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OAK RIDGE National Laboratory

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Environmental Sciences Division

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Paul G. Matson[*]
Kevin M. Stewart[*]
Gbadebo A. Oladosu[*]
Emrat Nur Marzan[†]
Scott T. DeNeale[*]

[*]Oak Ridge National Laboratory
[†]Natel Energy

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OAK RIDGE NATIONAL LABORATORY
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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

CR	conventional relicense
DOE	US Department of Energy
EA	environmental assessment
EIS	environmental impact statement
FERC	Federal Energy Regulatory Commission
FOA	Funding Opportunity Announcement
IQR	interquartile range
NID	National Inventory of Dams
NSD	new stream-reach development
NPD	non-powered dam
ORNL	Oak Ridge National Laboratory
PM&E	protection, mitigation, and enhancement
SMH	standard modular hydropower
TVA	Tennessee Valley Authority
USBR	US Bureau of Reclamation
WPTO	Water Power Technologies Office

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EXECUTIVE SUMMARY

Hydropower represents a reliable source of renewable energy and accounts for approximately 7% of the total electrical generation in the United States. Future expansion of hydropower is likely to be in the form of either smaller new stream development projects or powering existing non-powered dams. For these new projects to be successful, careful analysis of risks, costs, and uncertainty to offset reduced power production as well as ensuring the protection and safe passage of migratory fish to gain public support, will be required. Exclusion and passage are two common approaches to protect fish from entrainment and impingement at hydropower facilities. The thresholds for entrainment risk and requirements for exclusion and passage often differ depending on the species involved, the characteristics of the facility, and the goals of stakeholders. While the costs associated with environmental mitigations represent a large proportion of the total costs required for the licensing of hydropower facilities, little quantitative information is present within the literature regarding the specific costs of fish exclusion and passage.

Working with FOA awardee Natel Energy, scientists at Oak Ridge National Laboratory were tasked with assessing the capital construction costs for downstream fish exclusion and passage infrastructure. This report used keyword searches of an existing environmental mitigation cost data set and manual extraction of additional cost data associated with protection, mitigation, and enhancement (PM&E) measures related to positive barrier screening and passage from regulatory licensing documents available in the Federal Energy Regulatory Commission (FERC) eLibrary. This approach yielded a total of 50 PM&E mitigation measures with estimated capital construction costs pertaining to positive barrier screens, 142 pertaining to passage studies, and 26 pertaining to passage-related studies. PM&E measures associated with positive barrier screens represented <10% of the 171 total FERC project dockets available in the data set. These data were highly skewed toward conventional relicensing projects, as <7% were associated with new stream development (NSD) projects. Results from these data indicate highly variable costs associated with fish screening, with flow-normalized costs one to two orders of magnitude higher for screening with the highest exclusion capability (≤0.09 in. spacing) compared with coarser screening (1 to 2 in.). Furthermore, estimated capital costs of passage infrastructure were positively related to the scale of the project based on installed capacity for some, but not all, types of passage. These data provide an initial baseline for estimating exclusion and passage costs for hydropower development and may help developers consider options for more fish-friendly generation technologies, though gaps remain relating to a lack of data, particularly for NSD projects. More data may still be available within the FERC eLibrary, but significant effort will be required to manually identify and extract the data for future analyses.

1. INTRODUCTION

Hydropower represents a reliable source of renewable energy around the world. In the United States, hydropower accounts for approximately 7% of the total electricity generation and 37% of the total renewable energy generation. Although massive hydropower generation facilities such as the Grand Coulee Dam can produce up to 6.8 GW of electricity, the future expansion of hydropower is likely to be in the form of much smaller projects (Hadjerioua et al. 2012; Kao et al. 2014) or focused on powering non-powered dams (Hansen et al. 2021). A reduction in potential power production increases the need for careful analysis of risks, costs, and uncertainty for future expansion to be successful. Regardless of facility size, the protection of river ecosystems, and in particular the protection and safe passage of migratory fish, is an important consideration for gaining public support for any hydropower project.

The mission of the US Department of Energy (DOE) Water Power Technologies Office (WPTO) is to enable research, development, and testing of new technologies to advance marine and hydropower energy systems to enable a flexible and reliable energy grid. The standard modular hydropower (SMH) paradigm, based on the design of standardized, modular, and environmentally compatible technology, would enable the expansion of efficient, cost-effective, and environmentally sustainable development of new hydropower facilities (Witt et al. 2017). These SMH facilities would comprise multiple types of modules depending on the needs of the project, including generation, passage (e.g., fish, sediments, water, recreational craft), and foundation.

In 2018, WPTO released a Funding Opportunity Announcement (FOA) targeting Facility Design Concepts for Standard Modular Hydropower Development (DE-FOA-0001836 Topic Area 1; EERE 2019). The purpose of this FOA was "to stimulate innovative designs for small, low-head hydropower facilities capable of lowering the capital costs and reducing the environmental impacts of development at new stream reaches" (i.e., "greenfield" sites). As an outcome, this FOA aimed to supply the hydropower industry with scientifically vetted SMH facility designs that can operate at significantly lower costs with smaller environmental footprints. The development of such modular facility designs will provide a critical benchmark for the technical, economic, and environmental feasibility of transformative new technologies and structures.

Among the two FOA awards granted, Natel Energy proposed to

> "create a blueprint for a new generation of water-power projects using a modern low-head hydropower technology that also utilizes best practices of stream restoration and whitewater recreation. Natel's environmentally friendly project includes generation modules and modular foundation design, nature-based passage functionality including head creation, water, fish, and sediment passage, sport management and recreation passage, and a novel set of module foundation concepts." (EERE 2019)

As part of this award, DOE's Oak Ridge National Laboratory (ORNL) scientists were tasked with providing technical assistance in several areas, including an assessment of fish exclusion. Specifically, ORNL has been tasked with assessing the life cycle costs and design impacts for fish exclusion capability. These analyses include a focus on the costs associated with the construction of downstream fish exclusion infrastructure.

2. BACKGROUND ON HYDROPOWER FISH EXCLUSION

2.1 NEEDS AND CONSIDERATIONS FOR DOWNSTREAM EXCLUSION BARRIERS AND PASSAGE

A key goal for sustainable hydropower production is to prevent fish injury and mortality due to facility operations. Downstream entrainment or impingement associated with hydropower infrastructure (e.g., turbines, spillways, sluiceways) represents a major hazard for riverine fish, where they may be subjected to a wide range of harm from mechanical, pressure, shear, and turbulence effects (Algera et al. 2020). Fish that enter operational turbines risk numerous dangers, including blunt force trauma, decapitation, descaling, hemorrhaging, barotrauma, and disorientation (Pracheil et al. 2016). Increased mortality, whether instantaneous or delayed, may have significant negative population-level effects (Nieland et al. 2015; Pracheil et al. 2015). Although any species of river fish could be entrained, the risks are higher for migratory species (i.e., anadromous, potadromous, catadromous) that may travel long distances within watersheds, thus increasing the potential likelihood of encountering a hydropower facility. Therefore, mitigating entrainment risk is often a requirement for licensing by the Federal Energy Regulatory Commission (FERC). This mitigation is generally implemented by either excluding fish from areas of entrainment or by providing alternative conduits for passage that avoid areas of entrainment.

Exclusion is the primary approach to reduce the risk of entrainment and impingement to fish. Passage is another approach to reduce the risk of entrainment and impingement to fish and may also be used in conjunction with exclusion at a hydropower facility. The threshold for entrainment risk and requirements for exclusion and passage often differ depending on the fish species involved, characteristics of the facility (e.g., design, turbine type), and the goals of stakeholders. Rivers containing migratory species that are listed as threatened/endangered at federal, state, or tribal levels or are of high commercial and/or ecological value tend to set lower thresholds for entrainment than rivers lacking such species. For example, rivers containing migratory salmon have more stringent requirements set by the National Marine Fisheries Service than rivers that have primarily resident (nonmigratory) populations of noncommercial fishery species such as sunfish. Furthermore, the requirements for exclusion are influenced by the biological characteristics of the fish species of interest, such as size and swimming ability, which change across life history. Additional considerations that pertain to the physical environment include the magnitude and variability of flow, water depth, debris and sediment loads, and the possibility of seasonal ice flows. In addition to having capital and operational costs, most passages also require a minimum amount of river flow to be diverted away from turbines to instead provide for the transport of fish, which may reduce the potential for electricity generation.

2.2 APPROACHES FOR FISH EXCLUSION AND PASSAGE

The overall goal is to mitigate fish entrainment by keeping them out of hazardous areas, and this can be accomplished using several different approaches: positive exclusion barriers, stimulating fish behavioral responses, providing an alternative conduit for passage, and/or removing the entrainment hazard. Positive exclusion barriers have the longest history of acceptance by fisheries resource agencies to protect fish at water diversions, usually in the form of positive barrier screens (USBR, 2006). These screens prevent fish from entering a hazardous area, such as a turbine intake, and have many options in terms of shapes, designs, and materials depending on the goals and site characteristics. Given that screens are a fixed structure, careful design consideration of approach and seeping velocity components is required to ensure that the screen does not become a hazard to fish because of impingement upon the screen (USBR, 2009). Higher approach flows and smaller screen spacing sizes may require larger screen areas to ensure proper performance. Screens are also indiscriminate of what is excluded, which can comprise organic and inorganic debris as well as fish. Regular cleaning is necessary, and additional trash racks may be required to protect the screen.

Behavioral barriers represent a targeted approach to use a stimulus to elicit a volitional response from a fish. Depending on the type of the stimulus, the fish would be encouraged to swim away from danger (negative), such as a turbine intake, or attracted toward a safer path (positive), such as a bypass conduit. Behavioral stimuli can take several different forms, such as accelerated flow from louvers to stimulate directional swimming, and lights and sounds that may either attract fish to or repel fish from a particular location. Given that there is no redundancy device to exclude fish that do not respond appropriately to the stimulus, behavioral barriers are not considered 100% exclusionary, particularly during high flow events or low visibility conditions. Furthermore, behavioral responses are highly species-specific, which could be problematic for sites with highly diverse fish assemblages. This is still an active area of research, particularly for hybrid systems that use multiple stimuli.

The long history of fish passage research has produced a wide array of approaches to facilitate the safe passage of migratory fish species across aquatic barriers (Katopodis and Williams, 2012). Such passage infrastructure can be specific to particular fish taxa (e.g., eel ladder versus salmon ladder), direction of movement (e.g., downstream bypass versus upstream fish ladder), and method of construction (e.g., nature-like versus technical fishways). Some passage technologies use a combination of alternative conduits and positive barrier screening/behavioral barriers to direct fish away from hazardous locations to transit across the barrier.

An alternative to attempting to exclude or protect fish from entering a hazardous location is to remove the threat from entrainment. Some facilities accomplish this by temporary generation shutdowns during migration events (e.g., nocturnal movements of American eels) at the cost of potential energy production. The design of fish-friendly infrastructure is intended to allow for the safe passage of fish while maintaining energy production. Such technology is currently in various stages of development and production in Europe and the United States.

2.3 NEED FOR COST ESTIMATES OF FISH EXCLUSION AND PASSAGE

The expansion of hydropower capabilities in the United States depends on the identification of suitable locations for the cost-effective generation of environmentally sustainable power. Tools and data sets have been created to aid hydropower developers in site selection (DeRolph et al. 2019), the prediction of environmental mitigations (DeRolph et al. 2016; Schramm et al. 2016), and costs associated with mitigating environmental impacts (Oladosu et al. 2021). Additional detailed analyses are needed to provide developers with proper information on the costs associated with the construction and operation of new hydropower facilities, whether for new stream-reach development (NSD) or retrofitting non-powered dams (NPDs). This is especially important given that most undeveloped sites are of a smaller scale in terms of hydropower potential capacity (Hadjerioua et al. 2012; Kao et al. 2014).

Environmental mitigation costs represent a large proportion of the total costs required for the licensing of hydropower facilities and may become an important decision variable for the initiation of future new development projects (Oladosu et al. 2021). Unfortunately, there is little quantitative information present within the literature regarding the specific costs of fish exclusion and passage. Given the amount of material required, positive barrier screens are generally considered to have relatively high construction costs (USBR, 2009). Behavioral barriers have generated considerable research interest because of perceived cost savings relative to more traditional positive barrier screens. However, their adoption has been limited to date because of a lack of sufficient evidence for sustained high levels of efficacy. Similarly, fish-friendly turbines designed specifically to avoid injury to passing fish represent an additional option (Hogan et al. 2014), though some are currently experimental, and most have not been widely deployed. Further testing will be required to determine the efficacy of these new technologies to justify their requisite costs.

The goal of this report is to provide a quantitative assessment of the costs of using positive barrier screens to prevent fish entrainment at hydropower facilities. This information will provide value to the hydropower community and establish a baseline from which to compare the cost effectiveness of alternative strategies to protect aquatic resources.

3. ANALYSIS OF FISH EXCLUSION COSTS

3.1 METHODS

3.1.1 Data Sources and Filtering Approach

Measures intended to mitigate the entrainment of fish into hydroelectric facilities (e.g., turbines, sluice gates, diversion valves) can be found within publicly available environmental impact statements (EIS) and environmental assessment (EA) documents associated with FERC hydropower license dockets in the FERC eLibrary (https://elibrary.ferc.gov/eLibrary). Data used in this report were obtained from two sources: ORNL's Costs of Mitigating the Environmental Impacts of Hydropower Projects data set (Oladosu et al. 2021) and directly from the FERC eLibrary. Oladosu et al. (2021) compiled an extensive database of 182 EIS/EA documents extracted from the FERC eLibrary from 1996 to 2018 (data available as Werble et al. 2021 at www.hydrosource.ornl.gov), which included 54,000 protection, mitigation, and enhancement (PM&E) measures along with associated projected capital costs and facility characteristics. For this report, PM&E measures were filtered to include those pertaining to aquatic species (Tier 1) and projected capital costs greater than zero.

To identify measures from this subset related to positive barrier fish exclusion, a search string consisting of the key words "screen, screens, bar, bars, spacing" was used. Measures that did not include physical construction (i.e., planning, development, or studies) or were associated with pumped storage hydropower facilities were removed from the search results. Additional data were manually extracted from EIS/EA documents associated with these measures as needed. The Oladosu et al. (2021) data set was supplemented by manual extraction of data from EIS/EA documents associated with hydropower licenses found within the FERC eLibrary that included PM&E measures related to fish exclusion. These included documents from 2009, 2016, and 2018 to 2021, with September 13, 2021, as the last date of accession. A list of projects included in this report is provided in Table 1.

Table 1. Source EIS and EA documents from the FERC eLibrary that provided data on fish exclusion mitigation measures. The number of measures (*n*) found within each document are listed. Facility types are conventional relicense (CR), non-powered dam (NPD), and new stream development (NSD).

FERC docket	Year	State	Facility type	*n*	Source	FERC EIS/EA PDF document
2130	2004	CA	CR	1	1	20050301-4004(4280395)
2195	2006	OR	CR	2	1	20061221-4000_09 FEIS Section 2 Action and Alternatives
11945	2006	OR	NPD	1	1	20070119-3020_17668082
11879	2007	ID	NPD	1	1	20070928-3035(13542763)
11841	2008	AK	NPD	1	1	20080702-3010(13626355)
803	2009	CA	CR	3	2	20081229-4001(30210771)
12555	2010	PA	NPD	1	1	20100323-3051(13802450)
12715	2010	WV	NPD	1	1	20111003-3022(13960237)
12626	2011	IL	NPD	1	1	20110705-3029(13934490)
12717	2011	IL	NPD	1	1	20110705-3029(13934490)
13237	2011	MA	NPD	1	1	20120702-3021(14035489)
13351	2011	IL	NPD	1	1	20111110-3047(13970437)
13953	2012	OH	NPD	1	1	20120229-5018_ATC-Mahoning Hydropower 401 WQC Application_2-28-12
12613	2013	WV	NPD	1	1	20130430-5021
12790	2014	CT	NPD	1	1	20140328-3018(14198578)
12486	2015	ID	NSD	1	1	20160427-4001(14453020)
13563	2015	AK	NSD	1	1	20151029-3010(14393405)
13629	2015	ID	NSD	1	1	20160203-3030(14425821)

FERC docket	Year	State	Facility type	*n*	Source	FERC EIS/EA PDF document
2484	2016	WI	CR	2	2	20160721-3031(31589824)
2337	2018	OR	CR	2	2	20180416-3015(32826900)
2520	2018	ME	CR	3	2	20180925-3000(33148866)
2593	2018	NY	CR	2	2,3	20181018-3003_P-2593-031etc-EA
2622	2018	MA	CR	1	2	20200925-3011_P-2622-013_Turners Falls Environmental Assessment
2809	2018	ME	CR	2	2,3	20180629-3008_P-2809 American Tissue Project EA
2727	2019	ME	CR	1	2	20190729-3018(33710980)
2808	2019	ME	CR	2	2	20190206-3006(33384654)
2837	2019	NY	CR	1	2,3	20191101-3040
3251	2020	NY	CR	1	2	20201130-3010_P-3251_Cornell Draft EA_20201130
3452	2020	NY	CR	1	2	20201013-3018_P-3452 Oak Orchard EA
14581	2020	CA	CR	1	2	20200707-3000(34141728)
2322	2021	ME	CR	3	2	20210701-3011
3063	2021	RI	CR	3	2	20210114-3028_P-3063-021_EA (1)
3273	2021	NY	CR	1	2	20210129-3028_P-3273-024 EA
10853	2021	MN	CR	2	2	20210518-3012
14799	2021	KY	NPD	1	2	20210225-3033_P-14799-002_EA

Sources: [1]Oladosu et al. 2021; [2]FERC eLibrary; [3]Natel Energy

To identify measures from this subset related to fish passage, PM&E measures were further filtered to include only those categorized as Fish Passage (Tier 2). Measures that were associated with pumped storage hydropower facilities were removed from the search results. In addition, measures categorized as Trash Racks (Tier 3) were also excluded because they were considered as exclusion technology (see Section 2). Measures that prescribed downstream passage-related studies, categorized as either Study or Eel Study (Tier 3), were also identified for a separate analysis. Lists of projects related to passage measures and passage studies included in this report are provided in Table 2 and Table 3, respectively. From these subsets, passage types were reclassified based on information contained in the PM&E measure and, if needed, from the original EIS/EA document to categorize each measure with greater resolution.

Table 2. FERC eLibrary dockets that provided data on fish passage measures specified for single or multiple dams within a project. The number of measures (*n*) found within each document are listed. Facility types are conventional relicense (CR), non-powered dam (NPD), and new stream development (NSD).

FERC docket	Year	State	Facility type	Multiple dams?	*n*	Source
11472	1996	ME	CR	No	3	1
11574	1998	CT	CR	No	2	1
11566	2000	ME	CR	No	1	1
2539	2001	NY	CR	No	2	1
2631	2001	MA	CR	No	2	1
2897	2001	ME	CR	No	2	1
2931	2001	ME	CR	No	3	1
2932	2001	ME	CR	No	3	1
2941	2001	ME	CR	No	2	1
2942	2001	ME	CR	No	3	1
233	2002	CA	CR	Yes	2	1
2233	2002	OR	CR	No	10	1
3090	2002	VT	CR	No	1	1
2516	2003	WV	CR	No	1	1
2517	2003	WV	CR	No	1	1

FERC docket	Year	State	Facility type	Multiple dams?	*n*	Source
2574	2003	ME	CR	No	4	1
2576	2003	CT	CR	No	6	1
2726	2003	ID	CR	No	2	1
178	2004	CA	CR	No	1	1
2114	2004	WA	CR	No	4	1
2364	2004	ME	CR	No	4	1
2365	2004	ME	CR	No	4	1
935	2005	WA	CR	No	1	1
1893	2005	NH	CR	No	1	1
1893	2005	NH	CR	Yes	1	1
2071	2005	WA	CR	No	2	1
2111	2005	WA	CR	No	2	1
2194	2005	ME	CR	No	3	1
2692	2005	NC	CR	No	1	1
2145	2006	WA	CR	No	2	1
2150	2006	WA	CR	No	1	1
2150	2006	WA	CR	Yes	2	1
2195	2006	OR	CR	No	6	1
2206	2007	NC	CR	No	4	1
2157	2008	WA	CR	No	1	1
2232	2008	SC	CR	No	1	1
2594	2008	MT	CR	No	1	1
9988	2008	GA	CR	No	1	1
2144	2009	WA	CR	No	1	1
2677	2009	WI	CR	No	1	1
13	2010	NY	CR	No	2	1
2850	2010	NY	CR	No	1	1
2851	2010	NY	CR	No	1	1
12569	2010	WA	CR	No	2	1
2713	2011	NY	CR	No	2	1
13368	2011	VT	NPD	No	1	1
14154	2011	ID	NSD	No	1	1
2696	2012	NY	CR	No	1	1
2305	2013	TX	CR	No	1	1
1888	2014	PA	CR	No	1	1
2984	2014	ME	CR	No	3	1
12790	2014	CT	NPD	No	2	1
308	2015	OR	CR	No	1	1
405	2015	MD	CR	No	4	2,3
7320	2015	NY	CR	No	1	1
12486	2015	ID	NSD	No	1	1
13563	2015	AK	NSD	No	4	1
13629	2015	ID	NSD	No	1	1
13701	2015	MS	NPD	No	1	1
13702	2015	MS	NPD	No	1	1
13703	2015	MS	NPD	No	1	1
13704	2015	MS	NPD	No	1	1
2335	2016	ME	CR	No	3	1
2457	2016	NH	CR	No	4	1
12496	2017	CA	NSD	No	1	1
2593	2018	NY	CR	No	2	2,3
2837	2019	NY	CR	No	1	2,3
2934	2020	NY	CR	No	2	2,3
1894	2020	SC	CR	No	1	2,3

FERC docket	Year	State	Facility type	Multiple dams?	*n*	Source
Sources: [1]Oladosu et al. 2021; [2]FERC eLibrary; [3]Natel Energy						

Table 3. FERC eLibrary dockets that provided data on passage studies. Single-species studies are indicated when present in the mitigation measure; otherwise, they are considered to refer to multiple species. The number of measures (n) found within each document are listed. Facility types are conventional relicense (CR), non-powered dam (NPD), and new stream development (NSD).

FERC docket	Year	State	Facility type	Multiple dams?	Tier 3 category (ORNL)	Passage type	*n*
11472	1996	ME	CR	No	Study	Study	1
2233	2002	OR	CR	No	Upstream	Lamprey study	1
2574	2003	ME	CR	No	Study	Study	1
2574	2003	ME	CR	No	Upstream	Study	1
2071	2005	WA	CR	No	Study	Trout study	1
2071	2005	WA	CR	No	Trap and transport	Trout study	1
2111	2005	WA	CR	No	Trap and transport	Trout study	1
2153	2005	CA	CR	No	Study	Study	1
2194	2005	ME	CR	No	Eel study	Eel study	1
2194	2005	ME	CR	No	Study	Study	1
2145	2006	WA	CR	No	Study	Lamprey study	1
2145	2006	WA	CR	No	Study	Trout study	1
2195	2006	OR	CR	No	Study	Lamprey study	1
2195	2006	OR	CR	No	Study	Study	1
2195	2006	OR	CR	Yes	Study	Study	2
2206	2007	NC	CR	No	Study	Study	1
2713	2011	NY	CR	Yes	Study	Study	1
13226	2011	VT	NPD	No	Study	Study	1
13160	2012	LA	NPD	No	Study	Study	1
1888	2014	PA	CR	No	Eel study	Eel study	2
1888	2014	PA	CR	No	Study	Shad study	2
2335	2016	ME	CR	No	Eel study	Eel study	1

3.1.2 Data Associated with Mitigation Measures

For each PM&E measure pertaining to fish exclusion, data were extracted that pertained to facility type (conventional relicense, CR; non-powered dam, NPD; or new stream development, NSD), projected capital costs for construction (henceforth referred to as capital costs), installed power capacity (kW), maximum hydraulic capacity flow (cfs), and the size of screen openings (in.). Installed power capacity and hydraulic capacity were limited to the powerhouses or generation units that were targeted for fish exclusion mitigation and summed if multiple units were involved; capacities may differ between mitigation measures for projects with multiple powerhouses or generation units. Capital costs were adjusted to US dollars in 2020 values using RSMeans historical cost indices (RS Means, 2019) for the original project and the 2020 estimate (239.1). One project (FERC Docket 2322) reported costs in US dollars in 2021 values, for which an index of 257.5 was used to convert to US dollars in 2020 values. Some mitigation measures addressed exclusion from non-hydropower generation structures (e.g., exclusion from sluice gates, diversion dams). Therefore, data pertaining to these measures were excluded from analyses involving power generation (installed capacity or theoretical head heights) but included in analyses involving flow. All fish exclusion data used in this report are publicly available on HydroSource (Matson et al., 2023).

Given that hydraulic head height was not consistently available in EIS/EA documents, theoretical hydraulic head was calculated using the hydropower equation:

$$P = \rho \cdot \eta \cdot g \cdot h \cdot Q_{max} \tag{1}$$

where P is the power output (W), ρ is the density of water (kg m^{-3}), η is the product of hydropower component efficiencies, g is gravitational acceleration (m^2 s^{-1}), h is the hydraulic head height (m), and Q_{max} is maximum hydraulic capacity of flow (shown as ft^3 s^{-1} but converted to m^3 s^{-1} for calculations). For the purposes of these analyses, η was assumed to be 1, ρ was assumed to be 1,000 kg m^{-3}, and the equation was rewritten to solve for h:

$$h = \frac{P}{g \cdot Q_{max}} \tag{2}$$

This calculation is not intended to represent the expected hydraulic head found at any of the included sites but instead to provide a diagnostic metric to discriminate between the projected costs associated with each measure at a given site.

For each PM&E measure pertaining to fish passage, data were extracted that pertained to facility type (CR, NPD, or NSD), number of targeted dams, projected capital costs for construction (henceforth capital costs; US$[2020]), and installed power capacity (kW). Installed power capacity was inclusive of the entire project. Hydraulic head height (ft) was estimated as 0.7 × dam height, using data from the US Army Corps of Engineers' National Inventory of Dams (NID) or directly from the project's EIS/EA documents. Capital costs were adjusted to US dollars in 2020 values using RSMeans historical cost indices for the original project and the 2020 estimate (239.1).

3.2 RESULTS

3.2.1 Costs of Exclusion

In total, 50 PM&E measures pertaining to fish exclusion with estimated capital costs were found: 18 measures in 17 FERC projects from Oladosu et al. (2021) and 32 measures in 18 FERC projects manually extracted from the FERC eLibrary. Results for mitigation measures were predominantly from projects in the Northeast (n = 17) and Northwest (n = 10), followed by the Mid-Atlantic (n = 9), Midwest (n = 8), West (n = 5), and South (n = 1). The types of hydropower projects included CR projects (n = 34), followed by NPD conversions (n = 13) and NSD (n = 3). Installed power capacities ranged from 76 kW to 87.9 MW, and capital costs ranged from <$5,900 to >$10,100,000. Screen spacing sizes reported in PM&E measures ranged from ≤0.09 in. (e.g., for exclusion of juvenile salmonids) to 2 in., but two measures did not specify sizes (Table 4). The largest screen spacing (2 in.) was only found for NPD projects, but CR and NSD projects contained measures for narrow screen openings; the two measures missing screen spacing size information were associated with CR projects. There is a trend of increasing the absolute numbers of exclusion-related PM&E measures and the specification of 0.75 and 1 in. screening through time (2004–2021), though there is a large amount of variability between years (Figure 1).

Table 4. Number of PM&E measures and project types referencing specific screen spacing sizes. Facility types are conventional relicense (CR), non-powered dam (NPD), and new stream development (NSD).

Screen spacing size (in.)	Project types	Measures
≤0.09	CR	6
	NPD	1
	NSD	2
0.75	CR	9
	NPD	1
1	CR	16
	NPD	6
1.5	CR	1
	NSD	1
2	NPD	5
N/A[a]	CR	2

[a]Size not specified in document

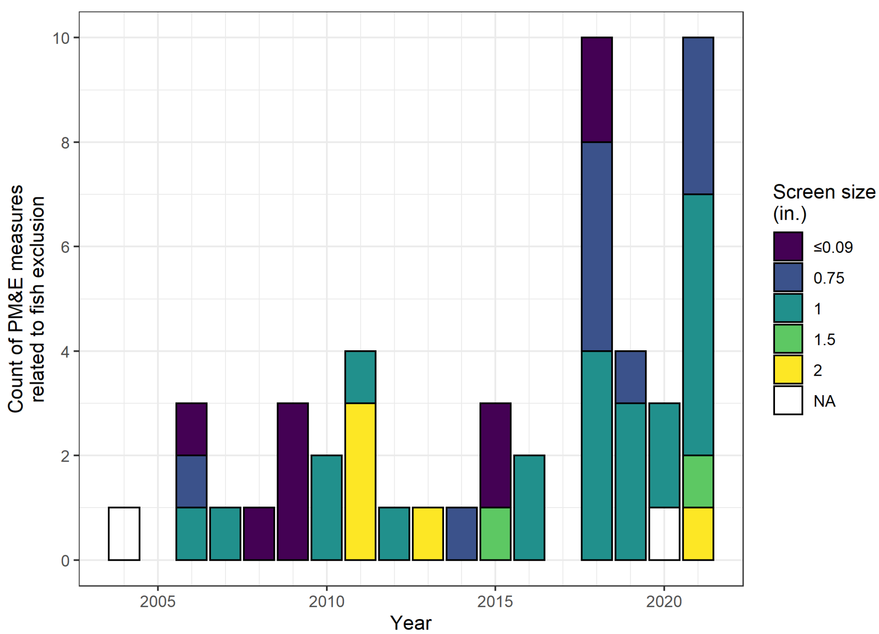

Figure 1. Annual counts of PM&E measures related to fish exclusion screening found within EIS/EA documents. Colors represent the size of screen spacing (in.) when available within the documents.

Capital costs varied greatly (up to approximately three orders of magnitude) within facility types, particularly for CR projects (Figure 2). The lowest capital costs were found in two NPD projects in the Northeast, and the four highest costs were associated with CR projects in California, three of which were from the same project (FERC Docket 803).

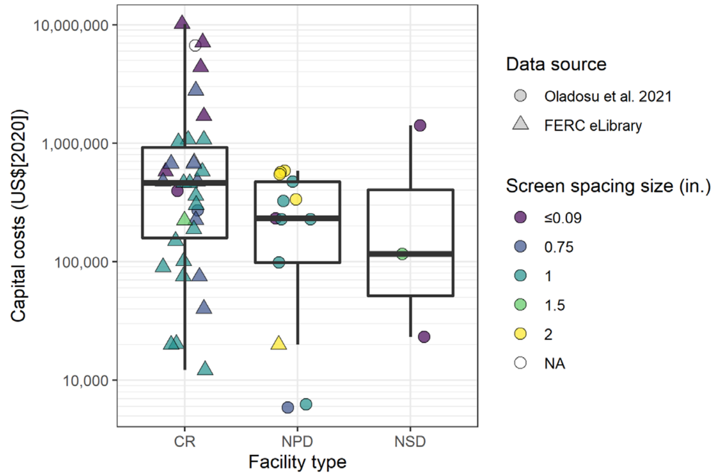

Figure 2. Distributions of capital costs (US$[2020]) of fish exclusion mitigation measures based on facility types. Each point represents a separate measure (n = 50) with the specified screen spacing size (color) and data source (shape). Unfilled points reflect measures for which screen spacing size was not specified in source material. Note the logarithmic scale on the vertical axis.

Given the large variation within and across project types, there was strong potential for the scale of the project (e.g., power generation or hydraulic flow) to influence capital costs. Regression analyses demonstrated that capital costs associated with fish exclusion screening generally increased linearly with installed capacity ($Capital\ Costs\ [\$] = 1{,}076 \times Installed\ Capacity\ [kW]^{0.664}$, $p < 0.0001$, adjusted R^2 = 0.43; Figure 3A). However, a significant relationship was not found with hydraulic capacity (p = 0.062; Figure 3B).

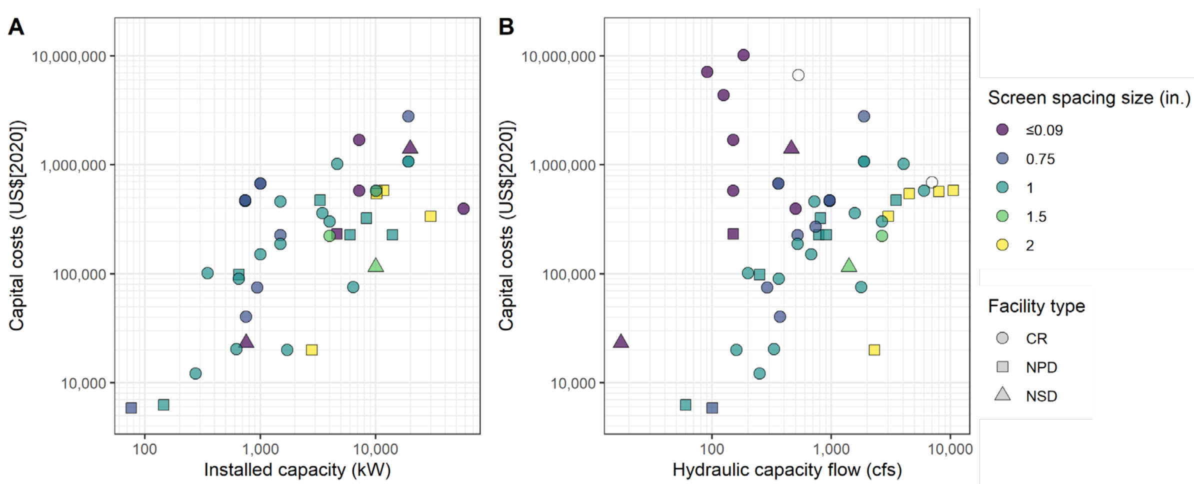

Figure 3. Relationship between capital costs (US$[2020]) and (A) installed capacity (kW) and (B) hydraulic capacity (cfs) for fish exclusion mitigation measures. Each point represents a separate measure (A: n = 44; B: n = 50) with the specified screen spacing size (color) and facility type (shape). Facility types are conventional relicense (CR), non-powered dam (NPD), and new stream development (NSD). Note the logarithmic scale on the vertical and horizontal axes.

When directly compared across measures, normalizing capital costs to flow (cfs) produced higher relative values (below the 1:1 line) compared with normalizing to installed capacity (kW) (Figure 4). Only five measures had higher capital costs when normalized to installed capacity, though these costs were only 6% to 32% higher, than when normalized to hydraulic capacity. Conversely, six measures stood out as being farthest below the 1:1 reference line, all of which were associated with the smallest screen spacing size (≤0.09 in.). Of the six, five had flow-normalized (cfs) capital costs that were 30 to 48 times higher than if those costs were normalized to installed capacity (kW). The highest value (116 times higher than cost normalized to installed capacity, FERC Docket 2195) may be artificially inflated by the measure stipulating that screening maintain a 500 cfs hydraulic capacity, much lower than the 6,000 cfs hydraulic capacity of the turbines. Given that hydrologically generated power is proportional to the product of hydraulic capacity and hydraulic head, estimating the theoretical hydraulic head (assuming 100% efficiency) associated with each measure could be helpful in explaining the variation in screening costs. A weak inverse linear correlation was found between common logarithms of theoretical head and hydraulic capacity (Pearson's r = -0.37, p = 0.015; Figure 5A). Measures associated with larger screen spacing were generally located within the upper left of the plotting space representing higher flow and lower head, whereas measures with smaller screen spacing were distributed in the lower right, representing lower flow and higher head. A positive linear relationship was found between capital costs normalized to flow and theoretical head (*Capital Costs [$/cfs]* =26.1 × *Theoretical Head [ft]* $^{0.628}$, $p < 0.0001$, adjusted $R^2 = 0.34$; Figure 5B), though a large amount of variability in cost remained unexplained. Maximum and minimum screen spacing sizes associated with measures again grouped separately in terms of flow-normalized capital costs and theoretical head.

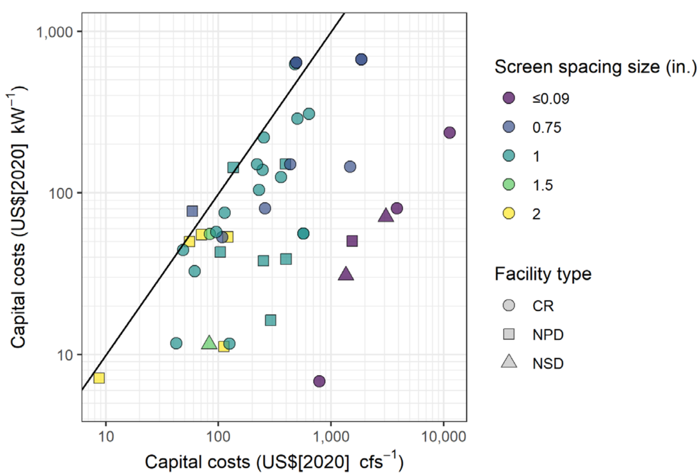

Figure 4. Relationship between capital costs normalized to installed capacity (US$[2020] kW^{-1}) and hydraulic capacity (US$[2020] cfs^{-1}) of fish exclusion mitigation measures. The black reference line indicates a 1:1 relationship. Each point is a separate measure (n = 44) with the specified screen spacing size (color) and facility type (shape). Facility types are conventional relicense (CR), non-powered dam (NPD), and new stream development (NSD). Note the logarithmic scale on the vertical and horizontal axes.

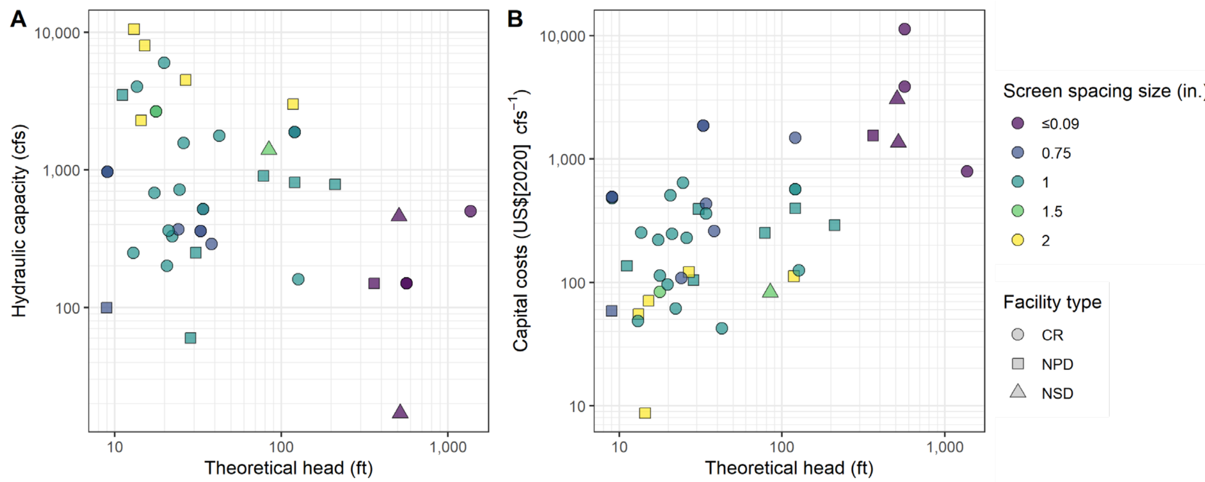

Figure 5. (A) Relationship between hydraulic capacity (cfs) and theoretical head height (ft) of fish exclusion mitigation measures, and (B) relationship between capital costs normalized to hydraulic capacity (US$[2020] cfs^{-1}) and theoretical head height (ft) of fish exclusion mitigation measures. Each point represents a separate measure (n = 44) with the specified screen spacing size (color) and facility type (shape). Note the logarithmic scale on the vertical and horizontal axes.

A substantial increase in capital costs normalized to hydraulic capacity was observed for measures associated with the smallest screen spacing size regardless of whether measures not directly excluding fish from hydropower generation were included (Figure 6A) or not (Figure 6B). For the latter case, median capital costs increased with decreasing screen spacing size from $71 cfs^{-1} for 2 in. spacing to $2,302 cfs^{-1} for ≤0.09 in. spacing. The largest relative increases in median costs associated with progressive decreases in screen spacing size were from 0.75 to ≤0.09 in. (369%), 1.5 to 1 in. (200%), 1 to 0.75 in. (96%), and 2 to 1.5 in. (18%).

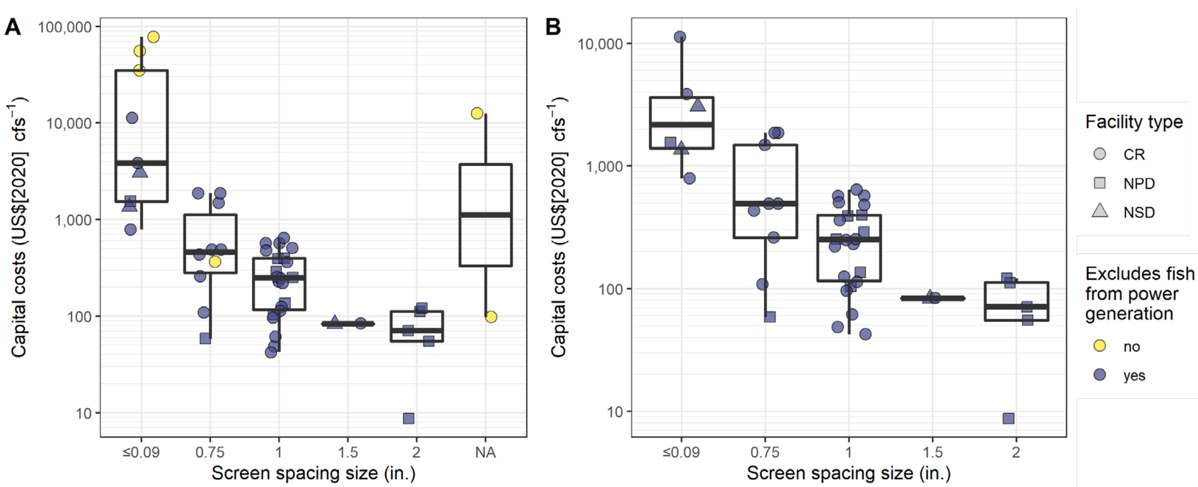

Figure 6. Distribution of projected capital costs normalized to hydraulic capacity (US$[2020] cfs^{-1}) across screen spacing sizes (in.) for (A) all measures (n = 50) and (B) only measures that exclude fish from power generation (n = 44). Each point represents a separate measure with facility type (shape) and exclusion from power generation status (color). Facility types are conventional relicense (CR), non-powered dam (NPD), and new stream development (NSD). Note the logarithmic scale on the vertical axis.

3.2.2 Costs of Fish Passage

In total, 142 PM&E measures from 66 FERC projects pertaining to fish passage with estimated capital costs were found from Oladosu et al. (2021) and selectively extracted from the FERC eLibrary. Results for passage-related mitigation measures were predominantly from projects in the Northeast (*n* = 58) and Northwest (*n* = 45), followed by the Mid-Atlantic (*n* = 22), South (*n* = 12), West (*n* = 4), and Midwest (*n* = 1). The types of hydropower projects included CR projects (*n* = 127), followed by NSD projects (*n* = 8) and NPD conversions (*n* = 7). Installed power capacities ranged from 76 kW to 1.99 GW, and capital costs of PM&E measures ranged from $2,500 to >$98,000,000. Most measures were specific to a single dam within a project (*n* = 138) while a smaller subset (*n* = 4) estimated combined costs for multiple dams within a project. Only two of the four projects with multiple dam mitigation measures (1893 and 2150) included mitigation measures for both single and multiple dams. All subsequent analyses focus on estimated costs for single dam mitigations. In total, ten passage types were identified in this study, which included measures specifying passage planning and flow requirements. Scales of variability in capital costs (US$[2020]) differed greatly (up to three orders of magnitude) among and between passage types (Figure 7).

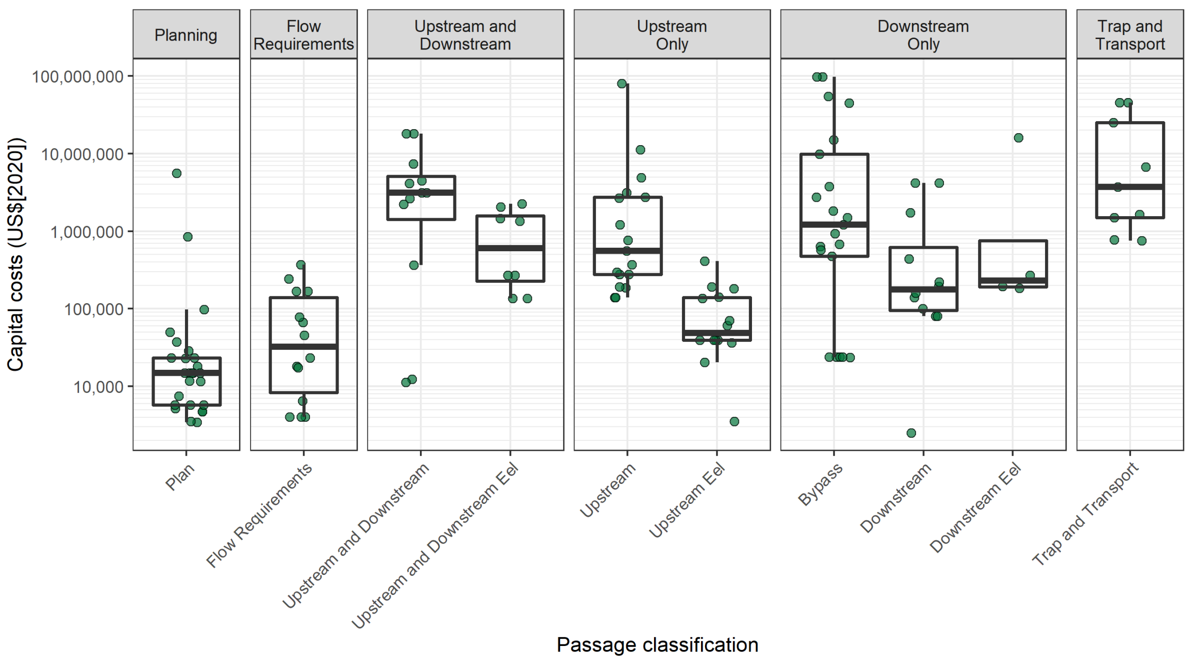

Figure 7. Distributions of capital costs (US$[2020]) of fish passage mitigation measures for each passage type at a single dam. Each point represents a separate measure (*n* = 137). Note the logarithmic scale on the vertical axis.

Linear regression analyses demonstrated that some of the variability in estimated costs was positively related to the installed capacity of the project in terms of power generation for some passage types but not others (Figure 8,

Table 5). Statistically significant ($p < 0.05$) relationships with installed capacity explained ≥50% of the variability in capital costs for measures classified as bypass, flow requirements, and upstream and downstream eel while having lower explanatory power for upstream and upstream eel passage. Of these passage types, the rate of change (slope) with respect to installed capacity (kW) was highest for bypass (0.98), followed by flow requirements (0.82), downstream (0.78), upstream (0.47), upstream eel (0.41), and upstream and downstream eel (0.40). A weak statistical relationship ($p<0.1$) was detected for passage planning, though this only explained 10% of the variation. The weak relationship for plan passage may be driven by the two large outlying planning measures in the group ($847,000 and $5,600,000). Both measures include the phase "develop and implement a . . . plan," suggesting that the scopes may extended well beyond planning; removal of these two measures from this classification results in a nonsignificant relationship ($p = 0.78$). Nonsignificant relationships with installed capacity were detected for the remaining passage types. Capital costs for trap and transport, which would be expected to be independent of installed capacity, were found to not be significantly related to project scale. Linear regressions of capital costs based on estimated hydraulic head (0.7 × dam height) found fewer significant relationships with passage type than installed capacity and explained less of the variation with the exception of upstream passage, for which estimated hydraulic head explained more than twice the variation in costs (adjusted R^2 of 0.48) versus installed capacity (adjusted R^2 of 0.20), and trap and transport, for which estimated hydraulic head explained 64% of the variation (Figure 9, Table 6). Notably, two fewer facilities were used for these analyses because of a lack of data on dam height; both fell within the upstream and downstream passage category.

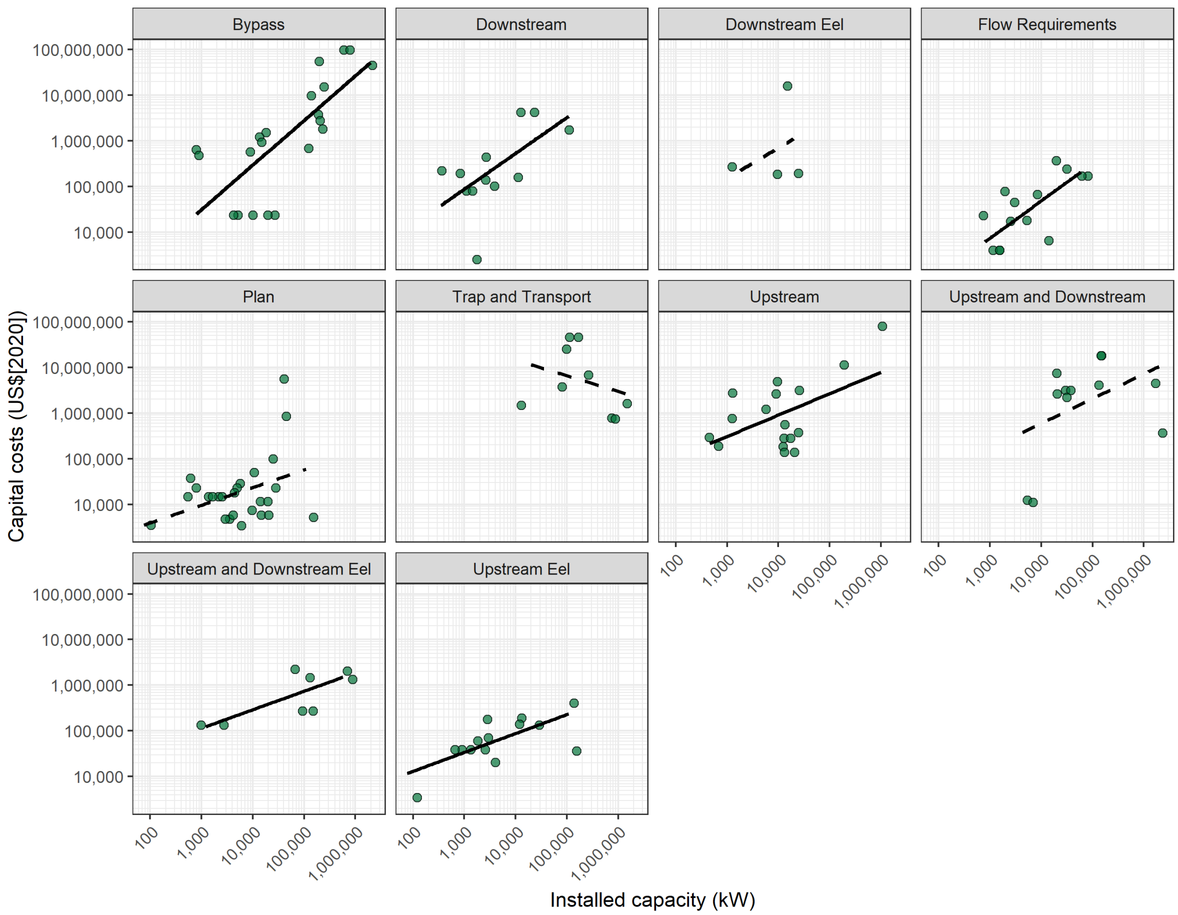

Figure 8. Relationship between capital costs (US$[2020]) of fish passage mitigation measures and installed capacity (kW) for each passage type at single dam facilities. The black line represents a significant linear regression ($p < 0.05$), and the dotted line represents a nonsignificant linear regression ($p \geq 0.05$). Each point is a separate measure ($n = 128$). Note the logarithmic scale on the vertical and horizontal axes.

Table 5. Results from log-linear regression of capital costs (US$[2020]) based on the installed capacity (kW) of a facility. Relationships were only tested for categories having two or more mitigation measures or studies. Significant relationships ($p < 0.05$) are in bold.

Passage type	*n*	Log10(intercept)	Slope	*p* value	Adj. R^2
Bypass	**21**	**1.56**	**0.98**	**<0.01**	**0.53**
Downstream	**12**	**2.59**	**0.78**	**0.04**	**0.31**
Downstream eel	4	3.18	0.67	0.66	-0.33
Flow requirements	**14**	**1.41**	**0.82**	**<0.01**	**0.50**
Plan	26	2.82	0.39	0.06	0.10
Trap and transport	9	8.53	-0.34	0.49	-0.06
Upstream	**17**	**4.08**	**0.47**	**0.04**	**0.20**
Upstream and downstream	12	3.60	0.54	0.16	0.11
Upstream and downstream eel	**8**	**3.85**	**0.40**	**0.02**	**0.54**
Upstream eel	**14**	**3.29**	**0.41**	**<0.01**	**0.43**

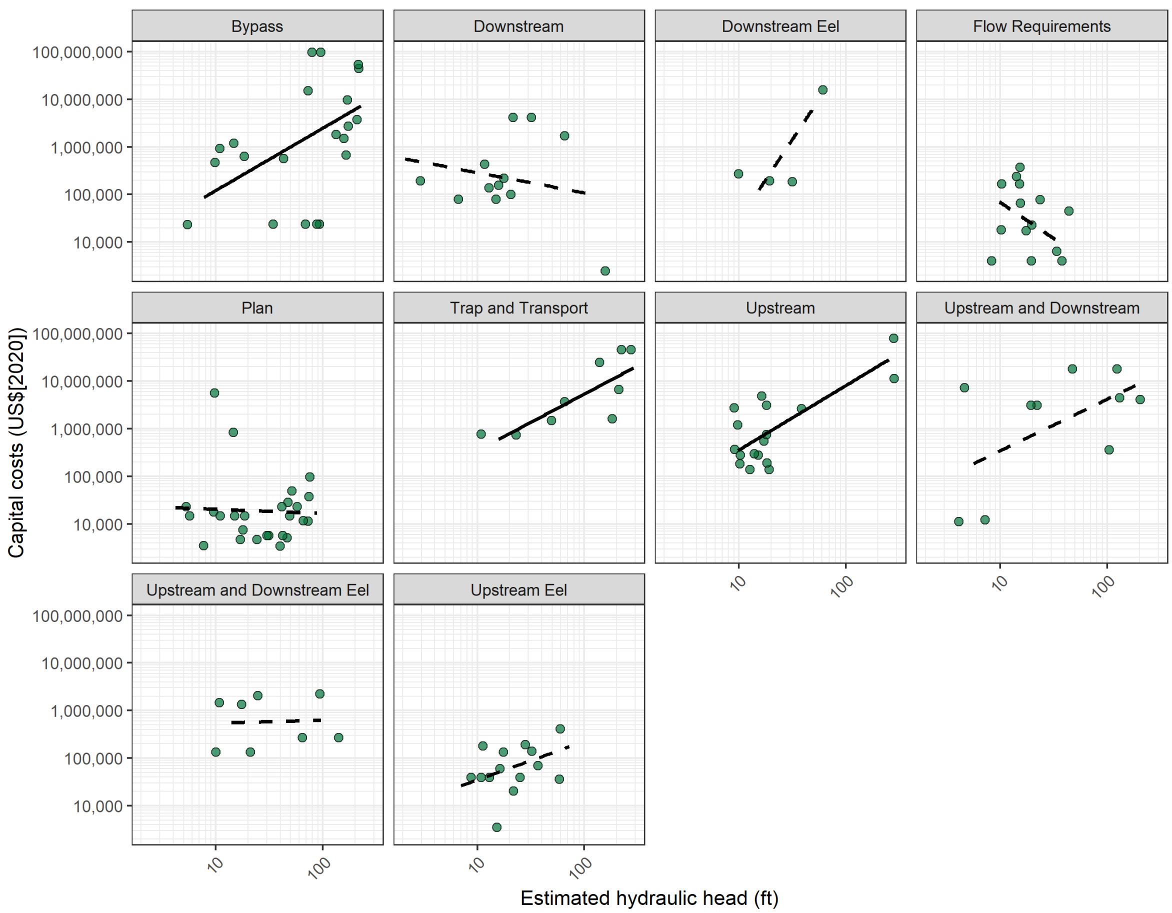

Figure 9. Relationship between capital costs (US$[2020]) of fish passage mitigation measures and estimated hydraulic head (ft) for each passage type at single dam facilities. The black line represents a significant linear regression ($p < 0.05$) while the dotted line represents a nonsignificant linear regression ($p \geq 0.05$). Each point is a separate measure ($n = 137$). Note the logarithmic scale on the vertical and horizontal axes.

Table 6. Results from log-linear regression of capital costs (US$[2020]) based on the estimated hydraulic head (ft) of a facility. Relationships were only tested for categories having two or more mitigation measures or studies. Significant relationships ($p < 0.05$) are in bold.

Passage type	*n*	Log10(intercept)	Slope	*p* value	Adj. R^2
Bypass	**21**	**3.78**	**1.31**	**0.03**	**0.18**
Downstream	12	5.88	-0.42	0.52	-0.05
Downstream eel	4	1.08	3.39	0.09	0.74
Flow requirements	14	6.35	-1.51	0.12	0.12
Plan	26	4.39	-0.09	0.83	-0.04
Trap and transport	**9**	**4.35**	**1.19**	**0.01**	**0.64**
Upstream	**17**	**4.20**	**1.36**	**<0.01**	**0.48**
Upstream and downstream	10	4.45	1.08	0.11	0.20
Upstream and downstream eel	8	5.68	0.06	0.49	-0.09
Upstream eel	14	3.73	0.81	0.09	0.15

Normalizing passage capital cost data to installed capacity (kW) reduced variability in median values across passage types (range between minimum and maximum values was \$102 kW^{-1} versus pre-normalization range that was >\$2,980,000). Variability in normalized capital costs within passage types remained high, with interquartile ranges (IQRs) varying from \$7 kW^{-1} for flow requirements to \$337 kW^{-1} for downstream eel (Figure 10). When limited to passage infrastructure only (excluding plan and flow requirements), variation in IQR differed by an order of magnitude (\$28 to \$337 kW^{-1}). The lowest median normalized capital costs were for plan and flow requirements (\$3 to \$5 kW^{-1}). Median normalized capital costs for both upstream eel and upstream and downstream eel passage were consistently lower (\$9 to \$22 kW^{-1}) than general equivalent passage types (\$80 to \$106 kW^{-1}) and possessed lower IQRs (\$28 to \$36 kW^{-1} for upstream eel and upstream and downstream eel versus \$131 to \$279 kW^{-1} for general upstream and upstream and downstream). The median normalized cost of downstream eel passage was higher than general downstream passage, though this may be an artifact of a small sample size (Figure 10, Table 5). Median normalized capital cost for bypass was similar (\$53 versus \$67 kW^{-1}) and had an IQR approximately half that of downstream (\$82 versus \$175 kW^{-1}). Trap and transport had the sixth highest median normalized capital cost (\$34 kW^{-1}) and third highest IQR (\$183 kW^{-1}). Similar overall relationships were found between passage types when capital costs were normalized to estimated hydraulic head, though greater separation was evident between eel-specific and general upstream passage (Figure 11).

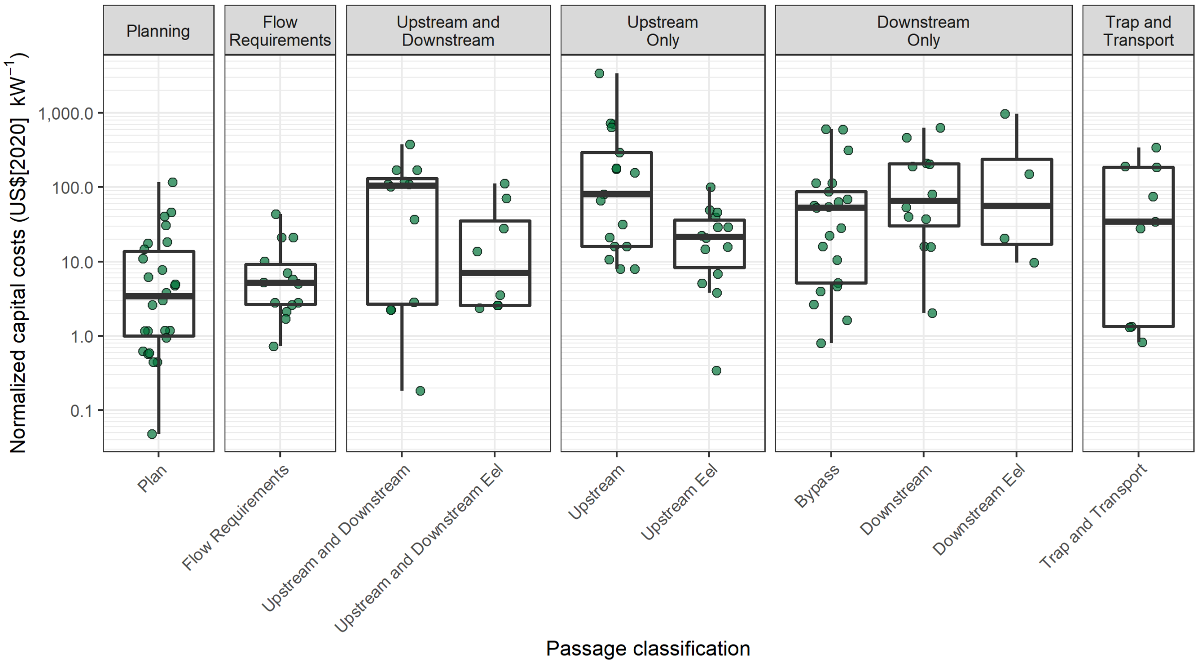

Figure 10. Distributions of capital costs normalized to installed capacity (US$[2020] kW^{-1}) of fish passage mitigation measures based on passage classification. Each point represents a separate measure (n = 137). Note the logarithmic scale on the vertical axis.

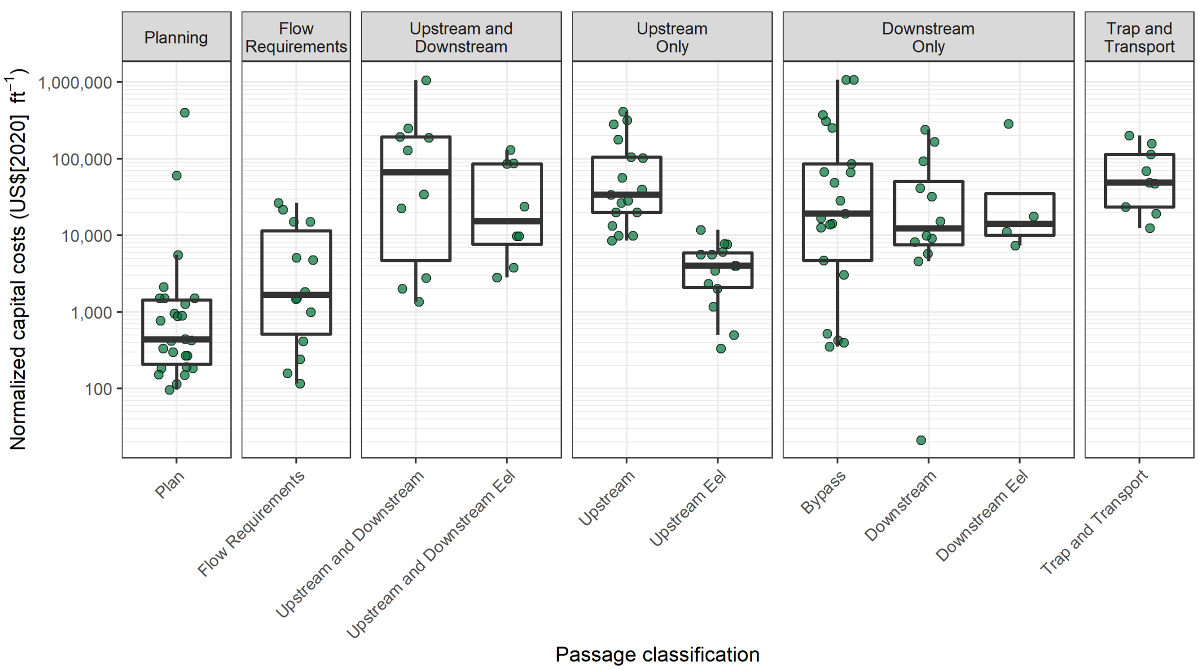

Figure 11. Distributions of capital costs normalized to estimated hydraulic head (US$[2020] ft^{-1}) of fish passage mitigation measures based on passage classification. Each point represents a separate measure (n = 135). Note the logarithmic scale on the vertical axis.

3.2.3 Costs of Passage Studies

In total, 26 PM&E measures from 16 FERC projects pertaining to studies of fish passage with estimated capital costs were found from Oladosu et al. (2021). Results for passage-related mitigation measures were predominantly from projects in the Northwest (n = 10) and Northeast (n = 7), followed by the Mid-Atlantic (n = 5), South (n = 3), and West (n = 1), and not from any projects in the Midwest. The types of hydropower projects included CR projects (n = 24), followed by NPD conversions (n = 2) and no NSD projects. Installed power capacities ranged from 1.05 MW to 1.4 GW, and capital costs ranged from $18,600 to >$7,600,000. Most measures were specific to a single dam within a project (n = 23), but a smaller subset (n = 3) estimated combined costs for multiple dams within a project. Studies spanning multiple dams had a higher median cost, though few data points were available (Figure 12). For single-dam studies, the median study cost was $98,434, with 25th and 75th percentiles ranging from $49,934 to $199,388. Various study types were identified, with the majority being passage effectiveness/evaluation (17) followed by movement/migration (4), trapping and collection (2), turbine avoidance/entrainment (2), and pulsed flow (1). The level of taxonomic specificity within each measure varied, with 13 of the 25 measures identifying a single fish species of interest, which included eels, lampreys, shad, and trout. Furthermore, all 12 measures were specific to a single dam. There was no significant linear relationship between study cost and installed capacity (p = 0.27, data not shown). Two projects had four studies (1888 and 2195), four projects had two studies (2071, 2145, 2194, and 2574), and the remaining nine projects had a single study only. Additionally, four of the 15 projects with studies also did not have a passage-related PM&E measure (1894, 2153, 13160, and 13226), which included both NPD projects.

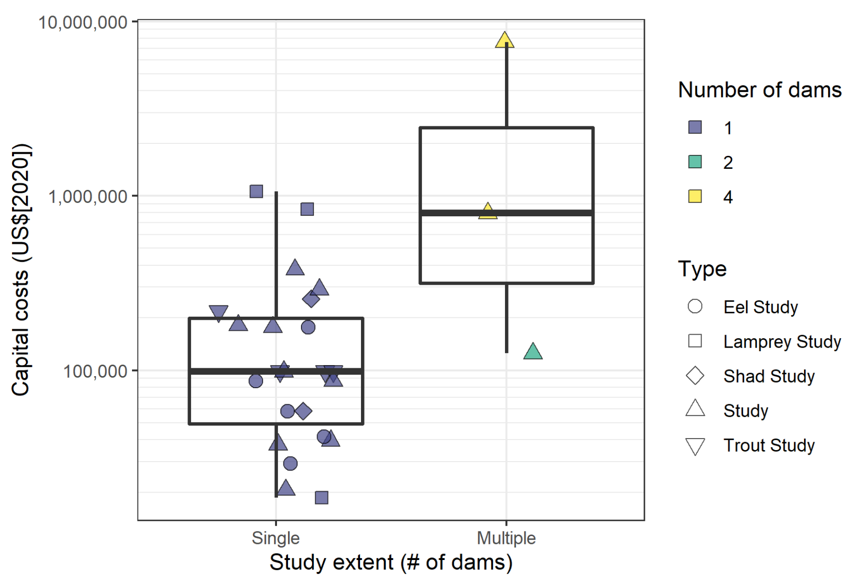

Figure 12. Distribution of projected capital costs (US$[2020]) for fish passage studies for FERC dockets addressing single (n = 21) or multiple dams (n = 3). Each point represents a separate measure with species specificity (shape), if available, and the number of dams involved (color). Note the logarithmic scale on the vertical axis.

3.3 AVAILABILITY OF DATA FROM FERC ELIBRARY

Environmental regulatory documents, such as EIS/EA documents stored within the FERC eLibrary, contain large amounts of data that can advance our understanding of the financial costs associated with the construction of hydropower infrastructure. Such knowledge will be of great use to developers of new hydropower projects, given the increasing requirement for sustainable energy generation and the high proportion of total costs associated with mitigating impacts to aquatic species (Oladosu et al. 2021).

However, the availability of these data is limited by long regulatory timelines involved in obtaining a 30- to 50-year license (meaning that a small subset of facilities are renewing or applying for licenses at a given time) and the large effort required to manually extract data from text in the regulatory documents. ORNL's Costs of Environmental Mitigation data set, which was the basis for analyses by Oladosu et al. (2021), contained 4,995 individual PM&E measures associated with CR, NPD, and NSD projects, but only a very small fraction (0.36%) contained estimates of capital costs associated with fish exclusion compared with the number of measures with estimated capital costs associated with fish passage (2.6%). Given the vast number of documents associated with each FERC docket in the eLibrary, additional data are likely available in non-EIS/EA documents. Correspondence documents between hydropower developers and agencies (both Federal and State) may provide cost estimates for fish exclusion mitigations that occurred outside the temporal scope of the EIS/EA document, but the large number of these documents in a typical FERC docket would require high levels of effort to search and manually extract data. Notably, an increased number of hydropower facilities are due to begin the relicensing process in the next several years (Figure 13). Given that the relicensing process typically exceeds 7 years based on analyses of licensing timelines from 107 FERC-licensed hydropower facilities and longer timelines are associated with projects requiring species protection (Pracheil et al. 2022), the number of available EIS/EA documents for facilities with soon-to-be-expiring licenses should increase. These license renewals will potentially provide new data points to estimate the costs of fish protection and amplify the need for such information for the hydropower industry.

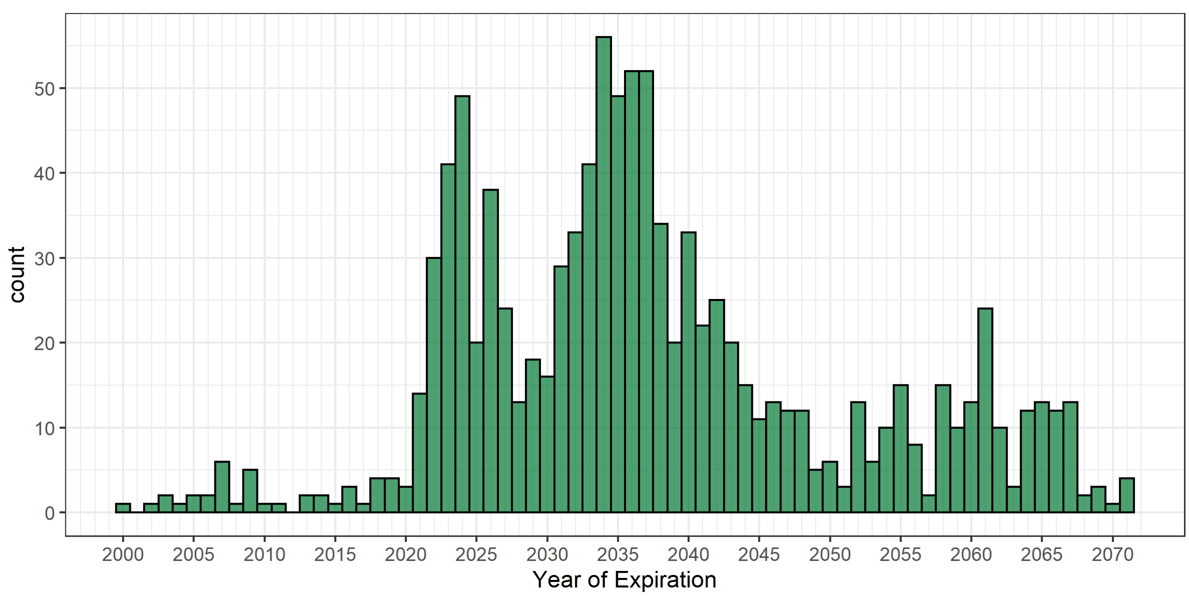

Figure 13. Histogram showing the number of active FERC licensed hydropower facilities based on the year in which a FERC license will expire. Data based on information extracted from the FERC eLibrary for this project by Natel Energy.

Projects with fish exclusion PM&E measures represented a small subset of the total number of projects present, with some characteristics appearing in skewed distributions. For fish exclusion, the projects from which these measures were found for this study represented 9.9% of the 171 FERC hydropower projects (CR, NPD, and NSD only) in the Oladosu et al. (2021) data set. These measures were highly skewed toward NPD projects (67%), and projects with data represented 2.9% of CR, 21% of NPD, and 27% of NSD projects in that data set. Including the 32 PM&E measures from 18 projects manually extracted from the FERC eLibrary not included in Oladosu et al. (2021), the data set presented here is highly skewed toward CR (68%) and NPD projects (26%) as opposed to NSD (6%). Most measures (68% of 50 total measures) were associated with powerhouse installed capacities >1 MW; there were a similar number of projects with installed capacities in the 1 to 10 MW class (18 projects) and >10 MW class (16 projects). Fish passage PM&E measures were even more highly skewed toward CR projects (89% of 142 non-study-related measures and 92% of 26 study-related measures).

3.4 SCALING COSTS OF FISH EXCLUSION

Hydropower projects possess high levels of site specificity, which contributes to difficulties in cost comparisons across multiple projects. One approach is to normalize costs relative to a common parameter, such as installed capacity, as shown by Oladosu et al. (2021). However, the amount of screening required to exclude fish is fundamentally dependent on hydraulic capacity such that higher flow would require greater quantities of material, different methods of exclusion (e.g., flat plate screens, traveling screens, drum screens), or different characteristics (e.g., spacing size) of screening material to provide adequate conditions for fish protection (USBR 2009). Venus et al. (2020) found that the log of screen area was a good predictor of capital costs at 17 European hydropower facilities, showing a 1.18% increase in costs for each additional percent of surface area. However, while Venus et al. (2020) did explore the effect of screen orientation (vertical versus horizontal, which was nonsignificant), they did not explore differences in screen spacing.

To relate both potential power generation and flow, theoretical head height was estimated, which, in simplified terms, is the ratio of installed capacity to hydraulic capacity assuming no losses to inefficiencies. The analyses showed that screen costs normalized to hydraulic capacity were greater for powerhouses with higher theoretical head heights (i.e., high power from low flow). The measures with the highest theoretical head heights also happened to specify the smallest spacing size (≤0.09 in.), so this may be driving some of the perceived pattern. Higher costs of fish exclusion at high-head facilities could be driven by increased costs associated with materials, difficulty of construction, or a combination of the two. A case study comparison with an ongoing low-head NSD project by Natel Energy on the James River near Richmond, Virginia estimated a 10-fold difference in the capital cost of exclusion if construction requires an entire standalone concrete structure (\$2,960 cfs^{-1}) as opposed to replacing existing trash rack panels with 0.75 in wedge wire screen (\$250 cfs^{-1}). Further exploration would benefit greatly from the inclusion of additional data.

3.5 SCALING COSTS OF FISH PASSAGE

Fish passage offers an alternative method to protect fish at hydropower facilities as well as enhance connectivity within catchments. However, much more diverse options for passage exist compared with fish exclusion screening, with a range of potential parameters for normalization. Passage technologies may be located separately from intakes to the power plant, making hydraulic capacity less appropriate for normalization across projects. Instead, installed capacity (kW) and estimated hydraulic head height (ft) were used as indicators of the overall physical scale of the project for normalization purposes. The analyses found that some (flow requirements, bypass, downstream, upstream, and upstream eel) but not all types of passage scaled with installed capacity, and estimated hydraulic head explained less variability for all types except upstream and trap and transport passage. Although the cost of trap and collection passage would be expected to be independent of project scale, it was significantly related to estimated hydraulic head height. It is more surprising that estimated costs of combined upstream and downstream passage PM&E measures did not scale with project capacity. Some of this may be because of the vague language used in some PM&E measures (e.g., "install downstream fish passage") and a lack of details for the targeted approaches for mitigation.

Venus et al. (2020) evaluated the costs of fish passage mitigation measures at European hydropower facilities using 327 case studies across five countries that included structural characteristics. Their analyses found that the length of the pass and the height of the obstruction, in addition to plant capacity, was able to explain 77% of the observed variation in total capital costs of upstream passage. Unfortunately, such data are not available within EISs/EA documents. Further, Venus et al. (2020) found levelized capital costs of upstream passage were lowered for nature-like upstream passage (roughened channel, 50 EUR kW^{-1}) than for technical (vertical slot pass, 130 EUR kW^{-1}) or combined measures (vertical slot and roughened channel, 450 EUR kW^{-1}), which roughly converted to \$58 kW^{-1}, \$150 kW^{-1}, and \$519 kW^{-1} (US\$[2020] based on an average euro/US dollar exchange rate of 1.12 for 2019). These estimates all fall within the interquartile range of values (\$16 to \$295 kW^{-1}) identified in this study for general upstream passage.

3.6 CONSIDERATIONS FOR DEVELOPMENT

The quantitative data on the costs of fish exclusion screening presented here are in general agreement with previously published qualitative information; complete exclusion of fish can require high capital costs. The highest flow-normalized capital costs (on the order of thousands to tens of thousands of US dollars cfs^{-1}) were associated with PM&E measures that specify the smallest screening size (≤0.09 in.), whereas measures that specify the larger spaced screening size (2 in.) were considerably less expensive (on the order of tens to hundreds of US dollars cfs^{-1}). These high costs are necessary if complete exclusion of both juvenile and adult fish is a requirement, such as for Federally recognized threatened or endangered species. In addition to excluding fish from turbine entrainment, capital costs may be required for the planning (median planning cost of \$4 kW^{-1}), construction (median bypass cost of \$53 kW^{-1}), and evaluation (median study cost of \$98,000) of infrastructure to provide safe passage of fish across a dam, depending on stakeholder objectives and the scale of the project. These combined costs provide a baseline from which to assess whether the costs associated with exclusion and passage could instead be put toward fish-friendly turbine technology. Such comparisons are beyond the scope of this report; however, one EIS/EA document from 2021 (FERC Docket 3063) included comparisons of project costs for three screening options (various iterations of 1 and 0.75 in. clear bar spacing projected at \$450,000–\$460,000) versus installation of fish-safe turbine technology (\$525,000). Despite its general requirement for fish protection, exclusion screening can contribute to additional bodily injury to some fish based on their morphology or behavior (Mueller et al. 2017). Fish-friendly turbine technology has an excellent opportunity to contribute to the expansion of hydropower if it can be shown to both decrease the risk of injury and death to fish while being cost-competitive with existing screening and passage technology.

4. CONCLUSIONS

Expansion of sustainable and cost-effective hydropower generating facilities requires careful consideration of construction and operating costs during the early scoping stages of project development. Costs required for mitigating environmental impacts, particularly to aquatic species, have been identified as a key decision variable for new projects in the United States. Quantitative cost estimates for the protection and exclusion of fish from hydropower infrastructure have historically been limited for or unavailable to developers, resulting in an important gap in knowledge for accurate projections of project costs. This report used keyword searches of an existing environmental mitigation cost data set and manual extraction of additional cost data associated with positive barrier screening and passage from regulatory licensing documents available in the FERC eLibrary. This approach yielded a total of 50 PM&E mitigation measures with estimated capital construction costs pertaining to positive barrier screens, 142 pertaining to passage studies, and 26 pertaining to passage-related studies. PM&E measures associated with positive barrier screens represented <10% of the 171 total FERC project dockets available in the data set. These data were highly skewed toward conventional relicensing projects, as <7% were associated with new stream development projects. Results from these data indicate highly variable costs associated with fish screening, with flow-normalized costs one to two orders of magnitude higher for screening with the highest exclusion capability (≤0.09 in. spacing) compared with coarser screening (1 to 2 in.). Furthermore, costs of passage infrastructure were positively related to the scale of the project based on installed capacity for some, but not all, types of passage. These data provide an initial baseline for estimating exclusion and passage costs for hydropower development and may help developers consider options for more fish-friendly generation technologies, though gaps remain relating to a lack of data, particularly for NSD. More data may still be available within the FERC eLibrary, but significant effort will be required to manually identify and extract the data for future analyses.

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