Dam Thy Neighbor: International Relations and the Externalities of Impounding Rivers

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Abstract

Using the context of dams around the globe, this paper provides the first quantification of how international relations shape transboundary environmental externalities. Leveraging a novel measure of dam exposure in a difference-in-differences framework, I find that dams lead to reductions in downstream growth in nighttime lights, both within and across borders, on the order of 2% of average growth over 2001-2013. Next, I compile quantitative measures of bilateral relations motivated by theories of cross-country cooperation. I find that the transboundary externalities of dams are driven by country pairs in which the downstream country has high coordination costs with or little geopolitical leverage on its upstream neighbor. When coordination costs are low, the externalities are mitigated to null. Among various measures of bilateral relations, joint membership in international institutions most strongly predicts the mitigation of transboundary externalities. As recent dams have predominantly been built in developing regions, these results uncover the role played by international relations in economic development, through the management of transboundary natural resources.

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1 Introduction

Policies are made and enforced within countries. Yet, environmental externalities, including air pollution, water pollution, dust and desertification, common pool resource depletion, species invasion, and, of course, greenhouse gas emissions, are transboundary in nature, propagating outside their country of origin (Early et al., 2016; Heo et al., 2024; McWhinnie, 2009; Middleton, 2017; Sigman, 2002). This means that around the world, key inputs to health and economic activity are potentially impacted by free-riding on the part of policymakers and economic agents in foreign countries.

What are the economic costs of transboundary environmental externalities? And, in the absence of an international regulatory authority, what can be done to avert or mitigate them? This paper studies these questions in the global context of dams on transboundary rivers, which elicit controversy by generating fears of disruption to water supply and ecological functions in downstream countries. I begin by measuring the causal impact of dams on downstream economic activity both in the same country as the dam and in foreign downstream countries. Then, I determine the extent to which the variation in externalities depends on international relations between riparian countries.

To estimate the causal effects of dams, including the far downstream effects, I leverage the spatial tributary structure of rivers to construct a novel continuous measure of exposure to an upstream dam. As a river flows downstream from a dammed location, it converges with the undammed flow of numerous tributaries. This means that as one moves downstream along the river, the share of the river discharge (that is, m^3/s of flow) originating from the dammed location decreases, diluting any potential hydrological impacts of the dam. For each location downstream of a dam and each year, I compute the location's "flow share" measure of dam exposure as the fraction of the pre-dam local river discharge that originates from the now-dammed location. Assuming that economic activity near rivers is adapted to the local pre-dam river discharge, flow share provides a continuous measure of hydrological exposure to dams that varies between locations along the same river, downstream of the same dam. Given the density of river tributary networks in much of the world, there is variation in flow share even among locations near each other. This allows me to identify the causal downstream effects of dams by comparing cells near each other that experience different levels of exposure to the dam, using difference-in-differences with the flow share measure as treatment.

My findings are summarized as follows. First, hydroelectric dams, which form the bulk of dams built in recent years, have precisely estimated negative effects on downstream nightlights. These effects are concentrated on irrigated cropland, suggesting that agricultural impacts are the primary channel. Second, these downstream economic costs accrue both within and across country borders. While the domestic costs may be offset by the direct benefits of dams or domestic policy mechanisms for compensation, the cross-border externalities are at least as large. Third, in the absence of a central international authority, upstream-downstream country pairs are nevertheless able to mitigate the potential externalities when they enjoy more cooperative international relations. The negative transboundary externalities of dams are concentrated in country pairs that face high coordination costs or broader non-alignment on international issues, with joint membership in intergovernmental organizations being the most predictive of realized externalities. For country pairs with median or better levels of coordination costs, I find small and insignificant transboundary externalities to nightlights growth.

Dams provide a suitable empirical setting to study transboundary externalities because their locations and years of construction are well-defined, and it is straightforward to identify the countries that built them as well as the downstream countries receiving potential externalities. The externalities of dams - potential and realized - are sources of discord in many parts of the world. Globally, 276 river basins cross national borders, together spanning 145 countries and encompassing 60% of Earth's freshwater supplies (UN Water). Out of about 31,779 geolocated dams in one database, 25% are upstream of foreign countries. While a dam can generate substantial benefits in the form of hydropower, irrigation, or flood control that may be deemed to outweigh the local environmental and human displacement costs, dam-building social planners may accord little weight to the potential consequences for drinking water supply, agricultural water supply and soil fertility, riverine fish supply, electricity, and flood and drought risk accruing to downstream neighboring countries. In fact, even when a dam is meant to support global social welfare (e.g. for hydropower generation to replace fossil fuels and meet the country's Paris Agreement commitment), it may be built and operated in a way that imposes negative or ambiguous externalities on regional neighbors. According to the UN, formal international coordination is commonly lacking: about 2/3 of transboundary rivers do not have any cooperative management framework. Many countries explicitly keep river flow and dam inflow and outflow data secret.

Although the overall pace of dam-building has slowed in recent years, large, high-profile, and controversial hydroelectric dams continue to be planned and built. In the 2010s, construction of the Grand Ethiopian Renaissance Dam (GERD), the largest hydropower dam in Africa, led to talk of sabotage and war between Ethiopia and downstream Egypt (*Ethiopia's Abiy Ahmed issues warning over Renaissance Dam*, October 22 2019; Tadesse, 2013). Most recently, China approved plans to build what would be the world's largest hydropower dam on the headwaters of the Brahmaputra River, drawing concern from downstream India and

Bangladesh (May et al., 2025). Their concern is potentially warranted: for example, water withholding by hydroelectric dams in China and Laos is suspected to have changed the quantity and seasonality of Mekong flows, threatening the supply of fish, a staple food in Southeast Asia (Fawthrop, 2022; Ziv et al., 2012), and exacerbating the effects of the 2019 drought in that region (Basist and Williams, 2020).

Yet, although conflicts and negative externalities generate attention, it is not always the case that upstream countries operate dams solely in the manner of self-interest. For example, Kyrgyzstan's Toktogul Dam on the Naryn River provides 40% of the country's electricity. When drought strikes, electricity generation would require withholding river flow to maintain a certain capacity in the reservoir; however, downstream Uzbekistan and Kazakhstan rely on the flow for irrigation. During a recent drought, the riparian countries reached a deal in which Uzbekistan and Kazakhstan would sell electricity from non-hydroelectric sources cheaply to Kyrgyzstan in exchange for allowing the river to flow (*Kyrgyzstan, Uzbekistan agree on power swap to restore reservoir levels*, March 25 2021). The fact that the Central Asian countries achieved such a Coasean solution, while the Mekong countries did not, demonstrates a wide variation in the realized externalities of dams and suggests that international politics plays a significant role in shaping the outcome. Moreover, to the extent that some downstream flow impacts are difficult to negotiate away, it seems possible that better communication and coordination between countries can facilitate on-the-ground adaptation: e.g. when the downstream country has information about how the dam will be operated in the next 1, 5, or 10 years, people can shift their economic activities accordingly to align with the expected quantity and seasonality of river flow.

The countries involved in the examples above are geographically representative of the fact that new dams, since the 1980s, have primarily been built in Asia, Africa, and South America (Zhang and Gu, 2023). Thus, the potential economic effects of dams, and the ability of governments and economies to avert or adapt to these effects, have direct consequences for economic development in low- and middle-income countries that either build dams or are dependent on rivers that have been dammed by their upstream neighbors.

This paper makes three contributions to the literature. First, this paper provides the first global-scale estimates of the international transboundary effects of dams. It therefore adds to our limited body of evidence on the economic costs of transboundary externalities. Existing evidence suggests that countries strategically locate economic and policy activities so as to offload negative externalities beyond their borders.[1] Most pertinent to this paper, Olmstead and Sigman (2015) show that upstream countries free-ride in dam location decisions: conditional on geographical suitability for dam-building, a river basin is more likely

[1] For example, in the contexts of water pollution (Sigman, 2002) and air pollution (Heo et al., 2024)

to be the site of a dam if it is upstream of another country. These studies invite the question of the economic costs of the resulting transboundary externalities. So far, a small body of evidence[2] suggest that the economic costs are large and deserve further study across more contexts. Most closely related to this paper, a recent paper by Lei (2025) measures the effects of Chinese dams on the Mekong in downstream Southeast Asian areas. He finds that the externalities for agricultural production can be either positive or negative depending on climate conditions. Whereas Lei (2025) provides a detailed profile of the externalities from dams on the Mekong, this paper is global in scope, calculating average causal treatment effects across all dams built between 2001-2013 for which location and construction year are available. A global average can be useful because the effects of dams are likely to differ across river basins based on factors such as climate, baseline hydrological dynamics, and downstream land use.[3] In addition, rather than using agricultural productivity as the outcome, this paper measures externalities in terms of changes in economic activity as proxied by nighttime lights. The latter is intended to capture total economic effects net of adaptation, accounting for agricultural, urban, health, and industrial mechanisms.

Second, to my knowledge, this is the first paper to empirically quantify whether positive international relations can mitigate negative transboundary environmental externalities. As such, it addresses the gap in our empirical understanding of how to mitigate transboundary environmental externalities. The empirical literature has studied mitigation of inter-jurisdictional spillovers in subnational settings. However, the solutions there[4] all require the authority of a central government. In international settings, which lack such a central authority, studies of how to mitigate transboundary externalities have primarily been theoretical.[5] Keohane and Ostrom (1995) consider countries as analogous to decentralized users of small-scale common pool resources (CPR) to whom the CPR design principles of Ostrom (1990) apply. In line with both Ostrom's principles and the theory of Coasean bargaining,

[2]Most notably, on the effects of China's air pollution and East Asia's regional dust on mortality in South Korea (Heo et al., 2024; Jia and Ku, 2019)

[3]For example, the global analysis of Olmstead and Sigman (2025) finds no evidence that dams negatively impact resilience to local droughts downstream, contrary to the results of Lei (2025).

[4]Such as establishing centralized or integrated resource management (Lipscomb and Mobarak, 2016; Sigman, 2005; Wang and Wang, 2021), altering bureaucratic incentives (Dipoppa and Gulzar, 2024; Kahn et al., 2015), or mandating compensation between jurisdictions (Bao, 2012; Chen et al., 2022)

[5]Within political science, a literature on hydropolitics has empirically established correlations between the existence of formal treaties over shared rivers and various dimensions of politics and coordination costs. For example, Tir and Ackerman (2009) find that formal treaties are more likely in river basins with greater power imbalance, trade, common democratic regime type, and water scarcity. Yet, formal agreements vary in how they (are perceived to) distribute the costs and benefits of resource use between countries. Then, given the terms of agreement, compliance is ultimately up to the signatory countries, and countries sometimes engage in protracted disputes over whether an action is in compliance with an existing agreement. Thus, the hydropolitics literature has left open the question of how international relations affect the ultimate economic consequences along shared rivers, whether through treaties or other mechanisms.

Libecap (2014) proposes differences in transaction costs as a key source of variation in the international community's success at addressing different global environmental externalities. Yet, we lack empirical evidence on the extent to which transaction costs and CPR design principles alter externalities in practice, as well as their underlying determinants among countries. By quantifying the role of international relations in mediating dam externalities, this paper addresses that empirical gap.

Finally, this paper adds to our understanding of the economic impacts of dams, especially hydroelectric dams, an issue of policy relevance as many countries seek to expand renewable energy. The existing literature on the impacts of dams primarily focuses on the local effects around the dam or relatively close downstream.[6] Most closely related to this paper, using the same global rivers and dams datasets, Du and Zhang (2025) find that hydroelectric dams induce a variety of environmental changes and net losses to agriculture and aquaculture within 100km downstream of dams. These results empirically motivate, while leaving open, the question of whether such negative impacts propagate farther downstream and hence whether the concern of downstream riparians such as Egypt, India, and Bangladesh are justified. The flow share measure of dam exposure allows me to generate evidence on what those far downstream impacts are. There is also a need for more evidence on the impacts of dams across economic sectors. Jeuland (2020) notes that a key reason why decisions to build dams are rarely informed by economic evidence is that existing economic evidence on dam impacts do not account for multi-sector impacts. Evidence is especially scarce on channels other than the direct impacts of local dam construction and irrigation access (Dillon and Fishman, 2019).[7] In conducting a global study with nighttime lights - a measure of economic activity - as the outcome, this paper contributes evidence on the effects of dams across economic sectors, accounting for inter-sectoral reallocation and adaptation.

The rest of this paper proceeds as follows. Section 2 provides background information on dams and theories of international cooperation. Section 3 presents the methodology, data, and results for the downstream impacts of dams. Section 4 presents the methodology, data, and results for adding international relations to the analysis. Finally, Section 5 concludes.

[6]For example, Duflo and Pande (2007) use a river gradient instrumental variable to study the agricultural effects of Indian irrigation dams in their own districts and directly neighboring districts. Strobl and Strobl (2011) use a similar IV to study the effects of African dams up to two river sub-basins downstream. Zhang (2018) measures the costs of displacement from the area flooded by the reservoir of a hydroelectric dam.

[7]The lack of conclusive evidence is reflected, for example, in the World Bank's flip-flopping over the past decades on whether it finances dams. Most recently, in 2024, it again changed course as it approved financing for multi-billion dollar hydropower projects in Africa and Central Asia (Leslie, 2024).

2 Background

2.1 Dams and their hydrological impacts

Around the world, there are at least 62,000 large dams.[8] The benefits of dams are typically the irrigation, hydropower, urban and industrial water supply, or flood control that the dams were constructed to provide (International Commission on Large Dams, 2025). On the costs side, in addition to upstream costs of displacement (Zhang, 2018) and soil quality (Duflo and Pande, 2007), known downstream economic costs of dams include losses to agriculture and aquaculture (Du and Zhang, 2025), fisheries (Ziv et al., 2012), and drought resilience (Lei, 2025).

What are the downstream hydrological impacts of dams that lead to these costs? Appendix Table B1 lists a selection of these impacts and how they have translated into economic effects. First, dams alter the quantity of water that flows downstream. Irrigation and water supply dams do this by allowing for water withdrawal from the river. Although hydropower generation does not directly consume water, the impoundment of a large reservoir leads to higher rates of evaporation. Second, dams alter the timing of flow to suit the purposes of the dam operator. Irrigation and water supply dams store up water during wet or non-growing seasons, then release it during dry seasons (when rainfall and the natural flow of the river are insufficient) or growing seasons depending on local downstream agricultural needs. Hydropower dams rely on maintaining a minimum water level within the reservoir to ensure a ready supply of water to power the generation turbine. To achieve this storage level, dam operators withhold flow during dry periods, potentially exacerbating downstream water scarcity during dry seasons and droughts (Richter and Thomas, 2007). Thus, different types of dams generate different timing impacts, with hydropower dams in particular causing changes in direct conflict with the needs of downstream agriculture. Third, dams alter the quality and contents of downstream flow. The dam structure generally traps sediment and species. Downstream water temperature changes when the dam only releases water from a certain depth, and a reduction in flow velocity leads to a reduction in water nutrients. These hydrological impacts lead to reductions in downstream soil fertility, biodiversity, and water quality (He et al., 2024).

Yet, even conditional on the extensive margin decision to build a dam, on the intensive margin, policy levers are available to reduce the realized extent of hydrological and economic effects. Measures to mitigate potential downstream impacts are available to dam builders

[8] Defined by the International Commission on Large Dams as those with a minimum height of 15m or impounding a reservoir of a minimum volume of 3 million m^3

in the design stage[9] and operation stage.[10] Importantly, however, such mitigation measures come at a cost of decreased capacity and flexibility for electricity generation and/or increased construction expense. Thus, increased weight on downstream welfare in the dam builder's objective function, which can be achieved through downstream political influence or upstream-downstream cooperation, can play a critical role in determining downstream externalities.

This paper will separately analyze the effects of hydroelectric dams and other types of dams, for two reasons. First, hydroelectric dams are the most policy-relevant type of dam today. Although irrigation has historically been the most common purpose of dams, Figure 3 illustrates that in recent years, new dam construction has been primarily for hydropower development. Second, hydroelectric dams are built and operated differently from other dams, likely with larger detrimental downstream impacts. As discussed above, the water storage and release needs of hydropower generation can be at odds with downstream water needs. In addition, Table 1 shows that hydroelectric dams are by far the largest in terms of both dam size and reservoir impounded. This gives hydroelectric dams greater capacity than other dams to store water and control the flow of the river.

2.2 Theories and measurement of power and propensity to coordinate

What determines the propensity of countries to internalize transboundary externalities in the absence of meaningful international authorities? Within the international relations (IR) literature to date, rather than a consensus regarding what induces countries to coordinate or how to measure coordination, multiple theories prevail.

One prevailing school of thought is realism, which is founded on the assumption that countries are self-interested agents seeking to maximize security. This assumption implies that countries are likely to prioritize relative gains over absolute gains, reducing the likelihood of a country engaging in interstate cooperation that benefits other countries, even if cooperation generates absolute gains for the country itself (Waltz, 1979). However, cooperation can occur under certain circumstances. In the context of upstream and downstream

[9] For example, a hydroelectric dam builder may choose to construct a "run-of-the-river" dam, which does not have a reservoir, rather than a storage-based dam. Run-of-the-river dams rely on the natural movement of water to generate electricity. Although they still cause some degree of flow timing alteration and other impacts (Kuriqi et al., 2021), they are typically considered to have less potential for downstream impacts than storage-based dams. A dam builder can also choose to install fish passages, fish-friendly turbines, sediment bypass tunnels, and other mechanisms to reduce the impacts on the quality and contents of river flow (He et al., 2024).

[10] The dam operator may choose a water release schedule that better mimics the natural flow regime (He et al., 2024).

riparian states, realists would predict that, first, power imbalance in favor of the downstream country, which puts the downstream country in a position to threaten the security of the upstream country, may induce the upstream country to internalize externalities. Second, realists would predict that common strategic interests in other realms may increase cooperation over river-sharing (Tir and Ackerman, 2009).

Another prevailing school of thought is liberalism. The liberal perspective emphasizes that institutions, shared norms, and economic interdependence can induce potential gains from cooperation and reduce the transaction costs of cooperation. This leads to cooperation towards mutual long-term gains even without power politics. For example, democratic peace theorists posit that domestic politics can affect international cooperation: two countries are more likely to cooperate if both are democracies. Among other reasons, democratic regimes share common norms, are more transparent about their aims and activities, and face domestic pressure to avoid costly conflict (Lipson, 2003; Maoz and Russett, 1993; Neumayer, 2002).[11] Another liberalist theory is liberal institutionalism, which stresses the role of intergovernmental organizations (IGOs) such as the United Nations, World Bank, and European Union in reducing the transaction costs of coordination and cooperation (Keohane, 1984; Keohane and Martin, 1995). IGOs perform this role by providing third-party mediation, monitoring, and dispute arbitration, fostering economic interdependence, and promoting norms of cooperation.

Anecdotal evidence lends credence to each of these theories' applicability in the realm of transboundary river management. For example, China, the most upstream and most powerful of the Mekong Basin countries, has declined to join the Mekong River Commission, which facilitates joint river management between the Lower Mekong countries of Southeast Asia. Realists might attribute this to China's lack of strategic incentives for coordinating with downstream neighbors and the relative inability of those neighbors to retaliate against China's use of the river, owing to China's position as the upstream hegemon. Regarding the heatedness of the dispute over the GERD between non-democratic Ethiopia and Egypt, democratic peace theory might predict that the dispute would not have been so heated, or perhaps would have been averted from the start, if the countries involved had instead been democracies that trusted each other and whose leaders would have been held accountable by displeased domestic constituencies over threats of armed conflict.

As for liberal institutionalism, several notable instances of successful coordination over shared waters illustrate the roles that IGOs can play. One such role is the provision of

[11] A smaller number of studies posit that two autocracies are also likely to cooperate, for example, because they have longer time horizons and face fewer domestic political constraints when searching for mutually beneficial arrangements (Garriga, 2009).

mediation. For example, the World Bank was a key mediator in negotiating the Indus Waters Treaty between India and Pakistan, which is widely regarded to have successfully minimized water-related conflict and ensured the flow of waters to downstream Pakistan from 1960 until it was suspended in 2025. As a signatory to the treaty alongside the riparian countries, the Bank continued to be involved in the treaty's implementation. In 2007, a Bank-appointed neutral expert was crucial to resolving a dispute over India's proposed hydropower dam. Likewise, the negotiation of the 1995 Mekong Agreement between Cambodia, Laos, Thailand, and Vietnam required these states to overcome histories of rivalry and conflict. The efforts of an official mediator appointed by the United Nations Development Programme were critical to this achievement (Dinar et al., 2013).

Another channel through which IGOs may facilitate coordination is by creating norms of cooperation. When the IGO is a provider of economic aid, it has leverage with which to enforce these norms. In the previously mentioned Central Asian example, the Soviets initiated the practice of using compensatory side payments of fossil fuel energy to ensure the flow of the river from the Kyrgyz dam during dry periods. Yet, the persistence of such coordination was tenuous after the collapse of the central Soviet authority. Ultimately, the continuation of the arrangement was due in large part to the insistence of IGOs such as the World Bank on the formation of inter-state cooperative institutions as a condition for aid (Weinthal, 2002).

These three theories each motivate a different set of empirical measures of bilateral relations between upstream dam-building countries and downstream countries. First, realism motivates the use of trade dependence and GDP imbalance as measures of power dynamics, and the use of voting similarity in the United Nations General Assembly as an indicator of strategic alignment. Second, democratic peace theory motivates the use of regime type similarity. Third, liberal institutionalism motivates the use of joint membership in IGOs. The use of these measures as proxies of relative power and coordination costs echoes previous work in the hydropolitics literature, such as Tir and Ackerman (2009) and Zawahri and Mitchell (2011), and in the geoeconomics literature, such as Kleinman et al. (2024). I describe the compilation of these quantitative measures in Section 4.2.

3 Downstream economic effects of dams

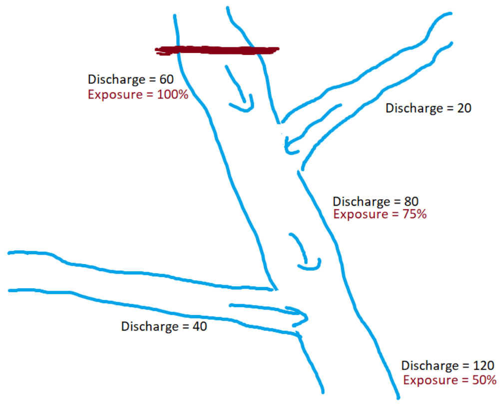
3.1 Empirical method

3.1.1 Estimating the causal effects of dams using flow share

To causally identify the effects of dams, including on regions far downstream, the main challenge is finding a comparable control group. Possible "naive" approaches might be to compare places near rivers with places farther away, places near dammed rivers with places near undammed rivers, or places upstream versus downstream of a dam. However, areas in these pairs may not be comparable: for example, historical development has been concentrated near large rivers. And empirically, in my sample which will be described in the next section, neither balance nor parallel trends is satisfied when comparing places near rivers downstream of dams with places near undammed rivers, even in the same level-2 administrative region. Existing work, primarily focused on estimating local impacts, has often used a river gradient IV for local dam placement (Duflo and Pande, 2007; Hansen et al., 2011; Strobl and Strobl, 2011). For estimating impacts on far downstream areas, such an IV is unlikely to have a strong first-stage.

Instead, I construct a novel measure of dam exposure and identify the causal effects of dams under two assumptions. The first assumption is that local populations and economies near rivers are adapted to the pre-dam long-term river discharge (that is, the volume of water flowing through in a given interval of time) of the nearest river reach. Under this assumption, I leverage the tributary network of rivers to generate spatial variation in exposure to the dam *along the same river*. Restricting the sample to locations near rivers, let i denote location and d denote dams. Then, for each i that is near a river reach downstream of d, I calculate the *flow share* from d to i as the pre-dam river discharge of the branch that was dammed as a fraction of the pre-dam total river discharge at cell i if i is downstream of d. For example, consider the river network in Figure 1. The black text indicates pre-dam river discharge (e.g. in m^3/s). For cells just downstream of the dam, 100% of the river flow that the area is used to having comes from the stretch of the river that was dammed. However, downstream of the first tributary, only $60/80 = 75\%$ of the traditional flow is affected by the dam, because the other 25% comes from the undammed tributary. Similarly, further downstream, below the second tributary, only $75\% * 80/120 = 50\%$ of the traditional flow is affected by the dam. Thus, the share of baseline local river flow that is now dammed provides a continuous measure for exposure to a dam among locations along the same river.

Figure 1: Flow share from dammed area (red bar) along downstream river stretches



With the flow share measure in hand, the second assumption is parallel trends for continuous treatments: within any level-2 administrative county (e.g. US counties, Indian districts, or Chinese prefectures, henceforth called "county"), for any dammed flow share, locations near the dammed river would see parallel trends in outcomes if all were subject to that same flow share (Callaway et al., 2025). This motivates a two-way fixed effects (TWFE) approach with county-specific time dummies.[12] For grid cell i in county j, in year t, near a river subject to dam d, I estimate the TWFE regression

$$Y_{ijt} = \beta \sum_{d} FS_{id} C_{idt} + \alpha_i + \gamma_{jt} + \varepsilon_{ijt} \tag{1}$$

where FS_{id} is the pre-dam long-run average flow share from d to i, $C_{idt} = 1$ if dam d was constructed no later than year t and there is no other dam in the sample located downstream of d and upstream of i in year t.

Similarly, I can estimate heterogeneous effects of dams satisfying different criteria, such as dams in the same country as i or in a foreign upstream country, by estimating separate

[12]The stated parallel trends assumption follows the "strong" parallel trends assumption of Callaway et al. (2025) of no selection-on-gains into treatment *dosage*. Under this assumption, TWFE identifies the weighted average of the marginal effect of an increase in dammed flow share and the effect of some dammed flow share relative to none. The regression weights are non-negative and sum to 1, but are generally not equal to the population distribution of flow share. In this analysis, locations with higher flow share within each county would be given disproportionate weight. An alternative estimator for difference-in-difference with continuous treatment that provides more easily interpretable results is that of de Chaisemartin and d'Haultfoeuille (2024). However, this estimator would require variation within counties in the timing of first dam exposure. Hence, it would restrict the estimation sample to counties containing dams and counties with multiple rivers that have upstream dams. Since such a sample restriction severely reduces the ability of this analysis to answer the research question of far downstream impacts and foreign externalities, I continue with TWFE.

coefficients on the flow share affected by dams falling in different subsets:

$$Y_{ijt} = \beta \sum_d FS_{id}C_{idt}X_{idt} + \phi \sum_d FS_{id}C_{idt}(1 - X_{idt}) + \alpha_i + \gamma_{jt} + \varepsilon_{ijt} \tag{2}$$

where X_{idt} is a binary indicator that could vary at the dam-, dam by cell-, or dam by cell by year-level. For example, to separately estimate the effects of domestic and foreign dams, I define $X_{id} = 1$ if dam d is in the same country as cell i and $X_{id} = 0$ otherwise.

Note that the flow share measure combined with two-way fixed effects will identify the effects of dams *via changes in river flow only.* Dams may generate costs or benefits through other channels such as electricity provision, but within a downstream county, these are likely to affect areas equally, and will be absorbed by the county time trends γ_{jt}.

3.1.2 Estimating pre-period and dynamic effects

Since the flow share measure is continuous and changes multiple times during the sample period for cells with multiple upstream dams, I use two methods to estimate dynamic effects and assess pre-period parallel trends. First, following Suárez Serrato and Zidar (2016) and Fuest et al. (2018), I estimate the following distributed lag regression:

$$Y_{ijt} - Y_{ij,t-1} = \sum_{\tau \neq -1} \phi^{\tau} \sum_d FS_{id}(C_{id,t-\tau} - C_{id,t-\tau-1}) + \gamma_{jt} + \varepsilon_{ijt} \tag{3}$$

where, as in Equation (1), $C_{idt} = 1$ if dam d was constructed by year $t - \tau$ and there is no other dam in the sample located downstream of d and upstream of i in year t. Since Equation (1) posits a relationship between contemporaneous flow share and outcome Y, this implies a relationship between change in flow share and ΔY, hence the annual change on the left-hand side of Equation (3). Cell fixed effects are differenced out. For event time τ, the coefficient ϕ^{τ} provides the effect of an increase in dammed flow share that occurred τ years earlier. If the strong parallel trends assumption holds, then $\phi^{\tau} = 0$ for $\tau < 0$. That is, within-county variation in the annual change in nightlights in any year should be uncorrelated with variation in how much flow share was dammed in a future year.

Second, I transform the continuous flow share measure into a binary measure and estimate a standard event study. To construct the binary measure, for each county j, I begin by identifying the year T_j in which any cell in j was first subjected to any upstream dam constructed after 2000. For each cell i in county j, I then determine whether the cell's flow share from all dams in year T_j is above or below the county-specific median in that year:

$$HighFS_i = \mathbf{1}[FS_{i,T_j} > MedianFS_{j,T_j}].$$

In addition, I define county-level binary event-time treatment dummies $D_{rt}^{\tau} = \mathbf{1}[t - \tau = T_j]$. These quantities allow me to estimate the event study

$$Y_{ijt} = \sum_{\tau \neq -1} \psi^{\tau} HighFS_i \times D_{it}^{\tau} + \alpha_i + \delta_{jt} + \varepsilon_{irt} \tag{4}$$

where ψ^{τ} represents the effect of having above-median flow share, τ years after dam exposure in the county began. With a binary treatment, the identification assumption becomes the more standard parallel trends assumption, of which a placebo test is whether $\psi^{\tau} = 0$ for $\tau < 0$. For robustness, I repeat this analysis with $HighFS_i$ defined based on the county-specific median flow share in 2013 (end of sample period).

3.2 Data

3.2.1 Dams

I obtain dams information from the Global Dam Tracker (GDAT). Out of the 35k dams around the world recorded in GDAT, 31,780 are geolocated, and most dams have non-missing data for year that construction finished, main purpose, and other attributes. Although GDAT does not capture close to the universe of dams in the world, it is significantly more comprehensive than other freely available dam databases (Zhang and Gu, 2023), and excluded dams tend to be smaller structures.[13]

There are 1525 dams with geolocation in GDAT that were finished between 2001-2013. Of these, 1410 were matched to downstream populated cells (cells discussed below). Dynamic event studies are estimated on panels of cells balanced in event-time, which received at least one upstream dam no later than 2009. There are 1200 dams built between 2001-2009. Out of the 1525 dams, 668 (44%) are known to be hydroelectric dams, 506 (33%) are known to be irrigation or water supply dams, and 82 (5%) are known to be flood control dams. The rest have unknown purpose (17%) or serve recreation or fisheries (1%). Although some dams are multipurpose, I use the "main purpose" variable in GDAT to classify dams into a single purpose category. Based on this categorization, almost all dams known to produce electricity are classified as hydroelectric dams.

The 1525 dams finished between 2001-2013 are distributed across 63 countries. Among them, 543 (39%) are upstream of one or more foreign countries, and are hence in a position

[13]For instance, there are over 91,000 dams in the US alone by the US government's count, but only 7% of these, or 6370, are considered "large" dams according to the definition of the International Commission on Large Dams (National Inventory of Dams, n.d.). GDAT records 7012 dams in the US, of which 5999 are "large" dams. Thus, if coverage in the US is comparable to in the rest of the world, then GDAT would have an inclusion rate of over 90% for "large" dams.

to potentially impose transboundary externalities. Figure 2 shows the geographical spread of the dams, with blue dots indicating that the dam is upstream of one or more foreign countries. Although many dams exist in North America and Europe, since the 1980s, new dams have primarily been built in Asia, Africa, and South America (Zhang and Gu, 2023). Figure 2 reflects the predominance of dams in low- and middle-income countries in those regions. Of the 1525 dams, only 5% are in countries classified as high-income by the World Bank in 2024.

Figure 2: Geolocated dams with construction finished in 2001-2013 (GDAT)

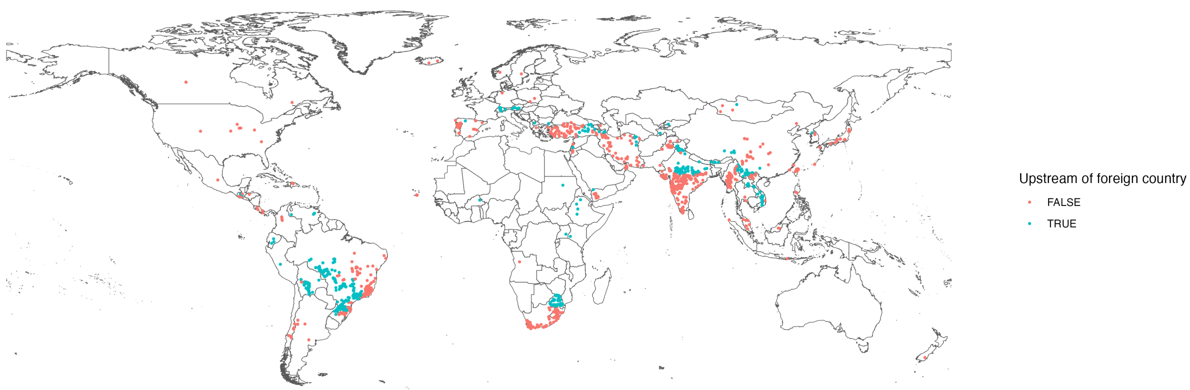


Table 1 shows the prevalence and size of different types of dams constructed between 2001-2013. Out of the dams for which the main purpose is known, hydroelectric dams are by far the largest in terms of both dam height and reservoir capacity. Moreover, Figure 3 shows that although the number of dams constructed has declined over time, the decline is mainly driven by non-hydroelectric dams. Although my sample ends in 2013, the fact that new dams in recent years have been almost exclusively hydroelectric makes hydropower the most policy-relevant type of dam today.

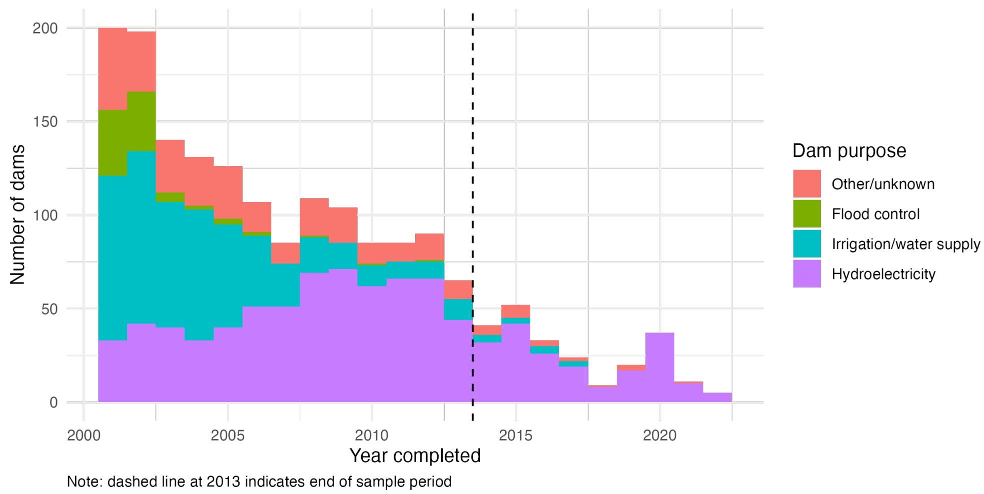
3.2.2 Rivers and discharge

I obtain geospatial data on river courses and tributary networks from HydroRIVERS. To measure pre-dam discharge, I use the discharge attribute included in HydroRIVERS, which represents the average across 1971-2000 as estimated from the WaterGAP integrated water balance model. Therefore, I restrict the sample of dams to those with recorded year built of 2001 or later. Furthermore, because small streams are ubiquitous in much of the world, I sparsify the river network by restricting the sample to river reaches at or above the 80th

Table 1: Average height and reservoir capacity of dams built 2001-2013

		Height (m)		Reservoir volume (millions m^3)	
Dam purpose	N	Mean	Median	Mean	Median
Hydroelectricity	668	52.5	35	1689.1	58.8
Irrigation/water supply	506	31.4	23.9	26.0	0.8
Other/unknown	269	20.8	12	72.8	0.3
Flood control	82	14.7	8.8	41.3	0.1
All	1525	35.8	21.2	442.4	0.6

Figure 3: Dam completion by purpose and year



percentile of 1971-2000 average discharge rates, which is 2.17 m^3/s. For reference, the discharge rate of the Chicago River soon after branching out from Lake Michigan, averaged over 2000-2006, was 3.9 m^3/s. I make this restriction because (1) a dam on a very small stream may not amount to the same treatment as a dam on a large river, and (2) small streams are so ubiquitous that the spatial resolution of analysis would need to be very fine to avoid having multiple streams/rivers in the average cell.[14]

[14] Although it would be ideal for this study, to my knowledge, there is no data product that would allow me to measure *changes* in river discharge caused by dams at a global scale. River gauge networks (e.g. as maintained by the GRDC) are spatially sparse, and data in recent decades are not available for most of Africa and Asia. While reanalysis products such as WaterGAP and the GloFAS are spatially and temporally complete, they only incorporate dams via basic modeling that does not account for how each dam is actually operated.

3.2.3 Dependent variables

Satellite-derived nighttime lights data are a widely-used proxy for economic activity, with approximately unit elasticity with respect to GDP in developing countries (Henderson et al., 2012), which describes most dam-building and dam-affected countries in recent decades. I use the DMSP nightlights product, available from NOAA for 1992-2013. I aggregate nightlights in each year to the 0.05 degree resolution. Following Burlig and Preonas (2024), I do so by taking the maximum rather than the mean across small cells. The nightlights index ranges from 0 to 63, with 0 indicating complete darkness. Nighttime lights, especially the older DMSP product relatively to the more recent VIIRS, have known shortcomings, including top-coding, satellite sensor sensitivity, capturing extensive margin more than intensive margin changes, and capturing urban growth better than rural growth. However, they remain the best option available for analyzing economic activity at a local level globally.

As a robustness check, I also use PM2.5 air pollution concentrations as an outcome. Gridded satellite-based PM2.5 air pollution data for the globe is available for each year from 1998-2021 (Shen et al., 2024), and I obtain the 1998-2013 data. Since PM2.5 concentrations are partly determined by factors such as pollution regulations that do not strictly track with economic activity, the use of PM2.5 as a rough proxy for economic activity relies on the assumption that those factors are either time-invariant or change in similar ways for all cells within each county. If that is the case, then effects on PM2.5 capture a combination of effects on population, traffic, industry, and agricultural burning - all components of economic activity.

3.2.4 Other data

I obtain gridded population estimates for the year 2000 from WorldPop, and aggregate to the 0.05 degree resolution by summing. I obtain gridded land cover classifications, also for the year 2000, from the ESA Climate Change Initiative. I aggregate the 10 arc-second resolution land cover data to the 0.05 degree resolution by taking the population-weighted mode. For both variables, I use 2000 data so as to capture pre-dam baselines.

3.2.5 Final sample

The unit of analysis is 0.05 x 0.05 degree grid cells, which have area of roughly 30 km^2, or 1/20 the area of the city of Chicago. The main sample consists of cells within 25km of river reaches that are downstream of at least one of the 1525 dams constructed between 2001-2013. I further subset to cells that had population of at least 100 people in the year 2000. This yields approximately 75,000 cells, spanning 95 countries. For each cell, nightlights data are available from 1992-2013, giving a panel of 1.8 million cell x year observations.

The 1525 dams of which the cells are downstream span 63 countries. In addition to cells within the same countries as the dams, there are 106 pairs of foreign upstream dam country/downstream cell country.

3.3 Results

3.3.1 Overall effects of dams on downstream economic activity

Given that different types of dams vary greatly in their physical scale and typical impacts on the river's quantity and seasonality of flow, I separately estimate the effects of hydroelectric and other types of dams. Table 2 presents the estimates of the static TWFE specification of Equation (1), with dams divided by purpose and nightlights as the outcome. The largest negative impact comes from hydroelectric dams (Column 1), consistent with the large size of hydroelectric dams relative to other dams. The average cell in the sample had about 17% of its pre-2001 flow share impounded by hydroelectric dams by the end of the sample period in 2013. Scaled by this factor, the estimate in Column (1) implies that the hydrological effects of hydroelectric dams caused a reduction in nightlights of 0.06 during the sample period, which is 2% of the average growth in nightlights of 2.79 among sample cells from 2001-2013. Panel (a) of Figure 4 shows the the distributed lag estimates for the cumulative effects of flow share from hydroelectric dams. Consistent with the parallel trends assumption, there are no significant cumulative effects throughout the pre-period. Reductions to growth begin to accumulate following dam construction, becoming statistically significant at the 95% level two years post-construction, with no indication of recovery to pre-dam growth trends up to four years after dam construction.

Column (1) of Table 2 and Appendix Figure B1 show that non-hydroelectric dams, by contrast, have small and insignificant effects on average. While Column (3) of Table 2 finds that dams primarily operated for flood control have a large positive marginal effect, such dams constitute only 5% of the dams constructed between 2001-2013. Going forward, I will focus on hydroelectric dams.

To understand the mechanisms driving the downstream growth reductions from hydroelectric dams, I estimate the effects separately for subsamples of cells with different pre-dam land use. Table 3 shows that cells classified as irrigated cropland in 2000 experience the largest and most precisely estimated decreases to economic growth following the construction of upstream dams, suggesting agriculture as the primary channel for dam impacts. Relative to the average increase of 3.93 in nightlights over 2001-2013 experienced by this subsample, the effect at the mean 2013 flow share represents a 4% reduction in potential economic growth. Panel (b) of Figure 4 displays the cumulative effects estimated from a distributed lag regression over irrigated cropland cells. In the subsample, the parallel trends assumption continues to hold, while the post-period reductions accumulate more quickly and steeply. The more severe economic cost over irrigated cropland is consistent with the fact that a majority (60%) of irrigated land globally was irrigated by surface water sources, such as rivers, in the 2000s (Siebert et al., 2013), and would hence be vulnerable to changes in surface water.

Table 2: Static TWFE estimates of effects of flow share from dams on nightlights, by dam purpose

	(1)	(2)	(3)
Flow share from hydroelectric dams	-0.395***		
	(0.124)		
Flow share from non-hydroelectric	-0.0350		
	(0.108)		
Flow share from irrigation dams		-0.268	
		(0.178)	
Flow share from non-irrigation		-0.151*	
		(0.0907)	
Flow share from flood control dams			2.507***
			(0.802)
Flow share from non-flood control			-0.192**
			(0.0831)
Observations	1773618	1773618	1773618
Mean 2013 flow share	0.155	0.0435	0.00288
Effect at mean 2013 flow share	-0.0615	-0.0117	0.00722

Notes: Mean 2013 flow share is the mean of flow share from dams of the dam type of interest in 2013, the end of the sample period. Effect at mean 2013 flow share is the product of that mean and the coefficient on flow share from the dam type of interest. For comparison, average change in nightlights from 2001-2013 in the sample was 2.79. All specifications include cell and county x year fixed effects. Standard errors in parentheses, clustered by river reach.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

As a robustness check for the distributed lag specification, Appendix Figure B2 shows event study estimates following Equation (4) for the effect of above-median within-county flow share from hydroelectric dams. They are qualitatively similar to the results in Panel (a) of Figure 4. In addition, as a robustness check for nightlights as a measure of economic activity, Appendix Table B2 and Appendix Figure B3 show that the effects on PM2.5, though noisier, are consistent with the effects on nightlights. Finally, whereas the main specifications are estimated on the sample of cells within a 25km buffer from rivers, Appendix Table B3

Table 3: Effects on nightlights, by pre-dam land use

	(1) Rainfed crop	(2) Irrigated crop	(3) Urban	(4) Vegetation	(5) Sparse or barren
FS from hydroelectric dams	-0.249	-0.936***	0.283	0.0397	2.558***
	(0.212)	(0.253)	(1.960)	(0.176)	(0.967)
FS from non-hydroelectric	0.0187	-0.483*	-1.711*	0.0203	-0.348
	(0.158)	(0.254)	(1.027)	(0.182)	(0.493)
Observations	669086	230494	21252	480788	167530
Mean 2013 flow share	0.124	0.174	0.138	0.208	0.118
Effect at mean 2013 flow share	-0.0309	-0.163	0.0391	0.00825	0.302
Mean change in nightlights, 2001-13	3.430	3.930	2.930	1.700	2.090

Notes: Mean 2013 flow share is the mean of flow share from hydroelectric dams in 2013, the end of the sample period. Effect at mean 2013 flow share is the product of that mean and the coefficient on flow share. The mean change in nightlights from 2001-2013 among cells in the sample of each land cover type is provided for comparison. All specifications include cell and county x year fixed effects. Standard errors in parentheses, clustered by river reach. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

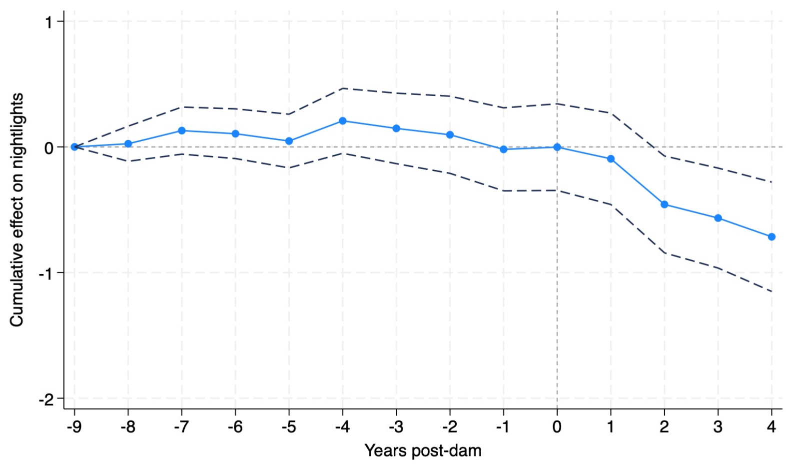
shows that the results are robust to the buffer width from which cells are included in the sample.

One advantage of the flow share measure of dam exposure is that it allows for the identification of dam effects far downstream from the dam. To test whether the negative economic effects of hydroelectric dams are concentrated near the dam or propagate far downstream, I estimate a version of Equation (1) that includes a separate term for flow share from hydroelectric dams within each of the intervals $[0, 0.1), [0.1, 0.2), \ldots, [0.9, 1]$. Figure 5 plots the results. As one travels downstream from a hydroelectric dam, the marginal effect on nightlights of additional flow share from the dam is negative and consistent in magnitude until flow share reaches 0.3. In the $[0.2, 0.3)$ interval, it remains negative and may increase in magnitude. This indicates that the hydrological impacts of hydroelectric dams indeed propagate far downstream. For example, the Lancang River, which is the headwaters of the Mekong in China, contributes 16% of the Mekong's total annual flows. The results in Figure 5 suggest that China's series of hydroelectric dams on the Lancang would be expected to have a measurable negative impact on economic activity in most of the river basin upstream of the Mekong River Delta (Mekong River Commission, n.d.). Moreover, the consistency of the marginal effect across most of the flow share distribution lends support to the assumption that impounded flow share has a linear relationship with nightlights.

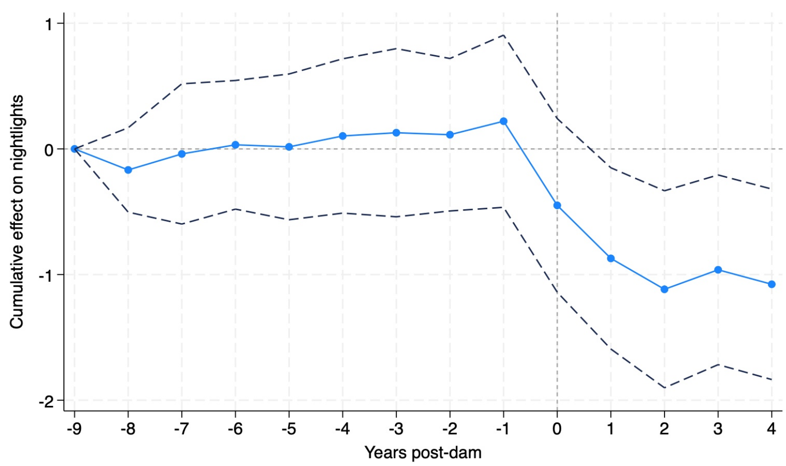
3.3.2 Cross-border externalities

Since dams impose downstream economic costs, including far downstream, I now turn to explicitly estimating the cross-border effects. Table 4 displays the results of estimating separate effects of hydroelectric dams in the same country, and in foreign upstream countries, as the grid cell, over all cells and subsamples by pre-dam land use. Column (1) shows that even though the average flow share exposure to foreign dams (5.17%) is smaller than that to domestic dams (10.4%), the marginal effect of flow share from foreign dams is more than twice as large. Consequently, the implied magnitude of the externality at average flow share levels is higher across the border than within the dam's country. Columns (2)-(6) suggest that in foreign downstream countries, again, the primary channel is agriculture. Cumulative dynamic effects of both domestic and foreign flow share are plotted in Figure 6.

Figure 4: Hydroelectric dams: Dynamic effects of flow share on nightlights



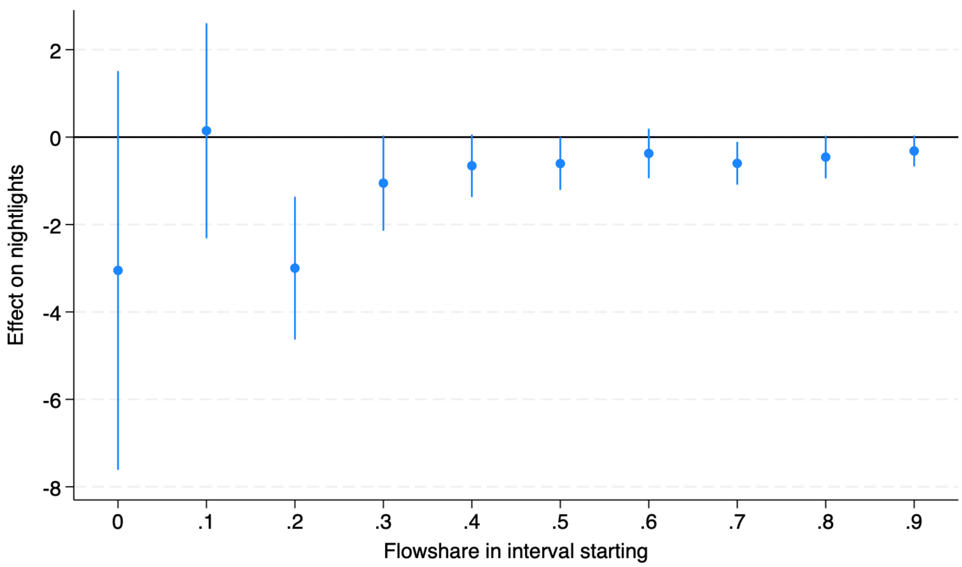
(a) All land use



(b) Irrigated cropland

Note: This figure plots distributed lag regression coefficients and 95% confidence intervals for flow share from non-hydroelectric dams, obtained by estimating Equation (3) with separate terms for flow share from hydroelectric dams only and flow share from all non-hydroelectric dams. The figure plots the cumulative effects on nightlights relative to 9 years prior to dam construction, that is, $\sum_{k=-9}^{\tau} \phi^k$. Panel (a) displays cumulative effects over the entire sample, and Panel (b) displays cumulative effects estimated over the subsample of cells classified as irrigated cropland in 2000. The coefficient on non-hydroelectric dams is omitted. The regression includes county x year fixed effects. Standard errors clustered by river reach.

Figure 5: Effects on nightlights of hydroelectric dams, by flow share bin



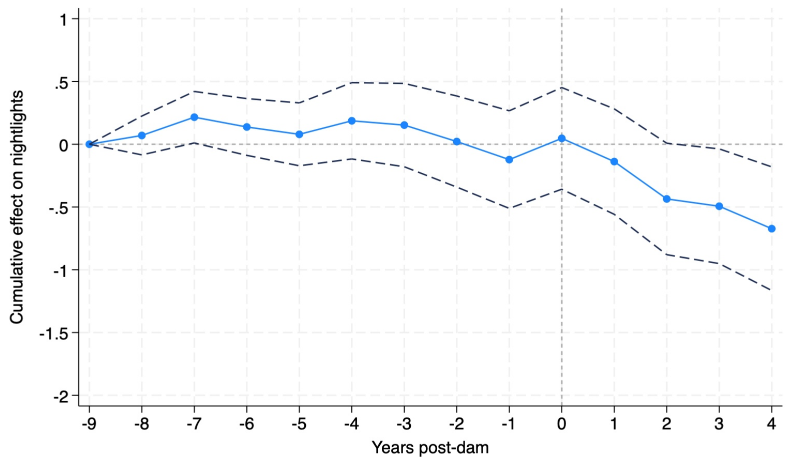
Notes: This figure plots the estimates and 95% confidence intervals from a regression that includes a separate term for flow share from hydroelectric dams within each of the intervals $[0, 0.1), [0.1, 0.2), \ldots, [0.9, 1]$. Each plotted coefficient represents the marginal effect of additional flow share impounded by hydroelectric dams when that flow share is within the specified interval. The specification further includes flow share from non-hydroelectric dams, cell fixed effects, and county x year fixed effects. Standard errors clustered by river reach.

Table 4: Effects of domestic vs foreign dams on nightlights

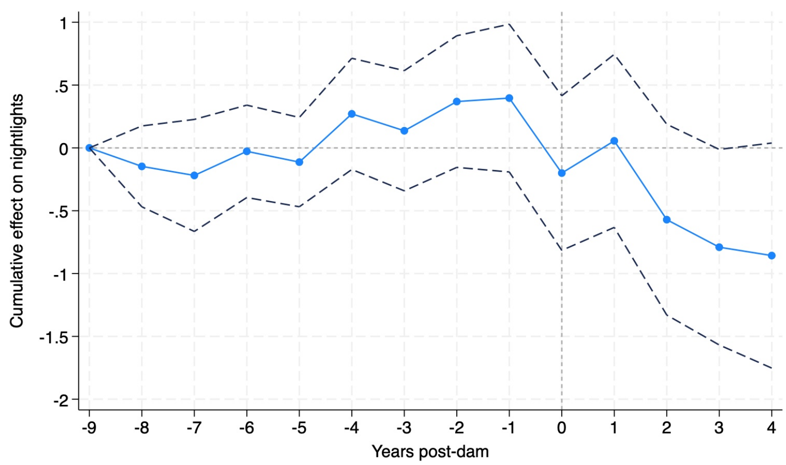
	(1) All	(2) Rainfed crop	(3) Irrigated crop	(4) Urban	(5) Vegetation	(6) Sparse or barren
FS from domestic hydro	-0.291**	-0.175	-0.556	0.331	0.0624	2.449**
	(0.135)	(0.216)	(0.414)	(1.996)	(0.184)	(1.069)
FS from foreign hydro	-0.814***	-1.084	-1.249***	-2.315	-0.255	2.872
	(0.308)	(0.856)	(0.320)	(3.364)	(0.496)	(2.272)
FS from non-hydroelectric	-0.0511	0.00938	-0.526**	-1.712*	0.0189	-0.346
	(0.108)	(0.159)	(0.255)	(1.027)	(0.183)	(0.491)
Observations	1773618	669086	230494	21252	480788	167530
Mean 2013 domestic FS	0.104	0.104	0.0630	0.0893	0.156	0.0383
Effect at mean 2013 domestic FS	-0.0302	-0.0182	-0.0351	0.0295	0.00973	0.0937
Mean 2013 foreign FS	0.0517	0.0200	0.111	0.0489	0.0521	0.0797
Effect at mean 2013 foreign FS	-0.0421	-0.0217	-0.139	-0.113	-0.0133	0.229
Mean change in nightlights, 2001-13	2.790	3.430	3.930	2.930	1.700	2.090

Notes: Mean 2013 flow share is the average flow share from hydroelectric dams in 2013, the end of the sample period. Effect at mean 2013 flow share is the product of that mean and the coefficient on flow share. The mean change in nightlights from 2001-2013 among cells in the sample of each land cover type is provided for comparison. All specifications include cell and county x year fixed effects. Standard errors in parentheses, clustered by river reach. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Figure 6: Effects of flow share from domestic vs foreign hydroelectric dams on nightlights



(a) Domestic



(b) Foreign

4 The role of international relations

4.1 Empirical method

4.1.1 Estimating the role of international politics

To estimate how the downstream effects of dams varies by bilateral relations between the dam's country and the downstream cell's country, I assume that, after location fixed effects have controlled for country-level baseline characteristics, the baseline *pairwise difference or relationship* in any characteristic between the upstream and downstream countries is orthogonal to the potential effects of a dam on cells in the downstream country. For example, a downstream country's GDP or total volume of trade with other countries may well influence how insulated local areas are to having the river flow altered, through access to capital or other mechanisms. However, after controlling for the downstream country's baseline GDP or total trade volume, the baseline difference in GDP between the downstream country and upstream dam-building country is plausibly exogenous to the dam effects.

To implement this, I simply estimate Equations (2) with an additional interaction term between flow share from each dam and the upstream and downstream countries' baseline bilateral relations. That is, for each downstream location i, let D denote the downstream country that i belongs to, let U index foreign countries upstream of D, and let R_{UD} denote a measure of baseline pre-dam relations between countries U and D. I estimate:

$$Y_{ijt} = \beta \sum_{d \in D} FS_{id} C_{idt} + \phi_1 \sum_{U} \sum_{d \in U} FS_{id} C_{idt} + \phi_2 \sum_{U} \sum_{d \in U} FS_{id} C_{idt} IR_{UD} + \alpha_i + \gamma_{jt} + \varepsilon_{ijt} \quad (5)$$

I interpret β as the effect of river impoundment by domestic dams, ϕ_1 as the effect of river impoundment by foreign dams given the lowest baseline level of the international relations measure IR, and ϕ_2 as the change to the cross-border externality ϕ_2 that is associated with an increase in IR. While flow share is assigned by river reach, IR measures are assigned by country pair. To be conservative, I cluster standard errors by country in regressions containing IR interaction terms.

4.1.2 Addressing confounders for international relations

In the absence of an instrument for the IR measures, one may be hesitant to interpret the coefficients of interaction terms between flow share and these measures as the causal effect of IR. I address this concern with two pieces of analysis.

First, I address the specific possibility that more favorable relations with one's neighbors could be correlated with domestic political, economic, or other factors that makes a country more resilient to environmental shocks in general. For example, if countries with more inclusive and responsive political institutions also tend to seek more cooperative foreign relations, then the interaction term coefficients could be capturing the effects of more effective domestic aid rather than international coordination. Or, wealthier countries that tend to get their way over their neighbors may also have private sectors better equipped to adapt to shocks.

To alleviate such concerns, for each country in the sample, I estimate the pre-period (1992-2000) sensitivity of nightlights to domestic drought and wetness shocks. I describe the estimation of these sensitivity parameters in Appendix A.1. Then, I re-estimate Equation (5) with additional interaction terms between flow share and the drought and wetness sensitivities:

$$\begin{aligned} Y_{ijt} = \beta \sum_{d \in D} FS_{id}C_{idt} + \phi_1 \sum_{U} \sum_{d \in U} FS_{id}C_{idt} + \phi_2 \sum_{U} \sum_{d \in U} FS_{id}C_{idt} IR_{UD} \\ + \phi_3 \sum_{U} \sum_{d \in U} FS_{id}C_{idt} DroughtSens_D + \phi_4 \sum_{U} \sum_{d \in U} FS_{id}C_{idt} WetSens_D + \alpha_i + \gamma_{jt} + \varepsilon_{ijt} \quad (6) \end{aligned}$$

The interaction terms with the sensitivities control for the downstream country's ability to deal with water-related shocks in general, without needing to specify the determinants of that ability, which may differ across countries.

Second, I use an alternative identification strategy that leverages within country-pair, over time variation in IR. The Integrated Crisis Early Warning System (ICEWS) has, since 1995, coded media reports of interactions between states, organizations, and citizens of different countries. This provides over-time variation in bilateral engagement between pairs of countries. Using counts of cooperative and hostile engagement events, as well as ICEWS-coded intensity scores of events, as measures of IR, I use a cell x dam country x year panel to estimate

$$\begin{aligned} Y_{ijUDt} = \beta \sum_{d \in D} FS_{id}C_{idt}\mathbf{1}[U = D] + \phi_1 \sum_{d \in U} FS_{id}C_{idt}\mathbf{1}[U \neq D] \\ + \phi_2 \sum_{d \in U} FS_{id}C_{idt} IR_{UDt} + \phi_3 \sum_{d \notin U} FS_{id}C_{idt} + \alpha_i + \psi_{UD} + \gamma_{jt} + \varepsilon_{ijUDt} \quad (7) \end{aligned}$$

where β is the effect of flow share from domestic dams, ϕ_1 is the effect of foreign upstream dams in country U when $IR_{UDt} = 0$, and ϕ_2,the coefficient of interest, is the additional effect of dams in country U when IR_{UDt} increases by one unit. The ϕ_3 term is a control for flow share from all dams in countries other than U. The inclusion of country-pair fixed effects ψ_{UD} accounts for any time-invariant factors that may be correlated with IR.

With time-varying IR measures, one may be concerned about reverse causality: that once a dam has been built and downstream economic impacts realized, bilateral engagement will shift in the following years in response. To alleviate this concern, I use 1-year lags of the bilateral engagement measures. In Section 4.2, I discuss the ICEWS dataset in greater detail.

4.2 Data

4.2.1 Power asymmetry

I compile two measures that proxy for power asymmetry, which realists would predict to be a determinant of propensity to cooperate. The first measure of political power is trade dependence. I obtain annual bilateral trade flows from the Correlates of War Project (Barbieri and Keshk, 2016). For each downstream cell x upstream dam pair, let U denote the upstream dam-building country, and D denote the downstream country containing the cell. I construct four measures of bilateral trade relations between U and D. The first three are measures of trade dependence: (1) the share of U's imports that come from D, (2) the share of the U's exports that go to D, and (3) the difference between D's share of U's imports and U's share of D's imports. A higher value of any of these indicates that U is more trade dependent on D, and hence, D has more leverage over U. The fourth measure of bilateral trade relations is (4) the undirected total trade volume between U and D, adjusted by the combined sizes of the two countries' GDPs. All trade flows and GDPs are measured at pre-dam baseline with the average value over 1990-2000.

Although trade dependence is a commonly used measure of power in the geoeconomics literature (Mohr and Trebesch, 2025), one disadvantage of the trade measure is that the direction of the effects of trade on political cooperation has been found to be contingent on other incentives and circumstances (Brooks, 2024; Martin et al., 2008). Thus, I use GDP imbalance as a second measure of power relations. To calculate GDP imbalance, I obtain country-level annual GDP data from the World Bank. I average across the baseline years of 1990-2000 for each country, and construct two binary measures for whether D's baseline GDP is at least 20% larger, or at least 20% smaller, than U's.

4.2.2 Strategic alliances

Power and cooperation can be influenced by geopolitical alliances or positions that trade flows and economic might may not capture.[15] To capture political alignment, also a realist

[15] Although China and the United States are not a country pair that shares rivers, for illustrative purposes, consider that China was the source of the largest share of American imports as recently as 2022. Their poor

measure of propensity to cooperate, existing economic and political science literature has used and validated measures of how similarly two countries vote in the United Nations General Assembly (UNGA) (Becko et al., 2025; Kleinman et al., 2024).Three measures of bilateral voting similarity, the S-, π-, and κ-scores, all begin with the sum across vote calls of the difference between two countries' votes. The S-score scales this difference measure by the squared maximum possible difference (Signorino & Ritter, 1999). The π and κ scores use slightly different methods to further adjust for the distribution of each country's votes, to account for the probability that two countries cast the same vote by chance (Cohen, 1960; Scott, 1955). A fourth measure, ideal point distance, seeks to account for the fact that year-to-year changes in voting similarity are partially due to changes in the content of the measures being voted on, rather than true changes in the relative positions of countries. It begins with each country's ideal point, which captures its political positions relative to the US-led liberal order. The ideal point distance is then the absolute difference between two countries' ideal points (Bailey et al., 2017; Kleinman et al., 2024). A larger value of the S-, π-, or κ-score indicates more similar votes, whereas a smaller value of ideal point distance indicates the same. For all four measures, I obtain pre-dam baselines by averaging each measure over 1993-2000, hence excluding Soviet years during which the measures were not available for former Soviet states.[16]

4.2.3 Regime type similarity

For regime type similarity, I begin with the democracy index and the autocracy index created by the Polity Project, version 5. Each index takes on integer values ranging from 0 to 10. A higher value of the democracy index indicates presence of more aspects of competitive, open elections, constraints on the executive, and rights to political participation. Likewise, a higher value of the autocracy index indicates the presence of more aspects of suppressed political participation and unconstrained authority of the executive. For example, at the extremes, the United States and many European countries have a democracy index of 10 and autocracy index of 0, and North Korea has a democracy index of 0 and autocracy index of 10, throughout the 1992-2013 sample period. China, where the executive is chosen from multiple candidates and does not have unlimited authority to the extent of North Korea's,

relations would not captured by trade, but would be by UNGA voting similarity.

[16]UNGA voting similarity provides an intuitive measure of political alignment in the context of great power politics. For example, Becko et al. (2025) and Kleinman et al. (2024) use it to measure countries' alignment with China vs the US. On the other hand, one drawback is that it may be somewhat less informative about bilateral relations concerning regional issues. For example, the S-, pi-, and κ-scores between India and Pakistan averaged over 1993-2000 were each above the 50th percentile among in-sample country pairs. Yet, the two countries were in strong disagreement over bilateral security issues and engaged in armed conflict during the same period.

has a democracy index of 0 and autocracy index of 7 throughout the sample period.

The indices move as the terms of executive constraints or political participation shift. For example, Myanmar's autocracy index increased from 5 to 6 following the hardening of military rule in 2004, then decreased to 3 in 2011 with the transition to civilian government led by Aung San Suu Kyi. Given the potential for significant and sudden fluctuations in the democracy and autocracy indices, and because the indices reflect a country's fundamental political institutions that are unlikely to be endogenous with the operation or recent impacts of dams, I use time-varying contemporaneous measures instead of the pre-period average.

I categorize a country pair as both democratic if both countries have democracy index above 5, and likewise for both autocratic. I then categorize the pair as having the "same" regime type if the countries are either both democratic or both autocratic. Of the 2207 country pair x year observations within my sample for which Polity data is available, 53% are categorized as having the same regime type. As alternative measures, I also categorize a country pair as having a large difference in democracy index or autocracy index if the magnitude of the difference is above the 75th percentile in the distribution of country pairs in my sample. By this method, for example, Thailand and China have large differences in both indices, while Ukraine and Austria do not.

4.2.4 Joint membership in intergovernmental organizations

A key challenge in using joint membership in IGOs as a proxy of propensity to coordinate is that there is a wide variety of IGOs with substantial variation in both purpose and clout. For example, the Correlates of War Project provides data on the membership of countries in over 500 IGOs, some of which are very niche. I construct two measures of joint membership in IGOs that targets the most relevant IGOs in different ways. For both measures, to obtain pre-dam baseline values, I use the values from the year 2000, as averaging across multiple years would necessitate accounting for the formation of new IGOs over time.

First, I subset to 51 organizations that are significant enough to be profiled in the Political Handbook of the World 2020-2021 (PHW). These include 13 organizations and agencies within the UN system, 5 regional development banks, and 31 other IGOs (plus the predecessors for two of them that went through renaming and rechartering during my sample period). The latter include global organizations such as the World Bank and World Trade Organization as well as regional ones such as the African Union and European Union. Out of these 51 IGOs, I count how many each upstream-downstream country pair is jointly member to.

Second, I use data from the Diplometrics Program at the Pardee Institute at the University of Denver. For each of 405 IGOs, this dataset assigns time-varying weights based on the frequency of media mentions as a proxy for the importance of the IGO in international affairs. For each country pair-year, it sums up the weights of the joint IGOs. These weighted sums are approximately normally distributed. I center and scale them based on the distribution of weighted sums across all country pairs (not just river-sharing ones) over 1992-2013.

4.2.5 Examples of country pairs along the distributions of international relations values

For one representative measure for each of power asymmetry, strategic alliance, regime type similarity, and IGO membership, Table 5 provides country pairs at the minimum, median, and maximum values along the distribution of the 106 in-sample country pairs. For all four measures, a higher value indicates a greater theoretical propensity for the upstream country to bear the downstream country's interests in mind when constructing and operating dams.

Table 5: Examples of country pairs along IR measure distributions. Format: upstream, downstream (IR value)

	Min	Median	Max
GDP % difference 1990-2000	China, Laos (-100%)	Burkina Faso, Benin (-17%)	Bhutan, India (1181%)
UNGA S-score 1993-2000	Syria, Israel (-0.18)	Guatemala, Mexico (0.87)	Spain, Portugal (0.98)
Same regime type Time-varying	South Africa, Eswatini (0)		Austria, Netherlands (1)
# Joint IGOs 2000	North Korea, South Korea (10)	Turkey, Georgia (18)	Austria, Netherlands (26)

Note: GDP % difference is the downstream country's GDP minus the upstream country's GDP, as a percentage of the upstream country's GDP. The count of IGOs with joint membership is out of the 51 IGOs, regional development banks, and UN agencies profiled in the Political Handbook of the World 2020-2021 for which country membership data is available through the Correlates of War Project.

In the top row, the IR measure of interest is the difference between the two countries' GDP as a percentage of the upstream country's GDP, averaged over 1990-2000. Realism would predict that Laos, which had an economy less than 1% the size of upstream China's, would have had little leverage over China's dam construction and operation decisions. On the other hand, India, which enjoys the opposite asymmetry relative to upstream Bhutan, may be able to credibly threaten meaningful retaliation if Bhutanese dams were to impose negative externalities on India.

The second row illustrates how voting similarity in the UN General Assembly serves as a proxy for international friendship. At one extreme, it captures the enmity between Syria and Israel, which have longstanding territorial disputes and a history of armed conflict, regarding bilateral and broader regional issues. At the other extreme, it captures the close bilateral accord and alignment on global issues between Spain and Portugal. Alliance and cooperation on other issues may be expected to mitigate transboundary externalities by giving downstream countries such as Portugal greater leverage on river-sharing issues, or by providing existing norms and channels for coordination.

Although the analysis uses time-varying regime type measures, in the third row, for simplicity of illustration, I give examples of country pairs that had either the same regime type or different regime types throughout 1992-2013. During this period, South Africa was a democracy with democracy index of 9, whereas Eswatini has been an absolute monarchy with autocracy index of 7. Democratic peace theory would therefore predict that all else equal, South Africa and Eswatini are less likely to cooperate on their shared rivers than Austria and the Netherlands, which, like several other European country pairs in the sample, were both democracies with democratic index of 10.

In the bottom row, the IR measure of interest is the number of IGOs listed in the PHW that two countries are jointly member to. The country pair in the sample that is jointly in the fewest IGOs is North Korea and South Korea, as expected from North Korea's isolation. At the other end of the distribution, European country pairs such as Austria and the Netherlands are in more than twice as many notable IGOs as the two Koreas. According to the theory of liberal institutionalism, the lesser availability of third-party mediation and monitoring afforded to North and South Korea by IGOs makes these countries less likely to cooperate on their shared rivers than the European countries.

4.2.6 Time-varying bilateral engagement

Finally, I use the Integrated Crisis Early Warning System (ICEWS) dataset as a source of high-frequency variation in IR. The ICEWS dataset, available from 1995-2023, records media mentions of interactions between socio-political actors of different countries, including government administrations, political parties, public figures, and citizens. The interactions range from the very hostile (e.g. armed conflict) to everyday diplomacy (e.g. hosting visits, giving praise or making accusations) to significant cooperative events (e.g. signing formal agreements, or providing economic or military assistance). Each interaction is assigned an intensity score ranging from -10 (very hostile) to +10 (very cooperative). From this dataset, I calculate three country pair x year level measures of bilateral engagement: the number of cooperative interactions (events with positive intensity score), the number of hostile interactions (events with negative intensity score), and the sum of the intensity scores across interactions.

I do not use the ICEWS bilateral engagement measures in the main specifications estimated with Equation (5) because cross-sectional comparison of bilateral engagement between country pairs is not a reliable metric for the extent of cooperation or hostility. For example, North and South Korea not only have a high number of hostile interactions, but also one of the highest numbers of cooperative interactions among country pairs in the sample, when the measures are averaged across the pre-period years of 1995-2000. On the other hand, as discussed by Liu and Yang (2025), bilateral engagement spikes during periods of major geopolitical shifts, such that *changes* in bilateral engagement over time do reflect *changes* in relations. This makes it an ideal source of high-frequency, over-time variation within country pairs that can be used in estimating Equation (7). For example, over-time variation in bilateral engagement between North and South Korea during the late 1990s and 2000s well captures the relative detente of the Sunshine Policy initiated in 1998 and the renewed decline in relations following nuclear and military tensions beginning in 2006.

In addition, part of the over-time variation in recorded interactions between country pairs may be due to differences in their media landscapes or other factors unrelated to true differences in IR. Thus, following Liu and Yang (2025), I standardize the annual observation of each measure by taking the z-score within the country-pair-specific distribution.

4.2.7 Other data

For estimating country-level pre-period drought and wetness sensitivities, I use SPEI data over 1992-2000 at the 0.5 degree resolution from the Global SPEI Database (Vicente-Serrano et al., 2010).

4.3 Results

Given that dams impose substantial transboundary externalities, are countries with cooperative international relations able to coordinate or bargain their way out of the potential costs?

In Table 6, Columns (1)-(4) display estimates of Equation (5). The regressors are flow share from domestic hydroelectric dams, flow share from foreign hydroelectric dams, and the interaction between the latter and one measure of IR from each of the theories of international cooperation described in Sections 2.2 and 4.2. For all four IR measures in the table, a higher value indicates greater propensity for coordination between upstream and downstream countries according to IR theory. Across IR measures, I find that when the propensity to coordinate is low, flow share from foreign dams has a precisely estimated negative effect. And for all IR measures except one, the coefficient on foreign flow share is larger in magnitude than, and statistically distinguishable from, the coefficient on domestic flow share. This suggests that when bilateral coordination is poor, country borders do matter, with more harm caused by dams in foreign upstream countries than by dams in one's own country. The average flow share from foreign hydroelectric dams, which are farther upstream, is necessarily lower than the average flow share from domestic dams (0.05 vs 0.10 in 2013). Nonetheless, the bottom panel of Table 6 shows that due to the difference in marginal impacts, under the scenario of minimum propensity to coordinate as proxied by the IR measures, the effect of the average foreign flow share level is still greater than the effect of average domestic flow share.

Yet, the positive coefficients on all four IR interaction terms indicate that as bilateral relations improve, or as the downstream country wields greater power over the upstream country, the negative transboundary externalities are mitigated. Figure 7 and Appendix Figures B5 and B6 plot the implied magnitudes of the coefficients in Columns (1)-(4), which are also listed in the bottom panel. At the median or better values of any of the IR measures except GDP difference, the implied magnitude of the effect of average flow share from foreign hydroelectric dams is close to and statistically indistinguishable from zero. This suggests that, whether through side payments like those of the Central Asian countries or through more indirect leverage or diplomacy, many country pairs are able to mediate away much of the potential negative transboundary externalities of dams in upper riparian countries.

Since there are multiple ways of quantifying GDP imbalance, UNGA voting similarity, regime type similarity, and joint IGO membership, Appendix Tables B5, B6, B7, and B8 show robustness of the results in Columns (1)-(4) to alternative measures discussed in Section 4.2. All results are qualitatively consistent with the narrative that hydroelectric dams have the potential to impose substantial negative transboundary externalities, and IR more favorable to the downstream country mitigates these externalities. In addition, Appendix Table B4 shows the results of using trade dependence as an alternative to GDP imbalance as a measures of power. For the most part, these results tell the same story when there is sufficient statistical power. The one exception is using the ideal point distance metric of UNGA voting similarity: as greater ideal point distance indicates less agreement on international issues, the positive coefficient on the interaction term here suggests that geopolitical alliance exacerbates dam externalities. However, this counterintuitive result is driven by a positive correlation between ideal point distance and other measures of voting similarity, and is imprecisely estimated.

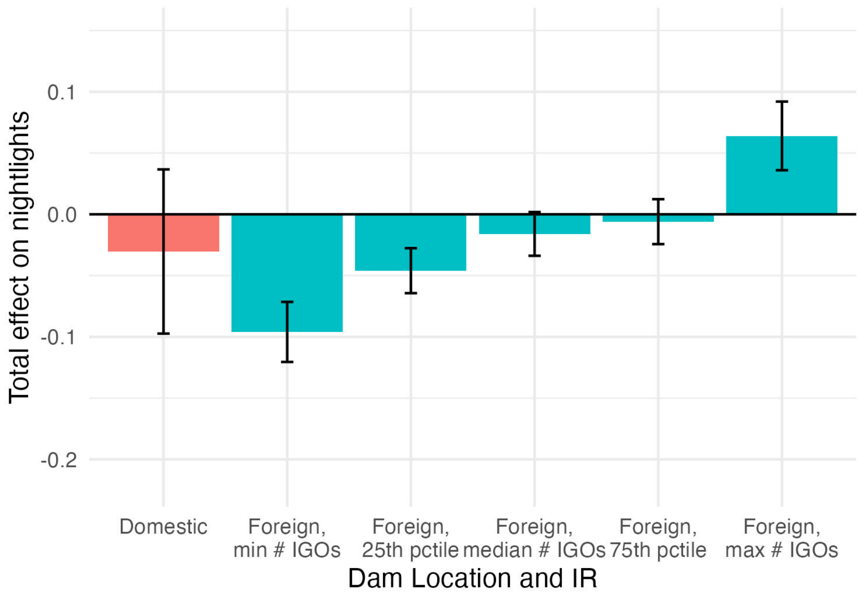
Since there can be correlation between IR measures, to determine whether each IR measure has explanatory power on transboundary externalities conditional on the others, in

Table 6: International relations and the effects of foreign hydroelectric dams on nightlights

	(1)	(2)	(3)	(4)	(5)
FS from domestic hydro dams	-0.291	-0.281	-0.288	-0.293	-0.297
	(0.324)	(0.326)	(0.324)	(0.325)	(0.326)
FS from foreign hydro dams	-0.806***	-3.772***	-2.429***	-3.789***	-3.792***
	(0.255)	(0.382)	(0.474)	(0.436)	(0.355)
x GDP % diff	0.000908***				0.00788
	(0.000274)				(0.0322)
x UNGA *S* score		3.815***			-1.812
		(0.193)			(2.562)
x Same regime type			2.235***		0.513
			(0.386)		(0.652)
x # IGOs with joint membership				0.193***	0.253**
				(0.0235)	(0.118)
FS from non-hydroelectric dams	-0.0510	-0.101	-0.0949	-0.0902	-0.101
	(0.176)	(0.173)	(0.167)	(0.174)	(0.173)
Observations	1740442	1752747	1713226	1773618	1690996
Effect of flow share at 2013 means:					
Domestic FS	-0.0307	-0.0300	-0.0313	-0.0303	-0.0328
Foreign FS, min IR	-0.0347	-0.180	-0.0902	-0.0960	
Foreign FS, median IR	-0.0347	-0.0187	-0.00722	-0.0160	
Foreign FS, max IR	0.0115	-0.00103	-0.00722	0.0640	

Notes: Effect of domestic flow share at 2013 mean is the product of the coefficient on domestic flow share and the mean flow share from domestic hydroelectric dams in 2013, the end of the sample period, which was .10. In Columns (1)-(4), The effect of foreign flow share at the minimum, median, or maximum value of the IR measure is the sum of (a) the coefficient on foreign flow share times the mean flow share from foreign hydroelectric dams in 2013, which was .05, and (b) the coefficient on the IR interaction term times the mean foreign flow share in 2013 times the minimum, median, or maximum value of the IR measure of interest among country-pairs in the sample. For comparison, average change in nightlights from 2001-2013 in the sample was 2.79. All specifications include cell and county x year fixed effects. Standard errors in parentheses, clustered by country. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Figure 7: Implied effects of domestic and foreign flow share from hydroelectric dams: heterogeneity by joint IGO membership

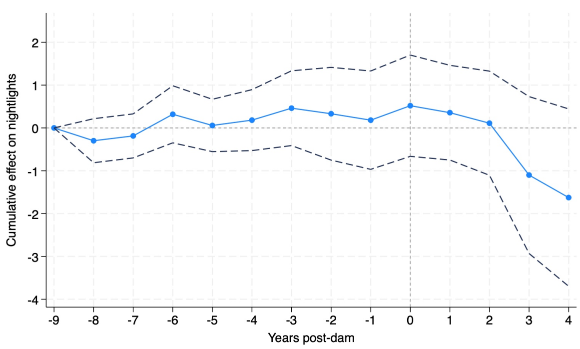


Notes: This figure plots the magnitudes and 95% confidence intervals of flow share effects implied by Column (4) of Table 6 at mean values of domestic and foreign flow share from hydroelectric dams in 2013, which were 0.12 and 0.05, respectively. For the implied effect of foreign flow share, the figure shows heterogeneity by the number among the 51 IGOs profiled in the Political Handbook of the World, 2020-2021, that a country pair is jointly member to. Among the 106 country pairs in the sample, the minimum, 25th percentile, median, 75th percentile, and maximum values of the number of joint IGOs were 10, 15, 18, 19, and 26.

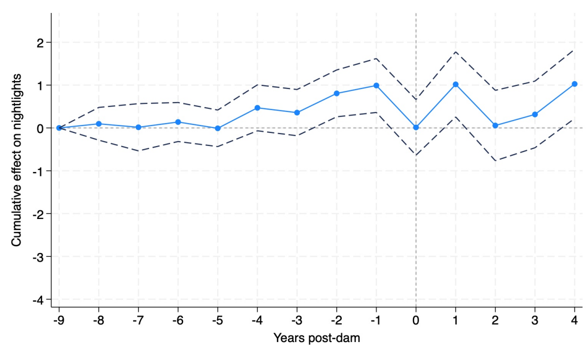
Column (5) of Table 6, I include interactions with all four measures from Columns (1)-(4) in one regression. Only joint IGO membership retains its precision. Moreover, scaling each interaction term coefficient by the mean value of the IR variable suggests that joint IGO membership has the greatest power to mitigate the potential negative externalities of foreign hydroelectric dams. This is consistent with anecdotal evidence on how riparian countries with formal cooperative river management frameworks were able to achieve them: for example, pivotal roles in negotiation were played by the UNDP for the 1995 Mekong Agreement, the World Bank for the Indus Waters Treaty of 1960, and the UN for the 1977 Ganges Water Sharing Treaty between India and Bangladesh (Dinar et al., 2013).

Figure 8 shows the distributed lag estimates of the cumulative dynamic impacts of flow share from foreign hydroelectric dams, estimated with separate coefficients for when joint IGO membership between dam country and cell country are in the bottom and top quartiles. The results again indicate that the negative transboundary externalities of flow share are concentrated in country pairs with high coordination costs, that is, in the bottom quartile of joint IGO membership.

Figure 8: Distributed lag regression: cumulative effects of flow share from foreign hydro dams, by joint IGO membership



(a) Bottom quartile



(b) Top quartile

Finally, I conduct two exercises to lend credence to the interpretation of the IR interaction coefficients as capturing the effects of IR rather than of potential confounding variables. First, to control for potential confounders that affect downstream countries' ability to cope with environmental shocks, Appendix Table B9 presents results of estimating Equation (6) with joint IGO membership as the IR measure. Across all specifications, I find that controlling for the interactions between flow share and country-specific sensitivities to drought and wetness does not qualitatively alter the result that foreign hydroelectric dams impose significant negative transboundary externalities, and that joint membership in more, or more influential, IGOs mitigates these externalities.

Second, Appendix Table B10 presents results of estimating Equation (7), using time-varying measures of bilateral engagement from ICEWS with country-pair fixed effects to account for any time-invariant correlates of IR. Qualitatively, this analysis tell the same story as the main results: as IR becomes more cooperative (more cooperative events, fewer hostile events, or a greater cooperative intensity of engagement across all events), the negative effects of hydroelectric dams in foreign upstream countries are mitigated. For the most part, the effects less precisely estimated than the main results using time-invariant IR measures. This could be because some of the effects of a dam are "locked-in" once the dam has been designed, sited, and built, and there is only partial flexibility to change the downstream effects over time on the intensive margin alone.

5 Conclusion

Many of today's most pressing environmental issues are transboundary in nature. This paper uses the context of dams around the world to generate evidence on the economic implications of transboundary externalities and on the determinants of countries' abilities to mitigate them. It is the first to conduct a causal analysis of the transboundary effects of dams at a global scale, as well as the first to measure how international relations shape transboundary environmental externalities of any kind.

I find that hydroelectric dams have far-reaching effects that translate into reductions in economic growth in foreign downstream countries. But despite the lack of a central international authority, bilateral international relations that reduce the transaction costs of coordination, particularly joint membership in intergovernmental organizations, are associated with a full mitigation of the transboundary externalities.

These findings hold two implications. First, given that new dams in recent decades have primarily been built by low- and middle-income countries, transboundary externalities and international relations matter for economic development. Second, international institutions play a significant role in facilitating transboundary resource management, alleviating the potential impacts of externalities on development. These implications motivate a rich agenda for future research on the international political economy of the environment, including on the mechanisms through which international institutions affect coordination, the strategic use of environmental externalities as leverage on other international political issues, and the potential efficiency gains of facilitating international cooperation over natural resources.

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Appendix

A Additional methodological description

A.1 Drought and wetness sensitivity

A.1.1 Measuring drought and wetness

To measure abnormal drought and wetness conditions, I use the Standardized Precipitation-Evapotranspiration Index (SPEI), available for the globe at the 0.5 x 0.5 degree resolution (about 3025 km^2 per cell) from the Global SPEI Database (Vicente-Serrano et al., 2010). Unlike commonly used measures of dryness and wetness that are based solely on precipitation (i.e. the "supply" of moisture), the SPEI is a measure of water surplus (negative values indicating deficit), as it also incorporates several other variables such as temperature, pressure, and wind speed that determine the potential evapotranspiration (i.e. the atmospheric "demand" for moisture). Thus, the SPEI better captures anomalies in the amount of moisture left available in the earth and water bodies for human use. For each cell and time, the SPEI measures this anomaly in units of standard deviations from the cell-specific long-run distribution.

I use two different methods to convert monthly SPEI data into annual measures. In the first method, I begin with 1-month timescale SPEI for each month of a given year, then average across the 12 months. For example, suppose the 1-month timescale SPEI for June 1995 in cell i equals -1. This means the water balance in cell i in June 1995 was one standard deviation below the mean water balance experienced in cell i across June of every year since 1901. This measure, for each month in 1995, is averaged to obtain the 1995 SPEI measure. As the mean of 12 standard normal variables that are positively correlated, the annual measure has a standard deviation of about 0.4. In the second method, I simply take the 12-month timescale SPEI calculated for December of each year. For example, a 12-month SPEI value of -1 in December 1995 indicates that the total water balance over January-December 1995 was one standard deviation below the mean of the distribution of total water balance over every January-December period since 1901. By construction, this measure has standard deviation of 1.

Finally, for each of these annual SPEI measures, I classify a cell as experiencing drought in a given year if SPEI $<$ -1 standard deviation and wet if SPEI $>$ 1 standard deviation. I further break down drought into severe drought, SPEI $<$ -2 standard deviations, and mild drought, SPEI between -1 and -2 standard deviations, and similarly for mild and severe wetness.

A.1.2 Estimating sensitivity to drought and wetness

For each country separately, over the pre-period years 1992-2000, I estimate

$$Y_{irt} = \sigma_1 Drought_{it} + \sigma_2 Wet_{it} + \alpha_i + \delta_{rt} + \varepsilon_{irt} \tag{A1}$$

and

$$Y_{irt} = \sigma_3 DroughtSev_{it} + \sigma_4 DroughtMild_{it} + \sigma_5 WetMild_{it} + \sigma_6 WetSev_{it} + \alpha_i + \delta_{rt} + \varepsilon_{irt} \tag{A2}$$

where i indexes 0.05 degree cells, r indexes administrative regions, and t indexes years. Since administrative regions of any given level vary in size across countries, for each country, I choose the smallest level r with average jurisdiction area of at least 6050 km^2, i.e. likely to contain two 0.5 degree cells to generate within-jurisdiction variation in SPEI. For example, the regressions for Brazil, India, and the United States are estimated with state-year fixed effects (level 1 administrative regions), and the regressions for China are estimated with prefecture-year fixed effects (level 2 administrative regions). For countries such as Uganda and Vietnam where subnational jurisdictions of any level tend to be small, as well as smaller countries, the regressions are estimated with a single set of year fixed effects for the whole country. Standard errors are clustered by the 0.5 degree SPEI cell to which 0.05 degree cells i are assigned.

A.1.3 Results

Appendix Table B9 presents results of estimating Equation (6) with joint IGO membership as the IR measure. In Columns (2) and (4), the drought and wetness sensitivity parameters are the estimates of σ_1 and σ_2 from Equation (A1). In Columns (3) and (5), the severe drought and severe wet sensitivity parameters are the estimates of σ_3 and σ_6 from Equation (A2). Across all specifications, I find that controlling for the interactions between flow share and country-specific sensitivities to drought and wetness does not qualitatively alter the result that foreign hydroelectric dams impose significant negative transboundary externalities, and that joint membership in more, or more influential, IGOs mitigates these externalities. This lends credence to the interpretation of the IR interaction coefficients as capturing the effects of IR rather than of other confounding variables that affect a downstream country's ability to cope with environmental shocks.

B Additional Tables and Figures

B.1 Tables

Table B1: Some costs and benefits of dams

	Economic Benefits	**Environmental Changes**	**Economic Costs**
Upstream & Reservoir Area	Hydropower	Inundation Waterlogging Salinity Seismicity	Displacement ↓ Ag soil quality
Downstream	Hydropower Irrigation Water supply Flood control	↓ Flow quantity Δ Flow schedule Δ Temperature ↓ Water nutrients ↓ Sediment load ↓ Fish stocks ↓ Biodiversity	↓ Ag production ↓ Fisheries, aquaculture ↓ Drought resilience ↓ Water quality ↓ Water supply
Far downstream	Hydropower Flood control		

Table B2: Effects of flow share from dams on PM2.5, by dam purpose

	(1)	(2)	(3)	(4)
Flow share	-0.387***			
	(0.0967)			
FS from hydroelectric dams		-0.596***		
		(0.119)		
FS from non-hydroelectric		-0.191		
		(0.165)		
FS from irrigation dams			-0.0184	
			(0.125)	
FS from non-irrigation			-0.474***	
			(0.112)	
FS from flood control dams				0.733
				(1.154)
FS from non-flood control				-0.392***
				(0.0963)
Observations	760672	760672	760672	760672

Notes: All specifications include cell and county x year fixed effects. Standard errors in parentheses, clustered by river reach. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table B3: Effect on nightlights of flow share from dams, by buffer width used to construct sample

	(1)	(2)	(3)	(4)	(5)
	0km	10km	15km	20km	25km
FS from hydroelectric dams	-0.508	-0.384***	-0.348***	-0.381***	-0.395***
	(0.357)	(0.149)	(0.130)	(0.124)	(0.124)
FS from non-hydroelectric	-0.0738	0.149	0.123	0.0388	-0.0350
	(0.255)	(0.143)	(0.128)	(0.117)	(0.108)
Observations	282040	1045924	1374164	1604284	1773618

Notes: In Column (1), the sample is restricted to cells that contain rivers. In each of Columns (2)-(5), the sample consist of cells within the specified distance from rivers. All specifications include cell and county x year fixed effects. Standard errors in parentheses, clustered by river reach. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table B4: Effects on nightlights from domestic vs foreign hydroelectric dams, by trade relations

	(1)	(2)	(3)	(4)
FS from domestic hydroelectric dams	-0.291	-0.291	-0.292	-0.291
	(0.324)	(0.324)	(0.324)	(0.324)
FS from foreign hydroelectric dams	-0.851***	-0.827***	-0.771***	-0.693***
	(0.261)	(0.240)	(0.198)	(0.214)
x share of U's imports coming from D	2.866			
	(1.815)			
x share of U's exports going to D		0.877		
		(3.955)		
x ($D \rightarrow U$ imp share) $-$ ($U \rightarrow D$ imp share)			2.407	
			(2.224)	
x total trade per $(GDP_U + GDP_D)$ (millions USD)				-149.3
				(287.9)
FS from non-hydroelectric dams	-0.0530	-0.0518	-0.0498	-0.0464
	(0.176)	(0.176)	(0.177)	(0.177)
Observations	1773618	1773618	1773618	1773618

Notes: All specifications include cell FEs and county x year FEs. All trade measures are all calculated as the average over 1990-2000. In Columns (1)-(3), a higher value of the trade measure indicates the upstream dam country U being more trade-dependent on downstream cell country D. In Column (4), a higher value of the trade measure indicates greater bilateral trade in either direction, adjusted by the sizes of the two economies. Standard errors in parentheses, clustered by country. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table B5: Effects on nightlights from domestic vs foreign hydroelectric dams, by GDP imbalance

	(1)	(2)	(3)
FS from domestic hydroelectric dams	-0.291	-0.290	-0.291
	(0.324)	(0.323)	(0.324)
FS from foreign hydroelectric dams	-0.806***	-0.795***	-0.854***
	(0.255)	(0.252)	(0.277)
x GDP % diff	0.000908***		
	(0.000274)		
x GDP_D much lower than GDP_U		0.0688	
		(0.950)	
x GDP_U much higher than GDP_D			0.756
			(0.906)
FS from non-hydroelectric dams	-0.0510	-0.0505	-0.0537
	(0.176)	(0.177)	(0.175)
Observations	1740442	1740442	1740442

Notes: All specifications include cell FEs and county x year FEs. GDP and GDP per capita % differences refer to the difference between the downstream cell country's value and the upstream dam country's value, as a fraction of the upstream dam country's value. They are measured as the average over 1990-2000. Standard errors in parentheses, clustered by country. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table B6: Effects on nightlights from domestic vs foreign hydroelectric dams, by UN General Assembly voting similarity

	(1)	(2)	(3)	(4)	(5)	(6)
FS from domestic hydro dams	-0.285	-0.287	-0.287	-0.346	-0.346	-0.340
	(0.332)	(0.332)	(0.332)	(0.327)	(0.326)	(0.327)
FS from foreign hydro dams	-3.083***	-3.671***	-2.776***	-2.279***	-3.667***	-3.642***
	(0.532)	(0.416)	(0.734)	(0.860)	(0.396)	(0.394)
x κ score	4.585***				-8.350	
	(0.797)				(21.58)	
x S score		3.727***			8.024	3.073**
		(0.209)			(5.388)	(1.250)
x π score			4.166***		1.884	
			(1.218)		(16.87)	
x ideal point distance				5.728	0.746	2.167
				(3.617)	(4.449)	(3.679)
FS from non-hydro dams	-0.286	-0.281	-0.288	-0.288	-0.280	-0.279
	(0.242)	(0.244)	(0.242)	(0.244)	(0.244)	(0.244)
Observations	1752747	1752747	1752747	1729834	1729834	1729834

Notes: All specifications include cell FEs and county x year FEs. All measures of UN General Assembly voting similarity are all calculated as the average over 1993-2000 for each country pair. A higher value of the κ, S, and π score or a lower value of the ideal point distance indicates greater voting similarity. Standard errors in parentheses, clustered by country. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table B7: Effects on nightlights from domestic vs foreign hydroelectric dams, by regime type similarity

	(1)	(2)	(3)	(4)	(5)
FS from domestic hydroelectric dams	-0.308	-0.304	-0.307	-0.298	-0.295
	(0.331)	(0.331)	(0.331)	(0.331)	(0.331)
FS from foreign hydroelectric dams	-0.871***	-0.931**	-0.776***	-2.234***	-2.374***
	(0.209)	(0.359)	(0.216)	(0.358)	(0.524)
x Large difference in democracy index	0.0410				
	(0.920)				
x Same democracy index		0.434			
		(0.706)			
x Large difference in autocracy index			-0.706		
			(1.004)		
x Same autocracy index				2.224***	
				(0.296)	
x Both democratic					2.124***
					(0.363)
x Both autocratic					2.507***
					(0.499)
FS from non-hydroelectric dams	-0.323	-0.322	-0.324	-0.308	-0.306
	(0.246)	(0.247)	(0.246)	(0.241)	(0.244)
Observations	1706122	1706122	1706122	1706122	1713226

Notes: All specifications include cell FEs and county x year FEs. The democracy index and autocracy index are products of the Polity Project, version 5. Each is provided at the country x year level and ranges from 0 to 10, with a higher score indicating greater democraticness or greater autocratic control, respectively. An upstream-downstream country pair is marked as having a large difference in democracy index in a given year if the difference is at or above four, which is the 75th percentile among foreign country pairs in the sample. Likewise, the country pair is marked as having a large difference in autocracy index in a given year if the difference is at or above five, which is the 75th percentile among foreign country pairs in the sample. The country pair is marked as being both democratic in a given year if both countries have democracy index of at least 5, and likewise for both autocratic. Standard errors in parentheses, clustered by country. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table B8: Effects on nightlights from domestic vs foreign hydroelectric dams, by joint membership in IGOs

	(1)	(2)
FS from domestic hydroelectric dams	-0.293	-0.297
	(0.325)	(0.324)
FS from foreign hydroelectric dams	-3.789***	-2.714***
	(0.436)	(0.625)
x # IGOs with joint membership	0.193***	
	(0.0235)	
x Diplometrics index		3.137***
		(0.573)
FS from non-hydroelectric dams	-0.0902	-0.0650
	(0.174)	(0.180)
Observations	1773618	1773618

Notes: All specifications include cell FEs and county x year FEs. The count of IGOs with joint membership is out of the 51 IGOs, regional development banks, and UN agencies profiled in the Political Handbook of the World 2020-2021 for which country membership data is available through the Correlates of War Project. The Diplometrics Program assigns weights to each IGO based on the frequency of its media mentions, then sums the weights of the IGOs that each country pair is jointly member to. The Diplometrics index used in Column (2) is the normalization of this measure. Values in the year 2000 are used for both the number of IGOs and the Diplometrics index. Standard errors in parentheses, clustered by country. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table B9: Controlling for country-specific drought and wetness sensitivity when estimating IR interaction term: IGOs with joint membership

	(1)	(2)	(3)	(4)	(5)
FS from domestic hydroelectric dams	-0.293	-0.286	-0.354	-0.288	-0.371
	(0.325)	(0.327)	(0.346)	(0.327)	(0.337)
FS from foreign hydroelectric dams	-3.789***	-3.938***	-3.267***	-3.899***	-3.737***
	(0.436)	(0.716)	(0.605)	(0.585)	(0.605)
x # IGOs with joint membership	0.193***	0.195***	0.181***	0.194***	0.178***
	(0.0235)	(0.0234)	(0.0145)	(0.0241)	(0.0140)
x Sensitivity to drought		0.290		0.220	
		(2.913)		(3.263)	
x Sensitivity to wet		2.235		2.200	
		(1.639)		(3.053)	
x Sensitivity to severe drought			0.919***		-6.713**
			(0.282)		(2.723)
x Sensitivity to severe wet			-1.658		-2.304
			(2.947)		(2.763)
FS from non-hydroelectric dams	-0.0902	-0.0914	-0.0979	-0.0887	-0.0833
	(0.174)	(0.176)	(0.174)	(0.175)	(0.177)
Observations	1773618	1769812	1602018	1770340	1579556
SPEI timescale		1	1	12	12

Notes: All specifications include cell FEs and county x year FEs. The count of IGOs with joint membership is out of the 51 IGOs, regional development banks, and UN agencies profiled in the Political Handbook of the World 2020-2021 for which country membership data is available through the Correlates of War Project. Values in the year 2000 are used for the number of IGOs. For each country, sensitivities to drought and wetness are estimated by regressing nightlights on binary drought and wetness indicators using a cell-level panel spanning 1992-2000. Drought and wet are defined as SPEI below and above one standard deviation, respectively. Severe drought and severe wet are defined as SPEI below and above two standard deviations, respectively. In Columns (2) and (4), the SPEI measure used is the average of 1-month timescale SPEI across months of the year. In Columns (3) and (5), the SPEI measure used is the 12-month SPEI in December of each year. Standard errors in parentheses, clustered by country. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

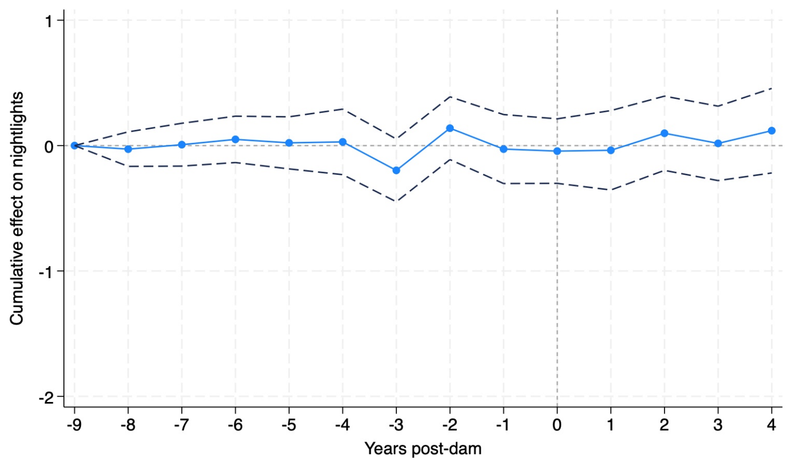
Table B10: Effects on nightlights using within country pair, time-varying bilateral engagement

	(1)	(2)	(3)	(4)	(5)	(6)
FS from domestic hydroelectric dams	-0.166	-0.167	-0.166	-0.166	-0.167	-0.165
	(0.133)	(0.133)	(0.133)	(0.133)	(0.133)	(0.133)
FS from foreign hydroelectric dams in U	-0.272*	-0.248*	-0.275*	-0.265*	-0.245*	-0.279*
	(0.152)	(0.141)	(0.151)	(0.150)	(0.137)	(0.154)
x cooperative events$_{UD,t-1}$	0.0611			0.0717		
	(0.0655)			(0.0792)		
x hostile events$_{UD,t-1}$		-0.00478			-0.0347	
		(0.0809)			(0.0615)	
x total event intensity$_{UD,t-1}$			0.0589			0.0752
			(0.0538)			(0.0687)
FS from hydroelectric dams in other countries	-0.0859	-0.0978	-0.0861	-0.0887	-0.100	-0.0859
	(0.209)	(0.204)	(0.208)	(0.207)	(0.205)	(0.207)
FS from non-hydroelectric dams	-0.241	-0.241	-0.241	-0.241	-0.241	-0.241
	(0.206)	(0.206)	(0.206)	(0.206)	(0.206)	(0.206)
Observations	1734678	1734678	1734678	1734678	1734678	1734678
Actors involved	Govt	Govt	Govt	All	All	All

Notes: The unit of observation is cell x dam country x year. Flow share from domestic (foreign) hydroelectric dams can be nonzero only when the dam country U is the same as (different from) the cell country D. The interaction terms are interactions between same-year flow share from foreign hydroelectric dams and previous-year z-scores of measures of bilateral engagement from ICEWS. Cooperative events refer to events coded by ICEWS as having a positive intensity score - for example, a diplomatic visit or the signing of a formal agreement. Hostile events refer to events coded by ICEWS as having a negative intensity score - for example, making a threat or reducing economic assistance. Total event intensity is the sum of intensity scores across events in the country pair x year, with a higher value indicating greater cooperation. In Columns (1)-(3), the events counted are those of the country pair x year in which the government of at least one of the countries in the pair was involved. In Columns (4)-(6), all events recorded of the country pair x year are counted. All specifications include cell FEs, country-pair FEs, and county x year FEs. Standard errors in parentheses, clustered by country-pair. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

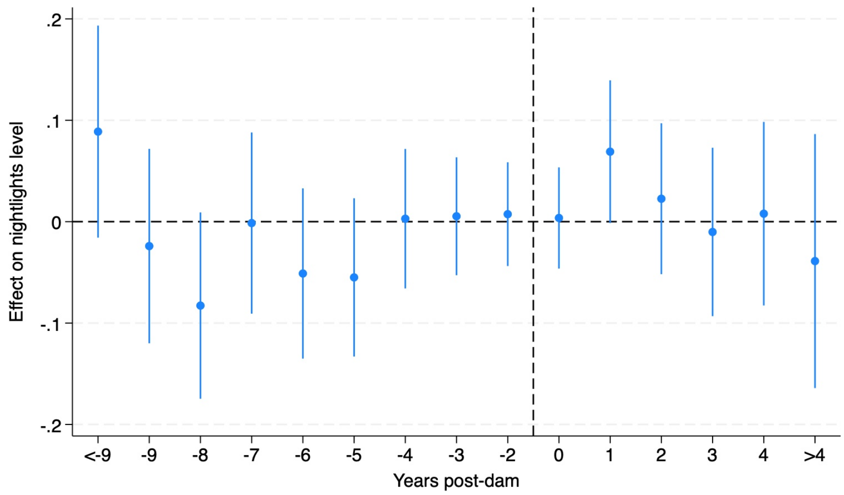
B.2 Figures

Figure B1: Non-hydroelectric dams: Dynamic effects of flow share on nightlights

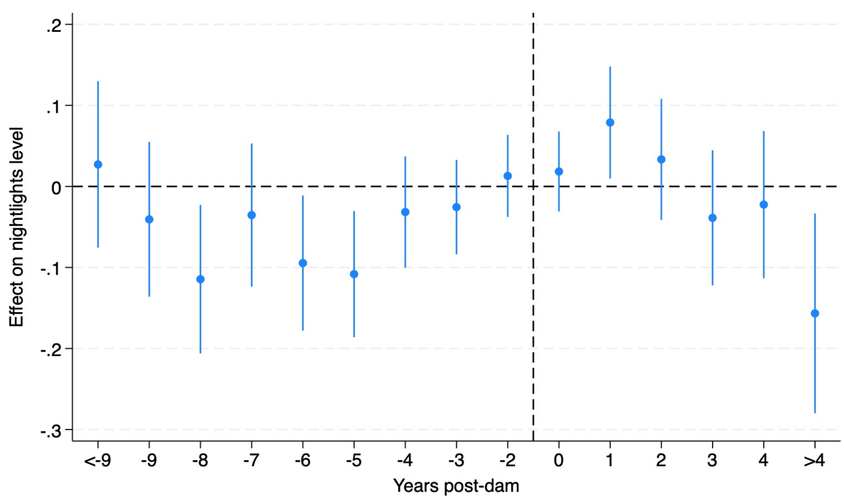


Note: This figure plots distributed lag regression coefficients and 95% confidence intervals for flow share from non-hydroelectric dams, obtained by estimating Equation (3) with separate terms for flow share from hydroelectric dams only and flow share from all non-hydroelectric dams. The figure plots the cumulative effects on nightlights relative to 9 years prior to dam construction, that is, $\sum_{k=-9}^{\tau} \phi^k$. The coefficient on hydroelectric dams is omitted. The regression includes county x year fixed effects. Standard errors clustered by river reach.

Figure B2: Dynamic effects of flow share from hydroelectric dams above county-specific median

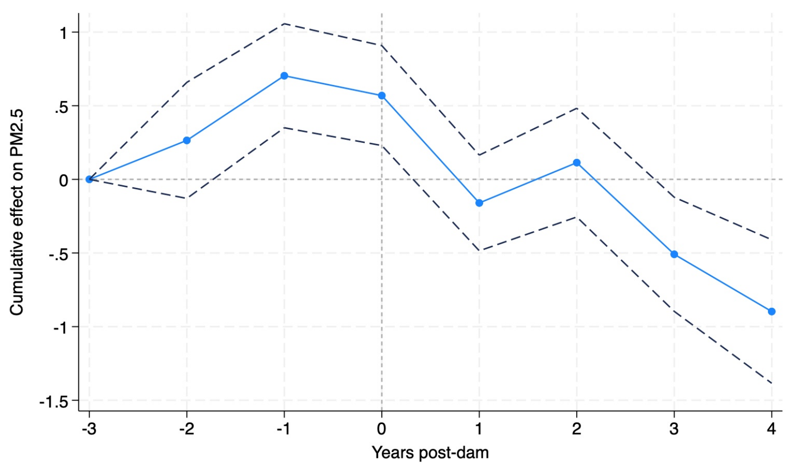


(a) County-specific median defined by first year of dam exposure



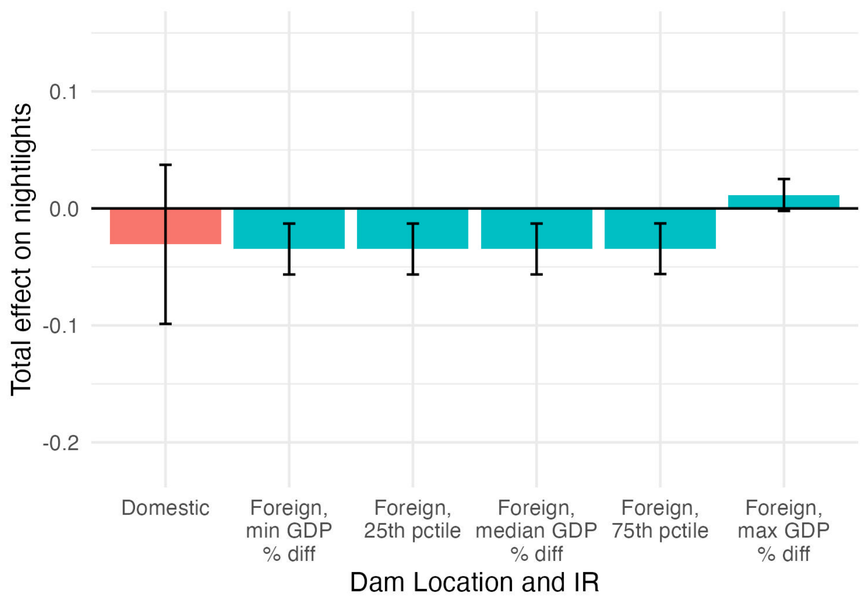
(b) County-specific median defined by 2013

Figure B3: Cumulative effects of flow share from hydroelectric dams on PM2.5



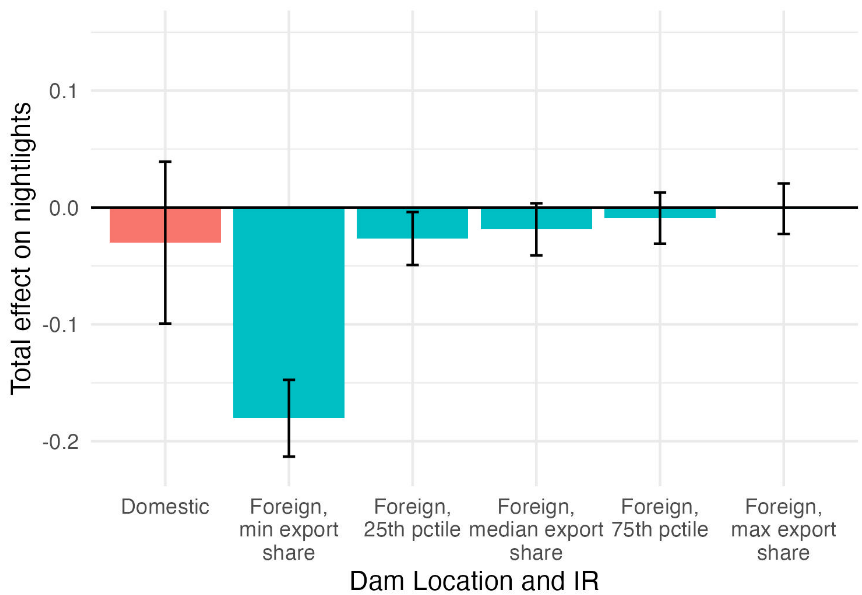
Note: This figure plots distributed lag regression coefficients and 95% confidence intervals from estimating Equation 3 separate terms for flow share from hydroelectric dams only and flow share from all other dams. Coefficients for flow share from non-hydroelectric dams are not shown. The regression also includes county x year fixed effects. Standard errors clustered by river reach. The figure plots the cumulative effects on PM2.5 relative to 3 years prior to dam construction, that is, $\sum_{k=-3}^{\tau} \phi^k$.

Figure B4: Implied effects of domestic and foreign flow share from hydroelectric dams: heterogeneity by GDP imbalance



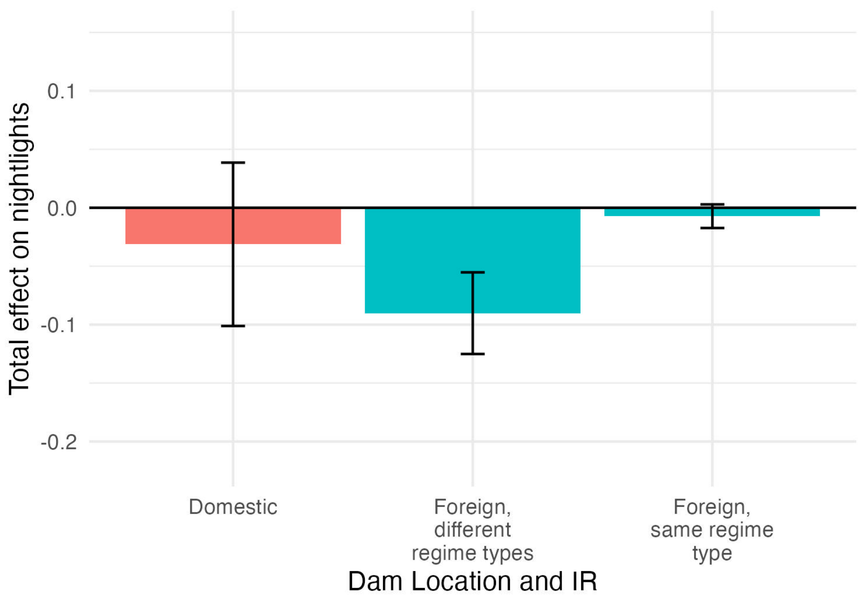
Notes: This figure plots the magnitudes and 95% confidence intervals of flow share effects implied by Column (1) of Table 6 at mean values of domestic and foreign flow share from hydroelectric dams in 2013, which were 0.12 and 0.05, respectively. For the implied effect of foreign flow share, the figure shows heterogeneity by the percentage difference in GDPs averaged over 1993-2000. This is calculated as the downstream country's GDP minus the upstream country's GDP, as a fraction of the upstream country's GDP. Among country pairs in the sample, the minimum, 25th percentile, median, 75th percentile, and maximum values of of GDP % difference are −100%, −90%, −17%, 596%, and 1181%.

Figure B5: Implied effects of domestic and foreign flow share from hydroelectric dams: heterogeneity by voting similarity in the UN General Assembly



Notes: This figure plots the magnitudes and 95% confidence intervals of flow share effects implied by Column (2) of Table 6 at mean values of domestic and foreign flow share from hydroelectric dams in 2013, which were 0.12 and 0.05, respectively. For the implied effect of foreign flow share, the figure shows heterogeneity by the S-score measure of voting similarity in the UN General Assembly averaged over 1993-2000. Among country pairs in the sample, the minimum, 25th percentile, median, 75th percentile, and maximum values of the share of the S-score are -0.18, 0.82, 0.87, 0.93, and 0.98.

Figure B6: Implied effects of domestic and foreign flow share from hydroelectric dams: heterogeneity by regime type similarity



Notes: This figure plots the magnitudes and 95% confidence intervals of flow share effects implied by Column (3) of Table 6 at mean values of domestic and foreign flow share from hydroelectric dams in 2013, which were 0.12 and 0.05, respectively. For the implied effect of foreign flow share, the figure shows heterogeneity by whether the upstream and downstream countries have the same regime type (either democracy or autocracy) in a given year. Among country pair-year observations in the sample, 53% are classified as having the same regime type.