How Standard Modular Hydropower Can Enhance the Environmental, Economic, and Social Benefits of New Small Hydropower Development

Adam Witt[1], Alisha Fernandez-McKeown[2], Miles Mobley[1], Scott DeNeale[1], Mark Bevelhimer[1], Brennan Smith[1]

[1] *Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN, USA*

[2] *McKeown and Associates LLC, Washington, D.C., USA*

Abstract

The recent *Hydropower Vision Report* identified development of next generation hydropower technologies as a critical action area for the hydropower industry. These technologies must not only enhance the performance capabilities of existing equipment, they must minimize environmental disturbance across a diverse spectrum of river ecosystems while maintaining low installed costs that are competitive with other generation resources. Oak Ridge National Laboratory (ORNL) is leading a multi-year R&D effort for the Department of Energy (DOE) to determine how standardization, modularity, and preservation of stream functionality can become essential and fully realized features of next generation hydropower technologies and project designs. This research effort, termed Standard Modular Hydropower (SMH), is focused on advanced facility designs with scalable and standardized families of modular turbines and modular civil structures that pass water, fish, sediment, and small recreational craft.

This paper describes the current status of small hydropower development in the U.S., and offers a vision for Standard Modular hydropower based on three focus areas of SMH research:

1. A framework for classifying potential SMH sites;
2. Establishing exemplary design criteria for SMH facilities ;
3. Leveraging small hydropower stakeholder perspectives to guide and improve SMH research.

Concluding thoughts outline how SMH can enhance the environmental, economic, and social benefits of new small hydropower development.

1. Background

The first hydropower plant to produce electricity in the United States used a single turbine to generate 12.5 kilowatts, enough power to light a single home, a single business, and the hydropower plant itself.[1] Today, the U.S. Fleet of hydropower plants consists of roughly 2,400 individual facilities spinning over 6,000 turbines, meeting roughly 7% of the annual electricity demand of the country with roughly 80 GW of installed capacity (Uria-Martinez, Johnson, and O'Connor 2015; Samu, Kao, and O'Connor 2016).

Small hydropower plants (SHPs), classified within this document as plants with less than 10 MW of nameplate capacity, provide 3.8 GW of installed capacity at over 1,700 individual facilities in 46 states (Figure 1). Over half of all SHP capacity is located in five states: California, New York, Idaho, Wisconsin, and Michigan. Though they represent only 4.7% of US hydroelectric installed capacity, over 73% of U.S. hydropower plants are SHPs, and over 58% of U.S. hydropower turbines are currently spinning at SHPs (Samu, Kao, and O'Connor 2016).

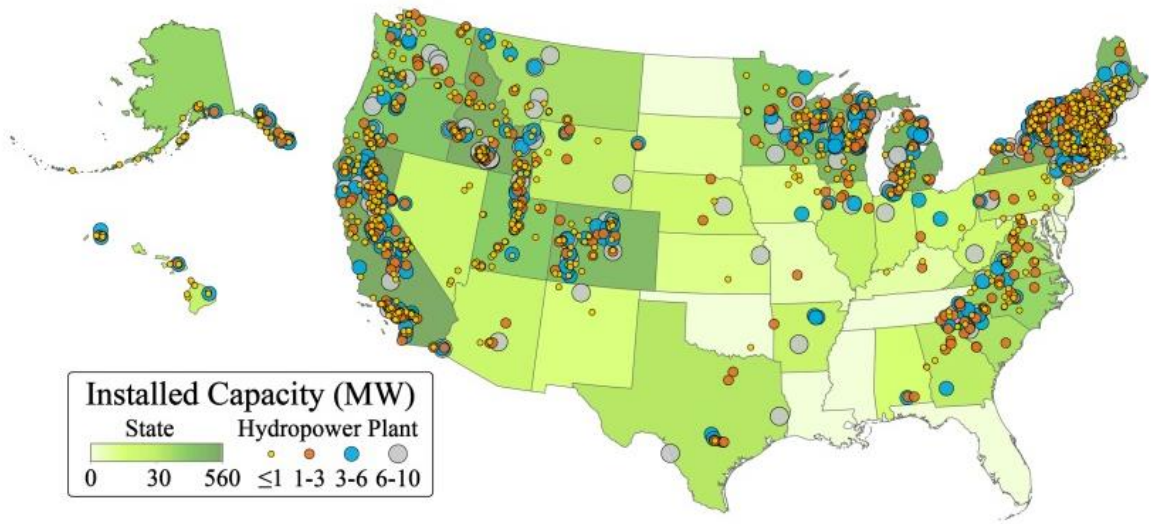


Figure 1. Geospatial distribution of SHPs in the US. Data from (Samu, Kao, and O'Connor 2016)**.**

The diversity of turbines types, technical specifications, and operational regimes make SHPs a highly unique source of renewable energy. Of the reported modes of operation, approximately 1/3 of SHPs are operating in canals and conduits, nearly all of which were installed after 1980 (Figure 2). The remaining SHPs are operated in streams as run-of-river, peaking, a combination of the two, or reregulating. The Francis turbine is the dominant turbine type in SHPs, with over 500 units installed at low head (<30 ft) sites and roughly 700 units installed at not low head (> 30ft) sites. Pelton, Kaplan, and fixed blade/propeller turbines make up the bulk of remaining turbines, with over 100 of each installed at SHPs in the U.S. In total, there are over 21 different turbine types installed at U.S. SHPs. While a handful of turbines are rated for greater than 1,000 ft of head, and even fewer for less than 10 ft of head, the majority of SHPs operate at a head between 10 and 60 ft, and with plant hydraulic capacity between 500 and 7,000 cfs.

[1] http://www.americaslibrary.gov/jb/gilded/jb_gilded_hydro_1.html

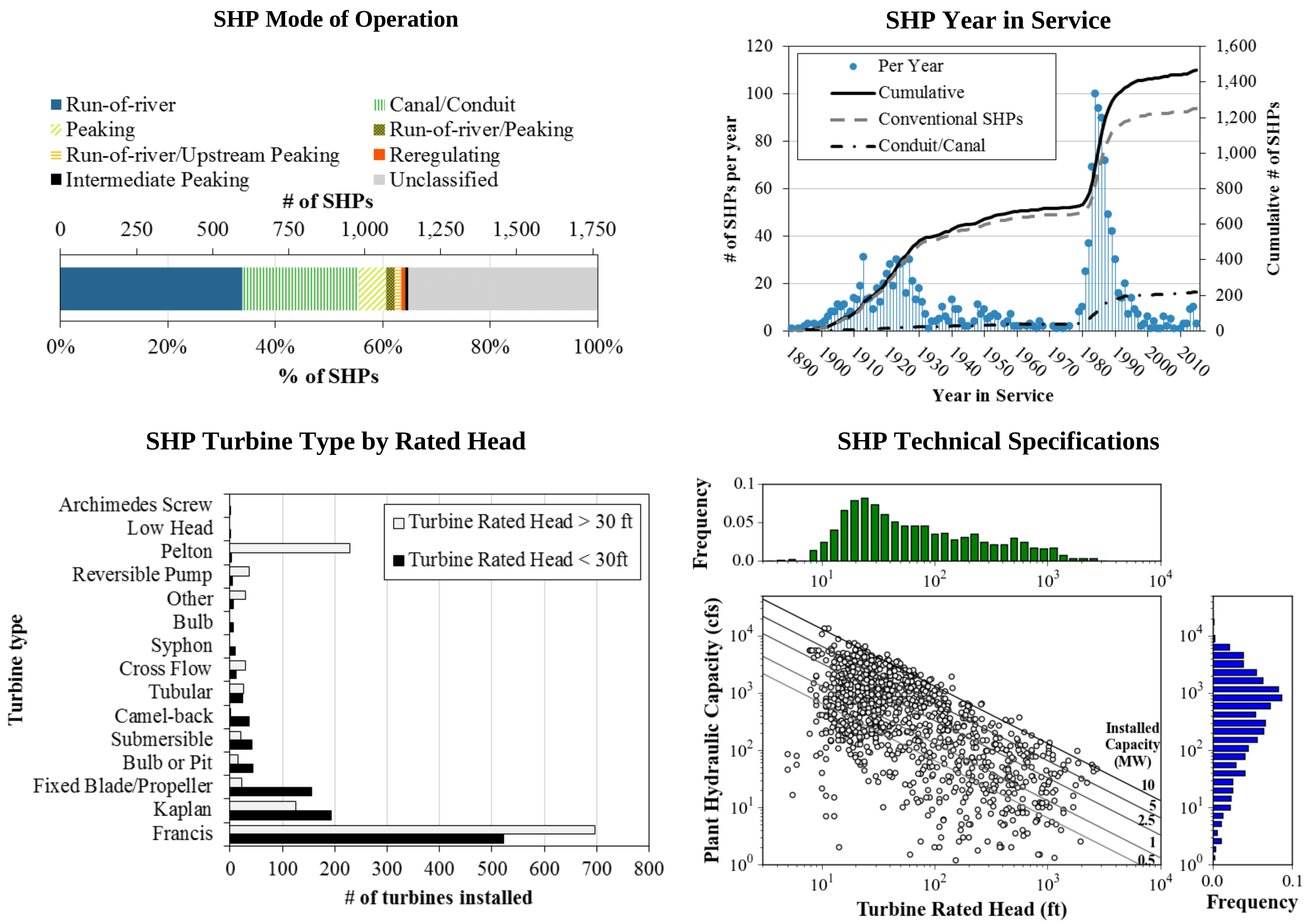


Figure 2. SHP mode of operation (top left); SHP year in service (top right, data unavailable for approximately 200 plants); SHP turbine type by rated head (bottom left); SHP technical specifications (bottom right). Data from (Samu, Kao, and O'Connor 2016)**.**

Recent trends in SHP development indicate a shift from Greenfield new stream-reach development (NSD) to powering existing water resource infrastructure such as non-powered dams (NPDs) and irrigation canals and conduits. Over the past 15 years, the majority of SHP preliminary permits filed with the Federal Energy Regulatory Commission (FERC) have been for powering NPDs (Figure 3). In that time, approximately 1,034 NPD preliminary permits have been filed, compared to only 127 preliminary permits for Greenfield NSD sites. In 13 of the last 16 years, the number of permit and exemption applications for canal/conduit projects has surpassed the number of permit applications for NSD projects.

Once a preliminary permit is filed, it must be approved by FERC before an application for an original license can be submitted. The mean time from submission of a preliminary permit to approval of an original license application is roughly 6 years for SHPs regardless of whether they are NPDs or NSDs. Since a project owner cannot begin construction until after obtaining a license, the mean time from inception of an SHP concept to commercial operation of a successful project is well over 8 years. With dynamic energy markets and increasingly competitive cost pressure from small-scale solar, wind, and battery installations, long development timelines are a major deterrent to adding SHP capacity to the grid.

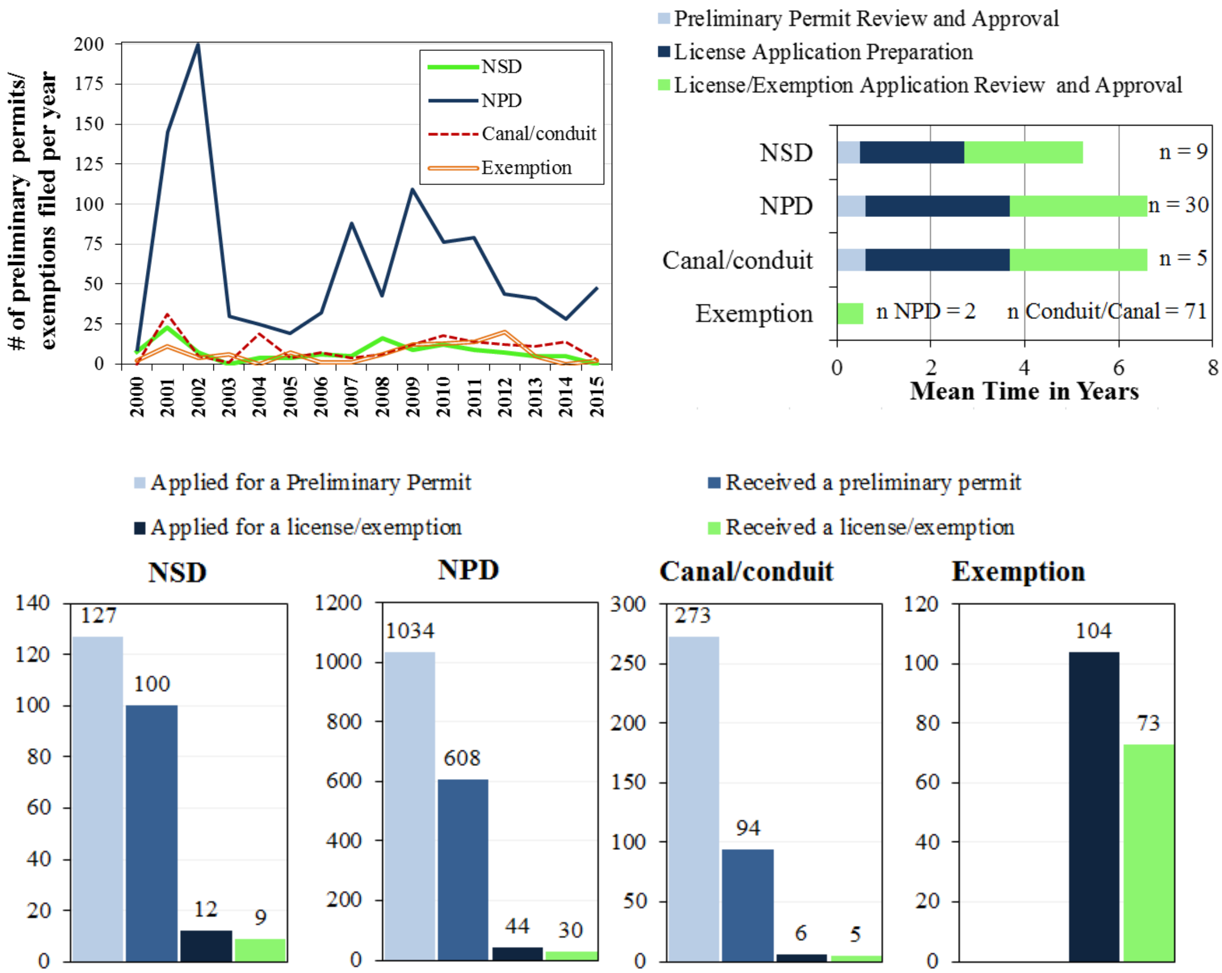


Figure 3. SHP development trends from 2000-2015. Number of preliminary permits/exemptions filed per year (top left); mean time in years for each step of the licensing process (top right); number of applicants that make it through each stage of the development process (bottom). Data from Uria-Martinez, 2017.

There is no single factor responsible for long SHP development timelines and the decline of U.S. Greenfield SHP development. Rather, a mixture of regulatory redundancy and uncertainty, challenging project economics, and environmental complexity often converge to strain the viability of new projects.

- **Regulatory:** The regulatory authorization and approval process for Greenfield SHPs is the same as large hydropower projects. This process has been described as a widely dispersed decision making process, where multiple agencies with mandatory conditioning authority often address similar issues independently (Robinson, 2013). Redundancy in application preparation adds time and cost to development timelines, especially for SHP projects which have fewer kilowatts across which costs can be spread. One apparent result of this complexity is a high rate of attrition (Figure 3, bottom) from preliminary permit application acceptance, where an applicant has no requirement to consult with federal agencies or stakeholders, to submission of a license application, where a potential licensee is required to have completed the consultation requirement, conducted all relevant studies, and established license terms that balance economic and environmental costs and benefits.
- **Economics:** Equipment customization and site-specific design of civil structures are significant cost drivers in small hydro development. The commonly used RETScreen tool estimates roughly 75% of small hydro development costs are site specific, a function of the location and site conditions (Minister of Natural Resources Canada 2004). The cost breakdown of SHP projects by category shows civil works (the cost of site preparation, hydraulic structures, water conveyances, and a powerhouse) as the largest project category cost, followed closely by electromechanical equipment (O'Connor et al. 2015). In general, a non-linear project cost increase is observed with decreasing capacity, driven by a lack of economies of scale. SHPs are thus more expensive to build per kilowatt than larger projects, and consequently, must recover more revenue per installed kilowatt to remain economically viable.
- **Environment:** A hydropower facility interacts continuously with the surrounding water resource environment, causing alterations of varying magnitude to the hydrologic, hydraulic, geomorphic, physio-chemical, and ecologic processes that occur within a river system. To obtain a hydropower license a developer must demonstrate sufficient knowledge of these processes as they are, of how an SHP will impact these processes, and of how an SHP will ensure their integrity is sustained within a suitable impact threshold. Successful navigation of this complex process demands expertise from numerous environmental and engineering disciplines, which can add substantial cost in the pre-revenue phase of development. An unforeseen issue uncovered during this phase could require re-engineering of the initial design or a new mitigation structure. The less that is known about river system processes in early development, the more likely the project is to fail.

In sum, traditional approaches to SHP development are no longer attractive or feasible at the vast majority of Greenfield NSD sites. Such sites, however, form the overwhelming majority of the Nation's existing technical hydropower resource potential - a 2014 study estimates roughly 29 GW of technical NSD SHP potential is distributed across more than 10,000 sites (Kao et al. 2014). The favorable characteristics of SHPs, including renewable and carbon free generation, low operations and maintenance costs, and high reliability, continue to make SHPs a desired source of energy. The SHP problem statement can thus be framed as follows: overcoming the strong headwinds outlined above and sustainably harnessing water resources for hydroelectricity requires a fundamental rethinking of SHP development.

2. Standard modular hydropower (SMH) in a nutshell

With funding from the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy, the standard modular hydropower (SMH) research project began in late 2015 to identify and overcome the challenges faced by SHPs. The purpose of SMH is to fundamentally rethink SHP development in the U.S. with the goal of reducing cost, increasing acceptance, enhancing environmental value, increasing predictability of outcomes, and increasing worth to stakeholders. SMH is not an individual technology or a specific facility design – it is a new way to think about small hydropower.

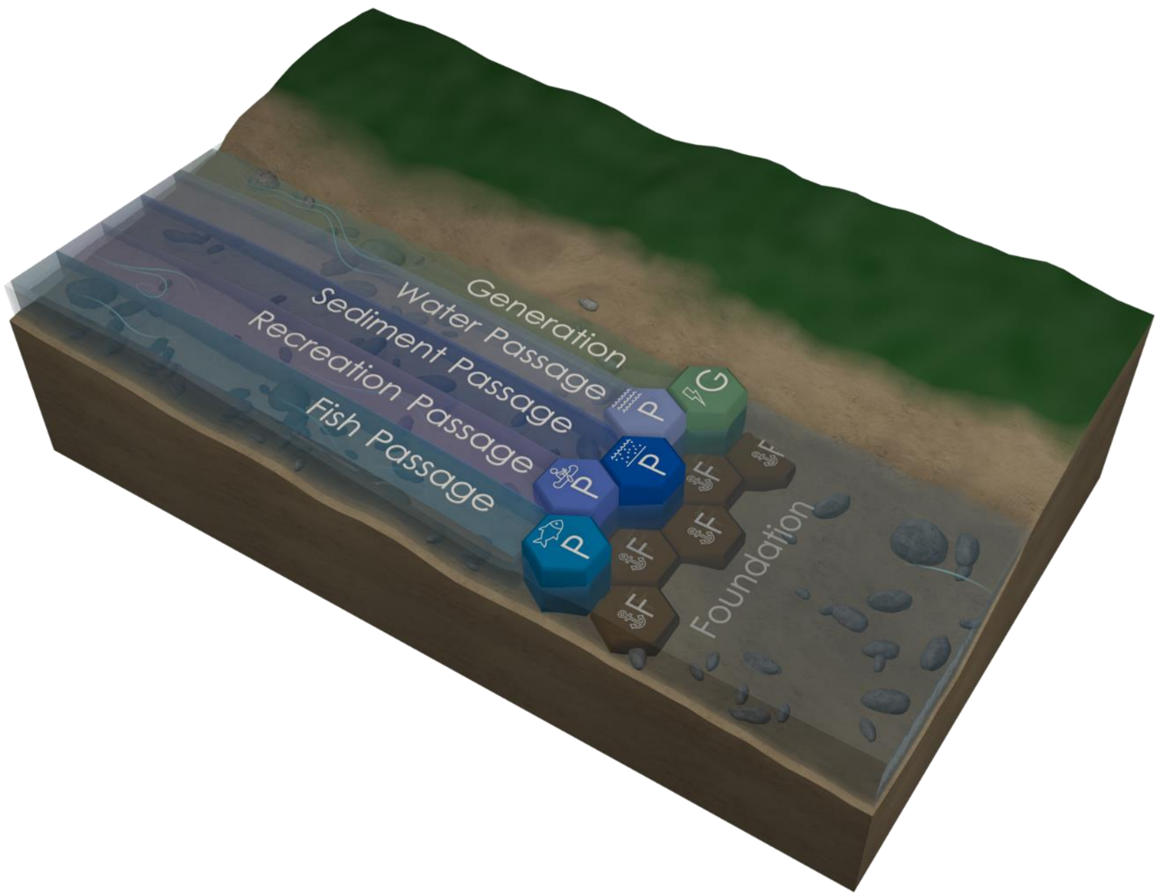
The standard modular hydropower (SMH) concept postulates that standardization and modularity are critical pathways towards environmentally compatible, cost-optimized SHP development. The SMH concept involves several key terms which will be referenced throughout this document:

- stream functionalities: The interactions among and across hydrologic, hydraulic, geomorphic, physiochemical, and ecologic processes that support and restructure the components and attributes of stream systems;
- standardization: A framework of guidelines, rules, and specifications (i.e., standards) implemented to maximize compatibility, acceptance, interoperability, safety, repeatability, or quality and minimize environmental disturbance. In a hydropower context, standardization of site classification, facility design, environmental review, regulation, manufacturing, operations, and maintenance, and other features are intended to reduce site specificity and project costs;
- modularity: The physical or virtual organization of system components into discrete functional units, known as modules;
- environmentally compatible: The preservation or reinstatement of stream functionalities to sustain water quality, water quantity, and ecological wellbeing. In a hydropower context, environmental compatibility should be maintained throughout a project's manufacturing, installation, operation, and decommissioning phases;
- cost-optimized: A design philosophy which emphasizes cost reductions through optimized siting, facility design, module assembly, and plant operation.

A future SMH facility can be conceptualized by deconstructing a small hydropower plant into discrete functional units each with a dedicated purpose and a common interface. Fundamental SMH units are defined as generation, passage, and foundation modules. The generation module contains a turbine, generator, and all equipment and systems necessary to convert moving water into electrical energy. Passage modules, individually or as a group of modules, ensure the safe, consistent, and reliable transport of water, fish, sediment, and small recreational craft across the facility. Foundation modules provide structural resistance and reliably interface with the streambed to support and stabilize generation and passage modules. Additional function-specific modules (e.g., monitoring and control, interconnection, and installation/retrieval modules) will be the subject of future research.

Standardization may be realized in the form of specifications that take local stream functionalities as inputs and convert them into design criteria for individual modules and SMH facilities. Such design standardization would reduce site-specific assessment needs, lower costs through increased design redundancies, and lead to more predictable stakeholder consultation, review, and approval outcomes. Standardization may also materialize in the form of standardized environmental templates, permitting processes, and licensing processes with expedited pathways for environmentally compatible designs.

Modularity in hydropower development may be realized in the form of function-specific modules which, when properly combined, ensure stream functionality. Particular module arrangements will vary from site-to-site; however, the current SMH paradigm envisions a series of generation, passage, and foundation modules which form the basis for modular development. Modularity also enables scalability in two attractive ways: (1) at a single site, by adding modules next to each other, and (2) among sites, through deployment of the same module at multiple sites. A graphical conceptualization of generation, passage, and foundation modules joined to form an SMH facility is shown in Figure 4.



Generation Module	Fish Passage Module	Sediment Passage Module	Recreation Passage Module	Water Passage Module	Foundation Module
Generates hydroelectric power from flowing water under pressure	Allows the unimpeded and safe passage (upstream and downstream) of fish through a SMH facility	Allows the transport of incoming sediment through a SMH facility	Allows the passage of small recreation craft consistently and safely through a SMH facility	Allows the conveyance of non-generating water through the SMH facility	Anchors passage and generation modules to the streambed and banks

Figure 4. SMH facility conceptual diagram (top); brief description of each module objective (bottom).

To organize SMH research, the ORNL team has assembled four coordinated research paths, or pillars:

- **Site Classification Scheme:** organizing a set of watershed, stream, and site attributes with a distinct and standardized classification scheme. The scheme will inform module design and determine which modules are needed to ensure environmentally compatible development and operation of a site;
- **Exemplary Design Envelope Specification:** identifying and specifying the unique module and system functionalities, objectives, requirements, and constraints that define holistic SMH facility design;
- **Simulation and Modeling Capabilities:** enabling improved SMH designs, performance, safety, environmental compatibility, reliability, manufacturability, and cost optimization through computational and numerical models and simulations;
- **Testing and Validation Capabilities:** enabling module design testing and validation at partial or full scale to improve and optimize safety, performance, and reliability.

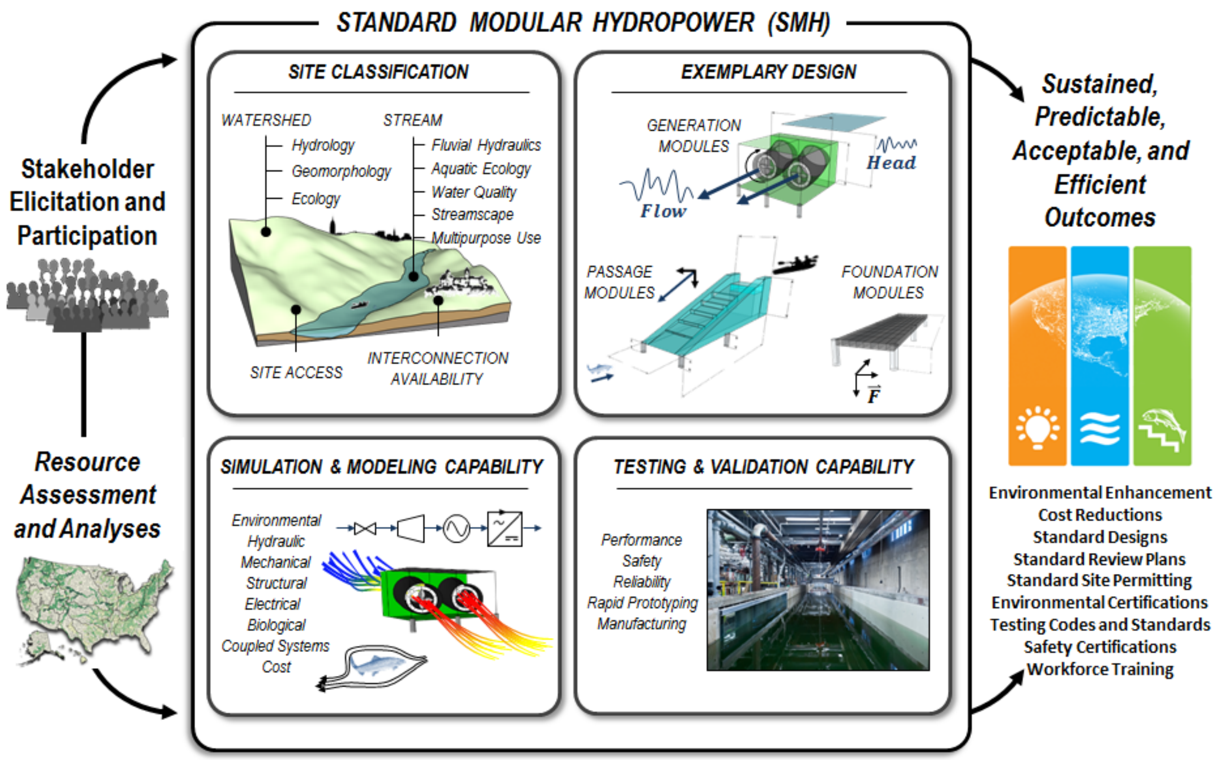


Figure 5. Overview of the relationship between stakeholders, SMH research pillars, and desired outcomes of the SMH research effort.

The research pillars are guided by stakeholder input and knowledge about the existing hydropower fleet and technical resource potential. They are designed to enable sustained, predictable, acceptable, and efficient SHP development outcomes. Individually, the pillars work in combination to identify and classify stream functions, and convert them into module and facility design criteria that fall within a suitable design specification envelope. Simulation, modeling, testing, and validation capabilities provide the means to ensure individual modules meet safety, performance, and reliability criteria.

The remainder of this paper will discuss the site classification pillar, exemplary design pillar, stakeholder engagement activities to date, and the desired outcomes of SMH research.

3. Site classification

Site Classification will address the perception that hydropower development is predominantly site-specific by classifying stream reaches into groups with similar stream and watershed characteristics for the purpose of informing module need (e.g., fish passage or sediment transport) and functionality. Grouping of items (i.e., stream reaches) based on similarities is a common means by which people assess similar issues and scalable solutions when dealing with large numbers of things. In the case of stream reaches, they can easily be classified by mean flow or by steam gradient; however, classifying by individual metrics quickly becomes unwieldy and difficult to interpret. Advanced statistical methods have been developed in recent years that can evaluate multiple characteristics simultaneously and provide groupings (i.e., classifications) that are focused on addressing particular targeted queries depending on the suite of input variables selected. For example, sites or river reaches that have similar stream gradients, hydrology, spawning habitat, and migratory fish species would be expected to have similar fish passage needs and design requirements as defined by the group characteristics.

The specific objective of Site Classification is to develop a framework for classifying potential SMH sites in terms useful for informing SMH consideration, module need, and module design requirements using existing and new classification schemes. The analysis will leverage recent research into ecoregions, stream classification, and prediction of required mitigation to maximize the efficiencies that can result from systematically applying knowledge and rubrics for how environmental and ecological systems respond to disturbances. It is impossible to eliminate all site specificity from hydropower development, but future development efforts should include the judicious application of validated site classification principles to select technology modules most appropriate for a site class, providing greater transparency, clarity, and predictability of outcomes for stakeholders.

Understanding hydrologic responses to instream disturbances will be a critical design constraint for SMH deployment to minimize environmental disruptions. However, the new site potential spans a wealth of streams with various streamflows and hydrologic character driven by regional differences in watershed attributes, climates, and landscapes. The geospatial distribution of known environmental attributes of NSD resources will serve as useful input in the design phase. For example, the distribution of certain hydrologic classes across the United States (McManamay et al. 2014) identifies groups of streams with similar hydrologic properties that may respond in predictively comparable ways to hydro development. Certain classifications may exhibit ecological patterns that span multiple potential hydropower sites, and a common passage module would be of benefit. Similarly, certain regions may share similar watershed characteristics that can be used to identify potential sediment transport inputs and sediment passage needs.

Results of the site classification will be used to inform module selection and exemplary design in a variety of ways. The characteristics that define various classes will provide an envelope or range of module design requirements. The number of sites or amount of stream reaches represented in various classes will be used to help identify which modules and design features should receive priority in design consideration. Site classification will also inform the testing and simulation pillars.

3.1 Analytical Methodology

Site Classification will incorporate multivariate statistical methods such as k-means clustering or decision tree analysis to classify or cluster stream reaches into groups based on a simultaneous consideration of 10-

20 attributes of those sites. Site Classification will be conducted for each of the design modules being considered (e.g., generation, fish passage, boat passage) with a suite of variables specific to each module to help determine which modules are needed and what specific design requirements should be considered.

In addition to using ORNL's National Hydropower Asset Assessment Program database that provides extensive national coverage of a variety of available environmental attributes and other publicly available databases, this analysis might also incorporate existing classification schemes, such as a hydrologic classification of streams (McManamay et al. 2014) and geomorphic stream classification (Rosgen 1994).

3.2 Example Classification

Classification of streams into water quality clusters will inform whether SMH development would likely result in additional water quality issues that would need to be addressed or alternatively have opportunties to include water quality improvement in project design to improve existing water quality. The initial attempt at classification based on water quality included ~11,000 stream reaches (a subset of the nearly 350,000 stream reaches that meet some minimal criteria for SMH consideration) classified into nine clusters based on 10 variables that influence local water quality. These variables included: stream order; mean annual flow; density of registered pollution sites; and the amounts of impervious surfaces, forested, and agricultral land cover. The resulting clusters can each be characterized based on the average values of the variables within each cluster (Table 1); streams that form clusters 7, 8, and 9 are shown in Figure 6. Classification for water quality and other modules will continue to evolve as we gather better datasets.

Table 1. Characterization of nine clusters of 11,390 representative stream reaches from across the US based on water quality 10 variables.

Cluster	Number	Characterization
1	940	Largest rivers, high flow, suburban, poor WQ
2	1,537	Medium size, suburban, poor WQ
3	1,029	Medium size, rural, agricultural
4	840	Medium-large, urban rivers, poor WQ
5	1,891	Medium size, forested ag mix, hilly terrain
6	1,659	Large rural rivers, flat terrain, good WQ
7	1,617	Small, forested, rural, good WQ
8	962	Small, urban streams, poor WQ
9	915	Small-medium size, high agriculture

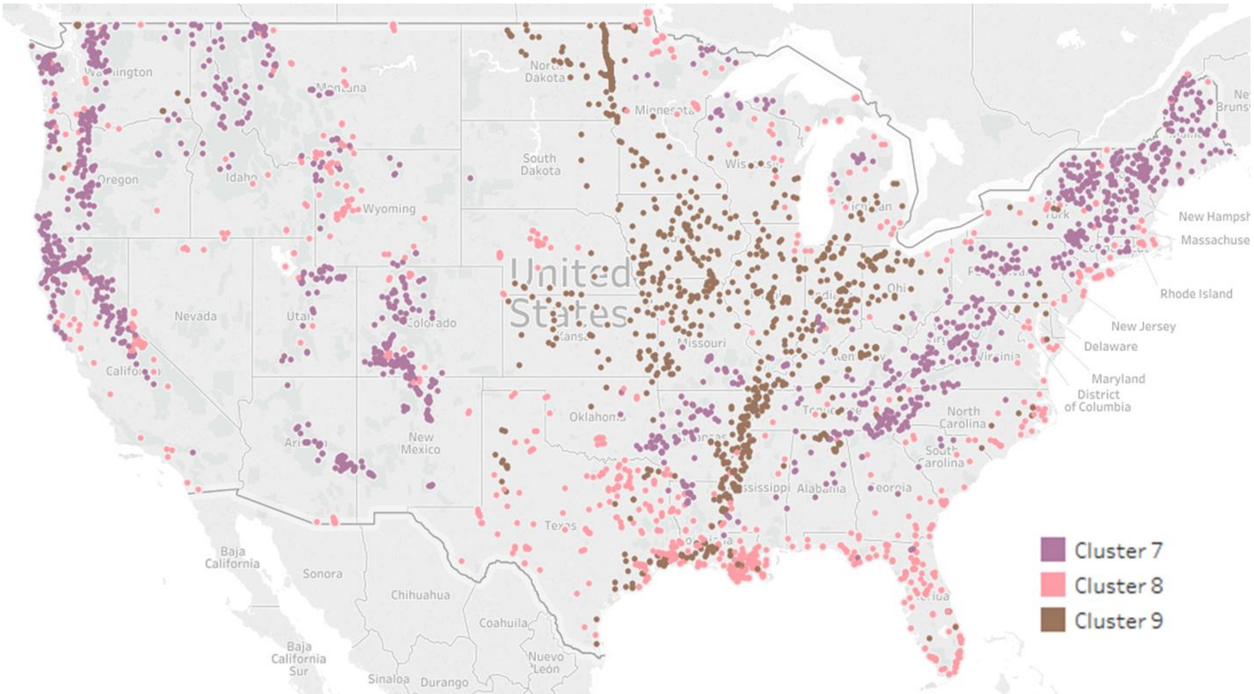


Figure 6. Map of three of the nine clusters of stream reaches based on various stream and watershed characteristics that are indicative of water quality.

4. Establishing an SMH facility exemplary design envelope specification

In the *New Pathways to Hydropower* industry report (Bishop et al. 2015), effective site selection is cited as "perhaps the single most important aspect in development of a small hydropower project." Site selection requires[2] both knowledge of the stream functions at a site (i.e., Site Classification), and an understanding of how a facility will interact with and alter those stream functions. Exemplary design envelope specification within the SMH paradigm sits in this role – converting stream functions into facility objectives, operational strategies, and design criteria to ensure environmental compatibility. It is intended as a tool to develop design concept alternatives and to assess the suitability of particular modular facility arrangements for unique stream contexts.

As discussed in Section 2, the SMH definition of stream function is the interactions among and across hydrologic, hydraulic, geomorphic, physiochemical, and ecologic processes that support and restructure the components and attributes of stream systems. This definition is synthesized from numerous frameworks developed by scientists and engineers that promote a function-based approach to stream assessment, stream restoration, and hydropower facility interactions with the stream environment (see e.g., Fischenich 2006; Escobar-Arias and Pasternack 2010; Harman et al. 2012; Yarnell et al. 2015). These frameworks have arisen in recent years to improve the outcomes of stream restoration projects and hydropower environmental flow prescriptions - conventional approaches that rely on restoration or maintenance of stream dimension, pattern, profile, and/or discrete minimum flow values do not sufficiently maintain stream function. The same can be said for conventional approaches to new SHP development – SHP designs that optimize power potential by maximizing head and severely regulating flow regimes at a site disrupt stream functions in ways that are unacceptable to many stakeholder. The SMH hypothesis assumes a broader understanding of stream function can guide modular SHP development to produce lower cost facilities that are more widely accepted in the broader stakeholder community.

Identification of stream functions begins with an understanding that a suite of hierarchically nested stream system processes operate over widely varying space and time scales. These individual processes are defined as (following Harman et al. 2012 and others) :

- **Hydrologic –** the supply and transport of water from watershed to channel;
- **Hydraulics –** the transport of water in the channel, on the floodplain, and through sediments ;
- **Geomorphic –** the transport of wood, sediment, and soils and evolution of channel shape;
- **Physiochemical –** the regulation of temperature and water chemistry and processing of organic matter and nutrients;
- **Ecologic –** the distributions, abundance and relations of aquatic and riparian species and their interactions with the environment.

Hydrologic and hydraulic processes can be considered the lifeblood of the stream system – the supply and transport of flow and flow energy is the medium through which geomorphic, physiochemical, and ecologic processes evolve. For example, the energy in flowing water initiates sediment movement and shapes channel structure over time. Flowing water transports nutrients delivered from the watershed and assimilates them into the stream over distance and time. Aquatic species navigate channel structures and

[2] In addition to other important factors such as geotechnical characterization of the subsurface, interconnection requirements, and local power system economics. These factors will be the focus of future research efforts.

flow fields in various ways throughout their lifecycle. The interlinkages, dependencies, and feedback between and among processes drives ecosystem complexity.

As described in Section 3, site classification within SMH is a method to organize ecosystem complexity by identifying and classifying stream characteristics on a local, or reach scale. Site classification serves two primary purposes: (1) it attempts to identify the presence or absence of a particular function, or of indicators of a particular functionality in a stream reach, and (2) it classifies stream reaches with similar characteristics into distinct groups. The implications for exemplary design are twofold: (1) the state of the stream establishes a design baseline from which facility objectives for generation and passage can be formulated and assessed, and (2) it enables scalability of module designs – design criteria for a particular module type (e.g., upstream fish passage or sediment passage) can be applicable at multiple sites that fall within the same site classification cluster.

The conversion of site classification into SMH facility objectives, operational strategies, and design criteria is a multi-step, integrated process that requires engineering and scientific judgment, multi-disciplinary decision making, knowledge transfer across disciplines, and integrated modeling and assessment tools. This process is outlined in Figure 7 and described in more detail below.

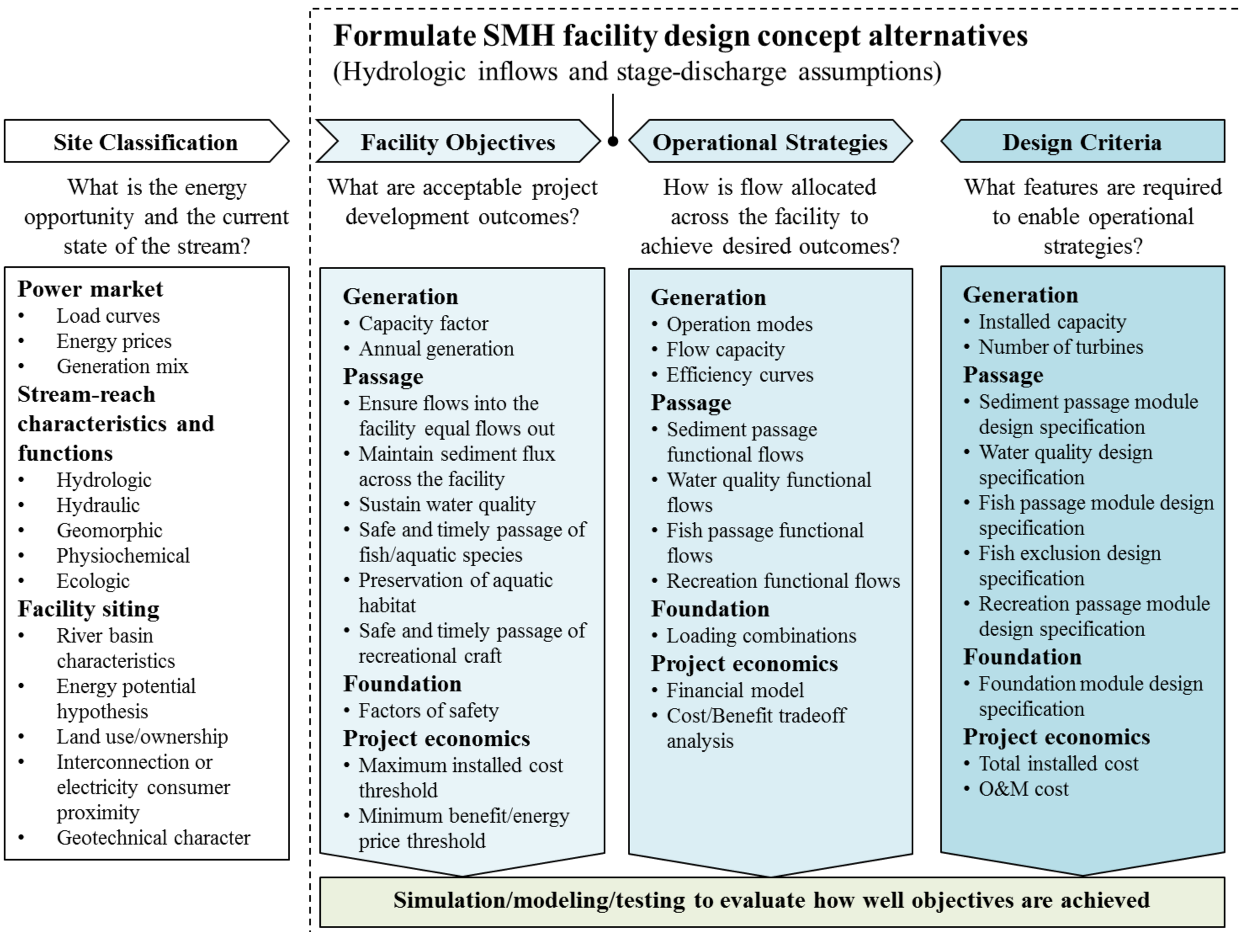


Figure 7. The conversion of Site Classification outcomes into an Exemplary Design Envelope Specification (enclosed by the dotted line), supported by simulation, modeling, and testing capabilities. Several objectives, strategies, and criteria are provided as examples.

4.1 Facility objectives

Based on the energy opportunity and the state of the stream, SMH facilities must establish clearly defined generation, passage, foundation, and economic objectives. An SMH facility objective must have the following elements:

- Objectives must be based on attributes or variables of the stream obtained from measurements, stream assessment or classification methodologies, or from comparisons to reference reaches with similar water resource characteristics;
- Objectives must be measurable and verifiable, and;
- Objectives must be accompanied with a specification for where, when, and how well they must be accomplished.

Generation objectives take the form of minimum thresholds that must be achieved to satisfy generation and economic expectations. SMH facilities are primarily energy infrastructure projects. The goal is to produce power at competitive cost, and thus objectives should relate to power, how often it should be available, and how much can be supplied.

Passage objectives take the form of minimum or maximum thresholds of acceptable performance or alteration that relate alteration of hydrologic and hydraulic regimes to geomorphic, physiochemical, and ecological variables. Some common existing threshold relationships for hydropower facilities include water quantity, sediment transport, water quality, fish passage, aquatic habitat, and recreation. Though these objectives will vary as a function of site classification, a few examples are offered below.

- **Water quantity:** most small hydropower facilities operate as run-of-river facilities, where flows into the upstream reach must equal the combined flows at the toe of the structure from generating and non-generating equipment and structures. This objective ensures the natural flow regime downstream of the facility is retained, a critical objective for sustaining stream health (Poff et al. 1997).
- **Sediment transport:** while small hydropower facilities and dams do not disrupt sediment regimes as much as large structures, they have the ability to trap sediment and deprive downstream reaches of critical habitat components and drivers of fluvial geomorphological evolution. A sediment transport objective may be to maximize sediment transport by limit the trapping efficiency of the structure, defined as the fraction of total incoming sediment retained by the reservoir. Trapping efficiency is a function of the settling velocity of sediment particles and the retention time of the impounded reach (Verstraeten and Poesen 2000). Maximum threshold values for retention time may be established based on the size of sediment estimated from site classification.
- **Fish and aquatic species passage:** the establishment of fish passage objectives passage will rely heavily on site classification, which may provide the species type, life stage, run size, period of migration, and spawning location and timing for particular fish species known to be present in a stream reach. Based on these values, a determination will need to be made as to whether installation and operation of a fish passage module is desired. If so, the fish passage objective is to ensure safe and timely (i.e., limit delays) passage through a pre-engineered fishway (following Fisheries 2008).

Foundation objectives are established to ensure the facility can maintain stability and resist loads imposed upon it. The conventional method to ensure hydropower foundation objectives are achieved is also adopted for SMH designs - satisfaction of factors of safety against overturning, sliding, and flotation.

Project economic objectives set targets for costs and benefits. A maximum total installed cost for all modules should be established. In turn, a minimum energy price or target should be established to enable a preliminary cost-benefit analysis.

4.2 Formulate SMH facility design concept alternatives

With a robust list of facility objectives established, some SMH facility design concepts can be established. The goal of this step is to put the right facility 'blocks' into place, e.g., passage, generation, and foundation modules with rough proportions and assumed functionalities based on facility objectives. One example of a facility design concept is provided in Figure 8. Different passage module types on the left side are intended to meet fish and water passage objectives, while generation modules on the right side are selected to meet a minimum capacity factor. Foundation modules provide stability for generation and passage modules. The most important input variables to determine at this point are hydrologic inflows and assumed stage-discharge relationships, as they will be used to approximate how and how much flow passes through each module. These relationships will also guide the development and assessment of operational strategies for each module and the facility.

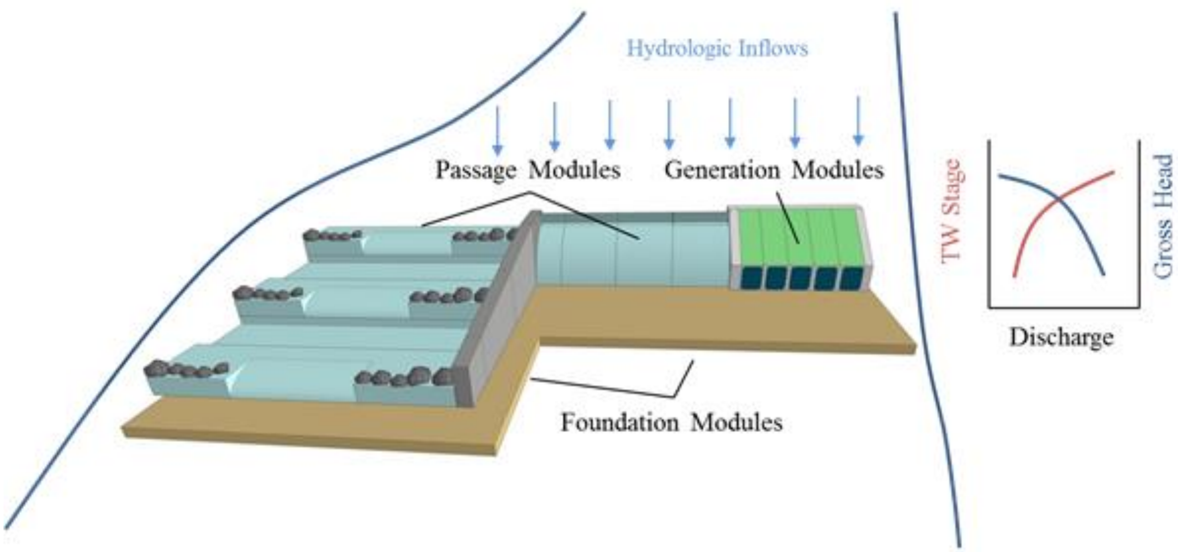


Figure 8. Example of an SMH facility design concept.

4.3 Operational strategies

SMH operational strategies are manifest as rules that allocate flow across the facility. They take hydrologic inflows and distribute them across modules based on facility objectives. These strategies are termed 'functional flows', as they are primary mechanism through which hydrologic and hydraulic processes at the reach scale can be engineered by an SMH facility to sustain geomorphologic, physiochemical, and ecologic processes and their interactions upstream and downstream (i.e., stream functions). A functional flow incorporates flow variables such as discharge, depth, and velocity at locations upstream, downstream, or across the structure, and relates them to specific non-generation objectives.

For functional flows to be effective, they must target a specific disturbance pathway from the facility (e.g., sediment trapping behind facility, physical barrier to fish movement, low dissolved oxygen in impounded reach) at defined time and space scales, and be developed as a function of the existing hydrograph of the potential site or of the reference reach used to establish the facility objective. This concept has been developed with relative success to prescribe environmental flow regimes at existing dams. For example, Shafroth and Beauchamp (2006) identified functional flow targets for the Bill Williams River below the Alamo Dam in Western Arizona. They established ‘building blocks’ that linked ecology to dam releases (Figure 9), with the objective of restoring natural flow variability in downstream reaches.

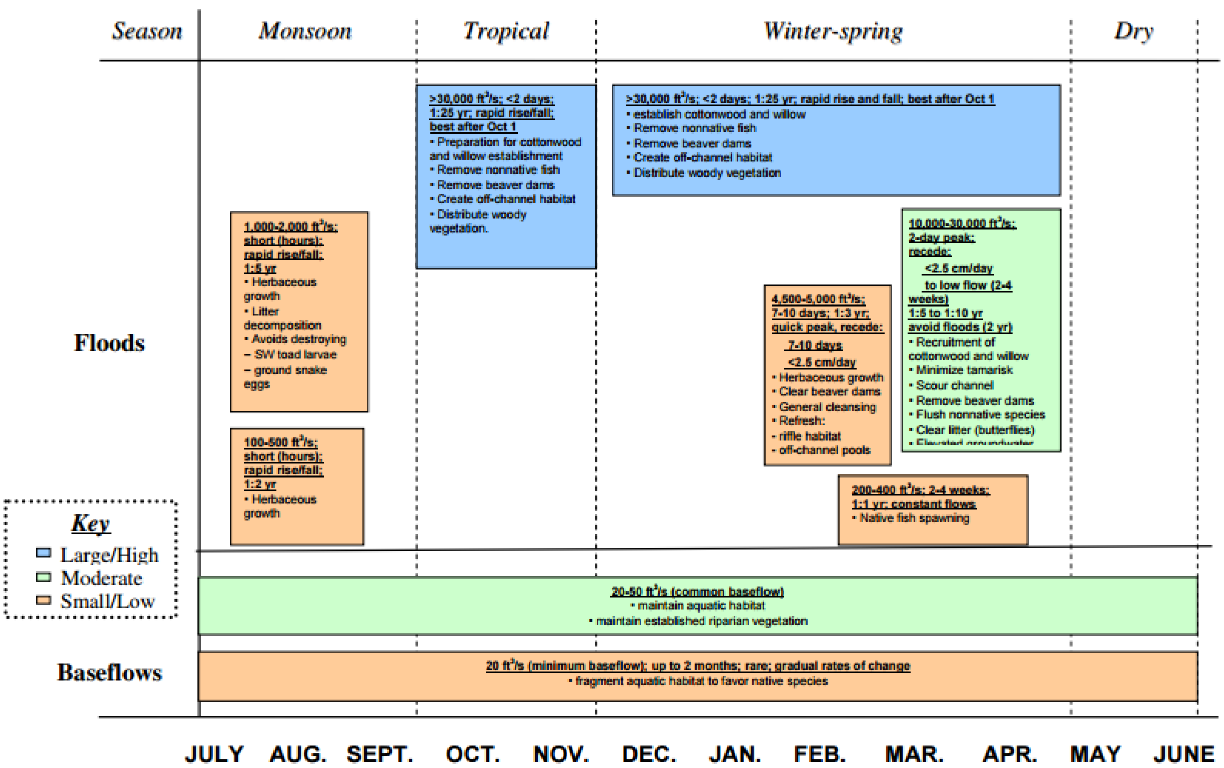


Figure 9. Unified flow requirements for the Bill Williams River, Ariz (Shafroth and Beauchamp, 2006).

A similar approach is envisioned for SMH facilities, where blocks of functional flows are prescribed for a site based on site classification and facility objectives. An example is shown in Figure 10, depicting a facility with two generation modules and several passage modules. The first generation module targets most of the annual flow, while the second operates during high flow periods in the early and late calendar year. The upstream fish passage module functions during spring migration season, while the recreation passage module functions during canoe/kayak season. The sediment passage module is active during high flows when sediment is transported, and does not function when sediment is not moving in the stream.

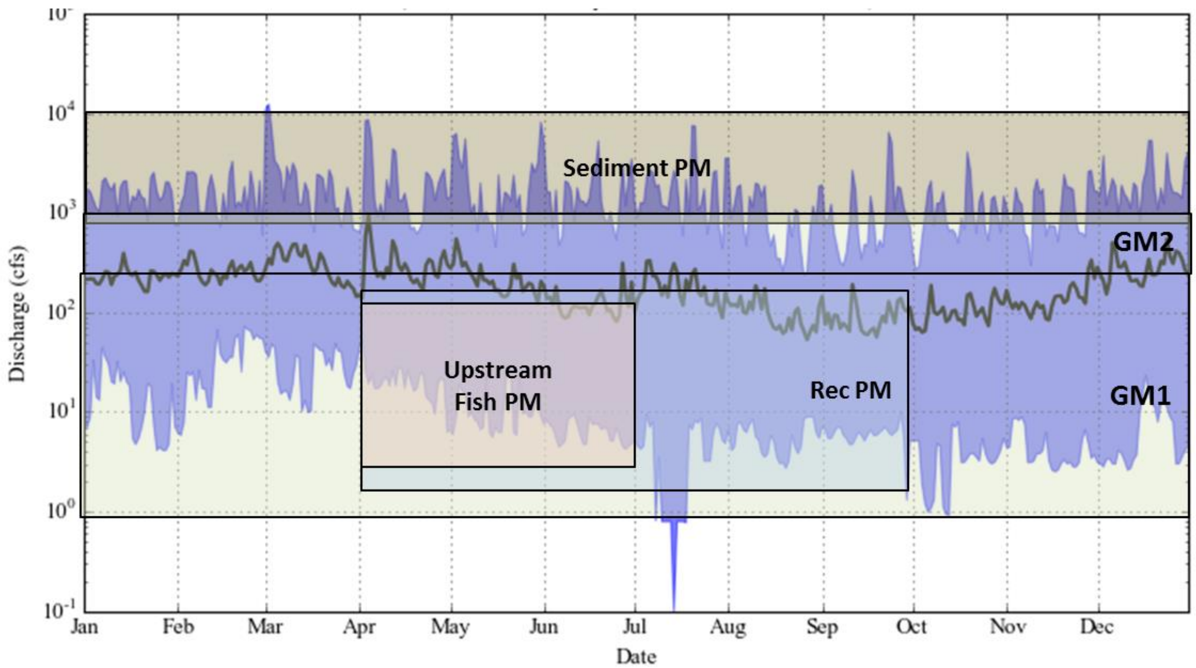


Figure 10. Example of operational strategies (functional flows) for an SMH facility with two generation modules and a sediment, upstream fish, and recreation passage module. The solid black line shows a 30-year average daily discharge, while the blue filled area represents daily observed minimum and maximum values over the same time period. Each module 'block' represents the temporal and discharge targets for implementing functional flows through the module. PM = passage module, Rec = recreation, GM = generation module.

The operational strategies established for generation and passage modules will produce inputs for foundation modules and project economics. Loading combinations on passage and generation modules serve as inputs to foundation module factors of safety analysis, while energy generation estimates feed the project economics benefit estimation.

4.4 Design criteria

Design criteria are specific standards for the physical dimensions, shapes, or components of a module. The role of ORNL in the SMH project is not to design an ideal facility or modules, but to establish the exemplary design envelope specification for modular technologies. Technology developers, specifically generation, foundation, and passage module innovators, will interface with ORNL at the design criteria step to explore how their designs are compatible with the broader exemplary design envelope specification. To help guide this effort, ORNL has established a technical document, the Exemplary Design Envelope Specification for Standard Modular Hydropower Technology (Witt et al., 2017), which outlines general design criteria for modules. It is anticipated that technology developers will use this document as a springboard to enter into SMH facility exemplary design.

It is anticipated that smaller modular facilities will exhibit smaller environmental footprints, and that standard facility design criteria and guidelines may be developed for a limited subset of site classes. For example, the National Oceanic and Atmospheric Administration has developed standard design criteria for fish ladders that may be applied in design without significant modification for stream with annual average flows between 500 and 5,000 cfs (Fisheries, 2008).

4.5 Simulation, modeling, and testing to validate the design envelope

Design criteria, operation strategies, and facility objectives for SMH can only be deemed feasible if they are supported and validated by models, simulations, and testing. ORNL has recently completed the Simulation and Modeling Capability for Standard Modular Hydropower (SMH) Technology, a technical report providing insight into the concepts, use cases, needs, gaps, and challenges associated with modeling and simulating SMH technologies (Stewart et al., 2017).

By identifying priority simulation use cases, a suite of modeling capabilities is documented for evaluating, predicting, and optimizing the safety, performance, reliability, and cost of SMH facilities, individual SMH modules, and module combinations. The current gaps and challenges associated with simulating critical SMH processes highlight opportunities to improve the state of hydropower modeling with a goal of increasing small hydropower development while maintaining the power and function of the natural stream. This simulation and modeling capabilities will be put to use in upcoming collaboration with specific SMH partners.

5. Perspectives from the small hydropower stakeholder community

Hydropower is perhaps the most unique renewable energy resource in terms of the diverse stakeholder groups participating in the design, acceptance, approval, and success of plant development. Consequently, elicitation of stakeholder perspectives and experiences is a vital SMH project goal.

To define and refine the SMH paradigm, ORNL has been conducting discussions with a subset of small hydropower stakeholders - technology innovators, suppliers of commercialized services and technology, and project developers and owners - with distinct perspectives, expertise, and experiences. Each conversation was structured as a one hour discussion centered on a set of 10 questions. The goal of these discussions was to learn more about the current state of the small hydropower development landscape, understand how to best incorporate and align small hydropower community needs and ideas into SMH research activities, and identify challenges, risks, and opportunities for improvement in the design, assessment, optimization, and deployment of SHPs.

Stakeholder feedback received to date has provided valuable insight into how stakeholders understand the SMH concepts and approach, including candid feedback on how to improve the concept based on industry experience. Major challenges identified by stakeholders for SMH to focus on include:

- Validation as a means to achieve broad stakeholder understanding and acceptance:
    - There is a significant need to obtain validation before a new technology or approach is deemed acceptable. Stakeholders suggested that in order to obtain validation, either for their technology and/or SMH, they would focus on working with local interested parties to validate the (module) design and installation to ensure cost effectiveness, minimal environmental disturbance, and quick approval. As an example, one stakeholder's largest concern is safe passage of small recreational craft; thus, they would advise demonstrating how a modular approach ensures safety at a low-head dam site using testing and modeling efforts with prospective developers. Another concern is the irregularity of environmental impacts, as they may be smaller or larger, depending upon the site. Obtaining broad understanding and acceptance requires a direct relationship with regulatory bodies to validate the environmental performance of modular facilities. Modular designs will usher in new conversations about what projects need to achieve to be considered pre-approved on the basis of minimal environmental disturbance.
- Streamlining permitting and regulatory compliance process:
    - In addition to standardization of technology design, stakeholders expressed a need for standardization in licensing processes. Standardizing and streamlining the requirements, assessments, and approvals needed to obtain an original hydropower license would reduce many cost and risk drivers from current practice, which often required specific, one-time analyses. Identifying state-level stakeholders from the inception of the project may help accelerate review and approval of specific modules if a technology developer can demonstrate their effectiveness at meeting facility objectiveness. Many stakeholders agreed having regulatory participation at the onset of a project development effort, and, by extension, involved in the early stages of the SMH project, will help facilitate the communication of regulatory needs and concerns that project developers must address in order to secure investment and get headway on a project.
- Mitigating commonly encountered environmental concerns:

    - Stakeholders would like to implement modular, standardized designs for a flexible and more non-invasive approach for native fish species passage, as opposed to a one-size-fits-all approach. Some stakeholders expressed concerns about engineered fishways – if the design does not work, the structure is already cast in concrete and difficult to change or remove. Discussions emphasized tailoring water and environmental objectives to the local watershed fish species and indexing project sites based on fish species to know which standard set of technology packages is the best option, as opposed to choosing the design based on another fish species.
    - One stakeholder has internally created their own standard incline screen design with a large surface area and low velocity for downstream passage that protects the fish/eels from entering the turbines. They purchased their own machine tool and can now produce plastic-based screens at significantly reduced cost.
    - Stakeholders agreed that modularity is important for driving down material costs and making site screening easier and more cost effective. There was a clear need for (1) standardizing environmental assessments (typically for maintaining dissolved oxygen levels) that are required for new development and existing sites, since the number of assessments can be cumbersome and costly, and (2) using modular technology for minimizing disturbances to the watershed.
- <u>Economic feasibility of small hydro projects:</u>
    - Navigating the hydropower regulatory process, licensing costs, and identification/satisfaction of state/federal environmental standards are challenges that strain the budgets of new small hydropower developers. The number of necessary assessments, and the costs to conduct them, present insurmountable barriers for bringing projects online. Stakeholders would like considerable collaboration across regulatory bodies (state and federal), project developers, and local stakeholders early on. For example, the environmental studies alone can take up to a minimum of 5 years to address all stakeholder issues during the relicensing process for an existing project. New small hydropower projects that have yet to generate revenue can rarely support these development timeframes.

Additional feedback revealed some interesting perspectives on the state of small hydropower development:

- <u>Standardization and modularity are currently being defined and used in interesting ways:</u>
    - Powertrain and civil works developers are using standard and modular designs to cut costs by eliminating custom engineering and design. Turbine developers are building units with predetermined ranges of capacity and heads to develop a catalogue of off-the shelf technology available to project developers. A standard turbine unit can be more easily obtained and is economically preferable to a custom unit, even if it does not maximize the efficiency associated with a site's hydrologic characteristics. In some cases, project design specifications may be tweaked to accommodate existing turbines that are readily available.
    - Site-specific civil works can account for a large portion of overall project cost. Precast concrete modules to be used in small dams and powerhouses are being developed to eliminate the need for on-site manufacturing and site-specific designs. These current efforts to utilize standardization and modularity in small hydro development by industry

members strongly supports the SMH work statement and provides an illustration of what a future SMH project could look like.

- Certain stakeholders are forced to act as both technology developer and project developer:
    - New technology developers may be forced into a project developer role to validate and test the performance of their specific designs. Those with new and innovative designs for small hydro powertrains and civil structures tend to find themselves in the unfortunate situation of having nowhere to install it. Furthermore, the hydro industry is mature and safety-centric - existing and new projects tend to favor proven and reliable technology utilized in the industry for decades over newer designs that have yet to prove their worth. This causes technology developers to take on an additional role as project developer and actively seek out potential projects and develop them just to install their designs and prove their effectiveness. This greatly hampers the resources of technology developers, creating a bottleneck on innovation in the industry.
- Some aspects of SHP development success are not necessarily scalable or transferable:
    - Some stakeholders have developed a successful business model using proprietary modular and standard techniques for small hydropower development. These stakeholders lower development costs by minimizing the layers of acquisition and number of vendors (i.e., fewer and local contractors and sub-contractors), and by implementing many duties in-house, including technology negotiating and purchasing, civil works construction, and fabrication of small components. These practices are not necessarily scalable, rather, they are enabled by extensive experience in the small hydropower industry that provides a developer with a sense of what techniques/approaches/solutions are likely to work, and which should be dismissed or modified early in the development process.
    - Other strategies for modular development include targeting multiple sites within the same watershed or river basin. In general, these sites exhibit similar environmental features, they may be amenable to similar environmental treatment, and they may be developed with similar modular technologies.
- Pre-approved standardized modules:
    - Pre-approved standardized interconnection modules would help reduce the cost and engineering complexity that results from customization and needing to comply with IEEE standards. One approach would be to develop a standardized package and electrical interface that takes electrical output from a generator and converts it to a voltage appropriate for a distribution line or an electricity end-user. This standardized module could make the small hydropower industry more cost-competitive and make plants easier to develop by emulating the "plug-and-play" ability of solar and wind technologies.

Collaboration between the SMH team and stakeholders is facilitating knowledge transfer and solidifying major challenges that need to be overcome during the full lifecycle of project development. Stakeholder engagement provides a platform for active communication between the SMH team and stakeholders as well as an opportunity for mutually beneficial collaboration. In the future, more formal collaboration mechanisms will be pursued with select stakeholders to accelerate the realization of important SMH goals.

6. Enhancing the environmental, economic, and social benefits of new development

If current trends are an indication of the future state of small hydropower in the U.S., it is clear that few, if any, new Greenfield SHPs will be supplying renewable energy to the grid in coming decades. In fact, the recent *Hydropower Vision* report (DOE, 2016) used advanced power system modeling to conclude no deployment of new hydropower projects will occur over the next 30 years under a business-as-usual modeling scenario. The SMH research project seeks to alter this trajectory by incorporating modularity, standardization, and preservation of stream functionality into a new development paradigm.

As outlined in previous sections, the SMH project attempts to prove that standardization, modularity, and stream functionality are essential pathways for hydropower technology cost reduction. Deployment of new SHPs relies not only on lowering costs, however, but on demonstrating the value of hydropower as an energy resource, and of hydropower facilities as beneficial for the environment, for project owners, and for society. Consequently, SMH facilities may have opportunities to enhance the environmental, economic, and social benefits of new development compared to conventional approaches.

<u>Environmental benefits:</u>

- Improving stream health - strategically selected generation and non-generation objectives may be implemented together to sustain or improve local environmental conditions, such as groundwater recharge, sustained low baseflows, and floodplain inundation. Modules could incorporate a suite of embedded sensors and operate as a monitoring platform for wider area analysis, providing detailed data on water quality trends, sediment passage evolution, and fish passage that has high social and academic value.
- Potential for water quality improvements – embedded sensors that detect periods of low dissolved oxygen could trigger operation of a water quality improvement module, such as an aerating turbine.
- Recreation passage modules – passage of kayaks and canoes at hydropower plants rarely occurs across the facility, though several canoe and kayak chutes have been successfully deployed at weirs and small hydropower plants in Europe. Safe, consistent, and cost-effective recreation passage modules could provide unique recreation opportunities that improve project acceptance.

<u>Economic benefits:</u>

- Lower costs through modularity – pre-fabrication of facility modules offsite could enable accelerated project development timelines, and reduce the need to work 'in-the-wet'. Shorter project timeframes and reduces risk during construction could drive some cost reductions in the development phase.
- Lower risk and uncertainty in development process through standard development templates – if broad acceptance of the SMH concept is achieved, standard development templates for certain classes of SMH sites may lead to accelerated development timelines and stakeholder acceptance, which could ultimately reduce the risk of development.
- Leverage growing desire and incentives for distributed energy resources – recent shifts toward development of distributed energy resources have largely ignored small hydro, despite favorable energy characteristics. SMH facilities capable of deploying with wider acceptance and low environmental disturbance may open new pathways for hydropower development. Currently, many state renewable portfolio standards (RPS) do not consider new hydropower facilities

eligible, as the Low Impact Hydro Institute, the certification entity often used to determine hydropower eligibility for RPSs and renewable energy credits, excludes new dams or diversions from certification consideration. Demonstration of an SMH facility and validation that it can achieve generation and non-generation objectives would be a powerful tool to reconsider the value of SHPs in incentive programs.

Social benefits:

- Strengthen project acceptance with mutually beneficial and acceptable outcomes – success in the SMH research concept would be demonstration and validation of a widely accepted project that saw multiple stakeholders unified over facility objectives and operational strategies. If this model could be scaled to additional facilities the hydropower industry could significantly enhance relationships with multiple stakeholder groups and improve public perception of hydropower as a sustainable and highly desired form of energy.
- Job creation and knowledge transfer – a significant lack of new SHP development over the past few decades has translated into a limited number of new hydropower jobs. The industry is often cited as mature, with a workforce that is nearing retirement. A new wave of widely accepted SHP development could create jobs across multiple technology, construction, and environmental sectors while acting as a conduit for knowledge transfer from current industry experts to a new generation of hydro professionals.
- Better stream health sustains social connections with the environment – hydropower facilities that are seen as fully integrated and compatible with the environment could offer significant potential for outdoor recreation activities that sustain social connections to the stream, such as hiking, fishing, and rafting.

7. Final thoughts

A standardized approach to modular hydropower development requires a high degree of knowledge sharing and collaboration across stakeholder groups - engagement is currently underway in numerous forms and the ORNL team is seeking potential partners for future SMH research. For more information on SMH research and potential partnership opportunities, please contact the authors or visit http://hydropower.ornl.gov/smh/.

8. References

Bishop, Norm Jr., Deborah Linke, Carl Vansant, Chuck Alsberg, Jay Anders, Ali Grovue, Sarah Hill-Nelson, et al. 2015. “New Pathways for Hydropower : Getting Hydropower Built — What Does It Take?” Oak Ridge National Lab - ORNL/TM-2015/48.

Department of Energy (DOE). 2016. Hydropower Vision Report. Available at https://energy.gov/eere/water/new-vision-united-states-hydropower

Escobar-Arias, M I, and Gregory B Pasternack. 2010. “A Hydrogeomorphic Dynamics Approach to Assess In-stream Ecological Functionality Using the Functional Flows Model, Part 1—model Characteristics.” River Research and Applications 26 (9). Wiley Online Library: 1103–28.

Fischenich, J Craig. 2006. “Functional Objectives for Stream Restoration.” DTIC Document.

Fisheries, NOAA. 2008. “Anadromous Salmonid Passage Facility Design.” NMFS, Northwest Region, Portland, Oregon.

Harman, William, Richard Starr, Melanie Carter, Kevin Tweedy, Micky Clemmons, Kristi Suggs, and Christine Miller. 2012. “A Function-Based Framework for Stream Assessment and Restoration Projects.” US Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds, Washington, DC EPA.

Kao, Shih Chieh, Ryan McManamay, Kevin Stewart, Nicole Samu, Boualem Hadjerioua, Scott DeNeale, Dilruba Yeasmin, M. Fayzul Pasha, Abdoul Oubeidiilah, and Brennan Smith. 2014. New Stream-Reach Development : A Comprehensive Assessment of Hydropower Energy Potential in the United States. http://nhaap.ornl.gov/sites/default/files/ORNL_NSD_FY14_Final_Report.pdf.

McManamay, Ryan A., Mark S. Bevelhimer, and Shih-Chieh Kao. 2014. "Updating the US hydrologic classification: an approach to clustering and stratifying ecohydrologic data." *Ecohydrology* 7.3: 903-926.

Minister of Natural Resources Canada. 2004. Small Hydro Project Analysis, Clean Energy Project Analysis: RETScreen Engineering & Cases Textbook.

O’Connor, Patrick, Katherine Zhang, Scott T Deneale, Dol Raj Chalise, and Emma Centurion. 2015. Hydropower Baseline Cost Modeling. Oak Ridge, TN: ORNL/TM-2015/14.

Poff, N Leroy, J David Allan, Mark B Bain, James R Karr, Karen L Prestegaard, Brian D Richter, Richard E Sparks, and Julie C Stromberg. 1997. “The Natural Flow Regime: A Paradigm for River Conservation and Restoration.” BioScience 47 (11): 769–84. doi:10.2307/1313099.

Robinson, J. 2013. "Six Steps to Advancing Hydropower Development," Hydro Review, Volume 32, No. 3. Retrieved from < http://www.elp.com/articles/print/volume-91/issue-4/sections/six-steps-to-advancing-hydropower-development.html>

Rosgen, David L. "A classification of natural rivers." *Catena* 22.3 (1994): 169-199.

Samu, Nicole, Shih-Chieh Kao, and Patrick O’Connor. 2016. “National Hydropower Plant Dataset, Version 1.” Existing Hydropower Assets, 2016 (FY16Q3, Internal Only) [Series].

Shafroth PB, Beauchamp V. 2006. Defining Ecosystem Flow Requirements for the Bill Williams River, Arizona. US Department of the Interior, US Geological Survey Open-File Report 2006–1314. (31 December 2009; *www.fort.usgs.gov/products/publications/21745/21745.pdf*)

Stewart, K., B. T. Smith, A. Witt, S. DeNeale, M. Bevelhimer, J. Pries. 2017. *Simulation and Modeling Capability for Standard Modular Hydropower Technology /R1*, ORNL/TM-2017/175, Oak Ridge National Laboratory.

Uria-Martinez, Rocio, Megan Johnson, and Patrick O'Connor. 2015. "2014 Hydropower Market Report."

Verstraeten, Gert, and Jean Poesen. 2000. "Estimating Trap Efficiency of Small Reservoirs and Ponds: Methods and Implications for the Assessment of Sediment Yield." Progress in Physical Geography 24 (2). Sage Publications: 219–51.

Yarnell, Sarah M., Geoffrey E. Petts, John C. Schmidt, Alison A. Whipple, Erin E. Beller, Clifford N. Dahm, Peter Goodwin, and Joshua H. Viers. 2015. "Functional Flows in Modified Riverscapes: Hydrographs, Habitats and Opportunities." BioScience 65 (10): 963–72. doi:10.1093/biosci/biv102.

Witt, A., B. T. Smith, A. Tsakiris, T. Papanicolaou, K. Lee, and K. M. Stewart. 2017. *Exemplary Design Envelope Specification for Standard Modular Hydropower Technology/R1*, ORNL/TM-2016/298, Oak Ridge National Laboratory.

9. Acknowledgements

This research was sponsored by the US Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy, Water Power Technologies Program. We acknowledge the following individuals for their significant contributions to the SMH research ideas offered in this paper: Norm Bishop, Jr. (Knight Piésold Consulting), Shelaine Curd (ORNL), Kyutae Lee (ORNL), Thanos Papanicolaou (University of Tennessee - Knoxville), Kevin Stewart (ORNL), and Achilleas Tsakiris (University of Tennessee – Knoxville). We thank Chris DeRolph, Nicole Samu, and Rocio Uria-Martinez of ORNL for assistance with data assessment and graphics.

10. Author biographies

Dr. Adam Witt is a R&D associate in the Energy-Water Resource Systems Group at Oak Ridge National Lab and Principal Investigator of the Standard Modular Hydropower project. He is a Water Resources Engineer with research experience in small hydropower eco-design, computational flow modeling, water quality modeling, and hydropower optimization. Dr. Witt received a B.A. in Physics from Carleton College and a Ph.D. in Civil Engineering from the Saint Anthony Falls Laboratory at the University of Minnesota under a fellowship from the Hydro Research Foundation. Dr. Witt can be reached at wittam@ornl.gov and 865-241-7367.

Dr. Alisha Fernandez is the co-owner of McKeown & Associates LLC, an energy-consulting firm that specializes in the analysis of renewable energy technologies, power markets, grid integration, stakeholder outreach, and scientific writing and communication. Currently, she leads the stakeholder engagement effort and communications for the Department of Energy/Oak Ridge National Laboratory Standard Modular Hydropower (SMH) project. Previously, Dr. Fernandez was the Senior Technical Research Analyst for BCS, Incorporated and provided direct support to the DOE Wind and Water Power Technologies Office on projects and programs focused on hydropower, climate change, grid services, and market policy analysis. Dr. Fernandez earned her doctorate in Energy Management and Policy (EMP) from the department of Energy and Mineral Engineering (EME) at The Pennsylvania State University, and a Bachelor's of Arts in Mathematics from the University of Colorado Boulder in 2007. Dr. Fernandez can be reached at alisha@mckeownandassociates.com and (206) 491-0392.

Mr. Miles Mobley is a post-bachelors research associate in the Energy-Water Resource Systems Group at Oak Ridge National Lab. He joined ORNL in May 2015 as a research intern where he worked to quantify the multiple economic benefits of hydropower projects before beginning his current position in August 2016. He holds a B.S. in Mechanical Engineering from the Georgia Institute of Technology in Atlanta. Mr. Mobley can be reached at mobleymh@ornl.gov and 865-806-8052.

Mr. Scott DeNeale is a Technical Staff Member in the Oak Ridge National Laboratory's Environmental Sciences Division. He joined ORNL in March 2013 and is currently involved in hydropower technology and cost modeling research, Nuclear Regulatory Commission (NRC) flooding hazard and probable maximum precipitation assessments, and various other DOE projects. He holds an MS in Environmental Engineering and BS in Civil Engineering, both from the University of Tennessee, Knoxville. Mr. DeNeale can be reached at denealest@ornl.gov and 865-241-7368.

Dr. Mark Bevelhimer has over twenty-five years of experience in aquatic ecology/fisheries biology ranging from basic research to fisheries management to environmental assessment. His recent work focuses on understanding and preventing various environmental impacts associated with power generation by conventional hydropower, hydrokinetic turbines, and thermoelectric plants. He has applied a combination of laboratory and field experimentation with computational analysis to better understand impacts of altered flow regimes, elevated temperatures, contaminant exposure, electromagnetic fields, underwater noise, and turbine injury. He has been lead or co-author on nearly 100 journal articles and reports.

Dr. Brennan Smith is Program Manager for Water Power Technologies and the Group Leader for the Energy-Water-Ecosystem Engineering Group at Oak Ridge National Lab. Dr. Smith's work focuses on energy, water and environmental optimization in hydropower-thermal systems. Specific interests include:

energy-water interdependencies in regulated water basins, water use optimization for integrated river systems and effect of hydropower on water availability and riverine ecosystems. He holds a Ph.D. in Civil and Environmental Engineering from the University of Iowa. Dr. Smith can be reached at smithbt@ornl.gov and 865-241-5160.