ORNL/TM-2021/2155

Non-Powered Dam Custom Analysis and Taxonomy Framework

Carly Hansen
Colin Sasthav
Mirko Musa
Scott DeNeale

**Approved for public release.
Distribution is unlimited.**

March 2022

ORNL IS MANAGED BY UT-BATTELLE LLC FOR THE US DEPARTMENT OF ENERGY

Cover credits: (Clockwise) Images courtesy of Mirko Musa (St. Anthony Falls, Mississippi River, MN); Carly Hansen (Lake Delton, Wisconsin River, WI); and Scott DeNeale (Byrd Creek Dam, Crossville, TN)

ORNL/TM-2021/2155

Environmental Sciences Division

NON-POWERED DAM CUSTOM ANALYSIS AND TAXONOMY FRAMEWORK

Carly Hansen
Colin Sasthav
Mirko Musa
Scott DeNeale

March 2022

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831-6283
managed by
UT-BATTELLE, LLC
for the
US DEPARTMENT OF ENERGY
Contract DE-AC05-00OR22725

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

ASCE	American Society of Civil Engineers
CONUS	contiguous United States
DOE	US Department of Energy
EPA	US Environmental Protection Agency
EROM	Enhanced Runoff Method
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
GIS	geographic information system
HIFLD	Homeland Infrastructure Foundation-Level Data
ICOLD	International Commission on Large Dams
IKSO	International Society of Knowledge Organization
NHDPlusV2	National Hydrography Dataset
NID	National Inventory of Dams
NLCD	National Land Cover Database
NPD	non-powered dam
NPDamCAT	non-powered dam custom analysis and taxonomy
NWIS	National Water Information System
NWS	National Weather Service
ORNL	Oak Ridge National Laboratory
PM&E	protection, mitigation, and enhancement
RISE	Reclamation Information Sharing Environment
SARP	Southeast Aquatic Resource Partnership
SMH	standard modular hydropower
US	United States
USACE	US Army Corps of Engineers
USBR	US Bureau of Reclamation
USEPA	United States Environmental Protection Agency
USFWS	US Fish and Wildlife Service
USGS	United States Geological Survey
WPTO	Water Power Technologies Office

KEY TERMS

Characteristic: a feature or quality used to identify or describe something.

Classify: to divide things into groups according to a defined characteristic.

Class or category: a group into which something is divided according to a defined characteristic.

Clustering: the process of grouping things based on similar characteristics, typically via statistical analysis (e.g., k-means clustering).

Dam: an artificial barrier that has the ability to impound water, wastewater, or any liquid-borne material, for the purpose of storage or control (FEMA 2004b).

Greenfield development: new hydropower developments along previously undeveloped waterways (DOE 2016).

Hydropower or hydroelectric power: electricity generated by converting the potential energy of water into mechanical energy.

Non-powered dam: dams that do not have any electricity generation equipment installed (DOE 2021) or were previously equipped to generate power (mechanical or electrical), but are no longer operational.

Taxonomy: the science or technique of classification.

Value: numerical or categorical information. For example, the characteristic of age for a particular dam has a numerical value, measured in years while the characteristic of federal regulatory authority is categorical and have a value of the name of a federal agency.

Variable: the quantitative or qualitative measure used to describe a characteristic. For example, the characteristic of size could be described by several variables, such as height, length, surface area, and volume.

ACKNOWLEDGMENTS

US Department of Energy, Water Power Technologies Office

The authors would like to acknowledge and express their appreciation to the US Department of Energy (DOE) Water Power Technologies Office (WPTO) for overseeing and funding this effort to develop a framework for classifying, analyzing, and building taxonomies of non-powered dams. The following DOE WPTO staff were heavily involved in reviewing this report and supporting this study.

- Marisol Bonnet
- Kathryn Jackson
- Kyle DeSomber
- Tim Welch
- Jennifer Garson

Oak Ridge National Laboratory

The following individuals from DOE's Oak Ridge National Laboratory provided technical review and support for this report:

- Jenberu Feyyisa
- Brennan Smith

Technical Reviewers

The following individuals provided additional, thorough technical reviews of this report. The listing of reviewers here does not imply their agreement with all findings of the report.

- Bo Saulsbury
- Greg Baecher

EXECUTIVE SUMMARY

Key takeaways of the Non-Powered Dam Custom Analysis and Taxonomy (NPDamCAT) Framework report:

- There are a variety of opportunities for non-powered dams (NPDs): retrofit, rehabilitation, and removal. NPD stakeholders involved in these opportunities and broader NPD interests are diverse.
- NPDamCAT defines a 5-step framework that can be used to develop customized classes of NPDs based on unique needs of individual stakeholders.
- A wide variety of information is needed to describe the full range of characteristics of NPD systems, including operational requirements, social, economic, and environmental conditions, and the range of temporal scales relevant to characteristics and processes within NPDs.

Over 85,000 non-powered dams (NPDs) exist in the United States that provide services such as flood control, navigation, and water storage for irrigation/domestic water use (USACE 2019). The existing infrastructure of NPDs poses an opportunity for improving economic and environmental performance and generating electricity, as well as a challenge for maintaining aging structures and remediating fragmented river systems. NPD stakeholders interested in the rehabilitation, retrofit, or removal of NPDs must have the relevant information about the population of dams to support decision-making. Each NPD has unique characteristics describing its design, operation, environmental impacts, social impacts, and economic potential. The large number of dams, the diversity of interests related to dams, the variety of dam characteristics, and the types of data required to describe dams all pose major challenges to an analysis of the entire dam population.

A Non-Powered Dam Custom Analysis and Taxonomy (NPDamCAT) framework is proposed to address these challenges and help categorize dams in ways that can be tailored to various stakeholder interests. NPDamCAT outlines 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.

NPDamCAT results in customized taxonomies in which dams can be classified and then analyzed according to an individual stakeholder’s needs. These taxonomies can be used to support a wide range of analyses, including identifying sites for rehabilitation, retrofit (including adding hydropower capabilities), or removal, as well as summarizing characteristics of NPDs relevant to understanding their environmental or socioeconomic impacts. Applying available information to the taxonomical structure can also help identify gaps in the available data. The NPDamCAT framework lays the conceptual foundations upon which interactive web-based tools can be built.

The NPDamCAT framework extends beyond previous classification efforts by drawing on a broad suite of NPD-related data from a variety of sources rather than using only the information contained in a single inventory or infrastructure data set. Most notably, NPDamCAT is designed to create classes of dams according to stakeholder objectives rather than being limited to a few characteristics that might be irrelevant to a stakeholder's objectives or decision-making process.

The process of gathering inputs (i.e., synthesizing data from a variety of data sources) to support NPDamCAT implementation has already highlighted gaps in current data (i.e., characteristics that are not supported on a large scale by existing, publicly available resources) and identified major research needs (e.g., representing uncertainty in dam characteristics). Defining the NPDamCAT framework is a key first step toward enabling more tailored and robust analyses of NPDs and is foundational for guiding the future development of tools. Web-based tools that implement NPDamCAT will put individual stakeholders in control to conveniently work with and gain insights from NPD data.

This report describes the 5-step NPDamCAT framework for developing customized taxonomies of NPDs and concludes that a flexible approach to classification responds to the complexity of NPD systems and variety of characteristics that are relevant to different NPD stakeholders. Ultimately, the NPDamCAT framework enables and supports analysis and decision-making related to NPDs by creating more convenient and workable groups of dams which an individual can use to understand variability among subgroups, create generalize descriptions of subsets, or select representative dams for more detailed analysis. Major data needs include addressing uncertainty or variability in characteristics and inventorying those characteristics that are relevant to objectives spanning multiple stakeholders' interests but are not yet referenced through publicly available data sets. Finally, there are further opportunities to extend infrastructure classification research beyond what is outlined in this report; the NPDamCAT framework may be adapted to apply to other methods of classification (i.e., statistical approaches) which can support specific objectives.

1. INTRODUCTION

Non-powered dams (NPDs) represent a specific category of dams defined as "dams that do not have any electricity generation equipment installed" (DOE 2021). This may include dams that were previously equipped to generate mechanical or electrical power but are no longer operational. Although they do not provide power services, NPDs represent valuable, critical infrastructure throughout the United States. Dams may be implemented individually or in concert with multiple dams, auxiliary storage infrastructure, or control infrastructure. The storage or control functionality provided by NPDs provides benefits such as irrigation, flood control, drought mitigation, navigation, water supply, and recreation (Bonnet et al. 2015).

The current public version of the US National Inventory of Dams (NID) reports over 85,000 main dams and supporting structures that do not include hydropower as a purpose (USACE 2019). These dams represent a heterogeneous mix of sizes, construction materials, locations, and environmental conditions. To make informed decisions related to NPD opportunities (i.e., removal, retrofit, or rehabilitation) on large scales and to better understand how NPDs interact with socioeconomic, water, and energy systems, stakeholders need data and tools beyond those that are currently available. This report describes a framework for classification, which enables those interested in the population of dams (or large subsets) to find similarities, evaluate diversity, and gain context that cannot be learned by analyzing dams individually.

This report describes the available data, the principles of NPDamCAT, and a possible path forward for implementing the framework. The report is organized in the following sections:

- **Section 1 Introduction:** Describes previous and ongoing efforts to understand opportunities related to NPDs and details major objectives, scope, and expected outcomes of the report.
- **Section 2 Background:** Provides background knowledge about NPD systems, the stakeholders interested in NPDs, and how NPDs have been classified in the past.
- **Section 3 Custom Analysis and Taxonomy Framework:** Describes the philosophy of the NPD Custom Analysis and Taxonomy and rationale for the framework structure. Additionally, this section uses an example implementation of NPDamCAT to illustrate how NPDamCAT may be applied in practice.
- **Section 4 Research Applications and Extensions:** Describes potential applications and implementation of the NPDamCAT within web-based applications. The section also discusses data gaps, and future research opportunities to highlight how readers and stakeholders may be able to implement and improve the NPD classification process.
- **Section 5 Summary:** Summarizes major findings of the report.
- **Section 6 References:** Provides a list of references.
- **Appendix:** Describes data sources currently identified and used to support development of tools that implement the NPDamCAT framework

1.1 RESEARCH CONTEXT

Retrofit, rehabilitation, and removal are opportunities related to NPDs in which diverse sets of information are used to make decisions about the opportunities that are most suitable for various NPDs. The ongoing Uncommon Dialogue initiative—led by the Stanford Woods Institute for the Environment, Stanford's Steyer-Taylor Center for Energy Policy and Finance, and the Energy Futures Initiative—demonstrates the diversity of groups that are interested in dams, NPD development, river management, and environmental restoration. This effort to bring various stakeholders to the table yielded a joint agreement in which members of the hydropower development, environmental protection, and conservation communities identified areas for collaboration ("Joint Statement of Collaboration on U.S. Hydropower: Climate Solution and Conservation Challenge" 2020). This document highlights the need to better evaluate these retrofit, rehabilitation, and removal opportunities for dams as the various parties involved work together to address the challenges of decarbonizing the energy system and reducing the environmental impacts of dams. The signatories of the Joint Statement[1] represent a subset of stakeholder groups that could benefit from a framework that can be used to classify NPDs. A more comprehensive listing of entities benefitting from this effort may be found in Section 2.1.2.

Interest in dam classification builds on several major efforts to better identify opportunities at NPDs. In 2012, the US Department of Energy's Oak Ridge National Laboratory (ORNL) conducted a resource assessment that analyzed more than 54,000 NPDs across the contiguous United States (CONUS) and reported an estimated total potential capacity of 12 GW and annual generation of 45 TWh (Hadjerioua, Wei, and Kao 2012). The reported NPD development potential corresponds to approximately 15% of the current total hydropower capacity. Other assessments have explored NPD development potential by using a variety of methods and levels of detail (Hansen et al. 2021).

Compared with greenfield hydropower development, adding generation capabilities to NPDs generally assumes "that many of the costs and environmental impacts of dam construction have already been incurred at NPDs and may not be significantly increased by the incorporation of new energy production facilities" (Hadjerioua, Wei, and Kao 2012). ORNL conducted a recent cost analysis that found that adopting near-term technological innovations could reduce the baseline costs for hydropower retrofit projects at NPDs (Oladosu, George, and Wells 2021), reducing capital costs per kilowatt and slightly increasing the capacity factor, thus reducing the levelized cost of energy. Advantages of retrofitting NPDs include reduced capital costs (which already were incurred during dam construction and reservoir formation) and fewer new impacts from flow and ecosystem alteration. Additionally, (Prairie et al. 2017). Thus, hydropower development at NPDs is considered a relatively attractive form of power development from a cost and environmental consequence perspective.

Since the assessment of NPD development potential (Hadjerioua, Wei, and Kao 2012) was published, several NPDs have been retrofitted and are now producing hydropower. Still, significant opportunity exists for capacity growth. Between 2010 and 2019, hydropower was added to 35 NPDs in the United States, yielding 445 MW of new, operational hydropower capacity (Uria-Martinez, Johnson, and Rui 2021; Uría-Martínez, Johnson, and Shan 2021). Additionally, the 2021 Hydropower Pipeline Database (Johnson and Uría-Martínez 2021) details 80 NPD projects in the US hydropower development pipeline, representing 88.8% of the total 0.86 GW proposed capacity additions (not including upgrades to existing plants). The remaining capacity comes from conduit projects (4.8%) and installations at previously undeveloped sites (6.4%). Specifically, 95% of these NPD pipeline projects are concentrated in the Northeast, Midwest, and Southeast regions, which is where most NPD resources are, for a total proposed capacity of approximately 0.73 GW. Most (70%) of the projects in the pipeline of all hydropower types are being pursued by private developers (i.e., nonfederal, nonutilities); this percentage is even greater for NPDs for which private developers proposed 94% of the projects. Although NPD projects are commonly

[1] Signatories include American Rivers, World Wildlife Fund, Union of Concerned Scientists, Great River Hydro, American Whitewater, Natel Energy, National Hydropower Association, Eagle Creek Renewables, Low Impact Hydropower Institute, Rye Development, Hydropower Reform Coalition, and Hydropower Foundation. Conveners of the Joint Statement of Collaboration include Stanford Woods Institute for the Environment, Steyer-Taylor Center for Energy Policy and Finance, and Energy Futures Initiatives.

proposed by private developers, most (69%) of the project dams are owned by federal agencies (e.g., US Bureau of Reclamation [USBR] or US Army Corps of Engineers [USACE]), and another 21% are owned by state agencies. Besides ownership, active and prospective NPD developments vary widely across a spectrum of scale, generation potential, feasibility, and existing operational purpose.

Rehabilitation is another alternative for NPDs. This option may include environmental protection, mitigation, and enhancement (PM&E) measures to improve environmental, economic, and socioeconomic conditions near NPDs. Examples of PM&E measures include the addition of fishways, establishment of sediment control plans, operational changes, investment in recreational resources, water quality monitoring, and many others. In some cases, rehabilitation occurs in tandem with hydropower development, often to mitigate the costs. A review of Federal Energy Regulatory Commission (FERC) licenses found that from the 57 NPD retrofit projects identified between 1996 and 2018, there were 1,455 PM&E measures (Oladosu et al. 2021). Safety is a major concern for stakeholders and can be a motivation for rehabilitation because most dams are over 50 years old, and age is a primary driver of dam failure (DeNeale et al. 2019). According to the *2017 Infrastructure Report Card* (ASCE 2017), the average age of dams in the United States is 56 years, which means that dams may be approaching their design lifespan. Mitigation and prevention are paramount considering that dam failures can lead to fatalities and major economic losses. Nonetheless, the rehabilitation of all US dams is expected to cost upward of $64 billion, so stakeholders must prioritize dams with the highest risk of failure and the highest cost of damages (DeNeale et al. 2019). Additionally, many original designs did not account for changing climate conditions; therefore, some of these designs are outdated. As the population of dams continues to age and conditions change, rehabilitation will be needed to prevent dam failure.

Dam removal activities have increased in the last two decades with over 1,300 removals in the United States (Foley et al. 2017). Dam removals are typically expensive projects with little to no source of revenue, so stakeholders must carefully select the dams whose removal will provide significant ecosystem benefits without considerable costs. So far, removal efforts have been focused on small dams; about 94% of removals consist of dams with heights less than 10 m (Foley et al. 2017). Additionally, it is not always possible for dammed streams to return to uncontrolled conditions; the ability to recover is likely based on a variety of characteristics, including dam size, accumulated sediment characteristics, and local species characteristics. Some entities have developed metrics and tools to help evaluate benefits of dam removal or remediation. For example, the Southeast Aquatic Resource Partnership (SARP) created a web-based app that prioritizes these opportunities and focuses on ecological benefits for aquatic barriers, including dams and road crossings, in the Southeast United States (SARP 2021).

The following sections describe specific entities who are interested in evaluating these opportunities at NPDs, as well as those interested in understanding and mitigating the impacts of NPD systems. The NPD Custom Analysis and Taxonomy (NPDamCAT) framework is proposed as a way to continue building on past research in this space and working with complex NPD-related data. This framework will extend and augment previous research efforts by simplifying analysis and providing an understanding of large-scale infrastructure needs.

1.2 RESEARCH OBJECTIVE

Although motivation is growing to extend research and support decisions to retrofit, rehabilitate, or remove NPDs, several challenges must be addressed. Among these challenges is a lack of documentation of the range, breadth, and variability of characteristics of the NPD population. Retrofit, rehabilitation, and removal opportunities at NPDs are often influenced directly or indirectly by multiple characteristics, requiring alignment with specific dam purposes and functionalities, as well as operational, engineering, environmental, and socioeconomic considerations. Analyzing each dam individually is inefficient from a data collection or processing perspective, and context would be limited if the individual dam could not be compared with the dam population. Conversely, an analysis of all dams as a single population would fail to capture variations in characteristics and conditions. Classifying the entire population of NPDs reduces what would otherwise be an overwhelming number of assets with an unknown spread of characteristics into more digestible information that can be used to support decision-making related to NPD opportunities and development, regulatory policies, or technological innovations.

NPDamCAT is proposed to provide a methodology for classifying NPDs. This characterization will enable classification for the entire population of NPDs into meaningful subsets based on shared or similar characteristics. NPDamCAT extends previous categorizations and classifications applied to dams by:

- Allowing for organizational structures that are relevant to development decisions; and
- Informing development decisions specific to stakeholders.

Taxonomies provide a top-down structure to data using a series of classifications. Typically, these classifications are ordered from most important to least important and create a tree-like hierarchy in which groups are systematically subdivided into smaller groups. However, the importance of a particular characteristic depends on the stakeholder's objective, so a single NPD taxonomy will not suit the needs of all stakeholders. NPDamCAT's flexible approach to taxonomy design allows each stakeholder to customize the series of classifications and create effective organizational structures for their needs. This framework provides the conceptual foundation for stakeholder-driven classification and compiles the multidimensional data and tools to support more efficient data analysis and decision-making.

1.3 SCOPE OF RESEARCH AND REPORT

This classification effort is focused on NPDs within the United States. However, data availability is an important consideration because many publicly available data sets are limited to the continental United States (i.e., do not include Alaska or Hawaii). Although this effort attempts to maintain consistency by using only data that follow the same data collection and quality standards across the entire region of interest, exceptions may occur when state or regional data sets are used, particularly for Alaska and Hawaii.

1.4 EXPECTED OUTCOMES

The long-term vision of these efforts is to support diverse NPD analyses via classification. Support includes: (1) sustained efforts to gather and process data sets; (2) the development of web-based geospatial tools that display data and enable exploration; and (3) tools that facilitate the process of classification based on the organizational scheme presented. This support will help stakeholders better understand NPD-related opportunities and make better informed decisions related to NPDs. The information presented in this report may also help prioritize future research and development activities related to NPD operations, management, safety, and hydropower development.

Research objective, scope, and expected outcomes

- **Objective**: Create a framework for organizing and characterizing NPDs according to the diverse needs and objectives of NPD stakeholders.
- **Scope**: Non-powered dams within the United States; publicly available data describing a significant proportion of the dam population.
- **Expected outcomes**: Enable more efficient exploration of NPD data and more effective outcomes for stakeholders interested in evaluating retrofit, rehabilitation, and removal opportunities and challenges associated with NPDs.

2. BACKGROUND

2.1 BACKGROUND ON NON-POWERED DAMS

The Federal Emergency Management Agency (FEMA) defines a dam as "an artificial barrier that has the ability to impound water, wastewater, or any liquid-borne material, for the purpose of storage or control of water" (FEMA 2004b). Dams can be built for purposes other than water storage and in variable environmental and physical settings. Despite the unique nature of each NPD, a standard vocabulary for describing NPD systems is proposed in Section 2.1.1, and a categorization of NPD stakeholders is proposed in Section 2.1.2.

2.1.1 Generalized Description of NPD Systems

NPDs generally consist of the following basic features:

- **Barrier Structure:** The main barrier structure must contain a foundation, which encompasses all the engineered structural features and ground treatments designed to provide structural stability and support, as well as to minimize water seepage (DeNeale et al. 2020).
- **Impounded Water:** Impounded water may range from a river channel to a large reservoir; in any case, hydraulic head between the surface of the impounded water and the surface of the water at the outlet is increased by the barrier.
- **Water Conveyance Features:** These features may be present in one or more forms, including spillways and other outlet works that allow water to bypass over, through, or around the dam. Spillways are typically located at the crest of the dam and release water downstream or into a side channel. Spillways are controlled or noncontrolled, depending on whether a gate is present, and may set the level of the reservoir. The water conveyance can be equipped with trash racks to prevent debris from flowing into intakes. Side channels may convey water for irrigation, water supply, or flood control.
- **Outlet Works**: These are hydraulic features that regulate water release and can be classified according to purpose, design, and operation (USBR 1987). They are typically conduits or channels that pass through or around a dam and can be gated or ungated. Outlets built in the lower level of the dam are closed conduits operating under pressure and can be used to empty the reservoir for maintenance. These low-level outlets are sometimes referred to as sluiceway gates.

Some dams may be accompanied by locks, which are large, gated channels, typically placed on one side of the dam and parallel to the river axis, that allow for navigability by adjusting the water level between upstream and downstream.

NPDs are linked to the surrounding environment through interactions with the river flow, the watershed, and its natural processes. By impounding water and regulating the natural flow, NPDs locally affect the site where they are developed and, on a larger scale, the entire watershed through the river reach (Figure 1). Water flow is altered by the dam, but so too is sediment continuity and the migration of aquatic organisms. These local perturbations of the natural conditions eventually lead to environmental effects, such as the geomorphological alteration of the river (Brandt 2000; Petts and Gurnell 2005), changes in ecosystems and biodiversity (Ziv et al. 2012; Winemiller et al. 2016; Lees et al. 2016) and water quality (Lessard and Hayes 2003; Bednarek and Hart 2005). Depending on the river's conditions, these environmental effects can evolve across spatial and temporal scales. For instance, sediment blockage can locally change the downstream reach cross section while nonlocally causing coastline retraction (Vörösmarty et al. 2003; Schmidt and Wilcock 2008; Kondolf et al. 2014). Conversely, the surrounding environment influences the design and operation of the NPD (e.g., precipitation and groundwater from the watershed drains into the river network and results in the flow which ultimately arrives at the facility) because the quantity of flow and its temporal patterns are determined by the watershed hydrology, climate, seasonality, and physical characteristics of the watershed.

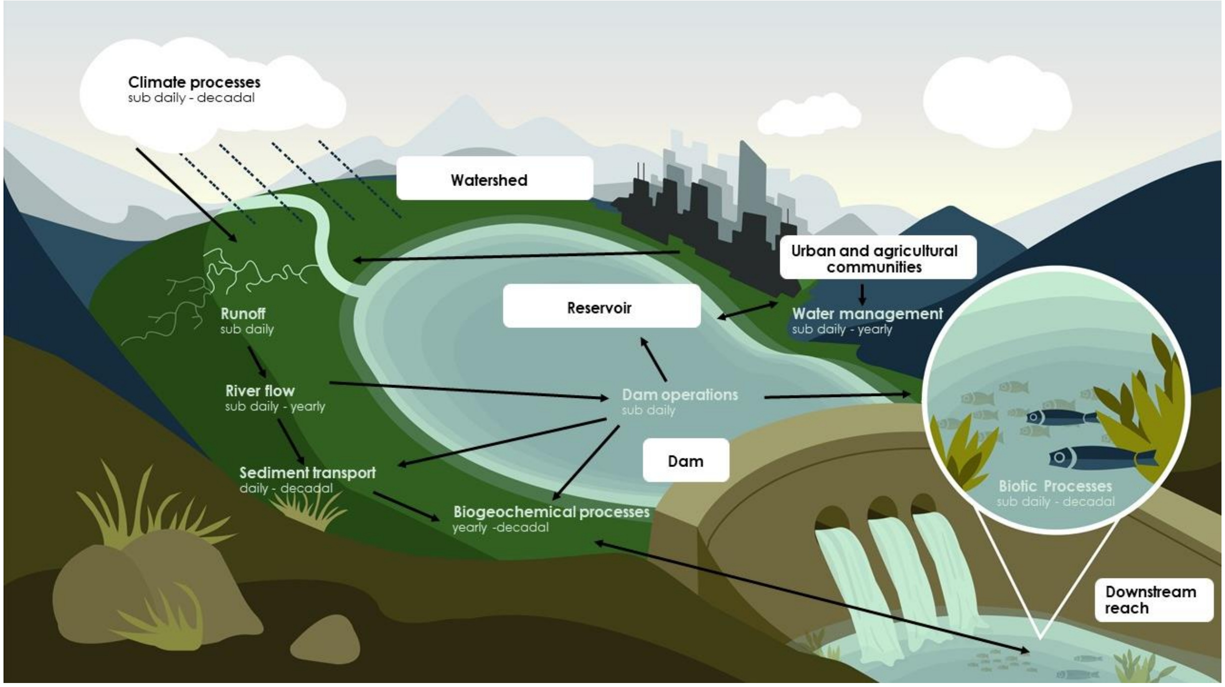

Figure 1. Complex interconnections of an NPD to other systems (e.g., the climate, watershed, downstream reach, and developed areas) and processes (e.g., dam operations, climate, rainfall runoff, sediment transport, biogeochemical, water management).

A holistic view of dam systems must include social and economic components because human populations both affect and are affected by NPDs. Communities build dams to serve one or multiple purposes, such as water supply, flood prevention, energy production, or recreation (e.g., fishing and boating) (Bonnet et al. 2015). On the other hand, communities are affected by dams via safety risks and operating reliability, which could result in catastrophes, loss of life or property, or failure to provide the required water quantity or quality. In some cases, the social components of dam systems may include multiple communities or populations because dams can affect populations beyond those that directly derive benefits from or operate the dam. Other aspects of NPD socioeconomic subsystems are the various institutional bodies involved in regulation, safety, and coordination of dam operations, as well as the economic structures and institutions (e.g., water supply markets) of which NPDs are a part.

Complex interactions occur within NPD systems, and NPD systems may be viewed through various lenses (i.e., physical, environmental, climatological, social, economic); therefore, a large range of characteristics and their various relevant spatial and temporal scales must be considered.

2.1.2 Ongoing and Varied Interests in NPDs

Major ongoing efforts exist to explore opportunities for NPDs; Figure 2 shows the variety of stakeholders involved in these opportunities. These stakeholders are interested in current operations and future development, rehabilitation, or removal. For instance, dam owners oversee the dam operation, maintenance, and safety; regulatory agencies manage licensing processes; evaluate the safety of existing structures; and approve emergency action plans, and water management entities regulate usage of water resources. Other stakeholders are interested in future opportunities that can stem from existing structures.

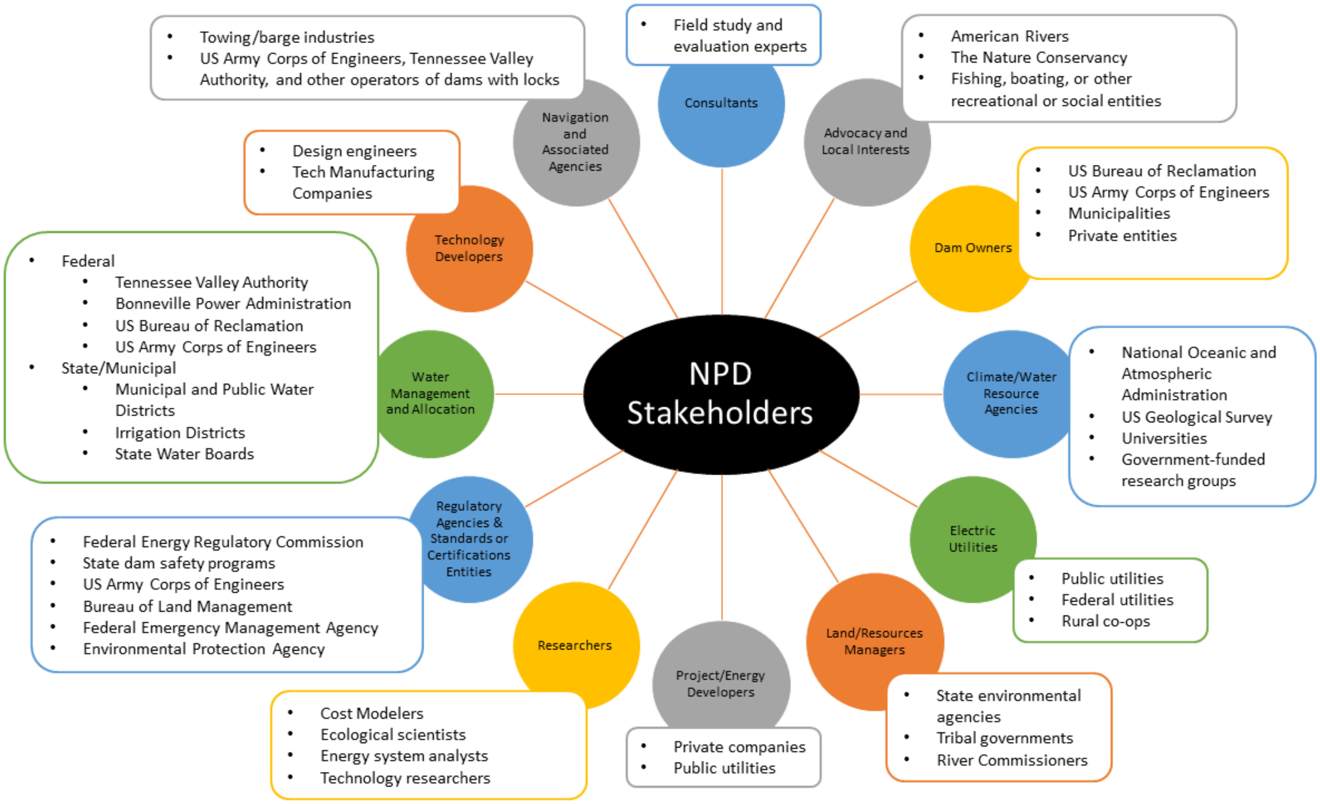

Figure 2. NPD stakeholders have a broad range of diverse interests.

These different perspectives and opportunities suggest that each stakeholder has a unique set of objectives; therefore, specific information is needed to meet those objectives. Some stakeholders, such as dam owners or local environmental protection/conservation agencies, may have a more focused interest in individual facilities (i.e., the number of dams of interest may be a small subset based on ownership or geographic jurisdiction). Other stakeholders, such as federal agencies that manage a large fleet of NPDs, may be interested in multiple locations and varying conditions. Additionally, some stakeholders that are interested in the same general topic (e.g., development of hydropower generation at NPDs) might have vastly differing perspectives. For example, utilities managing grid operations and infrastructure are interested in how much potential generation is available, whereas conservation and environmental protection groups and water resource management agencies might be interested in how NPD development would affect environmental and hydrologic conditions. Finally, there might be developers whose objectives span traditional categories of information; a developer interested in exploring hydropower generation opportunities while also improving the ecohydrological conditions of the stream reach might require information that typically is not found together (e.g., generation potential and environmental conditions of the site).

Profiles of each potential stakeholder illuminate the differences in current involvement, end goals and informational interests. These profiles can be constructed as follows:

> "As a [type of stakeholder], I am interested in [information or data] to accomplish or meet [specific goal or objective]."

These profiles demonstrate the diversity of NPD stakeholders and their different current or future interests and needs. Some of these stakeholders may already have the information they need for their day-to-day operation and goals. Others might be considered potential users of products that would come from the evolution and implementation of the proposed framework, including a centralized data set and/or tool that facilitates information gathering, processing, and display to help analyze necessary information. Examples of stakeholder profiles for several stakeholders involved with NPDs are detailed in Table 1.

Table 1. Profiles of select stakeholders interested in NPDs.

Stakeholder	Examples	Role	Information of interest	Example objective
Hydropower developers	USBR, USACE, TVA, municipalities, private entities	Pursues new projects; expands existing capacity	Physical, environmental, and societal/economical constraints on adding generation and/or developing hydropower; hydropower generation potential	Determine whether existing dams are suited for retrofit or rehabilitation
Entities owning and/or maintaining large fleets of NPDs	USBR, USACE, municipalities, private entities	Oversees and manages projects, operation, maintenance, and safety	Condition of NPDs; applicability of various regulatory and financial incentives; changes in operating conditions resulting from changes in energy portfolio and grid upgrade	Determine whether their facilities require any sort of modification or upgrade, either structural, technological, or operational (e.g., upgrade to pump-storage operation or integration with innovative technologies)
Hydropower licensing agency	FERC	Oversees licensing and permitting of hydroelectric projects	Hydropower generation potential; social and environmental effects; connections to other energy infrastructure	Determine what kinds of environmental effects and energy-related conditions are present at dams with hydropower development potential
Dam safety and emergency response agencies	State dam safety programs, FEMA	Conducts safety inspections; issues permits for operation and alteration of dams; provides guidance on emergency action plans	Hazards (human and environmental risks); condition of NPD; status of emergency action plan	Understand how conditions and hazard levels vary across different characteristics and types of dams; prioritize resources for improving/developing emergency action plans

Table 1. Profiles of select stakeholders interested in NPDs (continued).

Stakeholder	Examples	Role	Information of interest	Example objective
Land/resource managing authorities	US Environmental Protection Agency (EPA), state environmental agencies, tribal governments, city councils, river commissioners	Coordinates operations/manages resources for public and private use; evaluates and regulates water quality and quantity	Expected effects on water resources; changes in land usage and requirements; environmental conditions, impairments; operational modes	Identify the types of river- and lake-regulating structures affecting water quantity and quality decisions
Environmental advocates	American Rivers, The Nature Conservancy	Voice of public acceptance; assesses effects of current NPD operation and future opportunities on the environment	Environmental conditions, impairments; environmental hazards; operational modes	Identify opportunities for ecological improvements and river restorations by retrofitting or removing existing dams; evaluate effects of dams on recreation, fish populations, wildlife/habitat, and water quality
Local interests	Fishing, boating, and other recreational or social entities	Participates in recreation; voice of public acceptance; assesses effects of current NPD operation and future opportunities on community and economy	Environmental and social hazards; operational modes	Identify opportunities for ecological improvements and river restorations by retrofitting or removing existing dams; characterize flow/lake level patterns and water quality
Climate/water resource agencies	National Oceanic and Atmospheric Administration, United States Geologic Survey	Models and studies hydrology, hydrodynamics, and water budgets	Operational modes; hydropower generation potential; environmental, hydrologic conditions	Identify opportunities for hydrologic improvements and river restorations by retrofitting or removing existing dams; determine conditions related to water usage, storage, and release patterns at locations with retrofit/development potential

2.2 COMMON CLASSIFICATIONS OF DAMS AND DAM SYSTEMS

2.2.1 Classification Based on Characteristics

For general dam classification (i.e., classification not specific to hydropower dams), dam classification schemes have typically been narrowly focused on one characteristic of an NPD system. Several common classification schemes as described in another work (DeNeale et al. 2019) include the following:

- **Size:** A simple classification based on size is one of the most basic criteria used to determine which dams are to be included in major dam inventories. For example, the International Commission on Large Dams (ICOLD) uses a threshold of height >15 m or impoundment size >3 million m^3; all other dams are considered too small to be included in the register of large dams. The NID applies alternative size-based criteria for inclusion, including dams with height >8.5 m (25 ft) and impoundment size of 18,500 m^3 (15 ac-ft) or height >2 m (6 ft) and impoundment size of 61,000 m^3 (50 ac-ft). The USACE established guidelines in 1979 for size-based classification: small (25–40 ft, 50–1,000 ac-ft of storage volume), intermediate (40–100 ft, 1,000–50,000 ac-ft), and large (>100 ft, >50,000 ac-ft). This classification scheme has been adopted by many states and is the standard used by FEMA in published guidelines for hydrologic safety of dams (FEMA 2012).
- **Construction/Structural Type:** ICOLD suggests that there are a variety of different ways to classify dams, but the most prominent classification scheme they provide is based on the construction material and structural technology (ICOLD n.d.). Dams can be built of concrete, stone, or masonry which may be used for gravity, arch, or buttress dams. Alternatively, dams can also be constructed of earth, rock, or a combination of earth and rockfill which are used in embankment dams. These two characteristics are also used to define dam type in the NID (USACE 2019).
- **Hazard Potential:** State dam safety agencies are largely responsible for dam inspection, evaluation, and enforcement of safety standards and thus have particular interest in classifying dams with respect to safety characteristics. For example, Ohio Administrative Code 1501:21-13 defines four classes of dams based on a combination of size and probability of loss of human life, structural damage, disruption of water supply or treatment facilities, flooding, or damage to public utilities or roadways (Ohio 2020). Similar to the classification used by the state of Ohio, FEMA also groups dams according to downstream hazard potential code, which indicates whether there is low, significant, or high hazard (FEMA 2004a). This classification is used in the NID (USACE 2019).
- **Hydraulic Head and Technology Constraints:** One of the ways sites are classified is with respect to head ranges and corresponding turbine types (Zhang, Smith, and Zhang 2012). For example, low head technologies (e.g., axial flow Kaplan/propeller, cross-flow, Francis turbines) can be applicable for dams with hydraulic head in the 2-25m range while high head technologies (e.g., Francis, Turgo, and Pelton turbines) are more applicable for dams with hydraulic head >70m.

In each of these cases, classification is limited to one or two factors, which is likely insufficient for providing the actual information required by dam stakeholders to meet their diverse interests and objectives. In a few cases, simple means of classification can be related directly to specific objectives or informational needs. However, in most cases, classification based on one or two factors fails to respond to practical dam-related decisions. For example, classification based on hydraulic head provides valuable information about basic physical constraints that affect technology or infrastructure designs used in hydropower retrofits of NPDs, but it may not adequately address the needs of someone interested in more detailed development feasibility. And grouping dams to identify technology opportunities based on a classification system that only includes hydraulic head might include dams that cannot use a particular technology because of an issue unrelated to hydraulic head. Also, those interested in environmental protection generally require several types of information about the broader dam system (i.e., its watershed, river network, and the associated socioeconomic systems).

2.2.2 Classification Based on Hydropower Capabilities

Dams that already have hydropower capabilities are often described in broad operational schemes. Such classification separates dams into either storage or run-of-river (McManamay et al. 2016). In the video *Energy 101: Hydroelectric Power*, the Office of Energy Efficiency and Renewable Energy also describes hydropower dams in similar terms: impoundment or storage dams, run-of-river or diversion, and pumped storage (Office of Energy Efficiency and Renewable Energy 2013).

ICOLD divides hydropower dams into three similar groups based on operation (ICOLD n.d.). The idea of grouping similar dams and analyzing differences among groups of dams is closely tied to the desire to estimate hydropower development potential. In a 1977 assessment of potential energy at NPDs by the USACE, it was acknowledged that the large number of individual dams posed a major challenge to large-scale study. To overcome this challenge, potential was estimated by assuming that groups of dams shared enough similarities that they could be described by an "average," or representative, dam. In that assessment, USACE assumed "an experienced engineer who is familiar with a local area can allocate dams throughout a basin such that an assumed distribution of dams on the average will approximate the actual distribution of existing dams" (McDonald 1977). However, interest in NPDs extends beyond hydropower development, so regionally based groupings of dams with respect to a few characteristics relevant to estimating hydropower potential may not serve the interests of all NPD stakeholders.

2.2.3 Classification Based on Dam Systems or Sites

In addition to classification of the dams themselves, there have also been efforts to classify aspects of broader dam systems or sites related to dams. A stream reach classification system was developed to support needs for hydropower development (Bevelhimer, DeRolph, and Witt 2018). This system formed groups based on different modules that are tied to specific river functions or hydroelectric facility functions: generation, water quality, sediment passage, fish passage, foundations for the generating facility, and recreation. K-means clustering was used to create groups or clusters of similar sites. This approach effectively minimizes the differences among reaches that are grouped together. This data-driven method means that the grouping of sites was determined by the available data and selected variables; some variables did not have as much weight or influence on group determination, even if they have practical and significant consequences for development-related objectives. The groups of sites created by this classification approach are useful for describing a massive population (more than 300,000 individual stream reaches) in more convenient terms; however, the resulting classes are rigid and therefore fixed to the available data and assumptions used in the analysis.

Another approach to grouping streams is the Stream Classification System for the conterminous United States (McManamay and DeRolph 2019). In this approach, several statistical methods including Gaussian mixed model clustering and random forest models were applied to produce classes for these various physical characteristics: size, gradient, hydrology, temperature, bifurcation, and valley confinement. Because of the variety of possible uses and interest in this classification scheme, classes were created within a nesting structure of hierarchical classes that facilitate more flexible specification of classes. Resulting data sets with classes assigned to each stream reach in the National Hydrography Dataset (NHDPlusV2) river network are described through the lens of specific categories of characteristics rather than allowing for some combination of physical characteristics of interest. For example, a stream reach has a unique hydrologic class and a unique temperature class, but further analysis would be required to create a class based on both hydrology and temperature.

3. CUSTOM ANALYSIS AND TAXONOMY FRAMEWORK

3.1 NPDAMCAT PHILOSOPHY

The limitations of current dam classifications and the variety of characteristics that describe NPD systems pose a major challenge to the diverse group of stakeholders with varying informational needs and objectives who are interested in NPDs (Section 2.1.2). A new approach to classification that extends beyond simple single-characteristic methods or inflexible methods will allow stakeholders, based on their unique perspectives and interests, to aggregate and define groups.

According to the International Society of Knowledge Organization (IKSO) *Encyclopedia of Knowledge Organization*, there are two main theories of classification: feature theory, which is also called *classical theory*, and prototype theory (ISKO 2017).

- **Feature theory** states that elements within a class must share a certain characteristic and that classes can be subdivided into discrete, nonoverlapping subclasses as long as the elements in the subclasses share the same value for that particular characteristic. There is no requirement that the elements in a class share any other characteristics.
    - **Example:** The simple size-based classification used by the American Society of Civil Engineers (ASCE) and FEMA (FEMA 2012) is an implementation of feature theory in which the class of elements (dams) is divided into one of three subclasses: small (<1 kaf [kilo ac-ft] storage), medium (1–50 kaf storage), and large (>50 kaf storage).

- By contrast, **prototype theory** is based on the idea that elements can be similar without having certain binary features in common. Instead, classes coalesce around a central prototype, which may be an actual member of the class or a generic/theoretical entity. The elements in the class may share some characteristics or functions with other members of the class. However, this classification theory typically allows for greater disagreement in characteristics because the groups are not as strictly defined by certain features. Members of groups or classes defined by prototype theory are often described in gradable (i.e., nonbinary) terms of their similarity to and/or resemblance of the prototype.
    - **Example:** Grouping of facilities based on water and vessel storage/passage schemes (i.e., storage, run-of-river, lock and dam) may be useful for high-level descriptions of dams. There may be overlaps between groups: a lock and dam may include a reservoir with substantial storage, or there may be significant differences between dams within these groups: release schedules for storage reservoirs vary widely depending on the purpose of the storage.

> The NPDamCAT framework **implements the feature theory of classification to create customized taxonomies or organizational structures based on multiple characteristics that reflect the specific needs of various stakeholders.**

Many stakeholders interested in NPDs have diverse, sometimes conflicting objectives and informational needs. These varying needs make it impractical to create one universally relevant taxonomical structure. Feature theory, rather than prototype theory, is used in the NPDamCAT framework because it is more convenient to generalize the approach (i.e., any characteristic can be used to define two or more discrete classes that avoid arbitrary definitions of similarity). The NPDamCAT framework is designed to allow a level of customization that will ultimately inform decision-making activities that are most relevant to an individual stakeholder or group of stakeholders.

When executing the NPDamCAT framework, individual stakeholders influence how dams are classified by:

1) Selecting which characteristics are considered for creating subsets of the population of dams and grouping dams into classes;
2) Determining the level of importance or hierarchy of characteristics;
3) Defining how classes are described; and
4) Choosing which information or data sources are used to inform values for various characteristics.

3.2 NPDAMCAT

The philosophy of creating stakeholder-specific, discrete categories of dams based on multiple characteristics described in Section 3.1 translates to a framework composed of five major steps, as shown in Figure 3.

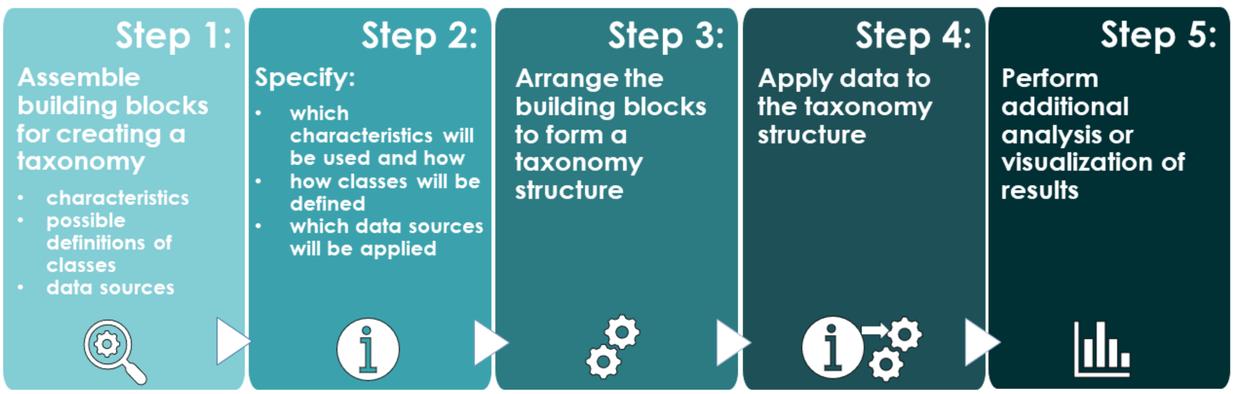

Figure 3. Processes within the NPDamCAT framework.

3.2.1 Step 1: Assemble Building Blocks for Creating a Taxonomy

As illustrated in Figure 4, the building blocks of the dam taxonomy framework include:

- Characteristics that are relevant for one or more of the NPD development stakeholders;
- Values that can be used to define classes related to each characteristic; and
- Data sources that can be used to determine the values for the population of NPDs.

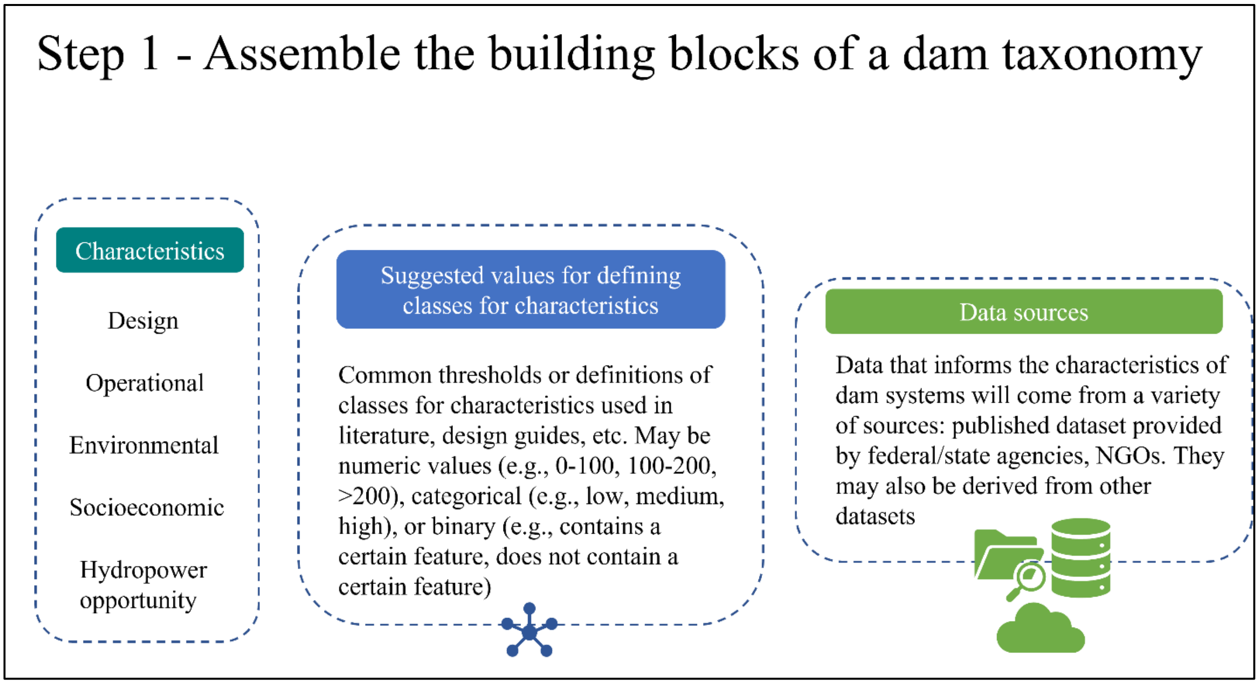

Figure 4. The building blocks of any dam taxonomy are the dam characteristics, the ways in which the classes of characteristics are defined, and the data sources that provide the values for those characteristics.

These characteristics, suggested data sources, and suggested values are based on reviews of dam design guides, reviews of recent hydropower retrofits of NPDs, and input from experts and stakeholders who participated in the December 10, 2020 workshop, *Challenges and Opportunities for Non-Powered Dams: Improving Classification and Data Access*.[2] However, some characteristics or categories of characteristics may not be supported by readily available data, some characteristics are supported by data sets that are incomplete, and some characteristics have a variety of data sources to choose from. One of the long-term goals of this research effort is the constant refinement of the available information as stakeholders begin to use the framework because the quantity and quality of supporting data sets keep improving.

A wide variety of entities collect or create the raw data that determine the broad suite of characteristics of dams and their environments, as shown in Figure 5. These data are published in a variety of forms, such as inventories (e.g., the NID) or geospatial data (e.g., georeferenced soil or land cover maps). Examples of key data sources that provide information for one dam characteristics are provided in Appendix A.

[2] https://smh.ornl.gov/docs/Non-Powered-Dam-Classification-and-Data-Access-Workshop-1-ORNL-Dec2020.pdf

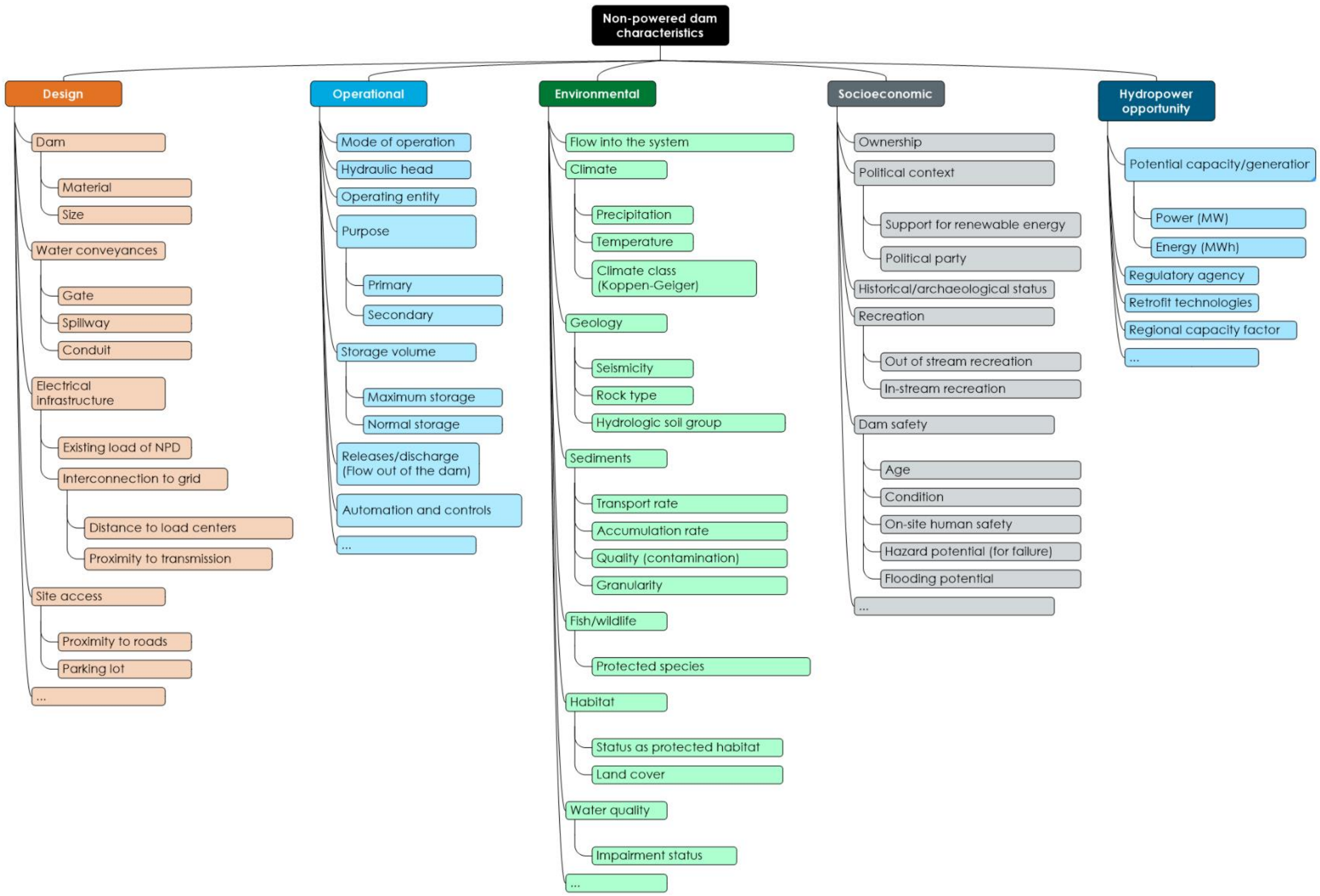

Figure 5. One of the fundamental building blocks of NPDamCAT: characteristics about the dams and their sites.

3.2.2 Step 2: Specify Characteristics, How Characteristics will be Used, Definitions of Classes, and Data Sources

With the building blocks gathered during Step 1, a stakeholder is equipped to make important decisions that will define the taxonomical structure for dam classification. These decisions, illustrated in Figure 6, are

- choosing the characteristics most relevant to their specific interests and objectives,
- specifying how the characteristics and classes will be used in the taxonomical structure (i.e., as an attribute to filter the data, to create groups, or to evaluate within or across groups during later analysis)
- specifying the number of classes to use for the characteristics used in classification and what values will define those classes, and
- selecting the data sources to be used to obtain the values for each characteristic

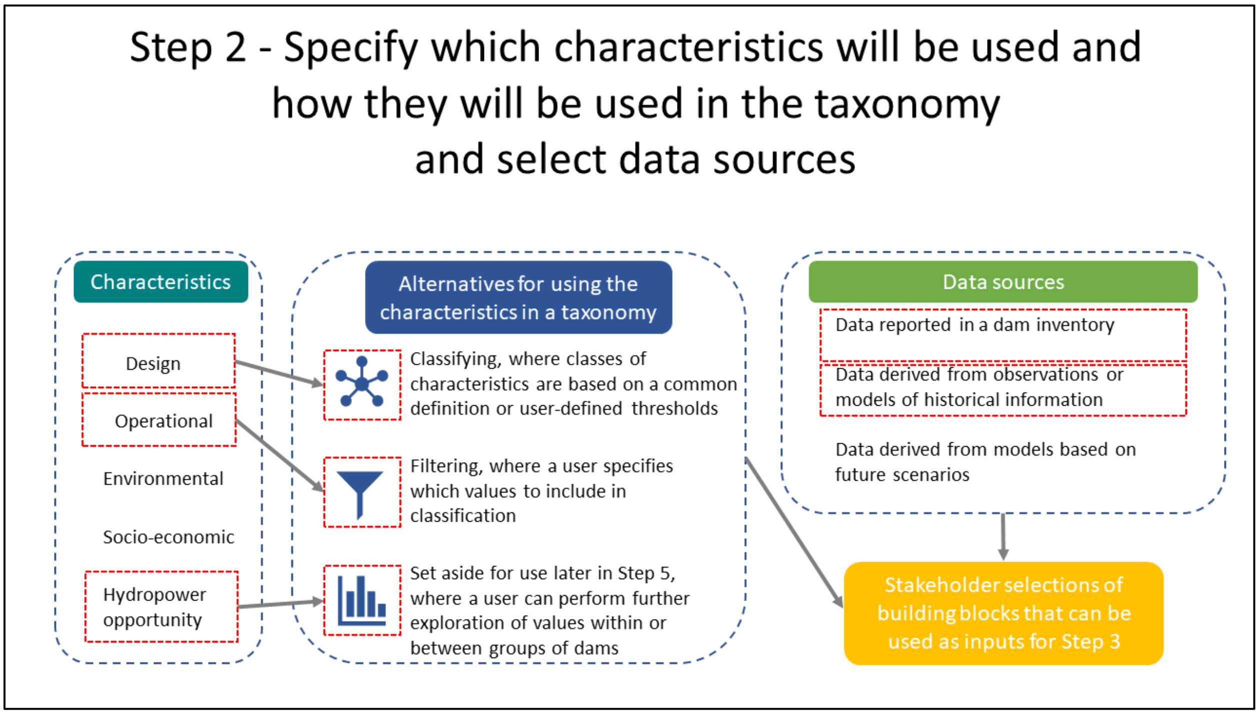

Figure 6. Representation of Step 2: selecting characteristics, specifying how the characteristics will be used in building a taxonomy or further analysis, and choosing data sources that will be applied to the taxonomy. Examples of selections are visualized with red outlines, where a stakeholder can choose relevant characteristics, specify the ways in which each characteristic will be used or explored in the taxonomy, and finally, select data sources to reflect their needs and priorities.

This step accounts for the specific objectives of an individual stakeholder, refining selections to include those characteristics that are relevant to their objectives. Importantly, this step allows an individual stakeholder to impose their own preferences and judgment by using classes and data values that are aligned with their needs and the assumptions they wish to make. For example, two stakeholders could be interested in classification with respect to hydrology (e.g., available streamflow at NPD sites) but have different preferences or needs for the measure of flow (e.g., design flow of 30% exceedance greater than some value vs. minimum flow greater than some value). A stakeholder will also be able to specify the source of the data set; for instance, a stakeholder may prefer the underlying assumptions, methodologies, or levels of quality control used to produce values for one data set over another. Especially in data derived from models (e.g., projected future streamflow), particular climate assumptions or development scenarios may be better aligned with a stakeholder's interests than the assumptions or scenarios used by another data set.

There are three alternatives for how a characteristic could be used in the proposed taxonomy, depending on an individual's preferences

- filter or create subsets of the population of dams. This strategy is generally helpful if some threshold, band of values, or specific category is relevant and an individual wishes to exclude those dams that fall outside of a specific interest.
- create classes and a hierarchy of dams. An individual must assign some order to all characteristics used in classification (e.g., which characteristic defines the groups of dams at one level, which characteristic will define groups of dams at the next level). Essentially, this order establishes a hierarchy of characteristics.
- set aside for later use in Step 5 when the individual can explore values within and across/between groups of dams. For some characteristics, there may be reason to explore the distribution or variation of values within a group of dams or to compare values between groups. In this case, a characteristic that is not used to filter or create the categories of the taxonomy, could be explored after the taxonomy is created. For example, an individual could explore the range or variability of values within a group. Alternatively, they could compare average values for a characteristic between two or more groups of dams.

3.2.3 Step 3: Arrange the Building Blocks

This step refers to the computational or data management process that incorporates stakeholder selections from Step 2 and establishes connections between the building blocks from Step 1 to produce a hierarchical organization structure. This structure is shown in Figure 7. By connecting the building blocks, Step 3 is essentially the command used by a data management software or program to query, filter, and subdivide the data into groups. Although the command has not yet been processed, the arrangement of building blocks forms a taxonomical structure that is a theoretical solution to the stakeholder's informational needs. The hierarchy of characteristics and classes is defined, even if no elements are populating the classes. By imposing a set of priorities, the informatics structure established during this step could be visualized as a tree relating classes and subclasses of dams determined by the individual's selections but not yet containing any information about the dams within the groups.

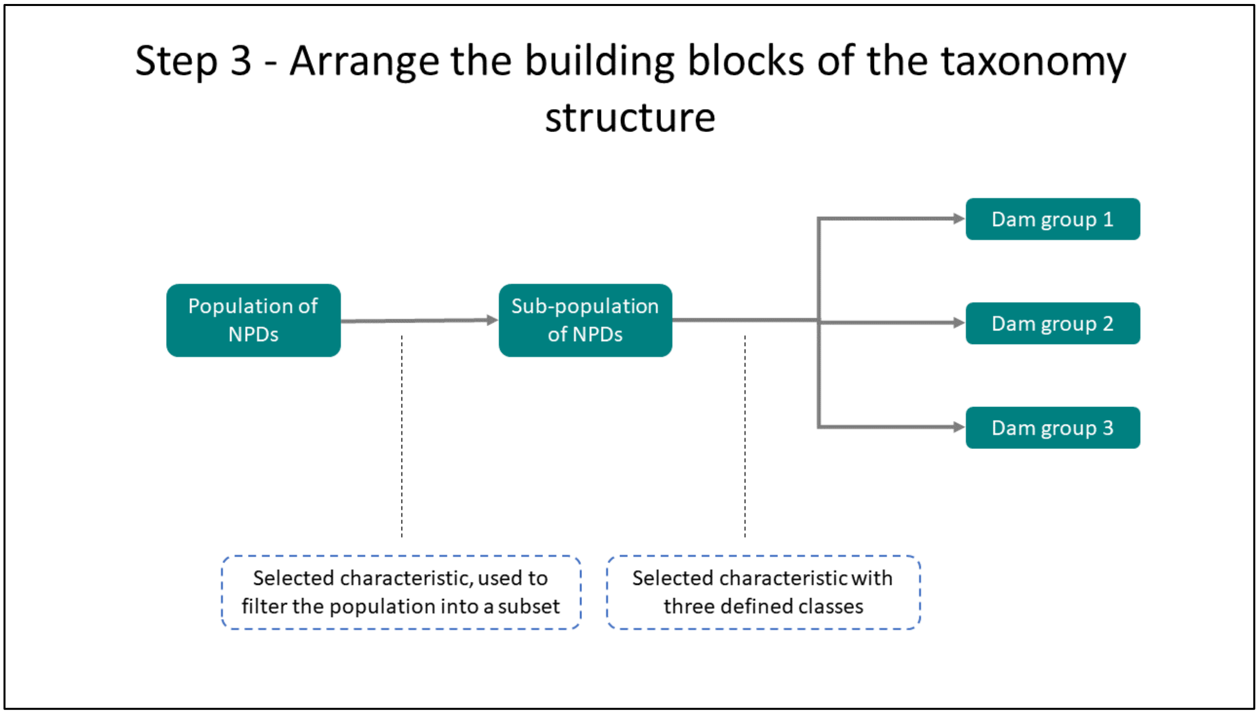

Figure 7. Representation of building blocks arranged to create a theoretical taxonomy structure. Step 3 describes the process of translating and connecting user selections to something that can be executed by a data management and processing program. This step is essentially what is done when crafting a Structured Query Language (SQL) statement.

3.2.4 Step 4: Apply Data

At this stage of the framework, data selected during Step 2 can be applied to the taxonomy, populating the classes. Once the data are connected to the taxonomical structure, the population of dams can filter through the criteria, and the composition of each group can be known.

3.2.5 Step 5: Perform Additional Analysis or Visualization of Results

After the steps of the NPDamCAT framework are completed, results can be visualized and interpreted in many different ways. The most basic outputs are simply the size of subpopulations and the respective lists of dams within each group. For those stakeholders interested in location information, results of the classification can be displayed via maps. Other informational products could include summary tables or plots that show how classes vary with respect to some characteristic. Stakeholders will be able to download their own customized data set along with their selected outcome visualization (e.g., map, plot, list).

3.3 EXAMPLE NPDAMCAT APPLICATION

Consider the example of a hydropower technology developer interested in understanding opportunities at NPDs in a specific region. The developer may have particular interest in dams of certain sizes and design flows because they are pursuing specific technologies. Using this information, a hypothetical stakeholder profile can be constructed:

> As a hydropower technology developer, I want to describe the range of dams in terms of dam size in which certain turbines are suitable so that I can communicate expectations about types of opportunities and better direct engineering design, testing, and modeling efforts.

Step 1: Assemble Building Blocks
To assemble the building blocks required to build a taxonomy that informs this particular stakeholder's interests, the individual must identify relevant characteristics, data sources that can be used to obtain values for these characteristics, and values that can be used to define classes for each of these characteristics.

In this hypothetical situation, the relevant dam characteristics are (1) hydraulic head, (2) flow, (3) geopolitical or hydrologic region of interest, and (4) size.

- Hydraulic head is not listed directly in any dam inventory, so the data values to determine this characteristic must be derived. A simple relationship suggested by the 2012 NPD resource assessment estimates hydraulic head as a function of dam height or hydraulic height, which can be obtained from the NID. For technology purposes, hydraulic head classes can be defined to reflect known turbine performance curves.
- Flow classes could also be defined to reflect turbine performance curves. The data to describe these flow values might be obtained from several different sources. For example, the US Geological Survey (USGS) gage records could provide historical average flows or other statistics; however, the population of dams would be limited to those locations where gages are present. Alternatively, national modeled flow data sets can be used to provide flow statistics at any dam location that has been mapped to a specific river segment.
- Region can be determined by linking a dam inventory to spatial data sets that describe geographic boundaries (e.g., state boundaries produced by the census, hydrologic boundaries published as part of the national Watershed Boundary Dataset). For the characteristic of region, class options are relatively straightforward; either the dam is in within the region of interest, or it is not.
- Size could be defined by several attributes. For example, dam height is a common metric of a dam's size, but size may also refer to the volume of water impounded or stored by a dam. Height is easily obtained from large dam inventories, such as the NID, and height-based classes could be defined to reflect common definitions of low- vs. high-head dams. If storage capacity is chosen to describe size, several options for data sources provide estimates of storage capacity (e.g., maximum capacity reported by the NID or a modeled reservoir volume data set, such as ReGeom (Yigzaw et al. 2018)]). If size is defined by storage capacity, several options exist for defining classes (e.g., small, intermediate, or large based on FEMA definitions (FEMA 2012)]; classes used by a state agency; or some custom definition of size classes).

Step 2: Select Data Sources and Configure Classes
Once relevant available data sources and options for defining classes are adequately evaluated in Step 1, the developer can make selections and impose priorities and preferences for how the data will be organized. Figure 8 shows a representation of this step.

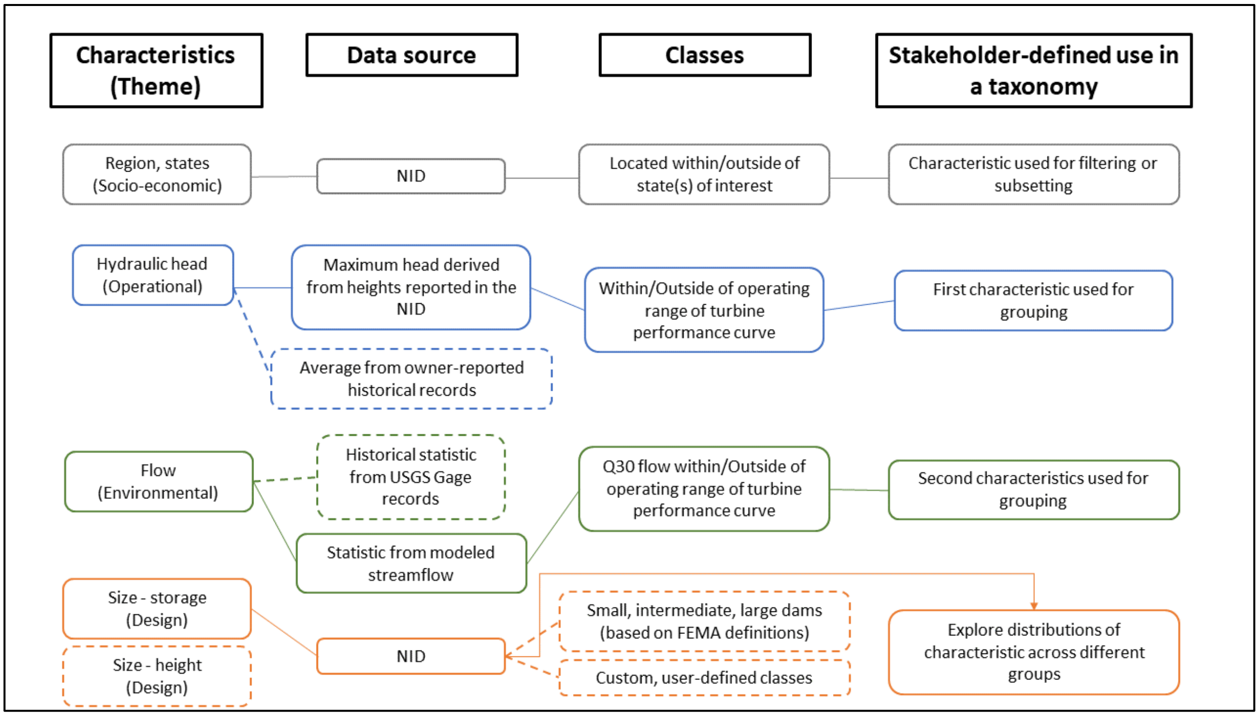

Figure 8. Example of Step 2 for a hypothetical hydropower technology developer. Solid lines represent selections made by the individual, and dashed lines represent alternative options that the individual did not select.

Depending on the characteristic, several data options or alternative category definitions may be available. In this example case, developers may choose the most widely available data possible; for flow at NPDs, they may select a certain flow statistic that is derived from modeled flow because that information is available for a broader number of dams than those that have the same statistic calculated from gage records. Then, individuals can determine how they want to use each characteristic to build the taxonomy and analyze the data. For example, an individual could choose to first use region to filter out dams outside the area of interest and then analyze the range or distribution of storage size among various classes of dams instead of creating classes based on storage size.

Step 3: Arrange the Building Blocks
At this stage in the framework, the taxonomical structure, or tree, of the customized taxonomy can be visualized, but no actual information is contained within the structure yet (i.e., individual dams have not yet been sorted into the groups, so size and distributions of subgroups are unknown). A representation of the structure is shown in Figure 9.

In Figure 9, the developer Next, creates two levels of groups: groups based on hydraulic head classes, then groups based on Q30 flow (30% exceedance flow).

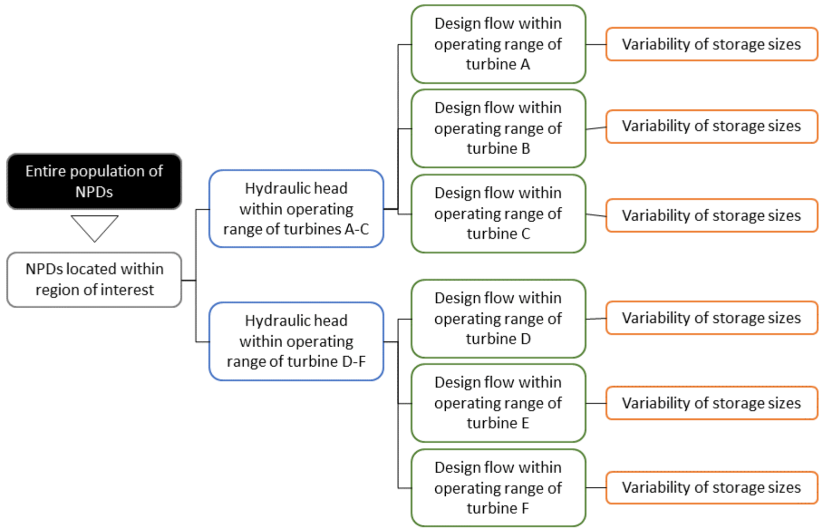

Figure 9. Example arrangement of building blocks (characteristics and classes) to create a custom taxonomical and analytical structure.

Steps 4–5: Apply Data and Visualize the Results
Once the data from sources specified by the developer are applied to the taxonomy, classification and analysis can be conducted. In this example, which is illustrated in Figure 10, the filter based on region creates subsets of the original population of dams, and the developer can conveniently understand what share of the NPD population this subset describes. The makeup of this subset can then be understood via the subgroups that are formed to reflect the user-defined interests in hydraulic head and flow. In this case, the groups and subgroups directly relate to specific technologies—simplified for this example to different types of turbines—so that the developer can determine the opportunity space for each turbine. Finally, the developer can describe the range and distribution of dams within each of these groups.

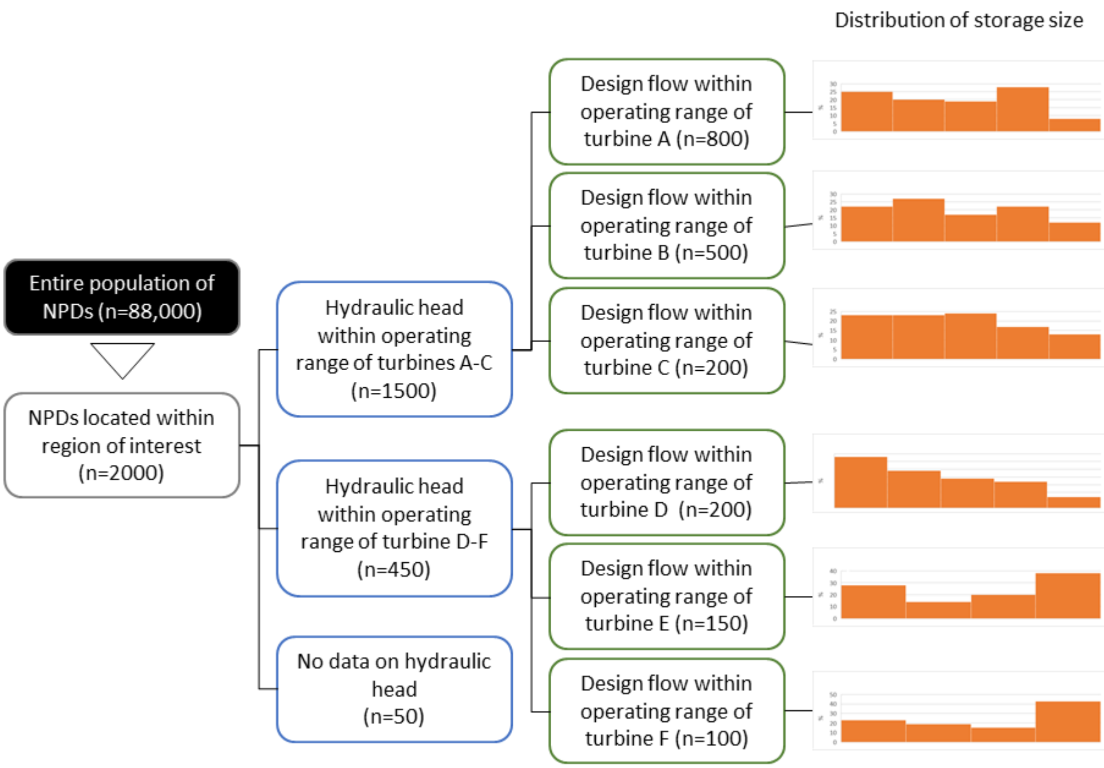

Figure 10. Example result of applying data to the taxonomical structure. At this stage, it is possible to produce statistical summaries or analyze groups (e.g., size of groups, distribution of characteristics within groups).

4. RESEARCH APPLICATIONS AND EXTENSIONS

4.1 NPDAMCAT APPLICATIONS

The NPDamCAT framework requires stakeholder input and explicit data sets to create a custom NPD taxonomy. The multistep process is well suited to implementation within an environment that includes a database and an interface. The database serves as the warehouse for taxonomy building blocks, and the characteristics, values, and class definitions could be stored in a centralized location, which would reduce the significant burden of time and effort required by individuals to collect data. The interface guides users through the classification process in a convenient way that would reduce the knowledge and skill barriers to working with complex databases or in creating visualizations of the resulting groups.

The NPDamCAT framework was designed to support stakeholder decision-making for a variety of applications. The example used in Section 3.3 described technology selection for hydropower development at NPDs. However, other possible applications of the NPDamCAT framework may include

- supporting standardization of designs and technologies standardization. To reduce costs, technology developers are interested in creating standardized designs that can be applied to multiple projects. By using the framework, stakeholders can identify classes of opportunities that can inform technology design or development potential.

- identifying sites with desirable characteristics or features for hydropower development. The NPDamCAT can help stakeholders identify groups of NPDs according to their desired characteristics, making the site selection process more efficient. Stakeholders can narrow their search by levels of detail to their taxonomy.

- identifying data-sparse sites and variables. Another important outcome of the NPDamCAT is explicitly identifying the characteristics that lack sufficient data representations and the sites that are missing common data fields. Once these deficiencies are identified, stakeholders can collect the relevant data and create more accurate classifications.

4.2 DATA GAPS

NPD classification depends on the available qualitative and quantitative data describing the population of NPDs. The overview of key NPD characteristics in Figure 5 illustrates the wide breadth of characteristics. Naturally, these characteristics are derived from a variety of data sources. This compilation of characteristics, data sources, and class definitions used in literature effectively constitutes the first step of the NPDamCAT framework. However, some characteristics do not have the high quality or widely available data sources that are needed for informed decision-making. Table 2 catalogs several characteristics for which improved data quality and access would be highly beneficial to stakeholders. A more thorough discussion of data needs with a focus on supporting hydropower development at NPDs can be found in “Hydropower Development Potential at Non-Powered Dams: Data Needs and Research Gaps” (Hansen et al. 2021).

Table 2. NPD data gaps.

Data gap	Description	Example applications	Possible sources
Historical/target operating rules	The policies governing storage and flow allocations for the facility throughout the year	Water management and available flows for potential hydropower generation	Dam owner/operator
Seasonal flow variability	The timing of inflows throughout the year. Assessments of water availability at or downstream of dams may be oversimplified if seasonal variability is ignored and only coarse aggregate measures (e.g., mean annual flow) are used.	Water management and hydropower potential estimates	NWIS[3] gage streamflow, NWS river forecasting modeled streamflow
Long-term flow variability	The expected hydrologic patterns in the future over the life of the project. Resource assessments typically use historical data and assume similar patterns will continue in the future.	Water management and hydropower potential estimates	NWIS[8] gaged streamflow, NWS river forecasting[4] modeled streamflow

[3] https://waterdata.usgs.gov/nwis

[4] https://water.weather.gov/ahps/long_range.php

Table 2. NPD data gaps (continued).

Data gap	Description	Example applications	Possible sources
Hydraulic head	Difference in water surface elevations upstream and downstream of the dam, including variability as levels fluctuate	Generation technology selection and hydropower potential estimates	Dam owner/operator, geographic information system, and remote sensing
Existing revenue and operating costs	The current profitability of the dam	Decisions related to retrofit, rehabilitation, and removal	Dam owner/operator
Current dam infrastructure dimensions	The size of various dam components, including conduit diameter and length, gate height and width, and spillway width	Requirements for retrofit and rehabilitation, generation technology selection	Dam owner/operator or dam designer
Sediment trapping and passage characteristics	The passage/trapping efficiency and flow rates of different particle sizes into and out of the reservoir	Generation technology selection, sedimentation mitigation measures	Dam owner/operator, field studies, literature, or empirical models
Reservoir water quality	The physical, chemical, and biological composition of the reservoir levels	Generation technology selection, water quality retrofit, rehabilitation, or mitigation measures	Dam owner/operator, field studies, literature, or empirical models
Inventories of affected fish and wildlife	The population sizes and species types of local fish and wildlife	Retrofit fish passage or water quality mitigation measures	Field surveys, dam permits/licenses, EPA
Local energy needs	The power and energy needs of the local power system	Market requirements for potential hydropower retrofit	Capacity expansion models

In some cases, characteristics may have supporting data, but the data may not be published or accessible in a manner that allows integration with other characteristics. For example, operational rule curves are typically detailed by the dam owner or operator; however, these data may not be accessible to the public, may be published in inaccessible formats (e.g., reports), or may not reference common identifiers (e.g., the ID used in the NID). An analysis of several characteristics of dams in the NID reveals that some basic data are missing for large portions of the dam population. For example, normal storage capacity is only available for 91% of NPDs, and discharge at the dam is only available for 39% of NPDs (Hansen et al. 2021). Examples of characteristics that might require additional research to generate the data are

- *Hydraulic head*. Existing resource assessments of NPDs often use proxies, such as dam height, for hydraulic head when estimating energy potential. However, this estimate may not be accurate, especially for systems in which the tailwater immediately downstream of the dam reduces the head or in which the head can vary substantially over time. Improved elevation data would lead to more accurate classification and analysis of hydropower development at NPDs. Possible sources of improved elevation data include satellite altimetry or remote sensing techniques.

    - *Flow*. Projected future streamflow conditions are important for long-term planning at NPDs. To obtain data about potential future streamflow characteristics, large-scale hydrologic or data-driven models may be used to generate estimates of future streamflow that are consistent over the spatial extent of the population of NPDs. Additionally, data about streamflow at NPDs should better represent the complexity of variable flows because other flow statistics are relevant to many NPD applications, such as minimum and maximum flows.

Hydraulic head and available flow are two examples of the many characteristics that have variability and uncertainty. Other characteristics that may change over time include operational rules, environmental conditions, watershed characteristics, climate conditions, and socioeconomic characteristics of the communities that affect and are affected by the dams. Because these data types can be highly variable depending on the source (i.e., the model and assumptions used and the time period the data represent), multiple sources of underlying data may need to be made available to stakeholders. For example, historical simulated or observed flow conditions may be of interest for some stakeholders, whereas future flow conditions are relevant to others. The data that would describe historical vs. projected flow conditions may come from different sources. The NPDamCAT framework recognizes the possibility for a variety of data sources and class definitions and therefore recommends an approach that is flexible and adaptable to accommodate different data sources and class definitions.

Uncertainty can also be introduced by questionable data quality. Attributes contained in the NID are determined by compiling locally reported data sets, and there may be discrepancies in the data validation/quality among data providers. Using data that are acquired and processed via standardized, consistent methods can help address this issue; however, intermediate processing—such as removing outliers, checking for consistent units, and using spatial data to confirm locations—remains an important input to Step 1. As the quality of information collected to be used as building blocks improves, the quality and efficacy of the taxonomies produced by NPDamCAT framework will also increase. Communicating the data quality is important to allow stakeholders to make decisions that align with their desired level of risk and accepted assumptions.

Finally, compilation of various data sources is often facilitated by formalized data management models that relate different types of information. For example, ORNL's HydroSource data model[5] describes relationships between disparate data sets related to hydropower dams and power plants. When common fields are shared and maintained, crosswalking between data sets and formal management of disparate data sets within a database is much more convenient. Such an approach is used for StreamCat, a data set maintained by the US Environmental Protection Agency (EPA), which provides metrics for streams that are referenced to the same unique identifier used in the medium resolution river network of the NHDPlusV2. Establishing crosswalks between data sets, formatting, processing, and managing the data are major tasks that can be time intensive for individual stakeholders. Efforts to link diverse datasets create a more comprehensive inventory of available data will significantly reduce this burden.

4.3 RESEARCH OPPORTUNITIES

Creating a dam taxonomy will often be the starting point for a wide variety of further analyses. Research activities may also provide alternative perspectives to dam classification by identifying which characteristics are most important for evaluating the following complex or cross-cutting NPD issues.

- *Hydropower development and impacts.* The NPDamCAT is designed to reflect individual stakeholder interests, assuming stakeholders knows at the outset which characteristics are most important to them.

[5] https://hydrosource.ornl.gov/sites/default/files/2020-09/ORNL_HydroSourceDataModel_v1.pdf

A simple survey of recent NPD development projects showed a great deal of variability in conditions and characteristics (Hansen et al. 2021). Further research is needed to identify which conditions or characteristics (i.e., design, operational, economic, environmental, social) are most influential to the success of an NPD hydropower development project or evaluation of its potential impacts. This research would help stakeholders better define the characteristics that should be prioritized when building a taxonomy to support hydropower development-related analysis.

  - *Costs and benefits of various alternatives (i.e., rehabilitation, removal, retrofit).* Selecting from various NPD alternatives is another decision that likely incorporates a complex array of characteristics. Specific stakeholders may already know which characteristics are most relevant to them. However, the decision to rehabilitate, remove, or retrofit a dam will affect multiple stakeholders. Research that better identifies the characteristics that are most important for selecting an NPD alternative is needed to direct classification and taxonomy building that is meant to serve this purpose. For example, developing techno-economic models to better estimate costs and benefits of each alternative will help identify which characteristics are most influential.

- *Clustering analysis for data-driven classifications.* The NPDamCAT framework has focused on a hierarchical, deterministic approach to create subsets of the NPDs via a series of discrete classifications selected by the stakeholder. Additional opportunities for classification could support specific decisions related to NPDs by using clustering and data-driven approaches. Similar classification techniques have been applied to stream reaches to support decisions related to individual standard modular hydropower (SMH) development modules (Bevelhimer, DeRolph, and Witt 2018) or to enable creating physically based river subsets (McManamay and DeRolph 2019). Common data-driven clustering and classification techniques, such as k-means clustering and random forest classification, could still use some of the same steps of the NPDamCAT framework (e.g., gathering data, selecting relevant characteristics and data sources, visualizing the classification structure and relationship between clusters or groups of dams). However, some important distinctions exist. This approach to classification would not involve a deterministic configuration of classes; rather, statistical algorithms would identify natural separations in the data to create groups of NPDs with similar characteristics. This approach may provide a fluid view of grouping individual dams that aligns more closely with the prototype theory than the feature theory behind the NPDamCAT framework. This approach would also enable some measure of similarity (i.e., how "close" an individual dam is to other groups or other individuals). Extending NPD classification into these types of techniques would likely be done with respect to specific goals. For example, clustering types of dams according to dam or river functions, similar to the SMH stream reach classification, would facilitate a more standardized approach to designing facilities that are tailored to the needs of each cluster.

5. SUMMARY

Organizing information to create a classification system is a powerful first step for analyzing and better understanding opportunities and issues related to NPDs. The complexity of NPD systems and variety of characteristics that are relevant to different NPD stakeholders requires a flexible approach to classification. The NPDamCAT framework supports individual stakeholders by detailing the process needed to create classification schemes that are meaningful and relevant to their specific objectives. The framework begins with the characteristics, priorities, class definitions, and data sources that are used to build taxonomies. Classification and taxonomy building processes could be greatly improved for individuals if they had access to a compilation of relevant characteristics, classes, and data. A database coupled with an informatic tool, such as a web application, would help individuals perform each step of the NPDamCAT framework.

Ultimately, the NPDamCAT framework enables summarization and supports further analysis and decision-making related to NPDs. Taxonomies enable descriptions of the entire population of dams and provide more convenient and workable groups that are more reasonable to work with, especially when trying to draw conclusions about the entire population or major subsets of dams. The organizational structures produced by following the NPDamCAT framework provide important context (e.g., “Is the subset of dams that meet certain criteria relatively small compared to the overall population?” or, “Are these types of dams common?”).

Several major data needs have been identified along with research activities that might improve the quality and robustness of data. As innovative techniques are used to derive more detailed and accurate values, understanding of the entire population of NPDs will improve. Additional research activities that would support future classification efforts include identifying characteristics that are most relevant to decisions or objectives that span multiple stakeholders and interests. Additionally, an opportunity exists to extend infrastructure classification research beyond what is outlined in this report. The NPDamCAT framework may be adapted to incorporate other approaches to classification—beyond hierarchical, discrete classification—that are data-driven and may support specific objectives in new ways.

6. REREFENCES

ASCE (American Society of Civil Engineers). 2017. “2017 Infrastructure Report Card.” www.infrastructurereportcard.org/wastewater/conditions-capacity/.

Bednarek, Angela T., and David D. Hart. 2005. “Modifying Dam Operations to Restore Rivers: Ecological Responses to Tennessee River Dam Mitigation.” *Ecological Applications* 15 (3): 997–1008.

Bevelhimer, Mark, Christopher DeRolph, and Adam Witt. 2018. “Site Classification for Standard Modular Hydropower Development : Characterizing Stream Reaches by Module Need.”

Bonnet, Marisol, Adam M. Witt, Boualem Hadjerioua, and Miles Mobley. 2015. “The Economic Benefits Of Multipurpose Reservoirs In The United States- Federal Hydropower Fleet.” https://doi.org/10.2172/1237622.

Brandt, S. Anders. 2000. “Classification of Geomorphological Effects Downstream of Dams.” *Catena* 40 (4): 375–401. https://doi.org/10.1016/S0341-8162(00)00093-X.

DeNeale, Scott T., G. B. Baecher, Kevin Stewart, E. D. Smith, and D. B. Watson. 2019. “Current State-of-Practice in Dam Safety Risk Assessment.” Oak Ridge, Tennessee.

DeNeale, Scott T., Norman Bishop, Larry Buetikofer, Richard Sisson, Colin Sasthav, Mirko Musa, Tarka Wilcox, Kevin Stewart, William Tingen, and Christopher DeRolph. 2020. “Hydropower Geotechnical Foundations : Current Practice and Innovation Opportunities for Low-Head Applications.” https://doi.org/10.2172/1649157.

DOE (US Department of Energy). 2016. “Hydropower Vision.” https://energy.gov/sites/prod/files/2016/10/f33/Hydropower-Vision-10262016_0.pdf.

———. 2021. “Glossary of Hydropower Terms.” 2021. https://www.energy.gov/eere/water/glossary-hydropower-terms.

FEMA (Federal Emergency Management Agency). 2004a. “Federal Guidelines for Dam Safety- Hazard Potential Classification System for Dams.” U.S. Federal Emergency Management Agency. 2004. https://doi.org/10.1002/hep.27822.

———. 2004b. “Federal Guidelines for Dam Safety: Glossary of Terms.” https://damsafety.org/sites/default/files/FEMA Federal Guidelines Glossary 148_04.pdf.

———. 2012. “Summary of Existing Guidelines for Hydrologic Safety of Dams.” https://www.hsdl.org/?abstract&did=757604.

Foley, M. M., J. R. Bellmore, J. E. O’Connor, J. J. Duda, A. E. East, G. E. Grant, C. W. Anderson, et al. 2017. “Dam Removal: Listening In.” *Water Resources Research* 53 (7): 5229–46. https://doi.org/10.1002/2017WR020457.

Hadjerioua, Boualem, Yaxing Wei, and Shih-Chieh Kao. 2012. “An Assessment of Energy Potential at Non-Powered Dams in the United States.” *Hydropower and Energy Potential at Non-Powered Dams*. https://doi.org/10.2172/1039957.

Hansen, Carly, Mirko Musa, Colin Sasthav, and Scott DeNeale. 2021. “Hydropower Development Potential at Non-Powered Dams: Data Needs and Research Gaps.” *Renewable and Sustainable Energy Reviews* 145: 111058.

ICOLD. n.d. “Technology of Dams.” Accessed October 11, 2020. https://www.icold-cigb.org/GB/dams/technology_of_dams.asp.

ISKO. 2017. “Encyclopedia of Knowledge Organization.” 2017. https://www.isko.org/cyclo/classification.

Johnson, Megan and Rocio Uría-Martínez. 2021. “US Hydropower Development Pipeline Data and Metadata, 2021.” https://doi.org/10.21951/HMR_PipelineFY21/1772802.

“Joint Statement of Collaboration on U.S. Hydropower: Climate Solution and Conservation Challenge.” 2020. https://woods.stanford.edu/sites/g/files/sbiybj5821/f/hydropower_uncommon_dialogue_joint_statement.pdf.

Kondolf, G Mathias, Yongxuan Gao, George W Annandale, Gregory L Morris, Enhui Jiang, Junhua Zhang, Yongtao Cao, et al. 2014. "Sustainable Sediment Management in Reservoirs and Regulated Rivers: Experiences from Five Continents." *Earth's Future* 2 (5): 256–80. https://doi.org/10.1002/2013EF000184.

Lees, Alexander C., Carlos A. Peres, Philip M. Fearnside, Maurício Schneider, and Jansen A.S. Zuanon. 2016. "Hydropower and the Future of Amazonian Biodiversity." *Biodiversity and Conservation* 25 (3): 451–66. https://doi.org/10.1007/s10531-016-1072-3.

Lessard, JoAnna L., and Daniel B. Hayes. 2003. "Effects of Elevated Water Temperature on Fish and Macroinvertebrate Communities below Small Dams." *River Research and Applications* 19 (7): 721–32.

McDonald, Richard J. 1977. "Estimate of National Hydroelectric Power Potential at Existing Dams." Army Corps of Engineers, Washington, DC.

McManamay, Ryan A., and Christopher R. DeRolph. 2019. "A Stream Classification System for the Conterminous United States." *Scientific Data* 6 (1): 1–18.

McManamay, Ryan A., C. O. Oigbokie, Shih-Chieh Kao, and Mark S. Bevelhimer. 2016. "Classification of US Hydropower Dams by Their Modes of Operation." *River Research and Applications* 32 (7): 1450–68.

Office of Energy Efficiency and Renewable Energy. 2013. "Energy 101: Hydropower." 2013. https://www.energy.gov/eere/videos/energy-101-hydroelectric-power.

Ohio. 2020. "1501:21-13 Classification and Design of Dams, Dikes, and Levees." 2020. http://codes.ohio.gov/oac/1501%3A21-13.

Oladosu, Gbadebo A., Lindsay George, and Jeremy Wells. 2021. "2020 Cost Analysis of Hydropower Options at Non-Powered Dams." Oak Ridge, TN, USA. https://info.ornl.gov/sites/publications/Files/Pub145012.pdf.

Oladosu, Gbadebo A., Joseph Werble, William Tingen, Adam Witt, Miles Mobley, and Patrick W. O'Connor. 2021. "Costs of Mitigating the Environmental Impacts of Hydropower Projects in the United States." *Renewable and Sustainable Energy Reviews* 135 (July 2020): 110121. https://doi.org/10.1016/j.rser.2020.110121.

Petts, Geoffrey E., and Angela M. Gurnell. 2005. "Dams and Geomorphology: Research Progress and Future Directions." *Geomorphology* 71 (1–2): 27–47. https://doi.org/10.1016/j.geomorph.2004.02.015.

Prairie, Y. T., Jukka Alm, A. Harby, S. Mercier-Blais, and R. Nahas. 2017. "The GHG Reservoir Tool (Gres) Technical Documentation: UNESCO/IHA Research Project on the GHG Status of Freshwater Reservoirs: Version 1.1."

SARP (Southeast Aquatic Resources Partnership). 2021. "SARP Aquatic Barrier Prioritization Tool." 2021. https://connectivity.sarpdata.com/.

Schmidt, John C. and Peter Richard Wilcock. 2008. "Metrics for Assessing the Downstream Effects of Dams." *Water Resources Research* 44 (4). https://doi.org/10.1029/2006WR005092.

Uría-Martínez, R., M. M. Johnson, and R. Shan. 2021. "U.S. Hydropower Market Report Data." https://doi.org/10.21951/HMR_Data/1759986.

Uria-Martinez, Rocio, Megan Johnson, and Shan Rui. 2021. "2021 Hydropower Market Report." Oak Ridge. https://www.energy.gov/sites/prod/files/2018/04/f51/Hydropower Market Report.pdf.

USACE (US Army Corps of Engineers). 2019. "National Inventory of Dams." https://nid.sec.usace.army.mil/.

USBR (US Department of the Interior Bureau of Reclamation). 1987. *Design of Small Dams*. Washington, D.C. https://doi.org/10.1002/3527603514.ch5.

Vörösmarty, Charles J., Michel Meybeck, Balázs Fekete, Keshav Sharma, Pamela Green, and James P. M. Syvitski. 2003. "Anthropogenic Sediment Retention: Major Global Impact from Registered River Impoundments." *Global and Planetary Change* 39 (1–2): 169–90. https://doi.org/10.1016/S0921-8181(03)00023-7.

Winemiller, K. O., P. B. McIntyre, L. Castello, E. Fluet-Chouinard, T. Giarrizzo, S. Nam, I. G. Baird, et

al. 2016. “Balancing Hydropower and Biodiversity in the Amazon, Congo, and Mekong.” *Science* 351 (6269): 128–29. https://doi.org/10.1126/science.aac7082.
Yigzaw, Wondmagegn, Hong-Yi Li, Yonas Demissie, Mohamad I Hejazi, L Ruby Leung, Nathalie Voisin, and Rob Payn. 2018. “A New Global Storage-area-depth Data Set for Modeling Reservoirs in Land Surface and Earth System Models.” *Water Resources Research* 54 (12): 10–372.
Zhang, Q. F., Brennan Smith, and Wei Zhang. 2012. “Small Hydropower Cost Reference Model.” *ORNL/TM-2012/501*. https://info.ornl.gov/sites/publications/files/pub39663.pdf.
Ziv, Guy, Eric Baran, So Nam, Ignacio Rodríguez-Iturbe, and Simon A. Levin. 2012. “Trading-off Fish Biodiversity, Food Security, and Hydropower in the Mekong River Basin.” *Proceedings of the National Academy of Sciences of the United States of America* 109 (15): 5609–14. https://doi.org/10.1073/pnas.1201423109.

APPENDIX A.

Table 3 provides examples of data sources that inform one or more characteristics about NPDs or their sites. While not exhaustive, the table illustrates the diverse entities who maintain data relevant for NPDs.

Table 3. Example data sources spanning various themes of NPD characteristics

Theme of characteristics	Data sources
Design, operational, socioeconomic	US Army Corps of Engineers National Inventory of Dams (NID)
Design	Homeland Infrastructure Foundation-Level Data (HIFLD)
Design	Census Bureau US Primary Roads
Environmental	Modeled streamflow statistics, derived from national historical streamflow model.
Environmental	USGS National Water Information System gage records
Environmental	USGS National Hydrography Dataset NHDPlus River Network and Value-Added Attributes
Environmental	USGS National Map 3D Elevation Program Downloadable Data Collection
Environmental	USBR Reclamation Information Sharing Environment (RISE) (for select USBR dams)
Environmental	World map of Köppen-Geiger climates
Environmental	USEPA Eco-Regions
Environmental	USEPA StreamCat
Environmental	National Land Cover Database
Environmental	NatureServe
Environmental	USEPA Watershed Assessment, Tracking & Environmental Results System (WATERS) Geospatial Data list of 303(d) impaired waters
Environmental	Critical Habitat (US Fish and Wildlife Service [USFWS] Threatened and Endangered Species Active Critical Habitat)
Hydropower opportunities	2012 NPD Resource Assessment (Hadjerioua, Wei, and Kao 2012a)

Table 3. Example data sources spanning various themes of NPD characteristics (continued)

Theme of characteristics	Data sources
Operational	Corps Water Management System (CWMS) (for select USACE dams)
Hydropower opportunities	HUC2-based historical (2001–2008) regional capacity factor (Hadjerioua, Wei, and Kao 2012a)
Socioeconomic	United States Protected Area Database
Socioeconomic	Yale Climate Opinion Maps