Modeling Power Generation Losses Due to Environmental and Fish Passage Attraction Flows at a Run-Of-River Hydroelectric Operation in the Northeast

MODELING POWER GENERATION LOSSES DUE TO ENVIRONMENTAL AND FISH PASSAGE ATTRACTION FLOWS AT A RUN-OF-RIVER HYDROELECTRIC OPERATION IN THE NORTHEAST

A Masters Project Presented by

ELIZABETH A. LOTTER

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ABSTRACT

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MASTER OF SCIENCE DECEMBER 2021

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Environmental mitigation represents an important, recurring cost to the hydropower industry, the largest renewable power source in the United States. Environmental flows are one such expense whereby hydro operations maintain a minimum flow in the river to mitigate impacts on aquatic and riparian ecosystems. Any hydroelectric facility may have a habitat maintenance flow requirement, but facilities with assisted aquatic organism passage structures, or fishways, may be subject to additional flow requirements associated with specific species migrations. This study assesses the economic impact of meeting environmental flow requirements in terms of losses to power generation at a representative hydroelectric facility and fish lift in the Northeast.

Three types of environmental flows are assessed: upstream fishway attraction flows, downstream fishway attraction flows, and habitat maintenance minimum flows. The physics-based model was developed with three years of hourly generation and flow data as inputs. Power is calculated as a function of adjusted gage flow, hydraulic head, and turbine-generator unit efficiency through the hydropower equation relation. The model simulates 27 years of historical generation.

Results indicate that both interannual and seasonal climatic factors impact the costs of meeting environmental flow requirements. Generation is most strongly curtailed during dry years and dry summers, which have the most significant generation losses due to environmental flows. Station hydraulic capacity was shown to strongly influence power generation, underscoring the importance of proper turbine sizing. Low-cost interventions that may reduce the economic impacts of environmental flows to hydro include investments in research and development of technologies suited to repurposing turbine discharge to be used for environmental flows.

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"Reducing environmental impacts mitigation costs is crucial for new U.S. hydropower projects."

-- Oladosu et al (2021)

1. Introduction

Hydropower is an essential component of the US energy landscape. It is the most common renewable energy source in the US, providing over 50 percent of renewable energy in the US, or 6.7 percent of total electricity generation. The Department of Energy predicts that hydropower supply could grow from 101 gigawatts (GW) today to nearly 150 GW by 2050 (US Department of Energy 2016). Yet, hydroelectricity production comes at a significant cost to riverine systems and to aquatic species. Dams create barriers to fish migration, blocking access to critical feeding and spawning habitats. The US Army Corps of Engineers counts over 90,000 dams in the country, of which over 2,000 produce hydroelectricity (NID, n.d.). Proliferation of dams in the 19th and 20th centuries is associated with dramatic declines in diadromous fish populations in the Northeast (Limburg & Waldman 2009, Mattocks et al 2017). Atlantic Salmon (*salmo salar*) populations are currently less than 2% of their historic levels (NMFS 2011). Restoration of fish migration routes can be partially achieved through the removal of obsolete dams and the construction of fishways, such as fish ladders. New and reissued operational licenses may require hydroelectric facilities to provide for fish passage in accordance with federal and state conservation regulations. However, the science of fish passage is a young and active field of research and there are large gaps in our knowledge in how to build high-performing fishways that make optimal use of a limited water resource.

While fish passage science is advancing, estimates of the costs of implementation are poorly documented. The costs of construction and maintenance are borne to owners and these costs are not routinely made public. Overall, environmental mitigation costs may account for between 5-40% of capital costs (Oladosu et al 2021). This figure includes not only fish passage but also protections or offsets for damages to habitat, landcover, and water quality, among other impacts. Many of these costs are reoccurring and require inputs of capital toward initial construction or retrofitting existing structures, as well as ongoing operational and maintenance costs. Given the importance of hydroelectric power to US energy security, as well as the stresses it imposes on aquatic and riverine ecosystems, it is important to improve our knowledge of the trade-offs between the economic benefits and costs of environmental impact mitigation interventions. An understanding of how mitigation costs impact hydropower is critical to not only the hydropower industry, but also to regulatory agencies, environmental non-profits and community advocacy groups who are all river stakeholders.

This study explores opportunities to improve both the ecological and economic outcomes of fish passage at hydroelectric dams. We model the costs of environmental flows in a detailed case study of a representative northeast hydroelectric facility. The case study is evaluated within a regional context through a regional analysis and literature review. Results indicate that improved management of environmental flows may result in significant cost savings without degrading the integrity of environmental protection measures.

1.1 Environmental Mitigation at Hydroelectric Projects

This section describes the economic challenges encountered by the hydro industry, types of environmental mitigation costs, the basics components of fish passages, the function of fishway attraction flow, and finally reviews the current literature on the costs of environmental mitigation at hydroelectric facilities. It provides context to the case study that will be presented in later portions of the report.

Increases in competition and production costs in the energy generation sector in the 21st century are decreasing profit margins in the hydropower industry. Increased supply of energy from sources such as natural gas, solar, and wind have resulted in decreased wholesale prices for hydroelectricity. The growth of solar electricity generation, which contributed 14% of California's energy grid in 2019, has transformed that state's energy market (US Department of Energy 2016). Excess supply of solar electricity at midday drives down energy prices during the day and increases competition on the grid. Meanwhile, dam infrastructure that was built in the 20th century has reached or exceeded its design life, becoming costly to maintain and rebuild. Finally, environmental mitigation costs, imposed beginning with enactment of the Clean Water Act in 1972, further reduce revenues.

Mitigation of environmental impacts of hydropower production requires significant economic resources. Costs of environmental compliance are classified into three broad categories here: 1) capital costs, 2) operations and maintenance costs, and 3) the loss of generation. Capital costs refer to costs of new construction or retrofits, such as installation of fish passage infrastructure (i.e., ladders, lifts, or bypasses) and water conveyance (i.e., pipes or spills). Operations and maintenance costs, unlike capital costs, are recurring annual costs, and are incurred throughout the life of the project.

Environmental minimum flows, also called fish flows or habitat flows, are commonly required to ensure that flows are larger than a minimum permissible level for species survival. The loss of generation refers to the opportunity cost of water diverted from generation for an environmental purpose. Environmental flows are necessary for maintenance of aquatic habitat as well as functioning of fish passage infrastructure.

Oladosu et al (2021) estimate that mitigation costs typically represent 5%-10% of the total levelized cost of energy (the minimum price at which energy must be sold for an energy project to break even) but can be as high as 40%. In addition to providing for fish passage, these costs can include protections or offsets for damages to other environmental assets such as aquatic species, water quality, recreational use of land, cultural resources, and hydrology. Yet, data on the magnitude of these costs is absent from the literature. Economic data collected by private and public hydroelectric operators are legally protected by federal Critical Energy Infrastructure (CEII) designations.

This research explores past studies to better understand fish passage economics in the 21st century. Of the three categories of costs outlined (capital costs; O&M costs, and loss of generation), the loss of generation (in the form of environmental flows) is the focus in this report. This study assumes that water not available for generation is lost revenue. Thus, we seek to quantify the cost of environmental flows in a case study in the Northeast that represents typical operations both in the present and into the future.

1.2 Environmental Mitigation Structures: Fishways

Environmental impacts of conventional hydro facilities include the fragmentation of aquatic habitat, the interruption of historical migration routes, and change in the natural hydrology. Fishways, such as fish ladders and lifts, are the primary means of facilitating migration for diadromous species at hydroelectric facilities. Native Northeast diadromous species such as American Shad (*alosa sapidissima*), American Eel (*anguilla rostrata*), Atlantic Salmon (*salmo salar*), Blueback Herring (*alosa aestivalis*), and Alewife (*alosa pseudoharengus)* migrate between fresh and saltwater environments during the course of their life cycle. River impoundments at dams and road crossings that impede natural migration can require engineered solutions to restore access to migration. Upstream and downstream passage may be facilitated by a single structure (e.g. a bypass channel), or by a combination of engineered solutions. For example, upstream passage can be facilitated by a fish lift, while downstream passage could be a simple barrier to or rack directing fish to the spillway.

Technical fishway designs are constructed of manufactured materials and include the common Denil-style fish ladders or baffle structures. Nature-like fishways include diversion or bypass channels that resemble natural waterways. Fishway design is highly specific to site and target species, but all must balance the objectives of minimizing achieving passage across the barrier and maintaining advantageous hydraulic conditions for fish locomotion while minimizing construction and operational costs.

Of the 91,000 dams in the US, the American Society of Civil Engineers (ASCE) estimates that only 3% generate hydroelectricity (ASCE 2021). Non-federally owned hydroelectric facilities are regulated by the Federal Energy Regulation Commission (FERC). Through issuance of licenses and exemptions, FERC regulates over 2,500 dams in the U.S. (FERC 2017). A smaller number of dams are operated by federal agencies such as US Army Corps of Engineers (USACE) and Bureau of Reclamation (FERC

2021). In 2000, of 1,825 dams licensed by FERC, fewer than 10% had fish passage or protection mitigation in place (Francfort et al 2001). While FERC licenses are implemented for several decades, typically between 30-50 years, the relicensing process is an opportunity to modify operational terms. Typically, environmental measures such as fish passage provisions are included in these modifications.

Fishway engineering design is complex and dependent on site-specific characteristics, yet broad and significant improvements in fishway efficacy have been realized (Dodd et al 2018, Larinier 2008, Mulligan et al 2019). In situ measurements of upstream passage efficiency for technical fishways can vary widely, from less than 50% to over 90% (Bunt et al 2011, Noonan et al 2012, Dodd et al 2018, Brown et al 2013). This observed range may be due, in part, to metrics being inconsistently applied in the studies (Silva et al 2018).

Fish passage entrance channels and their associated hydraulic characteristics are designed to attract fish to the fish passage structure. Entrance channel hydraulics plays a significant role in the efficiency of fish passage (Bunt et al 2001, Heise 2017, Mulligan et al 2019). Entrance channels typically have a relatively narrow pathway for fish to enter and the fish are attracted by water flows that mimic natural rivers. During upstream migration fish orient their bodies into the direction of flow. Entrance channel hydraulics attempt to elicit this ‘rheotactic response’ to attract fish into the fish passage structure. Stagnant water, eddies, turbulence, and entrained air can all cause migrating fish to become disoriented and fail to elicit rheotaxis. If a fish is not attracted to the entrance channel, the migration attempt fails. Therefore, the hydraulics of attraction flows at the fishway entrance is a critical design element (Gisen et al 2017, Heise 2017, Fiedler

2018). Because flow characteristics of waters downstream of a dam are “unnatural,” the hydraulics at entrance channels are critical.

1.3 Fishway Attraction Flows and Habitat Flows

To produce the desired hydraulic conditions at the fishway entrance, auxiliary water systems (AWS) are often employed. The flows associated with AWS serve to supplement an upstream fishway’s entrance flows, presenting a clear upstream gradient amidst competition from turbine discharge. The hydraulic parameters that result in these conditions are an active field of research (Fiedler 2018, Gisen et al 2017, Heise 2017, Rojas 2020, Odeh et al 2002). Typically, AWS flows are sourced from flows upstream of the powerhouse, such that their generation potential is lost (Figure 1). Crucially, these flows represent a potential source of revenue if they are passed through the turbines.

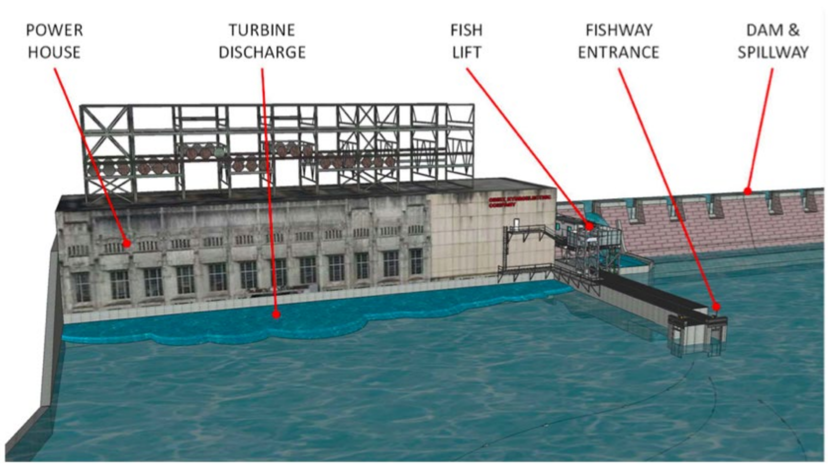


Figure 1. *Downstream view of hydroelectric facility with fish lift and entrance channel. Attraction flow is discharged at the entrance channel, but turbine discharge competes with that flow for fish attraction. (Image credit: Turek et al, 2016)*

Regulatory standards for minimum attraction flows range from 2% to 10% of turbine capacity or river high flows, but generally never less than 50 cubic feet per second (Larinier 2002, NMFS 2011, Rojas 2020, USFWS 2019). Current licensing agreements in the Northeast set upstream attraction flows at a minimum of 3-5% of the hydraulic capacity of the generating station. US Fish & Wildlife regulators recommend 5% of station hydraulic capacity or a minimum of 50 cubic feet per second (ft^3/s) (USFWS 2019). Minimum attraction flows have been revised upward in recent years and are continually under review.

The costs of providing environmental mitigation and protection measures are poorly documented in the literature. Multiple studies note the paucity of published information and the need for standardized documentation of these costs (Venus et al 2020, Oladosu 2021). The economics of environmental mitigation, and hydroelectric generation broadly, are difficult to document due to the sensitive nature of the cost and revenue data and the desire of hydropower systems to retain this proprietary information. "Critical Energy Infrastructure Information," (CEII) status in the United States is a federal protection that allows data on hydroelectric facilities to be redacted from the public record to safeguard the energy grid from foreign and domestic threats. Market factors can also complicate the availability of these data.

1.4 Economics of Run-of-River Hydropower

Economic considerations reviewed in this study focus on environmental mitigation costs, including costs of construction, operations and maintenance (O&M) and the cost of providing environmental flows. A significant consideration that acutely affects run-of-river hydro facilities in terms of both construction and operational costs is station hydraulic capacity. Proper selection of capacity of the turbines can have a significant effect on the efficiency with which the station generates power.

Specifications for the design hydraulic capacity of run-of-river facilities differ from peaking facilities. A hydroelectric project's profitability is impacted by the time its turbine is operating, which requires that the turbine capacity match the typical flows in the river. Creager and Justin (1950) point to a "rule of thumb" that the design capacity of the turbine should be set at the 30% exceedance probability flow for a given river (p. 264). However, peaking plants are designed to operate at much greater flows than run-of-river plants, even on the same river, given that they use their storage capacity to accept high flows through the turbines during times of high energy prices. Warnick (1984) recommends that baseload plants (e.g. run-of-river) set design capacity at 25-45% exceedance flow for the river. In contrast, peaking plants may choose a value between 15%-20% exceedance, a higher flow rate. The understood reason for this difference is that higher flows made possible by reservoir storage for a peaking plant makes a larger turbine profitable.

As for other construction and maintenance costs, peer-reviewed publications on the costs of fish passage at hydroelectric sites note the wide variation in both (Francfort et al 1994, Nieminen et al 2017, Armstrong et al 2010, WI DNR, Weyand et al 2006). Site-specific conditions such as the need for excavation, footing stabilization, and dewatering all impact construction costs. Planned costs commonly increase by as much as 30% in the construction phrase of these facilities (Venus et al 2020). Economies of scale exist for environmental mitigation. Larger facilities appear to incur a smaller cost of environmental mitigation per unit of energy generated (Oladosu et al 2021, Francfort et al

1994). There is a complex relationship between costs of fish passage that includes the site-specific geology, the hydrology of the stream, the size of the hydropower plant that is constructed, and state/federal environmental requirements.

The peer-reviewed literature states that fishway construction costs generally exceed O&M costs. While construction costs comprise the bulk of documented costs, the O&M costs of technical fishways (including supplementary attraction flow pumping, and regular removal of debris and sediment) are significant (Francfort et al 1994). In the US, median capital costs of aquatic species protection measures at relicensed dams were approximately $50 per kilowatt, while O&M costs for the same measures were less than $10/kw (in 2018 dollars) (Oladosu et al 2021). This analysis was based on an interest rate of 6% for all projects, and a project life of 30 years. Fishway maintenance is critical. Without annual removal of sediment and large debris, hydraulic performance and fishway functionality are impeded (O'Connor et al 2015). Unfortunately, maintenance is commonly delayed beyond the design schedule, and sometimes until failure. The true costs of maintenance may not be reflected in the literature but may rather be passed on as externalities through neglect by hydro operations to aquatic systems.

Nature-like fishways have advantages over technical fishways in both construction and O&M costs. Nature-like fishways employ materials such as gravel, bedrock and boulders to produce natural river forms like riffles (Figure 2). They may be visually indistinguishable from streams and rivers to the untrained eye (Katopodis et al 2001). Although they are not maintenance-free, the absence of diffusers, racks, and manufactured structures eliminates some of the routine maintenance incurred by technical solutions. In a survey of European fishways, Venus et al (2020), found that nature-like fishways cost less on a per-kilowatt basis than technical fishways over the life of the structure, with considerable site-to site variability.

Figure 2. *Pool and riffle nature-like fishway in Manitoba, from Katopodis et al 2001.*

Despite a scarcity of detailed, uniformly documented historical cost data, comparisons can be drawn between types of fish passage structures. Porcher and Larinier (2002) evaluated European fish passage structures and compared two types of ladders and three types of fish lifts. Of 300 pool ladders and 100 baffle ladders, the pool ladders were found to be roughly half the cost of baffle ladders of equivalent size. By contrast, the FIT Hydro study of European fish ladders (forthcoming) find no appreciable difference between pool and baffle fishways in terms of cost per meter of upstream passage (FIT Hydro wiki). Among baffle ladders, Harris and Thorncraft (2000) found a cost advantage among Denil ladders over vertical slot ladders for dams greater than 10 feet in height. This study was undertaken among Australian fish ladders built before 2000 (Fig. 3).

	Min (Euro)	Max (Euro)	Unit
Complete or partial migration barrier removal	2,000	1,000,000	per project
Nature-like fishways	5,000	20,000	per vertical meter
Pool-type fishways	10,000	100,000	per vertical meter
Baffle fishways	5,000	100,000	per vertical meter
Fish lifts, screws, locks, and others	10,000	500,000	per project
Vertical slot fishways	5,000	20,000	per vertical meter

Table 1. *Costs of European fishway solutions as reported by the Fishfriendly Innovative Technologies for Hydropower (FITHydro) project (Mainpage 2020)*

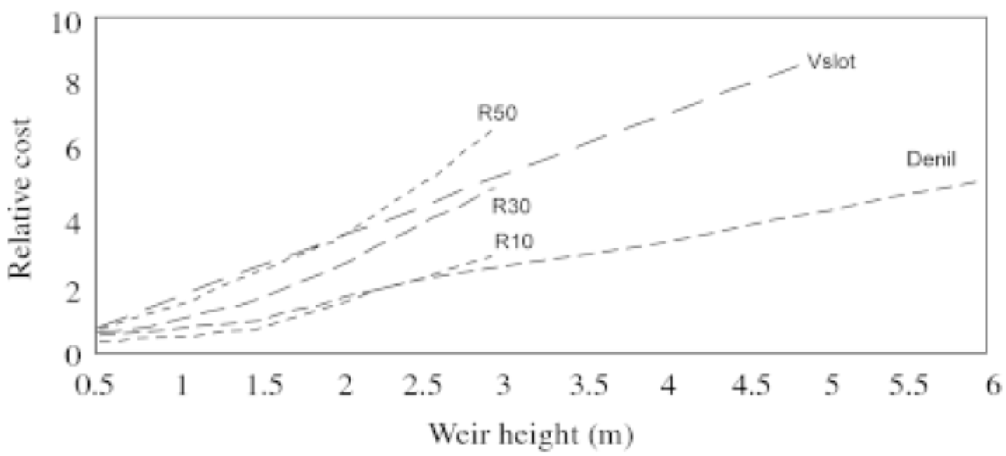


Figure 3. *Harris & Thorncraft (2000) compare relative preliminary cost estimates for fishway types. Y-axis values, "Relative cost", represent a unitless index. Original source is William Leader, New South Wales Department of Land and Water Conservation. Vslot = vertical slot ladder; Denil = Denil fish ladder; R50, R30, and R10 = rock ramps 50m, 20m, and 10m wide, respectively.*

A study compared the costs of 50 fish lifts designed for one of three species, shad, trout, and salmon (Porcher and Larinier 2002). Of these, shad lifts were more expensive than those designed for either trout species or salmon. Caveats for this finding are the relatively small sample size and the lack of documented engineering economic methods (e.g. how costs were normalized.)

Retrofitting existing hydropower plants with fish passage is more expensive than incorporating fish passage into an original design. In a study of 182 US hydro facilities, Oladosu et al (2021) found higher capital costs per kilowatt for relicensed conventional hydropower plants as compared to new development.

Few studies report directly on costs of attraction water, presumably due to the difficulty of obtaining these data. Hall et al (2003) compare the costs of seventeen fish passage structures at major US dams (Figure 4). In 1993 dollars, using a 20-year planning horizon, costs ranged from less than 1.0 $/kWh to over $21/kWh. Larger facilities benefited from a lower unit cost, apparently reflecting economic benefits of scale.

TABLE 5-2: Case Studies General Information

Plant name	Capacity (MW)	Annual energy production (MWh)	Diversion height (ft.)	Average site flow (cfs)	State	Upstream mitigation	Downstream mitigation	Mitigation cost (mils/kWh)[a]
Arbuckle Mountain	0.4	904	12	50	California	Y	Y	12.9
Brunswick	19.7	105,200	34	6,480	Maine	Y	Y	3.7
Buchanan	4.1	21,270	15	3,636	Michigan	Y	N	10.6
Conowingo	512	1,738,000	105	45,000	Maryland	Y	N	0.9
Jim Boyd	1.2	4,230	3.5	556	Oregon	Y	Y	21.1
Kern River No. 3	36.8	188,922	20	357	California	Y	Y	0.09
Leaburg	15	97,300	20	4,780	Oregon	Y	Y	5.2
Little Falls	13.6	49,400	6	n/a	New York	N[b]	Y	2.8
Lowell	15	84,500	15	6,450	Massachusetts	Y	Y	5.5
Lower Monumental	810	2,856,000	100	48,950	Washington	Y	Y	2.3
Potter Valley	9.2	57,700	63	331	California	Y	Y	n/a
T.W. Sullivan	16.6	122,832	45	23,810	Oregon	N[c]	Y	5.8
Twin Falls	24	80,000	10	325	Oregon	N	Y	0.9
Wadhams	0.56	2,000	7	214	New York	N	Y	1.2
Wells	840	4,097,851	185	80,000	Washington	Y	Y	1.0
West Enfield	13	96,000	45	12,000	Maine	Y	Y	3.9

Figure 4. *Hall et al (2003) compile costs of sixteen US fishways in 1993 dollars, per kWh of generation, based on 20-year averages. (Source: Hall et al 2003)*

Fishway design and evaluation is an active field of research, but the economic costs of providing fish passage in the US is not well-documented. Obvious gaps remain in knowledge surrounding the true magnitude of the economic burden that environmental protection/mitigation measures impose on hydroelectric dams. This information is crucial for all partner involved in the negotiations during the relicensing process. Given the importance of hydroelectric power to US energy security and the economic pressures facing the industry, this knowledge gap is a vital concern.

1.5 Research Objectives

This study applies a physics-based modelling approach to quantify the relative contributions of two different types of environmental flows to losses in power generation. Flows of interest are fish-passage specific flows and non-fish-passage-related flows (henceforth referred to as habitat flows). The three flows included in this study are upstream fishway attraction; downstream fishway attraction flows; and habitat flows, and they are described in depth in the Methods section.

This study quantifies the impact of these environmental flows to power generation in a representative case study. Further, how do key climatic and environmental conditions affect how these environmental flows impact power generation? Specifically, we test:

1. Hydrological conditions, e.g., high or low flow times: Do environmental flows have a greater impact on power generation during periods of low flow?
2. Discharge rate of environmental flows: Does an increase in environmental flow rates produce an equivalent decrease in generation?
3. Station hydraulic capacity: How do changes in turbine hydraulic capacity impact power generation, both independent of and in conjunction with, varying hydrological conditions?

Energy generation is modeled at a hydropower site in the Northeast where both habitat and fish passage flows are present. Its primary design and hydrologic features are varied to approximate hypothetical but plausible conditions into the future at a range of sites. We compare the present status quo operations to scenarios wherein attraction water flows are recaptured for generation. Possible future scenarios considered relate to climate and regulatory trends. We explore years and seasons classified as wet, normal, or dry since 1991. We also investigate the impacts of increased minimum flow requirements. Analysis of each scenario is further described in the Results.

Improved management of attraction flows may reduce the costs of producing hydroelectricity without degrading the effectiveness of installed environmental measures. These topics are of great interest to the hydropower community because attraction is crucial to enabling timely fish passage success. Additionally, improved management of these flows represents a potential cost savings to hydroelectric operations.

2. Methods

2.1 The Study Site

The Shetucket River, located in eastern Connecticut, is a 20-mile-long tributary of the Thames River system which drains into the Long Island Sound. Mean annual peak flows reach 1,400 ft^3/s in April (Fig. 5). Median monthly flow rates range between 200 and 1000 ft^3/s (Fig. 6). At the location of interest, the Shetucket River has a median flow rate of 552 ft^3/s, with 10% exceedance probability at 1,800 ft^3/s (the 10-year flood) and 25% exceedance at 1,060 ft^3/s (the 4-year flood) (Fig. 5).

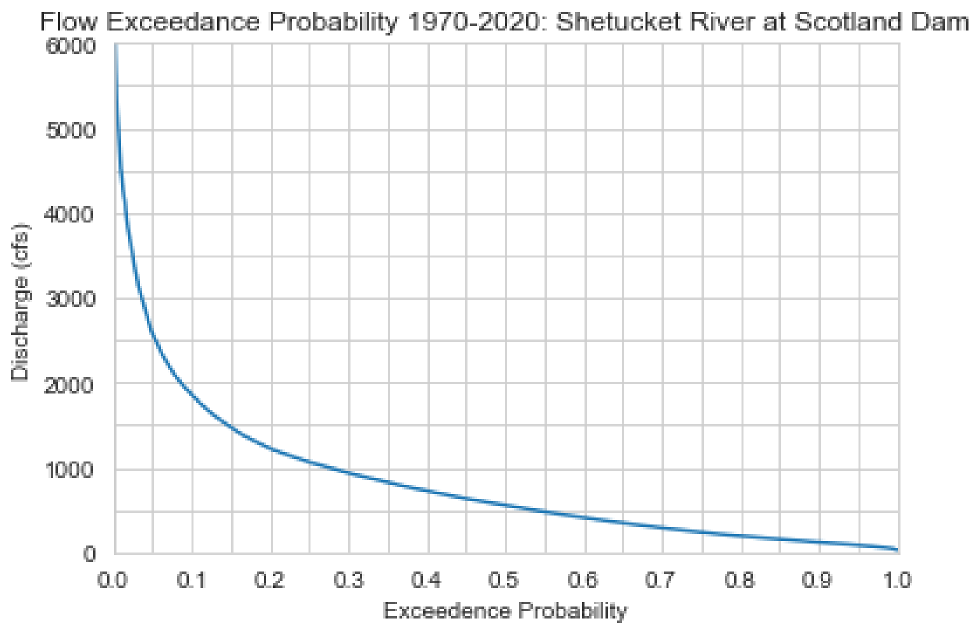


Figure 5. *Shetucket River at Scotland Dam Daily Flow Duration Curve. Daily flows at Gage 01122500 Shetucket River Near Willimantic, CT. Gage flows were adjusted with a drainage basin factor of 1.06 (429/404 square miles) due to the larger size of the powerhouse basin compared to the gage location approximately 4 miles upstream.*

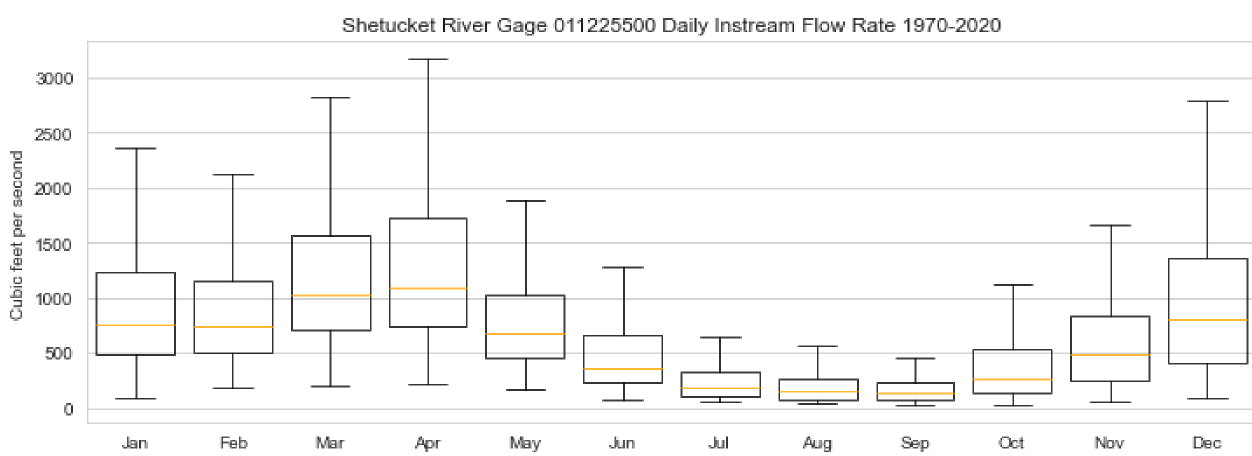


Figure 6. *Mean Daily Instream Flow Rate by Month 1970-2020 at Gage 01122500 Shetucket River Near Willimantic, CT.*

Scotland Dam is located on the Shetucket River near Willimantic, CT with a 429-square-mile drainage basin (Fig. 7). Owned by FirstLight Power Resources, its powerhouse is a single-unit, 2.0 MW capacity hydroelectric generating facility. The Scotland powerhouse was initially constructed in 1937 (Scotland Dam Generating Station, 2021). The powerhouse generates over 6,000 megawatt-hours annually with a turbine designed for a hydraulic capacity of 1,250 ft^3/s. Until 2017, it operated as a hydropeaking facility. Under its new license (FERC License #P-2662), it operates under run-of-river constraints. The head pond elevation deviation is limited to no more than 6 inches of elevation in its new license to reduce destruction of habitat and bank erosion both upstream and downstream of the dam.

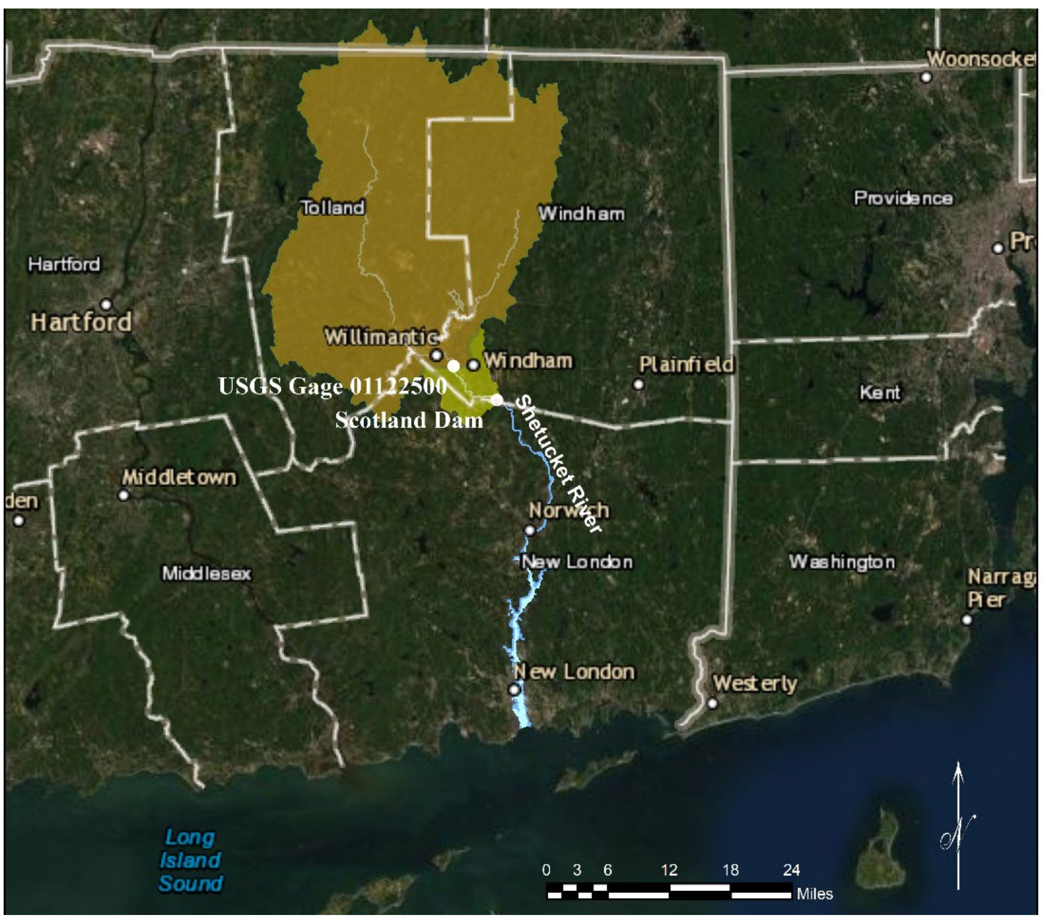


***Figure** 7. Map of Study Area in Eastern Connecticut illustrating locations and drainage basins of Scotland Dam and USGS Gage 01122500*

With the change of operational procedures in the 2010's, creation of a second generating turbine was proposed but has not been pursued. FirstLight Power Resources is the largest hydroelectric generator in Connecticut and operates facilities throughout Massachusetts and Connecticut. In 2017, a fish lift was constructed at Scotland Dam as a stipulation of license renewal (Fig. 8). The fish lift was required to mitigate the negative impacts to aquatic organism passage on the Shetucket River. The Scotland Dam fish passage facility consists of an elevator for upstream passage and spillway for downstream passage that operate for four months of the year, split between the spring and fall diadromous fish migration seasons.

Since installation of the fish lift, migratory fish attraction flows have been discharged on a seasonal schedule. Upstream fish lift attraction flows are discharged from April through June, depending on streamflow, at a rate of 58 ft^3/s, or 4.6% of station hydraulic capacity. Downstream attraction flows are discharged from April through June and October into November at a rate of 2.3% of station capacity or 29 ft^3/s. Habitat flows, which are independent of the fish lift, flow year-round at a rate of 29 ft^3/s, according to generation and discharge data for the year 2020 shared by FirstLight Power Resources.

Figure 8. *Scotland Dam Generating Station (41.6634° N, 72.1229° W) illustrating spillway, powerhouse, and fish lift tower (right). Image Credit: FirstLight Power Resources*

The Scotland Powerhouse site was selected for this case study because of its environmental mitigation protocols of interest, which are increasing in prevalence throughout the Northeast. These include head pond elevation constraints (or run-of-river operations), environmental flows, and fish lift. Under run-of–river operations, inflows are discharged such that storage remains constant over time. As previously stated, environmental flows consist of both seasonal fish lift attraction flows and year-round habitat maintenance flows. In the coming decades, as older licenses expire and are renewed, they are expected to include similar environmental regulations.

Figure 9. *Scotland Fish Lift Tower (right) and fishway entrance (left) Image Credit: Brett Towler*

2.2 The Model

To analyze the mitigation costs of environmental flows, a simulation model was developed to illustrate relationships between instream flows, environmental flow requirements, and power generation. The run-of-river system is modeled primarily as a volume flux balance, using a one-hour time-step over a twenty-eight-year period and modeling the releases, capacity limits, and operational constraints of the system.

Hourly environmental flows were obtained for one season, from April to November 2020. These data represent current operational procedures under the existing license requirements. Three environmental flows are discharged seasonally throughout the year (Figure 11). These flows are: 1) Aquatic habitat maintenance flows, 2) Upstream fish attraction flows, and 3) Downstream fish attraction flow. Aquatic habitat maintenance flows (hereafter called simply "habitat flows") are flows discharged continuously to maintain a minimum flow downstream of the dam. For this study, habitat flows refer to releases that maintain flow in the downstream river channel, essentially maintaining a wetted river channel downstream. Flows of 29 ft^3/s are released throughout the year as habitat flows. Attraction flows are discharged during fish migration season to attract migrating fish to the upstream or downstream fishway entrance. Upstream attraction flows are discharged April 15- June 30 from the entrance channel of the fish lift into the tailwater at a rate of 58 ft^3/s. Downstream attraction flows are discharged from October 15-November 30 for anadromous fish, at a rate of 29 ft^3/s. These three flows are additive. The combined flows are highest in May and June reaching 117 ft^3/s. In October and November, the combined flows are 58 ft^3/s and the remainder of the year environmental flows are at 29 ft^3/s (Figure 10).

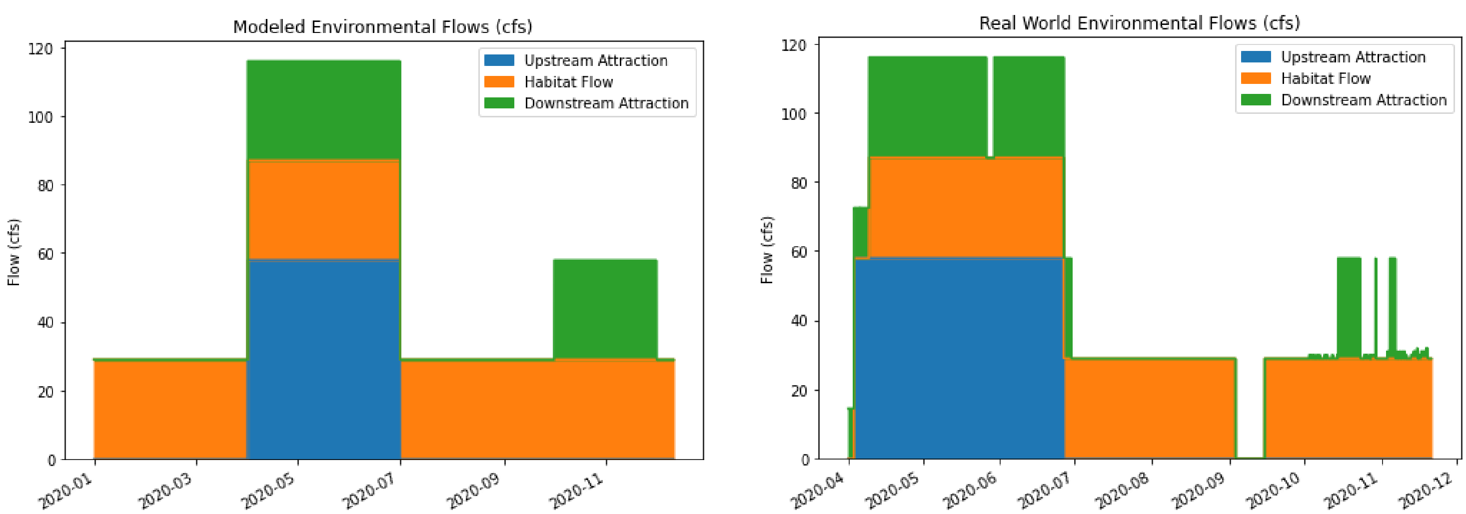


Figure 10. *Environmental Flows as modeled (left) and as reported for 2020 (right). Historical flows were obtained for May through November 2020 only but were modeled for the entire year.*

Power generation is simulated on an hourly timestep for 27 years between 1992 and 2020. Years are selected based on availability of hourly instream flow gage data as well as considerations of climate stationarity (Collins 2009). The USGS gage site

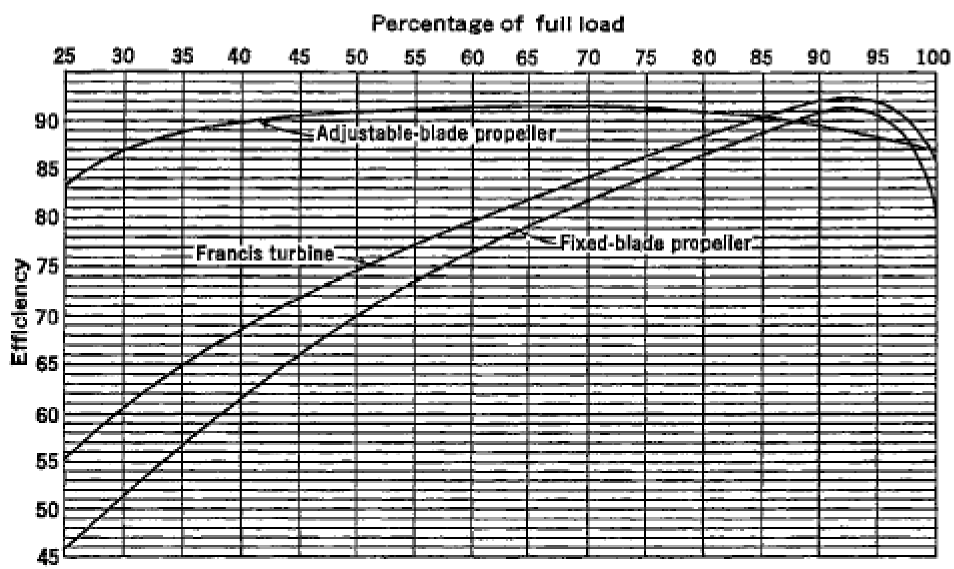
(#01122500, Shetucket River at Willimantic, USGS National Water Information System) was selected to represent inflows into the hydropower facility, as it is located approximately 5 miles upstream of the dam. Gage flow data were examined and filtered based on completeness of record as defined below. For annual analysis, years with less than 88% complete hourly data were discarded from the analysis. For the period 1990-2020, years discarded for incomplete records were 1990, 1991, 1994 and 1995. Gage flows were adjusted using a basin factor of 1.06, or (429 mi^2/404 mi^2) to account for the larger drainage area of the Shetucket at Scotland Powerhouse. Following FirstLight Power Resources (2007), the flows at the gage are assumed to be proportional to the area of the drainage basin, and maps of the drainage basins for the Shetucket River at both the Gage 01122500 (404 square miles) and Scotland Powerhouse (429 square miles) are presented in Figure 7.

After scaling for drainage area, the hourly instream flows served as inputs to model hourly power generation. Operational and physical data on the powerhouse were obtained through a combination of interviews with FirstLight Power Resources representatives and publicly available license documentation available through the Federal Energy Regulatory Commission (FERC) for project number P-2662.

Three years of historical hourly generation data (2018-2020) were used to calibrate the model to represent current operational protocols for the powerhouse and fishway. Prior to installation of the fishway in 2017, operations were less restrictive to power generation. We apply the model with the new operational protocols to a historical period operating under a different protocol. For that reason, historical values from prior to 2018 were not used to validate or calibrate the model directly. The model applies physical and operational constraints from the case study powerhouse, such as hydraulic head, turbine capacity, and unit efficiency. A Francis turbine efficiency curve based on Creager and Justin (1950) is applied to the turbine generation (Fig. 11). The power equation for water flowing through a turbine calculates the power generated during each hour:

$$P = Q * \gamma * \eta * h * C$$

where P is the power in kilowatt-hours, Q is the flow in ft^3/s, γ the unit weight of water in pounds per cubic foot; h the hydraulic head on the unit in feet; η the efficiency rate of the turbine (a number between 0 and 1); and C is a conversion constant applied to convert the output to kilowatt-hours.



Hydraulic capacity of the single turbine system is listed at 1,250 ft^3/s. According to interviews with operations representatives, generation is limited to flows less than 1180 ft^3/s and curtained at flows less than 350 ft^3/s. The reason for capping generation is understood to be the result of efficiency losses at extremes of turbine design capacity. The model incorporates these limits on generation. A constant hydraulic head on the unit of 23.43 feet, equal to, the mean value for the available historic record in 2020, is applied. Hydraulic head is calculated as the difference between headpond elevation and tailwater elevation.

Model Calibration: The model was calibrated to simulate sub-daily fluctuations in power generation over the study period. The model reproduces observed fluctuations in power generation rate at daily and sub-daily timescales. This result excludes January through March 2020, where there is a gap in available historical data. The model systematically overestimates generation by 8 percent per year compared to the historical record (Figure 12). The principal cause of this bias is understood to be the result of extra-system operational decisions such as offline time for maintenance or other factors. A further possible factor contributing to the bias is the assumption of constant hydraulic head. Constant hydraulic head was assumed and estimated based on available historical values of height between headpond elevation and tailwater elevation. Power generation is partly a function of hydraulic head, with a direct relationship between the two terms. In the real system, hydraulic head is known to fluctuate seasonally and sub-seasonally. For example, high hydraulic head values induced by temporarily-high headpond elevations may contribute to historical generation rates of higher than stated capacity. By contrast, low head values caused by high tailwater elevations lead to lower than expected generation rates. Therefore, the assumption of constant hydraulic head may be a source of the error observed in this model.

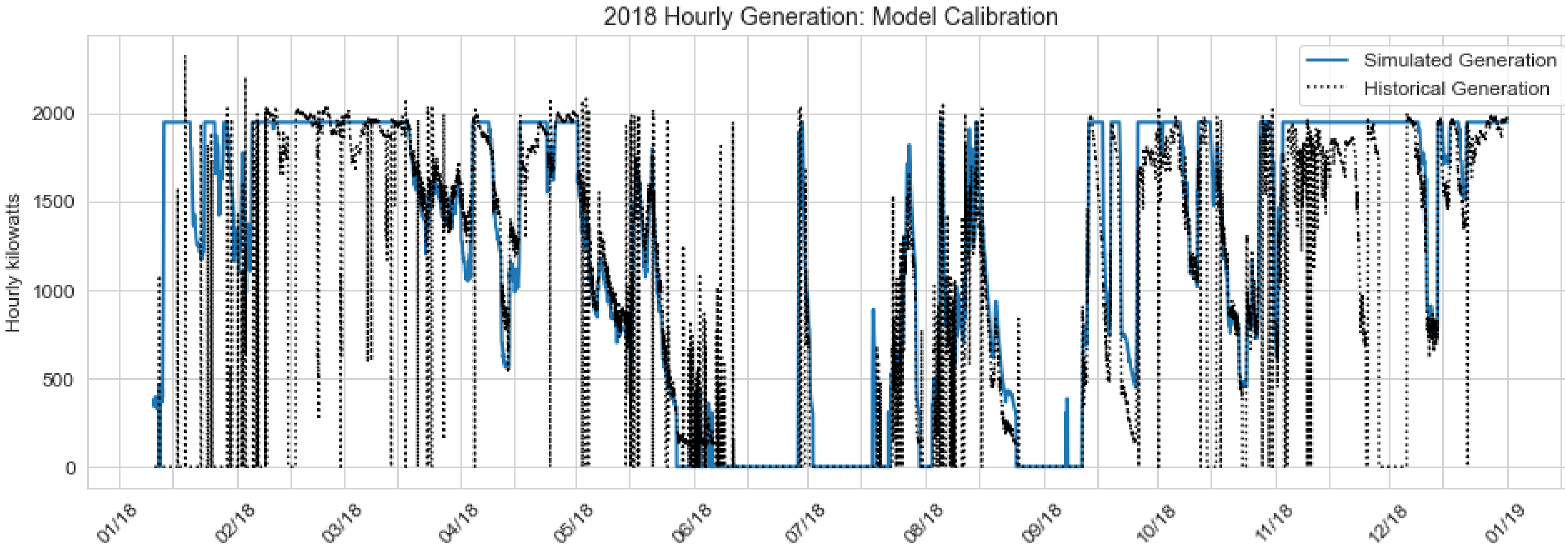


Figure 12. *Model Calibration: Hourly simulated and historic flows for 2018*

2.3 Experimental Design

Three experiments were conducted to quantify generation losses from environmental flows under varying climatic and operational conditions. The three experimental conditions are: 1) hydrological conditions, 2) environmental flow rate, and 3) station hydraulic capacity.

Hydrological Conditions: For the hydrological conditions experiment, generation losses are compared between wet, normal, and dry years classified as previously described. In additional to an annual analysis of hydrological conditions, we also perform a seasonal analysis which reports generation loss statistics by for the entire study period by quarters. These quarter are roughly equivalent to seasons, and are defined as January to March, April to June, July to September, and October to December. The annual and seasonal analyses comprise the hydrological conditions experiment.

Environmental Flow Rates: The experiment on environmental flow rates investigates a scenario whereby environmental flow rates are increased by double. Status quo flow rates meet the USFWS recommended minimums of 3-5%, but fall short of the NMFS recommendation of 10%. This experiment tests the effect of a 10%, or roughly doubled, environmental flow rate for both habitat and fish passage flows on generation losses. These experiments were performed for three years representative of wet, normal, and dry conditions at the Powerhouse, 2011 (wet), 2013 (normal), and 2016 (dry). Figure 13 illustrates daily flow rates for the three representative years.

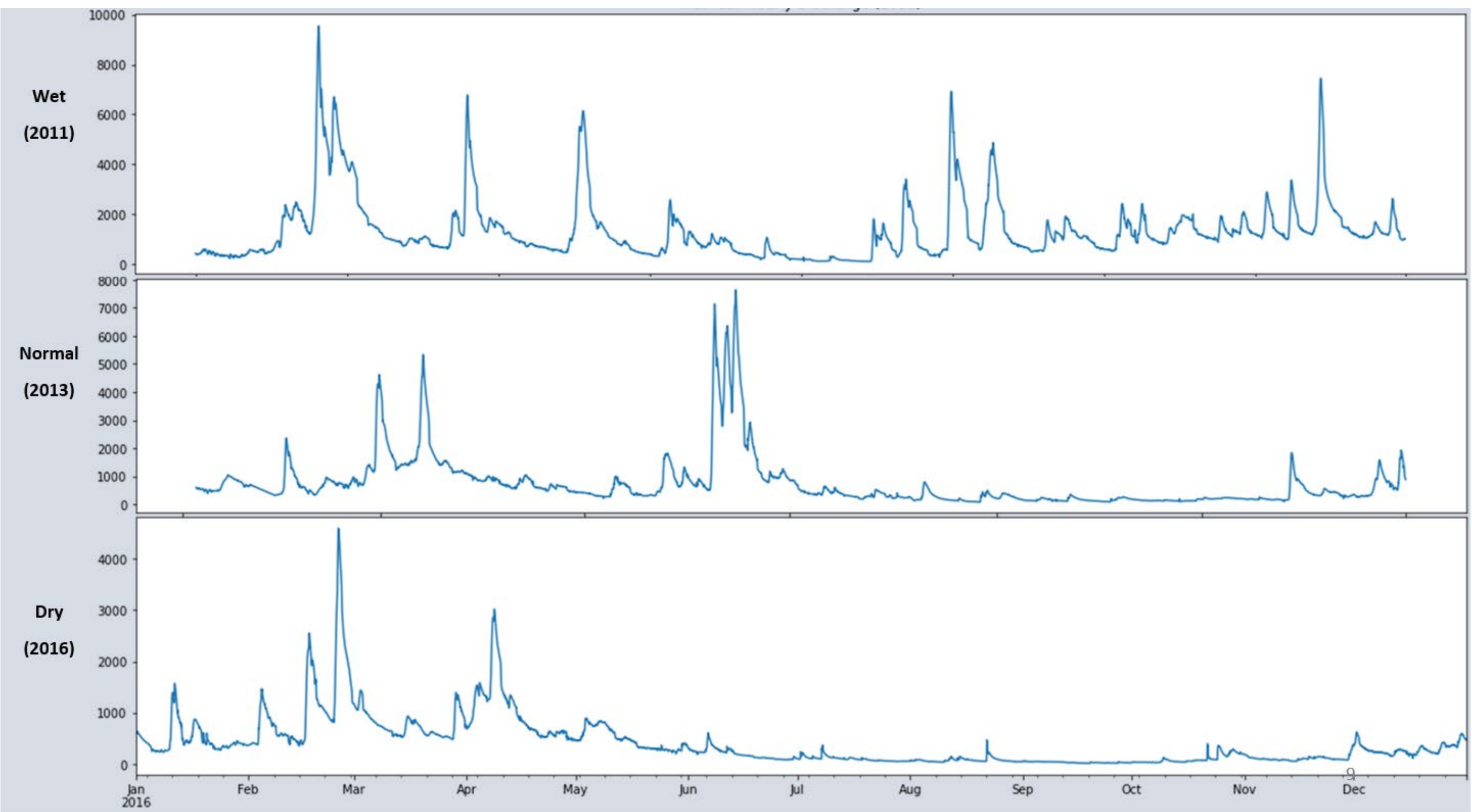


Figure 13. *Three representative hydrological years used for environmental flow rate and unit hydraulic capacity experiments: 2011 (wet), 2013 (normal), and 2016 (dry)*

Unit Hydraulic Capacity: Station hydraulic capacity is known to constrain power generation under both high flow and low flow scenarios. Generation is constrained under high flows to the maximum hydraulic capacity of the unit. Under low flows, generation is also constrained due to generally low efficiency of power turbines at the extremes of their operating range. This study simulates generation under three station capacities equal to were 700 ft^3/s, 1,250 ft^3/s, and 2500 ft^3/s, equal to 56%, 100%, and 200% of status quo station hydraulic capacity respectively. Values were chosen to represent a range of plausible station capacities for the Shetucket River. Status quo station hydraulic capacity is of 1,250 ft^3/s is equivalent to a flow exceedance probability of 14% for the Shetucket River at gage 01122500. 2,500 ft^3/s is roughly 8% exceedance probability, and 700 ft^3/s roughly 35% exceedance probability.

For each of the three experiments outlined above, baseline generation loss was calculated from simulated hourly power generation for the years 1995-2020. The initial experiments test annual and seasonal generation over the study period under two scenarios: 1) a scenario under which environmental flows are required and 2) a no environmental flow requirement. The difference in generation under the two scenarios represents the power that could be generated by environmental flows, or the opportunity cost of the water. We term this value “generation loss” because it is the modeled loss in generation due to environmental flows. Generation losses are reported in terms of both normalized and non-normalized (or absolute) generation. Results of these experiments are further analyzed by season and annual precipitation.

The generation loss due to environmental flows is defined as the lost power generation in kilowatt-hours attributable to the sum of all flows. Generation was calculated as the absolute difference in generation between a given environmental flow scenario and the status quo. The status quo represents present operations wherein all environmental requirements are met. Increased generation observed when environmental flow constraints are removed from the model are assumed to represent potential generation value of those flows.

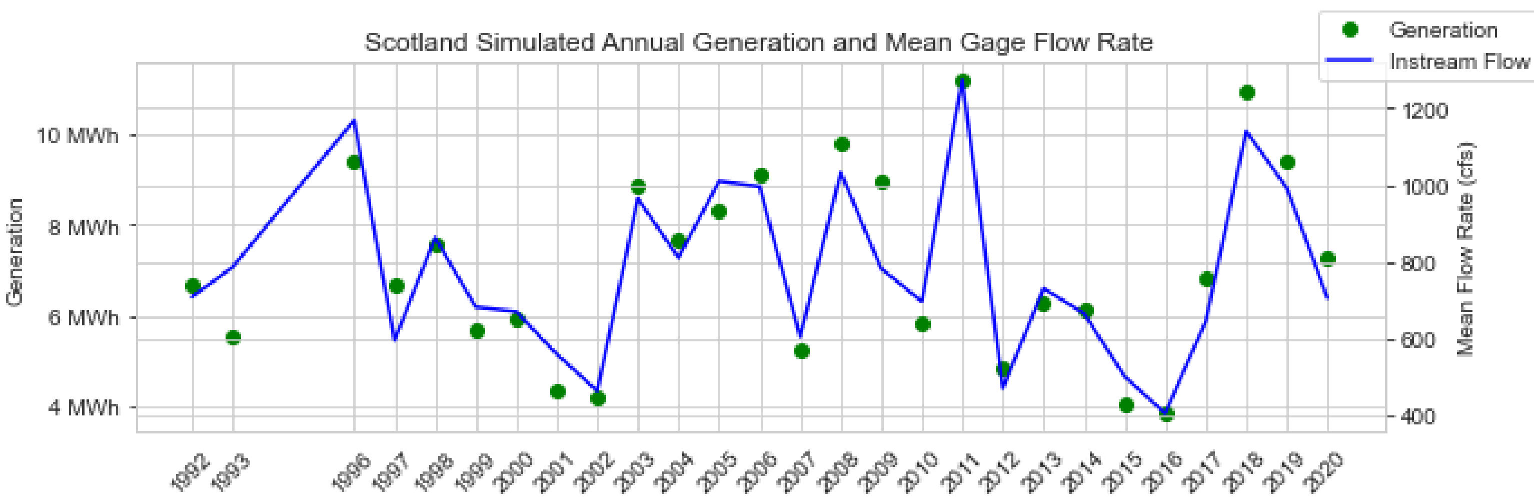
Because environmental flows are typically diverted from the powerhouse or discharged as spill, they do not contribute to power generation. Absolute generation lost or gained by addition of environmental flows through the turbines is reported in Megawatt-hours. Absolute generation typically varies with inflows, with higher flows producing greater generation. The normalized generation loss is the generation associated with environmental flows divided by the total generation. This metric reflects the relative importance of environmental flows to total generation, and it varies both seasonally and inter-annually.

$$Normalized\ generation\ loss = \frac{generation\ with\ environmental\ flows\ added - status\ quo\ generation}{status\ quo\ generation}$$

Generation was simulated over both seasonal and annual periods. Annual results were also analyzed based on whether annual streamflows were higher or lower than normal. Normal years are defined as years falling with the 25^{th}-75^{th} percentile for instream flow rate. Wet years are those above the 75^{th} percentile and dry years are below the 25^{th} percentile.

3. Results

Power generation was simulated for all years in the study period under two model permutations: “status quo” and a “no environmental flows” scenario. The difference in generation between the two scenarios is termed the generation loss. The model was then run under three further permutations to isolate each environmental flow type individually. The generation loss for each flow type was then calculated as the difference from the "no environmental flows" scenario. Generation losses from individual flows are therefore not necessarily additive, since the sum of upstream, downstream and habitat flow generation losses at times exceeds the losses from the all-requirements scenario. This observation can be explained by the fact that generation is simulated in unique runs for each scenario with the rule that when inflows to the powerhouse are insufficient to meet the environmental flow minimums, then generation is ceased. This rule was more often triggered by the status quo or "all requirements" scenario than in runs with testing only a single flow.



Generation loss was computed as the difference between the status quo scenario and the no environmental flows scenario. The Status Quo scenario generated 6,695 MWh per year on average with a minimum of 3,583 MWh and maximum of 10,859 MWh. The lowest generation occurred during the low-flow year of 2016 and the highest generation occurred during 2011, a year remembered for heavy rains and flooding associated with Hurricane Irene. Seasonal variation was observed consistent with precipitation and streamflow seasonal patterns of the Northeast. Highest daily generation occurred during the high-flow months of March and April, with lowest generation occurring during the historically dry months of July through September (Figure 14).

Compared to the Status Quo scenario, a system running with no environmental flows generate 545 MWh more power per year, or 8.9% of the total generation (Fig 15).

MWh	Status Quo	No Environmental Flows
Mean	6,695	7,240
Median	6,350	6,860
Standard Deviation	2,047	2,065
Max	10,859	11,378
Min	3,583	4,045

Figure 15. Annual Simulation Generation Statistics for two Scenarios. Values are reported in Megawatt-hours.

Habitat flows, representing roughly 3% of plant capacity and flow year-round, had a mean cost of over 250 MWh per year, or over 4% of total annually. Upstream attraction flows, which are discharged at a rate of roughly 5% of plant capacity for three months a year, reduce the plant's production by roughly 3% of generation, or 175 MWh, and downstream flows added an additional mean 2% cost, or 120 MWh.

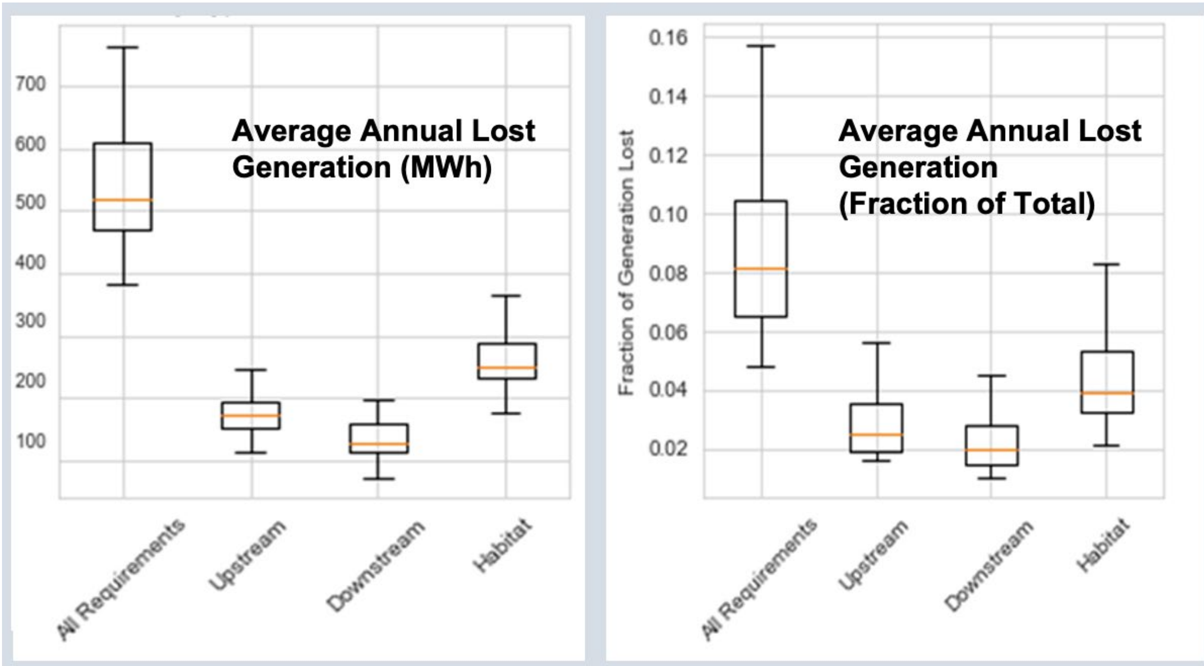
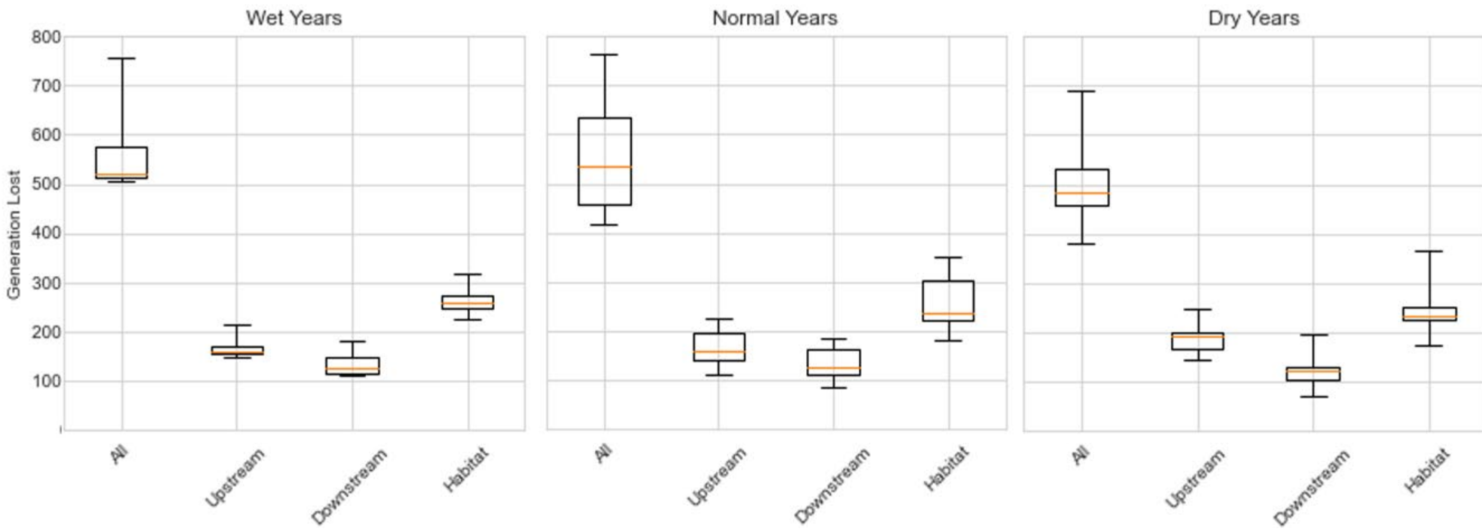


Figure 16. *Generation Lost by Type of Environmental Flow: Annual (1991-2020) Raw (left) and normalized (right) annual mitigation costs of environmental flows. "Upstream", "Downstream", and "Habitat" each refer to the cost of a single flow, while "All Requirements" refers to the total combined cost.*

Hydrological Conditions: To investigate impacts of flow requirements across the range of hydrological conditions, the historic record was divided data into "wet," "normal," and "dry" years and generation losses reported for each. During a wet year, the median generation losses due to environmental flows was 6%. During normal years that value increased to 9%, and during dry years, to 12% (Figure 17). Greater variation in generation loss during normal years is observed, which we attribute in part to variability in hydrology during normal years. In part, the decrease in variability of results during wet years may also be attributed to an upper boundon generation imposed by flows exceeding the unit capacity in a run-of-river system.

(a)



(b)

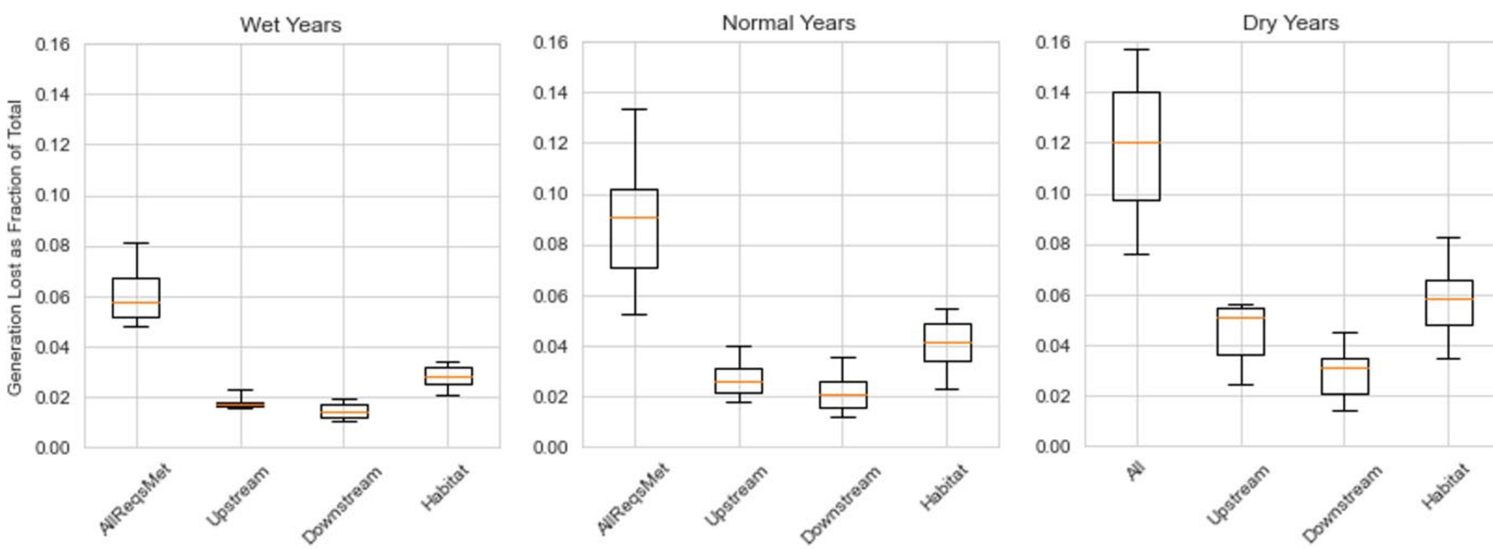


***Figure 17 (a)** Generation Lost to Environmental Flows by wet, dry, and normal years (MWh); and **(b)** Generation Lost to Environmental Flows by wet, dry, and normal years: Normalized as fraction of total generation 1991-2020*

Generation losses were further analyzed by season over the entire historic period. In terms of absolute generation, environmental flows diverted through the turbines produced more power during spring season than during any other season (Fig 18). Spring is also the period of both highest instream flow rates on the river and highest environmental flow rates, when all three environmental flows are active (upstream fish lift attraction, downstream fish lift attraction, and habitat flows). The normalized season plots illustrate the relative importance of flows during the dry season (Jul-Sept). Although flows drop to 29 ft^3/s, or 3%, during that period, they are associated with a greater than median 10% loss in generation.

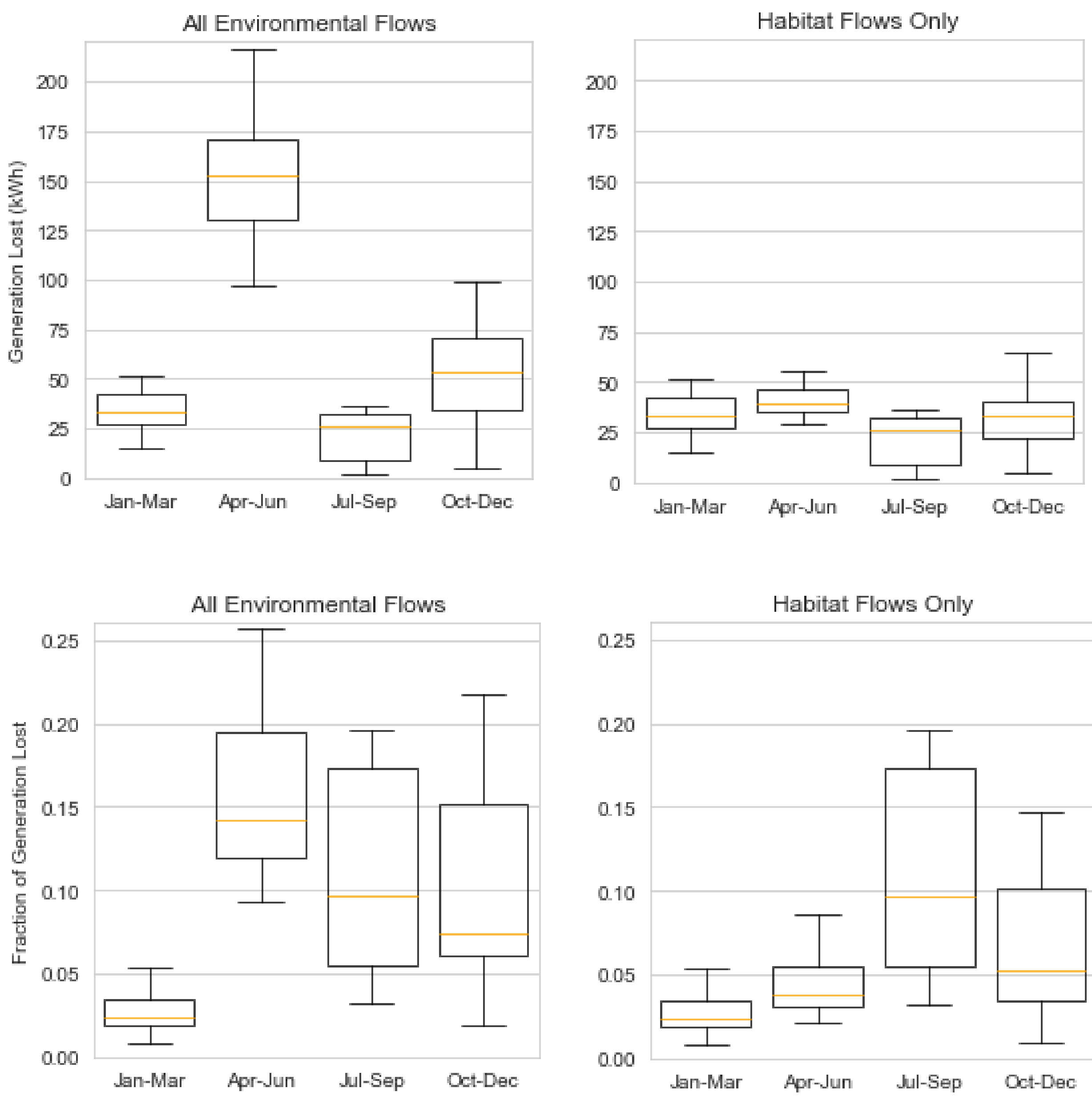


Figure 18. *Seasonal Generation Loss by Environmental Flow Type measured as (a) MWh, and (b) fraction of total generation*

Environmental Flow Rates: Three environmental flow rates were compared under the status quo statin hydraulic capacity for the representative wet, dry, and normal years. Flow rates tested were 0%, 5%, 10% of station hydraulic capacity. Flow rate refers to peak environmental flow rates, equal to the highest flow rate, the upstream attraction flow. The 5% flow rate is equal to the status quo scenario flow rates, 58 ft^3/s for upstream attraction, and 29 ft^3/s each for downstream attraction and habitat flows. The 10% flow rate scenario roughly doubles those values, and the 0% flow rate sets flows to zero.

As expected, higher environmental flow rates correlated with lower total power generation in all scenarios. In wet years, doubling the environmental flows (from 5% to 10%) only reduced generation from 10,814 to 10,213 MWh, or 5.5% (Fig. 19). In normal and dry years, the same increase in flows produced decreases in generation equivalent to 10.4% and a 12.1%, respectively.

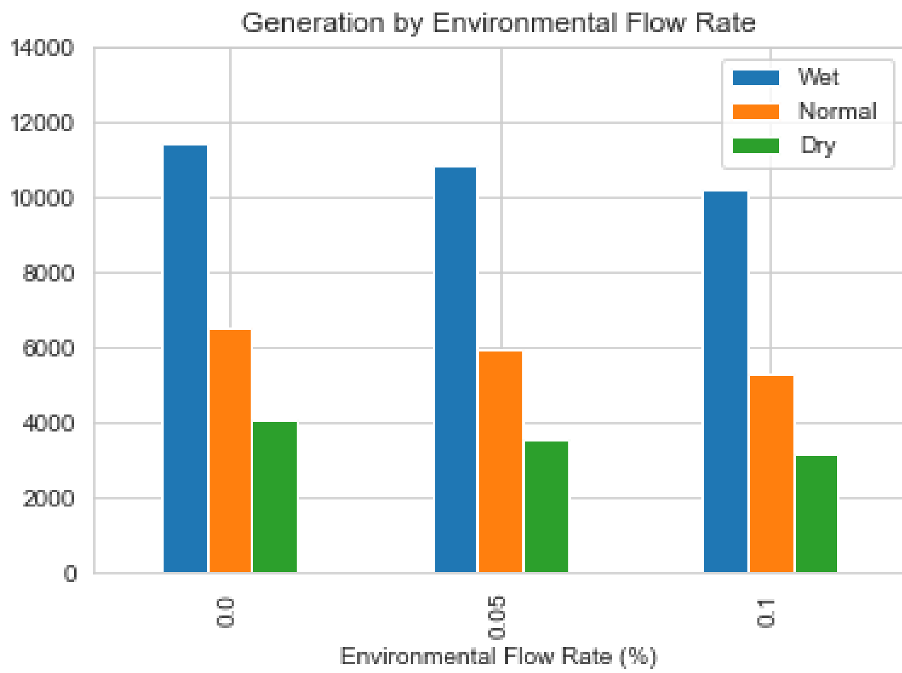


Figure 19. *Annual Power Generation Under Varied Environmental Flow Rates at Status Quo Station Hydraulic Capacity in Megawatt-hours.*

Station Hydraulic Capacity: Three turbine capacities were compared under the status quo environmental flow rate for the representative wet, dry, and normal years. The turbine capacities tested were 700 ft^3/s, 1,250 ft^3/s, and 2500 ft^3/s, equal to 56%, 100%, and 200% of status quo station hydraulic capacity respectively. In normal years, generation was greatest (5,290 MWh) at 1,250 ft^3/s of capacity, and lower under both the 700 ft^3/s capacity (5,370 MWh) and 2,500 ft^3/s capacity (5,087 MWh) scenarios. In wet years, larger turbine capacity resulted in the greatest generation, achieving a 732 MWh gain over the 1250 ft^3/s capacity unit, equal to 6.8%. By contrast, in dry years the 2,500 ft^3/s unit produced the least power, only 2,361 MWh, which is a 10.7% decline compared to the 1,250 ft^3/s unit.

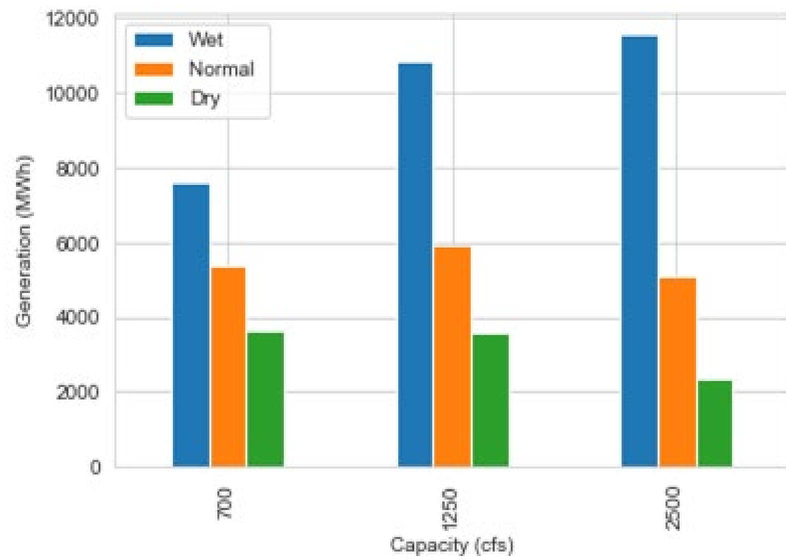


Figure 20. *Annual Power Generation Under Varied Station Capacities at Status Quo Environmental Flow Rate in Megawatt-hours.*

Regional Analysis: Over the past one-hundred and twenty years, hydropower facilities in the Northeast have been designed with a wide range of capacities as a function of the flow of the river on which they are located (Figure 21). Compared with the case study, Scotland's capacity is larger than one other facility (Jackson Mills) and smaller than seven others. Its design flow of 1,250 cubic feet per second has a 20% exceedance probability. The exceedance probability of its design flow is greater than six and smaller than two (Jay and Livermore) of the sites sampled. Exceedance probabilities of design flows ranged from less than 5% to 38%, with the majority of projects falling between 10% and 20%. For comparison, other sources describe design capacities ranging from 25% to 45% exceedance flow for baseload, or run-of-river, plants (Warnick 1984, Justin and Creager 1950). The higher the exceedance probability, the lower the flow, meaning that the turbines observed in the sample are larger than the values described in the literature.

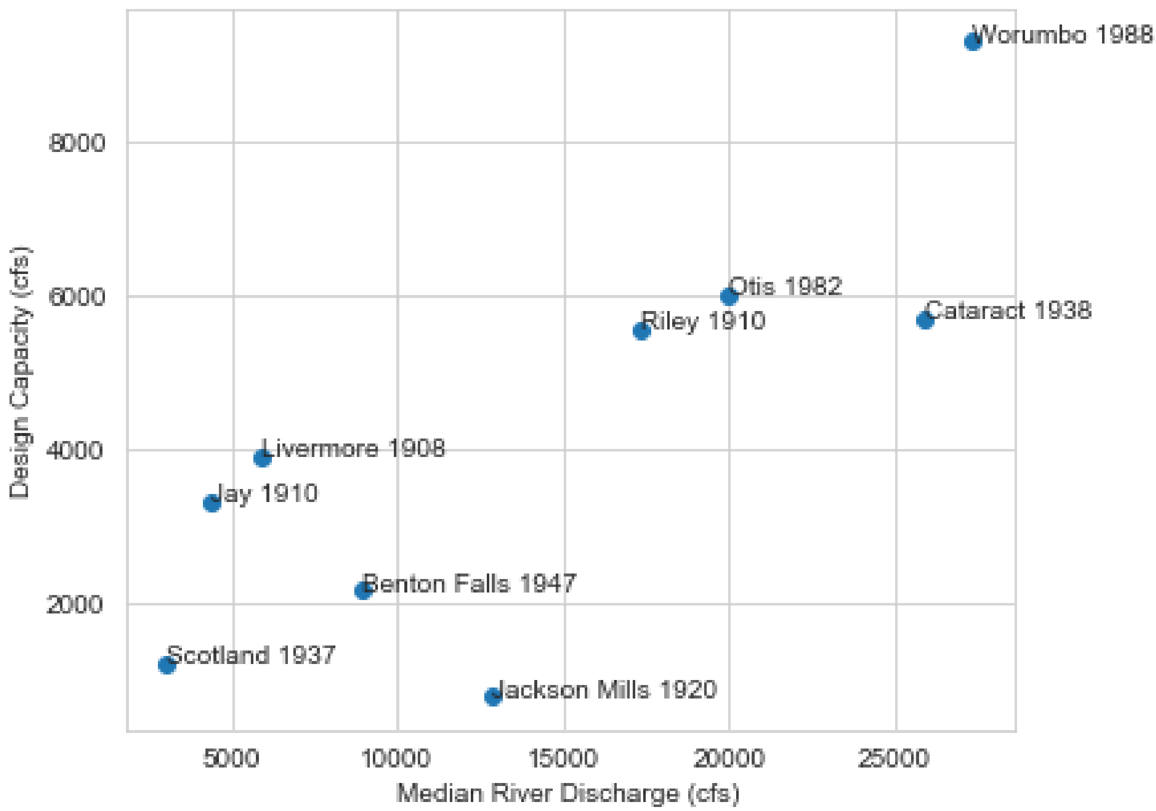


Figure 21. *Design Capacities of New England run-of-river hydro plants built after 1900*

4. Discussion

This study explored the impact of three variables on power generation of low head hydropower production relative to environmental flows: hydrologic conditions, environmental flow rate, and station hydraulic capacity. Hydrologic conditions strongly impacted generation, with power generation greatest during high flows, and generation losses greatest during low flows.

High flow time periods, such as wet years and spring, produced both high power generation. In terms of absolute generation, environmental flows diverted through the turbines produced the most power the spring season is when. This result reflects not only the high instream flows and high generation rates during the spring, but also the high flow rates for environmental flows. In spring, combined environmental flows are at their highest rate, approaching 120 ft^3/s. Although the spring season is the most productive for hydroelectric generation, the relative abundance of electricity on the market tends to drive down wholesale energy prices and thereby reduce market value.

Station hydraulic capacity also strongly impacted generation. Low efficiency of generation at the extremes of a turbine's operating range is believed to contribute to this observation. Finally, higher environmental flow rates are associated with reductions in generation at this site. Attraction flows, which are discharged at a higher flow rate but for a shorter portion of the year, had a marginally greater impact than habitat flows.

Regional Analysis: The Scotland powerhouse case study represents a small project relative to the sample of run-of-river sites in New England. Potential sources of error in this analysis include the small sample size as well as the use of raw gage data for determination of exceedance probabilities for each design flow. Inflow data was collected from gages within 25 miles upstream of a site.

Nonetheless, design capacities for the majority of sites are closer to the recommended value for peaking sites rather than run-of-river sites. Exceedance probabilities of design flows in the sample ranged from less than 5% to 38%, with the majority of projects falling between 10% and 20%. In this case, a larger design flow exceedance probability represents relatively a smaller turbine.) A possible explanation for this finding is represented by Scotland's own story. Originally a peaking plant, Scotland transitioned to a run-of-river operation as a condition of its license renewal. The original turbine was not altered, likely due to the substantial cost of retrofitting. Subsequently, the operation was left with what could be considered an oversized power unit. Scotland's transition from peaking to run-of-river may be representative of a larger trend in the hydro industry.

5. Conclusions

In summary, this study indicates that both hydrological conditions and station capacity have strong impacts on generation, both individually and in conjunction with each other. Dry periods produced less generation and greater losses due to environmental flows. Although the high-capacity turbine scenario generated increased power under high flow conditions, losses were greater during dry periods. By contrast, the impact of environmental flow rates to generation was comparatively modest, in the range of 3-12%. Increases in flow rates as a percentage of station capacity were associated with roughly proportional reductions in generation in the study system. Among different types of environmental flows, attraction flows were discharged at a higher flow rate, though seasonally, and showed a marginally greater impact than habitat flows.

Changes in the hydroelectric industry and climate have ushered in changes to how turbines are sized for economic performance. First, competing environmental uses for river water have dispelled the historical presumption that generation is the only, or even most important, use of river hydrology. Today's reality is that there is less water available to power turbines than there was 50 years ago even in an otherwise unchanged system. , Secondly, given advancements in our understanding of climate trends, there is a heretofore unrealized risk in any turbine sizing or site design process that relies on a fixed exceedance level based on historical trends in river hydrology. Climate and environmental constraints combined add risk and reduce the flows that hydro companies can safely expect.

Therefore, for new hydro developments, designers may opt to subtract environmental flows from gage flows when sizing units to more accurately represent flows available for power generation. For existing hydro projects, the reality that environmental constraints result in reduced water available for the turbine suggests that optimal turbine size might be smaller than what was originally installed.

Sensitivity to sizing suggests that hydro owners should consider turbine retrofits to optimize efficiency if their new license is now subject to fish passage and habitat flow requirements. For retrofits, choose a turbine with a flat efficiency curve, with a wide operating range, such as a Kaplan turbine. Francis-style turbines are most sensitive to changes in turbine discharge, so they suffer more from changing discharge. An alternative proposed in Creager & Justin (1950) is the installation of multiple, smaller turbines. For example, one turbine would run constantly on base flow and another would run intermittently to capture high flows. The drawback of both retrofit approaches is the high cost, with capital & maintenance costs typically being higher for multiple units than for the same capacity in a single unit.

A relatively inexpensive alternative to new construction or retrofits is using use turbine discharge for environmental flows. Technologies exist that pump downstream flows back up stream of the dam to release as attraction flows or habitat flows, but they are, as yet, uncommon outside of certain sites in Europe. Low-cost technologies are in development that may be suited to using turbine discharge toward environmental flows, such as the entrance palisade design. The entrance palisade is designed to allow turbulent turbine discharge to settle before being discharged as attraction water at the entrance of the fishway at appropriate velocity (Rojas 2020). Therefore, one way to mitigate the economic impacts of environmental flows on hydropower plants is to foster low-cost technologies that are suited to using turbine discharge as attraction water.

Our case study is representative of small-to-medium-sized hydro facilities, but results may not be generalizable to larger plants. The relative importance of different fish passage costs is believed to vary with the size of the project. For large projects, the capital costs for conveyance of water, including excavation, is a more significant than the impact to generation from environmental flows. Because environmental flow minima are typically set at a fraction of the plant capacity, a larger plant requires a larger flow rate that may exceed the capacity of a single pipe, requiring a more costly solution. By contrast, the impact of the mitigation cost of environmental flows may be greater for smaller projects. This is not only because of the relatively smaller cost of construction, but also due to the nature of regulatory requirements. In most cases environmental flows are set at a percentage of plant capacity. However, in the Northeast, the recommended minimum attraction flow is not to fall below 50 ft^3/s, regardless of the size of the river. For very small projects, 50 ft^3/s may represent greater than 8% of capacity, resulting in a greater mitigation cost of environmental flows. Therefore, the mitigation cost of environmental flows may represent the greatest cost for small units, especially those below 1,000 ft^3/s capacity.

Trends in flow requirements suggest future increases in the quantity of water devoted to supporting healthy habitat for projects of all sizes. Minimum flows have historically trended upwards with advances in the state of the science. For past projects like the Scotland Fish lift, attraction flow requirements were set at 3% of station capacity. However, in general, the higher the percentage of instream flow diverted to fish attraction, the more successful the upstream passage at a project (NMFS 2011). The NMFS recommends a minimum 5% of capacity for attraction flow, and up to 10% for non-powered dams (2011, USFWS 2019). Future flow rates of 10% would translate to at least a doubled cost of environmental flows for most projects in the Northeast.

Further environmental constraints on production incentivize innovation. Constraints on head pond elevation fluctuation have been successfully incorporated into licensing agreements at a number of dams in the Northeast. Headpond fluctuations are associated with ecological impacts such as altered aquatic and riparian habitats (Cushman 1985), impacts to riverbank stability and morphology (Sear 1995), and altered groundwater dynamics (Curry et al 1994). When head pond elevation is constrained, hydro operators are unable to maximize profits by only generating during hours of high prices, in a practice known as hydropeaking. Instead, operators are encouraged to make releases that mimic river flow at a more natural rate, or run-of-river.

Fluctuations in energy prices can also have a strong impact on the mitigation cost of environmental flows. Electricity prices dropped in the second decade of the 21st century amid proliferation of renewables and cheap natural gas. But a market correction on the horizon would mean higher hydroelectricity prices. Higher prices translate to greater corresponding opportunity costs of any water lost to the system, including environmental flows.

Finally, the estimating the impact of environmental flows is complicated by streamflow variability and uncertainty associated with climate change. Increased precipitation and higher high instream-flows may seem like a win for hydro. In fact, greater flow variability in the form of more dramatic extreme flows can cause headaches for power generation. Rapid storms that dump extreme rainfall over short periods may produce high flows that exceed an operation's capacity to capitalize on it. Excess flows that cannot be stored in a head pond are typically spilled downstream to prevent flooding, producing no revenue to hydro. A climate with higher intensity, intermittent rainfall is not a guaranteed win for hydro.

The full economic impact that environmental mitigation measures will have on the hydro industry remains untold. As licenses to generate expire (most last 30-50 years) and new facilities are constructed or retrofitted, new requirements are implemented. Many extant Northeast hydro projects predate environmental regulations introduced in the 1970s, and as such, were designed without environmental flows in mind. They may therefore be sized for flows that are not currently possible due to environmental constraints. A facility designed for higher flows may face mismatch between infrastructure design and real available flows. As environmental mitigation requirements approach ubiquity, they pose a growing recurring cost to the entire hydro industry.

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