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Curbing hydrological alterations in the Mekong—limits and opportunities of dam re-operation

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Abstract

In rivers around the world, hydropower development has altered the seasonal hydrological regime, which drives key ecosystem services. Dam re-operation efforts that minimize hydrological alterations are, therefore, critical to biological conservation, particularly in the tropics, where dam development is still booming. Here, we identify the limits and opportunities of alternative dam management strategies in the Mekong, a biodiverse but rapidly developing river. We show that basin-wide

efforts are needed to completely restore seasonal hydrological variability, probably an unfeasible solution in the Mekong's institutional landscape. Instead, re-operation efforts focused on the Lower Mekong could yield tangible opportunities for partially restoring key elements of hydrological variability while preserving hydropower production. In fact, changing production plans across a few critical dams could raise hydropower revenues by almost $150 million per year. Nexus solutions like this one are a concrete basis for safeguarding crucial economic interests and catalyzing sustainable river management in international rivers.

Tropical rivers and their floodplains are among the earth's most biodiverse and productive ecosystems [1]. For millennia, they have sustained humankind across continents [2]. Yet, their value is threatened by multiple anthropogenic factors, among which dam construction stands out for impact and preponderance [3]. By fragmenting the river network and controlling discharge, dams affect sediment and nutrient dynamics, block migratory routes of aquatic species, and dampen the annual flood pulse [4,5]—the principal driving force in river-floodplain ecosystems [6]. In rivers such as the Mekong, Congo, and Amazon, hundreds of existing and proposed dams threaten ecosystem services and biodiversity [7], with potential ripple effects on millions of individuals highly reliant on inland fisheries [8]. At these latitudes, the opportunities for improving the status quo through structural interventions are thin; dam removal, for example, is not a concrete option yet [9], since most dams are at the beginning of their life cycle; fish passages are promising [10], but have had limited success with tropical fish species and local community support [11,12]. The opportunity to curb an already critical situation may thus lie in management interventions, such as re-operating dams to curb hydrological alterations and restore environmental flows [13]. Finding economically feasible strategies to re-operate dams could be key to ensuring the preservation of hydrological and biological processes in tropical rivers for the years to come [14–16].

Inspired by the Natural Flow Regime Paradigm [17], several techniques for addressing environmental flows have been proposed during the past decades [14,15,18], leading to successful river restoration and preservation efforts across the globe [13,19]. What would it take to enable such efforts in major tropical rivers? Setting aside the need for adequate legislation and enforcement, one important aspect is the realization that it may not be possible to completely restore freshwater ecosystems back to their pristine conditions once large infrastructure are in place; instead, we ought to focus on designing flow regimes that provide key hydrological features known to be essential for ecosystem diversity and productivity [15,20,21]. Another complexity is the multi-country and multi-sector nature of dam re-operation problems. Dams are often located in international transboundary basins and used for hydropower production [7]; consequently, dam water releases in one country can have cascading effects on water and power availability of other countries. Moreover, modern hydropower financing is shifting from public international financial institutions to a diverse mix of private actors that prioritize short-term economic returns [22]. Because of these complexities, it is reasonable to hypothesize that prospective management interventions must necessarily span across national borders and economic sectors and, most importantly, provide tangible incentives to all parties involved. To date, the feasibility of such large-scale, nexus solutions has not been explored [12].

Here, we identify the challenges and opportunities for restoring environmental flows to the Mekong river floodplains (Figure 1A). The current situation in this basin is emblematic of the issues faced by large tropical rivers around the world: In about two decades, more than 100 hydropower dams have been built in the Mekong basin, increasing the active storage capacity of reservoirs from $\sim$5 to $\sim$70 km^3 [23]. Their operations are increasingly modifying the hydrological regime across the basin, primarily by dampening the naturally high fluctuation in river flows between the wet and dry season [23,24]. Many of these dams are also an integral component of the cross-border power-trade infrastructure shared by Thailand, Laos, and Cambodia (Figure 1B). The questions of interest are therefore the following: How does the reservoir storage controlled by the Mekong countries define the opportunities available for re-operation purposes? Which components of the flow regime can be enhanced? Is it possible to change the dam management strategies while meeting the infrastructural constraints and energy requirements of the integrated regional power grid?

To answer these questions, we adopted a multi-objective optimization framework and a high-resolution water-energy model that captures key interconnections between the river network and national power systems. In particular, we used a spatially-distributed, hydrological-water management model to simulate the relationship between hydro-meteorological forcings and river discharge, including watershed hydrology across the Mekong basin as well as the storage dynamics and turbine release of 108 dams. With this model, we created two daily discharge time series representing developed (business-as-usual) and baseline (natural) conditions during a common climatic reference period (1996–2016), which helped us separate human influences on flow regimes from climatic influences [14]. This hydrological foundation was complemented by multiple dam re-operation strategies aimed to determine the opportunities available for dam re-operations and to explore the trade-off between hydropower production and hydrological alterations. The differences between developed, baseline, and re-operated conditions were characterized in terms of ecologically-relevant components of the flow regime [5,14]. Because dam re-operations alter hydropower supply, we then evaluated the technical and economic feasibility of all scenarios with a power system model simulating hourly decisions in the Thai, Laotian, and Cambodian grids. The model captures decisions made at all power plants, including thermoelectric ones, thus allowing us to calculate the CO_2 emissions and power production costs associated with each scenario.

Results

Operational space. We begin by portraying the opportunities, or operational space, available for dam re-operations (Figure 2). This space is bound by developed and natural conditions, plus two additional, and hypothetical, scenarios where we assume dams are maintained at full storage in the entire basin (108 dams) or only in the Lower Mekong (81 dams). Under this situation, water release from dams is close to their inflow, and it is therefore possible to reduce the deviation from natural flow conditions at Stung Treng—a river discharge gauging station in north-central Cambodia directly upstream of the Mekong's floodplains. Naturally, these are not practical strategies, because maintaining dams at full storage increases the daily variability of hydropower production, thereby altering the management of the power grid. Moreover, such strategies increase the frequency with which spillways are used as well as the risk of dam breach—a catastrophic event recently experienced in Laos [25]. What is more important here is that these two scenarios help us characterize the opportunities available for re-operation purposes. First, they show that basin-wide efforts are needed to completely restore seasonal hydrological variability at Stung Treng, as it is only by re-operating all dams that we can shift the current deviation from natural flow conditions from 23% to 2.4%. Second, they highlight the fundamental role played by dams located in the Upper Mekong (aka., Lancang River): by re-operating dams in the Lower Mekong only, we have narrower opportunities for improving the deviation from natural flow conditions (from 23% to 15%). The explanation behind this result must be sought in the large reservoir storage controlled by China, about 61% of the total system storage.

To further study the potential of alternative dam management strategies, it is more suitable to ignore the re-operation of dams in the Lancang and focus only on the Lower Mekong. Such observation stems from the current policy landscape and, in particular, from the lack of coordination between China and the Lower Mekong countries (Laos, Thailand, Vietnam, and Cambodia) on infrastructure management. On the contrary, re-operation efforts in the lower part of the basin could be supported by inter-governmental water management organizations (e.g., Mekong River Commission), power grid interconnections, and a long history of power purchase agreements [26]. In this smaller control space, we designed 28 optimized re-operation strategies by coupling the hydrological-water management model with an optimization algorithm balancing average annual hydropower production, firm hydropower production, and the average annual ratio between the 30-day maximum and minimum flows (see Methods). This latter is a proxy for the Mekong's 'ideal' flow regime, characterized by a large fluctuation in river discharge between the dry and wet seasons. Importantly, the re-operation strategies involve only a small subset of dams (20 out of 81), strategically selected by virtue of their design specifications (about 96% of the system storage in the Lower Mekong) and single-purpose nature (hydropower production), a choice that would avoid conflicts with other traditional dam uses such as flood control and water supply (Figure S1, Table S1). Note that all strategies are close to the hypothetical minimum deviation of 15% from natural flow conditions. Moreover, their hydropower production is close, or better, than the one provided by current dam operating policies. These results are explained by the benefits attained by coordinating the operations of the selected storing facilities: because dam planning and construction have essentially proceeded project-by-project [27], dams are currently operated with management policies that account for site-specific objectives (e.g., meeting the obligations of a power purchase agreement), therefore lacking a system-wide view of the benefits that lie in coordinated decision-making. By coordinating daily release decisions in 20 strategic dams, we can therefore realize storage and release patterns that address the trade-off between conflicting objectives (Figure S2-S3). For the remainder of our analysis, we focus on one specific optimized solution (highlighted in Figure 2). This is the solution yielding the highest value of average annual hydropower production in Laos, Thailand, and Cambodia, and therefore has higher chances of positively impacting the operations of the power system.

Hydrological regimes. Among the various flow metrics available in literature [18], we explicitly optimize the fluctuation in the magnitude of river discharge between the wet and dry seasons because this indicator synthesizes well the river flow alterations observed in the Mekong in the recent past [24,28–30]. Moreover, this indicator is congruent with theory and observations of the linkages between the hydrological regime of flood-pulse rivers and their ecosystems [6,16,17]. Specifically in the Mekong, metrics like flow magnitude and flood extent have been linked to fish catch [20,31].

For baseline conditions (scenario NAT), the range in the ratio of annual 30-day maximum to 30-day minimum discharge varies from 6.9 to 20.8 (with a median of 11.5), reflecting the strong hydro-climatic variability characterizing Southeast Asia [32] (Figure 3). When contrasted against the current situation (scenario BAU), the effect of hydropower operations is clear: dams retain water during the summer monsoon and discharge it in the dry season, thus delivering higher low flows and partially dampening peak flows. This translates into a narrower range of the 30-day max-min ratio (4.7 to 12.0, with a median of 7.4) and a large number of years (about 30%) falling outside the envelope of natural variability. Our analysis demonstrates that optimizing for both hydropower production and hydrological alterations (scenario OPT) could ensure that river discharge fluctuations–and corresponding hydrological indicators–are closer to the range of natural variability. Given the limited storage available for re-operation purposes (recall that dams in the Lower Mekong account for $\sim$39% of the total system storage), the improvements are, naturally, not ample. For example, the range in the 30-day max-min ratio is 5.2-12.4, with a median of 7.7.

Yet, there are two important points worth noting. First, the performance of the optimized re-operation strategy is always better than the current management one, meaning that our solution is robust with respect to hydro-climatic variability (Figure S4-S5). Second, there are more years falling within the envelope of natural variability.

A deeper understanding of the impact of dam management strategies on discharge is offered by 48 flow metrics (evaluated post-optimization and based on the Indicators of Hydrological Alteration), which depict different characteristics of the flow regime, namely magnitude, timing, frequency, duration, and rate of change. Beginning with flow magnitude and the BAU scenario, Figure 4 shows that the largest deviations from natural flow conditions are observed in the dry season (particularly from December to March), when a substantial amount of water is released to sustain hydropower production during the dry season. For example, the median daily flow in January increases by about 39%. In contrast, the impact on peak flows is less evident (the flow in August decreases by 10%), as the effect of dam operations is partially concealed by abundant precipitation and high river discharge caused by the summer monsoon. In addition to the magnitude of flows, dams also alter the duration of both low and high pulse, with the former showing an average annual gap of almost 40 days. Smaller, yet often statistically significant, deviations are found for indicators of frequency, duration, and rate of change (Figure S6, Table S2-S3). Encouraging results could be achieved with the optimized re-operation strategies: for the selected strategy, we find consistent improvements with respect to the business as usual operations for all flow components (Figure 4, Figure S6-S7, Table S2-S3). For instance, the average length of the dry season (low pulse) could be extended by 11 days, while the positive deviation of the median daily flow in January could be limited to $\sim 11\%$. As for the case of the 30-day max-min ratio, the magnitude of these improvements is bounded by the total storage available for re-operation purposes. This is why several indicators characterizing the selected optimized strategy still present statistically significant deviations from the natural baseline (Table S2-S3). Given the large inter-annual variability of these flow-derived metrics, the statistical significance of the deviations is less important than the size of these detectable changes and their potential biological importance [28,33,34].

Power trading opportunities. The distinguishing feature of the re-operation strategies is a pronounced change in the magnitude of river discharge during the wet and dry season—a solution needed to increase the ratio of annual 30-day maximum to 30-day minimum discharge. This translates into different patterns of hydropower production (Figure S3), for which we used a power system analysis to validate its technical and economic feasibility (see Methods). Because the power system model captures important technical constraints (e.g., transmission capacity, unit commitment, design features of the thermoelectric plants), it is crucial to find that changing the patterns of hydropower supply from twenty major dams does not create any grid reliability issue. In other words, the Thai, Laotian, and Cambodian grids would be able to integrate alternative seasonal hydropower supply without causing electricity distribution disruptions. In fact, the increase in average annual hydropower production from $\sim$33.6 to $\sim$41.5 TWh (Figure 2, BAU and selected OPT scenario) would translate into important socio-economic benefits (Figure 5A). First, Laos could reduce its reliance on thermoelectric plants, leading to a decrease of average annual CO_2 emissions and production costs of 0.37 Mt and \$6.3 million (a 6.3% and 1.3% improvement). Similarly, Thailand could decrease CO_2 emissions by 2 Mt and costs by \$116 million per year. This larger difference is explained by the installed capacity of the Thai power system (Table S6) and, most importantly, by the fact that Thailand imports a large fraction of the Laotian hydropower production (Figure 5B-D). The flow of electricity from Laos to Thailand also explains the projected increase in Laos' hydropower revenue of almost \$150 million per year (Figure 5A). In sum, the re-operation of twenty strategic dams could help improve ecologically-relevant components of the flow regime while stimulating the exchange of hydropower among Lower Mekong countries. Importantly, such exchange of hydropower could be supported by the existing cross-border power-trade infrastructure and therefore would not entail any structural intervention.

Discussion

Our analysis reveals the challenges and opportunities behind the implementation of ecosystem-aware water management interventions in the Mekong River Basin. Beginning with challenges, we show that the restoration of natural flow conditions in proximity of the floodplains requires the cooperation of all Mekong countries, including China, a result explained by the hefty portion of total system storage built in the Upper Mekong. The challenge here arises from the regional geopolitical landscape. Specifically, there are multiple institutional and legal frameworks within the basin with overlapping mandates [35], but there is a lack of an institution representing the interests of all countries. China, for instance, is a dialogue partner, not a member, of the Mekong River Commission. This dialogue has recently resulted in a number of cooperation initiatives—such as the sharing of year-round water data or emergency releases from upstream reservoirs during droughts [36,37]—but we are arguably still far from a scenario in which dam operations are negotiated and centrally implemented. This result is therefore relevant for guiding future policy decisions—as it is indicative of what system-wide cooperation could achieve—but it may not be translated into immediate water-energy management practices.

Sustainable water management opportunities illustrated in this study stem from the coordinated re-operation of twenty large dams located in the Lower Mekong. This result highlights the limitations of the current piecemeal approach to regional hydropower development, which has historically focused on individual projects [27] and thus overlooked the opportunities provided by a more synergetic approach to infrastructural development and operations. Most importantly, the re-operation strategies for the Lower Mekong are both technically and economically feasible. The reason behind the technical feasibility stands in the flexible operations of other power generating sources, such as gas-fired plants, which can easily adjust their power output in response to alternative hydropower production plans [26]. Our analysis also shows that the re-operation strategies could foster electricity trading and improve Laos' hydropower revenue. Since regional hydropower investments are controlled by multiple actors mostly interested in short-term economic returns [22], we argue that such revenue is the tangible incentive that could reunite the interests of the regional hydropower industry. Clearly, this would require further strengthening current efforts on collaborative governance of water and energy resources, so as to conceive plans and licenses that meet a more diverse suite of interests [38].

Despite the bounds imposed by the actual storage available for re-operation purposes, we show that coordinated dam re-operation can partially restore key elements of river flow variability that are essential for numerous ecological factors in rivers worldwide [16]. Specifically in the Mekong, seasonal hydrological fluctuation affects sediment deposition, nutrient cycling, floodplain vegetation, fish habitat, and fisheries [20,31,34,39,40]. Naturally, we are fully conscious that approaches accounting for flow variability to resolve pressing river management issues may oversimplify the complexity of river-floodplain ecosystems [41]; as such, we encourage ecological research that could further demonstrate how the optimized flow regimes from our study would affect biological processes more directly. Such research could build, for example, on process-based or statistical tools that explicitly link indicators of hydrological variability to specific ecological components [20,42]. We also acknowledge that there are other environmental and societal factors beyond seasonal hydrological variability that are key drivers in river-floodplain ecosystems, such as river fragmentation, water temperature, and increased fishing efforts, which are indeed changing in the Mekong [43–46]. Yet, quantifying the space available for dam re-operation purposes and characterizing its corresponding limits and opportunities is a first fundamental step needed to inform the aforementioned research, particularly in basins like the Mekong where dam removal is not an option yet.

The compelling need for the coordinated management of hydropower reservoirs gains further importance if we consider that external drivers may reshape the regional power grid and, in turn, its impact on riverine ecosystems. There are at least three drivers worth mentioning here. First, all countries in the Mekong are planning to further expand their hydropower fleet—with an estimated 22 GW expected to be deployed in the coming decades [47–49]—an energy policy that would magnify the hydrological alterations we experienced so far. A potential solution is the deployment of other sources of renewable energy, such as solar photovoltaic, which has great potential in Southeast Asia [50] and is indeed an important component of regional energy policies [51]. Yet, the massive deployment of solar energy requires the availability of energy storage systems (e.g., water reservoirs) that help mitigate the variability in the output of renewables, but that could result in unexpected consequences, such as hydro-peaking [52]. The third key driver is the ASEAN Power Grid, a major infrastructural development that is expected to yield an integrated Southeast Asia's power grid system [53]—and of which the grid modelled in this study represents the first step. Such expanded grid could connect load centers to more production sites, thereby reducing the need for energy storage and thus the impact on riverine ecosystems. Understanding how the joint operation of water-energy systems should account for all these drivers is a topic certainly warranting more research.

Looking ahead, we believe that the maintenance of hydrological processes and ecosystem services in tropical rivers and their floodplains will benefit of the combination of two strategies [54]: a 'hard path' that relies on sustainable dam portfolios [27] and alternative energy sources [55]; and a 'soft path' that capitalizes on the synergies between sectors to improve the overall system performance rather than to seek additional sources of power supply. Given the appropriate geopolitical landscape and enabling institutions, this soft path could be undertaken in diverse socio-economic contexts and catalyzed by coordinated water-energy operations that offer more environmentally sustainable hydropower production plans.

Methods

Hydrological-water management model. To simulate daily river discharge and available hydropower generation, we relied on a two-step modeling approach. The first model is the Variable Infiltration Capacity (VIC) model, a large-scale, semi-distributed hydrological model that solves full water and energy balances [56]. The runoff computed in each VIC cell is then gathered by VIC-Res, which simulates the streamflow routing process, including the storage and release dynamics of water reservoirs [57]. In VIC-Res, each reservoir is represented through a cell accounting for dam location and multiple cells representing the water body, where the mass balance is resolved. Release decisions are determined by predetermined rule curves accounting for water availability, incoming inflow, and dam design specifications (Figure S8). Leveraging the information on hydraulic head and release, VIC-Res finally calculates the daily amount of electricity available to the power grid.

The model implementation has a spatial domain of $\sim$630,000 km^2, stretching from the upper reaches of the Lancang in China to the gauging station of Stung Treng in Central Cambodia (Figure S9). Here, we account for a total of 108 dams—operational in 2016—each having storage capacity or installed capacity larger than 1 Mm^3 and 5 MW, respectively. 27 of these dams are located in China, while the remaining ones are in Laos, Thailand, Cambodia, and Vietnam. By modelling the entire Mekong's reservoir network, we can therefore account for the differential impact of each dam on hydropower generation and discharge at Stung Treng. The models have a spatial resolution of 0.0625°, necessary to avoid allocating multiple dams to the same cell. The setup and input data are the same as those adopted in previous studies [26,58] (Table S4). The only exception stands in the hydrometeorological forcings. Here, we used the Global Meteorological Forcing Dataset [59] (instead of APHRODITE and CFSR, [60,61]), which is fully available for our study period (1996–2016). This warranted a re-calibration exercise, through which we set nine parameters controlling the rainfall-runoff and streamflow routing processes in eight sub-basins (Table S5 and Figure S9). The calibration was carried out by coupling the models with a multi-objective evolutionary algorithm that balanced the models ability to reproduce different features of the hydrograph—i.e., high flows, low flows, long-term water balance, and long-term variability of flows [62]. The performance was optimized and tested over the periods 1996–2005 and 2006–2016 (at nine and four gauging stations, respectively). These two decades are characterized by the commissioning of several dams [23]: ensuring that VIC and VIC-Res are able to reproduce the river discharge in such non-stationary conditions is, therefore, a testament to their reliability (Figure S10–S14). The validation also includes a comparison between average annual simulated hydropower production and annual design (or expected) production at key hydropower stations (Figure S15). A similar process was repeated for the Chao Phraya basin, home to two large dams playing an important role in the Thai power grid (Figure S15). The reader is referred to Text S1 for additional details about the models setup, calibration, and validation.

Like any other study based on hydrological-water management models, this work builds on a few assumptions—and associated limitations—that should be properly discussed. First, VIC ignores non-channel flow between grid cells [56], meaning that our modelling framework cannot capture horizontal subsurface flow or deeper soil flow effects on flow regimes. While this is obviously a limitation, there are no reasons to believe that including such physical processes would largely alter the model performance, since flow regimes in the basin are chiefly controlled by reservoir operations [23,30,34]. Moreover, our joint calibration of VIC and VIC-Res ensures that the representation of key hydrological processes is not flawed by the misrepresentation of dam operations [63], something that would hinder the model's capability of informing water management decisions. Second, our modelling framework does not explicitly capture flood dynamics as well as its connection to landscape processes and nutrient dynamics. Naturally, it would be interesting to simulate such processes, a challenging effort that could be achieved by adopting a flood inundation model [64]. However, that falls outside the scope of our research, which aims at showing that the design of more sustainable flow regimes is technically and economically feasible. Nonetheless, we complemented our analysis on flow conditions at Stung Treng with a simple analysis of flood extent based on well-established relationships between flood depth and extent (described in Text S2).

Simulation scenarios. The first scenario in our analysis is the one representing natural flow conditions (NAT). Since observed discharged data gathered during recent years are largely affected by dam operations [23], we generated naturalised discharge data via simulation [14]. To this purpose, we removed all 108 dams from VIC-Res and ran it with the hydro-meteorological forcings observed in 1996–2016. We then defined three additional scenarios to understand how the broadest range of dam operations reflects on available hydropower generation and discharge at Stung Treng (Figure 2). These scenarios represent the existing dam operations (BAU), plus an hypothetical situation in which reservoirs are maintained at the maximum storage level throughout the year in either the entire basin (MAX_MB) or in the Lower Mekong (MAX_LMB). The rationale is to depict a situation in which dams are operated like run-of-the-river dams where water outflows are close to inflows [65]. For these three scenarios, we simulated the presence of all dams (and forced the model with 1996–2016 hydrometeorological data), so as to isolate the effect of different dam operations from climatic influences—as recommended by [14].

The operational space identified by the four scenarios was explored by modifying the daily operations of twenty dams in the Lower Mekong basin. For this exercise, we selected single-purpose (hydropower) dams that account for $\sim$96% of the total storage (Figure S1), a choice that allowed us to reshape the hydrological regimes without unnecessarily entangling the dam re-operation. The problem is solved with a simulation-optimization approach know as Evolutionary Multi-Objective Direct Policy Search (EMODPS) [66]. EMODPS builds on the idea of coupling a simulation model (describing the dynamics of a given water system) with a multi-objective evolutionary algorithm tasked with the problem of optimizing the reservoir rule curves on the basis of the performance attained on a simulation period. The key advantage of EMODPS lies in the possibility of informing the search process with a simulation model that accurately reproduces the river basin dynamics, like VIC-Res. More formally, the problem is formulated as follows:

$$\theta^* = \arg\max_{\theta} \mathbf{J}(\theta), \tag{1}$$

where $\theta \in \Theta$ represents the decision variables (i.e., the parameters of the rule curves) and $\mathbf{J}$ a vector of three components accounting for hydropower production and dam impact, a typical choice for optimization studies trading-off power production and ecosystem services in the Mekong River Basin (e.g., [4,27,67]). The objectives (evaluated over the period

1996–2005) are:

1. Average annual hydropower production, J^{Hydro} (TWh/year, to be maximized):

$$J^{\text{Hydro}} = \frac{1}{N} \sum_{t=1}^{N} \sum_{j=1}^{365} \sum_{i=1}^{D} P_{t,j,i}, \tag{2}$$

   where N is the number of years in the simulation period, D the number of dams in the Lower Mekong basin, and $P_{t,j,i}$ the hydropower production (MWh/day) of the i-th dam in the j-th day of the t-th year.

2. Firm hydropower production, $J^{\text{Firm Hydro}}$ (TWh, to be maximized):

$$J^{\text{Firm Hydro}} = \min_{t=1,\ldots,N} \sum_{j=1}^{H_{dry}} \sum_{i=1}^{D} P_{t,j,i}, \tag{3}$$

   where H_{dry} is the number of days in the dry season (from December to May). In other words, $J^{\text{Firm Hydro}}$ is the smallest value of hydropower production attained during one of the N dry seasons. While the adoption of the first objective is somewhat obvious (as hydropower dams are operated to maximize hydropower production), the use of $J^{\text{Firm Hydro}}$ is explained by the fact that hydropower dams also need to keep a minimum power output throughout the year, so as to guarantee a reliable service [26,48].

3. Average annual ratio between the 30-day maximum and 30-day minimum flows at

Stung Treng, J^{Flow} (unitless, to be maximized):

$$J^{\text{Flow}} = \frac{1}{N}\sum_{t=1}^{N}\frac{q_t^{30-d,max}}{q_t^{30-d,min}}, \tag{4}$$

where $q_t^{30-d,max}$ and $q_t^{30-d,min}$ are the 30-day maximum and 30-day minimum flows calculated for the t-th year. J^{Flow} is a proxy of the 'ideal' Mekong hydrograph, characterized by one, ample, flood pulse followed by a long, dry season [2,20]. Though a total of 48 hydrological alteration indicators were estimated post-optimization (see section below), we opted for optimizing a single environmental flow metric, rather than multiple, so as to keep the optimization problem computationally manageable. Moreover, our correlation analysis shows that J^{Flow} is well correlated with the vast majority of the 48 indicators (Figure S16).

In sum, this problem formulation allows us to formalize the goal of the existing operations (maximize hydropower production while preserving grid reliability), explore opportunities to improve flow conditions in the Mekong's floodplains, and capture potential trade-offs between power supply and ecosystem services. Aside from the choice of these objectives, it is also the choice of the decision variables that is critical to make the problem formulation realistic—and therefore able to support real analysis of diverse technical preferences or ecological end results. By working on a subset of twenty dams in the Lower Mekong Basin (Table S1), we ensure that (1) there is a power infrastructure in place able to support different hydropower production plans (a matter further explored via simulation with the power system model), (2) there is a multi-country organization (i.e., Mekong River Commission) that could back the implementation of such plans, and (3) the operating objectives of other dams (e.g., irrigation water supply of dams in eastern Thailand) are not affected. Altogether, the problem yielded a total of 28 solutions, and their robustness with respect to the hydro-meteorological conditions was tested via simulation over the period 2006–2016 (Figure S4-S5). Additional details on the experimental setup and post-optimization evaluation are reported in Text S3.

Indicators of hydrological alteration. To quantify the impact of hydrological alterations across the different scenarios, we use the Indicators of Hydrological Alteration (IHA) [33], which we modified and complemented with a few additional indicators to fully characterize the hydrological regime of the Mekong (Text S4). Specifically, we defined 48 indicators that quantified the magnitude, timing, duration, rate and frequency of ecologically relevant flows at Stung Treng [28,29]. For each indicator (and each scenario) we calculated one measure of central tendency and one of dispersion (Table S2 and Figure S6). The statistical significance of changes across the scenarios was evaluated with the Kruskal-Wallis non-parametric test (Table S3).

The first group of indicators depicts the magnitude of monthly flow conditions, measured as the mean daily flow in each calendar month. The median values of the monthly flow conditions over the simulation period 1996–2016 (for the scenarios NAT, BAU, MAX_MB, MAX_LMB, and OPT) are illustrated in Figure 4(A) and reported in Table S2. The monthly percentage deviation from natural flow conditions (Figure 4(B)) is therefore defined as $\frac{q_t^j}{q_t^{nat}} \cdot 100$, where q_t^j is the simulated discharge in month t (for the j-th scenario) and q_t^{nat} the discharge in month t under natural conditions (NAT). The overall deviation from the natural flow conditions (Figure 2) is defined as:

$$f^{dist.,j} = \sqrt{\frac{1}{M}\sum_{t=1}^{M}\left(\frac{q_t^j - q_t^{nat}}{q_t^{nat}}\right)^2} \cdot 100, \tag{5}$$

where M is the number of months in the period 1996–2016. In this expression, the difference between q_t^j and q_t^{nat} is squared to account for positive and negative differences and divided by q_t^{nat} to avoid emphasizing the wet season values.

Power system model. The Thai, Laotian, and Cambodian power systems are modelled with PowNet [68]. The model depicts each power system as a set of nodes and arcs representing generating units, import and export nodes, substations, and high-voltage transmission lines. The model has an hourly time step and a planning horizon of 24 hours, over which it schedules the status of the generating units (unit commitment) and the amount of electricity they supply (economic dispatch). From a mathematical modelling standpoint, PowNet solves a Mixed-Integer Linear Program that minimizes the power production costs while meeting the electricity demand at the substations [69]. The production costs depend on several factors, such as the cost of imported electricity or the heat rate and fuel price for thermoelectric units. Similarly, decisions on scheduling and dispatch account for many factors, such as the available hydropower generation, the design features of the thermoelectric plants, or the capacity and susceptance of the transmission lines.

We setup PowNet to mimic the 2016 configuration of the three power grids (Table S6), the most recent year with comprehensive data availability. Since the electricity supply is controlled by three national authorities (i.e., Electricity Generating Authority of Thailand, Électricité Du Laos, and Electricity Authority of Cambodia), the three model instances account for the costs encountered by each individual country. That calculation also accounts for the costs/revenues of hydropower imports/exports, which are regulated by bilateral, long-term power purchase agreements (Table S7-S8). CO_2 emissions are calculated for each country using fuel-specific emission factors (Table S9). In all model runs, we kept the setup on power infrastructure and electricity demand constant, and force PowNet with the time series of available hydropower generation produced by VIC-Res, so as to quantify the impact of alternative hydropower rule curves on generation mix, production costs, and CO_2 emissions. We therefore ran a total of 31, 21-year-long simulations

(BAU, MAX_MB, MAX_LMB, plus 28 optimized scenarios). The time series of available hydropower produced by VIC-Res have a daily resolution, so we assumed that the hydropower profiles are uniformly available to PowNet throughout 24 hours. For the few dams falling outside the Mekong and Chao Phraya basins, we resorted to a simpler representation of the hydrological processes (Text S5). Additional details on the setup and calibration of PowNet are documented in [26,58,68].

Data availability

The data generated in this study have been deposited in Zenodo under the accession code `https://doi.org/10.5281/zenodo.5895205`.

Code availability

The hydrological-water management model VIC-Res is available at `https://github.com/thanhiwer/VICRes`. The implementation of the power system model (PowNet) for Thailand, Laos, and Cambodia is available at `https://github.com/kamal0013/PowNet`.

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Competing interests. The authors declare no competing interests.

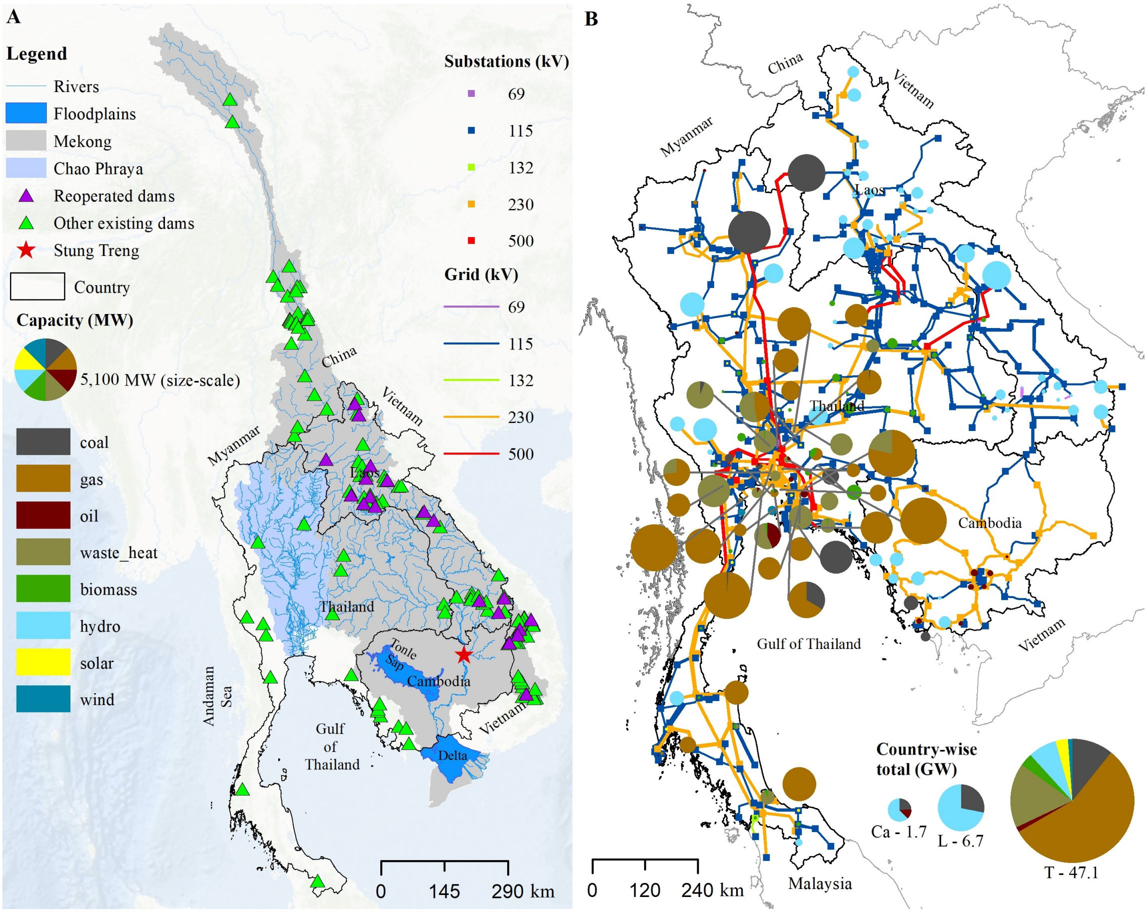

Figure 1: Study site. (A) Full spatial extent of the Chao Phraya and Mekong basins, together with the dams operated by all riparian countries (triangles). The dams represented by purple triangles are those re-operated in our study; for the green ones, we kept the current operating strategies. All dams falling within the two basins are modelled with the hydrologic-hydraulic model VIC-Res. For the remaining dams, we used a simpler modelling approach (see Methods). The Indicators of Hydrological Alteration are calculated at Stung Treng (red star), nearly at the head of the Mekong's floodplains. (B) Spatial representation of the Thai, Laotian, and Cambodian power system infrastructure. Circles, segments, and squares indicate power plants, high-voltage transmission lines, and substations (or import/export nodes). The pie charts illustrate cases in which more than one generator is connected to a substation. Each pie chart is proportionate to the size-scale shown in panel (A). The pie charts at the bottom right corner illustrate the country-wise total existing power capacity. All components of the power grids are modelled with PowNet.

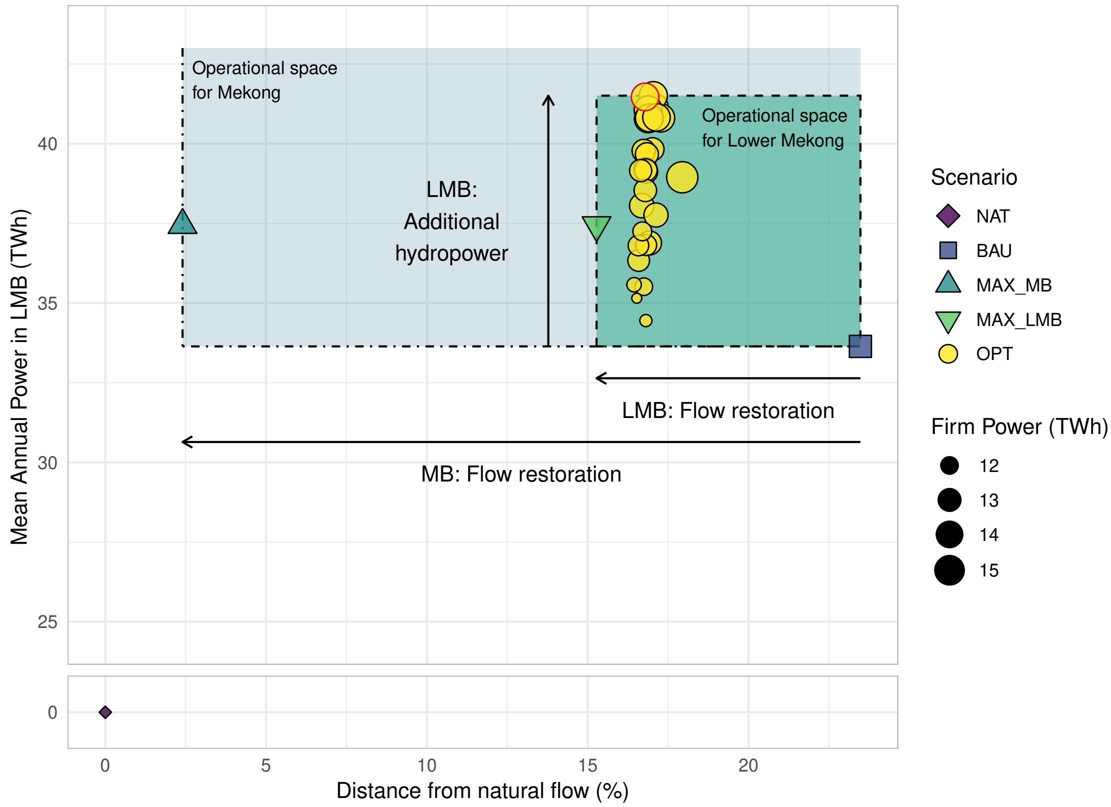

Figure 2: Average annual hydropower production, firm production, and deviation from natural flow conditions for 31 scenarios: Business as usual (BAU), dams maintained at full storage in the Mekong Basin (MAX_MB), dams at full storage in the Lower Mekong Basin (MAX_LMB), and 28 optimized re-operation strategies (OPT). All values are averaged over the period 1996–2016; the hydropower objectives are calculated for the dams in the Lower Mekong. Note the break in the y-axis, as the baseline conditions (NAT) yield no hydropower production. The arrows indicate the maximum extent by which hydropower production and distance from natural flow conditions can hypothetically be improved. The turquoise area represents the sub-space considered for the re-operation exercise. The optimized solution, as outlined in red, is further analyzed in Figure 3-5. This is the solution yielding the highest value of average annual hydropower production.

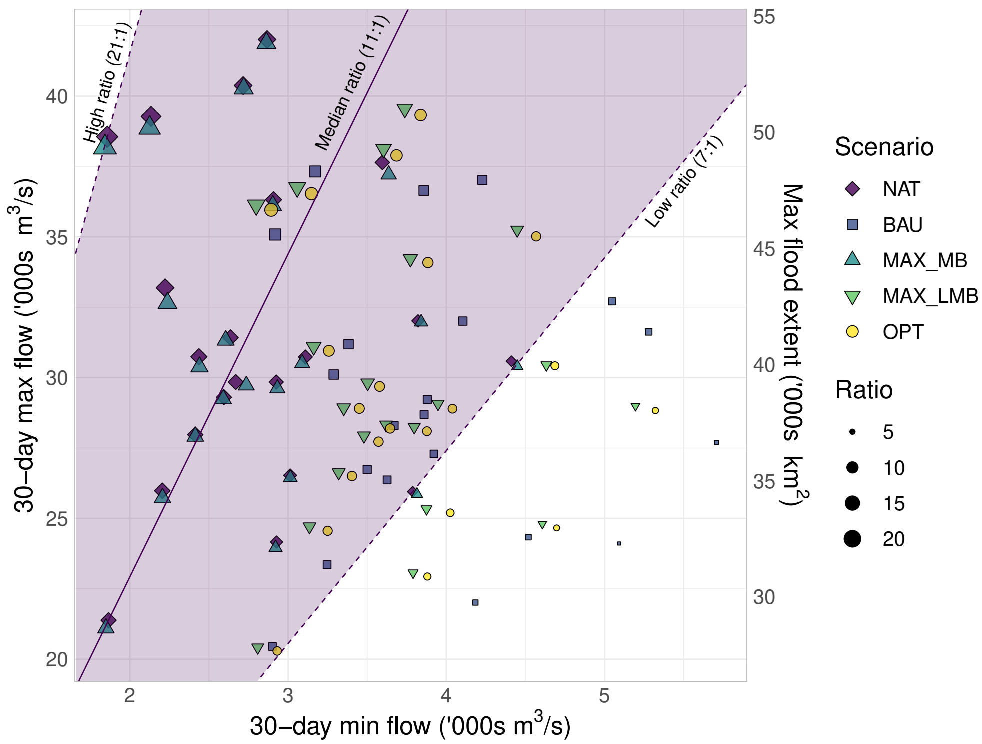

Figure 3: Relation between 30-day minimum and maximum flow conditions (at Stung Treng) and annual maximum flood extent in the Mekong. Each point corresponds to one year, while symbols represent five hydrological scenarios (natural conditions (NAT), Business as usual (BAU), dams maintained at full storage in the Mekong Basin (MAX_MB), dams at full storage in the Lower Mekong Basin (MAX_LMB), and one optimized re-operation strategy (OPT)). The size of each dot represents the ratio between 30-day maximum and minimum flow, while the shaded area shows the envelope of variability of the 30-day max-min ratio for natural conditions. The values of the maximum flood extent are calculated from published data (Text S3).

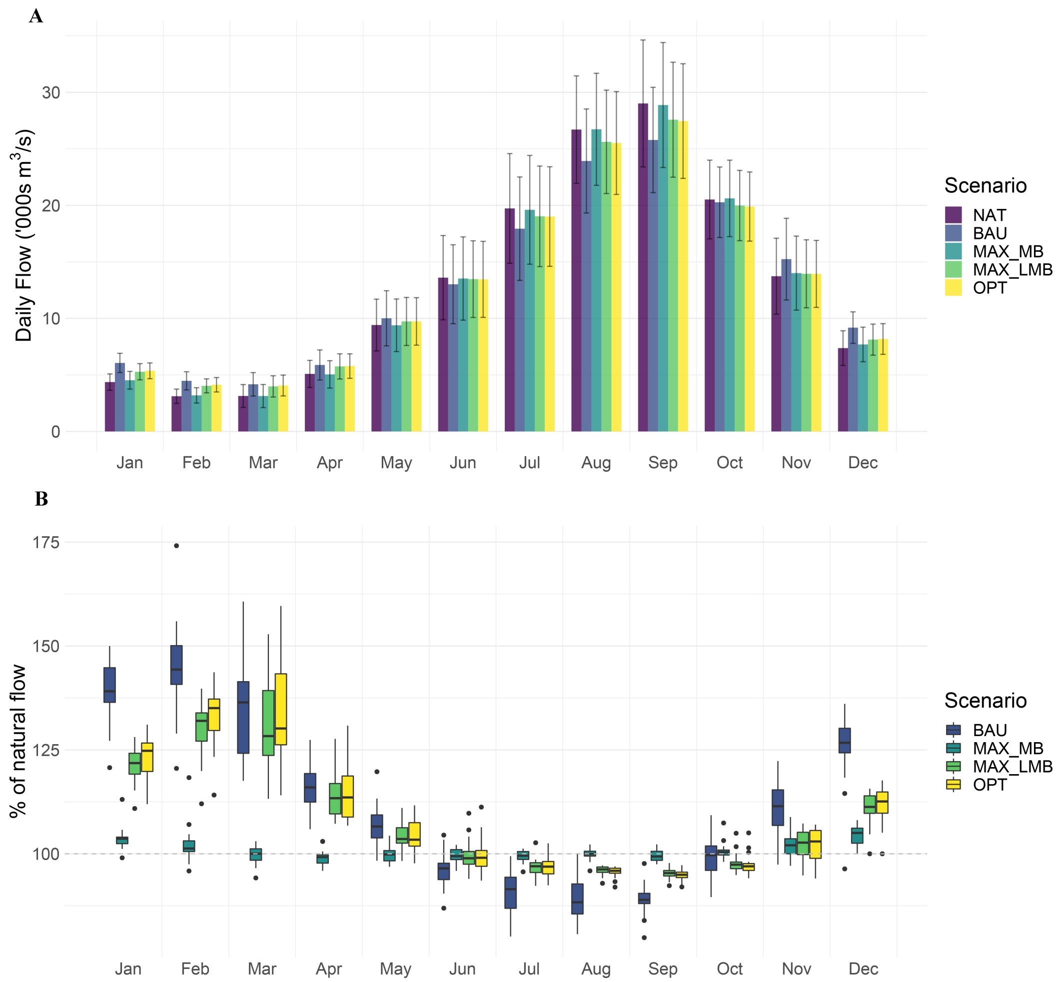

Figure 4: Flow conditions at Stung Treng (see location in Figure 1) under five hydrological scenarios (natural conditions (NAT), Business as usual (BAU), dams maintained at full storage in the Mekong Basin (MAX_MB), dams at full storage in the Lower Mekong Basin (MAX_LMB), and one optimized re-operation strategy (OPT)). (A) Bars represent the median daily flow in each calendar month, with whiskers representing the standard deviation. (B) Monthly streamflow expressed as a percentage of the natural flow. The upper and lower hinges correspond to the first and third quartile. The upper (lower) whisker extends from the hinge to the largest (smallest) value no further than 1.5 times the inter-quartile range (IQR), defined as the distance between the first and third quartile. Outliers beyond the whiskers are plotted individually. All values are calculated over the period 1996–2016.

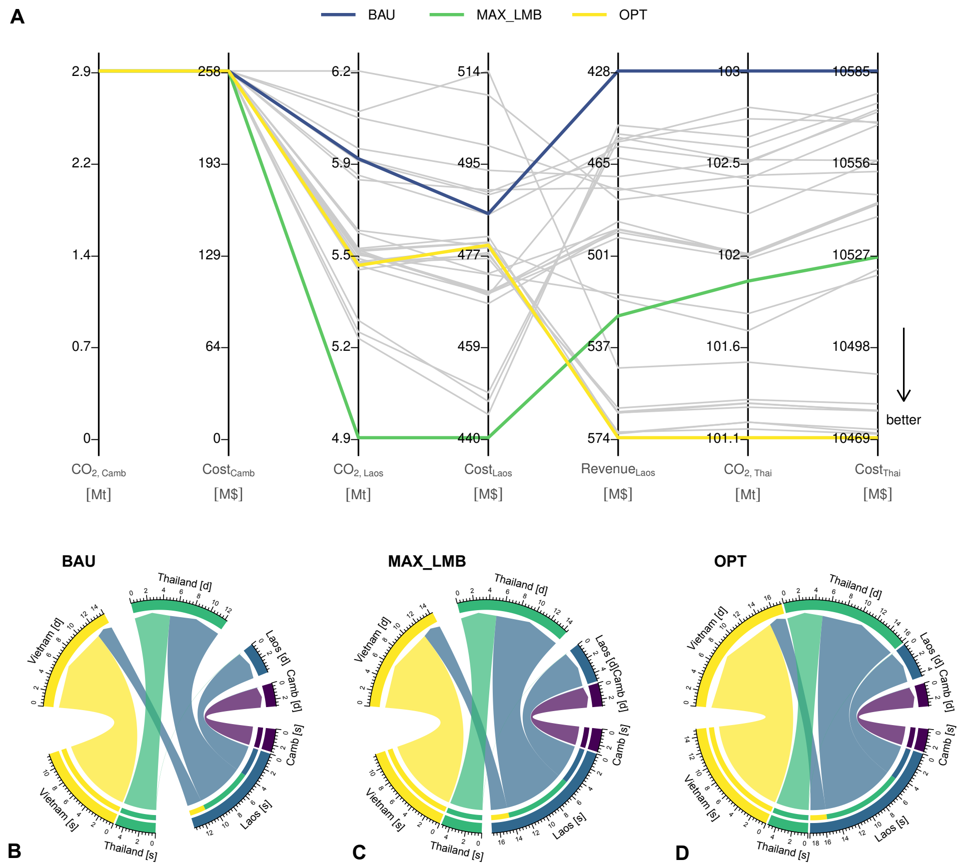

Figure 5: Performance of the Thai, Laotian, and Cambodian power systems. (A) The parallel coordinate plot illustrates the average annual CO_2 emissions and production cost for each grid (averaged over the period 1996–2016). For Laos, we also report the revenue from hydropower export. The blue, green, and yellow lines represent three scenarios: Business as usual (BAU), dams at full storage in the Lower Mekong Basin (MAX_LMB), and selected optimized re-operation strategy (OPT). The grey lines correspond to the other 27 optimized scenarios. Note that dam re-operation has no effect on the Cambodian system, since re-operation occurs primarily in Laos, and Cambodia exchanges a limited amount of electricity with the other countries. (B-D) The chord diagrams illustrate the exchange of hydropower between Cambodia, Laos, Thailand, and Vietnam (for the scenarios BAU, MAX_LMB, and OPT). Numbers indicate hydropower values (in TWh), while the link's colors correspond to the production country. The top and bottom half corresponds to hydropower demand and supply, respectively. Each arc begins at the same point for each scenario, hence the absence of gaps represents greater production/consumption.

Supplementary Files

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