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Timing is everything: Rethinking flexible hydropower operations for the economy and environment

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Abstract

Hydropower facilities can alter river flow regimes, leading to ecological degradation and conflicts between revenue generation and ecological objectives. This study develops a new and unique framework (FREE—Flexible Releases for Economics and the Environment) for hydropower management that uses operational flexibility to balance economic and ecological objectives that are, respectively, maximized through unrestricted hydropeaking and maintaining natural flows. FREE integrates flexibility by permitting reservoir releases to deviate from inflows when power generation is most economically valuable. Operational flexibility is characterized by the magnitude and frequency of deviations from an inflow-equals-outflow (IEO) regime and is applied seasonally to reflect varying economic and ecological needs throughout the year. FREE is implemented using an optimization model applied to three hydropeaking facilities on the mainstem Connecticut River that are currently in a relicensing process. Estimated impacts of operational flexibility are quantified on annual and seasonal scales, with economic goals measured by power and revenue, and ecological goals by a proxy measure: the Richard-Baker flashiness (RBF) index. To explore operational flexibility, two inflow regimes are investigated: existing inflows, which are altered by upstream hydropower operations, and estimated unaltered inflows. FREE was presented to interested parties engaged in the Connecticut River relicensing process, where it was applied in collaborative negotiations designed to develop integrated, dynamic, economically viable, and ecologically supportive hydropower operations. Trade-offs between estimated revenue generation and RBF, as applicable to these interested parties, were presented along a Pareto frontier.

KEYWORDS
flashiness, flexibility, flow management, hydropower, optimization, reservoir operations, riverine ecosystems

1 | INTRODUCTION

Alternative energy sources, such as solar, wind, and hydropower, continue to increase in importance as the energy sector reduces its reliance on fossil fuels (Tamaddun et al., 2023). However, all "clean" energy sources have environmental impacts that should be considered in their development and operations. Ecological consequences of hydropower are well-documented and include effects on migratory fish movement and population stability, as well as alterations to the hydrological, nutrient, sediment, and temperature regimes required to maintain riverine ecological function. Interference in river function can modify channel morphology, degrade water quality, diminish connectivity with riparian and floodplain habitats, change instream habitat availability and persistence, increase local species mortality, cause local extirpation, and reduce native biodiversity (e.g., Birkel et al., 2014; Burman et al., 2021; Freeman et al., 2001; Hajiesmaeili et al., 2022; Kennedy et al., 2016; Meile et al., 2011; Nilsson & Renöfält, 2008; Poff et al., 1997; Smokorowski, 2022).

Internationally and within the United States, there is an increasing need to develop tools that integrate ecological objectives and mitigation into hydropower operations (e.g., Alp et al., 2022; Bakken et al., 2023; Jelovica et al., 2023). In the U.S., most non-federal hydropower facilities are regulated by the Federal Energy Regulatory Commission (FERC) under authority given in the Federal Power Act (FPA) (Federal Power Act, 1920; Levine et al., 2021). The FPA requires that facility owners pursuing an operating license engage in consultation with Tribal Nations during the development of their applications, and that FERC considers the interests, concerns, and perspectives of all rights holders and interested parties. Furthermore, under the "equal consideration" clause of the FPA, FERC is required to consider energy conservation, protection of fish and wildlife, protection of recreational opportunities, and preservation of environmental quality, in addition to the power purposes of hydropower projects.

Today, an improved scientific understanding of ecological impacts, as well as better accessibility and accuracy of modeling tools, allow for more effective explorations of innovative protocols that better balance these energy and environmental needs. When models are used in these efforts, it is essential that they be designed to support the negotiation process of hydropower licensing. In the past, water resource agencies charged with management responsibilities, whether federal, state, public or private, commonly developed detailed and complex models of their system operations. These legacy models were often proprietary, in that they were owned by the agency and not openly shared with the public. These proprietary models play an important role in both strategic and tactical planning for their owners, but are often inappropriate for negotiations among system owners, rights holders, and engaged stakeholders.

Over the past three decades, computer models have become more readily available to public groups, rights holders, and engaged stakeholders, and better capture the important components of water resource systems operations (Thiessen & Loucks, 1992). This ongoing transformation created opportunities to integrate more user-friendly computer models into the exploration of operational alternatives (Palmer et al., 2013). These changes dramatically shifted the role of rights holders and engaged stakeholders, from simply receiving results from legacy models to actively defining the goals, functions, and manipulation of such models in supporting planning and decision making (Falconi & Palmer, 2017). This allows for a shared understanding of the trade-offs of operational policies against measures of system performance, such as revenue generated, system reliability, and environmental metrics. The research presented in this paper explores a flexible and adaptive modeling framework focused on seasonal hourly releases, hourly energy prices, and environmental objectives. In addition, this research supported collaborative decision making, supplemented legacy models, illustrated trade-offs, and developed more integrated hydropower operational policies, a practice that is being implemented worldwide (e.g., Pracheil et al., 2023).

This framework's modeled systems are peaking hydropower (or hydropeaking) projects, which hold water in their reservoirs while energy demand is low and release it when demand is high. While hydropeaking is designed to maximize energy generation and revenue, the resultant fluctuating streamflow regime can reduce habitat availability and persistence, forcing mobile species to expend considerable energy in seeking shelter and suitable habitat (Bätz et al., 2023; Bevelhimer et al., 2015; Bowen et al., 1998; Freeman et al., 2001; García et al., 2011; Kennedy et al., 2016; Korman & Campana, 2009; Scruton et al., 2005, 2008; Zimmerman et al., 2010). In addition, other species can experience stranding, desiccation, or displacement to unsuitable habitat (Burman et al., 2021; Gil, 2022; Kennedy et al., 2016; Nagrodski et al., 2012; Schülting et al., 2019). This leads to reduced rates of feeding, reproduction, and growth, resulting in declined health and abundance, and in some cases, local extirpation of native species, thus changing community composition and biodiversity (Abernethy et al., 2021; Bejarano et al., 2018; Kennedy et al., 2016; Korman & Campana, 2009).

Documentation of these ecological consequences has informed regulatory statutes that constrain operations to avoid, minimize, and mitigate environmental impacts of hydropeaking operations. However, they often implement static constraints, generally on low (minimum) and high (maximum) flows (Jager & Smith, 2008; Pérez-Díaz & Wilhelmi, 2010; Poff et al., 1997). These inflexible policies can be inadequate for managing dynamic ecological systems, as they do not address the full range of temporal flow patterns that are critical to dynamic ecological processes (Jager & Smith, 2008; Poff et al., 1997, 2010). A more ecologically appropriate management approach integrates the variability, quantity, and timing of more natural regimes and reflects the nonstationarity of climate, hydrology, and ecology (Horne et al., 2019; Milly et al., 2008; Poff, 2018; Smokorowski, 2022). The framework presented here proposes operations that incorporate variable economic and ecological objectives using a novel concept of operational flexibility, with the goal of meeting energy demand while also improving habitat persistence.

2 | METHODS

2.1 | Framework

Short of dam removal, the most effective approach to maintaining the ecological integrity of a flow regime is to release water through a dam with minimal manipulation. Run-of-river facilities minimize flow deviations by requiring that the inflows and outflows of an impoundment are essentially equal (FERC, 2017). This maintains the dynamic, natural daily, seasonal, annual, and interannual patterns of an unregulated system and facilitates biogeochemical processes that influence downstream habitat availability, composition, and integrity (Bevelhimer et al., 2015; Bunn & Arthington, 2002; Poff et al., 1997). Conversely, maximizing energy and revenue involves storing water when its economic value is low and releasing it when its value is high. Flexible operating rules recognize both the temporal value of the flow regime to the environment and of the energy generated by the hydropower facility.

This study uses an optimization model to develop flexible operations by quantifying economic and ecological components of hydropower operations. This framework is presented as Flexible Releases for Economics and the Environment (FREE). FREE applies a variation of a run-of-river protocol to mitigate sub-daily flow fluctuations from hydropeaking, particularly during seasons identified as critical for ecological needs. Because run-of-river operations typically refer to those in which upstream flows are minimally altered, FREE refers to this operational protocol as "inflow-equals-outflow" (IEO), to allow for consideration of systems with upstream hydropeaking. In such systems, run-of-river operations would not be reflective of natural flow. To blend the need for IEO requirements and hydropeaking, FREE restricts flow alteration to a limited number of hours over a year. Furthermore, it manages flow dynamically to address hydrological variability, quantity, and timing.

The FREE framework is evaluated through a suite of Pareto optimal (non-inferior) solutions that optimize the economic objective while imposing minimal losses to the ecological objectives (Messac & Mattson, 2004). In this case, the Pareto frontier is assessed with revenue generation as the economic variable and the Richard-Baker Flashiness index (RBF; Baker et al., 2004) as an ecological proxy.

2.2 | Framework metrics

In FREE, the optimization model generates hourly revenue, power, and reservoir releases that are analyzed for economic losses and hydrologic alteration. The economic objective is to minimize proportional losses in total revenue and power from daily hydropeaking operations. The ecological objectives are represented by RBF, a statistic that characterizes frequency and magnitude of flow oscillations over a given period (Baker et al., 2004). In the RBF function below, n represents the data points calculated for each day, in this case, 24 h. Hourly flow is indicated by q.

$$\mathrm{RBF}=\frac{\sum_{i=1}^{n}\frac{1}{2}\left(|q_{i+1}-q_i|+|q_i-q_{i-1}|\right)}{\sum_{i=1}^{n}q_i}.$$

Although indices of hydrologic alteration and corresponding impacts on ecology have been documented extensively (e.g., Bunn & Arthington, 2002; Haas et al., 2014; Meile et al., 2011; Poff et al., 1997; Richter et al., 1996; TNC, 2007), defining and quantifying direct ecological responses to changes in hydropower operations remains a challenge because of multiple interrelated and nonstationary ecological factors (Poff, 2018; Poff & Zimmerman, 2010). In this case, flashiness represents a critical hydro-ecological element of riverine function. The frequency and magnitude of hydropeaking flows are predicted to reduce habitat availability and persistence, leading to survival of diminished species. As such, greater flashiness suggests lower ecological value, and lower flashiness suggests higher ecological value, up to the threshold of natural variability, which is considered optimal flashiness.

Operational flexibility is incorporated into the model with hourly rules that govern outflows with two parameters: (1) energy price targets and (2) IEO deviations. These parameters define the frequency and magnitude by which system releases can deviate from inflows. Energy price targets characterize the frequency (number of hours) for which the system can forego the rule that inflow equals outflow and generate as much power as needed. For other time periods, FREE requires IEO, with an additional magnitude of flexibility, called the IEO deviation. When the model optimizes for revenue without any constraints, it is reflective of unrestricted hydropeaking, referred to as Current Operations.

2.3 | Case study site

The development of FREE is presented as a case study of three dams along the Connecticut River in Vermont and New Hampshire, USA. Wilder, Bellows Falls, and Vernon dams are all jointly managed by Great River Hydro, LLC, and located in series along 75.5 miles (121.5 km) of the Connecticut River mainstem (Figure 1). The Connecticut River flows 410 miles (660 km) from Chartierville, Quebec to Old Lyme, Connecticut, where it drains into the Long Island Sound. The watershed is comprised of 44 major tributaries and drains about 11,000 miles^2 (29,137 km^2) (CRC, 2019; Zimmerman et al., 2010).

Over 100 hydropower projects function within the Connecticut River basin (Haas et al., 2014), with 13 active hydropower facilities along the mainstem. All three dams in the study have current licenses that were issued in 1979 for a 40-year term (TransCanada Hydro Northeast Inc., 2012a, 2012b, 2012c). These projects currently operate as hydropeaking facilities, with a combined maximum capacity of 108.8 MW (Table 1). The three dams are preceded by Fifteen Mile Falls, another three-dam series that practices hydropeaking.

2.4 | Data

2.4.1 | Hydrologic data

In this analysis, two inflow datasets are evaluated. Observed streamflow data upstream of Wilder Dam are obtained from a USGS gage (USGS 01138500) at an hourly time-step from 2003 to 2018 (Figure 1). This gage is downstream of the Fifteen Mile Falls dam system, capturing impacted flow from upstream hydropeaking. Flows from additional tributaries downstream of this gage are projected for 2003–2018 using USGS's Connecticut River UnImpacted Streamflow Estimation (CRUISE) tool, a statistical tool for estimating daily flows unimpacted by river regulation (Archfield et al., 2013).

The Connecticut River is a highly regulated basin and applying FREE to less impacted sites could yield different results. The CRUISE tool was used to estimate representative streamflow data for unimpacted inflows into Wilder (Archfield et al., 2013; Steinschneider et al., 2014). Deriving these flows allowed for the exploration of a broader range of system impacts, specifically to determine how FREE could affect the Connecticut River system under both current ("existing") and estimated natural ("unimpacted") conditions.

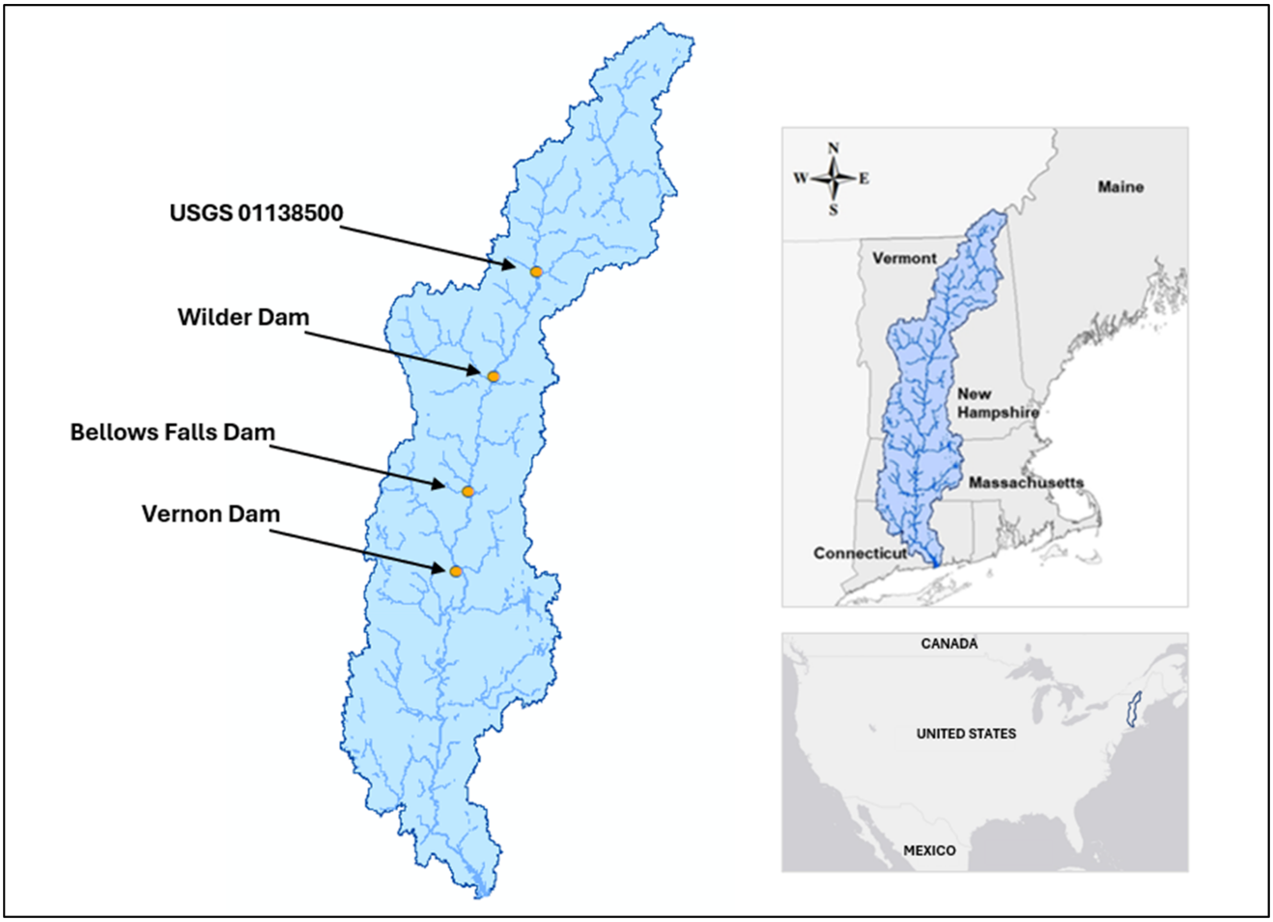

FIGURE 1 Map of the Connecticut River watershed, identifying the three modeled hydropower facilities and USGS 01138500, from which streamflow data were collected. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Specifications and requirements of hydropower operations of Wilder, Bellows Falls, and Vernon dams.

Characteristic	Wilder dam[a]	Bellows falls dam[b]	Vernon dam[c]
Year built	1950	1928	1909
Location (Connecticut River mile)	217.4	173.7	141.9
Drainage area (mi^2)	3375	5414	6266
Average annual inflow (cfs)	6400	10,500	12,200
Operating range elevation (ft)	380–385	288.6–291.6	212–220
Useable storage (acre-ft)	13,350	7476	18,300
Required minimum flow (cfs)	675	1083	1250
Number of turbines	3	3	10
Average turbine efficiency	0.9	0.8	0.82
Total turbine flow capacity (cfs)	10,700	11,400	17,100
Total turbine generation capacity (MW per hour)	35.6	40.8	32.4

Note: All three dams are on the Connecticut River in Vermont and New Hampshire.
[a]TransCanada Hydro Northeast Inc. (2012c).
[b]TransCanada Hydro Northeast Inc. (2012a).
[c]TransCanada Hydro Northeast Inc. (2012b).

2.4.2 | Energy prices

This analysis uses hourly energy market revenue, which has a sub-daily impact on flow (ISO NE, 2020a). The market prices are governed by an energy grid with greater dependency on natural gas and other power sources (Peterson & White, 2018). This suggests that high prices are independent of the river hydrology, increasing the likelihood that hydropeaking operations alter the river flow regime.

Hourly locational marginal prices (LMP) were collected from the Independent System Operator of New England (ISO NE) public data archives (ISO NE, 2020a). Hourly energy prices from 2012 to 2018 were available for use by the public at the time of the study. Energy price data for 2003–2011 were available from a prior study (Detwiler, 2016). The model application was developed from 2018 to 2020, during the relicensing process for this study site. As such, the data used in the model began in 2003 and terminated in 2018. The study results were presented in meetings and negotiations of interested parties from 2020 to 2023.

2.4.3 | Optimization model

Optimization models are used to evaluate the hydrologic impacts of hydropeaking and the economic effects of alternative operations (e.g., Guisández et al., 2013; Jager & Smith, 2008; Palmer & Cohan, 1986; Pérez-Díaz & Wilhelmi, 2010; Steinschneider et al., 2014). Such models can assist in the development of quantifiable objectives, generation and evaluation of alternatives, and facilitation of collaborative negotiations (Lund & Palmer, 1997). This study's model was developed in LINGO 18™software (LINDO Systems, 2018) to optimize scenarios of varying operational flexibility at an hourly time-step for each calendar year over a 16-year period. The resulting reservoir releases capture ecologically impactful sub-daily oscillations that are not quantifiable at a longer time-step (Haas et al., 2014).

The objective function is composed of two operational components. The first represents system revenue and consists of generated power and historic hourly energy prices ($C_{\mathrm{Price},h}$). Hourly energy prices are a function of hourly power demand and are assumed to reflect power needs and opportunity for sales (Lo & Wu, 2004). The second decision variable is the spill from the reservoirs. Spill is penalized to discourage the system from releasing water unless required by constraints. The penalty is several magnitudes smaller than the hourly value of power, thus spill is controlled without affecting the optimal revenue. Physical constraints on storage, generation efficiency, and turbine capacity are incorporated to maintain realistic operational bounds. The model incorporates additional operational policies to dictate minimum flow, ramping rate, and flexibility parameters.

The flexibility constraints are integrated into the model using energy price targets and IEO deviation parameters. In the model, energy price targets are calculated as a set percentile of the hours of highest energy prices for each season or year. During these hours, releases can quickly reach turbine capacity to capitalize on profitable opportunities. Specifically, this study focuses on the highest value

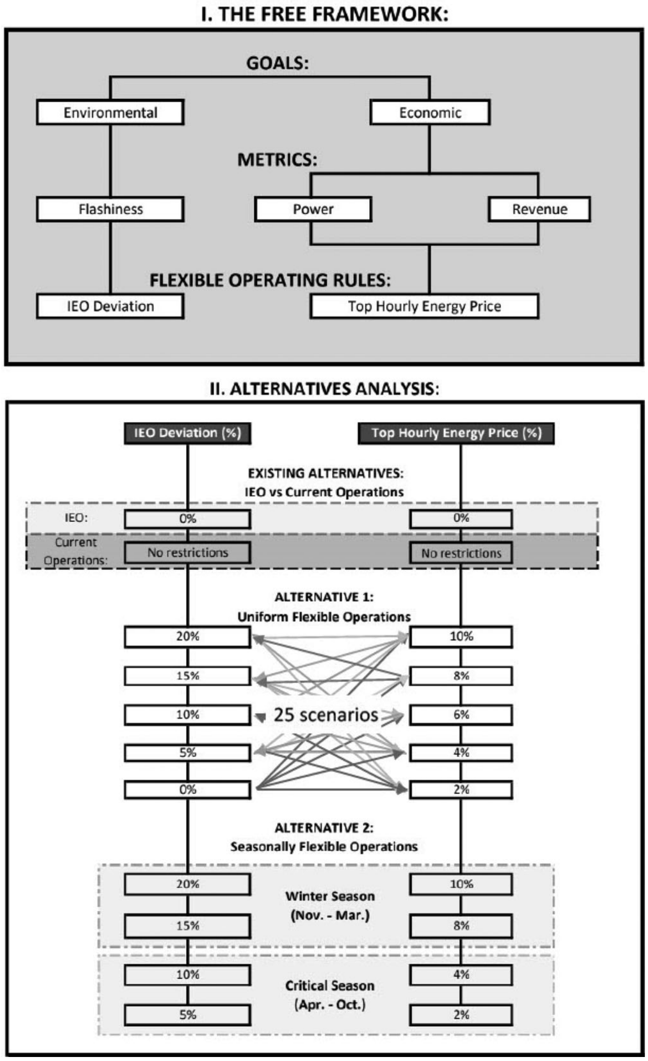

FIGURE 2 Description of the FREE framework and alternative analysis. IEO, inflow-equals-outflow.

energy price percentiles (2%–10%). The IEO deviation rules apply during the remaining hours, when the system releases can differ from inflows by a proportional bound that is constant over a defined timeframe (−20% to 20%). This provides some flexibility to manage hourly flows so that the reservoir can refill to capitalize on high energy prices, while retaining the general hydrologic pattern of the inflows.

2.5 | Analysis

This application of FREE evaluates two existing alternatives, variations of two new alternatives, and the convergence of a set of alternatives across a Pareto Frontier (Figure 2). First, the two primary existing alternatives (IEO and Current Operations) are optimized, and their economic and ecological metrics recorded. Second, 25 scenarios explore a new alternative for which the concept of flexibility is applied uniformly across the year (referred to as uniform flexible operation scenarios). These scenarios optimize all combinations of the

TABLE 2 Distribution of flexibility parameters applied in the seasonal flexibility scenarios for the Connecticut River mainstem.

Season	Energy price target	IEO Deviation
April–October	2%–4%	5%–10%
November–March	8%–10%	15%–20%

Note: These parameters are applied to Wilder, Bellows Falls, and Vernon dam operations in a linear optimization model.
Abbreviation: IEO, inflow-equals-outflow.

incremental changes in energy price targets and IEO deviations defined for this study, under existing condition inflows. They explore IEO deviation values of effectively 0%, 5%, 10%, 15%, and 20%, and energy price targets of 2%, 4%, 6%, 8%, and 10%. IEO deviations allow the hourly outflow to vary from the associated inflow by a percentage, when not meeting an energy price target. For example, at a 10% IEO deviation, a dam with an inflow of 10,000 cfs can release flow between 9000 and 11,000 cfs at off-peak hours. This allows the system to retain some water in the reservoir or release slightly more if appropriate. The strictest scenario (minimum flexibility) is assigned a 2% energy price target with a 0% IEO deviation, while the greatest flexibility allows peaking at a 10% energy price target and up to 20% IEO deviations.

Third, several scenarios explore the seasonal impact of varying IEO deviations and energy price targets. Previous research in the Connecticut River basin suggests that vital periods for spawning, reproduction, growth, and rearing for native migratory and resident species occur from April through October (hereafter referred to as the critical ecological season) (Kennedy et al., 2018; Normandeau, 2017). Improved habitat availability and persistence in this season are predicted to improve critical vital rates, such as reproduction and growth, and protect sensitive life stages of native species (Bätz et al., 2023; Bowen et al., 1998; Freeman et al., 2001; García et al., 2011). Furthermore, energy prices in New England are highest during the winter months (December through February), likely due to the power needed for electric heating systems (ISO NE, 2020b; Richter & Thomas, 2007).

To accommodate these seasonal economic and ecological needs, FREE allows the incorporation of seasons. During the critical ecological season, flexibility is restricted to more closely mirror an IEO protocol. This minimizes hydrologic alteration while still allowing the facilities to capitalize on the highest energy prices (2%–4%; Table 2). In the winter months (November through March), greater flexibility is allowed by increasing energy price targets and IEO deviations, potentially compensating for economic losses incurred during the critical ecological season (Table 2). In the winter, there are fewer peaking events and base flows are higher compared with Current Operations, which is predicted to increase habitat stability for overwintering species, and decrease the risk of stranding, desiccation, and displacement during peaking events. The seasonal analysis uses both unimpacted and existing inflows to illustrate the potential impacts when seasonally defined operational flexibility is applied under conditions ranging from upstream hydropeaking to a representative natural flow regime. This allows for an understanding of the impacts of seasonal flexibility if the upstream facility operations were to change in the future.

The final analysis step uses Pareto frontier optimality to identify those operational policies that balance economic and ecological objectives among the 25 uniform flexible operation scenarios. This frontier characterizes the inherent trade-offs in converging to a solution. An advantage of this analysis is that it allows interested parties and rights holders to visualize a suite of solutions, weigh their preferences, and either develop an alternative from the frontier that best meets the local need or identify new alternatives.

For all analyses, total revenue and power values are summed for the three projects, while the RBF is assessed for Vernon Dam, the most downstream releases from the system. Flows from Vernon are highly correlated with those of Wilder and Bellows Falls (correlation coefficient values of 0.894 and 0.932, respectively), indicating that hydrologic indicator patterns would be similar across all three reservoirs.

3 | RESULTS

3.1 | IEO and current operations

When IEO or Current Operations are applied across Wilder, Bellows Falls, and Vernon dams, RBF is greater under Current operations (0.088) than under IEO operations (0.024). Because IEO operations are influenced by the upstream hydropeaking Fifteen Mile Falls system, RBF is greater than would be expected in an unregulated system. For example, when IEO and Current Operations are compared with flows in the White River (USGS 01144000), a large, unregulated, high-gradient tributary of the Connecticut River, IEO is flashier than the unregulated flows (Figure 3). Current Operations are likely flashier than IEO due to several factors, including the distance between Fifteen Mile Falls and the lower projects (over 80 km from Wilder dam and over 200 km from Vernon dam), limitations placed on minimum and maximum flows when Fifteen Mile Falls was relicensed in 2002 (FERC, 2002), and daily hydropeaking operations across the dams.

When operating under a strict IEO protocol, the optimization model calculated losses of about 12.4% in revenue and 4.0% in power for the 16-year analysis period. This supports prior research that suggests that environmental policies tend to reduce revenue and power (Guisández et al., 2013; Nyatsanza et al., 2015).

3.2 | Annual application of operational flexibility

3.2.1 | Revenue and power

The application of FREE suggests similar patterns across losses in revenue and generated power between those of Current Operations and the 25 uniform flexible operation scenarios (Figure 4). Revenue findings suggest a 6.6% average difference (3.0%–9.6%) in losses, while losses in power exhibit only a 2.8% average

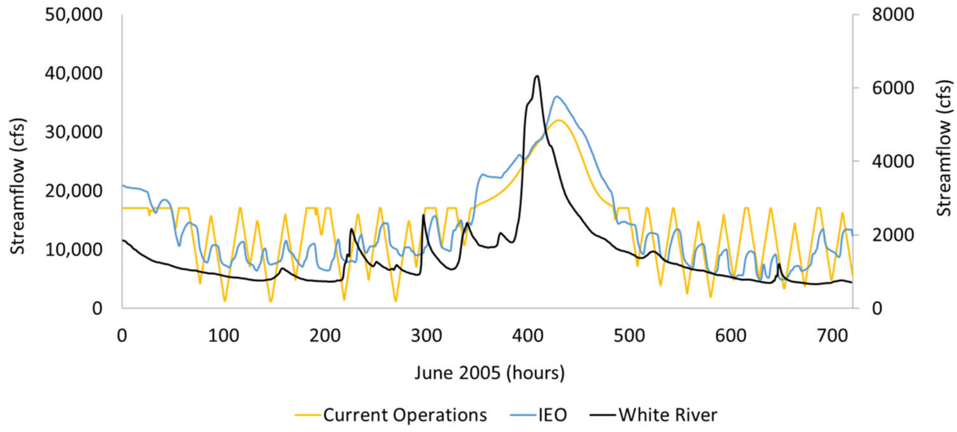

FIGURE 3 Hydrograph of projected flows under inflow-equals-outflow (IEO) and Current Operations at Vernon Dam and observed streamflow data for the White River (USGS 01144000) on an hourly time-step for June 2005. [Color figure can be viewed at wileyonlinelibrary.com]

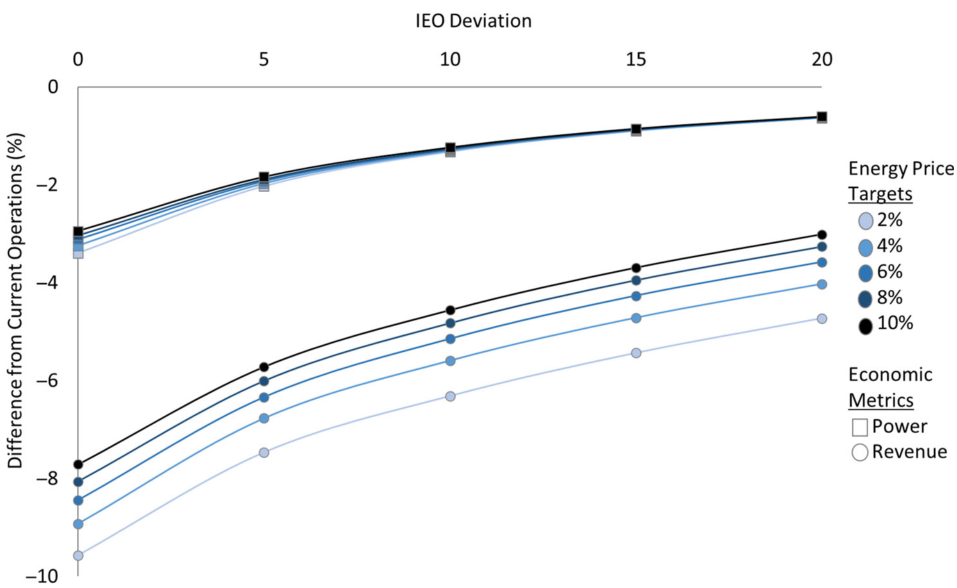

FIGURE 4 Percent losses in revenue (circles) and power (squares) for the 25 uniform flexible operation scenarios. IEO, inflow-equals-outflow. [Color figure can be viewed at wileyonlinelibrary.com]

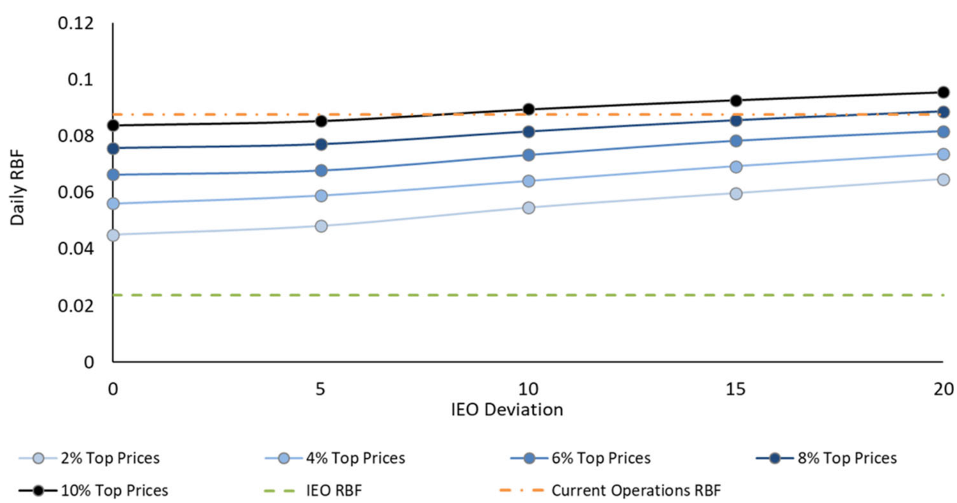

FIGURE 5 Quantified differences in mean Richard-Baker Flashiness (RFB) across 25 uniform flexible operation scenarios. Energy price targets are differentiated by lines. The inflow-equals-outflow (IEO) and Current Operation RBF values are represented by the dashed lines. [Color figure can be viewed at wileyonlinelibrary.com]

difference (0.6%–3.4%). Scenarios with a 0% IEO deviation have the largest impact on revenue, with losses ranging between 7.7% and 9.6%. These higher losses result from less opportunity to manage hourly releases and refill the reservoir between energy price target hours. Most scenarios with IEO deviations between 10% and 20% accumulate losses of less than 6%, suggesting that the increased hourly flexibility effectively allows the system to capitalize on the most valuable energy prices. Compared with revenue, total power losses are minimal, approaching 1% with increasing flexibility.

TABLE 3 Statistics for modeled losses from current operations to energy market revenue and power generation for seasonal operational flexibility scenarios.

		Minimum	Mean	Median	Maximum
Revenue losses	Existing conditions	−4.2%	−4.9%	−4.9%	−5.6%
	Unimpacted flows	−6.9%	−7.6%	−7.6%	−8.2%
Power losses	Existing conditions	−1.0%	−1.2%	−1.2%	1.5%
	Unimpacted flows	−0.8%	−1.0%	−1.0%	−1.3%

Note: The scenarios are applied to existing conditions on the Connecticut River flow regime and representative unimpacted flows.

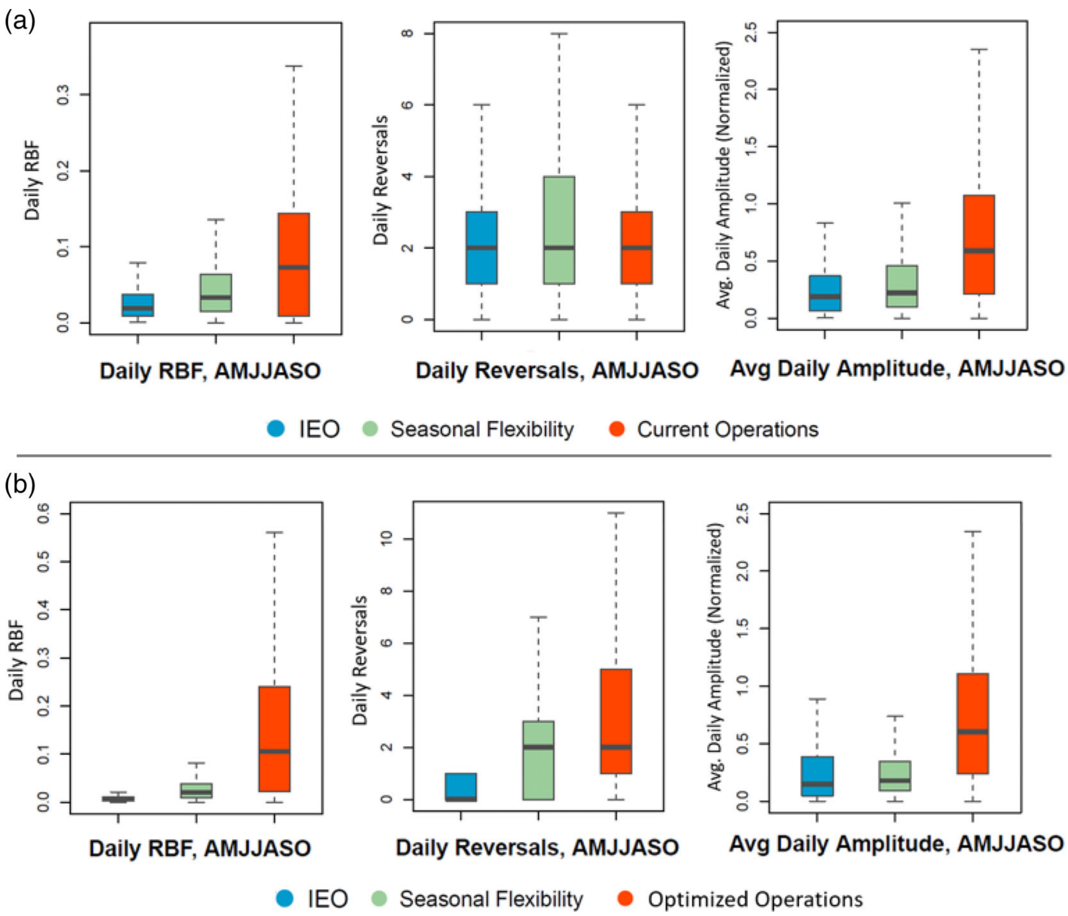

FIGURE 6 Ranges of three hydrologic indicators (Richard-Baker Flashiness [RBF], reversals, and average amplitude) calculated for a three-dam system under two sets of inflows: Existing conditions (a) and a representative natural flow regime (b). Hydrologic indicators are compared across three operational scenarios: inflow-equals-outflow (IEO), seasonal operational flexibility, and Current Operations. The season analyzed is the critical ecological season, April–October (AMJJASO). Hydrologic indicators are analyzed at an hourly scale and averaged for representative daily values. [Color figure can be viewed at wileyonlinelibrary.com]

3.2.2 | Richard-Baker flashiness

Most RBF values for the 25 uniform flexible operation scenarios fall between Current Operations and IEO (Figure 5). However, scenarios with a 10% energy price target and 10%–20% IEO deviations surpass the flashiness of Current Operations, suggesting that these alternatives may not offer ecological improvements. This is likely due to the IEO deviation, which allows small changes in flow between peaking events, and could be forcing the model to release many "micro" peaks to optimize revenue gains. This creates more variability within the 20% deviation bounds, and therefore more flashiness. These higher IEO deviations have more of an incremental impact on hydrologic flashiness than energy price targets (Figure 5).

3.3 | Seasonal application of operational flexibility

3.3.1 | Revenue and power

The application of a seasonal component to existing conditions suggests losses in revenue ranging from 4.2% to 5.6% (Table 3). These losses are less than half of those for a strict IEO operational policy (12%) and annually applied uniform flexible operation scenarios (up to

9.6%). Losses in revenue are greater for unimpacted flows than for existing conditions. The manipulation of existing condition inflows by the hydropeaking Fifteen Mile Falls system favors high energy prices, better aligning downstream peaking with the price curve. Unimpacted flows are independent of the energy price curve, requiring more streamflow modification to generate energy at high prices.

Seasonal operations limit the losses in total power to less than 2% across both conditions. This suggests that FREE can generate comparable total power under systems of differing upstream conditions.

3.3.2 | Richard-Baker flashiness

RBF was evaluated for the critical ecological season (April–October) (Figure 6) and disaggregated into two components: magnitude (amplitude) and frequency (reversals). Amplitude is the magnitude of flow measured between sets of reversals. Average daily amplitude is the average change in these magnitudes exhibited in a 24-h period. Daily reversals are the summed number of times each day that the hydrograph indicates a change between rising and falling slopes (TNC, 2007; Zimmerman et al., 2010). It quantifies the frequency and timing of peaks in hydrology.

Given existing condition inflows (Figure 6a), the seasonal flexibility scenario results in lower variability of RBF and daily average amplitude than under Current Operations, more closely resembling IEO conditions. All three scenarios have similar daily reversal medians, likely because of the common energy price curve, though the seasonal scenario indicates slightly higher variability. This may be due to the integration of IEO deviations of 5%–10%. The model may create additional small peaks within these bounds to optimize the system, which are captured by the reversals, but do not translate to a higher RBF index. These smaller peaks also have shorter amplitudes that may decrease the median amplitude and lessen the variability.

Under the estimated unimpacted inflows (Figure 6b), RBF metrics of the seasonally flexible scenarios are more similar to those of an IEO protocol than Current Operations. The amplitude variability is reduced below that of IEO, likely due to the optimization model allowing peaks with small amplitudes between the IEO deviation bounds. The model may also decrease high flows and increase low flows within these bounds to optimize the system under the imposed restrictions, resulting in dampened average daily amplitude values. This analysis suggests that seasonal flexibility may result in potential improvement to ecologically relevant streamflow parameters, compared with Current Operations.

3.4 | The Pareto frontier

Figure 7a presents the Pareto frontier for the 25 uniform flexible operation scenarios. The frontier uses revenue losses and RBF to represent economic and ecological objectives, respectively. RBF ranges from most ecologically impacted (high RBF values) to least impacted (approaching 0) on the x-axis.

The Pareto-optimal frontier is represented by a dotted line across the 25 scenarios. Solutions include a 2% energy price target with an applied IEO deviation of 0%–20%. Energy price targets of 4% or 6% require a large (20%) IEO deviation to limit revenue losses but they also increase the flashiness of the system. The Pareto frontier demonstrates that disaggregating hydropower operations into ecological and economic considerations results in trade-offs. When this tool considers seasonal goals, superior solutions can be identified to better address ecological objectives while targeting other seasons for power generation (Figure 7b). This balance reduces annual economic impact. When a critical ecological season is limited to IEO deviations of 5%–10% and energy price targets of 2%–4%, while the winter season is allowed flexibility of 15%–20% IEO deviations and 8%–10% energy price targets, the overall annual loss to revenue ranges from 4% to 6%. This tool can be used in negotiations of interested parties to define the sets of potential solutions that balance competing goals.

4 | DISCUSSION

4.1 | Application to Connecticut River hydropower relicensing

In the U.S., FERC grants operating licenses to non-federal hydropower projects for periods of 30–50 years. Five projects located in sequence on the Connecticut River mainstem are currently undergoing relicensing: Wilder Dam (FERC license # P-1892), Bellows Falls Dam (P-1855), and Vernon Dam (P-1904), which are all included in this study and owned by Great River Hydro (GRH), and Turners Falls Dam (P-1889) and Northfield Mountain Pumped Storage (P-2485), owned and operated by FirstLight Power. As part of the regulatory relicensing process, state and federal agencies, Indian tribes, and environmental conservation organizations may participate to ensure new licenses incorporate protection, mitigation, and enhancement measures for project-affected ecological, cultural, and recreational interests and values.

Several interested parties, including key state and federal resource agencies, engaged in the Connecticut River relicensing process and used this study's framework to develop alternative operations for the GRH projects. Alternatives were presented to GRH representatives, who in turn agreed to engage in collaborative discussions to examine opportunities for a viable operation alternative for its license renewal application. Great River Hydro used proprietary hourly inflow and optimization to support their rapid development of an alternative-specific simulation model, which examined feasibility, energy and economic viability of alternatives. The final license application submitted by GRH in December 2020 consisted of an inflow-equals-outflow (IEO), plus limited flexible operations, integrated as IEO deviations (Great River Hydro, LLC, 2020). The foundation of this operational scheme is “allowed hours” of “flexible operations,”

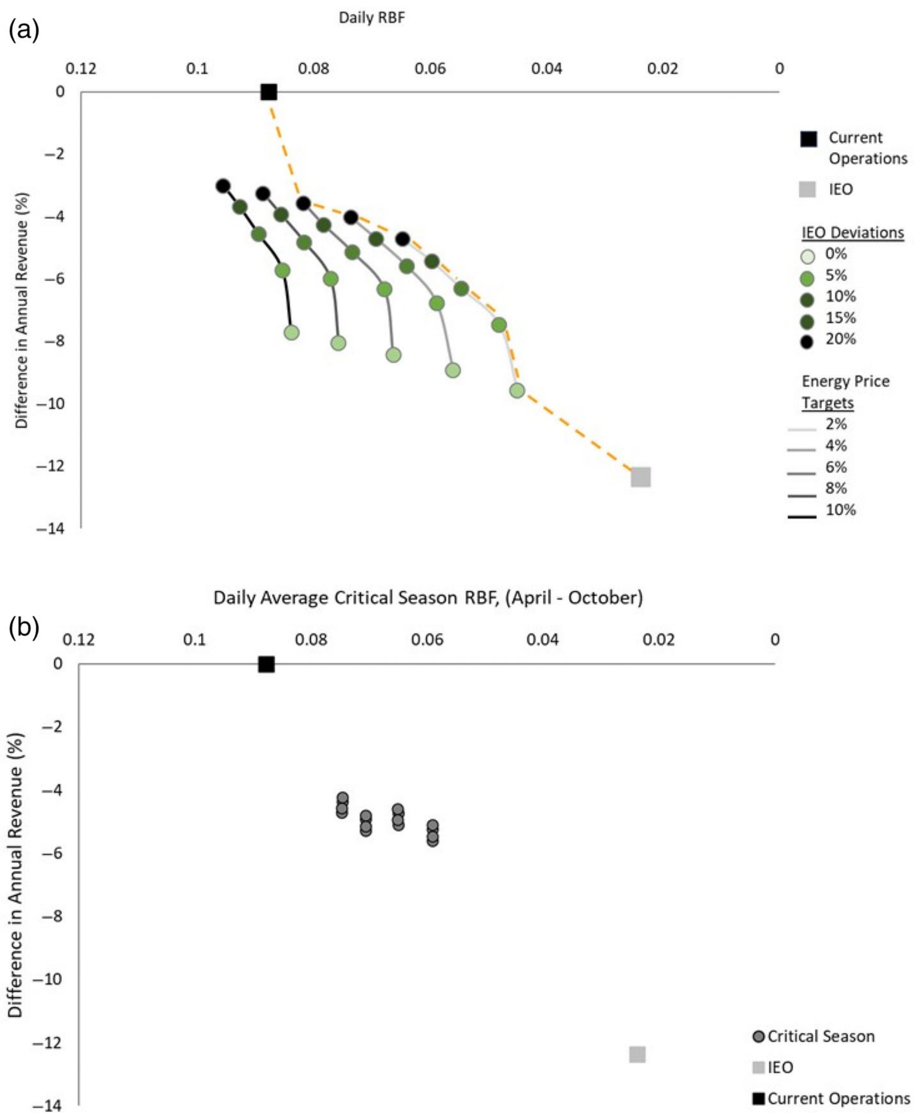

FIGURE 7 A Pareto frontier for uniform flexible operation scenarios, showing revenue losses versus daily Richard-Baker flashiness (RBF) values (a). The 25 are represented by circles on associated lines. Seasonal flexibility integrated as a stricter critical ecological season and more flexible winter season is applied (b). Inflow-equals-outflow (IEO) deviations of 5%–10% and energy price targets of 2%–4% in the critical ecological season paired with increases in the winter season (IEO = 15%–20%; energy price targets = 8%–10%) limit revenue losses to 4%–6%. [Color figure can be viewed at wileyonlinelibrary.com]

whereby the company agrees to IEO baseline operations, maintaining elevations of the project impoundment within a narrow operational band, with a set number of hours each month where they can deviate from IEO to either store or release water to meet energy demand. These hours vary seasonally based on predicted power demand and ecological requirements for migration, spawning, rearing, and growth. Based on their proprietary operations model, the operator predicted that this scenario would allow the company to continue to meet almost 100% of average annual energy and 98% of average annual revenue currently produced at these projects (Great River Hydro, LLC, 2020). This suggests that the results from FREE are conservative compared with models that use more detailed and accurate hourly data. Because FREE was not proprietary, it could be used to explore a wide range of operational alternatives, and its results were readily shared with public parties to inform discussions. The general concurrence of results between the models provided assurance that FREE captured the essential components of hydropower operations.

Although development of the alternative operations is proprietary and was only shared with parties in confidential discussions, it was agreed among the discussion participants that the resulting operational regime will be far more protective of target species and resources than current operations (K. Kennedy, personal observation). Furthermore, the Turners Falls project lies immediately downstream of the GRH Projects and has limited impoundment storage, so this practical IEO plus flexible operations scenario became the driver and basis for its modified operational proposal. Although the associated Northfield Mountain pumped storage project precluded the use of a simpler IEO baseline, the GRH operational scheme and the concept of "IEO plus flexible operations" established a firm basis for developing an operations protocol that substantially decreased peaking and its corresponding impacts on the downstream river ecosystem (FirstLight & Hydro, 2023).

4.2 | Modeling limitations

As in all modeling exercises, uncertainties exist in the data, model structure, and unidentified unknowns. First, optimization models cannot capture all nuances of hydropower operations, completely mimic actual operations, account for uncertainty in real time, or consider the many operational constraints and incentives that apply on hourly, daily or seasonal scales. Incorporating FREE's concepts of operational flexibility into proprietary operation models would help eliminate some of these limitations, as presented in this case study. Second, the only measure of revenue used in this model is historical energy market data, which changes hourly and is more likely to impact hydropower operations at a sub-daily scale. However, because this model only considers one source of revenue, it is possible that operational flexibility may have different impacts when considering all revenue sources. Additionally, energy prices change over time, so different patterns in future energy markets may also result in different impacts to system objectives.

Furthermore, the use of RBF as a proxy for ecological objectives is founded on the evidence-based hypothesis that high flashiness negatively impacts riverine habitat and biota, due to loss of habitat availability and persistence, and to physical effects on low-mobility species (Bätz et al., 2023; Bowen et al., 1998; Freeman et al., 2001; García et al., 2011; Gil, 2022; Kennedy et al., 2016; Nagrodski et al., 2012; Schülting et al., 2019). However, this framework may not be sufficient for addressing all environmental impacts of hydropeaking operations because other impacts may not be captured by flashiness. Further, the seasonal component was based on current understanding of life history needs of resident and migratory riverine biota. Several of these needs, such as required spawning conditions for some species, are based on factors that may change in the future as temperature and precipitation patterns shift due to climate change. While there has been considerable research on the effects of hydrology on complex ecology, there are still many gaps in our understanding (Poff & Zimmerman, 2010). For example, although some studies have begun to elucidate the ecological impacts of hydropeaking during the winter season (e.g., Person, 2013; Pracheil et al., 2009; Scruton et al., 2005, 2008), winter has been relatively understudied compared with other times of the year. The critical ecological season identified for this study was based on existing literature and data, but further research on the winter season and on the specific relationships between hydrology (i.e., magnitude, frequency, duration, timing, and rate of change; Poff et al., 1997) and species' life history needs could further improve this framework and the operational solutions that it informs.

4.3 | Study conclusions

Hydropower plays an important role in today's energy grid and will continue to do so into the future. Hydropower facilities will also continue to impact riverine systems on which they operate, creating a need to explore opportunities for dynamic policies that support both ecosystem function and future energy demand (Anderson et al., 2019; Horne et al., 2019; Smokorowski, 2022). As about 280 dams are expected to begin relicensing in the United States in the next decade (2024–2033), this study's approach is immediately applicable to hydropower practitioners (FERC, 2023). Additionally, although FREE was developed from the perspective of a FERC relicensing protocol, it is an adaptable collaborative approach for any non-FERC hydropeaking facility, both within the United States and worldwide.

The Pareto frontier (Figure 7) suggests that Current Operations is not necessary to maintain economic viability and support energy demands. Instead, allowing flexibility during a small portion of the year effectively limits economic losses while minimizing flashiness, suggesting that some of the ecological impacts of hydropeaking may be substantially reduced without high costs. When a larger IEO deviation is applied to these small energy price targets, revenue losses are further minimized while limiting flashiness, due to the flexibility to effectively manage hourly flows, accumulate revenue, and generate power. Seasonality factors can be refined to further minimize flashiness while maintaining seasonal revenue losses at about 6% (Figure 7); therefore suggesting that several potential alternative operations could balance system objectives on the Connecticut River mainstem.

Several advantages of FREE emerge in the analysis. First, flexible operational rules can vary depending on the priorities of the hydropower project and the ecological needs of the region. The seasonal component allows interested parties to integrate hydrologic timing and adjust operations throughout the year to minimize impacts to seasonal objectives. FREE demonstrates how innovative operations can incorporate the natural hydrologic dynamics of the system and maintain hydropower production and economic viability. When presented to interested parties during a relicensing process, it successfully informed negotiations and discussions around new operational protocols that limit peaking, better mirror IEO flows, allow for flexibility, and reduce impacts to the ecosystem. This framework has the potential to be a valuable tool for collaborative development of more integrated and dynamic hydropower operations.

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DATA AVAILABILITY STATEMENT

Research data are not shared.

REFERENCES

Abernethy, E. F., Muehlbauer, J. D., Kennedy, T. A., Tonkin, J. D., Van Driesche, R., & Lytle, D. A. (2021). Hydropeaking intensity and dam proximity limit aquatic invertebrate diversity in the Colorado River basin. *Ecosphere*, *12*(6), 8-12.

Alp, M., Batalla, R. J., Bejarano, M. D., Boavida, I., Capra, H., Carolli, M., Casas-Mulet, R., Costa, M. J., Halleraker, J. H., Hauer, C., Hayes, D. S., Harby, A., Noack, M., Palau, A., Schneider, M., Schönfelder, L., Tonolla, D., Vanzo, D., Venus, T., … Bruno, M. C. (2022). Introducing HyPeak: An international network on hydropeaking research, practice, and policy. *River Research and Applications*, *39*, 283–291. https://doi.org/10.1002/rra.3996

Anderson, E. P., Jackson, S., Tharme, R. E., Douglas, M., Flotemersch, J. E., Zwarteveen, M., … Arthington, A. H. (2019). Understanding rivers and their social relations: A critical step to advance environmental water management. *WIREs Water*, *6*, 1-21. https://doi.org/10.1002/wat2.1381

Archfield, S. A., Steeves, P. A., Guthrie, J. D., & Ries, K. G., III. (2013). Towards a publicly available,map-based regional software tool to estimate unregulated daily streamflow at ungauged rivers. *Geoscientific Model Development*, *6*(1), 101–115.

Baker, D. B., Richards, R. P., Loftus, T. T., & Kramer, J. W. (2004). A new flashiness index:Characteristics and applications to midwestern Rivers and streams. *Journal of the American Water Resources Association*, *40*, 503–522.

Bakken, T. H., Harby, A., Forseth, T., Ugedal, O., Sauterleute, J. F., Halleraker, J. H., & Alfredsen, K. (2023). Classification of hydropeaking impacts on Atlantic salmon populations in regulated rivers. *River Research and Applications*, *39*(3), 313–325. https://doi.org/10.1002/rra.3917BAKKEN

Bätz, N., Judes, C., & Weber, C. (2023). Nervous habitat patches: The effect of hydropeaking on habitatdynamics. *River Research and Applications*, *39*(3), 349–363.

Bejarano, M. D., Jansson, R., & Nilsson, C. (2018). The effects of hydropeaking on riverine plants: Areview. *Biological Reviews*, *93*(1), 658–673.

Bevelhimer, M. S., McManamay, R. A., & O'Connor, B. (2015). Characterizing sub-daily flowregimes: Implications of hydrologic resolution on ecohydrology studies. *River Research & Applications*, *31*, 867–879.

Birkel, C., Soulby, C., Ali, G., & Tetzlaff, D. (2014). Assessing the cumulative impacts of hydropowerregulation on the flow characteristics of a large Atlantic salmon river system. *River Research& Applications*, *30*, 456–475.

Bowen, Z. H., Freeman, M. C., & Bovee, K. D. (1998). Evaluation of generalized habitat criteria forassessing impacts of altered flow regimes on warmwater fishes. *Transactions of the American Fisheries Society*, *127*(3), 455–468.

Bunn, S. E., & Arthington, A. H. (2002). Basic principles and ecological consequences of alteredflow regimes for aquatic biodiversity. *Environmental Management*, *30*(4), 492–507.

Burman, A. J., Hedger, R. D., Hellstrom, J. G. I., Anderson, A. G., & Sundt-Hansen, L. E. (2021). Modellingthe downstream longitudinal effects of frequent hydropeaking on the spawning potential and stranding susceptibility of salmonids. *Science of the Total Environment*, *796*, 148999.

Connecticut River Conservancy (CRC). (2019). Watershed facts. https://www.ctriver.org

Detwiler, L. (2016). *Assessing the economic and flow regime outcomes of alternativehydropower operations on the Connecticut River's mainstem (Master's thesis)*. University of Massachusetts.

Falconi, S. M., & Palmer, R. N. (2017). An interdisciplinary framework for participatory modeling design and evaluation—What makes models effective participatory decision tools? *Water Resources Research*, *53*, 1625–1645. https://doi.org/10.1002/2016WR019373

Federal Energy Regulatory Commission (FERC). (2002). Order issuing new license (major project). US Gen New England. Project No. 2077–016. Accession No. 20020408–3018.

Federal Energy Regulatory Commission (FERC). (2017). Hydropower primer: A handbook of hydropower basics. In *A staff report of the Office of Energy projects/federal energy regulatory commission*. The Federal Energy Regulatory Commission.

Federal Energy Regulatory Commission (FERC). (2023). Complete list of active licenses. https://www.ferc.gov/licensing

Federal Power Act. (1920). 16 U.S.C. § 797.

FirstLight, M. A., & Hydro, L. L. C. (2023). Turners Falls Hydroelectric Project (FERC No. 1889), FirstLight MAHydro LLC, Northfield Mountain Pumped Storage Project (FERC No. 2485), Northfield Mountain LLC, Flows and Fish Passage Settlement Agreement and Explanatory Statement. https://elibrary.ferc.gov/eLibrary/filelist?accession_number=20230331-5600

Freeman, M. C., Bowen, Z. H., Bovee, K. D., & Irwin, E. R. (2001). Flow and habitat effects onjuvenile fish abundance in natural and altered flow regimes. *Ecological Applications*, *11*(1), 179–190.

García, A., Jorde, K., Habit, E., Caamaño, D., & Parra, O. (2011). Downstream environmental effects ofdam operations: Changes in habitat quality for native fish species. *River Research and Applications*, *27*(3), 312–327.

Gil, M. G. (2022). *Flow velocity affects spatial patterns and settlement of freshwater mussels*. Doctoraldissertation. University of Lisbon.

Great River Hydro, LLC. (2020). Great River Hydro, LLC; FERC project Nos. 1855, 1892, and 1904 submission of amended final license application. https://elibrary.ferc.gov/eLibrary/filelist?accession_number=20201207-5219

Guisández, I., Pérez-Díaz, J. I., & Wilhelmi, J. R. (2013). Assessment of the economic impact ofenvironmental constraints on annual hydropower plant operation. *Energy Policy*, *61*, 1332–1343.

Haas, N. A., O'Connor, B. L., Hayse, J. W., Bevelhimer, M. S., & Endreny, T. A. (2014). Analysis of daily peaking and run-of-river operations with flow variabitiy metrics, considering subdaily to seasonal time scales. *Journal of the American Water Resources Association*, *50*(6), 1622-1640.

Hajiesmaeili, M., Addo, L., Watz, J., Railsback, S., & Piccolo, J. J. (2022). Individual-based modelling ofhydropeaking effects on brown trout and Atlantic salmon in a regulated river. *River Research and Applications*, *39*, 522–537. https://doi.org/10.1002/rra.4037

Horne, A. C., Nathan, R., Poff, L., Bond, N. R., Webb, J. A., Wang, J., & John, A. (2019). Modeling flow-ecology responses in the Anthropocene: Challenges for sustainable riverine management. *Bioscience*, *69*(10), 789–799.

ISO NE. (2020a). ISO New England. https://www.iso-ne.com/

ISO NE. (2020b). Energy, load, and demand reports: Zonal information. https://www.iso-ne.com/isoexpress/web/reports/load-and-demand/-/tree/zone-info

Jager, H. I., & Smith, B. T. (2008). Sustainable reservoir operation: Can we generate hydropowerand preserve ecosystem values? *River Research & Applications*, *24*, 340–352.

Jelovica, B., Marttila, H., Ashraf, F. B., Kløve, B., & Torabi Haghighi, A. (2023). A probability-based modelto quantify the impact of hydropeaking on habitat suitability in rivers. *River Research andApplications*, *39*(3), 490–500. https://doi.org/10.1002/rra.4050500

Kennedy, K., Lutz, K., Hatfield, C., Martin, L., Barker, T., Palmer, R., Detwiler, L., Anleitner, J., & Hickey, J. (2018). *The Connecticut River flow restoration study: A watershed-scale assessment of the potential for flow restoration through dam re-operation*. Army Corps of Engineers, and University of Massachusetts Amherst. http://nature.org/ctriverwatershed

Kennedy, T. A., Muehlbauer, J. D., Yackulic, C. B., Lytle, D. A., Miller, S. W., Dibble, K. L., Kortenhoeven, E. W., Metcalfe, A. N., & Baxter, C. V. (2016). Flow management for hydropower extirpates aquatic insects, undermining river food webs. *Bioscience*, *66*(7), 561–575.

Korman, J., & Campana, S. E. (2009). Effects of hydropeaking on nearshore habitat use and growthof age-0 rainbow trout in a large regulated river. *Transactions of the American Fisheries Society*, *138*(1), 76–87.

Levine, A., Pracheil, B., Curtis, T., Smith, L., Cruce, J., Aldrovandi, M., Breslford, C., Buchanan, H., Fekete, E., Parish, E., Uria-Martinez, R., Johnson, M., & Singh, D. (2021). *Anexamination of the hydropower licensing and federal authorization process (No. NREL/TP-6A20-79242)*. National Renewable Energy Lab. (NREL).

LINDO Systems I. (2018). *LINGO 18.0 user's guide* (60642). LINDO Systems, Inc..

Lo, K. L., & Wu, Y. K. (2004). Analysis of relationships between hourly electricity price and load inderegulated real-time power markets. *IEE proc.-Gener. Transmission and Distribution*, *151*(4), 441.

Lund, J. R., & Palmer, R. N. (1997). Water resource system modeling for conflict resolution. *WaterResources Update*, *108*, 70–82.

Meile, T., Boillat, J. L., & Schleiss, A. J. (2011). Hydropeaking indicators for characterization of theupper-Rhone River in Switzerland. *Aquatic Sciences*, *73*, 171–182.

Messac, A., & Mattson, C. A. (2004). Normal constraint method with guarantee ofeven representation of complete pareto frontier. *AIAA Journal*, *42*(10), 2101–2111.

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., & Stouffer, R. J. (2008). Stationarity is dead: Whither water management? *Science*, *319*(5863), 573–574.

Nagrodski, A., Raby, G. D., Hasler, C. T., Taylor, M. K., & Cooke, S. J. (2012). Fish stranding infreshwater systems: Sources, consequences, and mitigation. *Journal of Environmental Management*, *103*, 133–141.

Nilsson, C., & Renöfält, B. M. (2008). Linking flow regime and water quality in rivers: A challengeto adaptive catchment management. *Ecology and Society*, *13*(2), 18.

Normandeau Associates, Inc. (2017). *ILP study 9—Instream flow final study report*. Preparedfor TransCanada Hydro Northeast Inc..

Nyatsanza, F. F., Graas, S., & van der Zaag, P. (2015). The impact of dynamic environmental flowreleases on hydropower production in the Zambezi River basin. *Journal of the American Water Resources Association*, *51*(4), 1029–1042.

Palmer, R. N., Cardwell, H. E., Lorie, M. A., & Werick, W. (2013). Disciplined planning, structuredparticipation, and collaborative modeling—Applying shared vision planning to water resources. *Journal of the American Water Resources Association*, *49*(3), 614–628. https://doi.org/10.1111/jawr.12067

Palmer, R. N., & Cohan, J. L. (1986). Complexity in Columbia River systems modeling. *Journal ofWater Resources Planning and Management*, *112*(4), 453–468.

Pérez-Díaz, J. I., & Wilhelmi, J. R. (2010). Assessment of the economic impact of environmentalconstraints on short-term hydropower plant operation. *Energy Policy*, *38*, 7960–7970.

Person, E. (2013). Impact of hydropeaking on fish and their habitat. *Communications du Laboratoire deConstructions Hydrauliques. E'cole Polytechnique Fe'de'rale De Lausanne, Suisse*, *5812*, 139.

Peterson, P., & White, D. (2018). *Connecticut River relicensing revenue findings: A review of current federal energy regularity commission hydroelectric facilities filings*. Synapse EnergyEconomics, Inc.

Poff, N. L. (2018). Beyond the natural flow regime? Broadening the hydro-ecological foundationto meet environmental flows challenges in a non-stationary world. *Freshwater Biology*, *63*(8), 1011-1021.

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., Sparks, R. E., & Stromberg, J. C. (1997). The natural flow regime: A paradigm for river conservation and restoration. *Bioscience*, *47*(11), 769–784.

Poff, N. L., Richter, B. D., Arthington, A. H., Bunn, S. E., Naiman, R. J., Kendy, E., Acreman, M., Apse, C., Bledsoe, B. P., Freeman, M. C., Henriksen, J., Jacobson, R. B., Kennen, J. G., Merritt, D. M., O'Keeffe, J. H., Olden, J. D., Rogers, K., Tharme, R. E., & Warner, A. (2010). The ecological limits of hydrologic alteration (ELOHA): A new framework for developing regional environmental flow standards. *Freshwater Biology*, *55*, 147–170.

Poff, N. L., & Zimmerman, J. K. H. (2010). Ecological responses to altered flow regimes: A literature reviewto inform the science and management of environmental flows. *Freshwater Biology*, *55*(1), 194–205.

Pracheil, B. M., Chalishazar, V. H., Schaffer, L., Harby, A., Hedger, R., Schonfelder, L., Halleraker, J., Sundt-Hansen, L., & Carolli, M. (2023). *Energy flexibility-environmental outcomes tradeoffs workshop report and research roadmap*. Pacific Northwest National Laboratory.

Pracheil, B. M., Pegg, M. A., & Mestl, G. E. (2009). Tributaries influence recruitment of fish in largerivers. *Ecology of Freshwater Fish*, *18*(4), 603–609.

Richter, B. D., Baumgartner, J. V., Powell, J., & Braun, D. P. (1996). A method for assessinghydrologic alteration within ecosystems. *Conservation Biology*, *10*(4), 1163–1174.

Richter, B. D., & Thomas, G. A. (2007). Restoring environmental flows by modifying damoperations. *Ecology and Society*, *12*(1), 12.

Schülting, L., Feld, C. K., Zeiringer, B., Huđek, H., & Graf, W. (2019). Macroinvertebrate drift response tohydropeaking: An experimental approach to assess the effect of varying ramping velocities. *Ecohydrology*, *12*(1), e2032.

Scruton, D. A., Pennell, C., Ollerhead, L. M. N., Alfredsen, K., Stickler, M., Harby, A., Robertson, N., Clarke, K. D., & LeDrew, L. J. (2008). A synopsis of 'hydropeaking' studies on the response of juvenile Atlantic salmon to experimental flow alteration. *Hydrobiologia*, *609*, 263–275.

Scruton, D. A., Pennell, C., Robertson, M. J., Ollerhead, L. M. N., & Clarke, K. D. (2005). Seasonal responseof juvenile Atlantic salmon to experimental hydropeaking power generation in Newfoundland, Canada. *North American Journal of Fisheries Management*, *25*, 964–974.

Smokorowski, K. E. (2022). The ups and downs of hydropeaking: A Canadian perspective on the need for,and ecological costs of, peaking hydropower production. *Hydrobiologia*, *849*, 421–441.

Steinschneider, S., Bernstein, A., Palmer, R. N., & Polebitski, A. (2014). Reservoir managementoptimization for basin-wide ecological restoration in the Connecticut River. *Journal of Water Resources Planning & Management*, *140*(9), 04014023. https://doi.org/10.1061/(ASCE)WR.1943-5452.000399

Tamaddun, K. A., Barrows, S. E., Usman, M. U., Meng, J., Woodruff, N., Harnish, R. A., Powell, D. W., King, A., & Mosier, T. (2023). Hydropower potential at non-powered dams: A multi-criteria decision analysis tool based on grid, community, industry, and environmental impacts. In S. Ahmad & R. Murray (Eds.), *World Environmental & Water Resources Congress 2023: Adaptive planning and Design in an age of risk and uncertainty* (pp. 23–31). American Society of Civil Engineers.

The Nature Conservancy (TNC). (2007). *Indicators of hydrologic alteration version 7 user's manual*. The Nature Conservancy.

Thiessen, E. M., & Loucks, D. P. (1992). Computer-assisted negotiation of multiobjective water-resources conflicts. *Water Resources Bulletin*, *28*(1), 163–177.

TransCanada Hydro Northeast Inc. (2012a). Bellows falls hydroelectric project pre-application document. FERC Project No. 1855.

TransCanada Hydro Northeast Inc. (2012b). Vernon hydroelectric project pre-application document. FERC Project No. 1904.

TransCanada Hydro Northeast Inc. (2012c). Wilder hydroelectric project pre-application document. FERC Project No. 1892.

Zimmerman, J. K. H., Letcher, B. H., Nislow, K. H., Lutz, K. A., & Magilligan, F. J. (2010). Determiningthe effects of dams on subdaily variation in river flows in a whole-basin scale. *River Research and Applications*, *26*, 1246–1260.

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