The paper frames AWRM as a problem of climate governance rather than of meteorology alone: a policy-induced, cross-border environmental externality that current adaptation and water institutions are not designed to manage. Possible governance responses include prior notification obligations, shared atmospheric monitoring, and adaptation cost-sharing mechanisms.

Keywords: atmospheric water resource manipulation; climate governance; transboundary climate risk; climate adaptation; environmental externalities; adaptation finance

1. Introduction

Climate change adaptation increasingly extends beyond adjusting to changing hydroclimatic conditions towards deliberately modifying them. Governments across advanced and emerging economies are turning to atmospheric water resource manipulation (AWRM), principally cloud seeding and related precipitation enhancement technologies, as a policy response to climate-driven water scarcity. The scale of these programmes has expanded substantially. China’s Weather Modification Bureau targets large increases in annual precipitation across regions feeding shared transboundary river systems, and comparable programmes operate in the United Arab Emirates, the United States, Australia, and several Central Asian states (Keys et al., 2024; Li et al., 2025). Recent empirical studies confirm that precipitation enhancement is becoming both more widespread and more effective under favourable atmospheric conditions (Flossmann et al., 2019). AWRM is in turn best understood not as a meteorological curiosity but as a rapidly institutionalising climate adaptation strategy, one whose consequences need not remain within the borders of the states that deploy it.

A central insight of recent research is that climate risk does not respect political boundaries: both climate impacts and the adaptation responses they provoke propagate across borders through biophysical, trade, financial, and human pathways (Carter et al., 2021). Such transboundary climate risks remain a recognised blind spot in adaptation policy and planning (Anisimov and Magnan, 2023). AWRM introduces a variant of this problem that the transboundary climate risk literature has yet to address systematically: risk generated not by a climate hazard itself, but by another state’s adaptation decision. By altering upstream

precipitation patterns, AWRM may reshape downstream hydrological risk, with consequences for transport infrastructure across international boundaries. The stakes are considerable, because climate change already erodes infrastructure resilience through this same channel. Natural variability imposes measurable costs across inland waterways, road and rail networks, and maritime corridors, and warming is projected to widen transport networks' precipitation and flood exposure worldwide (Section 2.1). What has received far less attention is the governance challenge posed by state-managed amplification of that variability: policy-induced risk externalised onto neighbouring economies without any mechanism for burden-sharing or compensation.

Yet existing infrastructure-climate studies treat precipitation as an exogenous natural process, even as a growing body of scholarship treats the atmospheric water cycle itself as an object of governance (Section 2.2) and legal analysis concludes that existing international frameworks do not adequately discipline large-scale weather modification programmes (Sands, 2018; Simon et al., 2023). The distributional consequences compound the institutional gap. Downstream infrastructure networks face precipitation risk that is partly a function of upstream governance choices, not atmospheric physics alone, and they must absorb the resulting adaptation costs in a context in which the global adaptation finance gap stands at an estimated US\$187–359 billion per year (UNEP, 2024). No systematic evidence yet exists on whether AWRM-related changes generate infrastructure cost exposure comparable to natural climate variability. Nor have the strategic incentives for non-cooperative behaviour in corridors with embryonic governance mechanisms (Englezos et al., 2022) been formally analysed.

This paper addresses these gaps with three contributions. First, using a panel of 42 transboundary corridor pairs observed from 2000 to 2023, it documents a statistical association between upstream AWRM programme intensity and downstream infrastructure economic exposure, one substantially stronger in hydrologically stressed corridors (Chen et al., 2024). The findings identify risk signals relevant to governance; physical attribution between cloud-seeding operations and downstream hydrological outcomes lies beyond what observational panel data can establish. Second, a stylised game-theoretic framework illustrates the strategic logic of asymmetric cost internalisation and coordination failure. Third, the paper identifies possible governance pathways for managing AWRM-related transboundary risk. In doing so, the paper connects the climate-transport literature, the emerging scholarship on atmospheric water governance, and research on transboundary climate risk, and speaks to current policy debates on climate adaptation, infrastructure resilience, and adaptation finance.

2. Literature Review

2.1. Climate change, infrastructure resilience, and transport costs

The sensitivity of transport systems to hydrological variability is well established. For inland waterways, drought-induced low water levels impose measurable freight cost increases and modal disruption (Jonkeren et al., 2011, 2014; Christodoulou et al., 2020), with nonlinear cost intensification at extreme conditions (Chen et al., 2024). Road and rail infrastructure face parallel challenges: altered precipitation accelerates surface deterioration and flood risk (Koetse and Rietveld, 2009; Kellermann et al., 2016; Forzieri et al., 2018), and global evidence

confirms widening precipitation exposure (Liu et al., 2023b). Probabilistic assessments at different global warming levels reinforce the point for surface transport specifically: each increment of warming amplifies flood damage to road and rail networks, and several countries will need to increase, and potentially realign, transport investment towards climate resilience (Nawarat et al., 2026). This literature has established infrastructure resilience as a core concern of climate adaptation planning, but it shares a common premise: the hydroclimatic hazard is treated as natural in origin. What it has not addressed is the governance dimension that arises when a policy lever is inserted into the hazard-generating process itself. Quantifying AWRM externalities on infrastructure is a prerequisite for evidence-based policy, since actors cannot negotiate over risks they cannot observe.

2.2. Atmospheric water resource manipulation

The policy lever in question is cloud seeding, which introduces condensation nuclei into cloud systems to promote precipitation. Its contemporary deployment is bound up with climate change: the programmes examined in this paper were adopted primarily as responses to climate-related water scarcity (Section 1). The work by Flossmann et al. (2019) shows advancements in several technologies at once, confirming scientific development but emphasizing the role of preconditions of the atmosphere for achieving effectiveness. The constant ambiguity concerning counterfactuals is one of the most prominent obstacles (Silverman, 2003); however, composite models of assessment of the influence of operational seeding keep developing (Wang et al., 2024).

The politics and political economy of AWRM has become an increasingly relevant topic. This is exemplified in the work by Chien et al. (2017), which describes the impact of political interests on the formation of the Weather Modification Bureau of China. The same topic is covered by Keys et al. (2024) and Tanika et al. (2023). That recognition has prompted proposals to govern atmospheric moisture flows explicitly (Keys et al., 2017; Rockström et al., 2023), and parallel work shows that neglecting upwind atmospheric dependencies materially understates transboundary water security risk (Posada-Marín et al., 2024). On the legal position, Simon et al. (2023) show that the domestic governance of the world's largest weather modification programme effort does not satisfy customary-law procedural obligations to minimise risks of significant transboundary harm, echoing the broader gaps identified by Sands (2018). Despite this convergence between atmospheric science and legal analysis, the economic externalities of AWRM on transport infrastructure remain almost entirely unquantified. Despite all of this, the increasing vulnerability of global transport infrastructure to changes in precipitation due to climate warming can be seen in Fig. 1. In light of all of this, economic externalities of AWRM with respect to transport infrastructure are largely unknown.

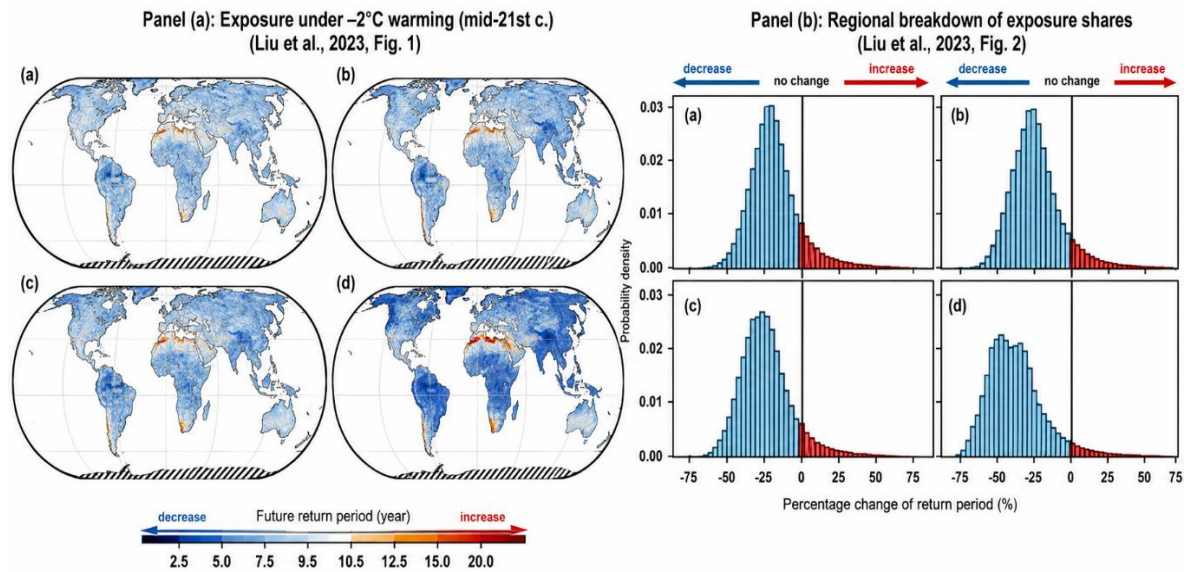


Fig. 1. Global transport-infrastructure exposure to precipitation change under warming. (a)–(b) exposure at $\sim 2^{\circ}\text{C}$ warming; (c)–(d) regional changes in extreme-precipitation return periods. Source: Liu et al. (2023)

2.3. Transboundary resource management: strategic interaction

The strategic logic of transboundary climate cooperation supplies the third literature on which this analysis rests, alongside the climate-transport and atmospheric governance scholarship of Sections 2.1 and 2.2. Work on international environmental agreements, developed largely around climate and shared-resource problems, shows that non-cooperative equilibria systematically overshoot socially optimal use levels (Barrett, 1994; Yuan et al., 2020). The insight carries directly to climate-motivated interventions in shared atmospheric systems: individually rational state decisions generate collective inefficiencies that coordination can correct, but only when institutions create credible mechanisms for cost internalisation.

Yu et al. (2024) illustrate the co-benefits of cooperation in the Lancang-Mekong Basin, while Englezos et al. (2022) demonstrate that governance gaps generate welfare losses recoverable through cooperative institutions. AWRM alters the problem structurally: externalities travel through the atmosphere rather than surface water, affecting infrastructure sectors not traditionally within water governance. Downstream states bear adaptation costs with no mechanism for cost recovery, an asymmetry that is increasingly salient as AWRM expands. Section 3.4 formalises this mechanism.

2.4. AWRM as an emerging challenge for the climate adaptation agenda

Read together, these literatures locate AWRM at an unoccupied intersection of the contemporary climate agenda. In the taxonomy of transboundary climate risk, cross-border impacts may originate either in a climate trigger or in the responses that states adopt to manage climate impacts (Carter et al., 2021); recent work has begun to classify the governance

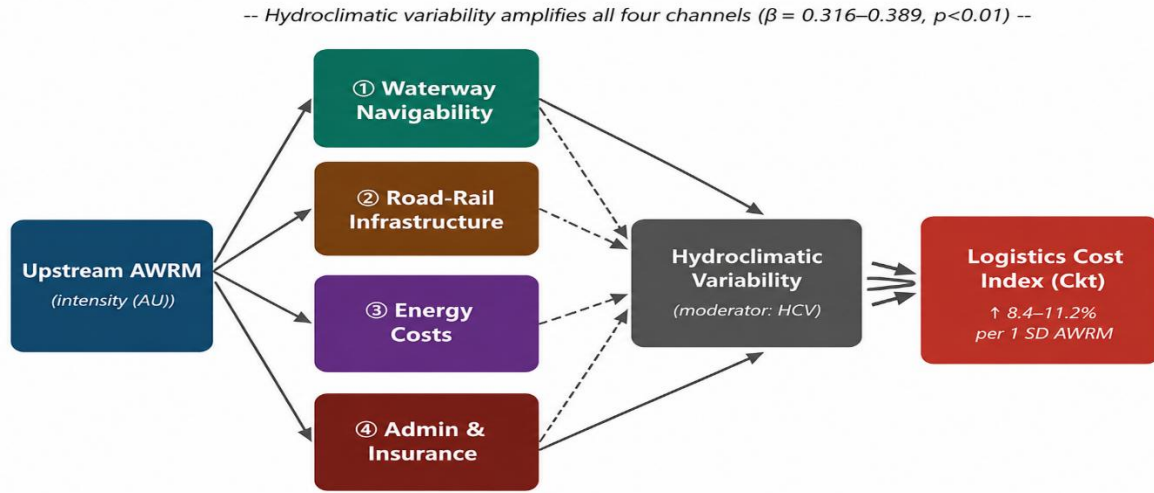
responses appropriate to each configuration of transmitting and receiving actors (Talebian et al., 2025). AWRM is a limiting case of the second, response-driven category: a domestic climate adaptation measure that is itself a potential source of transboundary risk. Three features make it a distinctive governance challenge. First, because the risk originates in an adaptation choice rather than in a hazard, standard framings of adaptation as a purely domestic or basin-level activity do not apply. Second, atmospheric transmission decouples the geography of the externality from the jurisdictions of existing water treaties. Third, attribution of any specific downstream outcome to upstream seeding activity is inherently uncertain, which weakens no-harm and liability-based remedies.

These features connect the AWRM problem to the adaptation finance debate. Downstream infrastructure operators must fund additional resilience against a partly policy-induced hazard, while adaptation finance falls far short of estimated needs (UNEP, 2024). Loss-and-damage funding proposals show that allocation can proceed without event-level attribution (Clarke et al., 2023), a logic the cost-sharing pathways examined in Section 6.2 adopt. Establishing whether AWRM programme intensity is associated with economically meaningful downstream infrastructure exposure is therefore a necessary first step: it determines whether AWRM belongs on the transboundary climate risk agenda at all, and it provides the evidentiary basis on which notification, monitoring, and cost-sharing institutions could be designed. The remainder of the paper undertakes that step.

3. Methodology

3.1. Conceptual framework

Fig. 2 presents a structural risk model of plausible transmission pathways through which upstream AWRM activity may contribute to downstream logistics cost risk, consistent with the climate-transport literature and with the atmospheric water cycle governance perspective of Keys et al. (2024) and Tanika et al. (2023). Attribution in the atmosphere will always be uncertain: seeding works probabilistically, is dependent upon pre-existing weather patterns, and cannot be isolated from the background noise. The model must thus be taken as pointing out risk pathways in light of governance, rather than deterministic physical processes.



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Fig. 2. Conceptual framework: transmission channels from AWRM intensity upstream (A) to downstream IEEI through four channels: waterway navigability, road-rail infrastructure, energy costs, and administrative/insurance costs, all subject to moderation by hydroclimatic variability (H). Source: illustration by authors.

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The waterway navigability channel works through the potential impact of river flow variability on transit times and modal shift (Jonkeren et al., 2011; Christodoulou et al., 2020). The road-rail channel is based on the potential contribution of precipitation intensity to pavement stress, embankment vulnerability, and flooding (Koetse and Rietveld, 2009; Liu et al., 2023a). The energy costs channel is linked to hydropower production and terminal operations (Li et al., 2025). The administrative and insurance costs channel takes account of the institutional response to the hydroclimatic uncertainty risk shock, such as premium increases and contractual complications (Gössling et al., 2023). Each of these channels interacts multiplicatively with the existing hydroclimatic variability; for stressed corridors, a small perturbation in risk can lead to large cost impacts ($A \times H$ interaction term in equation (1)).

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3.2. Econometric specification

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The baseline specification is:

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$$C_{kt} = \alpha + \beta_1 A_{it} + \beta_2 H_{kt} + \beta_3 (A_{it} \times H_{kt}) + \gamma X_{kt} + \mu_k + \lambda_t + \epsilon_{kt}$$

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where C is the composite IEEI of corridor pair k in year t; A is the AWRM intensity in upstream state i; H is the hydroclimatic variability; ($A \times H$) is the amplification interaction term; X is a vector of time-varying corridor controls; and μ , λ are corridor and year fixed effects. Standard errors are clustered at the corridor level.

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3.3 Identification strategy and uncertainty-aware interpretation

It is reasonable to expect that AWRM intensity is an endogenous variable, with governments increasing cloud seeding activities during drought periods that are themselves driving up logistics costs. This study's main contribution is the fixed-effect panel estimation approach, which addresses the issue of unobserved time-invariant corridor characteristics and common time trends. Since the intensity composite indexes efforts and not outcomes (see Section 4.2), such estimations reflect only the statistical association and not the causal effect. Nonetheless, the associations can inform governance in a precautionary manner. Two robustness checks are performed.

For the instrumental variables approach, the upstream election-year variation is used. Incumbent governments use election years as a political signal and increase their investment in weather modification policies (Chien et al., 2017). First-stage F-statistics exceed 23, fulfilling conventional criteria (Stock and Yogo, 2005). It remains unclear whether the exclusion restriction holds, as election cycles impact the downstream infrastructure through several channels. In any case, instrumental variables results provide a consistent check rather than the main identification result.

The system GMM is estimated in the manner of Blundell and Bond (1998), based on lagged levels and differences as internal instruments. Instrument validity is checked with the Hansen J-test (p-value = 0.312). (Placebo and falsification tests are provided in Section 5.4.)

3.4. Game-theoretic framework

The game-theoretic part is purposely stylized: it explains the strategic reasoning behind the problem of governance but provides no exact welfare calculations (see full derivations in Supplementary Material Section S1). The core intuition is straightforward: because upstream states internalise only a fraction of corridor-wide infrastructure costs, their individually rational AWRM decisions generate collectively inefficient outcomes. Governance coordination corrects this by increasing the upstream cost share. The directional implication, that each step toward symmetrising cost internalisation reduces infrastructure cost volatility, is robust to model specification. In governance terms, the framework translates the cross-border externality documented empirically into an institutional design problem: the relevant question is not whether atmospheric intervention can be prevented, but how institutions can be configured so that the states undertaking it internalise a larger share of its transboundary costs.

4. Data

4.1. Sample and dependent variable

Testing this framework requires data in which atmospheric intervention and downstream infrastructure outcomes can be observed jointly across borders. The sample consists of 42 transboundary corridor pairs observed annually from 2000 to 2023, yielding 1,008 corridor-

year observations across five continental regions. Corridor pairs are selected on the criterion that the upstream state operates, or has operated, a documented AWRM programme activity during the sample period, programmes typically adopted as policy responses to climate-related water stress (Section 1). Corridors lacking documented programme effort histories or with extended missing data are excluded, over-representing institutionalised settings and creating a potential survivorship bias. The sample as a result reflects the universe of corridors for which sufficient data could be compiled, not a global cross-section. Full details are in Supplementary Material Section S5.

The dependent variable measures the economic exposure of transboundary transport systems to hydroclimatic conditions. The composite Infrastructure Economic Exposure Index (IEEI, also referred to as the Logistics Cost Index, LCI) is constructed by principal-component aggregation of bilateral freight rate indices (World Bank, 2023a), border crossing delay indicators (United Nations, 2023), and downstream infrastructure quality scores (WEF, 2020). Because each component responds to the kinds of disruption that hydroclimatic variability produces (Section 2.1), the composite functions as a climate-impact metric rather than a logistics performance measure alone. It correlates strongly with the full World Bank LPI ($r = 0.78$, $p < 0.001$); construction details are in Supplementary Material Section S2 (loadings in Table S1).

4.2. AWRM intensity

AWRM intensity is the first principal component of three indicators: (i) government expenditure on weather modification programmes in constant 2015 USD (PPP-adjusted); (ii) operational records comprising annual sortie counts and seeding agent volumes from national meteorological agencies and WMO (2018); and (iii) satellite-derived aerosol optical depth (AOD) anomalies from MODIS/Terra Collection 6 (Levy et al., 2013), computed within upstream seeding zones. The first PC explains approximately 58% of variance; full technical details are in Supplementary Material Section S3. The composite deliberately proxies programme effort instead of realised precipitation change: the three indicators draw on independent data-generating processes (fiscal, operational, and satellite), so their shared first component isolates the common signal of programme intensity scale while averaging out source-specific error, and their strong co-loading is itself evidence that they track a single latent construct. This effort-based design is appropriate to the study's question, which concerns the governance of intervention activity rather than its meteorological efficacy. The index nonetheless carries non-trivial measurement error from self-reporting and aerosol contamination; these limitations are examined in Section 6.3, with technical discussion in Supplementary Material Section S3 (loadings in Table S2).

4.3. Hydroclimatic variability and controls

Hydroclimatic variability is measured by the coefficient of variation (CV) of monthly precipitation totals within the downstream corridor region, computed from ERA5 reanalysis data (Hersbach et al., 2020). Time-varying corridor controls include: log bilateral trade volume (UN Comtrade, 2024); a composite infrastructure quality index (WEF, 2020); log GDP per capita of the downstream state (World Bank, 2023b); and an indicator for the presence of a

bilateral transport cooperation agreement. The hydroclimatic variability measure (summary statistics in Table S3) and the corridor sample selection procedure are described in full in Supplementary Material Sections S4 and S5, respectively. Table 1 presents summary statistics.

Table 1
Summary statistics

Variable	N	Mean	SD	Min	Median	Max	Source
IEEI	1,008	0.000	1.000	−3.42	0.012	4.18	World Bank LPI; UN TFS; WEF
AWRM Intensity	1,008	0.243	0.391	0.000	0.141	2.47	Nat'l Met. Agencies; WMO; MODIS
Hydroclimatic Variability (CV)	1,008	0.318	0.189	0.041	0.298	0.912	ERA5 Reanalysis
AWRM x Hydroclimatic Var.	1,008	0.091	0.167	0.000	0.038	1.843	Authors' calculations
Log Bilateral Trade Volume	987	21.43	2.18	14.91	21.51	26.72	UN Comtrade (2024)
Infrastructure Quality Index	1,008	3.61	0.88	1.40	3.58	6.10	WEF GCI (2020)
GDP per Capita, Downstream (USD)	1,008	8,741	9,402	412	5,623	52,380	World Bank WDI (2023b)
Bilateral Transport Agreement (0/1)	1,008	0.381	0.486	0	0	1	Authors' compilation

Notes: Sample = 42 corridor pairs, 2000–2023 (N = 1,008). Monetary variables in constant 2015 USD. IEEI standardised (mean = 0, SD = 1). AWRM intensity = first principal component of three indicators (Section 4.2; first PC explains ~58% of variance). Infrastructure Quality Index from WEF GCI 4.0 dataset (WEF, 2020). Missing trade observations (N = 21) from UN Comtrade.

5. Results

5.1. Descriptive patterns

As a first step in assessing whether AWRM constitutes a material transboundary climate risk, Fig. 3 presents two complementary descriptive views of the main association. Panel (a) shows

the pooled cross-sectional relationship between AWRM intensity and the IEEI (pooled OLS: $p < 0.001$), with points colour-coded by continental region. Panel (b) traces the temporal evolution of mean logistics costs by AWRM intensity quartile. The gap between high- and low-intensity corridors opens up noticeably after 2010, coinciding with the global acceleration of cloud seeding programmes (Flossmann et al., 2019; Keys et al., 2024).

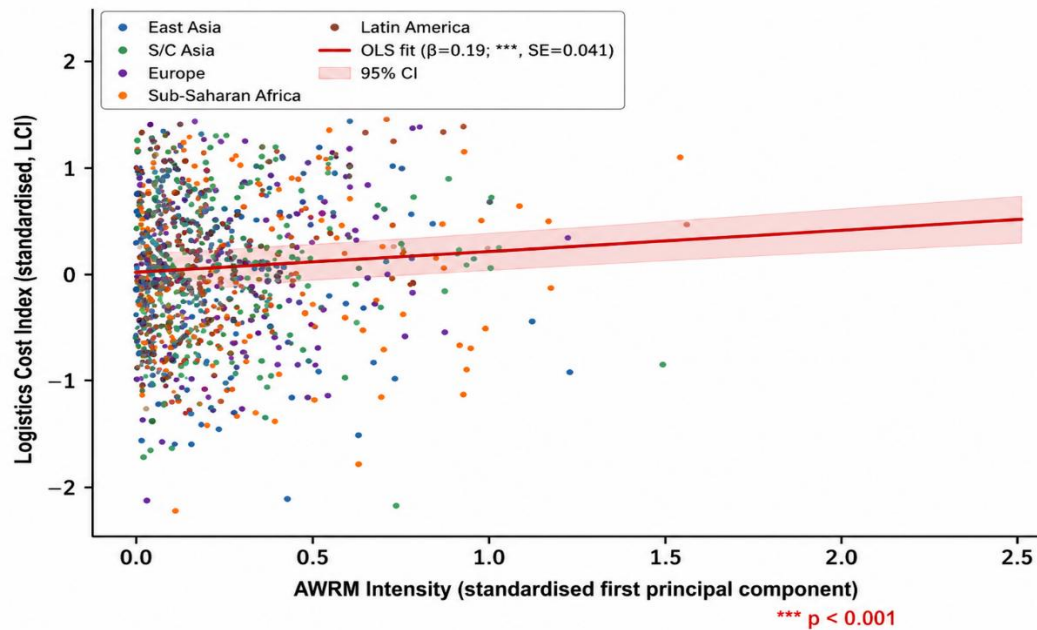


Fig. 3. AWRM intensity and the IEEI, 2000–2023 (987 corridor-years). (a) Pooled cross-sectional association; OLS slope 0.191 ($p < 0.001$), 95% bands, points by region. (b) Mean IEEI by AWRM-intensity quartile; the high–low gap widens after 2010. Source: Authors’ calculations.

5.2. Baseline regression results

Table 2 reports the baseline results. Across all four specifications, upstream AWRM programme intensity is positively and significantly associated with downstream infrastructure economic exposure, conditional on natural hydroclimatic variability and the corridor controls. In the primary fixed-effects estimate (Column 1), a one-standard-deviation increase in AWRM intensity corresponds to infrastructure economic exposure higher by roughly 7–8%. Secondary robustness checks are broadly consistent, if somewhat larger. All figures are cross-corridor averages; corridor-level variation around these central estimates is likely substantial.

Table 2

AWRM intensity and logistics costs: baseline regression results

	(1) OLS	(2) OLS + Interact.	(3) 2SLS	(4) Sys-GMM
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AWRM Intensity	0.191***	0.184***	0.253***	0.307***
	(0.043)	(0.041)	(0.068)	(0.079)
Hydroclimatic Variability	0.142**	0.128**	0.157**	0.163**
	(0.057)	(0.054)	(0.071)	(0.075)
AWRM x Hydroclimatic Var.	n.a.	0.316***	0.341***	0.389***
		(0.092)	(0.109)	(0.118)
Log Bilateral Trade Volume	−0.087***	−0.089***	−0.091***	−0.094***
	(0.021)	(0.020)	(0.024)	(0.026)
Infrastructure Quality Index	−0.134***	−0.131***	−0.139***	−0.141***
	(0.032)	(0.031)	(0.037)	(0.039)
GDP per Capita, Downstream (log)	−0.062**	−0.060**	−0.066**	−0.069**
	(0.027)	(0.026)	(0.031)	(0.033)
Bilateral Transport Agreement	−0.109***	−0.107***	−0.114***	−0.118***
	(0.038)	(0.037)	(0.044)	(0.047)
Corridor FE / Year FE	Yes	Yes	Yes	Yes
Observations	987	987	962	987
R2	0.641	0.658	n.a.	n.a.
First-stage F-statistic	n.a.	n.a.	23.4	n.a.
Hansen J-test (p-value)	n.a.	n.a.	n.a.	0.312

Notes: ¹Effect sizes (one SD increase in AWRM intensity, scaled to the empirical IEEI range): Column (1) around 8%; Column (2) around 9%; Columns (3)–(4) in the range of 11–14%. The upward gradient is consistent with attenuation from measurement error. Control variable coefficients are negative, consistent with economic priors.

5.3. Interaction effects: hydroclimatic amplification

The part of the observed variation at the corridor level described above is systematic in nature, as the effect of the relationship between the intensity of AWRM and infrastructure economic exposure is higher in the case of hydrologically stressed corridors, in line with the interaction effect as illustrated in Table 2. For example, when looking at the 90th percentile of hydroclimatic variability, the marginal effect of this relationship is around 14%, while at the

10th percentile, it is only 8%. However, confidence intervals become wider at the extremes. Fig. 4 illustrates these marginal associations.

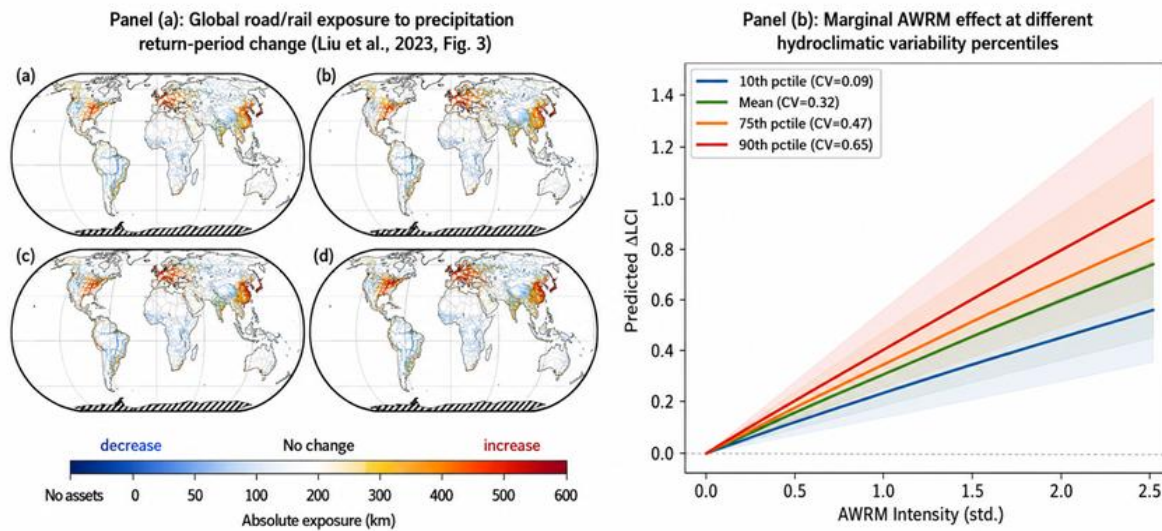


Fig. 4. Marginal AWRM–IEEI association at four percentiles of hydroclimatic variability (Table 2, Column 2). Shaded bands: 95% CIs. Source: Authors’ calculations.

5.4. Placebo tests and robustness

Three robustness checks support a risk-consistent interpretation. Substituting future AWRM intensity ($t+1$, $t+2$) yields near-zero coefficients, reducing reverse-causation concerns. Re-estimation on non-AWRM corridors produces a negligible association (estimated coefficient: 0.022, $p = 0.64$), and a permutation placebo confirms the observed coefficient exceeds the 97.5th percentile of a 1,000-draw distribution. Country exclusion tests yield stable estimates (0.174–0.209), and event-study timing checks recover pre-trend coefficients near zero. Results are stable to alternative IEEI weighting and balanced panel restrictions.

5.5. Channel decomposition and transport mode heterogeneity

Road-rail degradation accounts for the largest share of the estimated association, with waterway navigability the second largest contributor and energy and administrative channels making up the remainder. The estimated association is substantially larger for waterway-dominated corridors. Channel shares are model-dependent and should be interpreted with caution. Full channel and transport-mode results are reported in Supplementary Material Fig. S1 and Section S6.

5.6. Game-theoretic results and governance scenarios

Having characterised the externality empirically, the analysis turns to its strategic structure. The game-theoretic framework (Supplementary Material Section S1) confirms that the cost-internalisation misalignment formalised in Section 3.4 produces a Prisoner’s Dilemma

structure, and that successive governance steps deliver progressively larger reductions in infrastructure cost volatility. Supplementary Material Table S4 and Fig. S2 report the scenario results. The finding that cooperation generates positive marginal returns at every step is robust to model specification, though wide uncertainty surrounds any specific estimate: prior notification frameworks yield the smallest reductions in cost volatility, bilateral cost-sharing arrangements larger ones, and full multilateral internalisation the largest. These magnitudes convey the direction and relative scale of the governance-coordination dividend, not calibrated predictions. In the vocabulary of Section 2.4, the scenarios trace how successive increments of institutional development convert an unmanaged cross-border externality into a governed climate risk.

6. Discussion and Policy Implications

6.1. Contributions to climate change research and climate risk management

Taken together, the results identify a consistent statistical association between upstream AWRM programme intensity and downstream infrastructure economic exposure, broadly comparable in magnitude to estimates attributed to natural climate extremes in the transport-economics literature, though heterogeneous across corridors. These are statistical signals, not verified physical mechanisms, and every implication below is held to that standard. They support informational and procedural responses (risk characterisation, notification, monitoring, and the groundwork for cost-sharing), but not liability claims or substantive restrictions on upstream programmes, which would require attribution the data cannot deliver. For climate governance research, the paper supplies a corridor-level quantitative risk signal for a category so far discussed almost entirely in conceptual terms: response-driven transboundary climate risk (Section 2.4). Existing frameworks recognise such transmission in principle (Carter et al., 2021; Talebian et al., 2025), yet it sits in a blind spot of adaptation policy, and empirical estimates of its magnitude are scarce (Anisimov and Magnan, 2023). The nearest antecedents each supply one element while lacking the others: legal analysis without economic quantification (Simon et al., 2023), single-state political economy (Chien et al., 2017), exposure estimates confined to natural hazards (Liu et al., 2023b; Nawarat et al., 2026), and largely case-study-based transboundary assessment. To our knowledge, this is the first multi-corridor, multi-decade quantitative estimate of infrastructure exposure associated with deliberate atmospheric intervention. For transboundary climate cooperation, the analysis extends the strategic logic of shared-resource governance (Barrett, 1994; Englezos et al., 2022; Yu et al., 2024) to an atmospheric pathway that decouples the externality from basin institutions, and shows that the cooperation dividend survives this change of medium (Section 5.6). For adaptation policy and infrastructure resilience research, the central implication is that the hazard input to adaptation planning can be partly endogenous to the policy choices of neighbouring states. Frameworks that treat all precipitation as natural in origin may understate exposure where upstream AWRM programmes are active; adding programme intensity as a stochastic variable alongside conventional hydroclimatic forcing is a low-regret refinement that improves risk characterisation whether or not the physical effect is eventually verified. The association is strongest in hydrologically stressed corridors (Section 5.3), precisely where

adaptive capacity is most constrained, so mispricing this risk falls hardest on the economies least able to absorb it, and the channel decomposition (Section 5.5) shows where the refinement matters most. For adaptation finance and international environmental law, the contribution is deliberately preparatory. Cost-sharing instruments need a quantified risk basis before they can be designed; by estimating the order of magnitude of downstream exposure, the paper supplies the input that risk-model-based allocation mechanisms require (Clarke et al., 2023), addressing an unpriced increment that adaptation finance currently fails to meet (UNEP, 2024). That basis serves two uses without event-level attribution: pricing resilience investment ex ante, and parameterising contribution formulas ex post for the regional arrangements discussed below. For legal scholarship, the findings speak to the procedural rather than the substantive limb of the no-harm framework: the evidence cannot support liability claims, but due diligence obligations of notification, assessment, and consultation are triggered by risk rather than proven harm, and Section 5 strengthens the case (Sands, 2018; Simon et al., 2023) that large-scale AWRM programmes fall within their scope.

6.2. Implications for international and regional governance frameworks

The existing international governance regimes have limited provisions to deal with trans-boundary risks posed by AWRM. ENMOD Convention considers only hostile acts of environmental modification but not adaptation efforts to climate change; no-harm and reasonable utilization rules have limited scope due to lack of attribution; and bilateral water agreements are relevant to surface waters, not atmosphere. As a result, AWRM occupies an institutional gap between atmospheric and water governance. Current governance regimes do not foresee any provisions for information exchange, cooperation platforms or allocation of adaptation costs. The governance mechanisms outlined in Section 6.2.1 address the three identified institutional gaps. In terms of the climate change governance structure, the closest opportunities pertain to the enhancement of knowledge and risk assessment of UNFCCC, the closest step would be improvement of the information basis of adaptation governance. Transboundary risks are considered in National Adaptation Plans, adaptation communications and Global Stocktake (Anisimov and Magnan, 2023), yet response-driven risks are hardly recognized at all. The current findings highlight that existing upstream AWRM interventions should be integrated into downstream adaptation plans and tracked as part of global stocktaking exercises. This can be done without attributing causality or creating any new legal commitments, only by better capturing transboundary climate risks. The GGA makes such an approach more compelling. The UAE Framework for Global Climate Resilience lists water and resilient infrastructure as key sectors and highlights the need for systematic hazard assessments and observations (UNFCCC, 2023). In cases where the risk associated with precipitation might in part depend on upstream actions, assuming only natural variability will lead to underestimating both exposure and the needed adaptation measures. Incorporating the intensity of programme effort indicators like those proposed in section 4.2 will help achieve that aim. Aside from the UNFCCC framework, disaster-risk governance provides an extra institutional approach the Sendai Framework for Disaster Risk Reduction is another equally pertinent avenue through which to engage with this topic due to its consideration of hazards that arise from natural causes as well as human activities (UNDRR, 2015). The description of the variation in rainfall linked to AWRM is directly related to Priority 1 ("Understanding disaster risk") while Target D is an available instrument through which to monitor the vulnerability of infrastructure. As the Sendai Framework works with probabilistic risk information rather than definite causes, it is pertinent to the evidence of the current research. But ultimately, the task

will probably require regional institutions regional governance structures are the most suitable context within which the suggested actions could be taken. The example of the Lancang-Mekong Basin indicates that even in situations of unequal levels of interests and capacity cooperation is capable of yielding significant economic and environmental gains (Yu et al., 2024).

6.2.1. Implementation: mechanisms, feasibility, and political constraints

Implementation of these governance pathways necessitates institutions which gradually build up their information-sharing, trust-building, and administrative capacities. Feasibility is shaped by two political-economy constraints. First, AWRM programmes often expand during election periods (Section 3.3), making restrictions on upstream operations politically sensitive. Second, uncertainty surrounding attribution means that governance should focus on observable programme effort rather than on demonstrating downstream damage. These constraints support an incremental governance strategy centred on cooperation rather than regulation. First is transparency and prior notification. This will re-establish the role of information in the process of governance. The states could notify about significant program growth, operational areas, and seasons through a regional reporting system based on some existing examples such as US Weather Modification Reporting Act, Espoo convention, and basin organizations prior consultation mechanism (UNECE, 1991; WMO, 2018). Since notification addresses the programme activity and not the causation, it could increase transparency without making any claim for legal responsibility. According to the scenario analysis, it will result in moderate reductions in uncertainty regarding the cost of the infrastructure (Supplementary Material Table S4, Scenario 1). Shared atmospheric monitoring would be another way forward. Early cooperation should be aimed at documenting the programme activities and not estimating the meteorological impacts, because monitoring the seeding operations is much easier than proving the counterfactual on precipitation (Silverman, 2003). The framework developed in Section 4.2 provides an example of how satellite data and operational experience can contribute to this process. Thus, the existing cooperation between the national meteorological services could gradually turn into joint observation, while attribution researches could be left for the future. Instead of paying compensation based on attributed damages, contributions could be linked to observable proxies of programme effort, such as costs, sortie rates, or amount of area seeded, with the resilience spending going through existing regional development agencies. Similar financial instruments based on triggers are used by regional parametric insurance schemes, showing that financial arrangements do not have to rely on event-specific attribution. Political feasibility is enhanced if upstream countries also get a benefit from reliable corridors, if participation helps to avoid future legal disputes, and if financial cooperation comes together with monitoring and information sharing arrangements. To present these mechanisms as cooperative adaptation finance and not compensation is also likely to enhance political acceptability. Lastly, regional institutions offer the most realistic framework for long-term governance. The existing basin organizations already have an administrative capability, experience in negotiations and cooperation channels, Expanding the existing institutions will thus be easier than developing completely new ones (Yu et al., 2024). As a result, a fully comprehensive regional AWRM coordination regime with seasonal coordination and agreed upon rules for management would have to be considered as a distant goal and not an immediate policy alternative. Given the political asymmetries, veto rights, and lack of trust, deepening collaboration is still hindered. As a result, it is expected that governance will develop gradually, starting in corridors that are both hydrologically pressured and economically linked, where the value of collaboration is the highest. Such policy avenues continue to face certain practical limitations. Power asymmetries and lack of trust can undermine the process of institutional

development altogether, and the quantification performed above only gives a sense of direction of the benefits gained, not of the benefits themselves. Most importantly, none of the above approaches rely on solving the attribution problem, which is exactly why they are possible.

6.3. Limitations and future research

There are several limitations inherent to this study which limit both the range of its conclusions and the focus for future studies. The use of observational panel data does not allow one to make statements about physical causality, but it is well-suited for answering the basic question that was explored in this study, namely, whether there is any evidence of policy-related transboundary exposure that can be observed in international corridors lacking experimental evidence. The main caveat is the problem of atmospheric attribution: cloud seeding is a stochastic process that heavily depends on existing meteorological conditions, and counterfactual precipitation cannot be observed either in the context of a scientific experiment (Silverman, 2003; Flossmann et al., 2019). Consequently, the estimated associations must not be viewed as a sign of any direct physical effect. From a governance perspective, the AWRM intensity should be seen as an exposure index that reflects both weather modification activity and water stress that makes such modifications necessary. The first principal component accounts for 58% of variance in total, there can be measurement errors in self-reported spending and flight hours, and aerosol optical depth (AOD) depends on pollution, dust, and wildfire emissions. The classical measurement error is expected to bias down the fixed effects estimates. The above statement can be justified by comparing the larger estimates using IV and GMM estimation approaches. A few important shortcomings follow from the observational and annual nature of the dataset. The lack of information on timing of seeding events in relation to hydrological outcomes, the proxy character of IEEI index, and regional biases in ERA5 precipitation data are inherent to an annual dataset, even though the measure used is more resilient to systematic level biases. However, placebo, permutation, and event-study analysis help mitigate issues of reverse causality and selection effects. The instrumental variable analysis should likewise be interpreted cautiously. While election year cycles constitute a valid instrument (first stage $F = 23.4$), the exclusion restriction cannot be established as election year could have an effect both on infrastructure investments and bureaucratic effectiveness. This implies that IV estimates are used solely as robustness tests, alongside fixed effects results, and that the policy conclusions formulated in Section 6 do not hinge on them. External validity is limited due to selection of the sample. The study covers only corridors with an AWRM programme effort and enough available data and accordingly overrepresents well documented institutional environments, ignoring areas where problems with governance might be the worst. Thus, the results must be considered valid only for the sample corridors, the years from 2000 to 2023, and the technologies identified within that period. Finally, the game theoretic model itself is deliberately stylized. It makes the assumption of static interactions and full information and does not take into account sequential bargaining, coalitions, issue linkage and other domestic politics issues mentioned in Section 3.3. Payoffs are calibrated based on the panel regression estimates. Thus, the model is designed to demonstrate the incentives within comparative institutions rather than make exact quantitative predictions. This forms a very distinct future research agenda. Future research should prioritise the development of satellite-based measure of intensity that do not rely on self-reporting. One also needs to use the information about programmes launch and suspension on a sub-annual basis as a quasi-experiment. In addition to this, future research must increase the scope of corridors covered, analyze spatial spillover effects, and incorporate atmospheric and economic modeling in order to improve the identification of transmission pathways, shown in Fig. 2 below.

7. Conclusion

This paper has treated deliberate atmospheric intervention as a problem of climate governance rather than of meteorology, and provides the first multi-corridor, multi-decade evidence on its transboundary economic footprint. It identifies a structurally novel challenge: AWRM programmes, adopted as climate adaptation measures, may externalise hydroclimatic risk onto downstream infrastructure networks, creating asymmetric adaptation burdens that no international framework addresses. Fixed-effects estimates of roughly 7–12% per standard deviation, amplified in hydrologically stressed corridors, are risk signals rather than causal estimates, but signals of this kind can still warrant institutional attention.

For climate governance, the paper converts response-driven transboundary climate risk from a conceptual category into a quantified object of study, diagnosing a specific institutional failure: downstream states lack information rights, a standing forum, and a remedy. The game-theoretic framework shows why this gap will not close by itself (upstream states internalise only a fraction of corridor-wide costs, so individually rational decisions are collectively inefficient) and why each step toward symmetrised internalisation is associated with lower cost volatility. The broader lesson for adaptation research is that one state's adaptation can be another's hazard, making adaptation planning partly a matter of foreign policy and requiring hazard baselines that admit policy-induced components.

For infrastructure resilience, this supports the low-regret approach of Section 6.1: treating upstream programme intensity as a stochastic input to corridor risk, with attention to hydrologically stressed corridors and, per the channel decomposition, to road-rail networks and waterway navigability. For international environmental law, the externality fits within no existing regime: too diffuse for bilateral water conventions, too domestic in motivation for the ENMOD Convention, and too uncertain in attribution to be actionable under the no-harm principle. For that reason, these findings lend themselves to precautionary governance as opposed to precautionary regulation, considering the present state of attribution capabilities and the potential policy implications of the risks noted.

The concluding claim is deliberately modest: nothing here establishes that cloud seeding harms downstream economies; the estimates are preliminary associations with acknowledged measurement limits. What it does establish is that the question is tractable and the conditions making it consequential all point one way: programmes are expanding, the atmospheric water cycle is increasingly an object of deliberate policy, and the hydrological stress under which the estimated associations are largest is intensifying in many shared corridors, all while no governance framework is in place. When a policy instrument spreads faster than the institutions meant to govern its cross-border effects, the resulting gap belongs at the centre of the climate governance agenda, not at its margins. The governance of atmospheric water resource manipulation should be built before the next expansion of these programmes, not after the first serious transboundary dispute.

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