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Non-Powered Dam Retrofit Exemplary Design for Hydropower Applications

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OAK RIDGE National Laboratory

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Photograph (top-left) is of Cheoah Dam; located in Robinsville, North Carolina; photograph dated October 28, 2019.

Photograph (top-right) is of Byrd Creek Dam; located in Crossville, Tennessee; photograph dated November 10, 2019.

Photograph (bottom-right) is of a decommissioned turbine runner; located at Watts Bar Dam in Spring City, Tennessee; photograph dated November 20, 2018.

Photograph (bottom-left) is of Lake Sequoyah Dam; located in Highlands, North Carolina; photograph dated August 20, 2021.

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Environmental Sciences Division

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ABBREVIATIONS

DOE	US Department of Energy
EDES	exemplary design envelope specification
FERC	Federal Energy Regulatory Commission
LIHI	Low Impact Hydropower Institute
NID	National Inventory of Dams
NPD	non-powered dam
NPDamCAT	non-powered dam custom analysis and taxonomy
RD&D	research, development, and demonstration
REDS	Retrofit Exemplary Design Specification
SMH	standard modular hydropower
USBR	US Bureau of Reclamation
WPTO	Water Power Technologies Office

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EXECUTIVE SUMMARY

Non-powered dams (NPDs) represent complex systems, situated at the intersection of natural stream environments and the built environment. The presence and operations of NPDs affect stream constituents (e.g., fish, recreational craft, sediment, water) and serve one or more engineered purposes (e.g., recreation, flood control, water supply, irrigation, tailings and debris control, navigation). By definition, NPDs do not provide hydropower generation. However, every NPD contains some untapped hydropower resource potential, represented by the pre-existing hydraulic head created by the dam and presence of flowing water. Adding power generation to an NPD requires *retrofitting* the NPD, which could involve the addition of any new component or function beyond that currently installed. Because this research is funded by the US Department of Energy Water Power Technologies Office, adding hydropower to NPDs is among the primary objectives for research investment. However, NPD retrofitting extends beyond the purview of hydropower additions.

This report provides background information regarding NPD development in the United States, including an overview of the US NPD population, development potential, and recent development. It also summarizes challenges and opportunities facing NPD retrofit development, highlights the importance of maintaining or improving stream and dam functionality, notes key NPD characteristics, describes NPD retrofit methods, and identifies innovation areas for spurring future NPD retrofit development. Section 4 describes retrofit exemplary design principles and concepts that could apply to a wide range of NPD projects. These principles and concepts inform an **NPD Retrofit Exemplary Design Specification (REDS)**, as included in Appendix A.

The NPD REDS is heavily influenced by prior work under the standard modular hydropower technology acceleration research initiative, especially the work documented in the *Exemplary Design Envelope Specification for Standard Modular Hydropower Technology* (Witt et al., 2017). Whereas this prior work focuses on a particular technology class that applies most intentionally for new stream-reach development (i.e., greenfield sites), the NPD REDS contained herein applies more broadly to the NPD resource class and is *technology-agnostic* (i.e., the specific technologies intended to be described are not explicitly prescribed).

This report serves as a part of early-phase research on NPD retrofit development, aimed toward spurring additional, follow-on efforts to specifically address development challenges, capitalize on development opportunities, and inspire innovation. As documented in the landmark “Hydropower Vision” report (DOE 2016), “transformative technical innovations able to meet the co-objectives of environmental sustainability and low-carbon energy will be critical to enabling additional hydropower growth.” This report serves as an important step in steering transformation of US non-powered dam infrastructure.

Key takeaways of the Non-Powered Dam Retrofit Exemplary Design for Hydropower Applications report:

- Retrofitting represents a unique opportunity for NPDs and is referred to in this report as adding equipment or components to an NPD to augment its function (regardless of whether hydropower is involved)
- Key challenges facing NPD retrofit development include (1) dam design and operational constraints, (2) physical attributes of the dam system, (3) environmental considerations of the dam system, (4) development cost and timeline hurdles, and (5) alternative considerations for dam rehabilitation/refurbishment or removal.
- Key opportunities available through NPD retrofit development include (1) renewable energy growth and support of variable renewables, (2) co-development opportunities, (3) improved infrastructure reliability and performance, and (4) new technology innovation.
- Modern methods for accomplishing NPD retrofitting must maintain or enhance stream and dam functionality and consider key NPD characteristics that may be operational, engineering, environmental, socio-economic, or hydropower-related in nature.
- Methods for accomplishing NPD retrofitting consider going *through*, *over*, or *around* the NPD.
- Specifications for retrofit exemplary design may aide in NPD development, as documented in Section 4 and APPENDIX A.
- Information gleaned from recent NPD retrofits may prove educational for informing future NPD retrofit initiatives (as documented in APPENDIX B).

1. INTRODUCTION

Dams, or "barrier[s] preventing the flow of water or of loose solid materials,"[1] represent critical engineering infrastructure and can serve various purposes, including storing and controlling the flow of water. For example, a dam can support one or more of the following: navigation, recreation, flood control, irrigation, water supply, and hydropower (Bonnet et al. 2015). Dams without hydropower are referred to as *non-powered dams* (NPDs), defined as "dams that do not have any electricity generation equipment installed."[2] NPDs represent a significant majority of the dams both within the United States and globally and are the focus of this report. The 2019 National Inventory of Dams (NID)[3] documented 91,457 dams and supporting structures, more than 85,000 of which are non-powered. NPDs provide a source of untapped renewable energy potential (i.e., they control and/or impound water and create a head differential) and total roughly 12 GW of technical potential capacity in the United States (Hadjerioua et al. 2012).

Within the United States, more than 85,000 NPDs are scattered across every state as well as within Guam and Puerto Rico. These structures come in a wide variety of shapes and sizes, varying from simple embankments just a few feet tall to substantial structures thousands of feet long and hundreds of feet tall. They also vary in terms of age, purpose, construction, storage capacity, hazard potential, condition, and physical components, among other characteristics. Within a broader context, NPDs are part of complex systems interacting with the surrounding environment and community. Throughout history, dam development has evolved to become increasingly aware of these interactions, including the positive and negative effects of dam construction and operation within this broader context.

NPD *retrofitting*[4,5] must balance both economic value and environmental considerations. Moreover, such NPD hydropower development should seek to maximize return on investment while maintaining dam and stream functionality. These concepts are key to successful retrofit projects and are further explored in this report.

In support of these renewable energy growth opportunities, the US Department of Energy (DOE) Water Power Technologies Office (WPTO) funds research, development, and demonstration (RD&D) efforts across a wide range of private and public stakeholders. This report represents a research product funded by WPTO aimed toward enabling improved hydropower retrofit design specifications at NPDs based on common (standard) NPD characteristics, as informed by parallel, complementary research related to improving NPD classification and data access (Hansen et al. 2022). Whereas the NPD classification and data synthesis effort defines the breadth and similarities found within the US NPD population, the NPD retrofit assessment documented in this report provides a summary of exemplary (i.e., desirable) design approaches and specifications.

This report aims to provide useful information and resources to achieve successful NPD retrofit outcomes complementary of both economic and environmental needs. Although focused on NPD retrofit design for hydropower applications, the information contained herein may be useful for a variety of retrofit scenarios, whether related to hydropower or not (e.g., the addition of some passage design). This report is not intended to provide a central repository for detailed engineering design techniques or thorough

[1] Definition from Merriam-Webster: https://www.merriam-webster.com/ (Accessed: May 17, 2022).
[2] Definition from DOE: https://www.energy.gov/eere/water/glossary-hydropower-terms (Accessed: May 17, 2022).
[3] Based on the 2019 NID: https://nid.sec.usace.army.mil/ (Accessed: May 17, 2022).
[4] The term *retrofit* is defined by Merriam-Webster as "to install (new or modified parts or equipment) in something previously manufactured or constructed": https://www.merriam-webster.com/ (Accessed: May 17, 2022).
[5] Within this report, the term *retrofit* refers to the variety of equipment or components that may be added to an NPD to augment its function (regardless of whether hydropower is involved). For additional information, see Section 3.3.

review of scientific literature but strives to guide developers and other stakeholders in support of renewable hydropower growth within the United States and globally. When applicable, references to complementary literature and resources are provided. Some of the content included is inspired directly from prior work in which an exemplary design envelope specification (EDES) was developed for standard modular hydropower (SMH) technologies (Witt et al. 2017); this prior work was focused on new stream-reach development (i.e., greenfield development) rather than NPD application.

This report focuses on NPD retrofit applications with hydropower development in mind, but the importance of other decision alternatives (i.e., options for dam removal and dam rehabilitation/refurbishment) should also be recognized. These topics are discussed briefly in this report.

This report is organized into the following sections:

- Section 2 provides a detailed overview of US NPDs and development potential.
- Section 3 describes key considerations for NPD retrofit development.
- Section 4 identifies retrofit exemplary design principles and concepts.
- Section 5 summarizes the content and outcomes of the report.
- APPENDIX A includes an NPD Retrofit Exemplary Design Specification (REDS) for generation, fish passage, sediment passage, recreation passage, and foundation technologies. The specifications are intended to describe the objectives, requirements, constraints, and performance metrics for successful NPD retrofitting.
- APPENDIX B presents information on recent NPD development case studies.

2. NPD DEVELOPMENT BACKGROUND

An NPD differs from a powered dam in its lack of power generation equipment. The NPD may provide several services, but hydropower is not among them. Figure 1 provides example photographs of an NPD.

Figure 1. An NPD (Byrd Creek Dam, Crossville, Tennessee). (left) Upstream side of dam; (right) downstream side of dam. Images courtesy of Scott DeNeale.

To provide additional context, this section offers background information on US NPDs and development potential, recent NPD development, and challenges and opportunities associated with NPD development.

2.1 OVERVIEW OF US NPD POPULATION AND DEVELOPMENT POTENTIAL

As shown in Figure 2, NPDs are found throughout the United States and US territories and make up the majority of dams, with over 85,000 of the more than 91,000 dams documented by the NID being non-auxiliary NPDs.[3] The greatest concentration of NPDs is found in the central and eastern continental United States where such impoundments were built for one or more non-hydropower purpose. Given the significant untapped energy resource available at these NPD locations and the desire for increased flexible renewable energy and energy storage, much interest exists in retrofitting these dams to produce hydropower. These 85,000+ NPDs represent a wide array of dams with unique features and attributes important to NPD development. Further discussion and breakdown of key NPD characteristics is provided in Section 3.2.

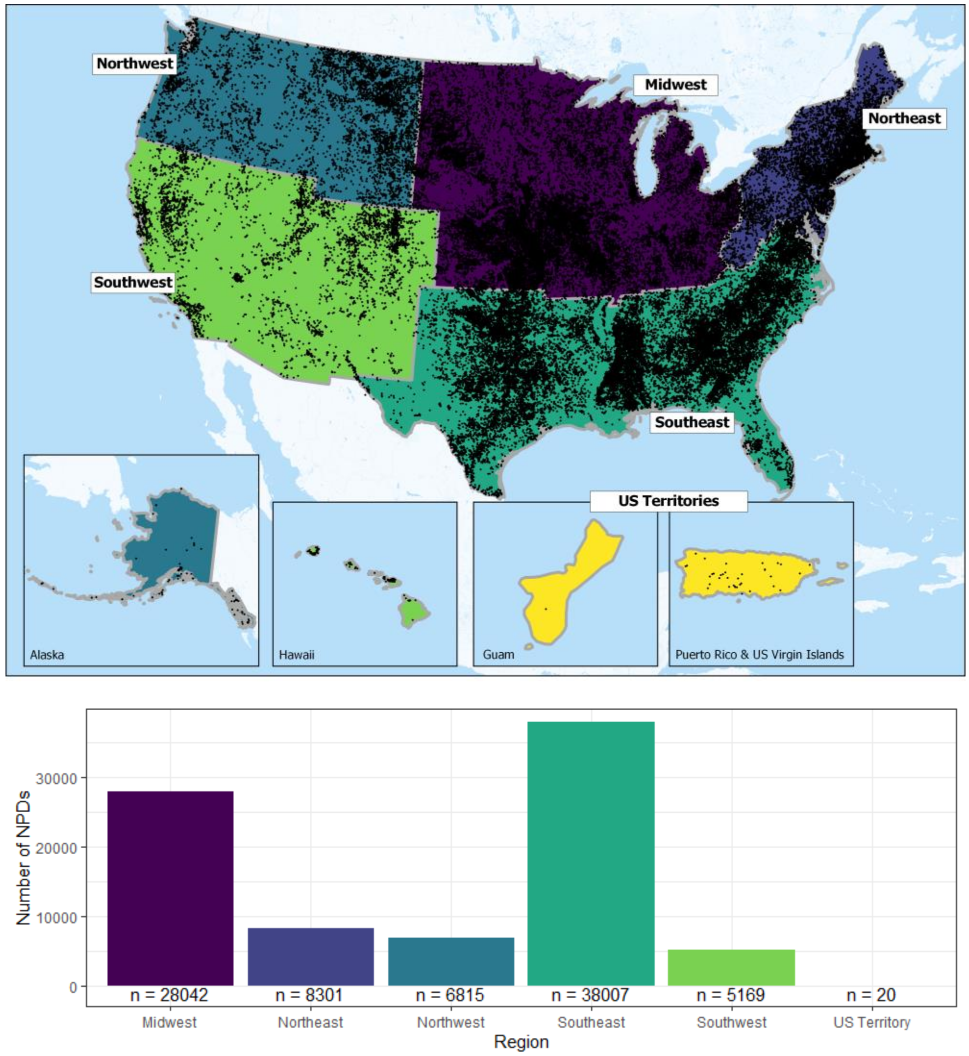

Figure 2. Distribution of US NPD locations in the United States and US territories. Data from the 2019 NID.[3]

Several resource assessments have been conducted to estimate the energy potential available at US NPDs. The most recent nationwide study by DOE's Oak Ridge National Laboratory (ORNL) and Idaho National Laboratory analyzed 54,391 dams and reported a total of up to 12 GW of potential capacity additions at US NPDs (Hadjerioua et al. 2012). That study and other hydropower development potential studies at NPDs, including their limitations, have been summarized (Hansen et al. 2021).

As a part of recent and ongoing R&D efforts, ORNL has conducted a detailed assessment and data collection of NPD characteristics. In addition to collecting NPD-relevant data, new analysis was conducted to better estimate descriptive statistics of inflows to US NPDs. These statistics (including historical average daily flow and flow percentiles) were derived from a runoff and river routing model for the continental United States (Hansen and Kao 2020).

2.2 RECENT NPD HYDROPOWER DEVELOPMENT

As of December 31, 2019, the US hydropower fleet consisted of 2,270 plants with a total generating capacity of 80.25 GW; an additional 43 pumped storage hydropower plants were operational, with a total generating capacity of 21.9 GW (Uria-Martinez et al. 2021). Hydropower growth in the United States has slowed in recent decades (Uría-Martínez et al. 2015). Historical hydropower development follows a linear timeline. Major activities include the birth of the power industry (1890s to 1920s), the "big dam" period (1920s to mid-1960s), targeted growth and a changing regulatory environment (mid-1960s to 1980s), and low-growth decades with a promising future (1990s to present). Growth in recent decades has faced major regulatory reform, and has faced the restructuring and uncertainty of the electricity market.

The needs to address climate change and support the increase in variable renewable energy resources (e.g., solar and wind) have increased the need for hydropower growth, as evidenced by increased permitting activity (Uría-Martínez et al. 2015); direct support for variable renewable energy growth requires large storage projects with available operational flexibility. To increase the efficiency of the hydropower permitting process, revisions in Federal Energy Regulatory Commission (FERC) licensing and exemption processes and adjustments to the regulations governing power additions to federal dams, canals, and conduits have occurred in the early twenty-first century (Uría-Martínez et al. 2015). For example, the Hydropower Regulatory Efficiency Act of 2013 increased the FERC license exemption from 5 MW to 10 MW,[6] enabling more and larger projects to be eligible for exemption.

With respect to hydropower growth at NPDs,

Figure 3 shows recent NPD capacity increases (additions) from 2010 to 2019 (

Figure 3a), and the NPD project development pipeline size (

Figure 3b), by region. Uría-Martínez et al. (2021) provided more information about the NPD project development pipeline.

- As shown in
- Figure 3a, the majority (289 MW; 65%) of NPD capacity increase from 2010 to 2019 occurred in the Midwest. The greatest number of new projects (13; 37%) commissioned over the same time period occurred in the Northeast. In total, 445 MW of new capacity was added to 35 previously developed NPDs across the United States during this time. Information on recent NPD development case studies is presented in APPENDIX B.
- As shown in
- Figure 3b, the largest amount of NPD capacity in the development pipeline stems from projects proposed in the Midwest, Southeast, and Northeast. Similarly, the largest number of NPD projects in the development pipeline are in the Northeast, Midwest, and Southeast. The US NPD development pipeline, as of December 31, 2020, included 88 projects, totaling 1,022 MW of capacity.

[6] To qualify for the exemption, a project must meet the various requirements, including having a powerhouse located no further than 500 ft from the existing dam and deriving at least 36% of the total head from the dam itself. For more information, visit: https://www.ferc.gov/industries-data/hydropower/licensing/smalllow-impact-hydropower-projects-project-comparison-chart (Accessed: May 17, 2022).

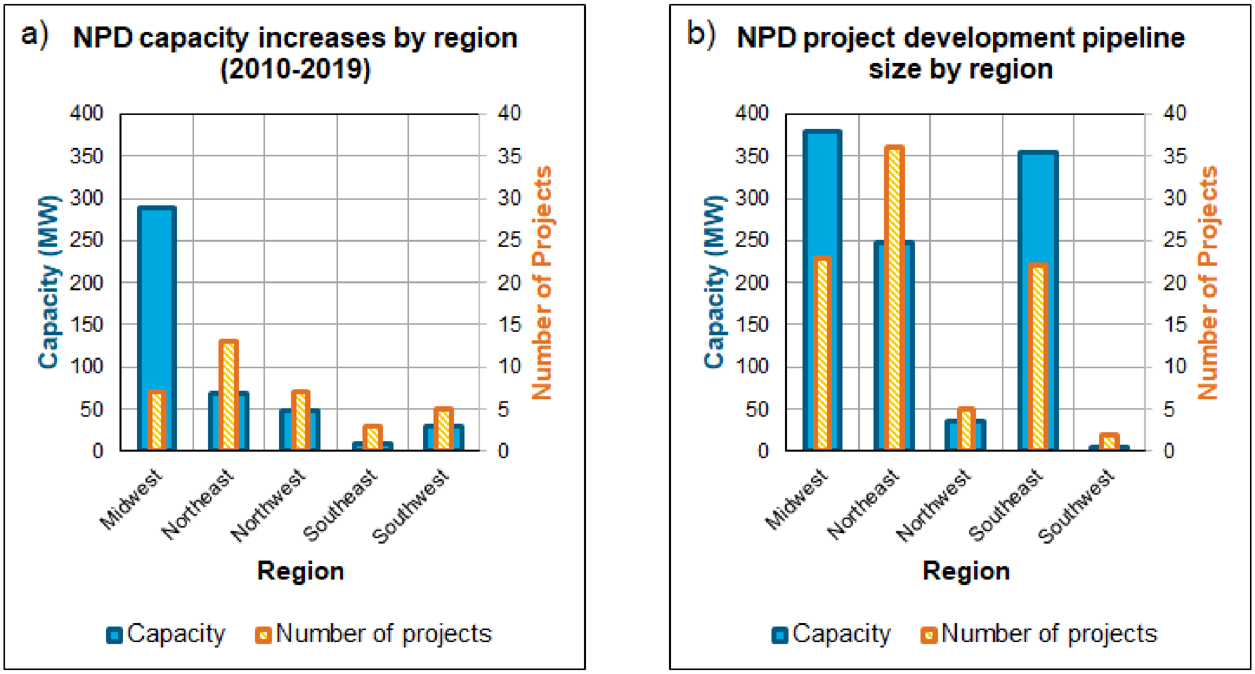

Figure 3. (a) Total number and capacity of US NPD projects added from 2010 to 2019, and (b) total number and capacity of US NPD projects in the development pipeline (as of December 31, 2020). Data from ORNL (Uría-Martínez et al. 2021).

2.3 CHALLENGES AND OPPORTUNITIES FOR DEVELOPMENT

NPD retrofit development faces several key challenges and opportunities, which must be considered. Recognizing the many challenges and opportunities presented by the more than 90,000 existing NID dams (including over 85,000 NPDs) in the US, a "Joint Statement of Collaboration on U.S. Hydropower: Climate Solution and Conservation Challenge" was published in October 2020. The joint statement "is the result of a diverse range of organizations, companies, government agencies and universities committed to charting hydropower's role in a U.S. clean energy future in a way that also supports healthy rivers"[7] and identifies seven areas for joint collaboration. These areas relate directly to NPD development and include goals to

1) *Accelerate Development of Hydropower Technologies and Practices to Improve Generation Efficiency, Environmental Performance, and Solar and Wind Integration*

2) *Advocate for Improved U.S. Dam Safety*

3) *Increase Basin-Scale Decision-Making and Access to River-Related Data*

4) *Improve the Measurement, Valuation of and Compensation for Hydropower Flexibility and Reliability Services and Support for Enhanced Environmental Performance*

5) *Advance Effective River Restoration through Improved Off-Site Mitigation Strategies*

6) *Improve Federal Hydropower Licensing, Relicensing, and License Surrender Processes*

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[7] https://woods.stanford.edu/research/hydropower (Accessed May 17, 2022).

7) Advocate for Increased Funding for U.S. Dam Rehabilitation, Retrofits and Removals[7]

The DOE WPTO and ORNL, among many other entities, are engaged in ongoing discussions surrounding this initiative, developed under Stanford University's Uncommon Dialogue process. Information and insights gleaned from such engagement will help shape future, federal RD&D initiatives.

2.3.1 Challenges

Challenges facing NPD retrofit development broadly include (as documented in Table 1):

(1) dam design and operational constraints,
(2) physical attributes of the dam system,
(3) environmental considerations of the dam system,
(4) development cost and timeline hurdles, and
(5) alternative considerations for dam rehabilitation/refurbishment or removal.

Dam design and operational constraints and physical attributes of the dam system represent engineering-related challenges. Environmental considerations and development cost and timeline hurdles represent constraints on development. Alternative dam rehabilitation/refurbishment or removal considerations represent decision-making challenges. Either individually or when combined, these challenges can contribute to reduced likelihood of project development success.

Table 1. Summary of challenges for NPD retrofit development

Challenges for NPD Development
1. Dam Design and Operational Constraints
1.1. Multipurpose water resource uses
1.2. Higher variability of water resources
1.3. Transmission requirements
2. Physical Attributes of the Dam System
2.1. Diversity of NPD site features
2.2. Staging space limitations
2.3. Aging infrastructure
3. Environmental Considerations of the Dam System
3.1. Stream connectivity
3.2. Environmental impact mitigation requirements
3.3. Low-head dam safety
4. Development Cost and Timeline Hurdles
4.1. Development costs
4.2. Development timelines
5. Alternative Considerations for Dam Rehabilitation/Refurbishment or Removal
5.1. Dam rehabilitation/refurbishment
5.2. Dam removal

The following subsections provide additional background on these NPD retrofit development challenges.

2.3.1.1 Dam design and operational constraints

"***Multipurpose water resource uses***: *Since NPD sites were originally developed for different, often multiple, purposes other than hydropower, the operation of these facilities are adapted for these purposes. A common requirement for hydropower additions at these sites is to preserve the original purpose and patterns of water resources use. This means that developers of NPD sites are constrained by resource use requirements, which are likely to be less than optimal from a hydropower generation viewpoint*." (Oladosu et al. 2021).

"***Higher variability of water resources***: *In addition to the small* [site-specific] *potential of hydropower at most undeveloped US NPD sites, the water flow and head at these sites generally have higher levels of variation than at hydropower sites with large amounts of reservoir storage. Even in cases in which the water flow and head variation are similar to those for much larger sites, the coefficient of variation, which is the ratio of the standard deviation to the mean, of head and flow values would be higher for the smaller sites. Since hydropower plants are traditionally designed for a specific optimal flow and head, higher variations pose a challenge for existing conventional technologies and require new technological advances*." (Oladosu et al. 2021).

"***Transmission requirements***: *Many potential NPD hydropower resources are not large enough to support the additional cost of constructing separate transmission lines and associated electrical infrastructure, requiring existing grid connection points near the site. Thus, the cost of electricity transmission can become a limiting factor for the development of NPD sites beyond 1 or 2 miles, depending on the actual project size*." (Oladosu et al. 2021). In addition, transmission costs are often largely fixed and independent of facility size, making them cost drivers for certain development opportunities.

2.3.1.2 Physical attributes of the dam system

"***Diversity of NPD site features***: *There is a variety of features for characterizing NPD dams* [see Figure 6 in Section 3.2]. *These include many features that are not currently captured by the available database on dams, such as the National Inventory of Dams (NID) but must be addressed by developers evaluating a site. Thus, a one-size-fits all approach to NPD hydropower facility design does not exist, requiring new innovative ways to arrange facility components or entirely new approaches to facility configurations and components*." (Oladosu et al. 2021).

"***Staging space limitations***: *Since NPD sites are already developed for purposes other than hydropower, the land surrounding these sites is often already developed or assigned to different purposes such as recreation, wildlife conservation, and so on. As a result, the cost of developing hydropower at an NPD site may be significantly affected by the need to account for space limitations around the construction site, potentially leading to increases in labor requirements, longer construction timeline, nonoptimal construction equipment, and nonoptimal facility design and technology choices, among other impacts*." (Oladosu et al. 2021).

Aging infrastructure: Analysis of the 71,466 NPDs for which the year of completion is available in the 2019 NID[3] reveals that 67% are at least 50 years old, with an average age of 59 years. When combined with other factors, such as condition and capacity, the age of the US dam infrastructure (a large majority of which are NPDs) has contributed to an overall rating of 'D' in the latest 2021 Infrastructure Report Card[8], published by the American Society of Civil Engineers. This rating is also exacerbated by the recent increase in the number of high-hazard dams, owing to the encroachment of commercial, industrial, and

[8] https://infrastructurereportcard.org/cat-item/dams/ (Accessed May 17, 2022).

residential development into previously rural areas, as well as a lack of funding for which deferred maintenance and upgrade activities have occurred.

2.3.1.3 Environmental considerations of the dam system

Stream connectivity: Dams present barriers to otherwise natural stream connectivity. Depending on the level of disruption, an NPD can present a challenge for permitting and licensing simply due to the level of hydraulic and aquatic dislocation posed by impoundment. Improving stream connectivity is one argument for dam removal in some cases (Wilkinson et al. 2017; Foley et al. 2017; Hart et al. 2002). Such considerations are a focus of many hydropower stakeholders and can present a challenge for NPD retrofit development. In particular, proper environmental mitigation impact assessment is required for NPD hydropower development; restoring stream connectivity could provide benefits to the stream ecosystem.

"***Environmental impact mitigation requirements***: *Hydropower projects at NPD sites with 10 MW or less capacity can benefit from licensing exemptions but are still required to submit environmental assessment documents. Environmental assessment documents identify measures to mitigate any environmental impacts of the project, and those required by the Federal Energy Regulatory Commission (FERC) must be implemented during hydropower development. The proportionally higher cost burden of these environmental requirements on smaller plants relative to larger plants implies a need for technological advancements to reduce environmental impact mitigation costs to accelerate NPD hydropower developments in the US (Oladosu et al. 2022).*" (Oladosu et al. 2021).

Low-head dam safety: With most US NPDs having a height of 30 ft or less (73% according to 2019 NID[3] height data), the potential for dangerous hydraulic conditions exists, as highlighted by the American Society of Civil Engineers (ASCE 2021). For some low-head dams, the potential exists for moderate-to-high flow to create dangerous turbulent and recirculating conditions in which recreational craft or individuals can be trapped under water, posing a drowning risk. As a result, several studies have evaluated the risk posed by such low-head structures, and consideration for human safety can present a challenge to NPD development without significant design modification.

2.3.1.4 Development cost and timeline hurdles

Development costs: As evidenced by the relatively small amount of new hydropower commissioned in recent decades, development costs can play a significant role in determining NPD retrofit viability. Oladosu et al. (2021) presents a detailed analysis of costs across nearly 20 NPD sites, estimating costs ranging from $2,200 per kilowatt (kW) to $34,000/kW, with most sites below $12,000/kW in 2020$; this wide range of normalized costs is attributed to site-specific considerations and the range of hydraulic heads encountered at the case study sites. Under normal market conditions, many of these sites would prove economically infeasible, suggesting that technology innovation is needed to improve project viability toward hydropower growth. Compared with other hydropower resource classes, such as new stream-reach development, NPD development is relatively cost-effective (O'Connor et al. 2015).

Development timelines: As with costs, development timelines present a major challenge to NPD retrofits owing to the financing required to support project development over long time periods. Despite their relatively smaller planning, engineering, and construction scope, NPD projects still require years of permitting and licensing before breaking ground toward construction. Additional insight into project development timelines is available in Uría-Martínez et al. (2021, 2018, 2015). Thanks to recent changes in licensing and exemption processes and adjustments, the regulatory process governing power additions to federal dams has been streamlined to an extent.

2.3.1.5 Alternative considerations for dam rehabilitation/refurbishment or removal

Dam rehabilitation/refurbishment: Besides NPD retrofit, a key alternative consideration is dam rehabilitation/refurbishment. Rehabilitation or refurbishment is typically needed when a dam subsystem or component no longer functions as originally intended or requires adjustment to improve functionality. Stanford University identifies the need to "rehabilitate" dams as surrounding decisions to "address safety problems, increase climate resilience and mitigate environmental impacts" [9]. Dam rehabilitation/refurbishment could be accomplished either in conjunction with or as an alternative to retrofitting.

Dam removal: Besides NPD retrofit and rehabilitation/refurbishment, a key alternative consideration is dam removal. Much scientific study has gone into advancing the understanding of dam systems and the decisions surrounding dam removal (Poff and Hart, 2002). Public safety, fish migration, environmental impact, and hydraulic connectivity are among the main considerations driving decisions for dam removal. Given the often multipurpose nature of dam operations, it is important to consider the advantages and disadvantages of any dam modification. Stanford University identifies dam "removal" as "when dams should be taken down because they no longer provide benefits to society, have safety issues that can't be cost-effectively resolved, or have harmful impacts on the environment that can't be adequately addressed"[9]. Dam removal is necessarily an alternative to retrofitting.

2.3.2 Opportunities

Opportunities presented by NPD retrofit development broadly include (as documented in Table 2):

(1) renewable energy growth and support of variable renewables,
(2) co-development opportunities,
(3) improved infrastructure reliability and performance, and
(4) new technology innovation.

Renewable energy growth and support of variable renewables represent energy outcomes deriving from project development success. Co-development opportunities represent non-energy outcomes deriving from project development success. Improved infrastructure reliability and performance represent engineering outcomes deriving from project development success. New technology innovation represents a unique opportunity for improving the likelihood of project development success; it addresses all five challenges identified in Section 2.3.1.

Table 2. Summary of opportunities and relevant challenges addressed for NPD retrofit development

Opportunities for NPD Development	Challenges Addressed
1. Renewable Energy Growth and Support of Variable Renewables	• Alternative considerations for dam rehabilitation/refurbishment or removal
1.1. Renewable Energy Growth	
1.2. Support of Variable Renewables	
2. Co-Development Opportunities	• Environmental considerations of the dam system
2.1. Co-Development Opportunities	

[9] https://news.stanford.edu/2020/10/13/new-agreement-u-s-hydropower-river-conservation/ (Accessed May 17, 2022).

Opportunities for NPD Development	Challenges Addressed
3. Improved Infrastructure Reliability and Performance	• Dam design and operational constraints • Physical attributes of the dam system
3.1. Improved Infrastructure Reliability and Performance	
4. New Technology Innovation	• Dam design and operational constraints • Physical attributes of the dam system • Environmental considerations of the dam system • Development cost and timeline hurdles • Alternative considerations for dam rehabilitation/refurbishment or removal
4.1. Standard Modular Technologies	
4.2. Near-Term Innovations	
4.3. Medium-to-Long-Term Innovations	

The following subsections provide additional background on these NPD retrofit development opportunities.

2.3.2.1 Renewable energy growth and support of variable renewables

Renewable Energy Growth: An obvious opportunity provided by NPD retrofitting is the ability to add renewable energy generation within a community. Thus, hydropower retrofitting aligns directly with the DOE WPTO's commitment to "*developing and deploying a portfolio of innovative technologies for clean, domestic power generation from resources such as hydropower, waves, and tides*."[10]

Support of Variable Renewables: By adding power to a NPD, additional energy storage capacity may be made available to support the continuing growth of variable renewable resources (e.g., solar and wind); this provision is more attributable to NPDs in which sizeable water storage and operational flexibility are available. With demand for energy storage continuing to rise, the flexibility and reliability offered by hydropower remains an attractive solution to evolving electric grid demands.

2.3.2.2 Co-development opportunities

Co-Development Opportunities: As a part of SMH research, ORNL has defined co-development as "*development of an energy project that creates or enhances a natural resource benefit as a result of, or in conjunction with, hydropower development*" (Bevelhimer et al. unpublished). Co-development at an existing NPD could take on varying objectives, such as restoring the river environment through modified flow regimes, removing and replacing an existing impoundment with a more sustainable design, or adding hydropower alongside some other passage function.

2.3.2.3 Improved infrastructure reliability and performance

Improved Infrastructure Reliability and Performance: Proper operational dam safety necessitates assessment of the relationship between equipment and component operations, decision-making, and dam failure (wherein the failure definition is not limited to catastrophic flow release). The consequences of dam failure dictate that reliability measures be taken. Such efforts align directly with the current Biden Administration's infrastructure initiatives. An NPD retrofit project offers an opportunity to improve infrastructure reliability through improved operational performance. In striving to meet water demands,

[10] https://www.energy.gov/eere/water/about-water-power-technologies-office-wpto (Accessed May 17, 2022).

an NPD may require balancing water use across multiple purposes. The performance of the system requires careful operational management, which can be partially improved upon through an NPD retrofit.

2.3.2.4 New technology innovation

Standard Modular Technologies: Among the DOE WPTO's portfolio of technology innovation projects, the SMH project has advocated for the conceptualization, development, and deployment of cost-effective, environmentally compatible technologies which leverage standardization and modularity (Smith et al. 2017a). Some current and emerging SMH-type technologies exist, and ongoing WPTO-funded R&D efforts are pursuing advancement of SMH modules and facility design concepts. While originally framed toward advancement of new stream-reach development opportunities, many of the same technology concepts and designs can serve for NPD retrofit application.

Near-Term Innovations: As documented in Oladosu et al. (2021), near-term innovations represent "technologies likely to reach wide acceptance within the next 5 to 10 years." With respect to near-term NPD innovations, Oladosu et al. (2021) identifies non-steel materials for water conveyance outlet linings and penstocks and modular matrix turbines as key opportunities to reduce development costs. Other, relevant technology advancements are ongoing. For additional information on NPD retrofit innovation opportunities, see Section 3.4.

Medium-to-Long-Term Innovations: Oladosu et al. (2021) also highlighted the potential for medium-to-long-term innovations but did not include such opportunities for evaluation, owing to a lack of complete information. It is expected as technology and methods continue to advance, that some expected and unexpected innovations with occur, with direct impact on the hydropower industry and NPD retrofit opportunities. For additional information on NPD retrofit innovation opportunities, see Section 3.4.

3. KEY DEVELOPMENT CONSIDERATIONS

When considering NPD retrofit development, a developer must balance several key objectives, most of which can be categorized as economic or environmental in nature. To better define some of these key considerations, this section (1) describes the importance of integrating retrofit design with existing stream and dam functions (Section 3.1), (2) summarizes key NPD characteristics and how they are distributed among the US NPD population (Section 3.2), and (3) presents an overview of current hydropower retrofit methods (Section 3.3) and innovation opportunities (Section 3.4).

3.1 STREAM AND DAM FUNCTIONALITY

When considering any kind of NPD development, including retrofit projects, the baseline stream and dam functionalities must be considered. A retrofit, although adding functionality, should not impair these baseline functions but rather maintain or improve them. A dam–stream environment represents a complex system of integrated and interrelated subsystems. In a general sense, the dam system is distinct from the stream system because of the presence of engineered infrastructure. Dams either partially or fully impound a flowing stream or reservoir, thereby controlling the timing, quantity, and quality of water both upstream and downstream of the impoundment. By controlling flow, dams also affect the flow and connection of fish, sediments, recreational craft, and other stream constituents. Thus, the modification to the dam system by an NPD retrofit necessarily modifies the broader stream system. Therefore, a primary objective of a retrofit project is to mitigate environmental impact to the greatest extent possible.

Similarly, the addition of NPD retrofit technologies necessarily modifies the dam system. Dam system functionality can be categorized by purpose, design, operations, and/or safety. As with stream functionalities, dam functionalities should be maintained or improved when retrofitting an NPD. For other NPD-related decision-making processes, such as dam rehabilitation or removal, dam functionalities may be more significantly modified or eliminated.

Various literature describe the intricacies and interconnections of dams with other natural and engineered systems (Hansen et al. 2022; Boyé and de Vivo 2016; Imhoff 1986). As shown in Figure 4, dams are situated immediately between an upper reservoir (or stream reach) and a downstream reach. Adjacent to the dam are the surrounding watershed and human communities. More broadly, the climate associated with the dam–stream system influences these terrestrial zones' characteristics. Figure 4 highlights some of the key processes and relevant time scales associated with these systems.

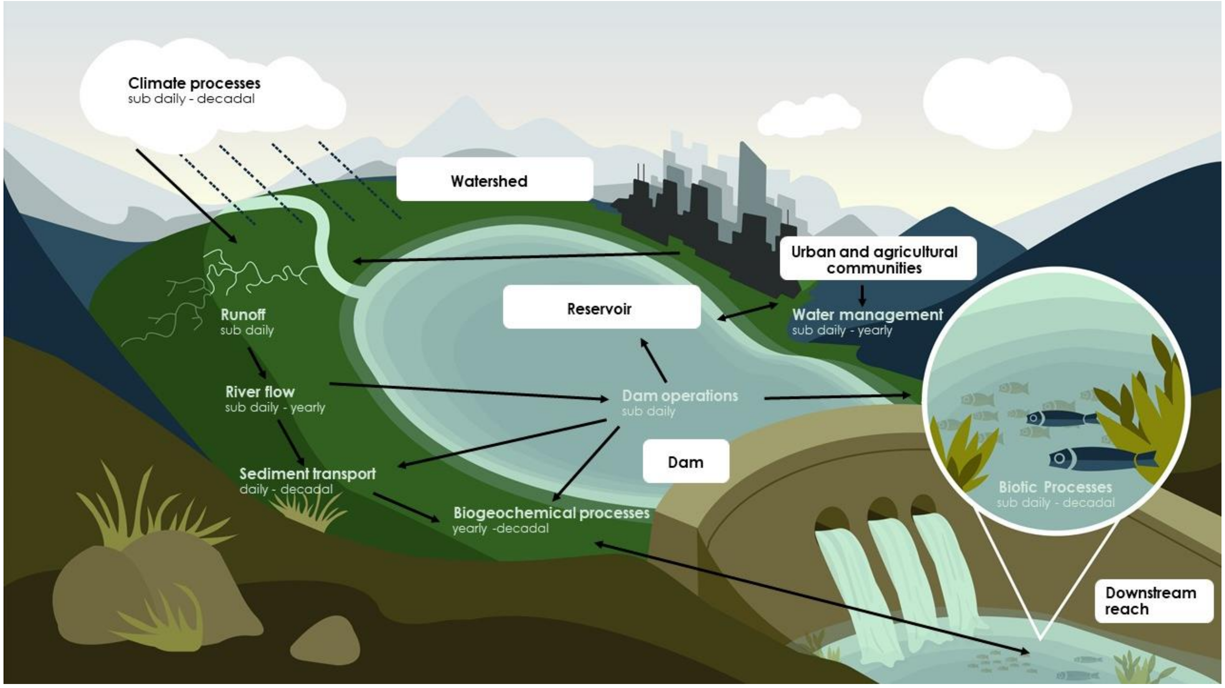

Figure 4. (a) Complex interconnections of a dam to other systems (e.g., the climate, watershed, downstream reach, and developed areas) and processes (e.g., dam operations, climate, rainfall-runoff, sediment transport, biogeochemical, water management) (Hansen et al. 2022).

The engineered dam system must balance these interconnections and processes. Processes related to NPD development are often influenced by multiple characteristics. Therefore, they require alignment with specific stream and dam functionalities as well as operational, engineering, environmental, and socioeconomic considerations to inform development decisions.

As shown in Figure 5, primary stream functions include the passage of fish, sediment, recreation, and water. Passage past a dam impoundment can be accomplished by one or more conveyances in which water is transported through, over, or around a dam. Downstream passage of each of these stream constituents may be required, whereas upstream passage is typically only required for certain fish species.

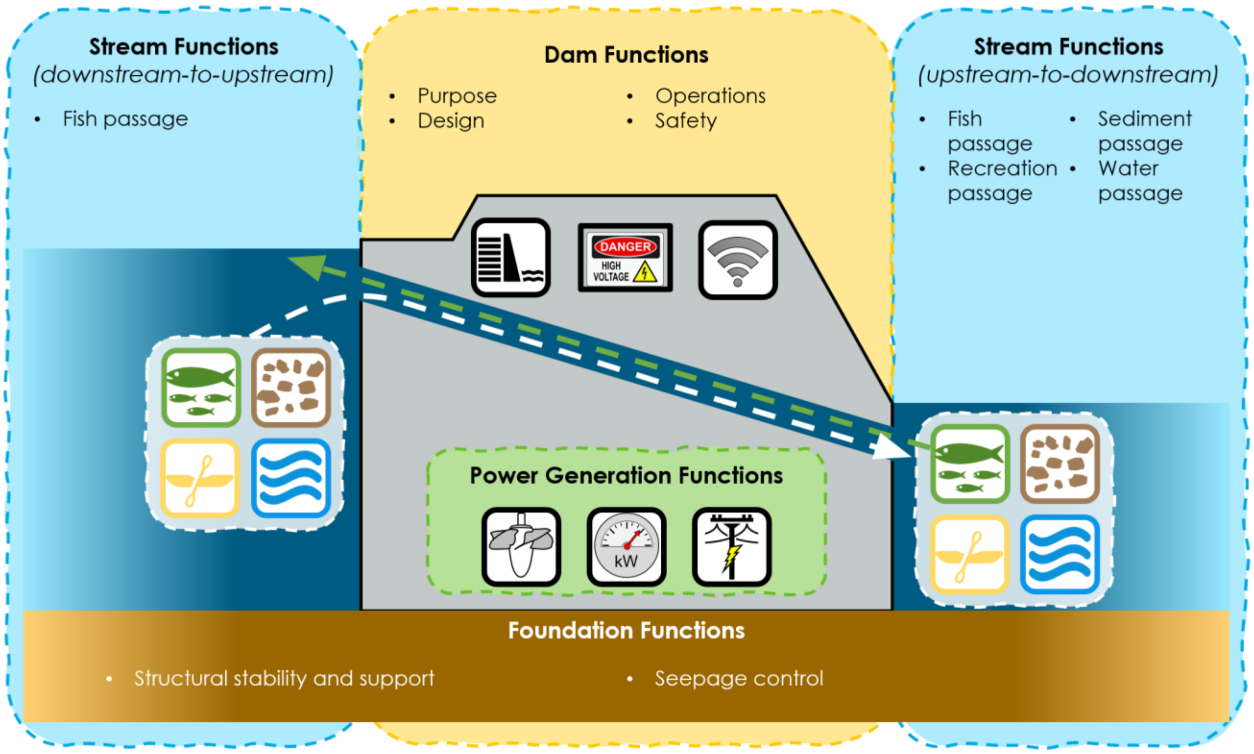

Figure 5. (a) Stream and dam functions relevant to NPD retrofits. Arrows show passage direction.

Functions related to a dam's purpose, design, operations, and safety could vary widely from dam to dam, given site-specific considerations. Based on data in the NID,[3] a dam's licensed purpose could include one or more of the following: irrigation; hydroelectric; flood control and storm water management; navigation; water supply; recreation; fire protection, stock, or small farm pond; fish and wildlife pond; debris control; tailings; grade stabilization; or other. Meeting a dam's stated purpose is a key dam function. Primary NPD design features include the impoundment, foundation system, water conveyances, monitoring and control systems, and electrical systems; the US Bureau of Reclamation (USBR) provides a comprehensive resource for small dam design, which is relevant to most NPD systems today (USBR 2006). Altogether, the dam's design ensures that structural stability and water control functions are accomplished to meet operational and safety functions. DeNeale et al. (2019) provided a review of the current state-of-practice in dam safety risk assessment, covering both operational and structural safety considerations and practice.

Figure 5 identifies the key dam functions and further identifies the relevant power generation functions that may be added via retrofitting. Power generation functions serve to convert energy from flowing water (*hydraulic energy*) to spin a turbine (*mechanical energy*) and generator before transforming to electricity (*electrical energy*). This power conversion requires the addition of powertrain equipment and electrical interconnection (i.e., transformer, switchyard, and transmission line) modification or addition.

Identifying stream and dam characteristics is important for understanding existing functions and enabling analysis (e.g., impact assessment, performance simulation, and technical and economic feasibility) and ultimately for improving the likelihood of successful NPD development. Given the complexities of stream–dam systems, proper evaluation presents a multivariate, multi-objective optimization challenge.

3.2 KEY NPD CHARACTERISTICS

NPD development decisions are often influenced directly or indirectly by multiple characteristics. Development decisions vary widely across stakeholders because differing objectives require unique consideration. The many characteristics relevant to decision-making can be broadly categorized as design, operational, environmental, socioeconomic, or hydropower opportunities.

Figure 6 lists these categories and their associated characteristics. Hansen et al. (2022) presented an approach to classification based on multiple characteristics: the NPD custom analysis and taxonomy (NPDamCAT) framework. This framework describes “a stakeholder-driven process that involves: (1) defining the key pieces or “building blocks” needed to create a taxonomy (i.e., classification), (2) selecting data sources and configuring classes, (3) arranging the building blocks into a taxonomical structure, (4) applying the data, and (5) visualizing and analyzing the results” (Hansen et al. 2022). This framework is designed to respond to the fact that different stakeholders may be interested in different characteristics or may define classes of dams differently depending on their various objectives and informational needs.

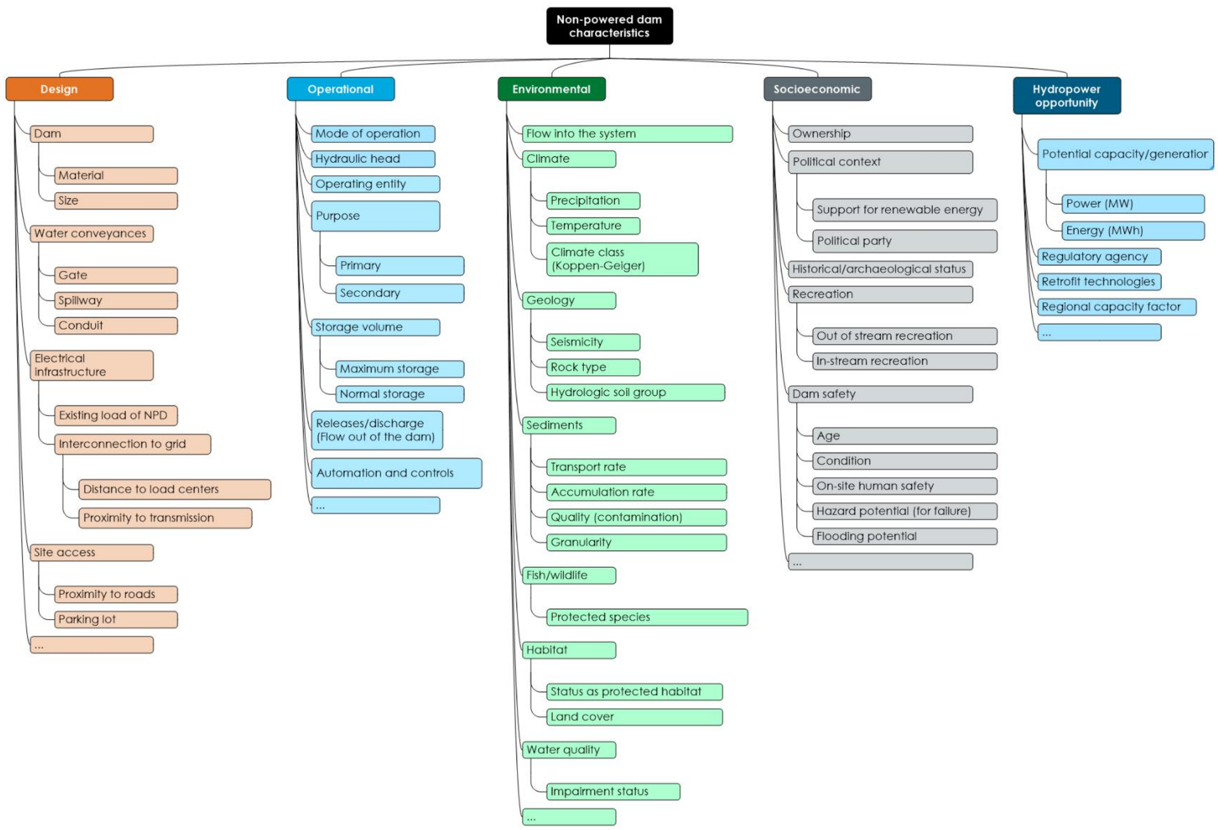

Figure 6. Example NPD characteristics (Hansen et al. 2022).

Many of the design and operational characteristics are static—dimensions, materials, and features of the dam largely remain constant throughout the life of the dam (with exceptions for dams that undergo major redesign or modification). NPDs are also influenced by or connected to complex environmental and socioeconomic systems, which can cause some characteristics to change significantly over the life of a dam. For example, environmental characteristics, such as hydrologic inputs (e.g., precipitation, runoff), can vary significantly over seasonal and interannual scales. These environmental characteristics, along with climate characteristics, are expected to continue changing because of changes in global climate conditions and local development/hydrologic alteration.

Data describing these characteristics can be derived from a variety of sources. Many design characteristics and socioeconomic characteristics related to regulation and ownership are detailed in dam inventories such as the NID database or the Global Reservoir and Dam Database. Other characteristics must be derived from other data sets that can be linked, generally using Geographic Information Systems software and methods. Examples of derived characteristics include streamflow characteristics, which may reference specific river reaches that are part of river networks (e.g., the National Hydrography Dataset Plus river network) that can be spatially matched to individual dams. Other characteristics can be derived from geographically distributed data, such as maps of climate or population density, or from data describing georeferenced locations of interest. For example, proximity can be determined in relation to locations of national landmarks, protected rivers, recreational sites, or existing energy infrastructure.

Figure 7 shows select design and operational characteristics for US NPDs.

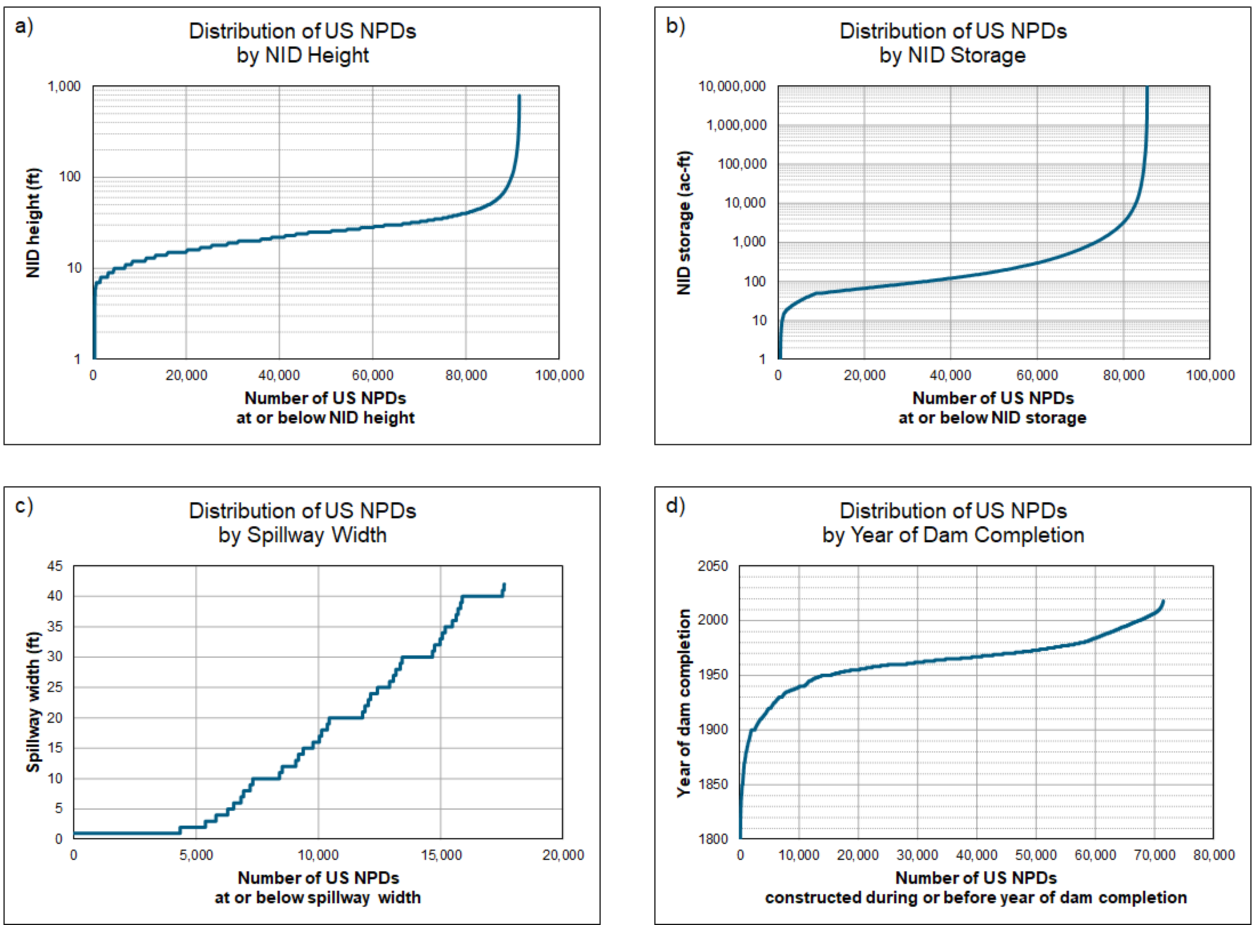

Figure 7. Distributions of US NPDs by (a) NID height, (b) NID storage, (c) spillway width, and (d) year of dam completion. Data from the 2019 NID.[3] Data are missing for some dams; the majority of NPDs report a spillway width of 0 and are not plotted in panel (c), and a number of NPDs constructed before 1800 are not plotted in panel (d).

The categories of characteristics described in the NPDamCAT framework align with specific dam purposes and functionalities (design and operational) and include categories that are relevant to development decisions (e.g., hydropower opportunities, environmental and socioeconomic characteristics). These characteristics are important when evaluating retrofit design opportunities.

3.3 NPD RETROFIT METHODS

This section highlights conventional NPD retrofit methods, beginning with an overview before briefly describing conventional approaches to retrofitting for power generation, fish passage, sediment passage, recreation passage, and water passage.

3.3.1 Overview

The "Joint Statement of Collaboration on U.S. Hydropower: Climate Solution and Conservation Challenge," published in October 2020, defines an opportunity for "retrofitting powered dams and adding generation at NPDs to increase renewable generation; developing pumped storage capacity at existing dams; and enhancing dam and reservoir operations for water supply, fish passage, flood mitigation, and grid integration of solar and wind." In this report, retrofitting refers to the variety of equipment or components that may be added to an NPD to augment its function (regardless of whether hydropower is involved). For example, NPDs can enhance dam and reservoir operations by adding technologies to add or enhance the passage of fish, sediment, recreation, or water.

Witt et al. (2018) evaluated 58 licensed NPD retrofits and identified six main categories of associated powerhouse layouts for adding power generation to NPDs:

1. Through dam: A portion of the existing dam, spillway, or abutment is removed or modified to accommodate an intake structure, penstock, or powerhouse.

2. Adjacent to dam: The powerhouse is constructed on an embankment or land parcel adjacent to the dam.

3. Through lock: A powerhouse structure is built inside a decommissioned lock.

4. Downstream of dam: A combined intake and powerhouse structure is built directly downstream of a dam or spillway gate in the river channel.

5. In gate: Generating units are placed within intake or spill gates.

6. Downstream penstock: A powerhouse is constructed downstream from the dam and connected to the reservoir via a penstock using a new or existing outlet.

From a water conveyance perspective, these approaches can be more generally categorized as retrofitting by going through, around, or over a dam. In addition, these retrofit approaches apply more broadly to other retrofit objectives than just power generation:

- Through: Going through an NPD requires either leveraging an existing, pressurized water conveyance (e.g., using a penstock, tunnel, or low-level outlet), or modifying an open channel (e.g., using an existing lock). Depending on the facility arrangement, retrofitting may require additional water conveyance components to be extended upon the pre-development features. For example, retrofitting a previous low-level outlet may require hundreds of feet of additional penstock to convey generating flows to a location suitable for housing the generating unit.

- Around: Going around an NPD requires clearing and excavation of land adjoining the dam structure. Such approaches can be alternatively termed as *bypass* approaches, given the water conveyance bypasses the in-line dam features. Bypass approaches can be particularly attractive for fish or recreation passage designs in which longer flow-approach designs may be required for effective performance. Powerhouses built to the side of a dam structure can use intakes and discharges along the shoreline, which may require special consideration for fish attraction, sediment buildup, and bed scour.

- Over: Going over an NPD involves passing flow (e.g., using a penstock) through an existing intake or spillway gate or using a siphon over the dam embankment or other structure.

Among the 58 licensed NPD retrofits evaluated by Witt et al. (2018), most were owned and operated by the US Army Corps of Engineers. For projects proposed by private or nonfederal public entities, generation flows are only allowed if the original purpose of the dam or lock remains unaffected. This *run-of-release* operational mode, in which outflow is dictated by controlled release, was proposed for 36 of the 58 licensed NPDs. *Run-of-river* operational mode, in which outflow equals inflow and generation avoids drawing down water surface elevation, was proposed for 17 of the 58 projects. The other five projects proposed operations based on a negotiated rule curve, established during the project's environmental assessment.

Hansen et al. (2021) summarized an assessment of recent, successful NPD retrofits in which newly operational generating units were installed. A total of 36 successful NPD retrofits were identified as becoming operational from 2000 to 2020, 81% of which were categorized as through retrofits. In addition, 94% of the projects were prohibited from allowing turbine operation to alter discharge patterns to affect the authorized dam purposes.

Of the 112 NPDs that failed to become operational during 2000 to 2020, 107 dropped (withdrew) prior to obtaining a license (Hansen et al. 2021). A common reason cited for unsuccessful development is low economic feasibility, which is attributed to various reasons, including low energy market prices, decreasing incentives, power producer acquisition challenges, and general lack of policy support. Permit surrender notices infrequently identified environmental or safety concerns, although those concerns may have affected overall project costs.

3.3.2 Power Generation

Whereas this report describes retrofits as broadly applying for any equipment or components that may be added to an NPD to augment its function, other literature primarily focuses on power generation additions. Adding turbomachinery to an NPD can provide a reliable source of renewable power, offsetting the initial capital costs incurred by development. Traditionally, an NPD power generation retrofit project involves activity spanning several key development processes: licensing and permitting, engineering, equipment procurement, construction, and commissioning. Each of these development phases can impart technical or economic uncertainty and risk to overall project success. As project development progresses toward completion, uncertainty and risk decrease.

Physically accomplishing a powered retrofit via engineering and construction involves connecting the upper and lower water bodies using a series of water conveyance components, typically comprising an intake structure, trash rack, penstock or other conduit, turbine chamber, and draft tube or other outlet. One or more gates or valves may be installed to increase control of water flow through the conveyance system, including isolation for maintenance and to facilitate emergency shutdown. As the mechanical energy captured by the turbine spins a generator, electrical energy is generated and a transformer increases the power voltage to match the transmission line voltage. Conventionally, the powertrain and ancillary plant electrical and mechanical equipment are located in a powerhouse superstructure. For NPD retrofits, the same basic components shown in Figure 8 apply; however, the configuration and integration differ.

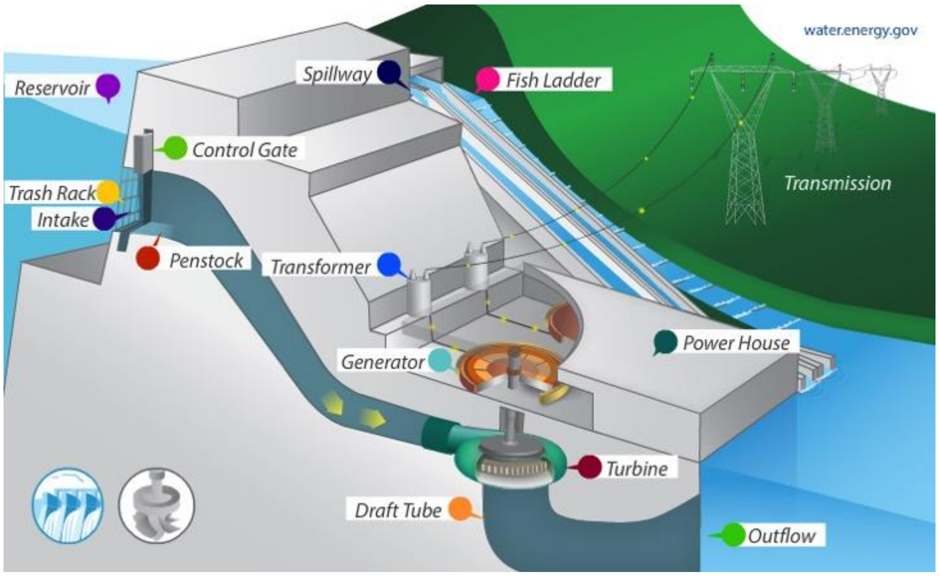

Figure 8. Major components of a hydropower plant (DOE 2017).

A primary design decision for NPD power retrofits is the method used to convey water to the powertrain. The approach is fairly straightforward when an existing penstock or other conduit is available. Flow passing through a penstock is subject to pressure (head) losses from friction, expansions, contractions, and other factors. The most critical source of head loss is friction, and it can be estimated in several ways. For instance, pipe manufacturers produce tabular information or nomograms that can be used for estimating head loss when other information is known (e.g., friction loss can be approximated if two of the following are known: inner pipe diameter, flow rate, and flow velocity). Alternatively, empirical formulas can be used; a few commonly used formulas include the Colebrook-White equation and Darcy-Weisbach equation (Moran, 2018).

Oladosu et al. (2021) specified conceptual baseline facility designs for lake and lock NPD retrofit projects. For lake dams, the default design assumption includes the use of a slip-lined water conveyance in which a smaller-diameter pipe is installed within an existing pipe or conduit. The slip-lined pipe would be connected to a new penstock to supply water to a turbine. Alternatively, lake dam retrofit configurations could include the construction of a new, pressurized tunnel through or around the dam (e.g., the through-abutment penstock constructed for the Dorena Lake Dam project; FERC, 2006) or siphons to pass water over or around the dam. Given the high costs associated with tunnel excavation, such retrofit solutions are typically cost-prohibitive for most of the remaining NPD resources.

For lock dams, the default design assumption used in the conceptual baseline facility designs includes construction of a new channel or conduit built around the dam abutment or integrated into a rebuilt dam section (Oladosu et al. 2021). This design approach has been used in several recently operable NPD retrofit projects and requires significant excavation and foundation treatment to accommodate the inlet and intake structures, powerhouse, and tailrace. Such historical development has also been constrained by a lack of usable staging area during construction.

From a cost perspective, Oladosu et al. (2021) demonstrated that the majority of initial capital costs associated with NPD power retrofits stems from the water conveyances, powerhouse, and electromechanical equipment. Whereas lake dams incur the highest fraction of cost from water conveyances (40% to 60% in most cases), lock dam costs are primarily driven by the powerhouse and electromechanical components (partially attributed to the larger turbine sizes used to capture higher design flows).

For an NPD REDS on generation technology, see Appendix A.1.

3.3.3 Fish Passage

Many historical dams did not include fish passage as a design objective. An NPD owner may seek to add fish passage technology to provide upstream fish passage, downstream fish passage, or both. The decision to add fish passage to an existing dam is largely driven by regulatory needs and economic incentives, which may be species- or region-specific. Fish passage mitigation can represent a major financial investment and require sizable civil works to construct.

Upstream fish passage technologies primarily include fishways, lifts and locks, and collection and transport systems. Common fishway designs include pool-type or ladder (e.g., Denil) systems, baffle-type systems, and nature-like channels (WDNR, 2017). The overall design selection will depend on the site's hydraulic conditions, such as flow rate and velocity, turbulence, and drop height, and the target fish species' swimming characteristics and behavior are used to inform the hydraulic design criteria. Whereas fishways are passive designs, relying on the controlled or uncontrolled inflow of water into the system, lift and lock and collection and transport systems require active operations and maintenance to transport fish upstream. Most upstream fish passage systems have been developed for anadromous fish species, particularly salmonids.

Downstream fish passage design requires similar information on the site's hydraulic conditions and target fish species characteristics. Common downstream fish passage technologies include fish-friendly turbines, spillways, and bypass systems (WDNR, 2017). Collection and transport systems may also be used. Fish exclusion devices (e.g., positive barriers such as screens, gates, racks, and/or guidance structures) are needed to ensure that fish are not entrained into certain parts of the facility, such as conventional turbines, or highly turbulent outflows in which disorientation, injury, or death may occur.

Some common fishway design examples are shown in Figure 9. For an NPD REDS on fish passage technology, see Appendix A.2.

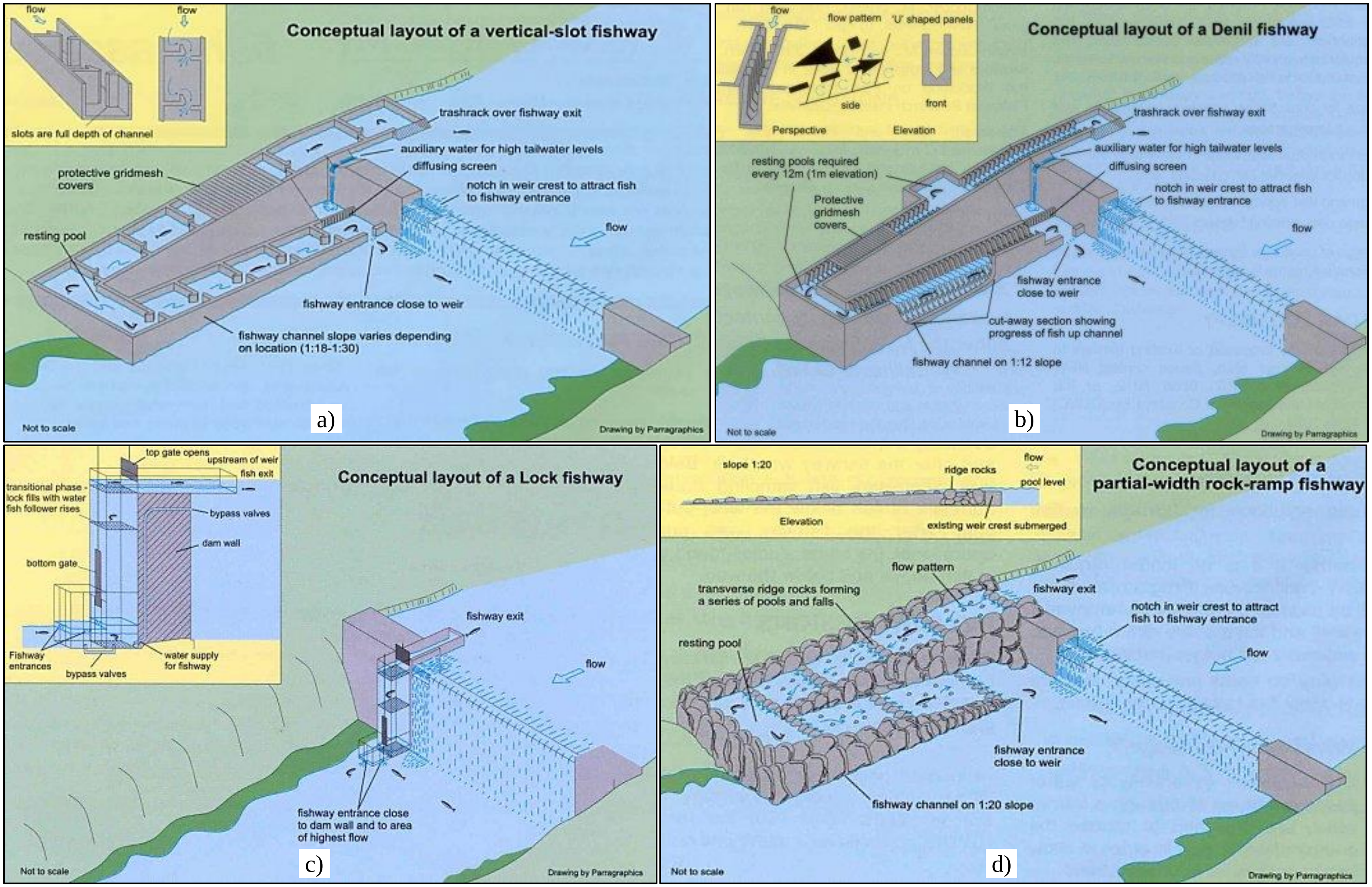

Figure 9. Common fishway design examples (New South Wales Department of Primary Industries [2021]).

3.3.4 Sediment Passage

Dams disrupt the natural sediment transport process by accumulating sediment upstream of the impoundment and reducing downstream sediment deposition. Because sediment is an important part of the riverine ecosystem, maintaining sufficient sediment transport is an important consideration for dam operations. Existing dams may require mitigation to improve sediment transport to improve river channel form and ecosystem health.

Sediment passage retrofits may be achieved via sediment bypassing, sluicing, or flushing (Kondolf et al. 2014). Sediment bypassing involves diverting sediment-laden water (during high-flow periods) from well upstream of the dam and around the upper reservoir before returning the flow downstream of the dam. Sluicing involves passing high flows through the dam during high-flow periods to reduce sediment accumulation; this is typically achieved using a controlled gate. Drawdown flushing involves resuspending deposited sediment to transport it downstream, which is typically accomplished using a low-level gate when the reservoir is at minimal water elevation. Dredging or other mechanical means of removal may also be considered but are not considered a retrofit solution.

Some common sediment passage design examples are shown in Figure 10. For an NPD REDS on sediment passage technology, see Appendix A.3.

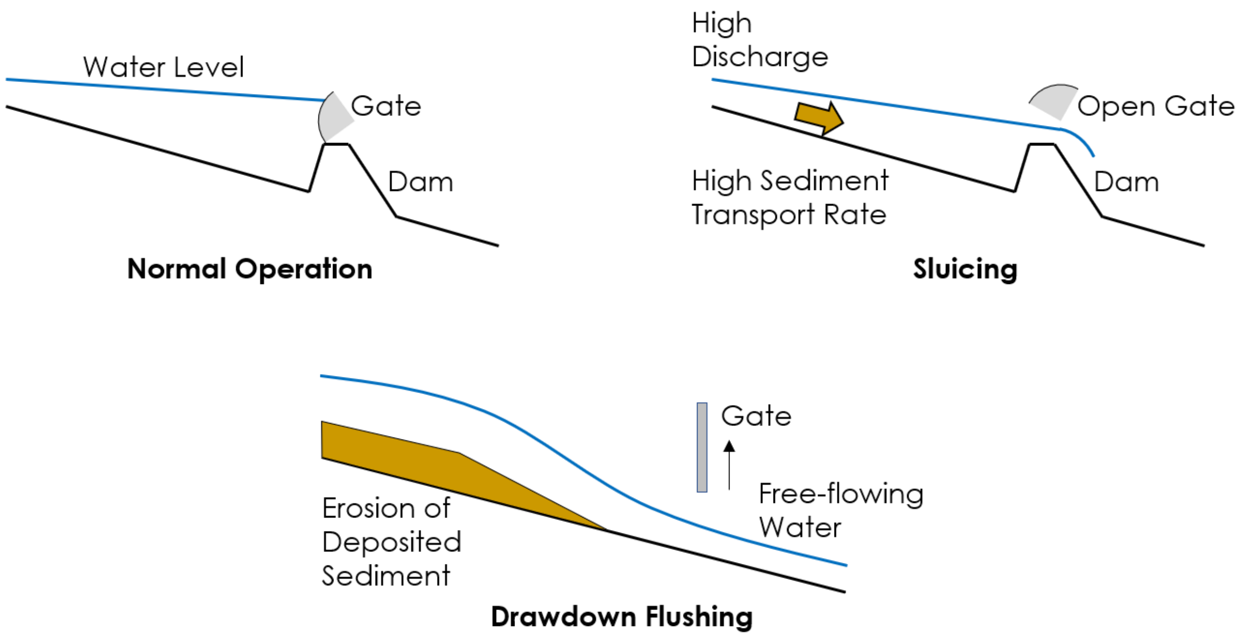

Figure 10. Common sediment passage techniques. Modified from Kondolf et al. (2014).

3.3.5 Recreation Passage

NPD retrofitting can offer recreation opportunities in several ways. For example, a bypass channel could be added to divert a portion of the incoming flow through a channel designed to enhance river aesthetics and provide canoe and kayak passage (assumed to occur from upstream to downstream). Whitewater parks have become a popular attraction at some low-head dams, and in some cases, they have been installed to improve or correct a dam safety challenge. Under certain hydraulic conditions, some low-head dams can create a recirculating current that poses danger to canoers and kayakers. To mitigate the risk of injury or death, some low-head dams have been rehabilitated or altogether removed to enable safer recreation passage.

For an NPD REDS on recreation passage technology, see Appendix A.4.

3.3.6 Water Passage

Historical dam designs include spillways or other outlets to pass inflow design flood flows (FERC 2015) during high-flow periods. Such water passage features may be controlled or uncontrolled and are used to convey water safely past the impoundment. Although water passage already exists at NPDs, regulatory requirements vary by state, and the conveyance condition or capacity may require rehabilitation in some form. Ultimately, there is limited application for direct retrofitting to enhance water passage.

3.4 AREAS FOR INNOVATION

Innovations are needed to address the challenges and opportunities presented in Sections 2.3.1 and 2.3.2. To summarize, the goals of these innovations are to reduce project development time, costs, and risk while improving economic, social, and environmental performance. These innovations can be technological, such as new equipment or components, or process-based, referring to improvements in the development process. This section outlines and informs innovation areas that could contribute to improved NPD development.

Table 3 describes some technological opportunity areas that could improve the value proposition of NPD retrofits. The opportunity areas include

- **Advanced manufacturing and civil works.** DeNeale et al. (2020) concluded that foundation and civil works costs are the largest cost components of conventional hydropower projects; therefore, reducing the material or installation costs of these components will be beneficial.
- **Standard modular technologies.** Smith et al. (2017b) listed eight key areas for hydropower innovation, captured within the modular technologies and advanced manufacturing categories.
- **Hybrid systems.** Hybrid systems refer to the proposition of combining the development of multiple energy resources to distribute costs of shared equipment and improving the versatility of a project.

Table 3. Example technological opportunities for NPD retrofit-related innovation

Advanced manufacturing and civil works
Use of alternative and composite materials: These materials can be used to reduce costs and improve performance of conduits, turbine runners, and other conveyances in comparison to common construction materials (e.g., cast iron and steel).
Advanced construction and installation techniques: Similar to the development of standard modular technologies, standardized installation and construction of these technologies can reduce construction times and costs. Methods that preclude the need for dewatering, expansive staging areas, or extended interruption of dam services can also reduce costs and development times.
3D printing of components: 3D printing technologies enable hydropower components to be custom-designed for sites in short time frames with limited material waste. Printing composites for turbine runners and concrete for conveyance structures can reduce construction times and, in some cases, improve performance.

Smaller and reduced reinforced-concrete structures: Designs that reduce the need for concrete structures and foundation modifications, such as floating powerhouses, can reduce construction complexity and costs.
Standard modular technologies
Generation technologies: Recent advancements in turbine technologies are aimed at improving generation performance at low-flows and low-heads, improving fish-friendliness, and reducing the facility footprint. For example, modular matrix turbines are being used within locks to reduce excavation requirements.
Environmental mitigation technologies: Following the opportunity for co-development described in Section 2.3.2.2, technologies can provide added environmental value to the site, such as aerating turbines, sediment passage, and selective withdrawal technologies for improved temperature regulation.
Recreation features: These features, such as boat chutes, whitewater parks, or boat launches, can improve stakeholder acceptance and provide social value to the local community.
Modular powerhouses and interconnection technologies: The powerhouse and interconnection infrastructure are major components of any power retrofit, so reducing costs through modularity and standardization will be beneficial.
Advanced monitoring and controls systems: These technologies can improve performance of the facility via optimized operation and maintenance practices.
Hybrid systems
Pumped storage: Combined hydropower with pumped storage is an emerging strategy for improving the generation value of the project using energy arbitrage and other ancillary services.
Microgrid: To address the challenge of transmission costs, NPD retrofit projects could be paired with a microgrid system to provide energy and storage for a local power system.
Wind, solar, or batteries: Pairing NPD retrofits with another energy resource, such as solar, wind, or batteries, can improve the generation value of the project and improve the cost per kilowatt by sharing the costs of transmission infrastructure and increasing overall capacity.

Table 4 outlines several process-based innovation areas for improving the value proposition of NPD retrofits. These innovations do not require technologies to improve project success, but instead improve the development process by reducing cost, time, and risk. The opportunity areas include

- **Improving data for decision-making.** This area is a valuable first step because it reduces the risk of starting the licensing process and surrendering preliminary permits or licenses when cost constraints arise.
- **Improved development practices:** This area highlights the roles that regulators, investment firms, and entrepreneurs can play in NPD development.

Table 4. Example process-based opportunities for NPD retrofit-related innovation

Improved data for decision-making
Site-specific design features and operating data: Complete and comprehensive information about dam design and operation, such as conduit dimensions, headwater elevations, operating rules, and flow requirements, would enable developers to characterize optimal retrofit methods and project feasibility earlier in the development process. The NID[3] has considerable information on dam design, but the data coverage can be inconsistent for certain attributes; it also does not collect operational information.
Improved resource assessments: Improved resource assessments would enable developers to more accurately identify feasible projects. The previous NPD resource assessment (Hadjerioua et al. 2012) provided a valuable starting point but was limited by the data available at the time of publication. Notably, the effects of operation requirements, head changes, and the trade-offs concerning generation design flow could not be included.
Decision support tools: Decision support tools can help stakeholders compile information about specific projects and facilitate the decision-making process for whether to retrofit, remove, or rehabilitate the NPD.
Improved development practices
Business models: One challenge identified in the recent review of NPD retrofits (Hansen et al., 2022) is the inability to establish power purchase agreements. Innovative business models, such as those that are pair generation with co-development, could improve the success of development projects.
Innovative policies: Local, state, and federal policies could help improve the value proposition of NPD retrofits by reducing licensing timelines, providing incentives, or initiating projects. Many NPDs require rehabilitation or relicensing as they reach the end of their expected life, so pairing retrofits with rehabilitation efforts may be valuable to governmental organizations. For example, these organizations often use Lease of Power Purchases to allow nonfederal entities to produce power at federal NPDs.
Standardized environmental impact assessments: The environmental impact assessment process of licensing requires significant time and investment, so standardizing the process for NPD retrofits with similar expected environmental impacts could reduce those costs. Pacific Northwest National Laboratory, for example, is working on a programmatic approach to conducting these assessments.

4. RETROFIT EXEMPLARY DESIGN PRINCIPLES AND CONCEPTS

This section is heavily influenced by the work of Witt et al. (2017), *Exemplary Design Envelope Specification for Standard Modular Hydropower Technology*, in which a framework is presented. The focus of that work was SMH technology, and it was applied to new stream-reach development, or greenfield, sites where no structures previously existed. By contrast, this report is intended to focus more broadly on hydropower and related technologies (wherein SMH is one example category), and it is intended to apply more specifically to NPD applications. Whereas the original SMH EDES had a different focus and application, the majority of its exemplary design principles and concepts translate well for informing NPD retrofit opportunities. With this in mind, this section heavily leverages the SMH EDES; in addition, APPENDIX A is complementary to the SMH EDES by highlighting the cases in which NPD retrofit applications demand different exemplary design specifications than documented by Witt et al. (2017).

Retrofitting an NPD with hydropower equipment or other components often presents complex considerations and uncertainty. Such development must balance the existing dam system's capacity and requirements for physical and operational adjustments, as well as the following from Witt et al. (2017):

> the essential and highly-valued functions of the stream, the benefits of the renewable energy to be produced, and the costs of creating and deploying technology that can sustain these stream functions and produce energy concomitantly. Development that does not sustain stream functions is neither acceptable nor possible in modern regulatory contexts. However, creating and deploying technology capable of sustaining stream functions while producing power engenders costs that must be balanced by the revenue and other benefits of power production. This is the essential and existential challenge for new hydropower technology.

This section is organized to present exemplary design principles for NPD retrofits (Section 4.1), features of successful NPD development (Section 4.2), and a framework for implementation through functional decomposition (Section 4.3). The structure follows that of Witt et al. (2017).

4.1 EXEMPLARY DESIGN PRINCIPLES

The design of NPD retrofits must holistically consider the constraints of the NPD system, requiring alignment with specific dam purposes and functionalities, as well as operational, engineering, environmental, and socioeconomic considerations to inform development decisions. The following principles build on these concepts to provide a framework for NPD REDS (Figure 11):

Principle 1: The NPD REDS prescribes functionality rather than detail or methodology (see APPENDIX A). The NPD REDS describes the objectives, requirements, constraints, and performance metrics for successful NPD retrofitting. To provide industry with an open design space for innovation, the NPD REDS does not prescribe specific technologies or methodologies. This *technology-agnostic* or "black-box" approach describes the functionality requirements that the technology needs to meet, rather than describing how it must meet the requirements. Multiple designs may meet the functionality requirements in vastly different ways, but overall outcomes must meet or exceed these requirements.

Functionality is defined as the inputs, processes, and outputs needed to meet a specific goal of the facility. For example, water passage is a basic functionality that requires facilities to handle inflows safely, store and pass water without major losses or quality degradation, and maintain adequate downstream flows. More complex functions, such as recreation, habitat provision, and sediment passage, are also described in this NPD REDS and covered in additional detail in the SMH EDES. Principle 2 further differentiates functionality as dam functionality and stream functionality, which represent the requirements of the engineered system and the natural stream, respectively.

Functions across the facility are often interdependent because of their effects on the shared hydraulic system. The principle of *functional decomposition*, which is discussed in Section 4.3, aims to compartmentalize these functions into specific technologies to better parameterize the costs and outcomes of a facility. Although this decomposition was particularly helpful for new stream-reach development as addressed in the SMH EDES, NPD retrofits may provide opportunities for combining functionalities by implementing new technologies, modifying existing infrastructure, or changing operational schemes. Therefore, retrofit designers must understand the effect of their design on multiple functions across the NPD system.

Principle 2: Functionality demanded by the NPD REDS follows from the existing dam functionality and the existing stream functionality. NPD retrofits must maintain or improve the existing dam functionality, which encompasses the purpose, operations, and safety considerations of the existing infrastructure. Any added functionality, in the form of new technologies or changes to the existing system, should not impair the status quo of the NPD system. These NPDs often operate to accomplish a licensed purpose, such as supplying water or supporting recreation, while maintaining safe structural and hydraulic conditions. Impairment of the existing dam functionality can be identified by any increased safety risks or operational difficulties and the inability of the NPD to meet licensed purposes. NPD retrofits may improve dam functionality by reducing operational costs and maintaining or improving structural and operational reliability.

SMH projects must also maintain or improve the existing stream functionality, which generally comprises the environmental processes within natural streams, including fish passage and sediment passage. Because NPDs create regulated upstream and downstream flow conditions, retrofit projects must maintain the environmental processes associated with regulated stream systems. Optionally, improvements to stream functionality can be achieved by progressing the stream reach toward more natural stream conditions that were present prior to dam development.

Principle 3: The NPD REDS parameterizes the technology and facility functionality to enable evaluation of cost and feasibility. Feasibility relates to economic and engineering feasibility, as well as stakeholder acceptance. A benefit of functional decomposition is the ability to parameterize, or evaluate on a per unit basis, the trade-offs between costs and benefits of specific functionalities. Stakeholder acceptance largely relies on the ability to meet environmental functionalities, which can be provided by retrofits. Cost parameterization helps inform the design process to best meet the needs of the NPD and relevant stakeholders. Inventors must design with parameterization in mind to explicitly couple design choices and functional outcomes.

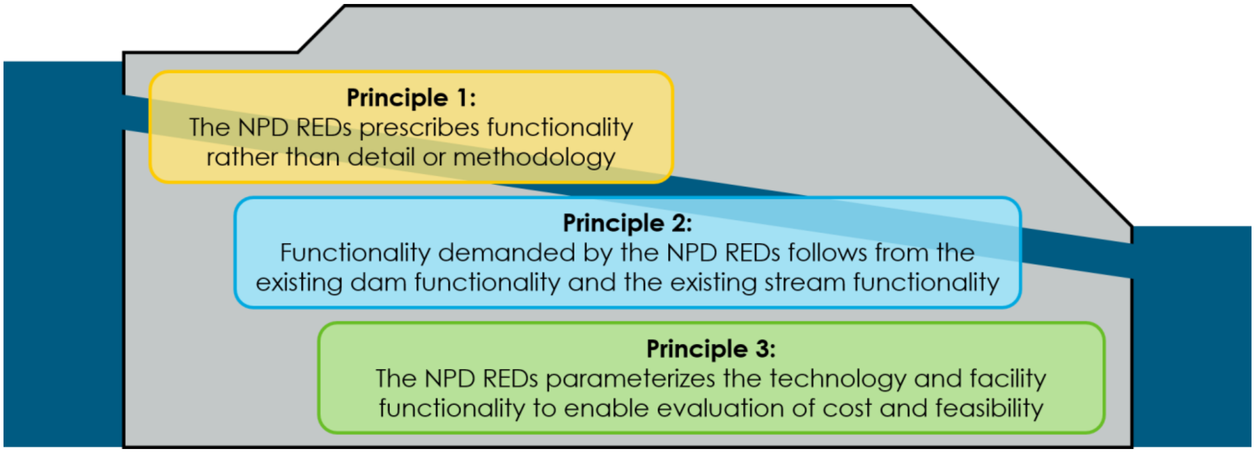

Figure 11. Overview of NPD REDS principles.

4.2 FEATURES OF SUCCESSFUL NPD DEVELOPMENT

For an NPD retrofit to be successful, Principle 2 must be observed (i.e., existing dam and stream functionalities should be maintained or improved). Beyond this key outcome, a facility must be able to reliably generate electricity (for powered retrofits), minimally change the surrounding environment, and be cost-effective. Furthermore, compared with new stream-reach development applications, NPD retrofits must address additional challenges that stem from the exiting dam system. For example, maintaining dam safety and meeting the dam's licensed purpose are key elements to successful NPD development. Regulatory requirements impart additional challenges that must be overcome.

Features of successful NPD retrofits include

- predictable and somewhat regular production of electricity,
- environmental mitigation technology (functionality) inherent within and integral to the retrofit design (including fish passage, water quality, and sediment management design),
- minimal change in water surface elevation regulation compared with pre-retrofit operations,
- minimal civil works and cost, and
- standardized design to improve acceptability and reduce installation and maintenance costs.

Among the many organizations supporting new hydropower development, the Low Impact Hydropower Institute (LIHI) is a source of information for developing low-impact hydropower at NPDs. As a part of LIHI's certification process, a "certified low impact hydropower project (facility)" must "meet eight specific science-based environmental, cultural and recreational criteria."[11] These eight criteria are listed in

[11] https://lowimpacthydro.org/certification-criteria/ (Accessed May 17, 2022).

Table 5 and apply to projects that do not involve construction of new dams or diversions after August 1998.[12]

Table 5. LIHI certification criteria (LIHI, 2020)[11]

Criteria	Goal
1. Ecological flow regimes that support healthy habitats	Flow regimes in riverine reaches that are affected by the facility support habitat and other conditions are suitable for healthy fish and wildlife resources
2. Water quality supportive of fish and wildlife resources and human use	Water quality protected in water bodies directly affected by the facility, including downstream reaches, bypassed reaches, and impoundments above dams and diversions
3. Safe, timely and effective upstream fish passage	Safe, timely and effective upstream passage of migratory fish so that the migratory species can successfully complete their life cycles and maintain healthy, sustainable fish and wildlife resources in areas affected by the facility.
4. Safe, timely and effective downstream fish passage	Safe, timely and effective downstream passage of migratory fish. For riverine (resident) fish, the facility minimizes loss of fish from reservoirs and upstream river reaches affected by facility operations. All migratory species can successfully complete their life cycles and to maintain healthy, sustainable fish and wildlife resources in the areas affected by the facility.
5. Protection, mitigation and enhancement of the soils, vegetation, and ecosystem functions in the watershed	Sufficient action taken to protect, mitigate and enhance the condition of soils, vegetation and ecosystem functions on shoreline and watershed lands associated with the facility.
6. Protection of threatened and endangered species	The facility does not negatively impact listed species. Facilities shall not have caused or contributed in a demonstrable way to the extirpation of a listed species. However, a facility that is making significant efforts to reintroduce an extirpated species may pass this criterion.
7. Protection of impacts on cultural and historic resources	The facility does not inappropriately impact cultural or historic resources that are associated with the facility's lands and waters, including resources important to local indigenous populations, such as Native Americans.
8. Recreation access is provided without fee or charge	Recreation activities on lands and waters controlled by the facility are accommodated and facility provides recreational access to its associated land and waters without fee or charge.

As described in APPENDIX A, the NPD REDS includes a variety of specifications for enabling successful NPD development. The implementation framework used for the NPD REDS is defined in Section 4.3. To provide additional real-world insight into feature of successful NPD development, APPENDIX B offers a summary of recent NPD development case studies.

4.3 FRAMEWORK FOR RETROFIT EXEMPLARY DESIGN

The NPD REDS (APPENDIX A) decomposes dam and stream functionality into facility-level functions, subsystem-level functions, and subsystem interdependencies. This approach is referred to as *functional decomposition* and mirrors the approach developed by Witt et al. (2017). All retrofit technologies added

[12] For more information on the LIHI certification program eligibility, visit https://lowimpacthydro.org/program-eligibility/ (Accessed May 17, 2022).

to an NPD must include some form of foundation technology (often integrally designed) to prevent the superstructure from failing structurally. Many retrofit projects include added generation technology to enable power generation and thereby a reliable source of revenue. All retrofits must ensure appropriate flow passage and control across pre-existing and added subsystems to enable safe and reliable operation. Other passage functions, such as fish, sediment, and recreation passage, may be of interest to a developer and require technology retrofitting. For projects in which power generation is added, some form of electrical interconnection, monitoring and controls, and installation/retrieval is also required. Technologies covered in the NPD REDS include

- generation technology (Appendix A.1),
- fish passage technology (Appendix A.2),
- sediment passage technology (Appendix A.3),
- recreation passage technology (Appendix A.4),
- water passage technology (Appendix A.5), and
- foundation technology (Appendix A.6).

The exemplary design principles of Section 4.1 and features of successful NPD development in Section 4.2 are explicitly addressed within the four functional decomposition design concepts:

Primary and design objectives include (1) the primary objective to be achieved as a result of deploying and operating a technology or facility (e.g., fish passage for fish passage technology and power production for generation technology) and (2) the design objectives (e.g., requirements and constraints).

- ***Requirements*** are features of a technology or facility that (1) are essential to achieving the primary objective, (2) are verifiable through testing, measurement, or observation, and (3) indicate—in combination with other requirements—that the technology or facility is achieving its primary objective. Examples of requirements are to convert hydraulic power into mechanical power with a hydraulic turbine runner (generation technology) or to minimize sediment deposition downstream of the facility (sediment passage technology). Requirements are prescribed by Witt et al. (2017) as functional, performance, interface, or a combination thereof. Functional requirements relate to the actions that a technology must perform, performance requirements are quantified by how well a technology must perform a function, and interface requirements involve interactions with other subsystems. When prescribed in this way, requirements can be assessed on both an individual technology scale and a holistic facility scale.

- ***Constraints*** are limitations on the value of design parameters or limitations on effects of deployment or operation that must be satisfied and verifiable to ensure feasibility of a technology or facility. Examples of constraints are to avoid creating a recirculating hydraulic jump under normal conditions (recreation passage technology), and to not appreciably increase the temperature of water as it moves through the unit (generation technology). Whereas constraints were uniquely identified by Witt et al. (2017), the NPD REDS merges them with requirements because both requirements and constraints function to achieve the primary and design objectives.

Necessary inputs are the site-specific variables that must be known when designing and selecting technologies.

Functional relationships are the fundamental linkages between inputs, design variables, and outcomes used during the design process.

Measures of performance are a set of quantifiable indices or metrics that enable the evaluation of a technology with respect to how well it accomplishes specific and primary technical objectives. Measures of performance include proportion of fish passing through a design (upstream or downstream fish passage technology), unit efficiency (generation technology), and an index of incision potential (sediment passage technology).

Using the specifications found in APPENDIX A, a technology developer can iteratively design, simulate, fabricate, and test the technology's efficacy until it satisfies the design concepts. The input/output specifications for a specific technology will require interdependency evaluation toward establishing a precise arrangement within the facility.

5. CONCLUSIONS

This report provides information relevant to NPD retrofit development and exemplary design. It is intended to inform development decisions and design approaches, primarily related to power generation, fish passage, sediment passage, recreation passage, water passage, and foundation technology design for NPD retrofitting. Like other hydropower development classes (e.g., new stream-reach development), NPD retrofitting entails considerable site specificity—the idea that no two sites are alike. However, recent and ongoing research funded by the DOE WPTO is aimed toward reducing this site specificity and other NPD development challenges. These research efforts also aim to highlight opportunities and areas for innovation to begin addressing these challenges.

For example, "a wide variety of information is needed to describe the full range of characteristics of NPD systems" (Hansen et al. 2022). The framework presented in that study suggests a pathway for streamlining NPD classification or characterization. In concert with this site characterization, design-centric information, such as that contained in this NPD REDS report, is aimed toward enhancing understanding of NPD retrofit opportunities and design considerations and supporting for future R&D initiatives. In the future, coupling site assessment and design approaches may be considered.

Three main design principles (see Section 4.1) describe the specifications included in this report (in APPENDIX A). These principles build upon the understanding that NPD systems are complex and are at the intersection of natural environmental systems and the built environment. NPD systems also often represent critical infrastructure, and any NPD retrofit solutions should address stream and dam functionality in a sustainable manner. Section 3.3 documents modern NPD retrofit methods.

Section 3.4 highlights innovation areas that may prove useful in improving the likelihood of NPD retrofit success and sustainable energy growth. These include innovations in technologies (through advanced manufacturing and civil works, making technologies standardizable and modular, and exploring hybrid systems), and in retrofit processes (improving data for decision making and improving development practices). Beyond these innovation opportunity areas, additional RD&D is needed, along with careful planning and sequencing of RD&D initiatives. Near-term efforts led by the DOE WPTO will aim to address the challenges currently facing NPD development, inform stakeholders across a wide variety of interest areas, and offer significant solutions. This report plays a role in informing these early-phase RD&D efforts.

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APPENDIX A. NPD REDS

This Appendix outlines the design specifications for six categories of hydropower-related technologies (generation, fish passage, sediment passage, recreation passage, water passage, and foundation) based on the retrofit exemplary design principles described in Section 0. The specifications are divided into four sections for each technology category:

- **Design objectives:** the functional requirements and constraints needed to safely and effectively accomplish the primary objective of the technology category
- **Necessary inputs:** the site-specific variables that must be known when designing and selecting technologies
- **Functional relationships:** the fundamental linkages between inputs, design variables, and outcomes used during the design process
- **Measures of performance:** the metrics that can be used to quantitatively or qualitatively describe the technologies' ability to safely and effectively accomplish the primary objective

This appendix is heavily influenced by the work of Witt et al. (2017), *Exemplary Design Envelope Specification for Standard Modular Hydropower Technology*, in which a framework is presented.[13] Whereas much of the SMH EDES was centered on new stream-reach development, this appendix provides technology-area-specific information intended to highlight NPD-centric design specifications. Whereas the SMH EDES presented its specifications with respect to "*modules*," this NPD REDS presents information with respect to *technologies*.[14] The term *technologies* is more comprehensive because it applies to conventional, custom-designed technologies, the modification of existing structures or operations, and modular technologies that are possible at NPDs (described in Section 3.4). Information is presented with a black-box approach that focuses on the inputs and outputs of each technology rather than the internal processes. Additionally, the intent of the content presented herein is to focus on functionality and design considerations rather than specific, detailed design. Hydropower technologies often serve multiple functions (e.g., a fish-friendly generation technology can also serve the function of fish passage), so designs must carefully consider the relationships and trade-offs between these functions.

The appendix sub-sections are organized according to the following list. Each appendix section shows four tables outlining the technology specifications. Notes are included throughout to reference the corresponding section in the SMH EDES report, and readers are encouraged to refer to the SMH EDES report for more information (Witt et al. 2017). The original SMH EDES had six specification categories, but for this appendix, the objectives, constraints, and requirements tables have been combined into a single table describing design objectives. This specification also excludes water passage technologies, such as spillways, because existing structures are assumed to have existing methods for passing water. Exclusion of a technology class, such as water passage, water quality enhancement, or non-overflow/embankment structures does not mean they are irrelevant to NPD retrofit; rather, they are outside the scope of this report.

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[13] Readers are encouraged to review Witt et al. (2017) for additional information regarding technology considerations.

[14] Generally, the term *module* can be used interchangeably with the term *technology*. In many cases, text from source material includes modification to suggest alternative wording. Such alternative wording is included as [bracketed] text (e.g., "module [technology]," "module [unit]," "module [system]").

- **A.1 Generation Technology** documents an NPD REDS. See Appendix A of Witt et al. (2017) for the original SMH EDES for generation modules.
- **A.2 Fish Passage Technology** documents an NPD REDS. See Appendix B of Witt et al. (2017) for the original SMH EDES for fish passage modules.
- **A.3 Sediment Passage Technology** documents an NPD REDS. See Appendix C of Witt et al. (2017) for the original SMH EDES for sediment passage modules.
- **A.4 Recreation Passage Technology** documents an NPD REDS. See Appendix D of Witt et al. (2017) for the original SMH EDES for recreation passage modules.
- **A.5 Water Passage Technology** documents an NPD REDS. See Appendix E of Witt et al. (2017) for the original SMH EDES for water passage modules.
- **A.6 Foundation Technology** documents an NPD REDS. See Appendix F of Witt et al. (2017) for the original SMH EDES for foundation modules.

It is worth reiterating that the REDS follows the exemplary design principles outlined in Section 4.1, namely: (1) the NPD REDS prescribes functionality rather than detail or methodology; (2) functionality demanded by the NPD REDS follows from the existing dam functionality and the existing stream functionality; and (3) the NPD REDS parameterizes the technology and facility functionality to enable evaluation of cost and feasibility.

A.1 GENERATION TECHNOLOGY

The primary objective of generation technologies is to generate hydroelectric power from flowing water under pressure (Witt et al. 2017). The generation technologies include all the equipment needed to convey water into and out of the powerhouse, to produce electricity, and to integrate these technologies into the surrounding infrastructure. Generation technology components include turbines, generators, intakes, draft tubes, switchgear, and transformers. Power generation technology retrofits at NPDs are described in Section 3.3.2. The following content describes the design objectives, necessary inputs, functional relationships, and measures of performance for generation technology.

Generation Technology Primary Objective
To generate hydroelectric power from flowing water under pressure

Design Objectives: Generation Technology

The following specific design objectives must be accomplished to achieve the primary objective. Figure A-1 illustrates these design objectives, and Table A-1 lists these design objectives (1, 2, etc.) and associated requirements and constraints (1a, 1b, etc.).

1. Intake flow
2. Bypass flow
3. Direct the flow to the hydraulic turbine chamber
4. Convert hydraulic power to mechanical power
5. Convert mechanical power into electrical power
6. Prepare electrical power for distribution to the customer
7. Release flow
8. Operate safely within operating conditions
9. Limit adverse environmental impacts
10. Integrate structurally into the foundation system

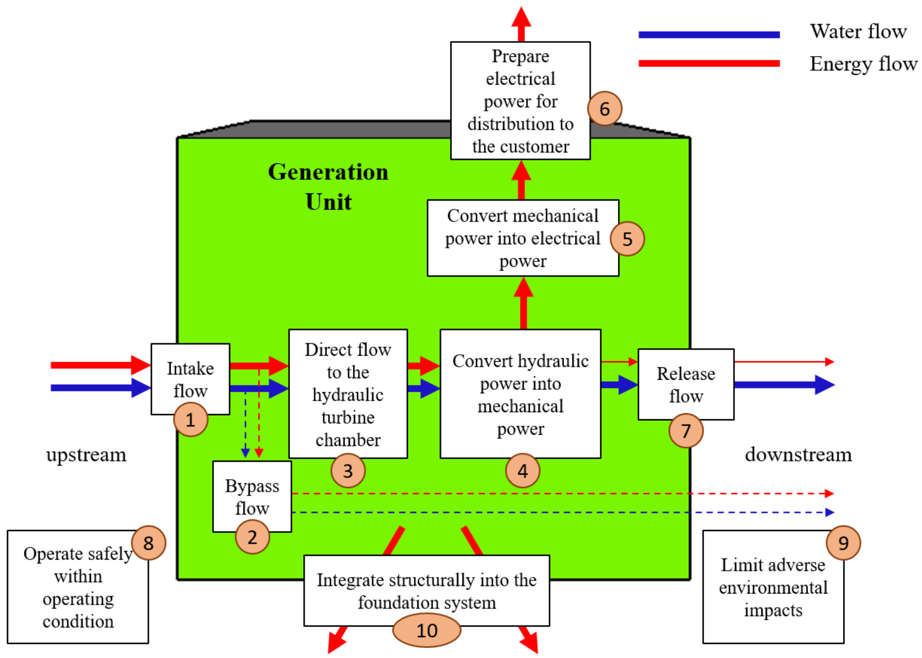

Figure A-1. Conceptual schematic of the design objectives of a generation unit. Adapted from Witt et al. (2017).

Table A-1. Generation technology design objectives. Adapted from Appendix A of Witt et al. (2017)

		Design objectives
1	**Intake flow**	
	1a	Guide upstream flow to the generation intake
	1b	Provisions for shutoff
	1c	Provisions for trash racks
2	**Bypass flow**	
	2a	Provision for bypass flow around the turbine chamber during times of maintenance or other shutdown periods
3	**Direct flow to the hydraulic turbine chamber**	
	3a	Adjust the direction of the flow for optimal power extraction
4	**Convert hydraulic power into mechanical power**	
	4a	Maximize the work done by the fluid on the runner blades
	4b	Optimize turbine shape, size, number of blades, and speed to minimize head losses across the runner associated with turbulence, disk friction, and leakage
5	**Convert mechanical power into electrical power**	
	5a	Encompass all equipment and systems for safe and reliable electricity generation
	5b	Optimize generator speed control for ease of use, cost, frequency, and compactness
6	**Prepare electrical power for distribution to the customer**	
	6a	Send electrical current to interconnection technology
	6b	Produce 3-phase power at 60 Hz
7	**Release flow**	
	7a	Maximize kinetic energy recovery out of the generation technology
8	**Operate safely within operating conditions**	
	8a	Maintain safe operation of equipment and systems within the generation unit during all operational scenarios (normal operations, flood, drought, special hydraulic operations, emergency shutdown, startup, and ramping up and down)
	8b	Do not interfere with other licensed purposes
	8c	Operate within the expected/licensed variations of head and flow
	8d	Do not be excessively loud
	8e	Conform with all relevant standards and codes for hydropower generators
9	**Limit adverse environmental effects**	
	9a	Do not appreciably increase the temperature of water as it moves through the unit
	9b	Use biodegradable oil and lubricants or water-lubricated bearings
	9c	Do not kill or injure fish
10	**Integrate structurally into the foundation system**	
	10a	Transmit all forces safely into the foundation
	10b	Minimize effects on the structural stability of existing infrastructure

Necessary Inputs: Generation Technology

Accomplishing the generation technology design objectives relies on knowledge of the necessary site inputs to inform design. These necessary inputs are outlined in Table A-2.

Table A-2. Necessary inputs for generation technology design. Adapted from Appendix A of Witt et al. (2017)

Identification of key inputs	Rationale
Available flow	Flow statistics are needed to determine turbine design flows and to predict operating conditions. Flow statistics may include flow duration curves, mean annual flows, and minimum environmental flow requirements. NPDs may have other licensed water uses that impact the amount and timing of flow available for generation.
Head	The range of gross heads (headwater and tailwater high and low elevations), net heads, and tailwater submergence levels are needed to inform the hydraulic system design.
River geometry	Information on the wetted perimeter, width, and bottom width of the river may play a role in powerhouse placement and retrofit design.
Existing water conveyance geometry	An NPD retrofit design may capitalize on existing water conveyances (e.g., low-level outlet, spillway) or may require construction of new features. Inputs such as conduit length, material, and cross-sectional area are necessary to inform design.
Desired power characteristics	Produced power must meet desired qualities, such as voltage, frequency, total harmonic distortion, and power factor.

Functional Relationships: Generation Technology

The functional relationships that govern generation technology operation, with a summary of their importance, are described in Table A-3.

Table A-3. Functional relationships governing the generation technology operation. Adapted from Appendix A of Witt et al. (2017)

Relationship of	To	Rationale/importance
Site characteristics	Range of head and flow	An existing NPD operates with fluctuations in available head and flow to meet a series of requirements and constraints that vary depending on multiple physical, environmental, and socioeconomic objectives. To the greatest extent possible, such objectives should aim to maintain or improve predevelopment stream and dam functionality, including minimizing disruptions from head and flow fluctuations.
Range of head and flow	1. Performance characteristics 2. Rotational speed 3. Turbine runner diameter 4. Cost	1. Relationships between design head and flow and important turbine performance characteristics are necessary to establish how a generation unit will operate at a given site. These relationships include power output vs. head and flow, torque vs. head and flow, and hydraulic efficiency vs. head and flow. 2. The rotational speed of the turbine can be derived from the specific speed once the head, flow, and power potential of a site are known. 3. The turbine runner diameter is specific to the manufacturer and runner design, and it may be developed empirically based on physical testing. Relationships defining how the runner diameter varies with head, flow, and specific speed are necessary to standardize module development. 4. Standardized and scalable cost estimates help determine whether a design is economically feasible.
Technology scaling	1. Hydrologic statistics and technology performance characteristics 2. Existing water conveyance geometry	1. The traditional approach to determine how many hydropower turbines are necessary at a site is based largely on the flow duration curve, annual hydrograph or other flow statistics, and turbine performance characteristics. This approach will be a starting point for assessing turbine scalability. 2. In addition to hydrologic statistics and technology performance characteristics, determining how many hydropower turbines should be designed for an NPD site also depends on the existing or planned water conveyance system geometry used to supply water for hydropower generation.
Specific speed	Turbine shape	In conventional turbine design, specific speed, which is a function of head, flow, and rotational speed, determines the appropriate values for a variety of turbine and generator characteristics such as turbine type and number of poles in the generator..
Input hydraulic power	Shaft power and output electrical power	Turbine efficiency describes how well a turbine converts input hydraulic power to shaft power, and unit characteristics describe the efficiency of converting input hydraulic power to electrical power. Both of these efficiency estimates for turbines must be known for a wide range of head and flow to inform techno-economic models of site feasibility.

Measures of Performance: Generation Technology

The primary performance measure for generation technology is the ability to generate revenue to economically justify project development. General targets for measures of performance are presented in Table A-4.

Table A-4. General measures of performance for generation technologies. Adapted from Appendix A of Witt et al. (2017)

Measure	Standard of measurement	Target
Generation unit efficiency characteristics	How well the technology converts hydraulic input power to electrical power	Maximize the expected power output over the life of the unit. While high capacities and efficiencies are desired, designs must optimize tradeoffs between peak efficiencies, efficiencies at partial flows, and the useful life of the unit. The design determines how the turbines perform within a range of heads and flows.
Scalability	How well the technology can be applied at a variety of sites with different flow regimes	Technology consists of a standard turbine runner and generator available in a range of installed capacities.
Size	Overall dimension of a fully operating technology.	Technologies and their components are amenable to standard transportation methods and facilitate ease of installation and minimized civil works.
Installed cost	How much it costs to manufacture, deliver, and install the unit	The total installed cost for retrofitting an NPD should prove economically viable and be used to inform lifecycle cost analysis. Target costs depend heavily on project size, energy prices, and project life among other variables. The Annual Technology Baseline provides up-to-date cost estimates for NPDs and can be used as a reference for target cost (NREL, 2021).
Estimated useful life	How long a unit is expected to remain in operation before needing replacement	Employ fit-for-purpose, environmentally compatible technology designs that trade off cost, efficiency, durability, and modular replacement.
Maintainability	How expensive routine maintenance is on average in terms of cost and time.	Minimize the need to remove equipment during repairs. Also, minimize the number of man-hours required to complete maintenance by limiting complexity.
Asset retirement costs	How expensive removal of the unit is after its useful life.	Enable complete removal of a unit from the foundation system in a single day with minimal removal costs.
Availability	The range of operating conditions (flows & heads) under which the unit can operate.	Maximize the up-time and overall energy generated by the unit across the unit's life.

A.2 FISH PASSAGE TECHNOLOGY

The primary objective of fish passage technologies is to allow the unimpeded and safe passage (upstream and downstream) of fish through a facility (Witt et al. 2017). Fish passage technologies must include favorable geometry and hydraulic conditions to enable safe fish passage while minimizing fatigue, disorientation, injury, and mortality. Fish passage retrofit technologies at NPDs are described in Section 3.3.3. The following content describes the design objectives, necessary inputs, functional relationships, and measures of performance for fish passage technology.

Fish Passage Technology Primary Objective
To allow the unimpeded and safe passage (upstream and downstream) of fish through a facility

Design Objectives– Fish Passage Technology

The following specific design objectives must be accomplished to achieve the primary objective. Figure A-2 illustrates these design objectives, and Table A-5 lists these design objectives (1, 2, etc.) and associated requirements and constraints (1a, 1b, etc.).

1. Guide fish to the passage inlet.
2. Allow fish to cross the facility.
3. Allow fish to exit safely into the river (downstream or upstream of the facility).
4. Integrate structurally into the foundation system.

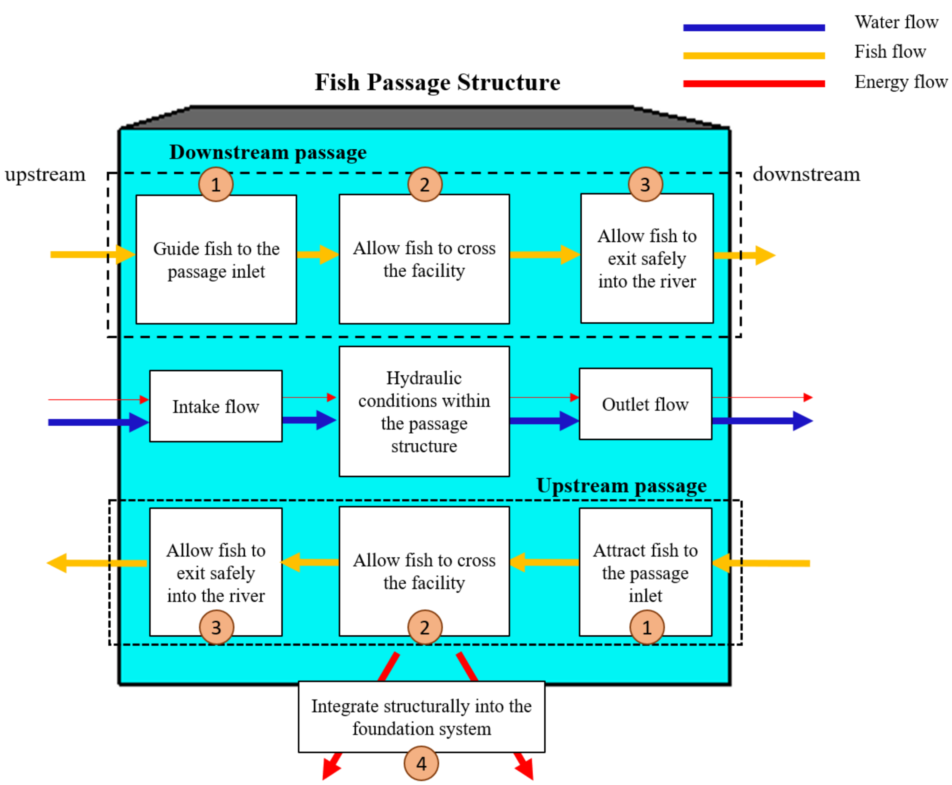

Figure A-2. Conceptual schematic of the design objectives of a fish passage structure. Adapted from Witt et al. (2017).

Table A-5. Fish passage technology design objectives. Adapted from Appendix B of Witt et al. (2017)

	Design objectives	
1		
	1a	Passage entrance accessible from fish's preferred habitat
	1b	Maintain favorable flow conditions and patterns at the fish passage inlet
	1c	Attract fish to the safe passage inlet using species-specific attractive behavioral guidance[15] (e.g., flow, temperature, turbulence, light, sound) or active collection technologies
	1d	Deter fish from entering unsafe passageways using species-specific behavioral guidance[15] (e.g., light, sound, electricity, flow, turbulence) and/or positive barriers (e.g., screens/walls/grates/adjustable curtains)
	1e	Accomplish predetermined fish attraction and entrance rates
2	**Allow fish to cross the facility**	
	2a	Divert a sufficient portion of the river flow
	2b	Sustain appropriate flow conditions and patterns (e.g., passage slope, depth, length, velocity, turbulence)
	2c	Retain passage/structure dimensions to levels manageable by the fish
	2d	Guide fish toward the exit
	2e	Prevent excessive sediment accumulation in the passage
	2f	Maintain dissolved oxygen and bubble entrainment within levels manageable by fish
	2g	Do not create barriers or drops higher than the jumping ability of encountered fish species
	2h	Minimize pressure differentials and prevent descaling and physical injury through appropriate flow and surface design
	2i	Reduce piscivore predation pressure in areas where fish density increases
3	**Allow fish to exit safely into the river**	
	3a	Minimize fish stress, disorientation, barotrauma, and physical injury from mean flow, pressure differentials, and turbulence
	3b	Retain exit structure height to levels manageable by fish
	3c	Keep air bubble entrainment within levels manageable by fish
	3d	Reduce piscivore predation pressure in areas where fish exit into river
	3e	Accomplish predetermined fish passage rates
4	**Integrate structurally into the foundation system**	
	4a	Transmit all forces through noncritical components into the foundation
	4b	Minimize effects on the structural stability of existing infrastructure

[15] Guidance stimuli may elicit behavioral responses that differ in both magnitude and direction depending on the species of interest.

Necessary Inputs: Fish Passage Technology

Accomplishing the fish passage technology design objectives relies on knowledge of necessary site inputs to inform design. These necessary inputs are outlined in Table A-6.

Table A-6. Necessary inputs for fish passage technology design. Adapted from Appendix B of Witt et al. (2017).

Identification of key inputs	Rationale
Fish species and accompanying biological traits	Swimming performance, physiological capacity, and behavioral responses are highly specific to both species and life-history stages. Important variables used to inform the correct selection of passage technology and physical dimensions include but are not limited to species, age, body size (length & weight), burst and sustainable swimming speeds, jump height, and physiological condition.
Flow variables	The range of flow discharges encountered, watershed hydrologic characteristics, flow depth, turbulence kinetic energy, turbulence dissipation, characteristic eddy length, water temperature, and friction factor are all important variables used to inform the hydraulic design.
Geometric variables	The type of passage technology, elevation difference upstream and downstream of the facility, passage slope, passage length, passage width, and passage element (e.g., baffle, weir, step/pool) height further inform the overall physical design.
Geomorphologic variables	The sediment grain size distribution, friction factor, sediment fall velocity, and sediment characteristics (shape, angularity) inform the geomorphologic effects of fish passage placement on the upstream and downstream reaches and potential sediment buildup within the passage structure.

Functional Relationships: Fish Passage Technology

The functional relationships that govern fish passage technology operation, with a summary of their importance, are described in Table A-7.

Table A-7. Functional relationships governing the fish passage technology operation. Adapted from Appendix B of Witt et al. (2017)

Relationship of	To	Rationale/importance
Fish behavior	Fish species, age, discharge, turbidity	The volitional responses of fish to guidance stimuli (e.g., light, acoustics) may differ between species and life history stages and be influenced by environmental conditions (e.g., turbidity, flow velocity, ambient noise)
Fish swimming speed	Fish species, body size, water temperature, and age	The swimming speed (burst and sustained) that a fish can achieve depends on the fish species, body size, water temperature, and age (i.e., whether it is an adult or juvenile individual)
Fish length	Fish species and age	The different lengths (sizes) of various fish species relate to the sizes of the turbulent eddies that fish can overcome
Fish endurance	Fish species, swimming speed, water temperature	The endurance of fish relates to their sustained swimming velocity, species, and age
Fish jump height	Fish species, water temperature	The passage cannot have obstacles with heights exceeding the jumping height of the target fish species.
Flow velocity in fish passage	Discharge, passage geometry, passage roughness, flow depth	Flow velocities higher than the fish swimming speed cause excessive fatigue and disorientation in fish.
Flow depth in fish passage	Discharge, passage geometry, passage roughness, passage bed slope	A minimum flow depth, which relates to the target fish species, is required for fish to be able to swim.
Turbulence production and dissipation	Discharge, passage roughness, passage configuration/type	Excessive turbulent kinetic energy levels may cause fish displacement and disorientation. Increases in turbulence dissipation are sought.
Turbulence eddy length scale	Discharge, passage geometry, passage roughness	Fish can tackle eddies with characteristic sizes comparable to or smaller to their length. Therefore, smaller eddies allow smaller fish (e.g., juveniles) to pass.
Sediment transport	Depth, slope, friction, size distribution of transported material	Sediment may be entrained into the passage structure. In that case, its deposition must be prevented, especially at lower-flow conditions.

Measures of Performance: Fish Passage Technology

The primary performance measure for fish passage technology is the fish passage rate, but the condition of the fish is equally important. Fish passage measures of performance are presented in Table A-8 and are further described by Witt et al. (2017).

Table A-8. Measures of performance for fish passage technologies. Adapted from Appendix B of Witt et al. (2017)

Measure	Status
Fish behavior	More research needed
Proportion of fish passing the facility	More research needed
Fish survival rate	More research needed
Passage time delay	More research needed
Fish injury and sublethal stress	More research needed
Proportion of fish entering fish passage entrance	More research needed
Flow depth	Limits available
Flow velocity	Limits available
Fish passage module bed slope	Limits available
Flow acceleration	More research needed
Turbulent kinetic energy	Limits available
Energy dissipation function	Limits available
Turbulent eddy length scale	More research needed
Fish passage module bed elevation change	More research needed

A.3 SEDIMENT PASSAGE TECHNOLOGY

The primary objective of sediment passage technologies is to allow the transport of incoming sediment through a facility (Witt et al. 2017).[16] Sediment passage technologies must include favorable geometry and hydraulic conditions to enable transport of supplied sediment through the facility and prevent undesired deposition (and potential storage loss) upstream of the facility. Sediment passage retrofit technologies at NPDs are described in Section 3.3.4. The following content describes the design objectives, necessary inputs, functional relationships, and measures of performance for sediment passage technology.

Sediment Passage Technology Primary Objective
To allow the transport of incoming sediment through a facility

Design Objectives: Sediment Passage Technology

The following specific design objectives must be accomplished to achieve the primary objective. Figure A-3 illustrates these design objectives, and Table A-9 lists these design objectives (1, 2, etc.) and associated requirements and constraints (1a, 1b, etc.).

1. Deliver incoming sediment to inlet.
2. Sustain conditions for transporting sediment across passage structure.
3. Minimize sediment deposition downstream.
4. Minimize river geomorphic change further upstream and downstream.
5. Minimize fish habitat and water quality degradation due to sediment releases.
6. Minimize impact to facility components.
7. Integrate structurally into the foundation system.

[16] Note that specifications for sediment passage within Witt et al. (2017) and in the NPD REDS exclude non-sediment debris and are generally more applicable to dense sediment rather than fine, suspended sediment loads.

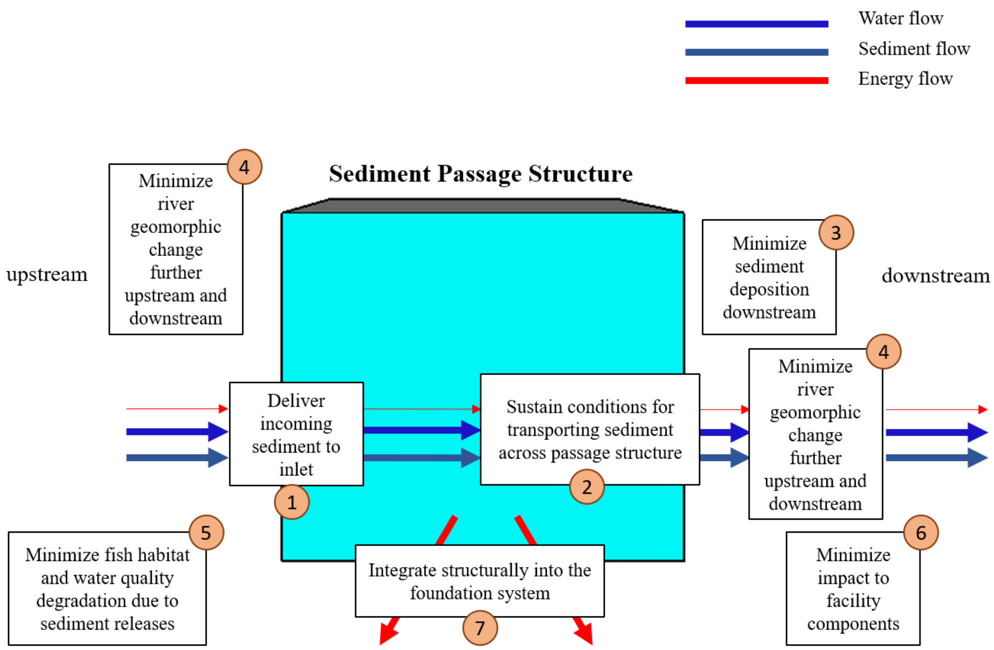

Figure A-3. Conceptual schematic of the design objectives of a sediment passage structure. Adapted from Witt et al. (2017).

Table A-9. Sediment passage technology design objectives. Adapted from Appendix C of Witt et al. (2017)

		Design objectives
1	**Deliver incoming sediment to inlet**	
	1a	Sustain appropriate hydraulic conditions and flow patterns to minimize sediment deposition and ensure transport of sediment to the sediment passage inlet
	1b	Use mechanical means: walls, traps, screens
2	**Sustain conditions for transporting sediment across passage structure**	
	2a	Divert a sufficient portion of the river flow
	2b	Sustain appropriate hydraulic conditions and flow patterns to ensure transport of sediment through the passage structure
3	**Minimize sediment deposition downstream**	
	3a	Sustain appropriate hydraulic conditions and flow patterns to ensure transport of sediment downstream of the passage structure
4	**Minimize river geomorphic change further upstream and downstream**	
	4a	Minimize channel narrowing and incision
	4b	Minimize channel armoring
	4c	Minimize bank erosion
	4d	Minimize changes in stream planform geometry
	4e	Supply sufficient amounts and sizes of sediment downstream
5	**Minimize fish habitat and water quality degradation due to sediment releases**	
	5a	Sustain hydraulic conditions to minimize settling and intrusion of fine sediment into the river bed substrate
	5b	Sustain hydraulic conditions to minimize suspended sediment concentration
6	**Minimize impact to facility components**	
	6a	Withstand the impact of the largest sediment expected
	6b	Prevent sediment from being entrained into generation unit
7	**Integrate structurally into the foundation system**	
	7a	Transmit all forces through noncritical components into the foundation
	7b	Minimize effects on the structural stability of existing infrastructure

Necessary Inputs: Sediment Passage Technology

Accomplishing the sediment passage technology design objectives relies on knowledge of necessary site inputs to inform design. These necessary inputs are outlined in Table A-10.

Table A-10. Necessary inputs for sediment passage technology design. Adapted from Appendix C of Witt et al. (2017)

Identification of key inputs	Rationale
Sediment characteristic variables	The sediment grain size distribution (e.g., median grain diameter, geometric standard deviation), friction factor, sediment fall velocity, sediment angularity, sediment shape, and relative protrusion are all important variables used to inform the passage technology selection and physical dimensions.
Flow variables	The range of flow discharges encountered, watershed hydrologic characteristics, flow depth, turbulent shear stress, water temperature, and friction factor are all important variables used to inform the hydraulic design.
Geometric variables	The geometry and shape of passage structure, elevation difference upstream and downstream of the facility, passage slope, passage length, and stream cross-sectional geometry upstream and downstream of the facility further inform the overall physical design.
Geomorphologic variables	The river bed slope, bed topography, friction factor, channel sinuosity, bank geometry, and bank soil composition further inform the overall physical design.

Functional Relationships: Sediment Passage Technology

The functional relationships that govern sediment passage technology operation, with a summary of their importance, are described in Table A-11.

Table A-11. Functional relationships governing the sediment passage technology operation. Adapted from Appendix C of Witt et al. (2017)

Relationship of	To	Rationale/importance
Bedload transport rate	1. Mean flow characteristics and patterns 2. Turbulent flow characteristics 3. Bed morphology 4. Critical bed shear stress for incipient motion	1. The main contributors to the bedload transport rate are the mean flow characteristics, which are quantified by the bed shear stress or stream power. 2. At near-incipient conditions, turbulence may increase the instantaneously applied shear stress to the sediment and lead to an increase in bedload rates and bedload intermittency. 3. Bedforms and/or other large roughness elements (e.g., boulders, large woody debris) bear a portion of the applied bed shear stress and reduce the bedload rates. 4. Sediment is transported as bedload because the applied bed shear stress by the flow exceeds the critical shear stress for incipient motion for a given sediment size.
Critical bed shear stress for incipient motion	Sediment characteristics	The critical shear stress for incipient motion depends on sediment size, size distribution (e.g., hiding effects), and the relative protrusion of the bed sediments.
Suspended sediment concentration	1. Mean flow characteristics and patterns 2. Turbulent flow characteristics 3. Supplied sediment 4. Settling velocity	1. The mean flow velocity is the main contributor to the transportation of suspended sediment downstream. 2. Turbulence causes diffusion and mixing of the transported sediment concentration. 3. The amount of sediment transported downstream in suspension depends on the amount of sediment supplied from upstream. 4. The sediment settling velocity quantifies the tendency of sediment to deposit or remain in suspension.
River morphological change	1. Bedload and suspended sediment transport capacity 2. Bank properties	1. The transport capacity of a river determines the amount of sediment that the river can transport for a given set of flow and sediment conditions. Imbalances between sediment transport capacity and supply result in aggradation or degradation of the river. 2. The type of material and geometry of the riverbanks determine how prone the river is to lateral migration and change in its planform geometry.

Measures of Performance: Sediment Passage Technology

Sediment passage measures of performance are presented in Table A-12 and are further described by Witt et al. (2017).

Table A-12. Measures of performance for sediment passage technologies. Adapted from Appendix C of Witt et al. (2017)

Measure	Status
Indices of Schmidt and Wilcock (2008)	Limits available—modeling needed
Indices of Grant et al. (2003)	Limits available—modeling needed
River width	Limits available
River topography	Limits available
Bedload transport rate	Limits available
Bed slope	Limits available
Grain size distribution	Limits available
River planform geometry	Limits available
Suspended sediment flux	Limits available

A.4 RECREATION PASSAGE TECHNOLOGY

The primary objective of recreation passage technologies is to allow the passage of small recreational craft consistently and safely through a facility (Witt et al. 2017). Recreation passage technologies must include favorable geometry and hydraulic conditions to enable safe transport of recreation craft across the facility . Recreation passage retrofit technologies at NPDs are described in Section 3.3.5. The following content describes the design objectives, necessary inputs, functional relationships, and measures of performance for recreation passage technology.

Recreation Passage Technology Primary Objective
To allow passage of small recreational craft consistently and safely through a facility

Design Objectives: Recreation Passage Technology

The following specific design objectives must be accomplished to achieve the primary objective. Figure A-4 visualizes these design objectives, and Table A-13 lists these design objectives (1, 2, etc.) and associated requirements and constraints (1a, 1b, etc.).

1. Operate within a known range of passage difficulty.
2. Provide a safe and visible entrance for recreational craft.
3. Allow recreational craft to safely cross the facility.
4. Allow recreational craft to exit safely into the river downstream.
5. Provide for emergency rescue personnel and apparatus.
6. Integrate structurally into the foundation system.

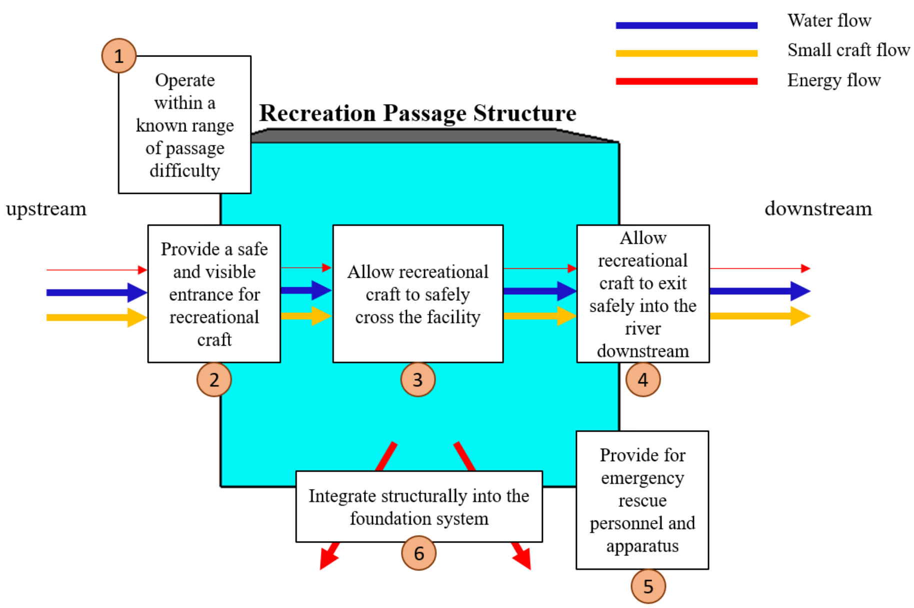

Figure A-4. Conceptual schematic of the design objectives of a recreation passage structure. Adapted from Witt et al. (2017)

Table A-13. Recreation passage technology design objectives. Adapted from Appendix D of Witt et al. (2017)

	Design objectives	
1	**Operate within a known range of passage difficulty**	
2	**Provide a safe and visible entrance for recreational craft**	
	2a	Exhibit consistent and smooth approach hydraulics
	2b	Provide for audible or visual warning signs identifying the passage entrance
	2c	Control inflow to acceptable levels
3	**Allow recreational craft to safely cross the facility**	
	3a	Exhibit consistent and smooth passage hydraulics
	3b	Optimize width
	3c	Optimize water velocity and depth through the passage structure
	3d	Provide nature-like features
	3e	Do not create a recirculating hydraulic jump under normal conditions
	3f	Limit the maximum hydraulic drop of individual drops
4	**Allow recreational craft to exit safely into the river downstream**	
	4a	Exhibit consistent and smooth exit hydraulics
	4b	Provide for a recovery pool
5	**Provide for emergency rescue personnel and apparatus**	
6	**Integrate structurally into the foundation system**	
	6a	Transmit all forces through noncritical components into the foundation
	6b	Minimize effects on the structural stability of existing infrastructure

Necessary Inputs: Recreation Passage Technology

Accomplishing the recreation passage technology design objectives relies on knowledge of necessary site inputs to inform design. These necessary inputs are outlined in Table A-14.

Table A-14. Necessary inputs for recreation passage technology design. Adapted from Appendix D of Witt et al. (2017)

Identification of key inputs	Rationale
Flow characteristics	The range of discharge available under normal conditions, inflow Froude number, and stage-discharge relationships for headwater and tailwater at a facility are all important variables used to inform the hydraulic design.
Head	The headwater and tailwater elevations under normal conditions and depth of flow are important to inform hydraulic design.
Site characteristics	The stream width, presence of boulders or other sharp or dangerous submerged structures, presence of eddies, design head of the facility, streambed elevation, and bed slope are important to inform site layout and design geometry.
Recreation vessel type	The type (e.g., canoe, kayak, raft), size, shape, weight, and depth of recreation vessel are important to inform design geometry.
Degree of difficulty	The intended use—whether kayak, canoe, or whitewater raft—and degree of passage difficulty are important to inform hydraulic design.
Characteristics of person on vessel	The weight, age, and experience of recreational craft operators are important when considering the overall recreation passage design.

Functional Relationships: Recreation Passage Technology

The functional relationships that govern recreation passage technology operation, with a summary of their importance, are described in Table A-15.

Table A-15. Functional relationships governing the recreation passage technology operation. Adapted from Appendix D of Witt et al. (2017)

Relationship of	To	Rationale/importance
Structural size, shape, number of drops, slope, and discharge	Type of hydraulic jump	A hydraulic jump occurs when high-velocity flow transitions to low-velocity flow. These conditions will be present at abrupt drops within the structure and at the point of discharge from the structure into the tailwater. Hydraulic jumps that maintain a positive downstream velocity at all times are desirable, whereas those that create recirculating rollers are not.
Range of discharges	1. Water velocity through structure 2. Water depth through structure 3. Regulation of water velocity and depth	The relationship between discharge and depth/velocity through the structure should be known to ensure the structure is passable under most flow conditions. If safe passage cannot be guaranteed, mechanical regulation of the inflow may be necessary, although this regulation may not prove economically feasible.
Gross head at site	Minimum structure length, gradient, and flow	Recreational craft require a safe gradient, which is accomplished using a single downstream sloping structure or a series of drops. A relationship predicting the length and gradient associated with each type based on the gross head at a site is necessary. The range of flow rates that can be sustained through the structure based on this gradient must be considered.
Size, velocity, and location of eddies around and in the structure	Travel path of recreational craft	Eddies dissipate turbulent kinetic energy, resulting in recirculation and swirling flows that could trap a small watercraft or a capsized paddler.
Exit hydraulics	1. Changes in downstream flow depth 2. Scour	A downstream depth that rises and falls during periods of variable discharge will have an effect on the exit hydraulics, within an area that is vulnerable to recirculating flow patterns. The flow exiting the structure may also result in some scour downstream. This relationship should be understood, and scour minimized.

Measures of Performance: Recreation Passage Technology

Recreation passage measures of performance are presented in Table A-16 and are further described in Witt et al. (2017).

Table A-16. Measures of performance for recreation passage technologies. Adapted from Appendix D of Witt et al. (2017)

Measure	Status
Passage difficulty	Limits available—more research needed
Hydraulic jump	Limits available—modeling needed
Viable range of flow	More research needed
Acceptable slope	More research needed
Cost of operation	More research needed

A.5 FOUNDATION TECHNOLOGY

The primary objective of foundation technologies is to anchor superstructure components to the streambed and banks (Witt et al. 2017). Additional information about foundation systems can be found from DeNeale et al. (2020). The following content describes the design objectives, necessary inputs, functional relationships, and measures of performance for foundation technology.

Recreation Passage Technology Primary Objective
To anchor superstructure components to the streambed and banks

Design Objectives– Recreation Passage Technology

The following specific design objectives must be accomplished to achieve the primary objective. Table A-17 lists these design objectives (1, 2, etc.) and associated requirements and constraints (1a, 1b, etc.).

1. Provide structural resistance against imposed loads.
2. Ensure stability of the superstructure.
3. Minimize the mechanical impacts of moving water and sediment on the streambed.
4. Integrate structurally into generation and passage structures.

Table A-17. Foundation technology design objectives. Adapted from Appendix F of Witt et al. (2017)

	Design objectives	
1	**Provide structural resistance against imposed loads**	
	1a	Resist maximum static loads from the superstructure
	1b	Resist the hydrostatic and hydrodynamic force of water, debris and sediments
	1c	Resist maximum dynamic environmental loads from extreme events (i.e., earthquakes and floods)
2	**Ensure stability of the superstructure**	
	2a	Maintain force and moment equilibrium without exceeding the limits of superstructure-to-foundation, or foundation-to-subsurface strength
	2b	Prevent seepage
	2c	Prevent uplift
	2d	Resist erosion or scour of the surrounding streambed
	2e	Prevent settling, subsidence, and downward migration of the superstructure
3	**Minimize the mechanical impacts of moving water and sediment on the streambed**	
	3a	Resist scour downstream
	3b	Resist deposition upstream
	3c	Prevent turbulent disruptions of the flow field
	3d	Minimize benthic habitat disturbance
4	**Integrate structurally into superstructure**	
	4a	Transmit all forces from superstructure into the subsurface
	4b	Minimize effects on the structural stability of existing infrastructure

Necessary Inputs: Foundation Technology

Accomplishing the foundation technology design objectives relies on knowledge of necessary site inputs to inform design. These necessary inputs are outlined in Table A-18.

Table A-18. Necessary inputs for foundation technology design. Adapted from Appendix F of Witt et al. (2017)

Identification of key inputs	Rationale
Flow variables	The range of flow rates, average hydraulic head, water depth, velocity, turbulence parameters, friction factor, watershed hydrologic characteristics, flood frequency and magnitude, and inflow design flood are all important variables used to inform foundation design.
Head	The average hydraulic head and hydraulic head at flood conditions are important to inform foundation design.
Superstructure loads	The envelope of loads (static and dynamic) resulting from normal operation of the superstructure systems is an important input for foundation design.
Geomorphologic variables	The riverbed slope, bed topography, friction factor, channel sinuosity, substrates, soil type, depth to bedrock, structure of strata (strength, thickness, inclination, fracturing, porosity, gradation, angularity, shape, moisture, shear strength, and permeability) are used to inform foundation design and treatment requirements.
Sediment characteristic variables	The sediment grain size distribution (e.g., median grain diameter, geometric standard deviation), friction factor, sediment fall velocity, sediment angularity, sediment shape, and relative protrusion are important design variables.
Stream cross sectional area	The stream's bottom width, wetted perimeter, depth, and side slope are important to inform foundation system geometry and design.
Location of potential failure planes	The most vulnerable areas where imposed loads will cause failure is important for informing foundation design and treatment.
Externally imposed force variables	The expected magnitude of hydrostatic forces, hydrodynamic force, and earth and silt forces, is important for informing failure mode identification and foundation design.
Superstructure dimensions	The superstructure dimensions are important for informing the foundation system dimensions.
Foundation construction material	The density, strength, stiffness, porosity, permeability, and erodibility of foundation material are important for engineering design of the foundation design.
Foundation anchor design	The anchoring material properties, dimensions, and installation method are important for informing foundation design.

Functional Relationships: Foundation Technology

The functional relationships that govern foundation technology operation, with a summary of their importance, are described in Table A-19.

Table A-19. Functional relationships governing the foundation technology operation. Adapted from Appendix F of Witt et al. (2017)

Relationship of	To	Rationale/importance
Static and dynamic loading of the foundation system	Bearing pressure and mechanical properties of the soil and subsurface	The bearing pressure of the subsurface is related to the geology, bed material, topography, and bathymetry, with consideration of their evolution throughout the life of the project. These features must be identified and classified for the most common deployment scenarios, emphasizing both streambeds and stream banks, to determine viable foundation designs.
Static and dynamic loading of the FM	Strength of foundation module materials	The deformation, displacement, vibration, compression, and material failure characteristics of the foundation system material must be understood with respect to the envelope of static and dynamic loads to be encountered. A relationship predicting the shear friction within the foundation and at the foundation interface with the subsurface and superstructure is necessary.
Module designs	1. Undercutting 2. Uplift 3. Sliding 4. Overturning 5. Benthic habitat disturbance 6. Scour and deposition of sediments 7. Erosion of the FM	1. Effective design of the foundation system may prevent undercutting. 2. Effective design of the foundation (e.g., the use of proper drain system) may prevent uplift. 3. Effective design of the foundation system will minimize the excessive shear stresses caused by dead and live loads. 4. Effective design of the foundation system will prevent overturning. 5. The footprint of the foundation system design may determine the degree of benthic habitat disturbance. 6. Effective design of the foundation system may prevent excessive scour and deposition of sediments around the structure. 7. Effective design of the foundation system may prevent the erosion of the structure.
Flow depth upstream of facility and foundation material composition	Seepage potential	Seepage under the foundation system and subsurface erosion must be considered a possibility at all sites. The use of new and innovative foundation methods and materials will require new relationships to identify seepage potential and the best means to incorporate seepage mitigation measures into the foundation system design.
Generation and passage module flow energy	Energy dissipation requirements	The energy carried by water flow out of the generation and passage structures may require dissipation by the foundation system to reduce the possibility of scour past the downstream end of the foundation system.

Measures of Performance: Foundation Technology

Foundation technology measures of performance are presented in Table A-20 and are further described by Witt et al. (2017).

Table A-20. Measures of performance for foundation technologies. Adapted from Appendix F of Witt et al. (2017)

Measure	Status
Stability against sliding	More research and modeling/testing needed
Strength of foundation module materials	More research and modeling/testing needed
Scalability	More research needed
Size	More research needed—minimize instream and subsurface volume
Cost	More research needed
Environmental disturbance	More research needed—deposition and scour minimized

APPENDIX B. CASE STUDIES FOR RECENT NPD DEVELOPMENT

This appendix describes three example NPD retrofits to provide context for how NPDs have been developed in the past. These examples were selected to represent a variety of capacities, dam types, and development pathways. Hanover Pond Dam represents a small, low-head project built around an existing previously powered NPD. The Meldahl project represents a large retrofit installed through an existing lock and dam. The Jordanelle Dam retrofit represents a medium sized project constructed using an existing conduit built for the purpose of future hydropower additions. A brief history and a summary of the important design decisions are provided for each project in the sections below. Information was gathered from FERC licenses and online project descriptions.

B.1 HANOVER POND DAM

The original Hanover Pond Dam was a timber-crib dam on the Quinnipiac River in Connecticut, created in 1855 to provide mechanical power to the Meriden Cutlery Factory. The dam was demolished in the 1930s when the factory was also demolished. In 2005, the dam was reconstructed by the City of Meriden as a concrete and earth dam with a Denil fishway (Figure B-1). The dam is 25 ft tall and 397 ft wide and has several ogee spillways and one broad crest spillway that create a 71 ac/1,800 ac-ft impoundment. In 2015, New England Hydropower Company applied for a license to build a 220 kW hydropower facility at the existing dam. Because the planned capacity was less than 10 MW, New England Hydropower Company was able to obtain a license exemption from FERC. The project became operational in 2017.

The Hanover Pond Dam project was the first implementation of an Archimedes screw turbine for hydropower. These turbines benefit from being fish friendly and applicable to low-head sites. The turbine was retrofitted by excavating around the dam into the earth embankment. A new intake, a 78 ft long and 12 ft wide concrete penstock channel, a brick and concrete powerhouse, a 15 ft concrete tailrace, a steel and concrete turbine bay, a boulder lined fish passage channel, a 35 kV transmission line, an automatic control system, and other appurtenant facilities were also included in the retrofit. The facility operates as run-of-river with a minimum flow of 30 cfs and produces approximately 900 MWh annually. Several other environmental studies and mitigation measures were implemented, including mussel surveys, water quality monitoring, invasive species monitoring and control, and fish passage studies. The Hanover Pond Dam project exemplifies small, low-head NPD retrofits, which will likely use fish-friendly low-head turbines, such as the Archimedes screw turbine.

Figure B-1. Aerial imagery of Hanover Pond Dam. Imagery from Google Maps.

Sources:

1. https://lowimpacthydro.org/lihi-certificate-165-hanover-pond-dam-hydroelectric-project-connecticut/

2. Hanover Environmental Assessment – Available in the FERC E-Library (https://elibrary.ferc.gov/eLibrary/search) under Project No. 14550-001 – CT, released on May 19, 2016.

B.2 MELDAHL LOCK AND DAM

Captain Anthony Meldahl Lock and Dam is located on the Ohio River in Kentucky; it first entered operation in 1965 for the purposes of navigation and recreation (Figure B-2). The facility originally consisted of a 1,384 ft wide concrete spillway, a 1,200 ft long by 110 ft wide main lock, a 600 ft long by 110 ft wide auxiliary lock, and a 310 ft wide concrete overflow weir (total width of 2,015 ft). The lock and dam is owned and operated by the US Army Corps of Engineers. The city of Hamilton, Ohio applied for a license to build a 105 MW hydropower plant at the facility in 2006 and was granted the license in 2008 using the Integrated Licensing Process. Meldahl is one of several large NPDs on the Ohio River that was retrofitted to produce power (others include Cannelton, Willow Island, and Smithland). These projects are locally owned by members of American Municipal Power Inc., which is a nonprofit that owns and operates electric facilities for its members. The Meldahl hydropower plant came online in 2016.

The powerhouse and requisite conveyances were built through a portion of the original concrete overflow weir on the opposite side of the locks. Two-thirds of the overflow weir was demolished, and an intake and approach channel was built to direct flow from the headwater through a powerhouse with three horizontal bulb-type turbines and then downstream through a tailrace channel. Trash racks and a 5 mi 138 kV transmission line were also constructed. Numerous environmental studies and mitigation measures were implemented, including run-of-river operation, sediment control plans, water quality monitoring, and fish entrainment studies. On average, the facility produces 558,000 MWh annually.

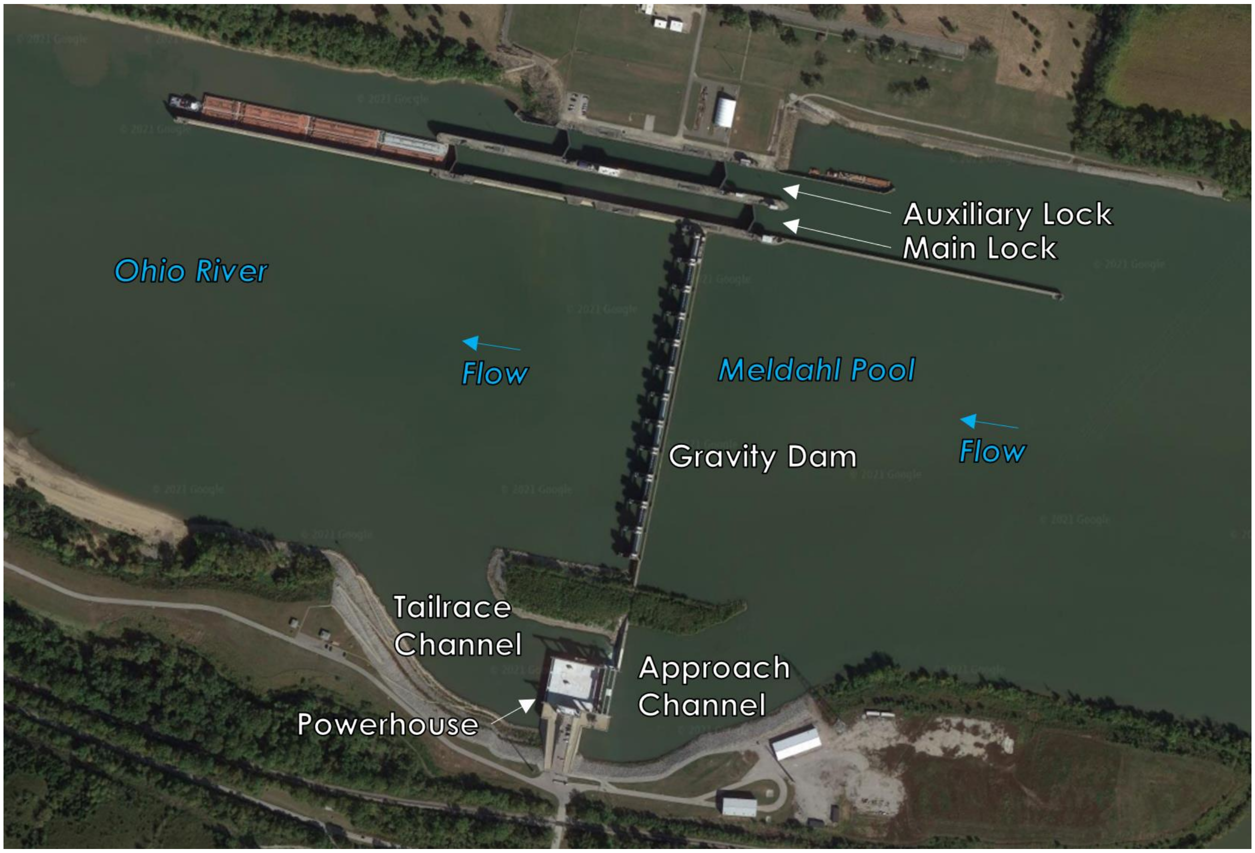

Figure B-2. Aerial imagery of Meldahl Lock and Dam. Imagery from Google Earth.

Sources:

1. https://www.journal-news.com/news/hamilton-hydroelectric-power-plant-ohio-river-largest-nears-completion/MZEwijYqTMIf0ehxn1jwhK/

2. https://www.amppartners.org/generation/hydro/meldahl-hydro-project

3. https://alberici.com/projects/meldahl-hydroelectric-project/

4. Meldahl Environmental Assessment – Available in the FERC E-Library (https://elibrary.ferc.gov/eLibrary/search) under Project No. 12667-003, released on April 25, 2008.

B.3 JORDANELLE DAM

Jordanelle Dam was built by the USBR in 1993 on the Provo River in Utah for the purpose of maintaining local water supply (Figure B-3). The original dams consisted of a 3,820 ft wide and 391 ft tall rolled-earth dam with a fuse plug emergency spillway and outlet works. The dam enables approximately 363,000 ac-ft of water storage, which is allocated to irrigation, municipal, and industrial water supply needs. The original dam was built with the intent to install hydropower in the future by connecting a penstock to the existing outlet works. Although, the dam is owned by the USBR, it is operated by the Central Utah Water Conservancy District which was created to manage water distribution under the Central Utah Project. The Central Utah Water Conservancy District applied for a license to develop hydropower at Jordanelle dam via a Lease of Power Purchase, which allows nonfederal organizations to use federal infrastructure for power production as long as federal purposes are not interrupted. The 13 MW powerhouse became operational in 2008.

The retrofit consisted of a concrete powerhouse at the toe of the dam, two horizontal Francis units, a 150 ft long and 84 inch diameter bifurcated steel penstock, and other requisite control and transmission equipment. The penstock was attached to an existing connection in outlet works. The plant is operated as store and release according to the USBR's water supply obligations and produces about 39,000 MWh annually. Although the plant is not regulated by FERC, the project maintained similar environmental standards and conducted wildlife, fishery, and water quality studies along with the requisite mitigation measures as a part of the environmental assessment.

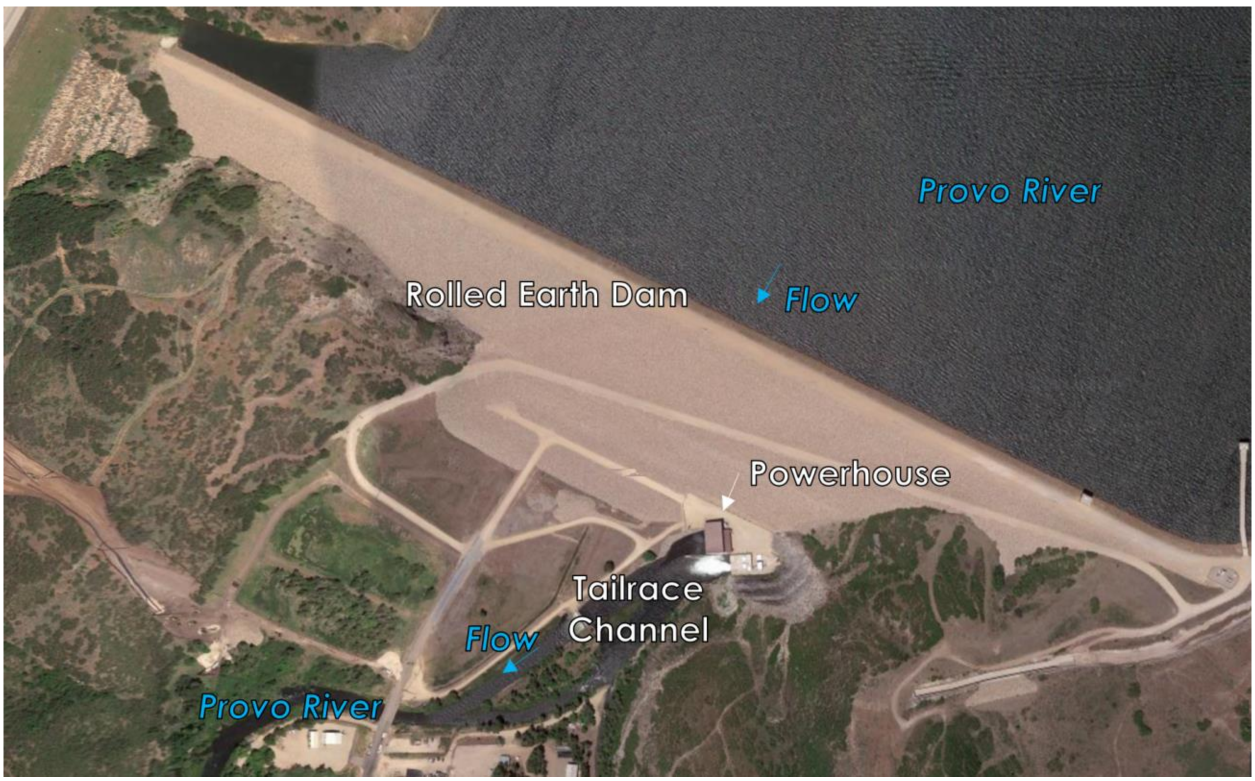

Figure B-3. Aerial imagery of Jordanelle Dam. Imagery from Google Maps.

Sources:

1. https://www.renewableenergyworld.com/storage/jordanelle-developing-new-hydro-at-an-existing-dam/#gref

2. https://www.hydroreview.com/world-regions/adding-hydro-at-existing-dams-project-profiles/#gref

3. https://lowimpacthydro.org/lihi-certificate-29-jordanelle-hydroelectric-project-utah/