Journal of Environmental Management 353 (2024) 120231

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

An electricity market-based approach to finance environmental flow restoration

Ana Paula Dalcin[a,*], Guilherme Fernandes Marques[a], Amaury Tilmant[b], Joshua H. Viers[c], Josué Medellín-Azuara[c]

[a] Instituto de Pesquisas Hidráulicas (IPH), Universidade Federal do Rio Grande doo Sul (UFRGS), Porto Alegre, RS, 91501-970, Brazil
[b] Department of Civil and Water Engineering, Université Laval, Quebec City, QC G1V 0A6, Canada
[c] Department of Civil and Environmental Engineering, University of California Merced, Merced, CA, USA, 95343

ARTICLE INFO

Keywords:
Ecosystem restoration
Hydropower operation
Compensation fund
Environmental flows
Sustainable energy
Electricity market

ABSTRACT

As environmental flow demands become better characterized, improved water allocation and reservoir operating solutions can be devised to meet them. However, significant economic trade-offs are still expected, especially in hydropower-dominated basins. This study explores the use of the electricity market as both an institutional arrangement and an alternative financing source to handle the costs of implementing environmental flows in river systems managed for hydropower benefits. A framework is proposed to identify hydropower plants with sustainable operation within the portfolio of power sources, including a cost-sharing mechanism based on the electricity market trading to manage a time-step compensation fund. The objective is to address a common limitation in the implementation of environmental flows by reducing the dependence on government funding and the necessity for new arrangements. Compensation amounts can vary depending on ecosystem restoration goals (level of flow regime restoration), hydrological conditions, and hydropower sites characteristics. The application in the Paraná River Basin, Brazil, shows basin-wide compensation requirements ranging from zero in favorable hydrological years to thousands of dollars per gigawatt-hour generated in others. Each electricity consumer's contribution to the compensation fund is determined by their share of energy consumption, resulting in values ranging from cents for residential users to thousands of dollars for industrial facilities. Finally, the compensation fund signals the economic value of externalities in energy production. For residential users, achieving varying levels of ecosystem restoration led to an electricity bill increase of less than 1 %. For larger companies, the increase ranged from less than 1 %–12 %.

1. Introduction

Water rights and infrastructure have traditionally been allocated and expanded to meet demands at the lowest cost, often disregarding the benefits of environmental services. This has resulted in drastic changes of natural flow regimes and the loss of freshwater ecosystem biodiversity and habitats (Maskey et al., 2022). Despite advancements in new strategies around flow regime restoration, known as environmental flows (e-flows), and multiobjective water allocation frameworks, studies have indicated that measurable trade-offs in several sectors (such as hydropower and irrigation) for environmental prescriptions are inevitable (Rheinheimer et al., 2013; Widén et al., 2022; Willis et al., 2022). In this context, the analysis of e-flows should go beyond predicting expected trade-offs, which is fundamental to support policy reconfiguration, and should advance on creating policy and financing mechanisms to foster effective implementation (Brown et al., 2018; Horne et al., 2017).

Economic compensation mechanisms can directly remunerate users who suffer economic losses due to restoration of flow regimes (Acreman, 2016; Pang et al., 2013, 2018; Sisto, 2009), but are still highly dependent on organization funds or government economic incentives, such as subsidies on taxes and energy tariffs, applied to utilities that implement e-flows. Arthington et al. (2023) highlight the high dependence on donor funding as a constraint on e-flow implementation in various basins worldwide, such as the Nile River Basin in Africa and the Ramganga River in India. Involving beneficiaries of ecosystems services in the cost-sharing process, as mentioned in Benayas et al. (2009) and Palmer and Filoso (2009), can also increase the availability of financing sources. However, in hydropower dominated basins, the economic loss resulting

* Corresponding author.
E-mail address: dalcin.anap@gmail.com (A.P. Dalcin).

https://doi.org/10.1016/j.jenvman.2024.120231
Received 15 December 2023; Received in revised form 17 January 2024; Accepted 24 January 2024

from hydropower reduction is usually much greater than the perceived value of improved ecosystem services, either because it is localized (e.g., increased fish abundance benefiting local fisherman) or because a significant portion of the benefits (e.g., biodiversity) is intangible and poorly represented in planning (Klain and Chan, 2012).

Transferring economic hydropower losses to electricity tariffs can also help mitigate financial needs and share costs with society's expectation of ecosystem preservation. Ruan et al. (2021) quantified that if all the losses resulting from adopting a 10 % mean annual e-flow strategy in the Fujian Province of China (estimated to reduce the total electricity production by 9.38 %) are transferred to users, the impact on people's original electricity bills would be approximately 0.56 %. However, without an arrangement framework, equal cost-sharing solutions may lead to inequitable cost distribution, since varying demands and electricity consumers (including industrial facilities, companies, and irrigation districts) are not considered. Additionally, when compensation is based on static (fixed) e-flow requirements, it may lack flexibility in accommodating different hydrological conditions and clearly communicate the associated environmental benefits. These shortcomings can hinder engagement, negotiations, and agreements as society may perceive it as an additional environmental fee.

Trading in water markets, like in United States and Australia, has also been used to augment stream flows for environmental outcomes (Brown, 2006; Debaere and Li, 2022; Qureshi et al., 2010). Examples include establishing environmental water transaction programs to acquire water rights from willing sellers and reallocate it for environmental purposes (Grafton and Horne, 2014; Hanak et al., 2021; Kendy et al., 2018). In order to reduce reliance on state/federal funding for these programs, water demands for ecosystem needs have also been approached as a water right, rather than solely limiting water rights for society consumption (Erfani et al., 2015; Mount, 2018; Mount et al., 2017). Under this proposal, the environmental manager could purchase, trade, and even sell water to best serve environmental needs. However, despite the advantages of bringing management flexibility, the implementation of formal water markets faces several challenges in many countries, especially due to poorly defined and enforceable water rights (Grantham and Viers, 2014), a lack of control and oversight, as well as issues related to institutional monitoring, and considerations of cultural values (Wheeler, 2021).

The present study proposes an alternative mechanism to finance e-flow restoration through trade-offs sharing/compensation, having the electricity market arrangement and trading as a source of resources. Like the classification of renewable energies that contribute to reduce carbon emissions, hydropower plants that contribute to the restoration of aquatic ecosystem functions could benefit from a similar arrangement concept. Thus, the proposed mechanism identifies hydropower plants that contribute to the restoration of flow regimes in the portfolio of power sources, and the degree of contribution, allowing consumers to purchase electricity from these sources through trading mechanisms such as policy and voluntary purchase.

The suggested financing mechanism for implementing e-flows aims to reduce the need to create new institutions, as in the case of water markets, and decrease reliance on external, government funds. According to O'Shaughnessy et al. (2021), voluntary buyers procured about 35 % of all non-hydro renewable energy generated in the United States in 2020, indicating that electricity demand is driven not only by price and policy but also by voluntary action. Additionally, electricity markets are well-stablished in many countries, usually adopting competitive and/or regulated arrangements for trading electricity between consumers and generators (OECD, 2022; Sioshansi, 2013).

Finally, the proposal allows compensation needs from meeting e-flows to be dynamically adjusted according to varying hydrological conditions and restoration levels, rather than relying on fixed rules for cost-sharing as proposed in Marques and Tilmant (2018). The methodology builds upon modelling frameworks that identify strategies for environmental flows restoration based on ecological-flow relationships and the corresponding trade-offs to hydropower production (water--energy-ecosystem nexus). Economic losses are then addressed based on a novel dynamic compensation funding framework, supported by energy trading. During periods when e-flow requirements can be met with minimal trade-offs, the compensation is automatically reduced, following a compensation-on-demand approach.

This study starts by describing the electricity market-based approach to finance e-flow restoration initiatives. The methodology is then demonstrated in the context of a large-scale hydropower system, the Paraná River Basin, in Brazil. In the results and discussion section, we assess the compensation fund range, its spatial distribution, and the economic impacts on different electricity consumers.

2. Methodology

The methodology is structured in three sections. The first section describes the general structure of retail electricity markets and presents the concept of a market-based proposal as a way to finance the restoration of environmental flow regimes in basins impacted by hydropower production. The second section describes the proposed concept and mechanism of the environmental compensation fund. The third section describes the mathematical approach used to simulate the compensation fund and the cost-sharing mechanism in a study basin.

2.1. The electricity market-base framework to finance sustainable hydropower operation practices

Electricity is traded in wholesale and/or retail markets. Typically, the retail electricity market operates under two fundamental structures: (a) the regulated market, where consumers purchase power from the designated utility company in their area and have no choice in selecting their power provider, and (b) competitive markets, where consumers can shop for competitive prices or renewable options from different power suppliers, although utility companies continue to own and maintain the transmission infrastructure. Examples of electricity consumers include, industrial facilities, residential users, irrigation districts, among others.

As indicated in Fig. 1, in a regulated electricity market, the negotiation flow is unidirectional. That is, electricity is provided to the consumer from a mix of generating sources run by a pool of producers, and the consumer only decides their electricity demand. Conversely, in a competitive electricity market, the negotiation flow is bidirectional; consumers can choose not only how much electricity to purchase but also from which generating source or producer.

In this context, we propose distinguishing hydropower plants that contribute to e-flow regime restoration, either individually or as part of a cascade system (i.e., centralized dispatch system), within the available power source portfolio (depicted in Fig. 1 as *Hydropower - sustainable operation*). By doing so, consumers can make electricity purchases from these sources through the market arrangement and contribute to a compensation mechanism.

Additionally, we propose classifying hydropower plants based on their sustainable operation level, ranging from Tier 1 (very high environmental performance) to Tier 10 (very low environmental performance). We also refer to Tier 10 as traditional operation, which prioritize hydropower production and do not actively participate in restoration plans.

The tradeoff between tiers (energy production and environmental performance) increases as the desired level of restoration increases, as illustrated by the Pareto Front in Fig. 2. To compensate for the energy loss, the electricity produced by a powerplant that adjusts its operation to restore e-flows and bring additional environmental benefits (sustainable operation) is priced differently (higher) based on a compensation amount.

In a cascade system, whether in parallel or series, the restoration of e-flows to sustain ecosystem needs often entails reconfiguring energy

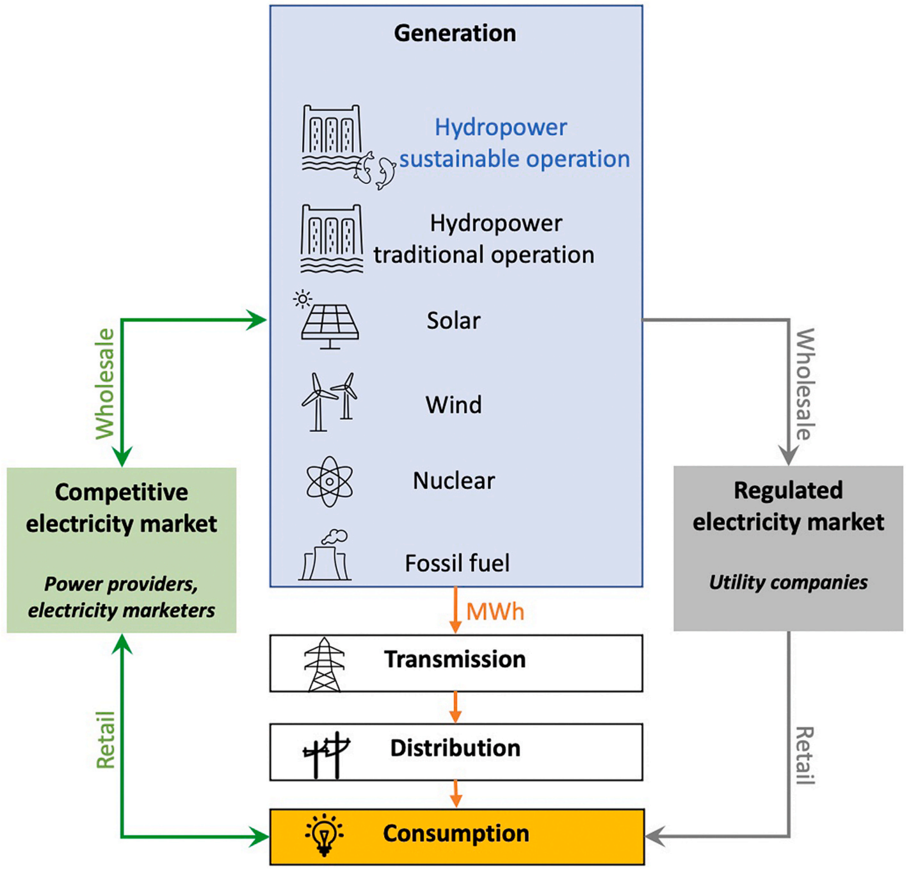

Fig. 1. Electricity market as a cost-sharing arrangement to implement environmental flows.

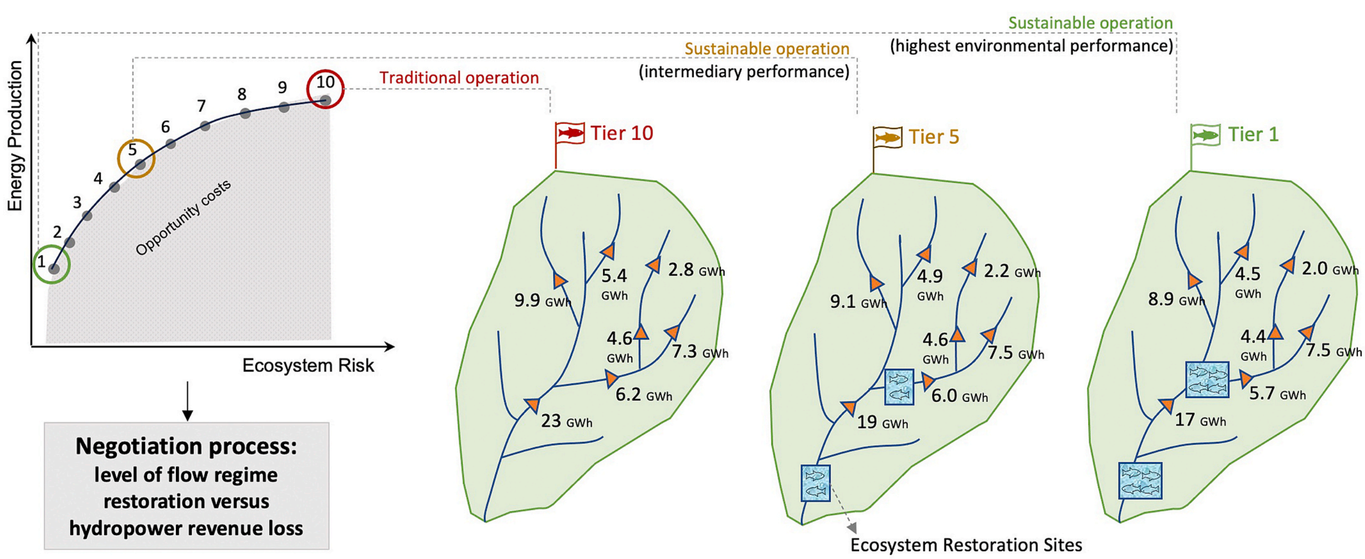

Fig. 2. Tier classification based on the level of sustainable operation.

production by adjusting the timing and magnitude of releases and reservoir refill. The resulting energy production loss thus vary depending on each hydropower plant's position in the cascade, reservoir storage capacity, and local incremental flows. Additionally, energy gains can be realized when hydropower plants reduce overall storage to increase downstream flows, thereby boosting turbined flows during specific periods (e.g., reallocating releases from the dry season to the wet season).

While plant-level impacts may vary, the framework assigns the same tier classification to all hydropower plants contributing to a specific restoration site, as depicted in Fig. 2. The delimitation of the cascade system includes all hydropower plants with reservoir located upstream of target environmental sites. This tier-classification approach enables electricity consumers to identify the level of restoration commitment of a particular hydropower plant or the cascade system.

To adequately address the restoration sites and the trade-offs associated with various e-flow strategies, incorporating ecological-flow relationships into hydroeconomic models using modeling tools can provide valuable insights and initiate informed discussions. Choosing e-flow alternatives that sustain vulnerable ecosystem sites and functions offers a strategic framework for developing ecological-flow relationships (Grantham et al., 2020; Whipple et al., 2017; Yarnell et al., 2015) and more measurable indicators of environmental performance. Water-dependent vegetation, waterbirds, and native fish population are some good examples of indicators to quantify environmental outcomes (Murray–Darling Basin Authority, 2020), although more holistic approaches are needed. As described by Grantham et al., (2014), such an approach would identify dams for which there is evidence of both flow alteration and ecological impairment, and where a policy nexus warrants the more time-consuming investments in environmental flow assessment is needed.

Trade-offs between energy production and ecosystem maintenance are one such policy nexus. After identifying trade-offs, a negotiation process should be established among water managers (seeking to resolve potential conflict and implement solutions that benefit the watershed as a whole), energy producers (seeking to maximize power generation), and water users and environmental agencies (seeking to protect ecosystem functions and services). This negotiation process ideally should produce a minimum level of e-flow restoration at a designed target site (minimum Tier), which will then serve as the basis for an economic compensation mechanism to offset the power generation revenue loss.

Finally, although this study directly deals with flow regime restoration, a successful ecosystem restoration plan requires the integration of multiple elements for floodplain functionality, including the connectivity between river and floodplain (Opperman et al., 2010), as well as dynamic sediment transport and deposition (Yarnell et al., 2010, 2015). Thus, instead of prioritizing e-flow releases downstream of hydropower plants as a restriction to water allocation (hydropower generation), we propose framing the problem by considering sensitive environmental sites as water users in the hydro-system (basin scale). Each user has specific water and land demands according to the ecosystem function(s) willing to be restored (e.g., fish migration and reproduction). This systems analysis approach also addresses barriers to e-flows implementation by looking at the entire catchment, as opposed to individual facilities (Facincani Dourado et al., 2023).

2.2. The environmental compensation fund mechanism

As economic impacts vary within a cascade system when restoring e-flows, to avoid financial risks to the hydropower plants whose operation is more impacted, we propose the creation of a compensation fund covering the entire basin. The management of this fund could be entrusted to the basin authority, aligning with the approach suggested by Arjoon et al. (2016) in their analysis of sharing benefits from water allocation in transboundary basins.

The proposed basin-wide total economic compensation amount considers the difference in economic outcomes between operating the system without restoration goals (traditional operation at Tier 10, Fig. 2) and operating the system with an agreed level of restoration at target sites. This ensures that negatively impacted hydropower plants are fairly compensated for their economic losses, while the gains from hydropower plants that are positively impacted contribute to offsetting these losses.

The economic losses should encompass both revenue deficits or/and the need to supplement their energy supply by purchasing from other power suppliers. Electricity markets typically offer trading arrangements, such as spot markets, where electricity suppliers have the flexibility to purchase electricity from other sources at varying (usually higher) prices to fulfill their supply contracts. Thus, the compensation fund should adequately address such economic implications faced by hydropower plants in the context of the electricity market dynamics.

Fig. 3 represents the money fluxes between end-use consumers and hydropower plants in the compensation fund mechanism. End-use consumers, such as industries and irrigation districts purchasing electricity from the suppliers of the cascade system, contribute to the compensation fund based on the compensation amount required to implement a given tier (Tier 5 in figure case) and their respective share of energy consumption (Consumers X and Y in figure case). The total amount is then redistributed among the affected hydropower plants, according to their losses (Supplier A and B in figure case).

To avoid the uncertainty of oscillating compensation costs for the electricity buyers, a constant average contribution amount could be determined based on a long-term requirement estimation, subject to periodic review. For example, the contribution amount could be derived from an average long-term compensation requirement (e.g., 10 years planning) with periodic reviews. This proposal prevents cost oscillations for electricity buyers, which is crucial for mitigating risks when they opt for sustainable sources.

Finally, the electricity bill on the consumer would include two charge components: one to cover the consumed electricity (as is usual), and another to address the compensation fund proportion. The compensation amount would then be distributed among the hydropower plants in the basin based on their individual economic impacts on-demand. This approach ensures that the burden of compensation is shared among electricity buyers according to their consumption levels and decision to opt to purchase electricity from a more sustainable operation powerplant. Furthermore, the compensation amounts are reallocated to the affected hydropower plants based on the extent of their economic losses with respect to business-as-usual conditions.

2.3. Simulation of the compensation fund to sustain sustainable hydropower operation practices

To demonstrate the implementation of the proposed methodology, three main steps were followed, as demonstrated in Fig. 4. The first step involved defining the study area and identifying the specific ecological function(s) and environmental site(s) targeted for restoration within the watershed. This process required establishing ecological-flow relationships to guide the restoration efforts.

The second step involved the quantification of the economic implications of implementing e-flow restoration solutions (trade-off analysis). This process required implementing an integrated ecosystem-hydropower economic model. In the third step, the compensation budget amount required to finance sustainable operations and its spatial distribution were calculated together with the impacts on electricity buyers.

The proposed framework provides a starting point to highlight the potential role of the electricity market in supporting flow regime restoration initiatives in hydropower systems. Yet other specific market issues, such as transaction costs, the broader effects of alternative energy sources and price dynamics, and how the supply deficit resulting from reduced hydropower generation would be compensated by other energy sources, are beyond the scope of this study.

2.3.1. Defining the study area and the ecosystem functions to be restored

The methodology is applied to the Paraná River Basin in Brazil, which hosts a cascade of 65 hydropower plants with a combined installed capacity of 48,381 MW, representing approximately 50 % of Brazil's total reservoir storage (Agência Nacional de Águas, 2020; CCEE, 2020). Currently, the e-flow requirements in this basin are based on fixed minimum flow constraints downstream of the hydropower plants (ONS, 2022).

For the analysis of flow regime restoration, a specific environmental site was chosen located between two major power plants: Porto Primavera (1540 MW) and Itaipu (14,000 MW). This site is particularly important as it represents the last remaining dam-free lotic environment within the original floodplain. With a length of 230 km, it still retains

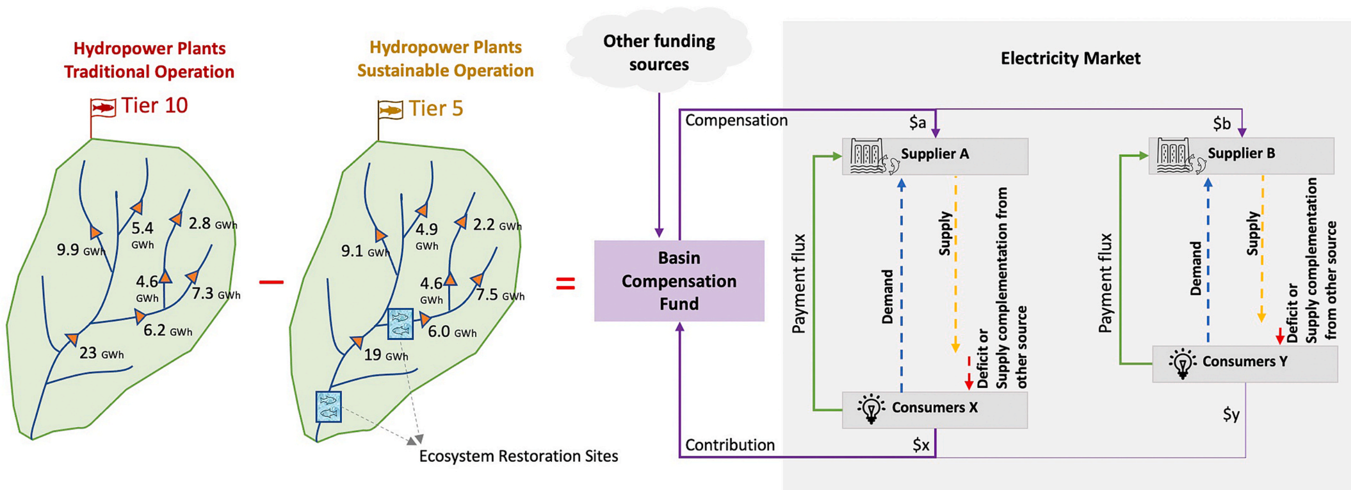

Fig. 3. The electricity market as a financing mechanism to implement e-flows for ecosystem restoration.

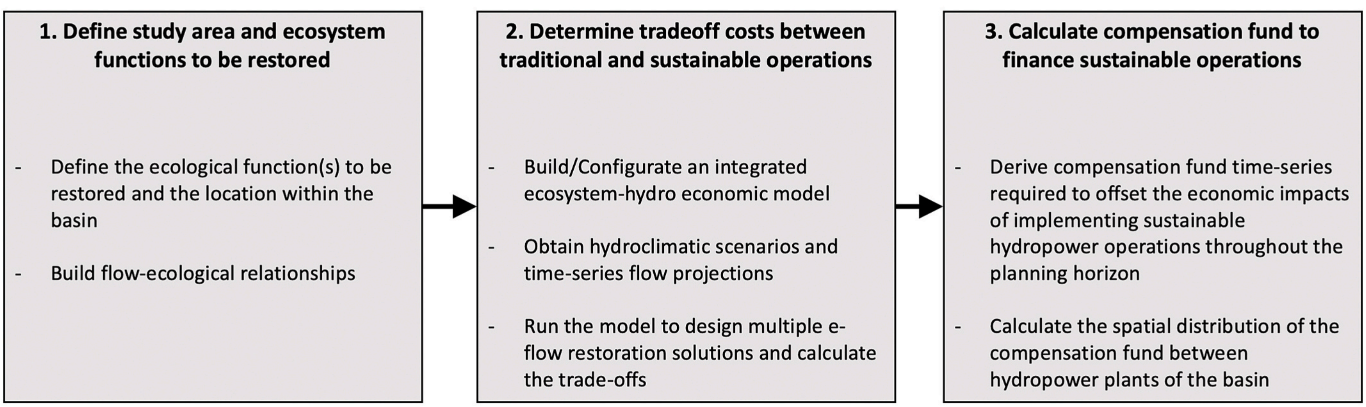

Fig. 4. Steps applied to simulate the electricity market as a cost-sharing mechanism to implement sustainable hydropower operations.

some natural characteristics that promote floodplain connectivity and provide suitable conditions for fish migration and spawning (Agostinho et al., 2008). The hydropower plants upstream and the first downstream to it (53 in total) were used to evaluate energy production and economic/environmental trade-offs. The spatial location is demonstrated in Fig. 9.

The performance of the flow restoration was measured by a clear ecosystem indicator, which is the recruitment abundance of migratory fish species. Many studies evaluating the modification of downstream flow regimes by reservoir operations highlight a functional simplification of the ichthyofauna diversity, often with poor representation of migratory fish species (Cooper et al., 2017; Loures and Pompeu, 2018; Pringle et al., 2000) that require both habitat connectivity and flow availability to sustain this ecological function.

The fish-flow model was based on Dalcin et al. (2022), which applies an artificial neural network (ANN) method to predict the annual migratory fish abundance using annual flow regime metrics (indices) as predictors (Equation (1)). In our study area, we selected nine specific indices that capture both dry and rainy seasons, as well as conditions historically associated with fish migration and the initial growth of migratory species in the region. These indices include flood duration for different magnitude thresholds during the wet and dry seasons, flood delay in the wet season, number of flood pulses during the wet season, uninterrupted flood duration during the wet season, and interannual flood occurrence.

The fish-flow model was previously trained based on the observed time-series of daily streamflow/level and fish sampling data during the 1992 to 1994 and 2000 to 2019 campaigns. The migratory fish abundance was represented by the sum of five long-distance migratory fish species *Brycon orbignyanus, Pseudoplatystoma corruscans, Pterodoras granulosus, Prochilodus lineatus,* and *Salminus brasiliensis*, which are between the most abundant among the long-distance migratory fishes native to and present in the study area (Agostinho et al., 2007; Oliveira et al., 2015).

$$g_{k,y} = \varphi_o \left\{ \beta_k + \sum_j w_{j,k} \varphi_h \left(\beta_j + \sum_i w_{i,j} x_{i,y} \right) \right\} \quad (1)$$

Where the index j represents the hidden neurons, i represents the input neurons, and k represents the output neurons, x_i is a vector of the input variables (represented by the flow regime indexes), g_k are the output variables (represented by the migratory young-of-the-year fish abundance; $k = 1$). β_k and β_j are the biases associated with the hidden and output layers, φ_o and φ_h are activation functions for the hidden and output layers (here represented by the sigmoidal function).

2.3.2. Determining trade-off costs between traditional and sustainable operations

The fish-flow model was coupled to a hydro-economic model to derive operating policies (e-flow restoration solutions) for the multi-reservoir hydropower system. We applied the Dynamically Adaptive Environmental Flows (DAE-flows) approach from Dalcin et al. (2023a), which allows to design flexible e-flow solutions that are dynamically reconfigured along the time horizon on demand, adapting as system conditions change (e.g., hydrological and storage conditions). Such solutions conserve water in some periods, at the expense of some ecosystem loss (e.g., fish recruitment) to improve long-term ecosystem functioning.

The hydro-economic model defines how much water to release r_t, at which time, from which node of the hydro-system (dams or environmental sites) and under which system state conditions (i.e., storage s_t and inflow q_t) in order to maximize the sum Z of the sequence of benefits f_t from system operation over a planning period T (Equation (2)). The model is based on the stochastic dual dynamic programming approach (Pereira and Pinto, 1985; Tilmant and Kelman, 2007), an established approach to model explicit stochastic systems avoiding issues of dimensionality, used in hydropower systems, including Brazil (Maceira and Damázio, 2006; de Matos et al., 2015) and Norway (Helseth et al., 2022).

$$Z = max\ E\left[\sum_{t=1}^{T} f_t(\boldsymbol{s}_t, \boldsymbol{q}_t, \boldsymbol{r}_t) + v(\boldsymbol{s}_{T+1})\right] \tag{2}$$

$$\boldsymbol{r}_t = \boldsymbol{s}_t + \boldsymbol{q}_t - \boldsymbol{e}_t - \boldsymbol{s}_{t+1} \tag{3}$$

where variables in bold represent the vector of nodes, t is the time-step (e.g., monthly, weekly); S_t is the storage vector at stage t; q_t is the inflow vector at stage t; and r_t is the release vector at stage t; e_t is the evaporation vector variable, E is the expectation operator to observed hydrological conditions given the previous hydrological states, and $v(s_{T+1})$ is the terminal value function. Discounting is not shown for notational simplicity.

We evaluated the opportunity cost of different levels of flow regime restoration and hydropower production by coupling the hydro-economic model with a multi-objective evolutionary algorithm named Borg MOEA (Hadka and Reed, 2013), which has been successfully applied in the investigation of adaptive operating policies, water management infrastructure and stakeholders' interests, as seen in Rodríguez-Flores et al. (2023), Gold et al. (2023), and Deb et al. (2023). The higher the preference for the ecosystem preservation, the higher the implementation of e-flows that sustain fish migration and reproduction along the planning horizon, and therefore the lower the energy production. The solutions resulting in better hydropower and environmental performance conform a Pareto frontier.

For the hydropower objective function (OF1), the performance indicator consisted in maximizing the sum of the total cascade dams N hydropower generation along the planning horizon (Equation (4)). For the environmental objective function (OF2), the performance indicator of the hydro-system operation was measured as the risk (from 0 to 1) of a given operating solution to limit migratory young-of-the-year fish recruitment over the planning horizon (Equation (5)).

$$\text{OF1 : max}\left[\sum\nolimits_{n=1}^{N} \sum_{t=1}^{T} \widehat{HP}_t\right] \tag{4}$$

$$\text{OF2 : min}\ [Ecosystem\ Risk\ Index_T = w1 * (1 - reliability_T) + w2 * (1 - resiliency_T) + w3 * (vulnerability_T)] \tag{5}$$

The e-flow restoration solutions were designed based on three hydroclimatic scenarios to incorporate the implications of climate change on hydropower generation and ecosystem preservation. The first scenario considered the historical pattern as representative of the future hydroclimatic conditions. This scenario was called historical climate and considered naturalized flow time-series spanning from 1994 to 2019, according to data from (ONS, 2021). The second and third scenarios considered hydroclimatic projections spanning from 2021 to 2065 from two climate models, Eta-MIROC5 and Eta-HADGEM2-ES, under RCP 4.5 and 8.5 emission scenarios, respectively (Dalcin et al., 2023b). These scenarios were called minor and major climate change scenarios and were selected as they represent minimum and maximum extremes of climate change conditions in the region (Chou et al., 2014; INPE, 2021).

For the simulation of the hydro-system operation, synthetic time-series for a 20-year planning horizon were generated based on each climate scenario. The planning horizon thus encompasses different sequences of water year types, which gives enough room to identify the ecosystem and hydropower performance in the long run. Fig. 5 presents the Pareto Front results obtained for each hydroclimatic scenario in a total 20-year planning horizon.

2.3.3. Calculating the compensation fund to finance sustainable hydropower operations

The time-step environmental compensation fund amount was calculated as the basin-wide economic energy revenue change to meet a certain level of flow regime restoration with respect to traditional operation (Equation (6)). To determine the contribution of electricity consumers to the basin-wide fund (Equation (7)), it was considered the average long-term compensation fund requirement and the ratio between the individual electricity buyer consumption (*ConsumerDemand*$_t$) and the basin-wide electricity production (*BasinProduction*$_t$). The basin compensation balance (*BasinBalance*$_t$) at each stage (year) was determined by Equation (8).

$$BasinBudget_t = \sum_{n=1}^{N}\left(Energy_{trad,n,t} xPrice_{trad,t} - Energy_{sus,n,t} xPrice_{sus,t}\right) \tag{6}$$

$$ConsumerContribution_t = \left[\frac{\left(\sum_{t=1}^{T} BasinBudget_t\right)}{T} x \left(\frac{\sum_{t=1}^{T} ConsumerDemand_t}{\sum_{t=1}^{T} BasinProduction_t}\right)\right] \tag{7}$$

$$BasinBalance_t = BasinBalance_{t-1} + \left[\sum_{i=1}^{I} ConsumerContribution_t - BasinBudget_t\right] + other\ funding\ sources \tag{8}$$

where, the index n represents the hydropower plants, i is the electricity buyers, T is the total planning horizon (e.g., 10 years), *Trad* represents the traditional operation and *Sus* represents the sustainable operation.

In this study, we adopted the marginal electricity value practiced in the spot market (real-time market) as the hydropower price to calculate the economic losses (or complementation of the generation from other sources to honor their contracts). In Brazil, the spot market price represents the cost of producing an additional unit of energy in the overall interconnected power system and is expressed in dollars per megawatt-hour ($/MWh) (CCEE, 2018).

Although different factors influence spot market prices, such as hydrological conditions, and demand and supply balance, we considered a reference spot market value to quantify the economic impacts along the planning horizon in the example of application to demonstrate the methodology (and equal to all modeled hydroclimatic scenarios). The reference value was based on the median monthly value of the historical period 2001–2022 (CCEE, 2023), which results in R$100/MWh (Brazilian currency) or $20/MWh (applying a conversion rate of 5 R$/$). For simplification, we did not apply a discount/interest rate over the period

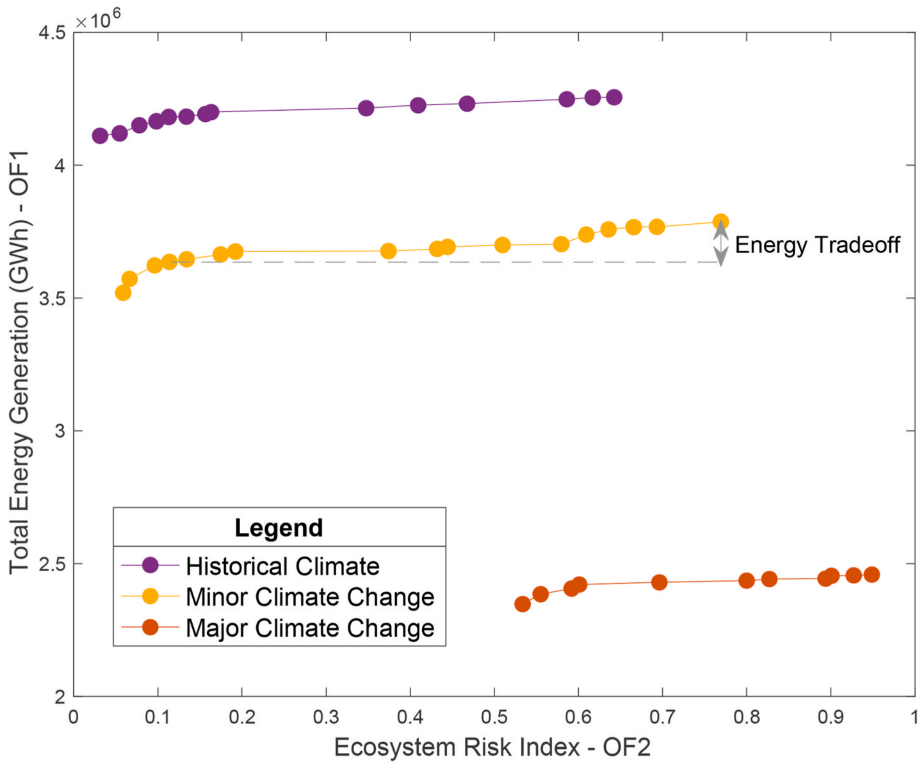

Fig. 5. Pareto Front solutions for Hydropower versus Ecosystem Risk performances (over a 20-year planning horizon). Adapted from Dalcin et al. (2023)a.

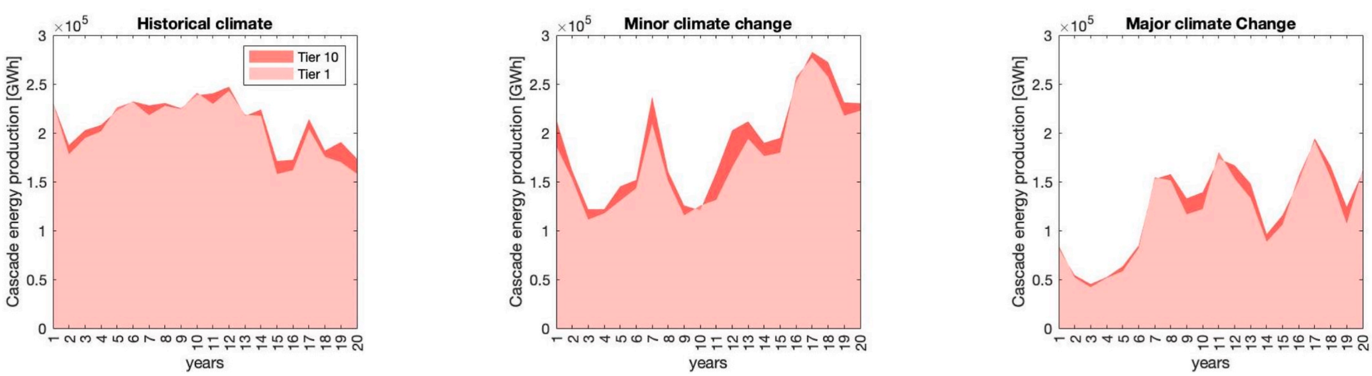

Fig. 6. Cascade energy production loss (in gigawatt-hour - GWh) between different climate scenarios, under Tier 1 (very high environmental performance) and Tier 10 (very low environmental performance).

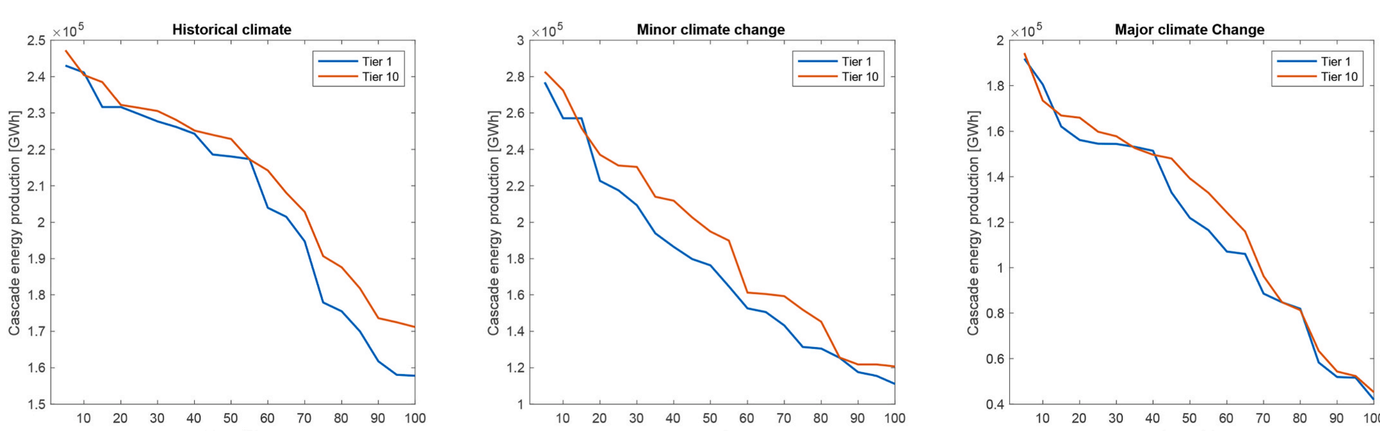

Fig. 7. Cascade energy production frequency curve of Tier 1 (very high environmental perfomance) and Tier 10 (very low environmental performance).

of analysis.

3. Results and discussion

3.1. Economic losses and compensation fund analysis along the planning horizon

The annual energy loss in the Paraná hydropower cascade resulting from adopting a sustainable operation strategy varies depending on the level of flow regime restoration and the hydrological conditions. Fig. 6 illustrates the variability in energy loss when producing energy under very low to high environmental performances (Tier 10 to 1) for each hydroclimatic scenario. These values represent the trade-offs between energy production and environmental performance, with higher environmental gains leading to higher energy losses in the system.

For the historical scenario, the annual energy losses associated with achieving the highest environmental performance (Tier 1) reached up to 10 % in the system. In the minor climate change scenario, the energy losses almost doubled, reaching approximately 18 %. Under the major climate change scenario, hydroclimatic changes pose a big challenge to hydropower production and ecosystem historical functioning, leaving limited options to manage water between both users (as we can see in the initial years of Fig. 6 – right graph).

Fig. 7 presents the energy production frequency curve between the two tiers. Operating the reservoir system under Tier 1 (very high environmental performance) instead of Tier 10 (very low environmental performance) would mean a trade-off of 0,1 GWh/year 90 % of the time, considering historical climate. Under future climate change scenarios, there is not only a significant loss in the energy produced, but also a reduction in the difference from Tier 1 to Tier 10, likely due to more severe water scarcity, which reduces the possibilities to shift water allocation from hydropower to e-flows.

Such energy losses translate into economic impacts that can be compensated through the proposed cost-sharing mechanism and environmental compensation fund. Fig. 8 illustrates the range of the annual compensation amount throughout the simulated horizon and under different sustainable operation tiers.

For the historical climate scenario (Fig. 8 - left graph), the environmental fund requirement averaged $129 million/year under Tier 1 (very high environmental performance), ranging from zero in years with high water availability to $415 million/year in years with lower water availability. For the minor climate scenario (Fig. 8 - middle graph), the environmental fund requirement averaged $266 million/year under Tier 1, ranging from zero in years with high water availability to $760 million/year in years with lower water availability.

It is possible to reduce the compensation values, however, with a higher ecosystem risk. For an intermediate environmental performance (Tier 5), the results indicate an annual average revenue to the environmental compensation fund of $15 million/year under the historical scenario, ranging from zero (in years with high water availability) to $139 million (in years with low water availability). For the minor climate scenario, the values averaged $102 million/year under Tier 5. Under the major climate change scenario (Fig. 8 - right graph), the hydroclimatic changes indicate no operating practices achieving an ecosystem risk below 0.5. It implies that future tiers may be associated with diminished perfomances.

Relative to the compensation amount per GWh produced, the results show average compensation amounts of $631/GWh under Tier 1 and $70/GWh under Tier 5 for the historical climate scenario. In other terms, this means that for each GWh of energy commercialized, the compensation requirement is $70 to achieve Tier 5 or $631 to achieve Tier 1. For the minor climate scenario, the values ranged from $1510/GWh under Tier 1 and $555/GWh under Tier 5.

3.2. Economic impact on electricity consumers

To calculate the impact on different electricity consumers, we applied two hypothetical consumption scenarios. In the first scenario, a company buys 20 GWh/year through the competitive market from a hydropower plant part of the modeled cascade system operating under Tier 5 of restoration. Based on the results of section 3.1, which identified an average annual basin compensation fund of $15 million/year along with average basin production of 2.1×10^5 GWh/year for the historical climate scenario, the annual contribution from this company to the basin compensation fund, calculated using Equation (7), would amount to $1429/year, averaging about $120/month.

Considering energy contracts with electricity prices varying from 25 % to 100 % of the spot market value (from $5/MWh to $20/MWh, see section 2.3.3), the compensation requirement translates into an increase of 0.35 %–1,4 % in the company's energy bill.

Similarly, to achieve Tier 1 of restoration, the annual contribution from this company to the basin compensation fund would amount to $12,285/year, averaging about $1023/month. Thus, a higher increase in the energy bill is expected, ranging from 3.1 % to 12.3 %. Despite the higher price, companies and organizations can gain benefits by enhancing indicators that measure their sustainable practices within the market. For instance, they might focus on improving Environmental, Social, and Governance (ESG) indicators (Boffo and Patalano, 2020), which serve as a tool for investors, consumers, employees, and regulators to assess a company's commitment to sustainable and responsible practices.

The second scenario simulates a residential electricity consumption. A utility company that distributes energy to different cities with 20 million inhabitants in total (as an approximation of the São Paulo metropolitan area) purchases energy from the generators of the same modeled cascade system. Considering an average annual residential demand per capita of 792 kWh/year (EPE, 2022) (which totalizes an annual consumption of 15,840 GWh/year) and the same average

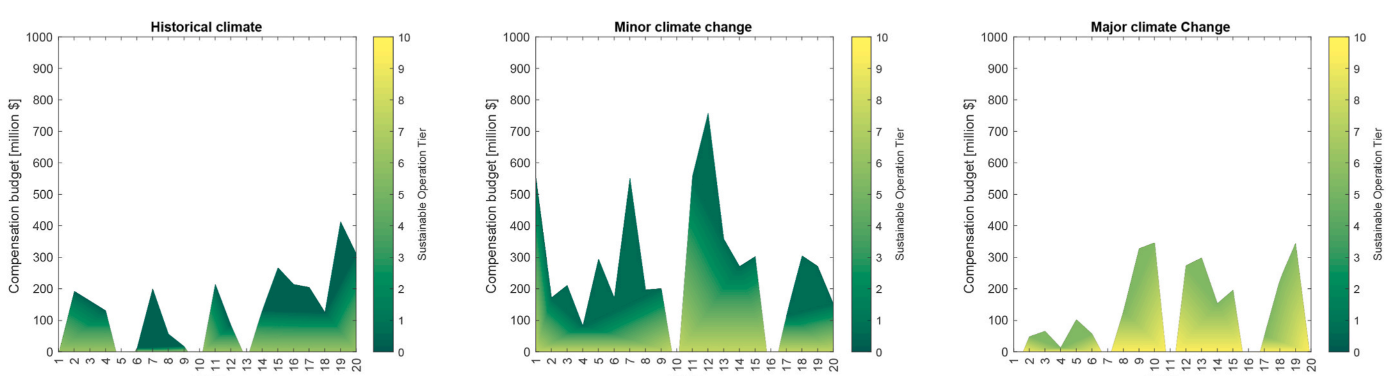

Fig. 8. Annual compensation fund under different climate scenarios and levels of ecosystem risk (Tiers).

compensation requirement of $15 million/year along with basin production of 2.1×10^5 GWh/year to operate under Tier 5, the utility company's total annual contribution to the basin compensation fund would amount to $1.13 million/year. Under Tier 1, the utility company's total annual contribution would amount to $9.9 million/year.

Considering an average residential electricity bill of $119/year (ANEEL, 2023), the incremental cost with the compensation fund would represent an increase of 0.06 % in the individual residential energy bill under Tier 5 (assuming all residents buy from the utility company) and 0.42 % under Tier 1.

Such a mechanism allows different electricity end-use consumers, including companies, residents, and irrigation districts, to contribute to ecosystem restoration through a clear mechanism. This approach contrast with a simple equal distribution of the compensation amount among the population, which often lacks clear arrangements, goals, and consideration of varying end-use consumer demands.

3.3. Spatial distribution of compensations

Although sustaining environmental water demands leads to a negative economic impact balance in the cascade system, hydropower plants within the system may experience varying degrees and types of impacts. In the study area, the results indicate that two specific hydropower plants are significantly affected by flow regime restoration measures. Fig. 9 shows that these plants (the higher the circle, the higher the impact magnitude) are situated at the junctions of tributaries or subbasins, which means they bear the brunt of accumulated impacts both from upstream and lateral sources. Negative impacts are also scattered within the headwaters of tributaries.

On the other side, increased downstream flows at the expense of upstream depleting storage, can positively impact subsequent hydropower plants along the cascade. This pattern highlights the importance of implementing a compensation budget that considers the varying impacts experienced by different hydropower plants, rather than applying static compensation rates that could disproportionately penalize plants with higher losses. In the long-term, an average of 7 % of the compensation amount can be internally produced by gaining hydropower plants, which reduces the financial burden on electricity consumers.

4. Limitations and further considerations

The implementation of the compensation scheme as proposed here is likely to face some institutional challenges, mostly due to the need to integrate both water and energy planning, as highlighted in Rheinheimer et al. (2023). While an in-depth discussion of those aspects is beyond the scope of this study, we address some key issues in this section as a starting point for further reflection to support the implementation of the proposed compensation solution in a near future.

While in the short term the energy trade-offs can be adjusted and compensated, in the long term they will eventually reflect on the planning for energy sources expansion. Hence, the selection of the desired operating tier (environmental goal) requires a careful consideration of the impacts (and costs) on the long-term energy expansion planning. The energy trade-offs and funding compensation mechanism proposed here can be useful in the evaluation of the economic feasibility of future arrangements of power production under consideration of environmental impacts.

Additionally, the current transitional moment in which electrical grids throughout the world find themselves involves the increasing participation of non-dispatchable renewable sources, especially wind and photovoltaic solar. Notable characteristics of non-dispatchable renewable sources include the inability to produce synchronicity and the inability to store energy (IEMA, 2016). In this context, the use of water storage to mitigate power fluctuations from non-dispatchable sources may affect the capacity to meet e-flows, which brings the need for more energy storage solutions and planning.

Although we modeled a hydropower-dominated use basin, other competing water users (e.g., irrigation) can be included in the problem. It is important, however, that the trade-offs associated with other users are excluded from the electricity compensation fund to avoid electricity consumers bearing the impacts caused by these users. The multi-objective evaluation framework and trade-off curves must be adjusted to include the other demands, and the negotiation process must involve the corresponding participants.

Finally, while the method was applied to a case study area with specific features, other regions in the world can also benefit from a similar approach, provided there is a clear identification of environmental flows demands and their components, which may not be readily available in many watersheds.

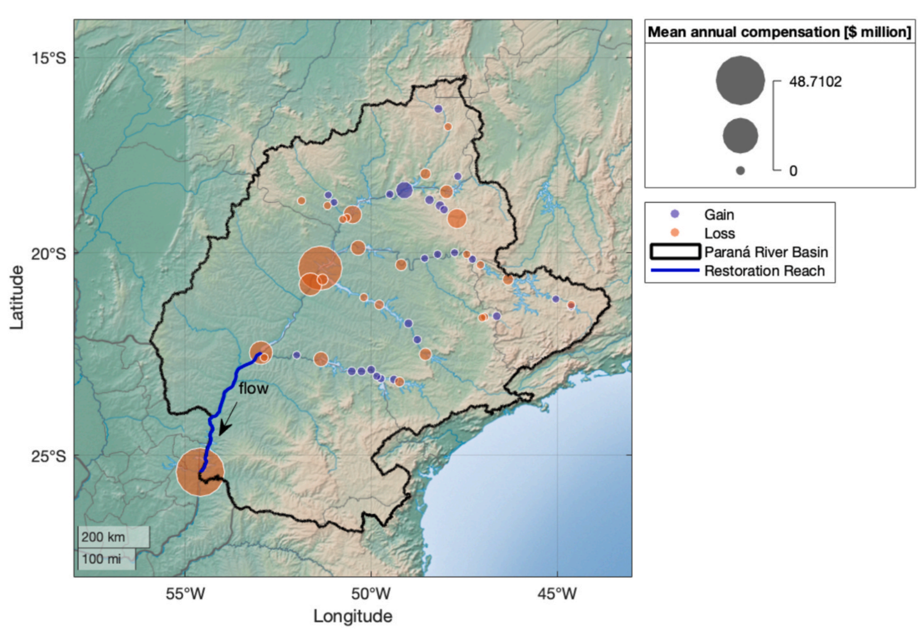

Fig. 9. Spatial distribution of compensation gain/loss between hydropower plants contributing to sustain environmental water needs under Tier 1 (each circle represents a hydropower plant).

The Mekong River, which originates from the Tibet Plateau and flows through six countries (China, Laos, Myanmar, Thailand, Vietnam, and Cambodia) (Li et al., 2017), exemplifies the need to bridge between operators and water managers in order to conserve the remaining wetland ecosystems and restore floodplain connectivity and flow regimes (Quan et al., 2018). Despite being considered the third most biodiverse river systems globally (Intralawan et al., 2018), the conversion of wetlands to agriculture and hydrological alteration due to hydropower development have been a significant threat to its ecosystem (Beveridge et al., 2020; Li et al., 2017).

In Chile, Alvarez-Garreton et al. (2023) point out that safeguarding long-term ecological river functions requires changes in environmental flow limits and the water allocation process. The Nile Basin, although having a well-developed strategy for the management of e-flows, the high dependence on local donor funding is a constraint on e-flow implementation and monitoring of outcomes (Arthington et al., 2023). All these examples highlight that successful, long-term conservation initiatives will likely necessitate significant investments and careful consideration of trade-offs.

5. Conclusion

This study examined the potential role of the electricity market in financing the restoration of flow regimes to meet biological and physical needs of riverine ecosystems in hydropower systems. By identifying hydropower plants with sustainable operation within the portfolio of power sources, the framework takes advantage of market trading mechanisms where electricity consumers can purchase electricity from these generators and contribute to a compensation fund aimed at offsetting the economic losses incurred. Four main conclusions can be drawn from the proposed approach.

Financing e-flow restoration is likely to be less costly when shared more equitably. The electricity market possesses several desirable elements to facilitate the implementation of e-flows, including an institutional framework (trading mechanisms), operational coordination of power supply with a focus on economic efficiency, and existing mechanisms for auditing. By taking advantage of this existing framework, we can reduce transaction costs.

By incorporating hydrological conditions into the calculation of the compensation amount, it can provide more flexibility to negotiate water reallocation between users, especially during different water type years. The opportunity to increase energy production in some hydropower plants (when part of a cascade system) can also help reduce the cost of compensation to end-use consumers.

As there is no single solution for meeting e-flows, to properly define a compensation amount one must negotiate the trade-offs, here represented by operating tiers. Both the selection of the environmental objective (operating Tier) and the compensation mechanism should be planned together.

The compensation fund contributes to signaling the economic value of externalities in energy production. For the study case, achieving varying levels of ecosystem restoration resulted in an energy bill increase of less than 1 % for residential users. For larger companies, the increase ranged from less than 1 %–12 %.

Finally, the results and conclusions of this study have significant implications for policy development.

Pathways to restore environmental flows under changing climate and competing water demands need new solutions with integrated water and energy policies. The study highlights that hydropower-based electricity production carries environmental externalities that may be challenging to manage without appropriate price signaling. By better integrating water and energy policies, the easier it becomes to implement approaches such as the one proposed here.

Future drier climates can further reduce hydropower generation, which can also limit the opportunity to allocate water to e-flows. In this case, the proposed compensation mechanism can be useful to allow a gradual transition to higher performance environmental policies, while allowing more resources to be invested in other power generation sources that are less dependent on water. This strategy could facilitate the transition and adaptation to future drier conditions, while restoring environmental sites.

CRediT authorship contribution statement

Ana Paula Dalcin: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Guilherme Fernandes Marques:** Writing – review & editing, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Amaury Tilmant:** Writing – review & editing, Methodology, Formal analysis. **Joshua H. Viers:** Writing – review & editing, Formal analysis. **Josué Medellín-Azuara:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ana Paula Dalcin and Guilherme Fernandes Marques report financial support was provided by Inter-American Institute for Global Change Research and Conselho Nacional de Desenvolvimento Científico e Tecnológico. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors thank the Inter-American Institute for Global Change Research (IAI) for financial support under the SGP-HW program, project SGP-HW 091, and CNPq for the financial support through grant 308549/2019-8 and 404242/2019-7.

References

ANEEL, 2023. Ranking da tarifa residencial - R$/kWh. A. N. de E. E. Retrieved from. https://portalrelatorios.aneel.gov.br/luznatarifa/rankingtarifas.
Acreman, M., 2016. Environmental flows-basics for novices. Wiley Interdisciplinary Reviews: Water 3 (5), 622–628. https://doi.org/10.1002/wat2.1160.
Agência Nacional de Águas (ANA), 2020. SAR - Sistema de acompanhamento de reservatórios. Retrieved from. https://www.ana.gov.br/sar/.
Agostinho, A., Pelicice, F., Gomes, L., 2008. Dams and the fish fauna of the Neotropical region: impacts and management related to diversity and fisheries. Braz. J. Biol. 68 (4 Suppl. l), 1119–1132. https://doi.org/10.1590/S1519-69842008000500019.
Agostinho, A.A., Pelicice, F.M., Petry, A.C., Gomes, L.C., Júlio, H.F., 2007. Fish diversity in the upper Paraná River basin: habitats, fisheries, management and conservation. Aquat. Ecosys. Health Manag. 10 (2), 174–186. https://doi.org/10.1080/14634980701341719.
Alvarez-Garreton, C., Boisier, J.P., Billi, M., Lefort, I., Marinao, R., Barría, P., 2023. Protecting environmental flows to achieve long-term water security. J. Environ. Manag. 328, 116914 https://doi.org/10.1016/j.jenvman.2022.116914.
Arjoon, D., Tilmant, A., Herrmann, M., 2016. Sharing water and benefits in transboundary river basins. Hydrol. Earth Syst. Sci. 20 (6), 2135–2150. https://doi.org/10.5194/hess-20-2135-2016.
Arthington, A.H., Tickner, D., McClain, M.E., Acreman, M.C., Anderson, E.P., Babu, S., et al., 2023. Accelerating environmental flow implementation to bend the curve of global freshwater biodiversity loss. Environ. Rev. 1–27. https://doi.org/10.1139/er-2022-0126.
Benayas, J.M.R., Newton, A.C., Diaz, A., Bullock, J.M., 2009. Enhancement of biodiversity and ecosystem services by ecological restoration: a meta-analysis. Science 325 (5944), 1121–1124. https://doi.org/10.1126/science.1172460.
Beveridge, C., Hossain, F., Bonnema, M., 2020. Estimating impacts of dam development and landscape changes on suspended sediment concentrations in the Mekong River Basin's 3S tributaries. J. Hydrol. Eng. 25 (7) https://doi.org/10.1061/(ASCE)HE.1943-5584.0001949.

Boffo, R., Patalano, R., 2020. ESG Investing: Practices, Progress and Challenges. Retrieved from. www.oecd.org/finance/ESG-Investing-Practices-Progress-and-Challenges.pdf.

Brown, C., King, J., Hughes, J., Zakaria, V., Cardinale, P., 2018. Environmental Flows for Hydropower Projects: Guidance for the Private Sector in Emerging Markets. World Bank Group, Washington, D.C.

Brown, T.C., 2006. Trends in water market activity and price in the western United States. Water Resour. Res. 42 (9) https://doi.org/10.1029/2005WR004180.

CCEE, 2018. Preço de liquidação das diferenças - Versão 2018.1.0. Brasília, DF, Brazil.

CCEE, 2020. Hydroedit - apoio à leitura de arquivos. Retrieved December 10, 2020, from. https://www.ccee.org.br/acervo-ccee?especie=44884&keyword=hydroedit&periodo=5000.

CCEE, 2023. Histórico de preços. Retrieved May 2, 2023, from. https://www.ccee.org.br/.

Chou, S.C., Lyra, A., Mourão, C., Dereczynski, C., Pilotto, I., Gomes, J., et al., 2014. Evaluation of the Eta simulations nested in three global climate models. Am. J. Clim. Change 3 (5), 438–454. https://doi.org/10.4236/ajcc.2014.35039.

Cooper, A.R., Infante, D.M., Daniel, W.M., Wehrly, K.E., Wang, L., Brenden, T.O., 2017. Assessment of dam effects on streams and fish assemblages of the conterminous USA. Sci. Total Environ. 586, 879–889. https://doi.org/10.1016/j.scitotenv.2017.02.067.

Dalcin, A.P., Marques, G.F., Galego de Oliveira, A., Tilmant, A., 2022. Identifying functional flow regimes and fish response for multiple reservoir operating solutions. J. Water Resour. Plann. Manag. 148 (6) https://doi.org/10.1061/(ASCE)WR.1943-5452.0001567.

Dalcin, A.P., Marques, G.F., Tilmant, A., Olivares, M., 2023a. Dynamic Adaptive Environmental Flows (DAE-flows) to reconcile long-term ecosystem demands with hydropower objectives. Water Resour. Res. https://doi.org/10.1029/2022WR034064.

Dalcin, A.P., Brêda, J.P.L.F., Marques, G.F., Tilmant, A., de Paiva, R.C.D., Kubota, P.Y., 2023b. The role of reservoir reoperation to mitigate climate change impacts on hydropower and environmental water demands. J. Water Resour. Plann. Manag. 149 (4) https://doi.org/10.1061/JWRMD5.WRENG-5810.

Deb, K., Fleming, P., Jin, Y., Miettinen, K., Reed, P.M., 2023. Key Issues in Real-World Applications of Many-Objective Optimisation and Decision Analysis, pp. 29–57. https://doi.org/10.1007/978-3-031-25263-1_2.

Debaere, P., Li, T., 2022. Water markets' promise: the murray–darling basin. Environ. Res. Lett. 17 (12), 125003 https://doi.org/10.1088/1748-9326/aca343.

EPE, 2022. *Anuário estatístico de energia elétrica 2022: Ano base 2021*. Brasília, DF. Retrieved from. https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/anuario-estatistico-de-energia-eletrica.

Erfani, T., Binions, O., Harou, J.J., 2015. Protecting environmental flows through enhanced water licensing and water markets. Hydrol. Earth Syst. Sci. 19 (2), 675–689. https://doi.org/10.5194/hess-19-675-2015.

Facincani Dourado, G., Rallings, A.M., Viers, J.H., 2023. Overcoming persistent challenges in putting environmental flow policy into practice: a systematic review and bibliometric analysis. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/acc196.

Gold, D.F., Reed, P.M., Gorelick, D.E., Characklis, G.W., 2023. Advancing regional water supply management and infrastructure investment pathways that are equitable, robust, adaptive, and cooperatively stable. Water Resour. Res. 59 (9) https://doi.org/10.1029/2022WR033671.

Grafton, R.Q., Horne, J., 2014. Water markets in the murray-darling basin. Agric. Water Manag. 145, 61–71. https://doi.org/10.1016/j.agwat.2013.12.001.

Grantham, T.E., Mount, J., Stein, E.D., Yarnell, S., 2020. Making the Most of Water for the Environment: A Functional Flows Approach for California's Rivers. San Francisco, CA, United States. Retrieved from. https://www.ppic.org/wp-content/uploads/making-the-most-of-water-for-the-environment-a-functional-flows-approach-for-californias-rivers.pdf.

Grantham, Theodore E., Viers, J.H., Moyle, P.B., 2014. Systematic screening of dams for environmental flow assessment and implementation. Bioscience 64 (11), 1006–1018. https://doi.org/10.1093/biosci/biu159.

Grantham, Theodore E., Viers, J.H., 2014. 100 years of California's water rights system: patterns, trends and uncertainty. Environ. Res. Lett. 9 (8), 084012 https://doi.org/10.1088/1748-9326/9/8/084012.

Hadka, D., Reed, P., 2013. Borg: an auto-adaptive many-objective evolutionary computing framework. Evol. Comput. 21 (2), 231–259. https://doi.org/10.1162/EVCO_a_00075.

Hanak, E., Sencan, G., Ayres, A., 2021. *California's Water Market*. California. Retrieved from. https://www.ppic.org/wp-content/uploads/jtf-water-market.pdf.

Helseth, A., Mo, B., Hågenvik, H.O., Schäffer, L.E., 2022. Hydropower scheduling with state-dependent discharge constraints: an SDDP approach. J. Water Resour. Plann. Manag. 148 (11) https://doi.org/10.1061/(ASCE)WR.1943-5452.0001609.

Horne, A.C., O'Donnell, E.L., Acreman, M., McClain, M.E., Poff, N.L., Webb, J.A., et al., 2017. Moving Forward: the implementation challenge for environmental water management. In: Water for the Environment. Elsevier, pp. 649–673. https://doi.org/10.1016/B978-0-12-803907-6.00027-9.

IEMA, 2016. Prioridades para a integracao das fontes renováveis variáveis no sistema elétrico. São Paulo.

INPE, 2021. Eta Model. Retrieved from. http://etamodel.cptec.inpe.br.

Intralawan, A., Wood, D., Frankel, R., Costanza, R., Kubiszewski, I., 2018. Tradeoff analysis between electricity generation and ecosystem services in the Lower Mekong Basin. Ecosyst. Serv. 30, 27–35. https://doi.org/10.1016/j.ecoser.2018.01.007.

Kendy, E., Aylward, B., Ziemer, L.S., Richter, B.D., Colby, B.G., Grantham, T.E., et al., 2018. Water transactions for streamflow restoration, water supply reliability, and rural economic vitality in the western United States. JAWRA Journal of the American Water Resources Association 54 (2), 487–504. https://doi.org/10.1111/1752-1688.12619.

Klain, S.C., Chan, K.M.A., 2012. Navigating coastal values: participatory mapping of ecosystem services for spatial planning. Ecol. Econ. 82, 104–113. https://doi.org/10.1016/j.ecolecon.2012.07.008.

Li, D., Long, D., Zhao, J., Lu, H., Hong, Y., 2017. Observed changes in flow regimes in the Mekong River basin. J. Hydrol. 551, 217–232. https://doi.org/10.1016/j.jhydrol.2017.05.061.

Loures, R.C., Pompeu, P.S., 2018. Long-term study of reservoir cascade in south-eastern Brazil reveals spatio-temporal gradient in fish assemblages. Mar. Freshw. Res. 69 (12), 1983. https://doi.org/10.1071/MF18109.

Maceira, M.E.P., Damázio, J.M., 2006. USE OF THE PAR(p) MODEL IN THE STOCHASTIC DUAL DYNAMIC PROGRAMMING OPTIMIZATION SCHEME USED IN THE OPERATION PLANNING OF THE BRAZILIAN HYDROPOWER SYSTEM. Probab. Eng. Inf. Sci. 20 (1), 143–156. https://doi.org/10.1017/S0269964806060098.

Marques, G.F., Tilmant, A., 2018. Cost distribution of environmental flow demands in a large-scale multireservoir system. J. Water Resour. Plann. Manag. 144 (6) https://doi.org/10.1061/(ASCE)WR.1943-5452.0000936.

Maskey, M.L., Facincani Dourado, G., Rallings, A.M., Rheinheimer, D.E., Medellín-Azuara, J., Viers, J.H., 2022. Assessing hydrological alteration caused by climate change and reservoir operations in the san joaquin River Basin, California. Front. Environ. Sci. 10 https://doi.org/10.3389/fenvs.2022.765426.

de Matos, V.L., Philpott, A.B., Finardi, E.C., 2015. Improving the performance of stochastic dual dynamic programming. J. Comput. Appl. Math. 290, 196–208. https://doi.org/10.1016/j.cam.2015.04.048.

Mount, J., 2018. A Water Budget for the Environment. California. Retrieved from. https://www.ppic.org/blog/a-water-budget-for-the-environment/.

Mount, J., Gray, B., Chappelle, C., Gartrell, G., Grantham, T., Moyle, P., et al., 2017. Managing California's Freshwater Ecosystems - Lessons from the 2012–16 Drought. California, USA. Retrieved from. https://www.ppic.org/wp-content/uploads/r_1117jmr.pdf.

Murray–Darling Basin Authority, 2020. Basin-Wide Environmental Watering Strategy, second ed. Murray–Darling Basin Authority, Canberra.

O'Shaughnessy, E., Burd, R., Heeter, J., 2021. Status and Trends in the U.S. Voluntary Green Power Market (2020 Data). National Renewable Energy Laboratory, Oak Ridge.

OECD, 2022. Competition in Energy Markets, OECD Competition Policy Roundtable Backgroung Note. OECD.

Oliveira, A.G., Suzuki, H.I., Gomes, L.C., Agostinho, A.A., 2015. Interspecific variation in migratory fish recruitment in the Upper Paraná River: effects of the duration and timing of floods. Environ. Biol. Fish. 98 (5), 1327–1337. https://doi.org/10.1007/s10641-014-0361-5.

ONS, 2021. Portal SINtegre. Retrieved from. https://sintegre.ons.org.b.

ONS, 2022. *Manual de Procedimentos da Operação - Módulo 5 - Submódulo 5.11 - CD-OR.PR.PAR*. Brasil. Retrieved from. https://www.ons.org.br/%2FMPO%2FDocumento. Normativo%2F2. Cadastros de Informações Operacionais - SM 5.11%2F2.3. Cadastros de Informações Operacionais Hidráulicas%2FCD-OR.PR.PAR_Rev.73.pdf.

Opperman, J.J., Luster, R., McKenney, B.A., Roberts, M., Meadows, A.W., 2010. Ecologically functional floodplains: connectivity, flow regime, and scale. JAWRA Journal of the American Water Resources Association 46 (2), 211–226. https://doi.org/10.1111/j.1752-1688.2010.00426.x.

Palmer, M.A., Filoso, S., 2009. Restoration of ecosystem services for environmental markets. Science 325 (5940), 575–576. https://doi.org/10.1126/science.1172976.

Pang, A., Sun, T., Yang, Z., 2013. Economic compensation standard for irrigation processes to safeguard environmental flows in the Yellow River Estuary, China. J. Hydrol. 482, 129–138. https://doi.org/10.1016/j.jhydrol.2012.12.050.

Pang, A., Li, C., Sun, T., Yang, W., Yang, Z., 2018. Trade-off analysis to determine environmental flows in a highly regulated watershed. Sci. Rep. 8 (1), 14130 https://doi.org/10.1038/s41598-018-32126-6.

Pereira, M.V.F., Pinto, L.M.V.G., 1985. Stochastic optimization of a multireservoir hydroelectric system: a decomposition approach. Water Resour. Res. 21 (6), 779–792. https://doi.org/10.1029/WR021i006p00779.

Pringle, C.M., Freeman, M.C., Freeman, B.J., 2000. Regional effects of hydrologic alterations on riverine macrobiota in the new world: tropical–temperate comparisons. Bioscience 50 (9), 807–823. https://doi.org/10.1641/0006-3568(2000)050[0807:REOHAO]2.0.CO;2.

Quan, N.H., Toan, T.Q., Dang, P.D., Phuong, N.L., Anh, T.T.H., Quang, N.X., et al., 2018. Conservation of the Mekong Delta wetlands through hydrological management. Ecol. Res. 33 (1), 87–103. https://doi.org/10.1007/s11284-017-1545-1.

Qureshi, M.E., Schwabe, K., Connor, J., Kirby, M., 2010. Environmental water incentive policy and return flows. Water Resour. Res. 46 (4) https://doi.org/10.1029/2008WR007445.

Rheinheimer, D.E., Yarnell, S.M., Viers, J.H., 2013. Hydropower costs of environmental flows and climate warming in California's upper yuba river watershed. River Res. Appl. 29 (10), 1291–1305. https://doi.org/10.1002/rra.2612.

Rheinheimer, David E., Tarroja, B., Rallings, A.M., Willis, A.D., Viers, J.H., 2023. Hydropower representation in water and energy system models: a review of divergences and call for reconciliation. Environ. Res.: Infrastructure and Sustainability 3 (1), 012001. https://doi.org/10.1088/2634-4505/acb6b0.

Rodríguez-Flores, J.M., Gupta, R.S., Zeff, H.B., Reed, P.M., Medellín-Azuara, J., 2023. Identifying robust adaptive irrigation operating policies to balance deeply uncertain economic food production and groundwater sustainability trade-offs. J. Environ. Manag. 345, 118901 https://doi.org/10.1016/j.jenvman.2023.118901.

Ruan, Q., Wang, F., Cao, W., 2021. Conflicts in implementing environmental flows for small-scale hydropower projects and their potential solutions—a case from fujian Province, China. Water 13 (18), 2461. https://doi.org/10.3390/w13182461.

Sioshansi, F.P., 2013. Evolution of Global Electricity Markets. Elsevier. https://doi.org/10.1016/C2012-0-00444-9.
Sisto, N.P., 2009. Environmental flows for rivers and economic compensation for irrigators. J. Environ. Manag. 90 (2), 1236–1240. https://doi.org/10.1016/j.jenvman.2008.06.005.
Tilmant, A., Kelman, R., 2007. A stochastic approach to analyze trade-offs and risks associated with large-scale water resources systems. Water Resour. Res. 43 (6) https://doi.org/10.1029/2006WR005094.
Wheeler, S.A., 2021. Water Markets: a Global Assessment. Edward Elgar Publishing, UK.
Whipple, A.A., Viers, J.H., Dahlke, H.E., 2017. Flood regime typology for floodplain ecosystem management as applied to the unregulated Cosumnes River of California, United States. Ecohydrology 10 (5). https://doi.org/10.1002/eco.1817.
Widén, Å., Malm Renöfält, B., Degerman, E., Wisaeus, D., Jansson, R., 2022. Environmental flow scenarios for a regulated river system: projecting catchment-wide ecosystem benefits and consequences for hydroelectric production. Water Resour. Res. 58 (1) https://doi.org/10.1029/2021WR030297.
Willis, A.D., Rheinheimer, D.E., Yarnell, S.M., Facincani Dourado, G., Rallings, A.M., Viers, J.H., 2022. Shifting trade-offs: finding the sustainable nexus of hydropower and environmental flows in the san joaquin river watershed, California. Front. Environ. Sci. 10 https://doi.org/10.3389/fenvs.2022.787711.
Yarnell, S.M., Viers, J.H., Mount, J.F., 2010. Ecology and management of the spring snowmelt recession. Bioscience 60 (2), 114–127. https://doi.org/10.1525/bio.2010.60.2.6.
Yarnell, S.M., Petts, G.E., Schmidt, J.C., Whipple, A.A., Beller, E.E., Dahm, C.N., et al., 2015. Functional flows in modified riverscapes: hydrographs, habitats and opportunities. Bioscience 65 (10), 963–972. https://doi.org/10.1093/biosci/biv102.