Designing Hydropower Flows to Balance Energy and Environmental Needs

December 2022

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HydroWIRES Topic A Final Project Report

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HydroWIRES

In April 2019, the Water Power Technologies Office launched the HydroWIRES Initiative to understand, enable, and improve hydropower and pumped storage hydropower (PSH) contributions to reliability, resilience, and integration in the rapidly evolving U.S. electricity system. The unique characteristics of hydropower, including PSH, make it well-suited to provide a range of storage, generation flexibility, and other grid services to support the cost-effective integration of variable renewable resources.

The U.S. electricity system is rapidly evolving, bringing both opportunities and challenges for the hydropower sector. While increasing deployment of variable renewables such as wind and solar have enabled low-cost clean energy in many U.S. regions, it has also created a need for resources that can store energy or quickly change their operations to ensure a reliable and resilient grid. Hydropower (including PSH) is not only a supplier of bulk, low-cost, renewable energy but also a source of large-scale flexibility and a force multiplier for other renewable power-generation sources. Realizing this potential requires innovation in several areas, such as understanding value drivers for hydropower under evolving system conditions, describing flexible capabilities and tradeoffs associated with hydropower meeting system needs, optimizing hydropower operations and planning, and developing innovative technologies that enable hydropower to operate more flexibly.

HydroWIRES is distinguished in its close engagement with the DOE national laboratories. Five laboratories—Argonne National Laboratory, Idaho National Laboratory, National Renewable Energy Laboratory, Oak Ridge National Laboratory, and Pacific Northwest National Laboratory—work as a team to provide strategic insight and develop connections across the HydroWIRES portfolio as well as broader DOE and national laboratory efforts such as the Grid Modernization Initiative.

Research efforts under the HydroWIRES Initiative are designed to benefit hydropower owners and operators, independent system operators, regional transmission organizations, regulators, original equipment manufacturers, and environmental organizations by developing data, analysis, models, and technology research and development that can improve their capabilities and inform their decisions.

More information about HydroWIRES is available at https://energy.gov/hydrowires.

Executive Summary

As the US increases variable renewable energy (VRE) generation, increased flexibility from other electricity sources to ensure that grid operations are reliable and resilient will be required (Cicilio et. al. 2021). Natural gas currently provides most generation flexibility, but hydropower and grid-scale energy storage are expected to provide more flexibility as fossil fuel generation retires to meet carbon emission targets. The role of hydropower is thus expected to evolve from providing baseload generation to ancillary services and may lead to increased hydropeaking operations—fluctuations in water releases as hydropower plants quickly ramp up and down—to balance VRE generation (Somani et. al. 2021; De Silva et al. 2022). Changes in downstream flows associated with these changes in operation can alter their environmental impacts and the types of mitigations needed (Jager et al. 2022). For example, rapid changes in hydropower flows to meet electricity demand can impact environmental needs as diverse as fish spawning, bird nesting, whitewater rafting, and municipal water supplies (Cameron and Pracheil 2022). However, flow requirements that limit hydropower flexibility may impact grid reliability especially as more VREs come online and there is currently no guidance for creating environmental flows that support grid reliability and no policies that require balancing environmental and grid needs in hydropower regulations (Table 1).

Table 1. Hydropower flows designed to protect the environment can have impacts on the grid that may affect grid reliability as more renewable energy sources are integrated. The hydropower flow requirements that limit grid services are shown in increasing severity, from green to red .

Grid Services	Grid Service Temporal Scale	Minimum Flow	Prescribed Flow	Ramp Rate Restriction
Load-following	Hourly plan, 5-10 minute	Yellow	Red	Red
Volt/VAR support	Continuous, <1 minute	Green	Green	Green
Frequency regulation	Seconds to minutes	Yellow	Red	Yellow
Spinning reserve	< 10 minutes	Green	Red	Red
Non-spinning reserves	< 10 minutes	Green	Red	Red
Replacement reserves	60 minutes to 2 hours	Green	Red	Red
System black start	As required	Green	Red	Red
Firm capacity	As required	Green	Yellow	Yellow

The hydropower regulatory process provides an opportunity to revisit environmental requirements to mitigate environmental impacts given the future risk forecasts. Non-federal hydropower makes up 51% of the hydropower fleet, 55% of which must obtain a 30-50-year license from FERC and will need to consider needs of the grid and environment through license expiration. Over the next 10-years, a large number of hydropower projects will begin relicensing and projects receiving their license today will need to consider and mitigate environmental impacts at least through 2052 for 30-year licenses (although 40-

year terms are standard (Levine et al. 2021) while the 45% of non-federal hydro that are exempt from licensing, must consider energy and environment needs for the life of the project. These timeframes are projected to see significant changes to the climate and power system requiring tools and techniques for maximizing environmental and power system outcomes to support increasing stress on river ecosystems and the electricity grid.

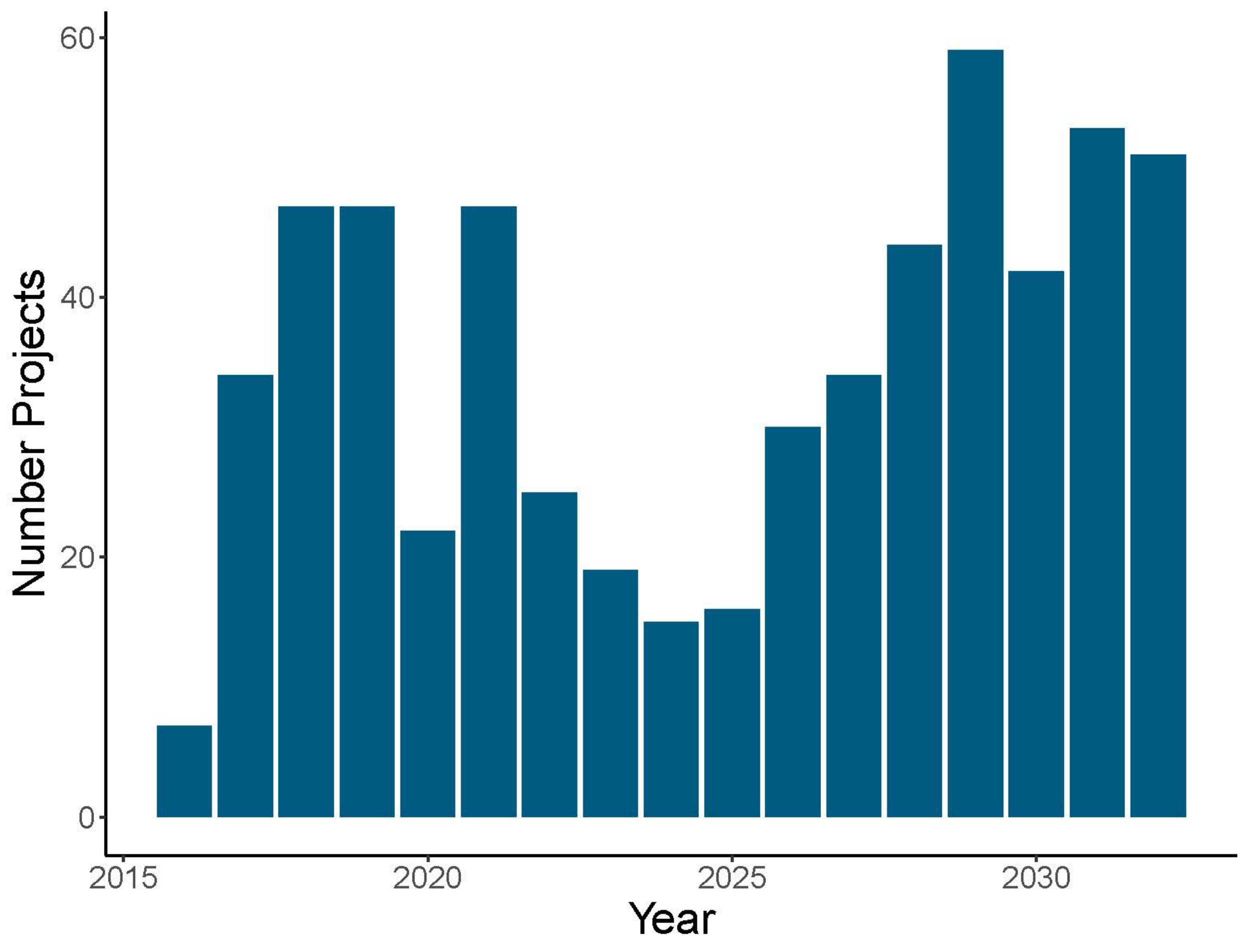

Figure 1. Many FERC-licensed hydroelectric dams are due to begin relicensing (number of projects expected to file Notice of Intent to relicense per year) through the FERC in the near future. Relicensing provides an opportunity to adjust environmental requirements, such as flow requirements, to co-optimize for energy and environmental outcomes using new tools.

The analyses and tools described in this report are centered on links between energy and the environment in hydropower systems. This understanding can provide an objective foundation for quantitative assessment of tradeoffs between increased generation flexibility that hydropower will be expected to provide and the environmental impacts of this flexibility. Moreover, this report aims to create building blocks for the future science and tools all parts of the hydropower community involved in regulatory proceedings will need to balance energy and environmental objectives through flow management.

Chapters in this report include:

- **Chapter 1** introduces the study and gives science and policy context for the report.

- **Chapter 2** provides a summary of environmental flow requirements from 50 FERC licenses. Key findings of this chapter include:
    - Numbers and types of flow requirements vary by region although minimum flow requirements—flow requirements that dictate a minimum amount of water that must be released— are the most common across all regions
    - Fisheries are the most common target of flow requirements
    - Flow requirements that are specific to time of day and month of year are most common during summer afternoons, especially in the South, which are periods of stress on the electric system
- **Chapter 3** describes links between flow and power system outcomes and flow and environmental outcomes that are needed to make quantitative energy-environment tradeoffs. This chapter describes an interactive diagram showing connections between flow and power system outcomes and flow and environmental outcomes.
- **Chapter 4** describes case studies in energy-environment tradeoffs and include description of a prototype Economic Valuation Tool meant to maximize generation revenue from previously designed flows, a case study in the Yadkin-Pee Dee river basin seeking to demonstrate how reservoir operational policies can be created to maximize fish survival and generation revenue, and a case study at Glen Canyon Dam that uses a prototype tool for finding energy-environment win-wins by trading-off generation revenue, fish growth rate, and sediment transport. Key findings of this chapter include:
    - Creating environmental and operational flows that meet environmental and economic objectives is possible and actionable.
    - Energy-environment win-wins demonstrated in this chapter include increased generation revenue and increased fish growth, increased generation revenue and increased fish survival, and increased generation revenue and increased sediment transport.
    - Research and knowledge gaps highlighted by this report are discussed.

Key Report Findings

- Affordable and widely available computing power enables solutions that optimize energy and environment outcomes in a way that was not previously possible, with the potential to revolutionize how flow requirements are created, allowing for quantitative assessments of energy-environment tradeoffs.

- Ecological outcomes, particularly those aimed at protecting fishery resources, are far and away the most common target of flow requirements across all regions and are likely indicative of the importance of this resource to hydropower stakeholders. These flows are rarely co-optimized for energy objectives and provide additional opportunities to improve the environment and revenue.

- Automatic generator control can enable hydropower facilities to limit their impacts from hydropeaking by precisely controlling peaking operations to times with the highest price signals. While many older and smaller facilities do not have this capability, optimization algorithms may still improve both environmental and revenue objectives.

- User-friendly tools are needed that would allow users to conduct energy–environment co-optimizations and design flows that maximize energy and environmental objectives.

- Using forecast-informed reservoir operations can allow for better management, potentially reducing the negative impacts of hydropower operations. Using this information to reduce uncertainty in planning means more environmental flows that can meet the requirements put in place by hydropower regulatory processes.

Research Needs Identified by Report

- Coupling batteries with hydropower systems has been suggested as a mitigation for negative environmental effects of hydropeaking. Continuing assessments may be warranted as battery technologies advance and tools that can provide this tradeoff assessment would be useful.

- Simultaneous valuation of economic and ecologic/environmental outcomes in a way that is geographically generalizable presents a challenge for creating tools with broad applicability. Software tools created to assess energy-environment tradeoffs must overcome the challenge of containing flow, economic, and ecologic input options that can account for the site-specific needs of each hydropower plant while still being general enough to provide insight to most hydropower facilities.

- Truly valuing flexibility has special challenges that must involve assessing ancillary services and effects of repeated and chronic flow fluctuations on fish and other aquatic biota. Coupling this assessment with other energy–environment tradeoff assessments is critical for fully understanding how economic and environmental outcomes are influenced by hydropower.

- Decisions on hydropower flow requirements are made on a facility-by-facility basis. Since other flow requirements and their energy impacts are not considered on a larger scale, it is possible there could be a cumulative impact on flexibility at many facilities that could impact reliability and manifest at the grid scale either currently or in a future grid with increased VRE generation. There is currently no understanding how or if the flexibility impacts of flow requirements on one facility scale to the grid scale. Current proposed solutions to decreasing FERC licensing timelines involve conducting basin-scale licensing assessments; similar solutions to improving grid reliability by considering grid-scale needs in licensing assessments may be useful.

Attribution of Work

Oak Ridge National Laboratory (ORNL) created the instream flow dataset (Cameron, Pracheil) and the flow to environment linkages (Pracheil, Moody, Hansen, Jager), conducted ecological modeling in the Yadkin-Pee Dee case study (Jager), led writing on introduction and conclusion chapter, edited final report, and provided overall project coordination (Pracheil).

National Renewable Energy Laboratory (NREL) conducted production cost modeling of U.S. power grid to provide price information for Yadkin-Pee Dee and Glen Canyon case studies (De Silva, Jorgenson), provide inputs for flow to power linkages, and contributed to report writing (De Silva).

RTI supported creation of the flow to environment linkages (Carney, Perrot), conducted CHEOPS and DDP modeling in the Yadkin-Pee Dee case study (Quebbeman, Watson), led modeling coordination between RTI, NREL, and ORNL for the case study (Carney), and provided associated writing and review for related chapters of the report.

Argonne National Laboratory conducted the Glen Canyon Dam demonstration case study (Veselka, Ploussard), contributed to the writing of this document, and created methodologies that explore and discover solutions that simultaneously improve hydropower economic value and multiple environmental objects. Also created the Win-Win Exploration Modeling Toolset and compared toolset results for the Base Case to results produced by an established model that has been used for Glen Canyon operations, planning, and studies for decades.

Acronyms and Abbreviations

AF	acre foot
ANL	Argonne National Laboratory
AST	Alternative Screen Tool
BAU	business-as-usual
DA	day-ahead
DDP	Dual-Dynamic Programming
CAISO	California Independent System Operator
CHEOPS	Computer Hydro Electric Operations and Planning Software
CRSP	Colorado River Storage Project
ECRE	Eagle Creek Renewables
EI	Eastern Interconnection
EIS	Environmental Impact Statement
EMMO	Energy Marketing and Management Office
FERC	Federal Energy Regulatory Commission
FSP	fuel security plan
GCD	Glen Canyon Dam
GHG	greenhouse gas
HBC	humpback chub
IFIM	Instream Flow Incremental Methodology
IPP	independent power producer
IRP	integrated resource plan
LMP	locational marginal price
LTEMP	Long-Term Experimental Management Plan
MAF	million-acre-feet
MIP	mixed integer programming
NREL	National Renewable Energy Laboratory
PCM	production cost model
RM	river miles
ROD	Record of Decision
RT	real-time
SERC	Southeastern Electric Reliability Council
SOS	special ordered set
TAF	thousand-acre-feet
UCRB	Upper Colorado River Basin
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

VRE	variable renewable energy
WAPA	Western Area Power Administration
WI	Western Interconnection
YOY	young of year

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1.0 Introduction

Average atmospheric temperatures are projected to increase by 2-6°C over the next 30- to 50-year Federal Energy Regulatory Commission (FERC) license term for hydropower projects issued licenses this year (U.S. Federal Government, 2021). Among the challenges of natural resource management in a rapidly changing climate is creating environmental measures in FERC hydropower licenses that can support the needs of the grid and environment today and into the future. Growing implementation of variable renewable energy sources such as solar and wind can facilitate decarbonization of the power sector but require support from flexible generation sources that can quickly ramp up and down production levels and generate additional energy when the sun is not shining or the wind is calm. Hydropower resources are well-suited to provide this flexibility, but the environmental consequences of increased hydropeaking operations can include stranding fish, inundating nests of terrestrial animals living near the water, eroding shorelines, or creating hazardous boating conditions.

Upcoming expirations for a large portion of the FERC-licensed hydropower fleet present an opportunity to design hydropower flows that enable wins for energy and the environment given current and projected future conditions (Figure 2). The relicensing process requires iterative negotiations between applicants and a diverse body of stakeholders that help determine project environmental impacts and mitigations that will be included in the FERC license (Levine et al. 2021). Flow requirements—a specification or restriction on the amount or rate at which water is released—are designed to offset flow alterations and support or improve environmental outcomes like fish spawning and recreational boating among the most frequently included environmental mitigations included (Pracheil and Singh 2021).

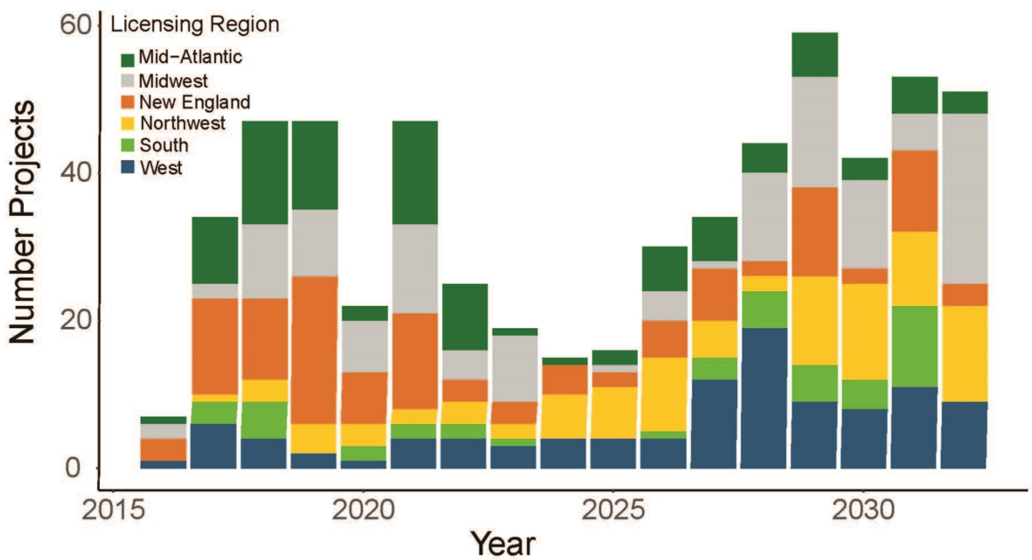


Figure 2. Expected Hydropower Relicense Notice of Intent (NOI) Filings Through 2032 by FERC region.

A review of 435 FERC licenses issued between 1997 and 2013 found that 1,424 mitigations of the 5,000 included in the review (28%) had some type of flow requirement (Schramm et al. 2016). This study reported that of the 1,424 flow requirements, 460 specified a minimum flow requirement and 22 specified ramp rate restrictions. Because flow requirements regulate the amount of water released from a hydropower facility, all have some interaction with operational flexibility. However, it is unclear whether or when bounds on flow releases are meaningful for grid reliability and resilience under current conditions, let alone the 30- to 50-year time horizon of the license.

1.1 Flow Requirements

While our understanding of interactions between flow requirements and the ability of a hydropower facility to provide functions and services to the grid is limited, we can make some initial predictions. For example, one prediction is that not all flow requirements have the same effect on hydropower functions or services. Table 2 details the function and services, their definitions, temporal scale, and the effects of different types of flow requirements on these functions and services. Green boxes indicate that a flow requirement is mildly limiting to that function or service, gold boxes indicate that a flow requirement is moderately limiting, and red boxes indicate that a flow requirement is significantly limiting. Prescribed flows, that is flow requirements that specify a constant flow rate or a very narrow band of allowable flow rates, have effectively no flexibility and are the most limiting to hydropower functions and ancillary services. On the other hand, we predict that flow requirements that allow for a wide range of operations between the minimum and maximum flow rate, and do not limit the speed at which generation can be ramped up or down, have the most flexibility.

Table 2. Hydropower flows designed to protect the environment can have impacts on the grid that may affect grid reliability as more renewable energy sources are integrated. The hydropower flow requirements that limit grid services are shown in increasing severity, from green to red.

Grid Services	Grid Service Temporal Scale	Minimum Flow	Prescribed Flow	Ramp Rate Restriction
Load-following	Hourly plan, 5-10 minute	Gold	Red	Red
Volt/VAR support	Continuous, <1 minute	Green	Green	Green
Frequency regulation	Seconds to minutes	Gold	Red	Gold
Spinning reserve	< 10 minutes	Green	Red	Red
Non-spinning reserves	< 10 minutes	Green	Red	Red
Replacement reserves	60 minutes to 2 hours	Green	Red	Red
System black start	As required	Green	Red	Red
Firm capacity	As required	Green	Gold	Gold

To support the role of hydropower in the evolving grid and changing climate, there needs to be a greater quantitative understanding of how or whether environmental flow requirements impact flexibility and how energy–environment win-wins may be realized. Typically, published studies that co-optimize flows for energy and environmental goals use energy generation as an optimization endpoint rather than services like flexibility (e.g., Ziv et al. 2012; Jager et al. 2015; Winemiller et al. 2016; Flecker et al. 2022). There is thus a need for new science to create new connections between energy and the environment that will allow these tradeoffs to be assessed.

1.2 Roadmap for the Report

As the future grid will rely on hydropower to provide both flexibility and robust environmental protections, the analyses and tools described in this report are centered on making links between energy and the environment in hydropower systems. This understanding of energy–environment linkages can provide the foundational understanding needed to quantitatively assess the tradeoffs between the increased generation flexibility that hydropower will be expected to provide and the environmental impacts of this flexibility. This report seeks to provide an objective foundation for building future science and tools that can be used by a broad spectrum of hydropower stakeholders involved in licensing or regulatory proceedings that are tasked with balancing energy and environmental objectives through flow management.

The remainder of this report details the components for creating a more mechanistic understanding of energy and environmental outcomes in hydropower systems that can yield meaningful quantitative tradeoff assessments. Section 2 characterizes environmental flow requirements from FERC hydropower licenses to help provide context for the environmental outcomes and how they are mitigated through flow requirements. Section 3 describes linkages between energy and environmental outcomes through the flow decisions and details from tools developed in this project. Tools discussed in this section include the Energy-Environment Linkage Map and the companion Model and Tool Database for detailing these linkages quantitatively. Section 4 uses a set of three case studies to explore strategies and tools for assessing energy–environment tradeoffs with the added goal of seeking out scenarios that lead to positive outcomes for both energy and the environment. Finally, Section 5 provides a summary of project findings and future focus areas for research and collaboration.

2.0 Characterization of Environmental Flow Requirements

Understanding tradeoffs between energy and the environment first requires a greater understanding of the complexity and nuance of environmental flow requirements. Currently, there is not a broad understanding of what types of flow requirements are in effect across the United States and whether there are regional patterns or what those patterns might be. Seasonal and hourly differences in energy demand mean that flow requirements vary not only by the type of requirement (e.g., minimum flow, ramp rate restriction), but also by any temporal (e.g., day of the week, hour of the day, month of the year) specifications of the requirement.

Currently, environmental flow requirements have not been named as a critically limiting source of operational flexibility within the hydropower fleet (although this may be true at some individual plants), but the degree to which the requirements may or may not constrain the ability of hydropower to support a transition to more renewable energy in the future power system is unclear. Moreover, climate change creates additional uncertainty and risk, potentially affecting power system reliability through water stress and extreme temperatures and weather. Gaining an understanding of the extent to which hydropower functions and services interact with flow requirements requires information about the type and distribution of requirements across the United States.

In this chapter, we describe and summarize environmental flow requirements from 50 FERC-licensed hydropower projects and discuss implications of flow requirements to hydropower operational flexibility, functions, and services. Detailed methods for this chapter are provided in Appendix A.

2.1 Methods

Information was recorded from 50 hydropower projects with FERC licenses issued from 2013 to 2019. Each flow was then characterized by augmentation type, which was the reason provided for the requirement (i.e., fish, general, recreation, industrial), flow requirement type (i.e., minimum flow, prescribed flow, and ramp rate restriction) and hours of the day, days of week, and months of the year that a requirement was in effect. The dataset created and analyzed for this chapter contains flow requirements from the Coosa River project (FERC number P-2146) which had a license vacated by a 2018 U.S. Circuit Court of Appeals for the District of Columbia decision because the court said the licensing decision was "unreasoned and unsupported by substantial evidence" (*American Rivers and Alabama Rivers Alliance v. FERC and U.S. Secretary of Interior*). As a result, flow requirement information incorporated from this license may not be representative of flow requirements from the region.

While this chapter focuses on flow requirements from FERC hydropower licenses, it is important to note that federal hydropower is also subject to satisfying environmental operational requirements. Federal projects were not included because a centralized repository of federal hydropower documents, similar to the FERC eLibrary, does not exist for federal hydropower.

2.2 Summary of Environmental Flow Requirements

The 50 licenses surveyed for this study included 98 individual hydropower facilities (see Figure 3). These facilities were not evenly distributed among regions, although licenses surveyed were randomly selected. Of the 50 licenses surveyed, eight were from the Northwest, nine from the Midwest, eight from the Mid-Atlantic, eight from New England, ten from the South, and seven from the West.

These FERC licenses had 1,461 individual instream flow requirements among the 50 projects. Flow requirements were not evenly distributed (see Figure 4), for example the Upper American River project in

California (FERC Docket number P-2101) contained 715 individual flow requirements, which was nearly half the requirements reported in this study and the most of any project. Only one other project, the Chili Bar project in California (FERC Docket number P-2155) with 119 requirements, had more than 100 flow requirements. No projects had zero flow requirements, although six projects—one project in every region except for the Midwest—had only one requirement. An additional 24 projects had ten or fewer flow requirements: five of eight projects in the Mid-Atlantic, all nine projects in the Midwest, six of eight projects in New England, six of eight projects in the Northwest, five of ten projects in the South, and four of eight projects in the West.

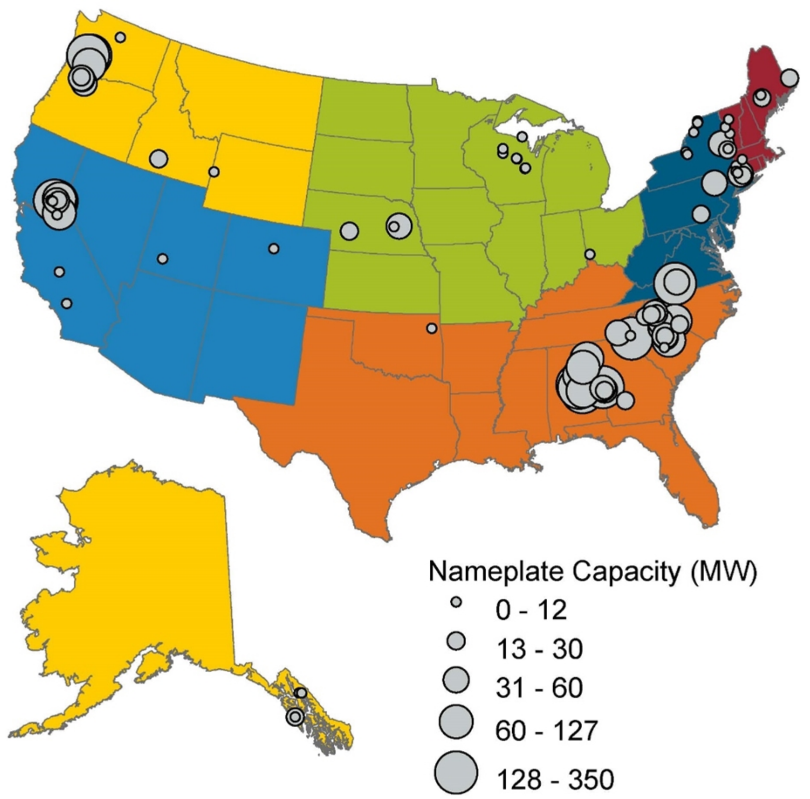


Figure 3. Locations and Nameplate Capacity Classification of Hydropower Facilities Surveyed

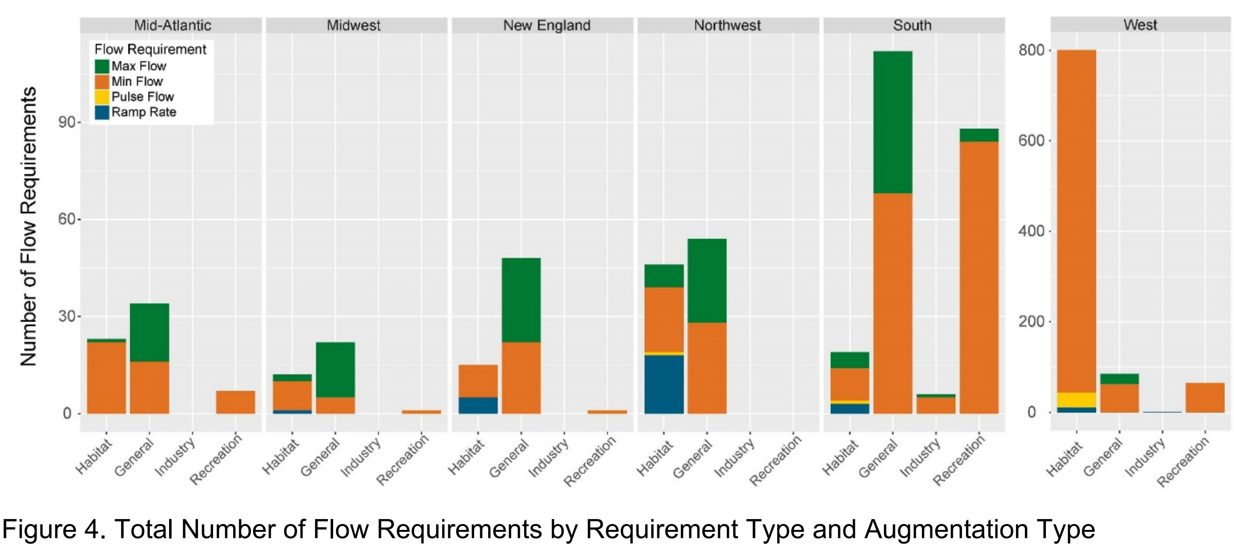


Figure 4. Total Number of Flow Requirements by Requirement Type and Augmentation Type

2.2.1 Augmentation Type

For most projects, requirements categorized as general flow were the most common augmentation type, although there are some instances of fisheries/habitat flow requirements dominating at a project. Two of eight projects in the Mid-Atlantic, one of nine projects in the Midwest, one of eight projects in New England, four of eight projects in the Northwest, and two of seven projects in the West had more fisheries/habitat flow requirements than general flow requirements. Figure 4 shows the average number of flow requirements per project by augmentation category and FERC licensing region. Bars represent standard error. Note that in Panel A, the West region has a different y-axis. In the West, the fisheries/habitat dominate the flow requirements—the Upper American River project where 684 of the 715 requirements were for fisheries/habitat—while recreation/boating appear to be less common. But if the Upper American River project is excluded, recreation/boating flow requirements were issued at two of seven projects and comprised 44 of 237 (19%) of the flow requirements.

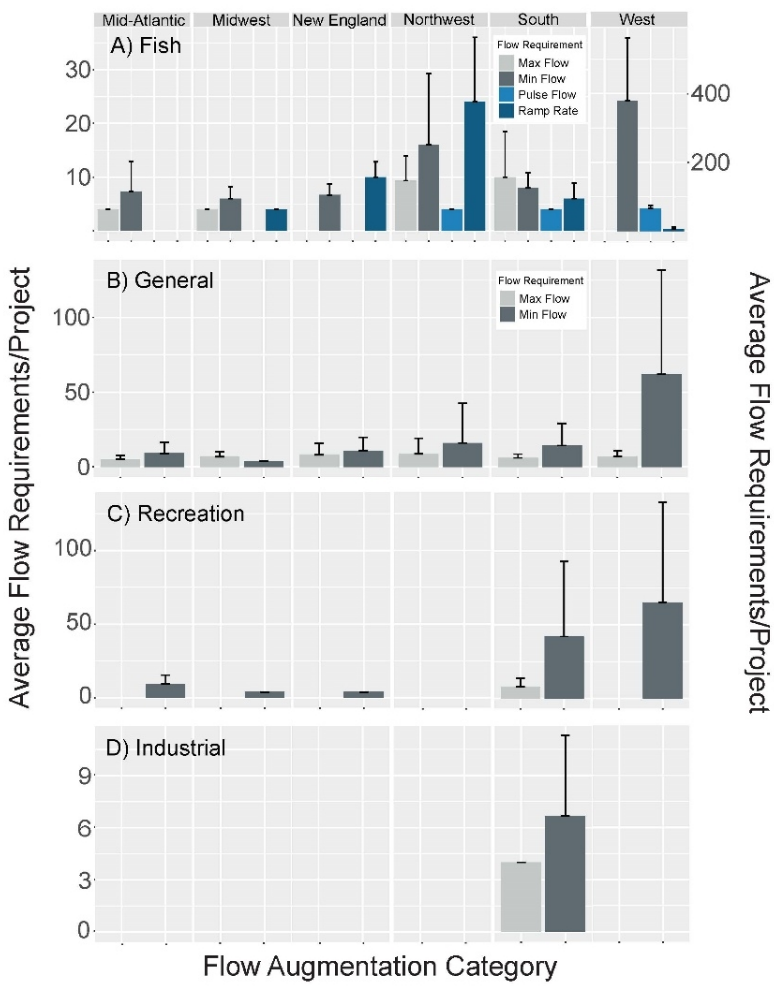


Figure 5. Average Number of Flow Requirements per Project by Augmentation Category

General flow requirements were the most common augmentation type in all licensing regions except for the West. The recreation/boating augmentation type was uncommon in all regions except for the South where it consisted of 88 of 225 (39%) flow requirements, but it also comprised 65 of 952 (7%) requirements in the West. Flow requirements for recreation/boating were the dominant augmentation type for three of 50 projects including one project in the Mid-Atlantic (Wallenpaupack Project FERC Docket P-487), and two projects in the South (Coosa River Project P-2146 and Nantahala Project P-2692).

2.2.2 Flow Type

Overall, minimum flow requirements were the most common (68%) followed by prescribed flows (23%), maximum flows (6%), and ramp rate restrictions (4%) as shown in Figure 6. The most common augmentation type differed by flow type with maximum flow requirements and ramp rate restrictions being most associated with general requirements, minimum flow requirements most associated with fisheries/habitat, and prescribed flows being most associated with recreation/boating. Prescribed flows were commonly issued in the Mid-Atlantic and South regions and were most associated with fishery/habitat in the Mid-Atlantic and recreation/boating in the South. Prescribed flows were issued relatively less commonly in the West and were exclusively issued for recreation/boating. Ramp rate restrictions were most issued in the Northwest, typically associated with the general augmentation type. Ramp rate restrictions were relatively uncommon in other regions.

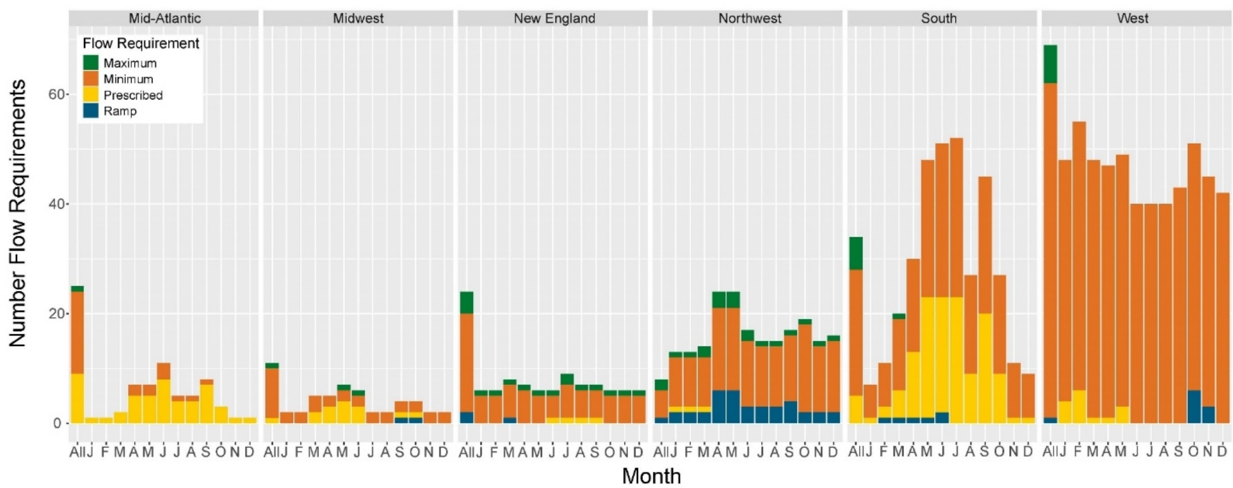
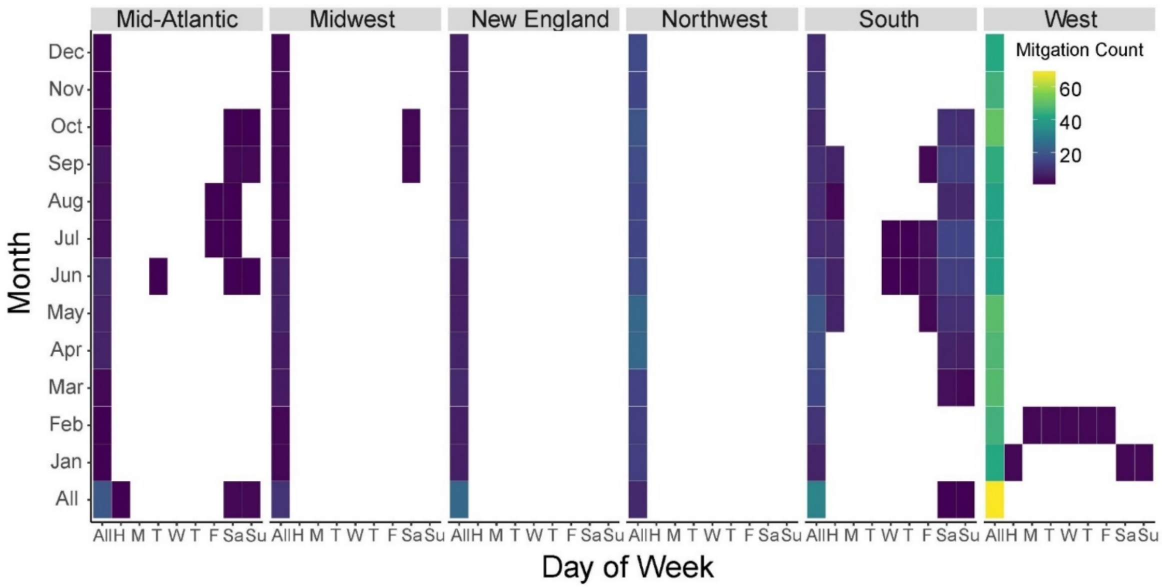


Figure 6. Total Number of Flow Requirements by Type, Month, and FERC Licensing Region

2.2.3 Timing of Flow Requirements

Flow requirements often had specified time periods in which they were active, including requirements applying to specific months, days, and hours of the day. Across regions, 12% of flow requirements were in place throughout the year. Most flow requirements were applied during all days of the week (84%) at all times of day (85%).

The months in which flow requirements applied differed by region and flow type (Figure 7). May was the most common month for flow requirements to be active, with 10% of 1,461 flow requirements active, followed by June, September, April. and July, each with 9% of 1,461 flow requirements active. In the West, the number of minimum flow requirements were greatest in the winter and spring months of January through May but were reduced in the summer months of July through August. Although prescribed flows were not common in the West, when they were issued, they were also issued in the January through May timeframe. In contrast, both minimum and prescribed flow requirements in the South were most common in the spring/summer months of May through September. When prescribed flows occurred, they were commonly associated with U.S. holidays, particularly those that bookend summer—Memorial Day in May and Labor Day in September—and Independence Day in July.



Abbreviations are for days of the week starting with M = Monday.
Other abbreviations are All = in effect all days of the week and H= holidays.

Figure 7. Heatmap of Total Flow Requirements in Each Region by Month and Day of Week in Effect

Across regions, 84% of flow requirements were active all days of the week. Flow requirements that specified days of the week most frequently listed Saturday and Sunday. Of the 15% of flow requirements that specify hours of the day they apply, 89% of are active from 10:00 to 15:00 with 98% active from 12:00 to 15:00 (Figure 8).

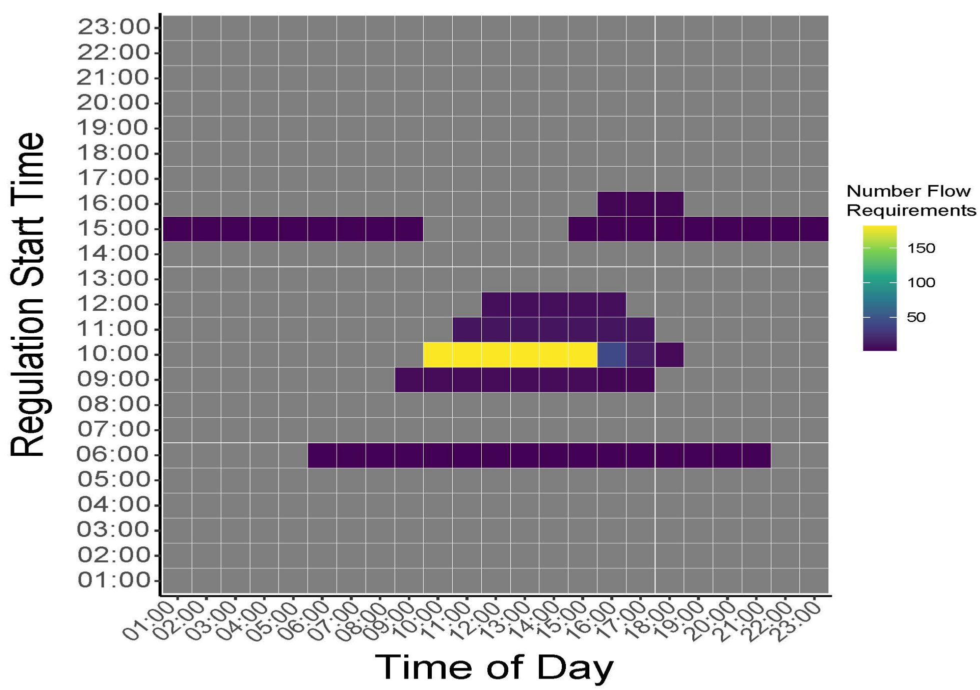


Figure 8. Heatmap of Total Flow Requirements in each Region by Time of Day Regulation Starts and Time of Day

2.3 Discussion

Minimum flow requirements are an important tool in the resource management toolbox for ensuring aquatic biota have suitable habitat in riverine ecosystems with altered flow regimes. These flows, which are the most ordered type of environmental flow license requirement, are likely to have relatively minimal effects on short-term operational flexibility because they do not limit ramp rates or maximum flows, both of which are important for maintaining many hydropower functions and services. However, longer term operational flexibility may be impacted due to reservoir water availability, which may become even more important in a changing climate where temperature and precipitation patterns change.

Prescribed flows are not commonly found across all regions and are a flexible type of flow requirement because they specify flow that removes the ability of a facility to ramp up or down in response to generation needs. In the South, for instance, prescribed flows are the most common requirement type. These flows occur during summer months, often during the hottest times of the day, when electricity consumption is high and flexibility and ancillary services may be most valuable. However, because prescribed flows in this region are typically in effect during weekends or holidays when electricity demand is lower compared to weekdays, the need for flexibility may not be as high. In the Southeast Independent System Operator, there is no ancillary services market so licensees and applicants may not be incentivized to maintain a higher level of flexibility and may be more willing to negotiate prescribed flows with other stakeholders than licensees/applicants in other regions.

Understanding where and how hydropower flexibility and instream flow requirements interact may help create a framework for negotiating instream requirements and creating energy–environment win-wins in comprehensive settlement agreements and/or basin-wide licensing approaches that are gaining interest in some parts of the country (Curtis and Buchanan 2019). This may enable greater value propositions for both energy and environmental stakeholders where less impactful types of instream requirements (i.e., minimum flows) at some facilities may be traded off for more restrictive requirements (e.g., ramp rate restrictions) at others.

Differences in stakeholder priorities are evident in instream flow requirements. In much of the United States, requirements support habitat for fish and other aquatic biota (probably including some that are classified as general for an unspecified reason in the Protection, Mitigation, and Enhancement section of the license order that was surveyed for this project), although recreation/boating is a very important source of instream flow requirements in some regions.

Conducting this initial assessment requires an understanding of many factors, including the type of flow requirements a facility has, time of year the requirements occur, time of day augmentations occur, generation capacity of the hydropower facility, and more. We expect minimum flows—the most common flow requirement listed among projects surveyed in this study— have relatively low impact on short-term operational flexibility, but it is important to note that our analysis is not commenting on the impact of flow requirements on the economics of hydropower generation or other industries that may rely on the water provisioning, aesthetic, recreational, etc. ecosystem services provided by a hydropower system.

2.4 Conclusions

Protecting fish and other aquatic life, recreation, and other authorizations of rivers and reservoirs in an uncertain future may require new and innovative water management strategies. For example, environmental flow requirements are often set using Instream Flow Incremental Methodology (IFIM) studies that help determine how much habitat is available at different flow releases. While IFIM methods will likely still be important for setting flow requirements into the future, there may be increasingly complex tradeoffs to be assessed in addition to the authorizations of rivers and reservoirs mentioned above. These tradeoffs may include grid reliability, water supply, water temperature, greenhouse gas emissions, etc.

Recent assessments looking to reduce the impacts of hydropower to natural resources via multi-objective optimization typically focus the energy side of the optimization on actual or potential megawatts generated or generation revenue (Winemiller et al. 2016; Flecker et al. 2022). However, hydropower is likely to take on a different role in the grid of the future, where its ancillary services will be valuable to the power system through contributions to grid reliability, such as black-start capability and real-time inertia rather than baseload generation. As such, multi-objective optimization in these future scenarios should also, or perhaps instead, be using one or more measures of ancillary services in their optimizations.

3.0 Assessments of Environment–Energy Flexibility Tradeoffs

Understanding the tradeoffs between energy flexibility and environmental impacts is critical to assessing sustainability of an energy system, but assessing these tradeoffs requires 1) an inventory of what power system and environmental outcomes are possible and 2) a mechanistic understanding of the factors affecting these outcomes. In a hydropower system, for instance, making energy–environment tradeoffs require some understanding of factors such as energy markets, hydrologic cycles, aquatic biodiversity, recreation, stakeholder priorities, and regulatory requirements. The complexity of factors involved in determining sustainability of a hydropower project can be seen in recognized hydropower sustainability protocols such the International Hydropower Association Sustainability Protocol that evaluates 24 criteria representing environmental, social, technical, and economic/financial perspectives (IHA 2020). While these criteria provide a framework of sustainable hydropower components, assessing tradeoffs still requires understanding the mechanisms of how outcomes arise that employ a diversity of technical lexicons and expertise that may lead to communication challenges with stakeholders from different professional backgrounds.

This chapter presents the conceptual links between power system and environmental outcomes for hydropower that are illustrated in a set of interactive maps. These maps are linked to a database of quantitative methods and tools for linking power system and environmental outcomes based on hydropower flow decisions that may be useful for identifying energy–water–environment tradeoffs and communicating these tradeoffs to diverse groups of stakeholders.

3.1 Methods

To create this webtool, hierarchical taxonomies of power system and environmental outcomes that can be related to flow were created based on input from project team domain experts. The links between flow and the highest levels of environmental and power system outcome taxonomy served as the building blocks for the executive summary map (https://hydrosource.ornl.gov/dataset/hydrowires-linkage-maps; Pracheil et al. 2021). Links between flow and specific power system and environmental outcomes are illustrated on submaps (Appendix B). These links were also determined by domain experts on the project team and a literature review examining the relationships between environmental and ecological outcomes with hydropower and flow, and hydropower production and flow. Taxonomy for environmental maps was based on Parish et al. (2019) and Aldrovandi et al. (2021). We also added an “Other” category that encompassed human health, agriculture, and water supply topics that were not covered in Parish et al. (2019) or Aldrovandi et al. (2021).

This literature search was also used to create a database of models and tools that can make quantitative links between flow and power system outcomes and flow and environmental outcomes to help stakeholders in hydropower regulatory proceedings communicate across disciplines. This database is not intended to be fully comprehensive, but rather allow the user to assess possibilities and potential solution pathways for their objective by answering five primary questions: (1) what is the outcome/metric of interest to be measured; (2) what type of modeling approaches are available for each discipline/outcome; (3) what input variables are needed; (4) how were the models validated; and (5) how can the models be applied and integrated across disciplines/outcomes? Further, this database lists the advantages and limitations of the models and tools and identifies challenges and opportunities for future research and development that aim to assess the energy–water–environment nexus.

3.2 Results

Due to the cross-disciplinary nature of the tool we have developed, there may be many linkages that will be unfamiliar to the average user. In this section, we focus on describing the intricacies of the linkages in the hydropower energy–environment system so that an aquatic scientist, for instance, may still be able to understand linkages in the power system part of the diagram.

3.2.1 Map Orientation and User Guidance

The Executive Summary Map serves as the starting point for exploring links between hydropower system performance outcomes and environmental outcomes (Figure 9). The map serves as the guiding reference for navigation to discipline specific submaps and outcomes. The central topic on this map is flow from hydropower system, which is connected to hydropower operations through flow through turbines and non-turbine flows, and to environmental outcomes through reservoir elevation and flow downstream of the hydropower system. To the left of these central topics, hydro-mechanical operations are linked through hydro-electrical operations to hydropower performance outcomes (reliability, resilience, revenue, emissions). On the right, environmental outcomes are grouped together by their physical location: upstream outcomes (upstream geomorphology, upstream recreation, upstream habitat, upstream biota and biodiversity, upstream water quality and greenhouse gas, outcomes relevant to both upstream/downstream or dam interface (navigation, dam safety and maintenance, human health, water supply, flood control, fish passage), and downstream outcomes (downstream geomorphology, downstream recreation, downstream habitat, downstream biota and biodiversity, downstream water quality greenhouse gas).

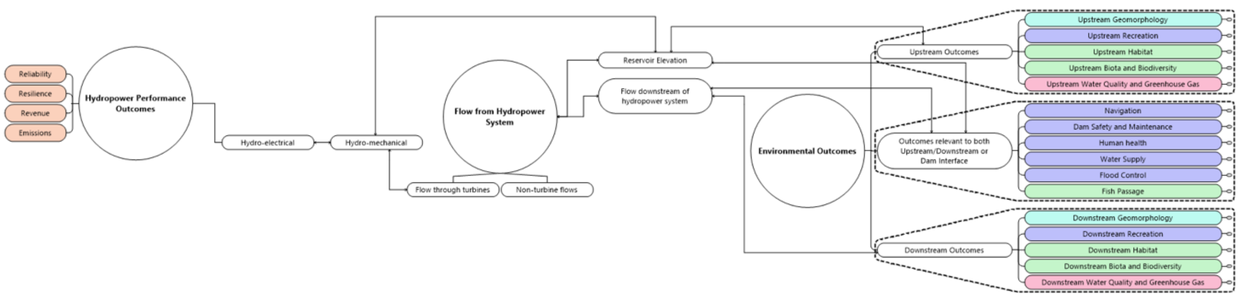


Figure 9. Executive Summary Map

Some topics in the maps are related through parent-child relationships which can be opened or collapsed (number within bubble denotes children within parent category) as shown in the Figure 10. In some cases, boundaries (dashed lines) are used to group the parent topic with all its child topics to visually delineate the respective relational grouping.

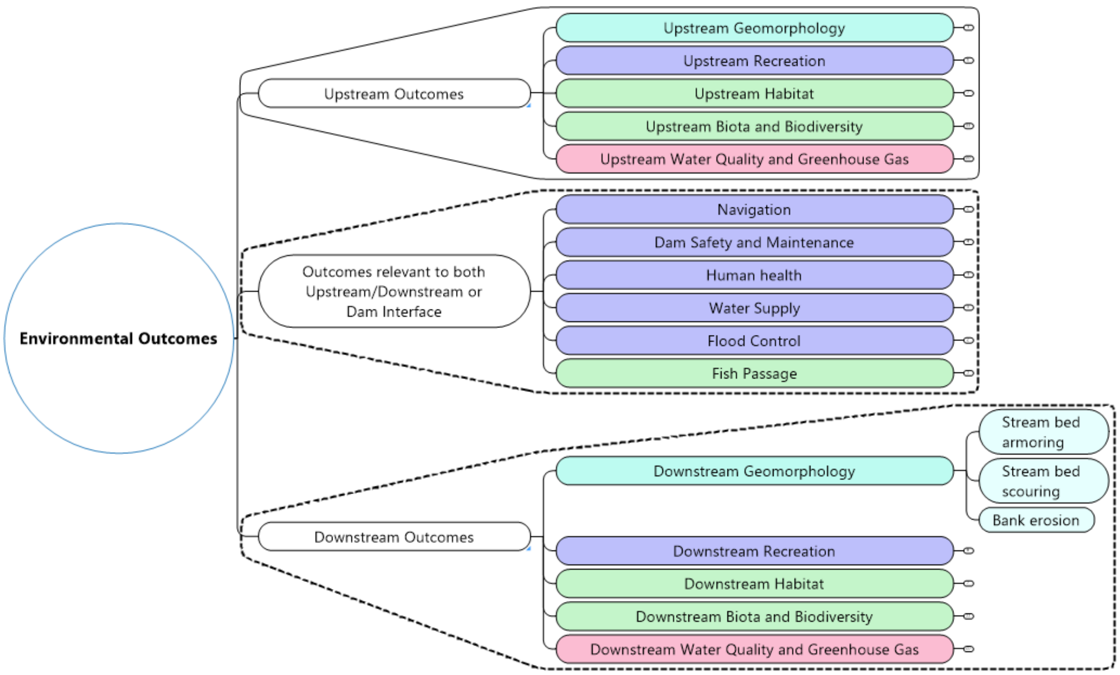


Figure 10. Parent-Child Relationships and Boundaries Showing Groupings of Similar Child Nodes

Figure 10 shows collapsed nodes for all categories of environmental outcomes, except for the Downstream Geomorphology category, which is shown expanded to reveal the child nodes (specific outcomes). Select nodes are linked to a submap with greater detail, describing specific elements and processes. Some topics have notes on the map (Figure 11) giving more detail about the corresponding topic, the processes that connects one element to another, and relevant references.

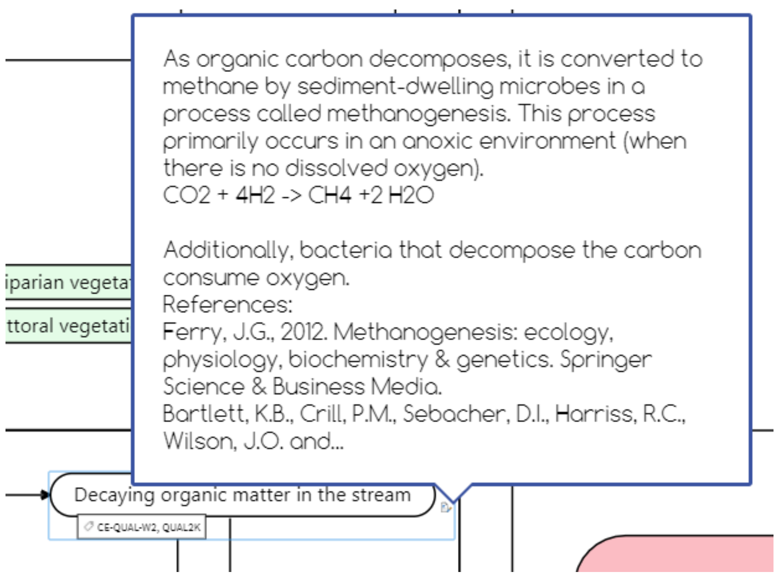


Figure 11. Example of Notes Describing a Specific Node and its Relationships to Other Nodes

Many topics include tags as shown in Figure 12. These tags suggest some of the most common models and modeling software used in academic literature and industry to model the corresponding topic. The tags on the map are not intended to be comprehensive or include every model/modeling software available but are a guide for users for model availability and applicability. Descriptions of the included models and tools, data inputs necessary, strengths and weaknesses, and further details about the characteristics of the models/tools are provided in our accompanying modeling inventory database (Appendix C).

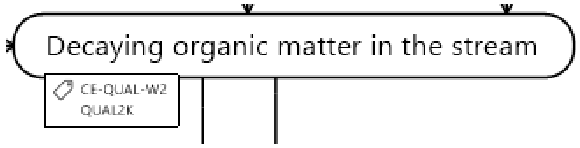


Figure 12. Tags Indicating Common Models that Include Representation of this Node

Relationships between topics are denoted with connecting lines. A solid line with no arrow between topics indicates that the two nodes inform each other (i.e., the relationship is bidirectional). A solid line with single-sided arrow indicates that the node on the point end of the relationship informs the node on the end with the arrowhead (i.e., the relationship is unidirectional). A colored solid line was generally applied to declutter the map and make relationships easier to follow. The color is based on the topic of origin and/or the boundary around a parent topic. Detailed descriptions of map components and mechanisms can be found in Appendix D.

3.2.2 Model and Tool Database

We compiled an inventory of common models and modeling software/tools that are relevant to specific hydropower or environmental outcomes. The model/tools inventory is designed to function as a single table within a relational database (Appendix C), as illustrated in Figure 13.

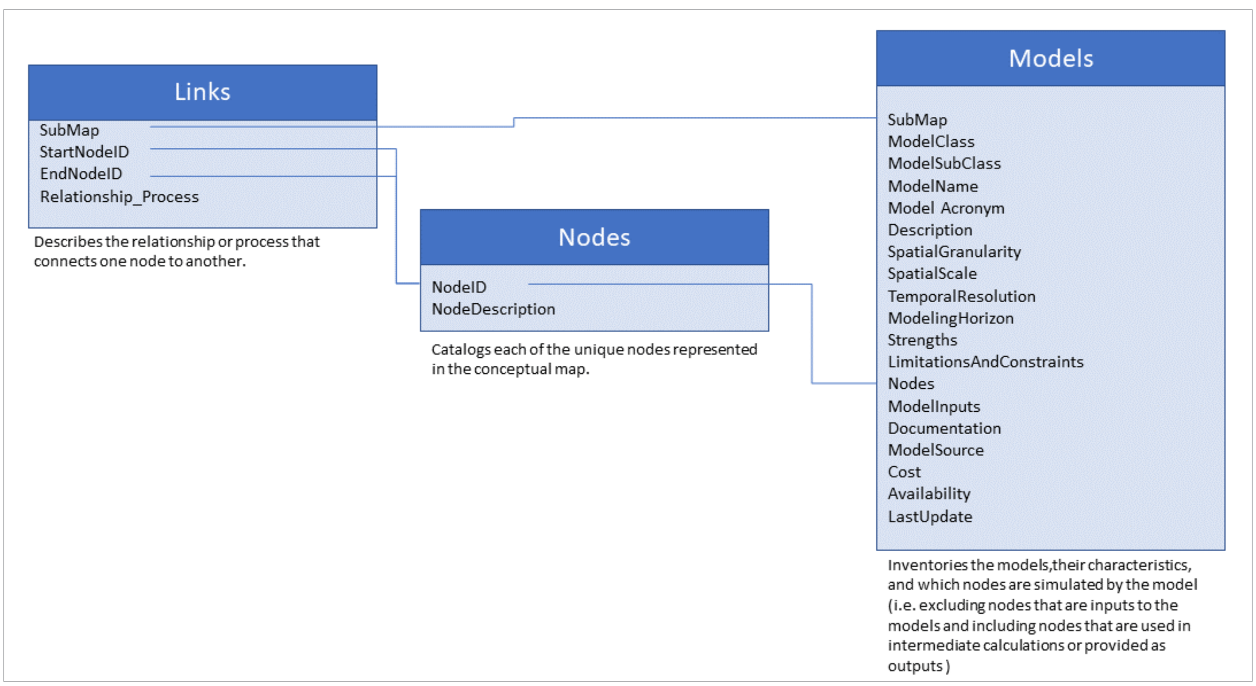


Figure 13. Simplified Entity-Relationship Diagram

The table contains the following information for individual models or modeling software: spatial and temporal scales and resolutions, a brief assessment of known modeling limitations, references, and availability/accessibility information. Structure of the database is important for enforcing relationships between the model inventory and other database tabs that contain the elements and links relating elements in hydropower and environmental systems. This strategy for detailing models and their connections to these elements enables the evaluation of gaps in modeling capabilities. For instance, dynamic queries can be used to discover which models have been documented for an individual element or multiple elements related to hydropower or environmental outcomes. Alternatively, queries can be used to subset those elements that are not yet represented in any documented model.

The model/tools inventory database complements the visual representation of the connections between hydropower, social, environmental, ecological systems, and outcomes in the linkage maps. For example, in Figure 14 processes are mapped to show the complex relationships that exist within these systems. The model or software listed in the inventory table has been included in this map as tags, indicating which models are applicable to a particular element, referred to as a node. Users can then search for a particular model of interest in the database (e.g., RiverWare, HEC-ResSim) to further assess its utility for their specific needs. Additionally, users can choose to visualize only particular models of interest and at what nodes or topics they occur across linkage maps by using the "tag" filter to select a model. In some cases, nodes (white) or processes (gray) may have one or more relevant models identified in the inventory (e.g., flow downstream of hydropower system), while others do not yet have any models (e.g., embankment erosion). Those without models represent gaps in the current inventory.

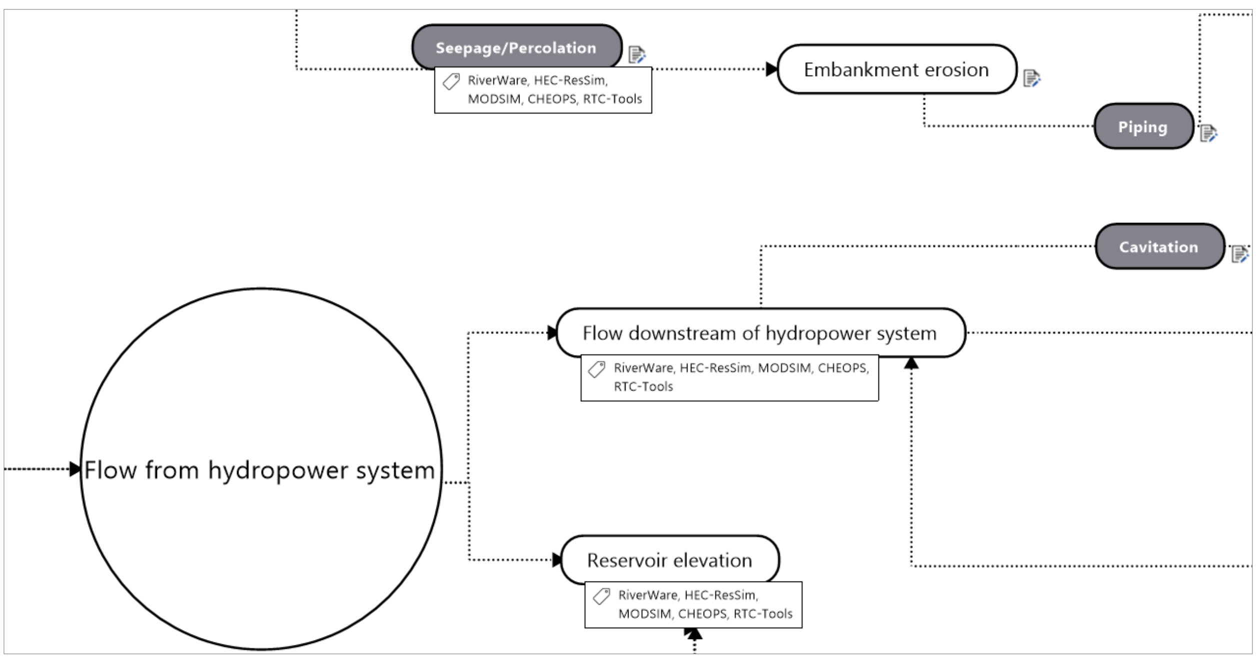


Figure 14. Excerpt of Linkage Map Showing Nodes Tagged with Relevant Models

3.3 Discussion

Environmental flow requirements of hydropower facilities, including providing flow hospitable for aquatic biota and habitats, human health, recreation, water supply, flood control, and more, can limit the ability of a hydropower facility to respond to needs of the grid. Conversely, extreme fluctuations in flow rate can dramatically affect the environment and biota in hydropower-impacted systems. Understanding and quantifying the opportunities for co-optimization of power production and environmental protection are necessary as future power production will rely more heavily on hydropower.

The linkage map framework presented here provides a qualitative and quantitative holistic perspective across the hydropower energy–water–environment nexus. While various frameworks, models, and tools have previously been developed to either optimize hydropower power production or understand the impacts of flow on environmental outcomes, our framework provides a unique and integrative path for understanding the relationships across the full spectrum. Specifically, our power–flow–environment linkage framework provides a greater understanding of how flexibility in environmental requirements can be leveraged to create positive outcomes for both the power system and the environment.

This framework provides a roadmap to understanding where these opportunities of co-optimization may arise. By using the framework, goal-oriented or hypothesis-driven inquiries can be examined through the lens of flow to investigate the impacts of hydropower. Not only can users examine these impacts within a discipline/area (e.g., fish passage) users can also determine how, when, where, and why integration across disciplines (e.g., fish passage – dam infrastructure – flood control flow – power production) can elevate our knowledge on the impacts of hydropower and arrive at win-win solutions that can be designed and implemented.

The linkage map framework is further supported with models and tools that can be used to understand the effects of flow and can potentially be used for integrative modeling approaches. For example, existing ecological models provide a basis to assess the impacts of hydrological regimes and water quality on the habitat suitability of fish, macroinvertebrates, and algae caused by the installation and operation of hydropower dams (e.g., PHABSIM, IFIM, SWAT). Despite their wide use, many of these models do not incorporate abiotic and biotic interactions, organismal processes (e.g., metabolism, population growth rate, genetic variation), or the limiting outcomes these factors can have on flow requirements and power production. However, through our linkage framework, users can readily identify models that are integrated together, and with advances in computational methodologies, this can result in increased parameter space being explored and higher-level questions being answered.

3.4 Conclusions

While our model and tool database cover all the aspects of our framework (power system–flow–environment), we did not develop this database with the intention of it being fully comprehensive or exclusive. Rather our database provides the launching point for users to discover the modeling and software tools available and their respective usages, strengths, and limitations. Further, many ecological, genetic, functional morphology, and fitness models are use-specific and written in Python, MATLAB, or R. Their functionality and replicability are beyond the scope of this paper, but it should be noted that such development is commonplace. Additionally, statistical models (e.g., regression, Bayesian, network) are implemented across multiple platforms and packages, and therefore their applicability is dependent on user questions and goals.

While we aimed to capture the interconnectedness within our linkage maps with arrows, links, models, and notes, we recognize there may be interactions we did not uncover in our literature search and could be iterated into the framework. We also acknowledge that, even though our linkage framework provides a roadmap for identifying energy–environment co-optimization opportunities, it may not be applicable to all situations. Not every hydropower project will be able or need to conduct studies that integrate across disciplines and scales. However, in these situations the framework could still provide valuable insight into the parameters of the intended objectives.

Understanding the opportunities for win-win outcomes between hydropower benefits and the environment will be critical for sustainable energy development and production. Arriving at sustainable solutions in hydropower will help illustrate power–flow–environment linkages that will be important in understanding outcomes under future climate scenarios. For example, research in the Mekong basin using future climate scenarios predict an increased streamflow and that hydropower–environmental tradeoffs will be amplified by streamflow variability. Further, maintaining current levels of environmental regulations in the future could result in a hydropower deficit in the Mekong basin for which thermal power would need to compensate, resulting in generating additional greenhouse gas emissions (Zhong et al., 2021). These results reveal the potential challenges facing hydropower and environmental sustainability in the future and emphasize the importance of developing adaptive mitigation techniques under climate change. Our framework would enable such studies to be conducted by understanding where climate change models could be incorporated.

Providing stakeholders and policy makers with transparent, rigorous, and thorough evaluations of energy–flow–environment co-optimization strategies will aid in future regulatory decision-making processes. The relative importance and applicability of each portion of the linkage map will vary from project to project, but the overall schematic and holistic viewpoint will aid in providing robust estimates of tradeoffs and further the decision-making procedures by providing hydropower regulatory participants a communication tool for illustrating energy–water–environment connections to participants with other expertise or priorities.

4.0 Case Studies in Energy–Environment Tradeoffs

As discussed throughout this report, a future electric grid that leans on hydropower to provide ancillary services will still be held to environmental protection standards that are critical to healthy ecosystems but may limit hydropower flexibility. Tools and analyses that can help find energy–environment win-wins will ensure that hydropower producers can satisfy environmental, grid, and economic needs. In this chapter, we present three case studies demonstrating different approaches and tools that can support these needs. These case studies demonstrate energy–environment win-wins that 1) maximize generation revenue from previously designed environmental flow requirements, 2) rapidly evaluate operating criteria for energy–environment win-wins, and 3) create reservoir operational policies that maximize fish survival and generation revenue.

Table 3. Summary Information for Case Studies

Study	Objective	Flow	Environmental Endpoint	Power System Endpoint
Economic Valuation Tool (INL)	Maximize generation revenue from previously designed environmental flow requirements		No explicit environmental endpoint, but provides valuation for flow requirements	Generation revenue
Yadkin-Pee Dee Case Study (ORNL, NREL, PNNL, RTI)	Create reservoir operational policies that maximize fish survival and generation revenue	CHEOPS reservoir operations model	Survival of egg, larva, and age-0 juvenile smallmouth bass	Generation revenue, generation (MW)
Glen Canyon Dam (ANL)	Rapidly creates and evaluates a large operating criteria landscape in search of energy-environment win-win solutions		Fish growth rate, sediment transport	Annual economic value of hydropower energy production

In all case studies, we will present brief methods used in the demonstrations, and highlights of how the case studies demonstrated energy–environment win-wins. Detailed methods and results can be found in Appendix E.

4.1 Maximizing Generation Revenue

Environmental flow releases can be designed for a variety of purposes, although requirements designed to improve outcomes for fish are the most common followed by flow requirements designed for recreation. Flow requirement targets, in part, dictate what the terms need to be and whether the requirement needs to be always met (continuous) or for an average over a certain time period (instantaneous). For example, minimum flow requirements designed to prevent dewatering of endangered salmon redds or mussel beds will likely need to be always met, whereas the intended outcomes of requirements designed for whitewater boating or aesthetics may be satisfied by flows averaged over a certain time period. It is in this latter case where there is some flexibility in the requirement, such that both the letter and the spirit of the requirement can be met (i.e., flows that support safe whitewater boating) even when allocating flows to maximize revenue.

This case study evaluates generation revenue using a two-stage optimization model that incorporates observed and forecasted hydrologic information, plant release capabilities, and uses hourly day-ahead (DA) and real-time (RT) electricity market prices to minimize the difference between prices to maximize revenue. This demonstration does not explicitly evaluate environmental outcomes. Instead, it represents a situation where environmental outcomes would have been assessed a priori by participants in a hydropower regulatory proceeding and generation revenue is maximized within those rules.

4.1.1 Brief Methods

To enable revenue-optimized environmental flows, a prototype algorithm was created that allocates hydropower generation using DA pricing signals and RT market prices within the bounds of environmental flow requirements to maximize revenue from electricity market participation (Figure 15). In this demonstration, the tool is implemented for a hypothetical hydropower plant using flow (both overserved and forecast) and California Independent System Operator (CAISO) locational marginal price (LMP) data corresponding to Trinity River above Coffee Creek near Trinity Center, California. This location was selected because 1) availability of observed and forecast flow data, 2) linkages between the power system and environment in this area are of interest, and 3) this location does not require proprietary information from an existing power plant. A set of synthetic data was then prepared to conduct the demonstration based on hypothetical environmental flow and storage requirements for the observed range from flow data. The tool enables more accurate valuation of a single-reservoir system and can compare multiple scenarios defined by a conceptually intuitive set of inputs to assess outcomes across scenarios.

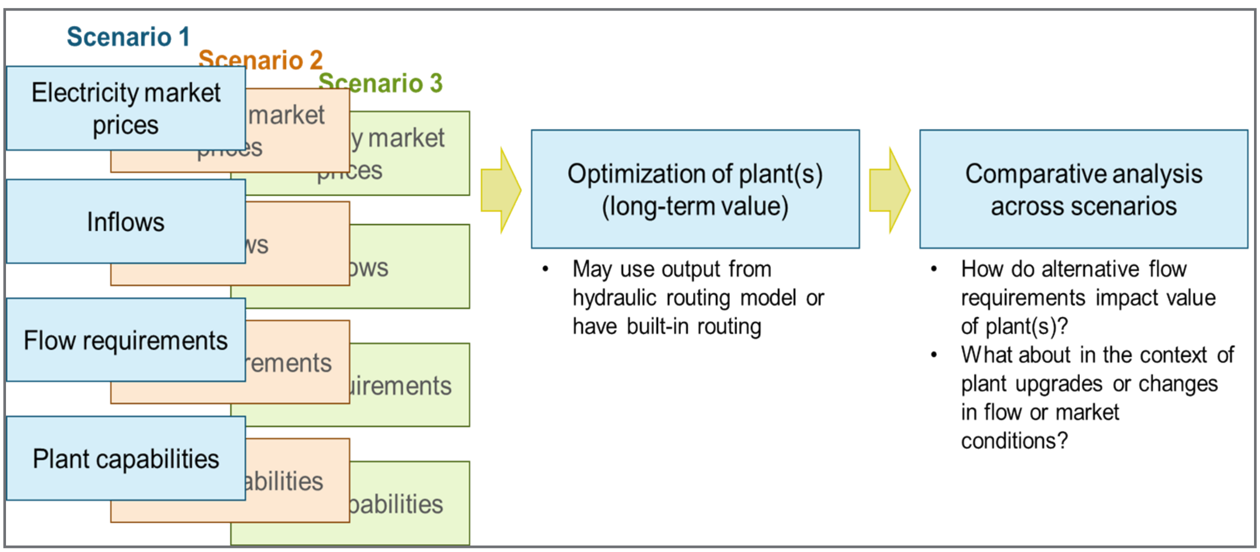


Figure 15. Hydropower Flexibility-Valuation Tool

We then used the tool to describe monthly and hourly generation revenue from flow patterns designed to represent the following representative scenarios: (a) run-of-river and peaking modes of operation; (b) plant capabilities (e.g., reservoir size of generation capacity); and (c) including inflow forecasting in generation planning or not. The tool's optimization model was designed to consider a single reservoir and corresponding power plant. It captures basic characteristics of each, such as reservoir storage, hydropower plant limitations, and operational considerations such as flow requirements. In this single-reservoir system, the tool is designed to evaluate multiple scenarios encapsulating differences in electricity market prices, water inflows, flow requirements, and plant capabilities using a two-stage optimization method. Figure 16 shows how the model feeds inputs through subroutines. In the first stage, the decision to participate in the DA market is optimized based on a forecasted flow. In the second stage, the decision about RT market participation is optimized based on forecast error and observed flow. Inputs to the tool can include hourly forecasted flow, hourly observed flow, and hourly DA and RT electricity prices. Other input data include power efficiency and power-generation rule, ramping rate, flow restriction based on type of year, and maximum hourly change in water spilling. Elevation head can usually be approximated to be fixed.

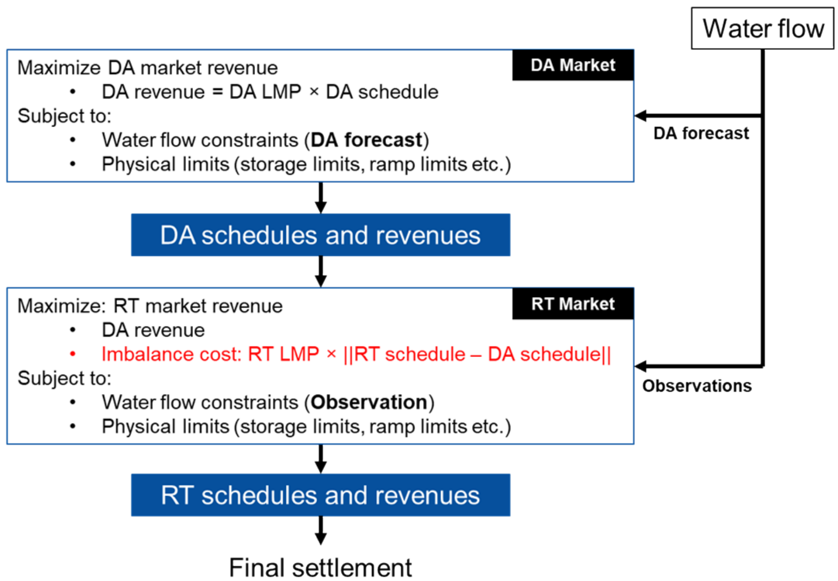


Figure 16. Process Flow of the Two-Stage Revenue Optimization Model

This model is designed to reflect competitive electricity markets with a two-settlement system that consists of a DA forward market and a RT spot market. This model implements a two-stage optimization method to provide accurate assessment of revenue difference caused by environmental-related flow related constraints (Figure 16). The environmental flow constraints are included in both stages of optimization. The DA energy market lets market participants commit to buy or sell wholesale electricity one day before the operating day to help avoid price volatility. The RT energy market lets participants buy and sell wholesale electricity during the operating day. For example, in CAISO the DA market closes at 10 a.m. one day prior to RT, and the imbalance caused by uncertainties are corrected in the RT market. The clearing price in the DA market occurs once per day, whereas the clearing price in the RT market occurs every five minutes. For our tool, the market clearing price is defined as the price where the demand for electricity by consumers is equal to the electricity that can be generated at that price; it is the price where supply and demand are equal. Market operators collect bids from market participants and clear the markets using unit-commitment and economic-dispatch models, which give the locational marginal prices (LMPs) for energy at each node. The revenue of a hydropower plant comes from selling energy to the electricity market, which includes forward transactions in the DA market and delivery of electricity in the RT market.

In this two-stage revenue optimization method, the decision to participate in the DA market is optimized based on a forecasted flow (Figure 16). The objective function in the first stage (DA market) aims to maximize the total generation of all hydropower plants during the planning horizon considering environmental flow and physical limit constraints (e.g., storage limits, ramp limits). In the second stage, the decision about RT market participation is optimized based on forecast error and observed flow. The objective function aims to minimize imbalanced energy costs caused by deviation of actual generation while maximizing the revenue for monthly operations on an hourly timestep. The plant operator determines the optimal schedules by maximizing total revenue based on hourly water inflow. Because of forecasting errors of water flow, the DA schedules usually differ from the RT schedules, which are settled by imbalanced costs based on RT prices.

Environmental flow can be applied in the model to allow comparison of multiple potential flow or operational regimes. Examples of the types of flows that can be simulated include minimum instream, ramping rate limits, hydropower output limits, and storage constraints. The regulatory requirements on stream releases can be defined as reservoir operating ranges and targets, as well as license and contract requirements under different water availability conditions (e.g., wet, normal, dry). These include minimum instream flow requirements, water rights, and reservoir-release capacities. A reservoir's hourly water-balance constraints determine flow release based on minimum and maximum water-storage requirement by hour. Ramping rate limits are determined by maximum hourly flow variations.

Scenarios implemented in the tool are defined by several factors, including (1) operational mode (e.g., environmental flow considerations), (2) hydropower plant configuration (e.g., reservoir and powerhouse), and (3) hydrology and market (e.g., inflow forecasting, inflow observations, and electricity price signals). Three examples are provided to demonstrate functionality within each of these categories, with only a small set of varied parameters to demonstrate the effect of those parameters. In real applications (e.g., as part of FERC proceedings), scenarios may be constructed and compared that utilize functionality across the categories.

The example demonstrating operational mode considerations looks at the effect of varying operational regimes on revenue. The three scenarios represent the span of flexibility a hydropower plant may have, from no flow constraints to natural variability, with a scenario in between of flow constraints representing a realistic set of requirements (Table 4).

Table 4. Operational Mode Example

Scenario name	No flow constraints	Flow constraints	Natural variability
Power plant capacity	120 (MW)	120 MW	120 MW
Minimum storage requirement	673 (acre-feet)	673 acre-feet	None
Maximum storage requirement	1140 (acre-feet)	1140 acre-feet	None
Maximum hourly up-ramping and down-ramping rates	None	±10% of hourly reservoir water release	None
Maximum water spill rate fluctuation	None	±100% of hourly water spillage	None
Forecasting method	Upstream HydroForecast*	Upstream HydroForecast	Upstream HydroForecast

*Palmer 2021

The example demonstrating the effect of hydropower plant configuration focuses on reservoir storage limits. The three cases considered are no storage, baseline storage, and increased storage (Table 5). In this example, only minimum and maximum storage are varied among scenarios and there are no changes in ramping rates or spill rate variability among scenarios. Input data utilized economic impact of reservoir/storage size and constraints. The base storage scenario has five days of storage, no storage has daily inflow and outflow being approximately equal, and increased storage has 10 days of storage.

Table 5. Hydropower Plant Configuration Example

Scenario name	No storage	Baseline storage	Increased storage
Power plant capacity	120 MW	120 MW	120 MW
Minimum storage requirement	None	673 acre-feet	673 acre-feet
Maximum storage requirement	None	1140 acre-feet	2280 acre-feet

Scenario name	No storage	Baseline storage	Increased storage
Maximum hourly up-ramping and down-ramping rates	±10% of hourly reservoir water release	±10% of hourly reservoir water release	±10% of hourly reservoir water release
Maximum water spill rate fluctuation	±100% of hourly water spillage	±100% of hourly water spillage	±100% of hourly water spillage
Forecasting method	Upstream HydroForecast	Upstream HydroForecast	Upstream HydroForecast

The example demonstrating functionality related to hydrology and market focuses on forecast product used for making DA market commitments. The inputs for this example are the same as the baseline storage case (as shown in Table 5), with the following forecast scenarios

- Perfect foresight that assumes the power plant operator has perfect foresight into the future and the forecasts used in the DA market equal exactly the observations in the RT market.

- Persistence forecast uses recently observed flow values as an estimate of future flows. The persistence forecast used in this scenario was created by averaging all instantaneous U.S. Geological Survey gage (11523200 Trinity River above Coffee Creek near Trinity Center, California) observations of streamflow taken within the 24 hours proceeding the forecast issue time. That average value is applied as the forecast value for all steps in the issued forecast.

- HydroForecast (median) uses long short-term memory networks to generate long-term (i.e., up to 10 days ahead) to short-term (hour-ahead) probabilistic water-flow forecasts in the form of percentiles.

The prediction model used in this research has three main input sources:

1. Weather forecasts (from the National Oceanic and Atmospheric Administration's Global Forecast System model and the European Centre for Medium-Range Weather Forecasts)

2. Near-real-time observations of the land surface such as snow cover, vegetation growth, and day and night land surface temperature (primarily derived from satellites operated by the National Aeronautics and Space Administration)

3. In situ streamflow observations from the U.S. Geological Survey.

These inputs are observed at up to an hourly frequency and aggregated over the entire drainage basin. At each timestep (in our case each hour or day), the long short-term memory takes in new inputs, updates a set of internal states it maintains that represent the hydrologic conditions of the basin, and then outputs a prediction for the current timestep. The model is designed to output the full probabilistic range of values for each model timestep, which can be useful to users in managing risk and using this information in downstream models. This scenario takes the DA median HydroForecast value as the input to the DA scheduling model.

4.1.2 Results and Discussion

The algorithm demonstrated here can be used to find flow requirement patterns that yield an energy–environment win-win for long-term planning such as what might be useful in a FERC license proceeding for communicating value propositions. However, this tool can also be useful for short-term planning by providing a method for helping producers conserve water for release on a future day (by incorporating the DA price signals) with the need for generation revenue based on RT market prices.

Of the scenarios we present in this case study, the one that examines differences between modes of operation is perhaps the most useful to understanding generation revenue outcomes associated with run-of-river (as an example of an environmentally driven flow pattern) and peaking (as an example of a profit-driven flow pattern). Interestingly, although the "no flow constraints" scenario provides higher revenue in each month, the differences are relatively modest in most months (Figure 17). For example, differences in revenue between the no flow constraints scenario (i.e., maximum revenue) and the natural variability scenario (i.e., maximum environmental benefit) is 19% across all months, but only vary 5% in April when revenue is highest for the year due to abundant water. However, revenue differences between the no flow constraints and natural variability scenarios are quite sizable in August through December ranging from 30.7%- 59.3%, although revenue generated during those months is much lower than in the spring.

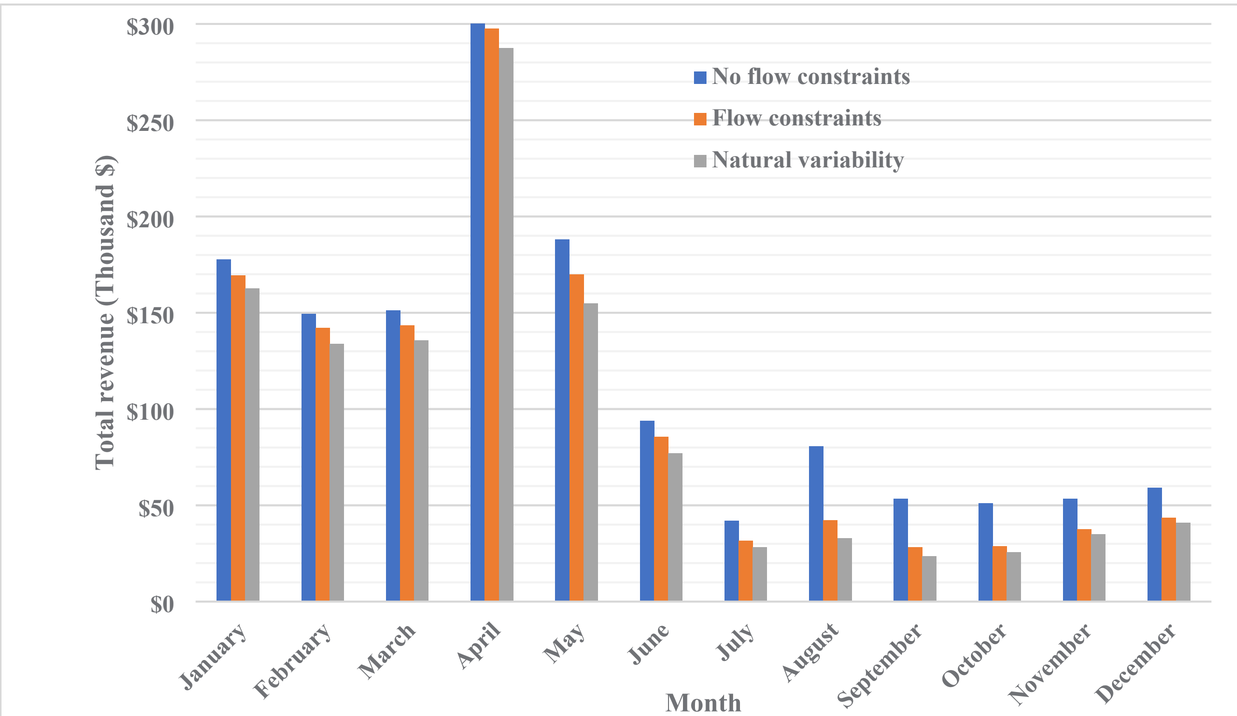


Figure 17. Generation Revenue for Three Flow Constraint Scenarios

On a sub-daily time scale, differences in operations between the three cases vary in a manner consistent with expectations: the no flow constraints scenario varies the most in response to price fluctuations over the course of the day and natural variability is relatively invariant in response to RT market prices because the flow pattern is generated by water availability and is slow to change over the course of the day (Figure 18).

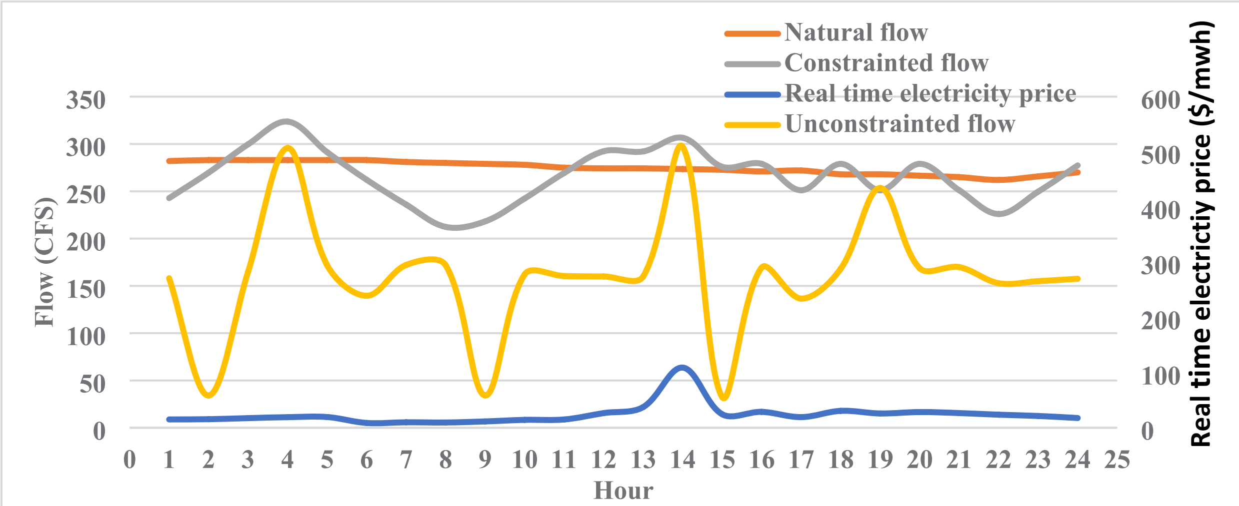


Figure 18. Hourly Water Flow and RT Electricity Price for Three Flow Constraint Scenarios for May 15

Of the scenarios we present in this case study, the one that examines differences between modes of operation is perhaps the most useful to understanding generation revenue outcomes associated with run-of-river (as an example of an environmentally driven flow pattern) and peaking (as an example of a profit-driven flow pattern). Interestingly, although the no flow constraints scenario provides higher revenue in each month, the differences are relatively modest in most months (Figure 19). For example, differences in revenue between the no flow constraints scenario (i.e., maximum revenue) and the natural variability scenario (i.e., maximum environmental benefit) is 19% across all months, but only vary 5% in April when revenue is highest for the year due to abundant water. However, revenue differences between the no flow constraints and natural variability scenarios are quite sizable in August through December ranging from 30.7–59.3%, although revenue generated during those months is much lower than in the spring.

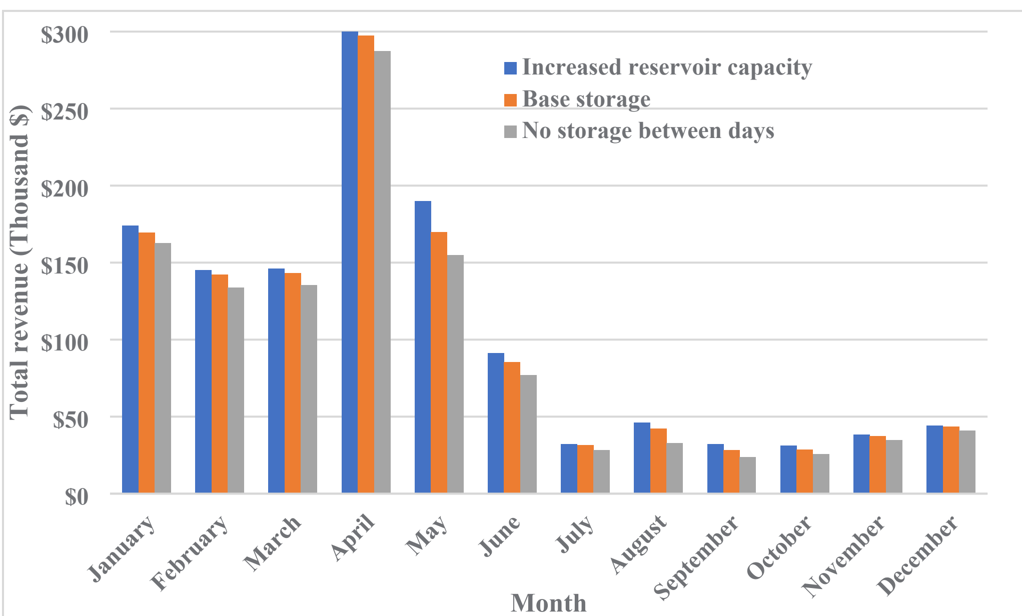


Figure 19. Economic Impact of Storage Scenarios

In general, reservoirs with longer storage times have more severe environmental impacts than reservoirs with low or no residence times, although reservoirs with higher storage have greater flexibility for meeting competing water demands at times of year when water is scarce. Like the findings for the no flow constraints versus natural flow scenarios, this scenario examining the revenue impacts on reservoir storage times also shows little difference in revenue between the higher impact/higher revenue and lower impact/lower revenue reservoir operations. Differences between reservoir operating policies resulted in an average of 6.73% difference in annual revenue with larger differences in May and lower differences in December.

This demonstration of the tool serves to highlight its functionality for assessing different scenarios and tradeoffs. When paired with additional analysis, this may enable identifying generation operations that improve environmental performance without reducing revenue, or at least enable informed discussions around the tradeoffs being evaluated. However, timing of generation is becoming more important for determining the value of generation, storing water today for potential future use can create tension between environmental and revenue objectives, which require their own flow patterns, and the power system requirements for electricity, which are encapsulated in LMPs. Identifying win-win outcomes in this context requires being able to discuss the value of flexibility across stakeholder groups. The intent of the hydropower flexibility valuation tool is to aid in these discussions by providing a straightforward framework that represents how power markets function and dispatch decisions are made and enables building scenarios that are relevant to different stakeholders.

This flexibility valuation tool is highly adaptable across power system and environmental contexts because the information required to set up simulations are relatively straightforward to assemble (flow, price signals, plant capabilities, and flow requirements). Yet, identification of specific win-win scenarios will depend on more information than just what is contained in this tool. It will require understanding how flow regime impacts aquatic species well-being, which is not part of this tool. Therefore, future work will need to link models and tools that relate environmental outcomes with flow to this flexibility valuation tool. These environmental-to-flow relational models are likely to be more regionally specific given that aquatic species and environmental biomes vary significantly between river systems. The role of this flexibility valuation tool is to be an integrator between these regionally specific environmental considerations and the power systems that a given hydropower plant is connected to.

This prototype tool works to assess economic value for flows in individual hydropower facilities in the CAISO market, but additional work is needed to make this tool more generally applicable to hydropower facilities across a broad geographic region. Future research priorities with this tool include creating functionality for implementation in different types of electricity markets (e.g., vertically integrated and competitive) and for different contract types (e.g., main stem, bypass reach, cascade of facilities).

4.2 Rapidly Evaluate Operating Criteria for Win-Wins

For this case study, we explore potential win-win strategies via a set of tools that quantify both environmental metrics downstream of the Glen Canyon Dam (GCD) on the Colorado River, including those in Grand Canyon National Park, and an economic metric for the Western Interconnection (WI) power grid. This case study finds energy–environment win-wins by searching for reservoir and hydropower operations that benefit environment outcomes through evaluation of both fish growth and sediment transport, and by estimating energy outcomes through evaluation of generation revenue. This case study is not intended to produce a final answer to or resolve the GCD operational, water, and/or environmental issues that have been studied by a multitude of researchers, analysts, and modelers for decades. Rather it creates an expansive landscape of plausible operating criteria that is far beyond other studies, and then identifies, in general terms, operating criteria specifications that could provide better solutions than current operating practices.

Past GCD studies have explored alternative operating criteria, but the number of criteria evaluated were limited by computational and labor resources. Many alternative operating criteria beyond those previously evaluated may yield better energy and environmental outcomes. To search for these criteria, Argonne National Laboratory (ANL) created a novel toolset that rapidly generates many thousands of operating criteria and evaluates energy and environment outcomes for each one. Rapid assessments allow for an exploration and evaluation of a vastly larger space than in the past. The toolset constructed and demonstrated in this study leverages existing models and builds new components in a novel framework. This new toolset and processes complement existing methods and models. It does not compete with or replace existing tools.

The GCD demonstration illustrates the types of insights that users can gain from analyzing toolset results. These insights can help decision makers select/formulate improved operating criteria through human-machine interactions. This means that model-derived insights can be used by modelers to finetune successive model runs to improve upon either (1) existing operating criteria or (2) previously discovered win-win solutions.

4.2.1 Brief Methods

The GCD located near Page, Arizona, is a key feature of the Colorado River Storage Project and is approximately 15 river miles (RM) above Lees Ferry (Figure 20). This marks the beginning of 277 miles of Colorado River that flows through the Grand Canyon and then on to Lake Mead, which is formed by Hoover Dam. The 710-foot-high GCD structure forms Lake Powell, which stores 24 million-acre-feet (MAF) of water. This corresponds to several years of water resources for GCD hydropower energy production and more storage capacity than all other Colorado River Storage Project resources combined. In addition to its water-storage value, the power plant at GCD has a total nameplate generating capacity of 1,320 MW, accounting for about 75% of energy and storage resources for the Colorado River Storage Project.

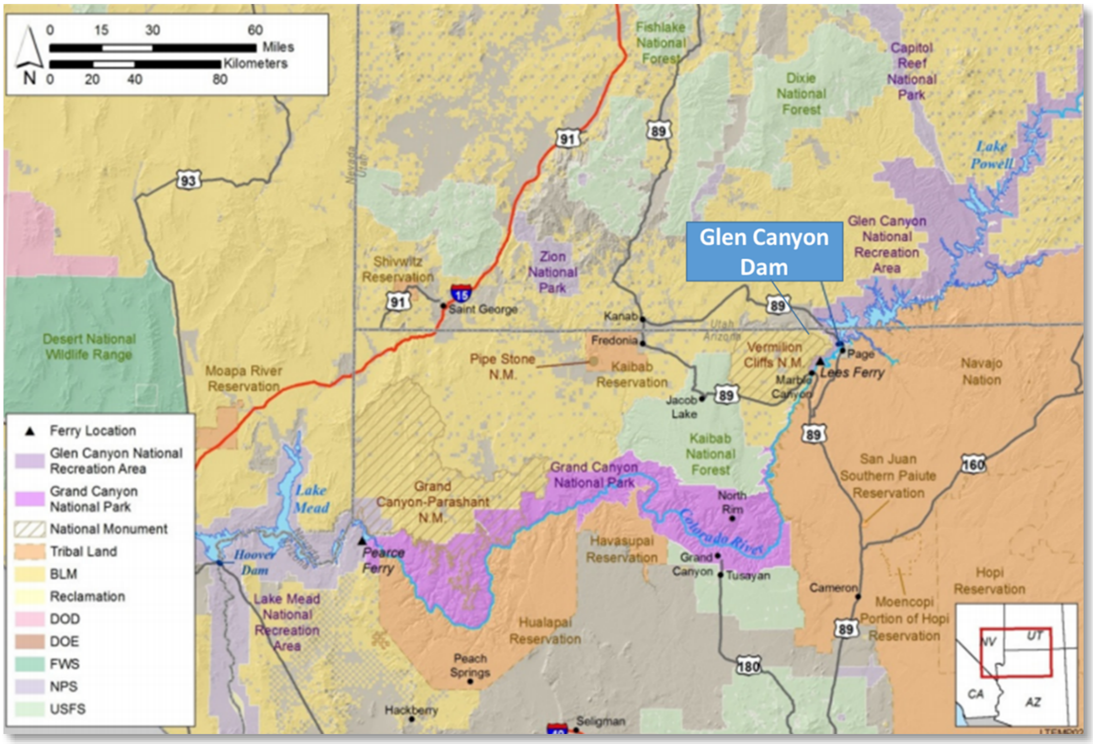


Figure 20. Map of GCD, Lake Powell, and the Colorado River Below the Dam

We selected 2028 as our study year to incorporate into the analysis the impacts of the evolving WI on hydropower operations. Within its geographical footprint, the WI is projected to increase wind and solar power production, retire several coal-fired power plants, and increase its reliance on highly efficient and flexible natural-gas-fired technologies. In total, these measures are expected to substantially reduce greenhouse gas emissions from the power sector, change the behavior of utilities that purchase GCD energy and capacity resources, and modify the utilization of the GCD hydropower resource. These changes are represented in the modeling process via evolving grid LMPs that are in part used to drive use of limited water resources for hydropower production. The toolset is designed for any price pattern such as historical or projected LMPs generated by either sophisticated models or other routines. For this study LMPs are from production cost modeling (PCM), which was used to simulate scheduling and dispatching of the WI power grid. The infrastructure year 2028 WECC's planned generation and transmission capacity as given in the WECC 2028 Anchor Dataset is modeled using a PCM, PLEXOS, to LMP data.

For the demo, we assumed a typical annual water release volume from GCD of 8.231 MAF. This typical volume may change (possibly decrease) in the future due to evolving hydrological conditions and increased water withdrawals from the Upper Colorado River Basin (UCRB). Although we assumed an annual water release volume of 8.231 MAF, the Win-Win Toolset is designed to model a large range of feasible annual water releases from Lake Powell. The modeling frameworks used by the toolset consists of three major parts. The first creates numerous (e.g., hundreds of thousands) of hourly water release patterns during a day and then, for each daily pattern, estimates associated economic and environmental implications using new algorithms and existing models from previous studies of the GCD and UCRB system. The second focuses on the monthly and daily allocation of GCD water release volumes and searches for win-win operations. The third creates two-dimensional Pareto frontiers that show tradeoffs between two objectives.

For this demo, criteria specified under the 2016 Long-Term Experimental Management Plan (LTEMP) Environmental Impact Statement (EIS) Record of Decision (ROD) are used for the business-as-usual (BAU) case and serve as the benchmark criteria from which other operating criteria are compared (see Table 5). For the win-win model demo, the BAU benchmark case assumes a typical GCD annual release of 8.231 MAF. In actual operations, the annual water target mainly depends on elevation in Lake Powell, temporal inflows, and water delivery obligations. Monthly water releases, however, sometimes deviate from the plan to support a LTEMP experiment. For example, more water is shifted into a month when a high-flow experiment is conducted and, to comply with the annual release targets, less water is released during one or more non-high-flow experiment months.

Table 6. Operating Constraints Under the 2016 ROD (applied October 2017 through the present)

Operational Constraints	2016 ROD Flows (From October 2017)
Minimum release (cfs)	8,000 from 7:00 a.m.–7:00 p.m. 5,000 at night
Maximum release (cfs)	25,000
Daily fluctuations (cfs/24 hr)	depending on monthly release volume
Ramp rate (cfs/hr)	4,000 up and 2,500 down

Daily fluctuation (change) equal to ten times the monthly volume (in TAF) in June–August, and nine times the monthly volume (in TAF) in other months; daily range not to exceed 8,000 cfs.

The maximum release rate is limited to 25,000 cfs under the 2016 ROD operating criteria. Maximum flow rate exceptions are allowed to avoid spills and/or conduct flood releases during high runoff periods. Under these very wet hydrological conditions, when the average monthly release rate is greater than 25,000 cfs, water must be released at a constant rate during the entire month.

Nonbinding agreements restrict Western Area Power Administration daily water release volumes during each month of the year. These guidelines are referred to as intra-monthly daily restrictions and do not change during the year; that is, daily release volume restrictions remain the same regardless of the month. These guidelines include:

- Weekday volumes are approximately the same each weekday throughout the month
- Saturday, Sunday, and holiday daily release volumes are ≥ 85% of the weekday average
- Saturday, Sunday, and holiday daily release volumes are capped at the weekday average.

For this case study, metrics used to identify operating criteria that result in environmental and hydropower economic win-win solutions for the year 2028 relative to levels computed under the 2016 ROD criteria include the following:

- <u>Economic Energy Value</u>: Historically, the majority of the GCD hydropower plant economic value is from its energy production. For this study, the projected economic value of GCD for the year 2028 is calculated by summing, over all hours of the year, GCD hourly energy production multiplied by the corresponding hourly LMP. Large annual water releases that drive its turbines, coupled with its high output capacity, enable the power plant to generate relatively large amounts of energy at times of the day when it has the highest value (i.e., LMPs). Although we only use one economic metric in this case study, other operational value streams such as ancillary services and capacity metrics can be accommodated by the toolset.

- Humpback Chub (HBC): The HBC is an endangered native fish of the Colorado River that evolved around 3-5 million years ago.[2] For this analysis, we use an existing HBC bioenergetics model that incorporates water temperature and flow to estimate growth at two key habitats in Grand Canyon National Park: 61 RM and 225 RM downstream of GCD. In general, slower river flow rates result in warmer water temperatures at these two sites and promote faster growth rates, especially during warm/hot summer months.

- Sediment Transport**:** Sediment controls the physical habitat of riverine ecosystems downstream of GCD. It is deposited or eroded from the various environments in the Colorado River, and sediment suspended in water determines water clarity. Changes in the amount and areal distribution of different sediment types cause changes in river channel form and habitat. For this case study, we estimate metric tons of sediment transport in the Lower Colorado River. It is primarily a function of water flow with sediment transport that increases with faster water flows.

The win-win tool methodology used in this case study employs a comparative approach. Essentially, metric values computed for the BAU operating criteria serve as a benchmark against which other operational regimes are evaluated. A comparative analysis approach such as this one has been used to measure changes in environmental and economic outcomes associated with alternative hydropower resource operating criteria in the UCRB for more than three decades.

4.2.2 Results and Discussion

Albeit at a much lower level of granularity and detail than some previous studies on the GCD system, the methodology discussed in this report explores many thousands of different water release patterns in search of win-win operating criteria—a scale that was previously not possible to be evaluated due to computational and human resource limitations. This ability to rapidly generate hundreds or thousands of potential operating criteria and quantitatively evaluate potential environmental and economic outcomes of those criteria has the potential to enable operational solutions that improve both environmental and economic outcomes.

Over the past 30 years, numerous financial and economic analyses have been conducted on various GCD operating criteria, experimental water releases, and the marketing of GCD hydropower plant resources. This includes LTEMP EIS studies that analyzed only six primary alternative operating criteria along with non-action operating criteria. None of the alternatives resulted in a win-win solution and, if implemented, only one was expected to provide small hydropower benefits (e.g., lower future energy scenario customer rates by about 0.27 percent).

A key feature of the new toolset methodology that distinguishes it from those used for past GCD studies is that it examines a very large number of alternative operating criteria over a broad range of feasible options in combination with monthly, daily, and hourly water release profiles in the search for win-win solutions. Because we examine a very large landscape/operational space, metrics for this vignette demonstration are, by necessity, measured with less accuracy as compared to very detailed modeling performed in support of previous analyses. Therefore, once potential win-win dam operations are identified, expanded and more detailed analysis should be conducted to determine the validity of the model's solutions. After we gain insights into the general types of operations that lead to win-win results, further adjustments to the criteria can be made to address other considerations outside of the modeling process that are difficult to measure but still important.

[2] https://www.coloradoriverrecovery.org/general-information/the-fish/humpback-chub.html

The Win-Win Toolset was used to search for solutions that simultaneously increase GCD hydropower economics and HBC growth at both 61 and 225 RM. Over 81,000 random runs were performed with an annual GCD release of 8.231 MAF. All complied with 2016 ROD hourly minimum and maximum water release rate limits and both hourly up- and down-ramp rate restrictions. The daily change limit also remained in place and did not deviate from the monthly levels used in the BAU case. These runs, however, differed from the BAU case as follows:

1. Monthly water release volumes (i.e., intra-annual criteria) were allowed to deviate from the BAU case

2. Relative daily release volumes deviated from those used it the BAU case, but remained within the nonbinding limits that restrict Saturday and Sunday release volumes to be at least 85 percent of the average weekday release

3. Selection of the "best" hourly release patterns to use for each day type is based on a multiple objective that includes both GCD energy production economics and HBC growth rates at RM 225.

Results for 81,000 model runs are shown in Figure 21 as a scatter plot of annual GCD economic value and corresponding HBC growth at RM 225. Each result is relative to the BAU scenario. Note that win-win solutions for power economics and HBC growth at RM 225 also resulted in faster growth at RM 61 (light blue points in the upper-right quadrant). There are, however, also operations that increase HBC growth at RM 226 but not at RM 61.

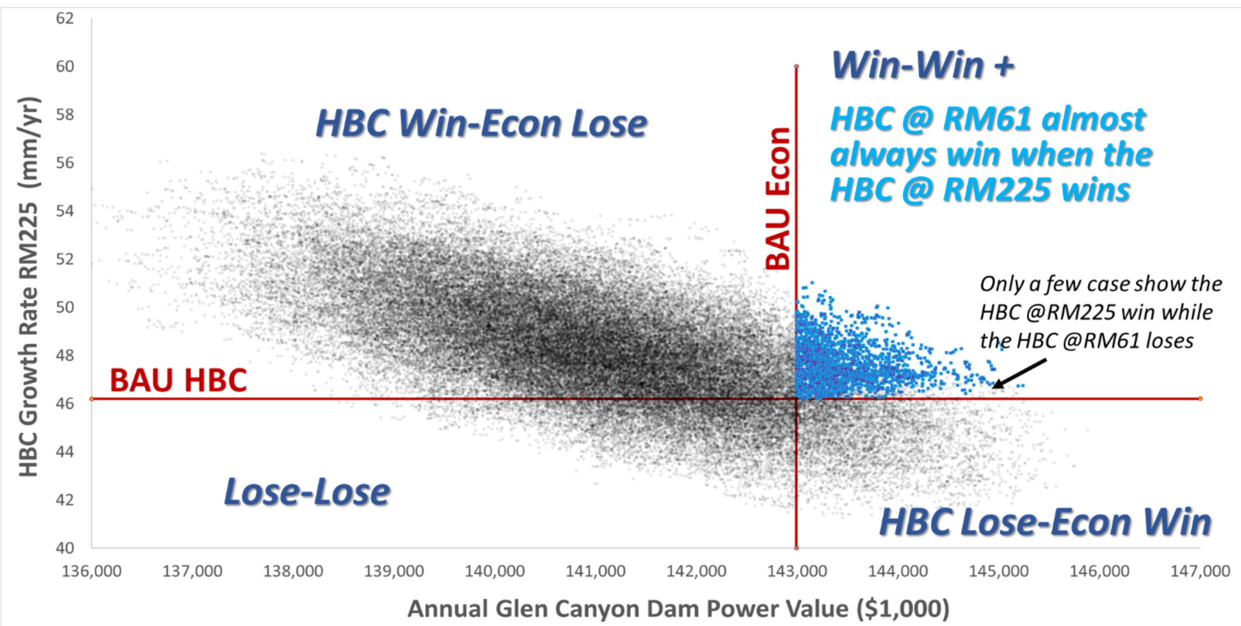


Figure 21. Win-Win Toolset Annual Results Highlighting Random Draws that Simultaneously Improve GCD Power Economics and HBC Growth at Both RM 61 and RM 225

One tool in the Win-Win Toolset creates Pareto frontier of tradeoffs between two metrics. Figure 22 shows monthly release volume patterns for three of these points: (1) max HBC growth at RM 225; (2) win-win outcomes for HBC growth and energy generation value; and (3) max energy generation value. Relative to the BAU case (blue bars), HBC growth is the greatest (top panel) when water releases are high during the winter and early spring months when HBC growth is zero or very low. To balance these higher winter release volumes, water release volumes are lower during other times of the year when warmer low-flow water encourages HBC growth; especially during the summer months and early autumn (e.g., September).

The opposite flow volume pattern occurs when maximizing the value of GCD hydropower energy production (lower panel). To maximize power value, water releases during the summer months and September are higher than the BAU case. Water is essentially reallocated from all other months of the year to support high generation levels when market prices are the most expensive.

Monthly water releases for the win-win case shown in Figure 21 is on Pareto frontier point approximately in the middle of the curve segment that spans win-win solutions. It is a compromise between the two extremes. Relative to the BAU case, more water is released during December and January to take advantage of higher prices during the peak winter load months. These high winter flows have no impact on HBC growth because they do not grow during this those two months.

Monthly release is also relatively high during June and July. These releases also support high economic value because prices are high during these two summer months. These higher flows dampen HBC growth relative to the BAU case. However, lower monthly release during the other times of the year, especially August and September, more than compensate for HBC slower growth during the June and July. More detailed information about the Win-Win Toolset and results for searches with expanded operating criteria landscapes (e.g., alternative intraday limitations such as ramping), under both higher and lower annual water releases, are provided in Appendix F.

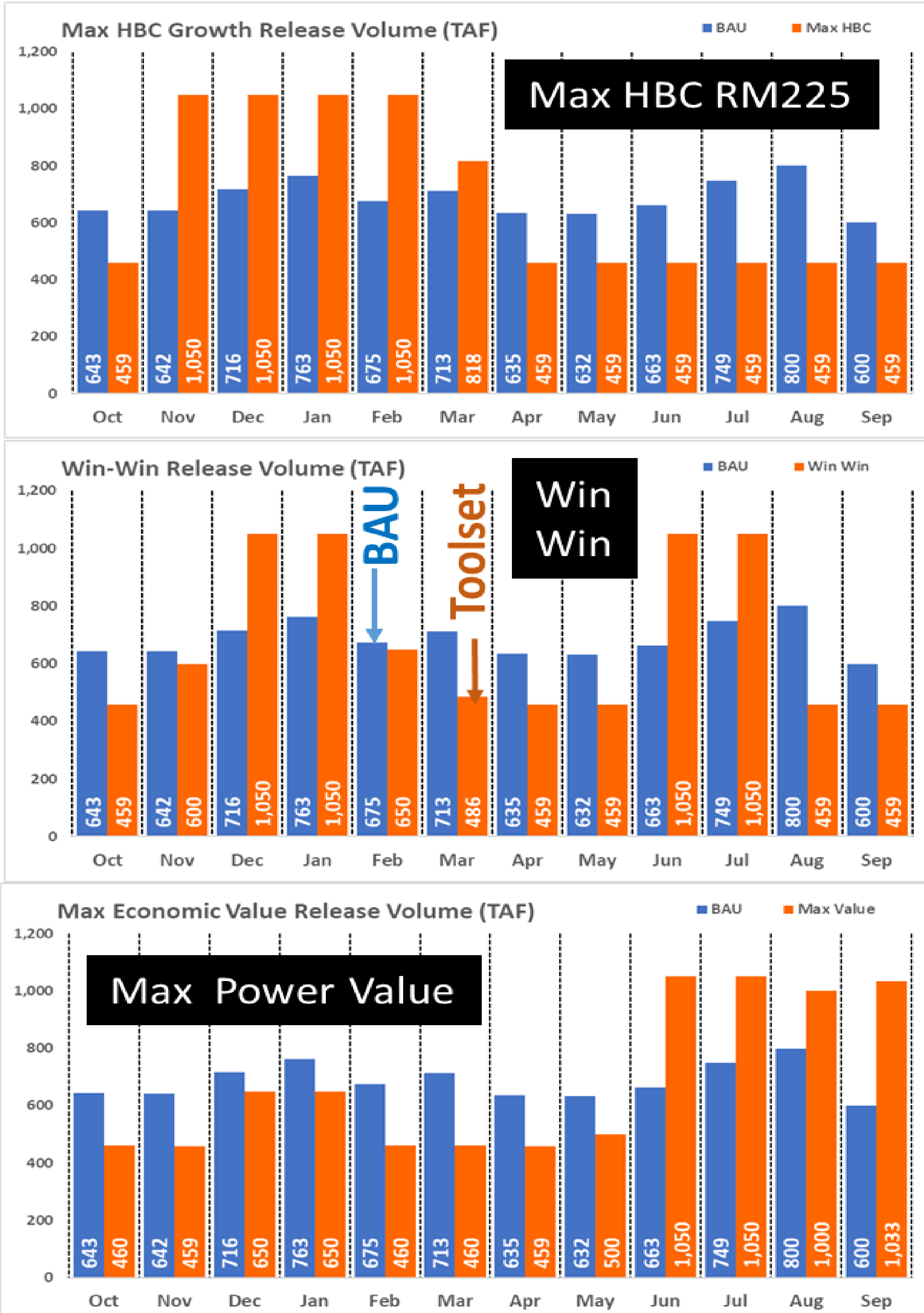


Figure 22. Monthly Release Volumes on the Pareto Frontier of Annual HBC Growth and GCD Hydropower Energy Value

While the model and resource issues explored in this case study are applicable to the GCD system, the general framework of the tools were designed to be generally extensible to hydropower sites across the United States, including sites that must comply with FERC hydropower regulatory criteria. For example, we envision future versions of these tools to evaluate growth of other fish species or potentially evaluate outcomes of resource or water quality issues aside from sediment transport.

The Win-Win Toolset is in the prototype phase of development and the application for the GCD demo site should be viewed as a proof-of-concept application. Future improvements to the toolset could potentially include:

- Developing a smarter win-win search algorithm
- Expanding drives that shape hourly release patterns, including use of multiple weighted drivers
- Expanding the capabilities of the Pareto frontier algorithm to solve for day type release volumes and simultaneously create frontiers for three or more metrics
- Structuring the toolset computer code to solve problems at various levels of granularity and, for many individual processes, run faster and in parallel.

4.3 Policies for Maximizing Fish Survival and Generation Revenue

This case study aimed to demonstrate another way of evaluating energy and environment outcomes to find opportunities that benefit hydropower production and the environment. In this demonstration, we created a set of reservoir policy and fish models based on publicly available information for six dams in the Yadkin-Pee Dee River basin. Specifically, this demonstration focused on understanding the importance of sub-daily, and even sub-hourly, operational flexibility in a hydropower system and the true environmental (fish survival) and hydropower (revenue) tradeoffs. This demonstration provides an example of information that can give improved data to decision makers involved in assessing appropriate operations within defined policies.

4.3.1 Brief Methods

This case study was conducted on the six facilities located in the Yadkin-Pee Dee River Basin in North Carolina and South Carolina (Eastern Interconnection). Reservoir development in the basin includes (from headwaters to mouth) one nonpower facility owned by the U.S. Army Corps of Engineers (USACE), four hydropower facilities owned by Eagle Creek Renewable Energy (ECRE), and two hydropower facilities owned by Duke Energy (Table 7 and Figure 23). This basin typifies many common and challenging aspects of river basin water management such as multiple licensees; diverse landscapes ranging from mountain headwaters to coastal plains; varying natural resource issues such as water supply, fish passage, recreational boating, water quality, and differing balancing authorities; generation capabilities; and generation schedule planning between the two hydropower owners.

Table 7. Summary of Yadkin-Pee Dee Hydropower Projects

Owner	Project Characteristics	Environmental Characteristics	Power System Characteristics
ECRE	Four facilities (215 MW): • High Rock (225,500 ac-ft; 40.2 MW) • Tuckertown (41,000 ac-ft; 38 MW) • Narrows (137,000 ac-ft; 110.4 MW)	• Dissolved oxygen • Species of concern – Freshwater mussels – Upland wildflowers – Bald eagle	• Participates in wholesale energy market • Automated generation control

	• Falls (2,300 ac-ft; 31.1 MW)	• Recreation – Canoe and kayak – Fishing	• Receive inflow from nonpowered USACE dam
Duke Energy	Two facilities (108.6 MW) • Tillery (132,600 ac-ft; 84 MW) • Blewett Falls (27,500 ac-ft; 24.6 MW)	• Dissolved oxygen • Fish passage – American eel – American shad – Atlantic sturgeon – Shortnose sturgeon • Recreation – Canoe and kayak – Fishing	• Vertically integrated utility • No automated generation control • Receive inflow from ECRE facilities so heavily influenced by ECRE decisions

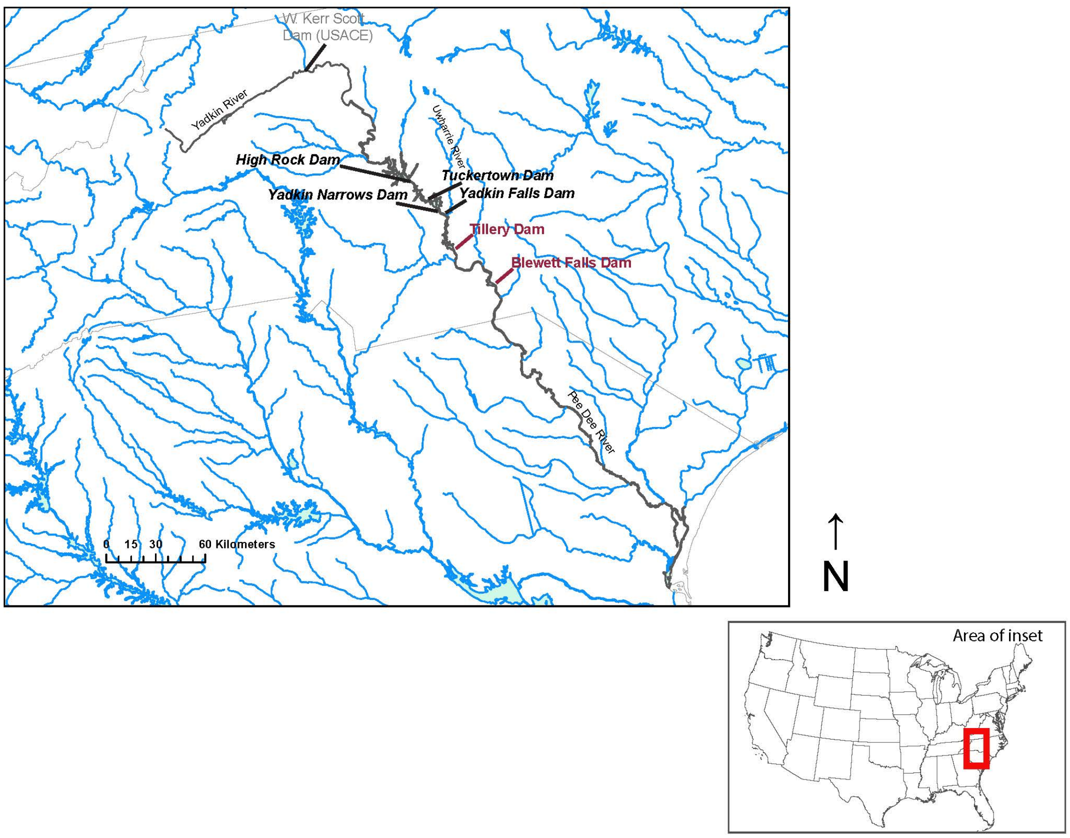


Figure 23. Map of Yadkin-Pee Dee Basin's Dams Including Those Owned by USACE (gray—no hydropower), ECRE (black), and Duke Energy (red)

To evaluate energy-environment tradeoffs and gain a better understanding of the links between power, flow, and the environment in this system, a general framework connecting power generation, flow, and environmental outcomes was developed using 1) a long-term simulation using reservoir policy model and 2) a detailed reservoir, grid, and ecological modeling and evaluation that allows impacts to be assessed at sub-daily time scales. As shown in Figure 24, our framework uses four sets of models/software including Computer Hydro Electric Operations and Planning Software (CHEOPS) for long-range reservoir policy, PLEXOS for DA and RT energy market simulation, Dual-Dynamic Programming (DDP) for optimization of sub-daily flow distribution, and QUANTUS for simulating linkages between flow and first-year smallmouth bass survival as mediated by flow-influenced temperature and prey availability. These independent models are integrated in a sequential fashion, passing the outputs from one model to the next in the framework. More detail on individual model descriptions and sequencing can be found in Appendix G.

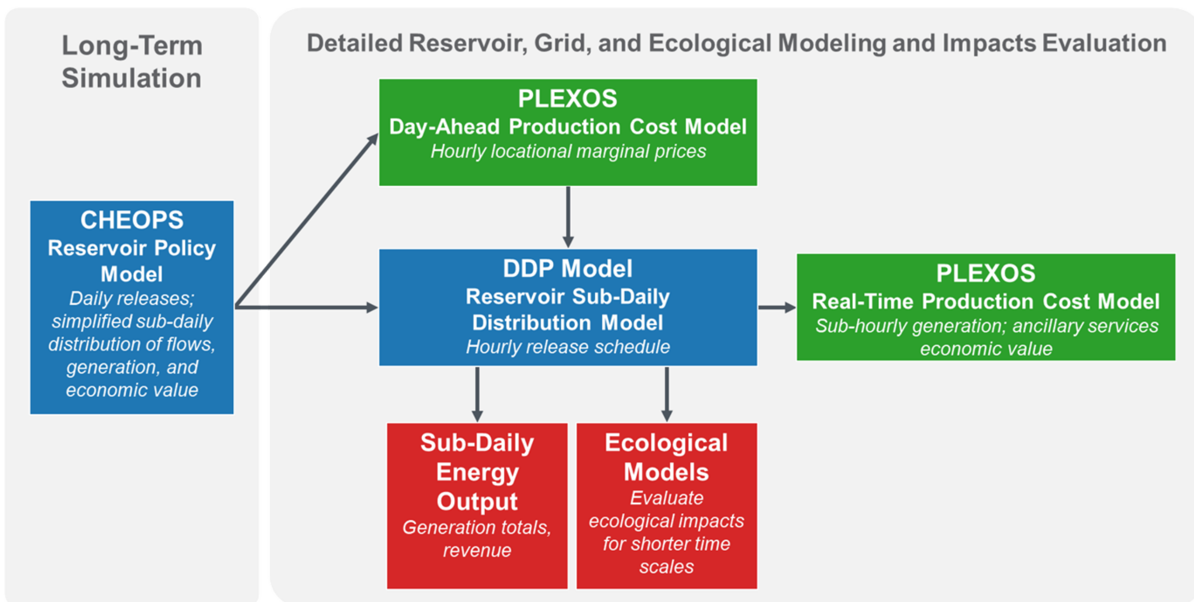


Figure 24. Yadkin-Pee Dee Coordinated Modeling Framework; QUANTUS Model Step Represented by "Ecological Models" Box

The coordinated modeling framework was used to explore operational flexibility for a combination of base cases and alternative reservoir policy scenarios as listed in Table 8. The base case load scenarios simulate three different generation load shapes that reflect current and increasing future renewable contribution levels. These scenarios are then coupled with alternative operating policy scenarios to investigate the impacts of alternative ramping policies. Production cost modeling (PCM) conducted using PLEXOS showed finer transmission details of the Southeast Regional Council to get the DA LMP specifics to the case study power plants. These scenarios are then coupled with alternative operating policy scenarios to investigate the impacts of alternative ramping policies. The hydropower generation for alternative ramping policies were modeled in PCM to understand potential revenue from finer time resolution RT energy markets for providing grid flexibility.

Table 8. Base Case Load Scenario and Alternative Operating Policy Scenarios with Ramp Rate Restrictions

Scenario Name	Base Case Load Scenario	Alternative Operating Policy Scenario
2024 Load-Base Ops	Base 2024 (Current generation)	Base case with current ramping restrictions (300 AF/hr)
2024 Load-Base Ops with Env Policy		Base case with nighttime environmental ramping restrictions (day: 300 AF/hr; night: 25 AF/hr)
2036 Load-Base Ops	Base 2036 (46% renewable capacity share)	Base case with current ramping restrictions (300 AF/hr)
2036 Load-Unrestricted Ramping Ops		Unrestricted outflow ramping at all times (day: 900 AF/hr; night: 200 AF/hr)

Scenario Name	Base Case Load Scenario	Alternative Operating Policy Scenario
2036 Load-Restricted Ramping Ops		Highly restricted outflow ramping at all times (day: 15 AF/hr; night: 10 AF/hr)
2036 Load-Base Ops with Env Policy		Base case with nighttime environmental restrictions (day: 300 AF/hr; night: 25 AF/hr)
2036 Load-Unrestricted Ramping Ops with Env Policy		Unrestricted outflow ramping during daytime (day: 900 AF/hr; night: 25 AF/hr)
2050 Load-Base Ops	Base 2050 (54% renewable capacity share with 2036 output power production)	Base Case with current ramping restrictions (300 AF/hr)
2050 Load-Base Ops with Env Policy		Base case with nighttime environmental restrictions (day: 300 AF/hr; night: 25 AF/hr)

This approach focuses on sub-daily variation to assess the potential benefits of allowing greater intraday (and intra-hour) flexibility. Conventional FERC-type policy evaluations often use assumed or simplified representations of grid needs at the sub-daily operational level and focus on long-term policy impacts. Impact evaluations of generation projections or grid needs are often considered independently from policy evaluations. While appropriate for long-term simulations to understand the impact of different operating policies across the range of natural variability, this often does not consider the need to provide flexibility on shorter time scales in the current or future system beyond basic consideration of ramp rate limitations with little detailed ecological modeling. By modeling the energy and ecological systems at a detailed level, we expect that greater insights can be gleaned regarding impacts of constraints on revenue streams and the energy and ecological systems to help identify new opportunities for win-win reservoir policies.

For this study, three scenarios comparing flexible and nonflexible generation, with and without environmental flow requirements (no nighttime ramping), were examined representing the current renewable (wind and solar) capacity share (year 2024: 20%), an intermediate level of renewable energy share (year 2036: 46%), and a high degree of renewable energy share(year 2050: 54%; Figure 25) for a representative wet year (using 2013 hydrologic data) and dry year (using 2012 hydrologic data). Figure 26 panels a and c show total daily generation by facility and panels b and d show total power generation by month and facility.

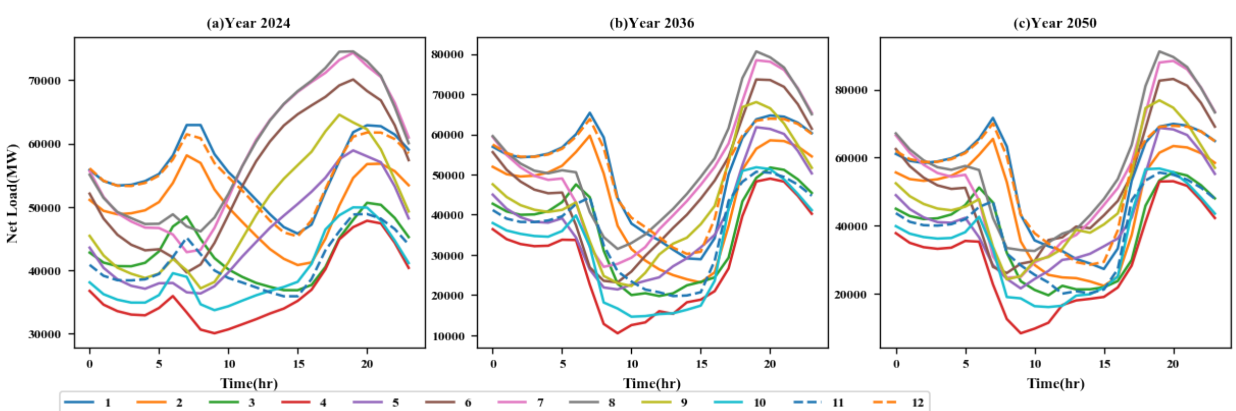


Figure 25. Average Monthly Load Shapes for (a) Year 2024, (b) Year 2036, and (c) Year 2050

These years were chosen to better understand how power system (generation and revenue) and environmental outcomes (young largemouth bass survival) will respond to environmental regulations that limit hydropower operational flexibility. Detailed hourly modeling was conducted for year 2036 to better understand how generation revenue and young largemouth bass survival would respond to flexible generation designed to follow LMPs both with and without nighttime flow restrictions. Nighttime flow restrictions in this case meant ramping hydropower production up or down was not allowed from sundown to sunrise.

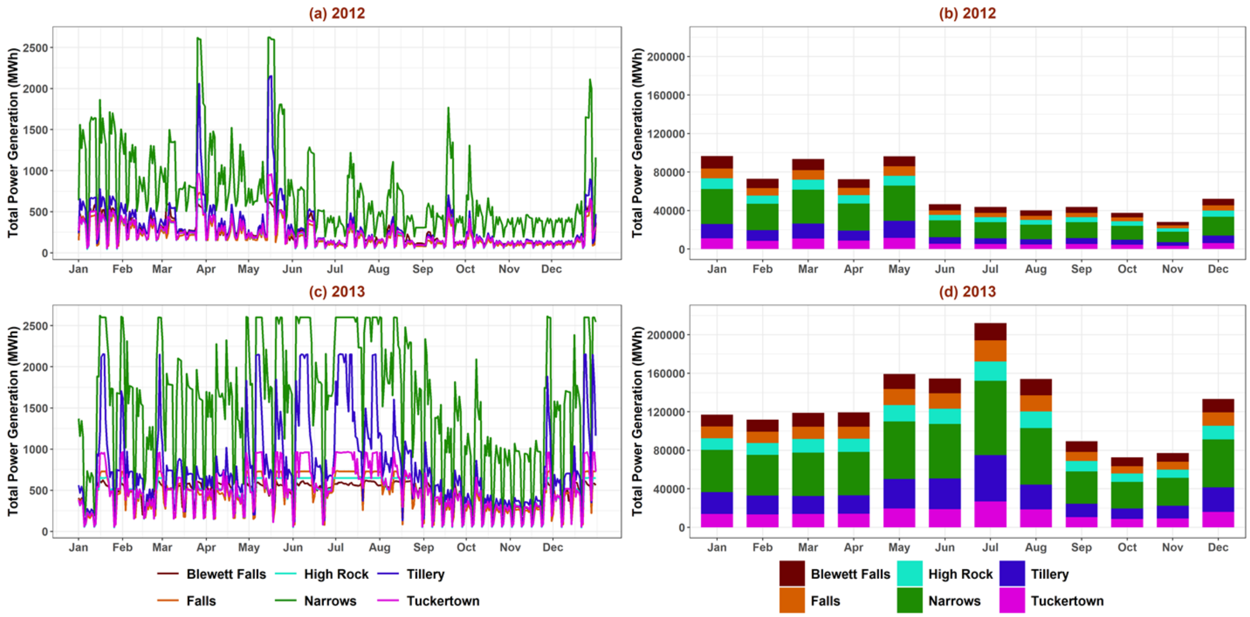


Figure 26. Yadkin-Pee Dee Hydropower Generation for a Dry Year (2012) and a Wet Year (2013)

4.3.2 Results and Discussion

This case study demonstrated that across the scenarios explored here, both energy and environmental objectives can be met while generating higher revenue compared to the CHEOPS model. In this case, restricting nighttime flow fluctuations allows for higher young largemouth bass survival in the 2024 scenario (Figure 27). This scenario allows for flexible generation during the day, following LMPs, while restricting this type of operation overnight when flexibility is less crucial for grid stability and less lucrative. This was apparent during the 2024 high-flow scenario where young largemouth bass had significantly higher survival with nighttime environmental flow restrictions, although nighttime restrictions also consistently showed higher (but not significantly higher) survival across early life history stages. While modeling additional environmental outcomes and scenarios was beyond the scope of this study, other energy–environment win-wins likely could have been identified.

In this case study, we were able to discern similar trends in impacts from reservoir operating policy across the three LMP datasets representing current and future grid needs. Ultimately, we showed that imposing the nighttime environmental policy using the optimization approach provided adequate flexibility in reservoir operations to respond more effectively to grid needs while maintaining desirable flows for fish species. This finding was true across the 2024, 2036, and 2050 scenarios. While we recognize that the benefits for fish species were small, we also realize that further iterations between policy changes and evaluation would allow us to refine the policy in such a way that we would expect greater benefits. There is opportunity to develop scenarios representative of other systemwide uncertainties, such as climate change scenarios, apply this framework, and identify policies that show improvement or desirable results across multiple plausible scenarios rather than develop policies that are tailored to specific representations of uncertainty.

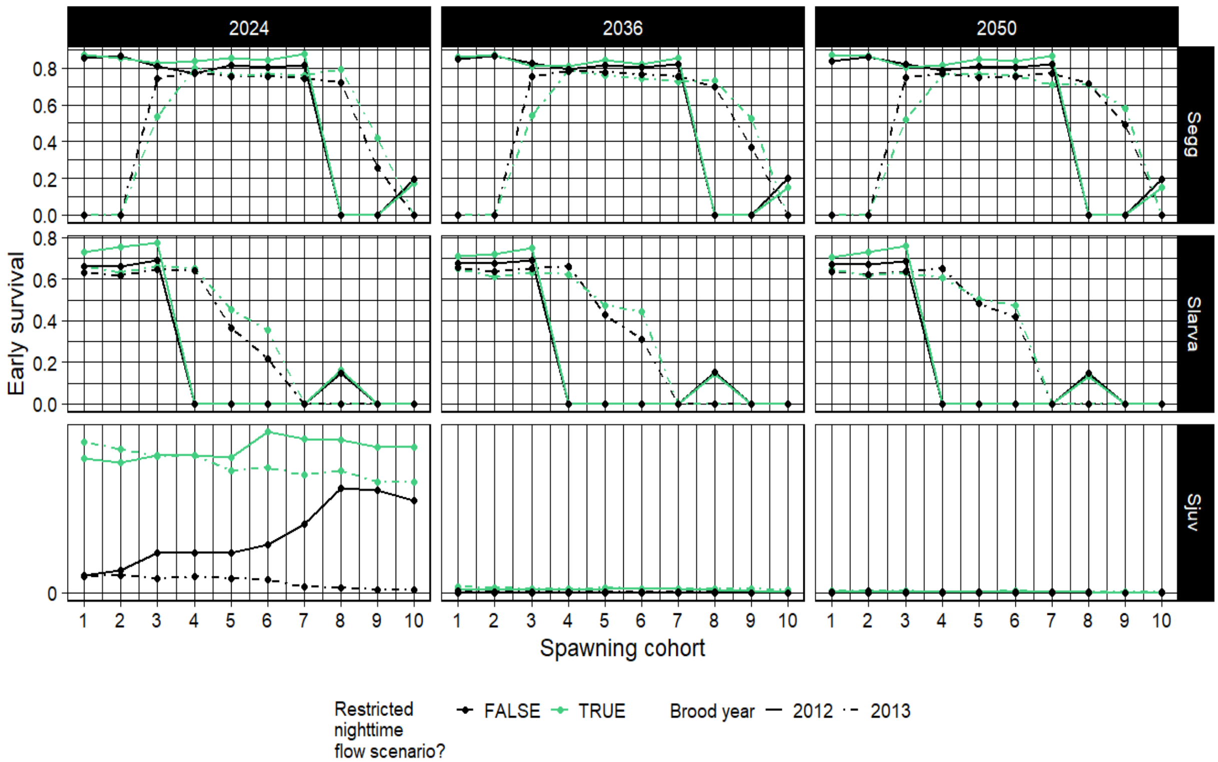


Figure 27. Early Life History Survival Under Nighttime Flow Ramping

High flow was identified as the most dramatic source of decreased survival for largemouth bass across their early life history, although cold shock also caused decreased survival for eggs and larvae. Figure 28 shows survival due to six causes under different operational scenarios for each of three early life stages. Lines connect median values averaged across spawning cohorts for each cause. Individual points represent different brood years. Abbreviations are Env = nighttime ramping restriction, NoEnv = no nighttime ramping restriction, EnvAHigh = unrestricted daytime ramping with nighttime ramping restriction, NoEnvAHigh = unrestricted daytime ramping with no nighttime ramping restriction, and NoEnvALow = load-restricted ramping. These sources of decreased survival may differ between species, life stages, locations, or times of year fish are spawning. However, partitioning environmental impacts in this finer scale may provide additional opportunities for energy–environment win-wins.

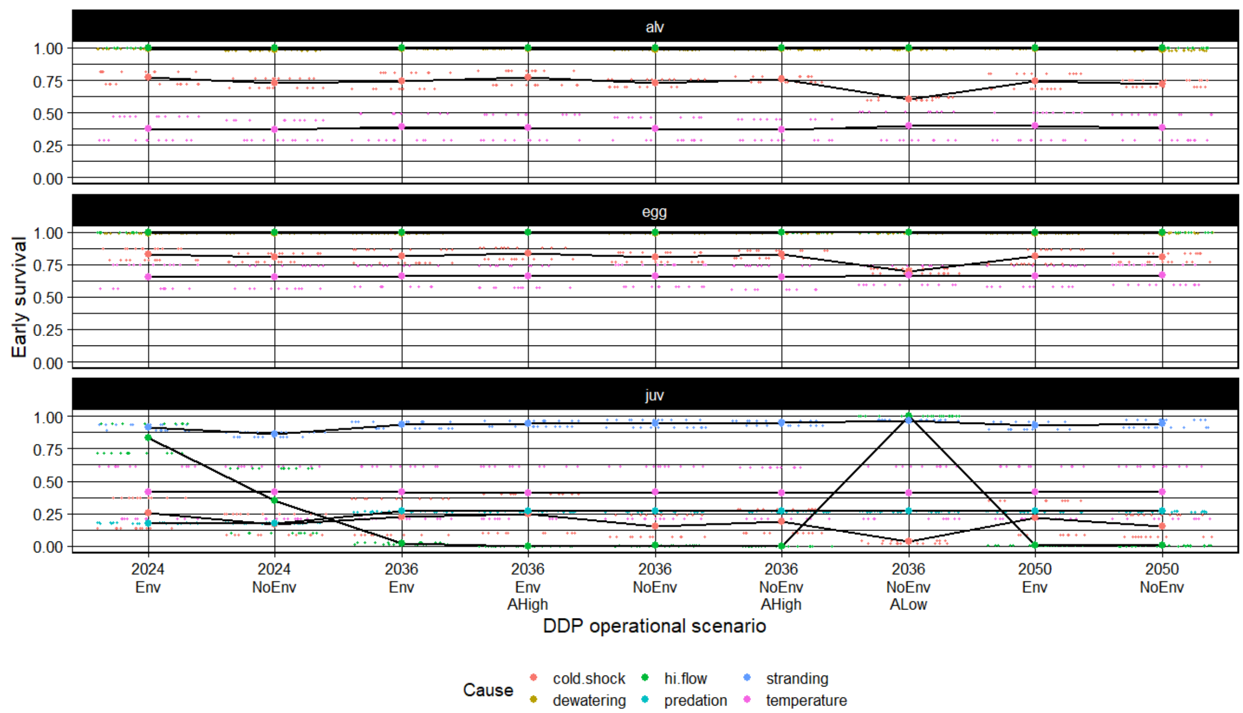


Figure 28. Survival Under Different Operational Scenarios

Differences in generation between the CHEOPS and DDP models within year types (i.e., wet year, dry year) had only modest differences, but differences in revenue between wet years and dry years and between the models were large (Figure 29). All scenarios were held to the same approved hourly generation budgets, yet we were still able to identify operations yielding higher revenue by using the DDP optimization model that would help to target generation during times with high LMPs. By operating the reservoirs in a more coordinated fashion, the optimization helped to gain generation flexibility and benefit to the system within defined constraints. This has implications for other systems that may currently be operated in a simplified manner but could benefit from more sophisticated operational decision-making to satisfy both grid and environmental needs.

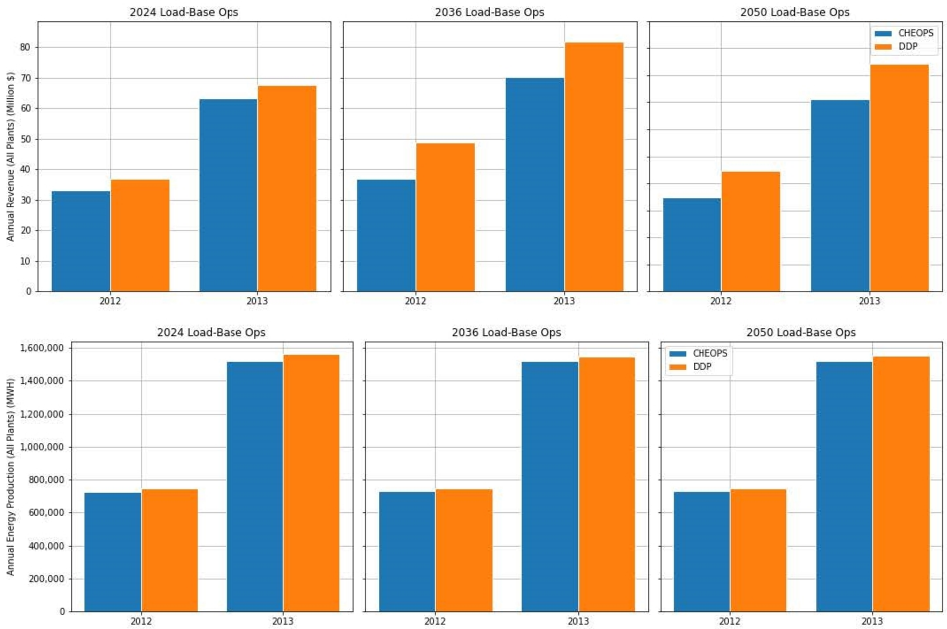


Figure 29. Annual Revenue (top) and Energy Production (bottom) for Base Case Load Scenarios Using CHEOPS (blue) and DDP (orange) Models

The DDP model also made it possible to find energy–environment win-wins within wet and dry year simulations of load scenarios for year 2036. In this future renewable energy generation projection, unrestricted daytime ramping with no nighttime ramping had the third highest revenue of the six scenarios for the wet and dry year simulations, although there was, again, limited differences among scenarios in generation (Figure 30). In fact, the base ops with no nighttime ramping policy—still an environmental benefit— also had higher generation revenue than the CHEOPS base operations and restricted ramping operation for both wet and dry year simulations.

In FERC licensing efforts, rule-based simulation models (like CHEOPS) are often used to represent operating policy and evaluate how reservoir systems operate across many years. These models can make broad assumptions regarding power generation and the needs of the grid that may obscure finer-scale environmental impacts. Although appropriate for understanding the total generation for a system, the simplifying assumptions can limit understanding how the needs for hydropower generation shift over time and may obscure finer-scale environmental impacts and changes over time. For instance, with greater renewable share, we anticipate that the value of hydropower will shift from solely being of interest for providing direct generation to its ability to provide supporting services through flexibility. Likewise, the simplification of rule-based simulations can also limit discovery of win-win or win-no loss outcomes and evaluation of tradeoffs. For example, by restricting peaking to daytime hours with the highest LMPs, the DDP model was able to find a solution that both benefited young largemouth bass survival and increased revenue compared to the rule-based model.

Interestingly, we found LMP datasets that span from the present day into the future with different assumptions regarding degrees of renewable buildout to be useful even without executing site-specific PCM modeling. While we recognize the limitations of using LMPs to inform the complete value that hydropower currently provides or will be asked to provide in the future, even generalized LMP datasets can be used in a manner like that employed for this case study to assess how the value of generation could change in the future for an individual facility.

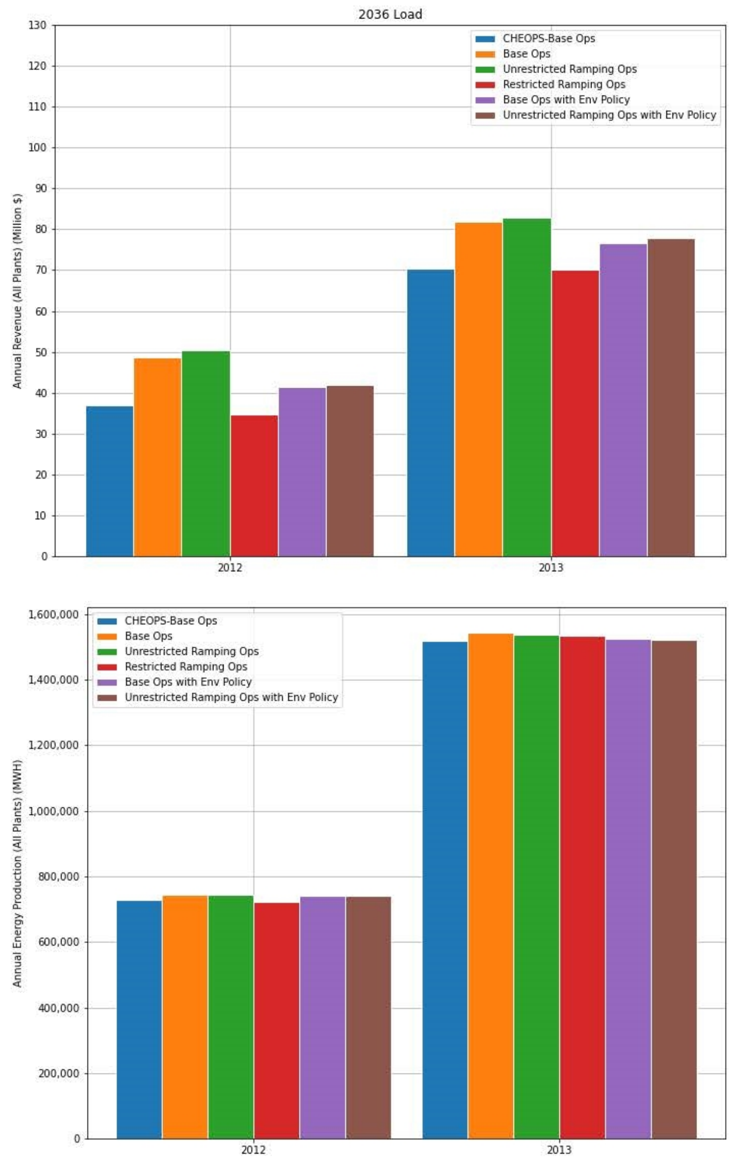


Figure 30. Annual Revenue (top) and Generation (bottom) for 2036 load Alternative Operating Policies Scenarios

The ability of hydro plants to quickly respond to market prices (LMPs) increases potential higher revenue than operating for fixed capacity levels. Shorter time resolution PCM indicates shorter term price variation, which can be realized as energy or ancillary service prices RT power market (Appendix G). These sub-hourly operation changes, which are not constrained by ecological requirements, can be enabled from investing for technical capabilities (e.g., auto governor control) to maximizes the hydropower revenue. While reduced time-lags between generation responses to price signals may increase revenue in a way that is agnostic to environmental impacts, little is known about the ecological impacts of short-term flow fluctuations and should be a high-priority subject of additional research.

5.0 Conclusions

As greater contribution of VRE achieves higher market share in the grid, the role of hydropower will become more important to providing grid reliability as a key source of flexible generation and ancillary services. However, the flexibility of hydropower that makes it so potentially useful for the future grid also can result in environmental impacts that are unacceptable to many stakeholders and regulatory process participants. And while there are burgeoning strategies for mitigating some of these impacts, such as using batteries coupled with hydropower to provide some flexibility rather than relying entirely on ramping the hydropower plant up and down, those solutions are not yet mature and will still require energy–environment tradeoff assessments in both the interim and long term. Providing frameworks and tools for making these tradeoff assessments is especially crucial to prepare for a future with VRE market share because flow requirements which, by definition, limit operational flexibility, are the most common instrument for protecting and improving environmental outcomes.

While the products of this initial energy flexibility–environmental tradeoff project do not provide a direct and generalizable solution to making energy–environment tradeoffs, when taken together they illustrate a diversity of approaches, scales, and pieces of frameworks for finding energy–environment win-wins and making tradeoff assessments.

- The instream flow dataset we created from 50 randomly selected FERC licenses provides insight into the types of flow requirements that may need to be evaluated with tools or frameworks created and investigated by this or future projects. We found that ecological outcomes, particularly those aimed at protecting fishery resources, are by far the most common target of flow requirements across all regions. The importance of protecting fishery resources through flow requirements indicates that valuation tools must be able to simultaneously value both ecological/biological and energy outcomes.

- The first step in assessing energy–environment tradeoffs for hydropower is gaining a mechanistic understanding of how energy and environmental outcomes are influenced by flow. The linkage diagram we created provides some of those pathways, in addition to a model and tool database that can help quantify and place value on these outcomes.

- Both the Yadkin-Pee Dee and GCD case study demonstrations provide examples of simultaneous assessment of energy and environmental outcomes of flows and generate both environmental (fish survival— Yadkin-Pee Dee; fish growth and sediment transport—GCD) and energy (revenue) outcomes. The Economic Valuation Tool case study demonstration provides a method of economically valuing a suite of flows with the assumption that the flow being valued was designed to meet a specific environmental need. Combining approaches used across these case studies may allow for a comprehensive framework for valuing energy–environment tradeoffs in hydropower regulatory proceedings.

This project has identified several important research gaps and challenges that must be addressed in addition to creating pathways for evaluating energy–environment outcomes.

- Coupling batteries with hydropower systems has been suggested as a mitigation for negative environmental effects of hydropeaking. Continuing assessments may be warranted as battery technologies advance. Tools that can provide this tradeoff assessment would be useful.

- Simultaneous valuation of economic and ecologic/environmental in a way that is geographically generalizable presents a challenge for creating tools with broad applicability. Software tools created to assess energy-environment tradeoffs must overcome the challenge of containing flow, economic, and ecologic input options that can account for the site-specific needs of each hydropower plant while still being general enough to provide insight to most hydropower facilities.

- Truly valuing flexibility has special challenges that must involve assessing ancillary services and effects of repeated and chronic flow fluctuations on fish and other aquatic biota. Coupling this assessment with other energy–environment tradeoff assessments is critical for fully understanding how economic and environmental outcomes are influenced by hydropower.

- Decisions on hydropower flow requirements are made on a facility-by-facility basis. Since other flow requirements and their energy impacts are not considered on a larger scale, it is possible there could be a cumulative impact on flexibility at many facilities that could impact reliability and manifest at the grid scale. However, this may not be the case, but there is currently no understanding how or if the flexibility impacts of flow requirements on one facility scale to the grid scale. Current proposed solutions to decreasing FERC licensing timelines involve conducting basin-scale licensing assessments; similar solutions to improving grid reliability by considering grid-scale needs in licensing assessments may be useful.

- Using forecast-informed reservoir operations can allow for better operations, potentially reducing some of the negative impacts of hydropower operations. Using this information to reduce uncertainty in operations planning allows for more environmental flows that can meet the requirements put in place by hydropower regulatory processes.

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