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The waterSHED Model User Guide

The **W**ater **A**llocation **T**ool **E**nabling **R**apid **S**mall **H**ydropower **E**nvironmental **D**esign

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Environmental Sciences Division

THE waterSHED MODEL USER GUIDE

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ABBREVIATIONS

ICC	initial capital costs
IDE	integrated development environment
GUI	graphical user interface
LCOE	levelized cost of energy
NSD	new stream-reach development
NWIS	National Water Information System
OOP	object-oriented programming
ROR	run-of-river
SMH	Standard Modular Hydropower
USGS	US Geological Survey
waterSHED	Water Allocation Tool Enabling Rapid Small Hydropower Environmental Design

EXECUTIVE SUMMARY

The ideal design and operation of small hydropower plants is a complex optimization problem with economic, social, and environmental objectives. The waterSHED (Water Allocation Tool Enabling Rapid Small Hydropower Environmental Design) model is a user-friendly tool that allows hydropower stakeholders to model the trade-offs among these objectives using the Standard Modular Hydropower (SMH) framework. The SMH framework employs modular technologies that can be represented as black-box objects and combined within a river to create a hydropower facility. For a given site, the waterSHED model aims to determine which modules should be placed in a facility and how those modules should be operated.

This user guide describes how to use the graphical user interface and related functionalities. This document also summarizes the background research and mathematical formulations that are explained in-depth in the accompanying doctoral dissertation. This model is an early step toward a new hydropower design process that employs standardization and modularity to reduce costs, development timelines, and challenges regarding social and environmental mitigation measures for low-head, small hydropower development.

The waterSHED model is a Python application that will require the ability to download a GitHub repository, import the necessary packages, and run a set of Python script files using an integrated development environment. The script produces a graphical user interface to coordinate inputs, simulate operation, and visualize results, so no coding experience is needed once the script is running. Additionally, the waterSHED Workbook is a Microsoft Excel file that works with the Python script to facilitate data entry. The files needed to run the waterSHED model can be found at the following link.

https://github.com/waterSHED-Model-ORNL/waterSHED-Model.git

The accompanying doctoral dissertation that this model is based on can be found at the following link; the published version will be available in trace.tennessee.edu in Summer 2022. While this user guide summarizes the reasoning behind the model formulation, the dissertation provides more in-depth information about the background research and methodology. The dissertation also provides two case studies that showcase possible applications of the model.

https://github.com/waterSHED-Model-ORNL/waterSHED-Model/blob/main/Documentation/Sasthav_Dissertation_Public_Draft.pdf

The waterSHED model described in this user guide is the first public version of the model. Feedback is crucial for future improvement of the model, so please direct any inquiries or comments to watershed.model.ornl@gmail.com. Technical support may be available to those interested in using the watershed model.

1. INTRODUCTION

The waterSHED (Water Allocation Tool Enabling Rapid Small Hydropower Environmental Design) model is a tool that supports feasibility and techno-economic analyses of modular hydropower projects. This model and research effort is part of the Standard Modular Hydropower (SMH) Technology Acceleration project at Oak Ridge National Laboratory, which is funded by the US Department of Energy Office of Energy Efficiency and Renewable Energy Water Power Technologies Office. The SMH project aims to improve the cost-effectiveness and environmental performance of new hydropower projects, especially at new stream-reach and non-powered dam sites. New stream-reach development (NSD) is the construction of hydropower capacity at sites without existing dam infrastructure. Non-powered dam development is the retrofit of electricity generation capabilities at existing water infrastructure. Assessments of hydropower potential in the United States have shown the potential to more than double the existing US hydropower capacity (NSD: 84.7 GW of technical potential; non-powered dam development: 12 GW of technical potential) [1,2]. However, NSD faces many challenges, including the following:

- The majority of NSD potential is found at small, low-head sites (<30 ft), which typically have higher installed costs per kilowatt compared with high-head sites and other renewable energy sources, such as on-shore wind and solar [3].

- New hydropower development faces regulatory and social pressure to meet high environmental and social performance standards [4].

- Previous industry practices of custom-designed facilities can lead to long siting, design, and licensing timelines that can make the development of multiple sites cost-prohibitive.

The SMH philosophy aims to address these challenges through standardization (the use of mass-produced technologies) and modularity (the compartmentalization of facility functions in discrete technologies or "modules"). Standard modular hydropower facilities can be created by combining modules of different types within a river, as illustrated in Figure 1. In theory, these principles create economies of scale that can reduce the cost of building one or more projects by reducing the time and costs throughout the siting, design, manufacturing, licensing, and construction processes. However, standardization and modularity are relatively new concepts within the hydropower industry, and a fully modular hydropower facility has not yet been built. The waterSHED model has been developed for multiple purposes, including to extend SMH from a concept to a virtual implementation. The Exemplary Design Envelope Specification report, published in 2017, laid the foundation for the modular design concept [5]. In 2018, an earlier, non-public version of the waterSHED model was used to perform a case study on a potential SMH site along the Deerfield River [6]. The case study effort used design procedures from the literature to create one module design for each module type, and then used simulation and sensitivity analysis to determine the optimal combination of modules for the Deerfield site. The current waterSHED model has been updated with a user-friendly implementation that will allow the model to be quickly adapted to new sites and new technologies. Several other functions, such as assessment of non-power benefits and design optimization, have also been included. This report serves as a user guide to aid the use of the waterSHED user interface, code, and related features. This report summarizes the background research that informed the model formulations, and full descriptions of the related research along with case study applications of the model are provided in the accompanying doctoral dissertation, *Environmental design and optimization of modular hydropower plants* [7]. This report heavily leverages content from the dissertation and particularly focuses on the application of the model.

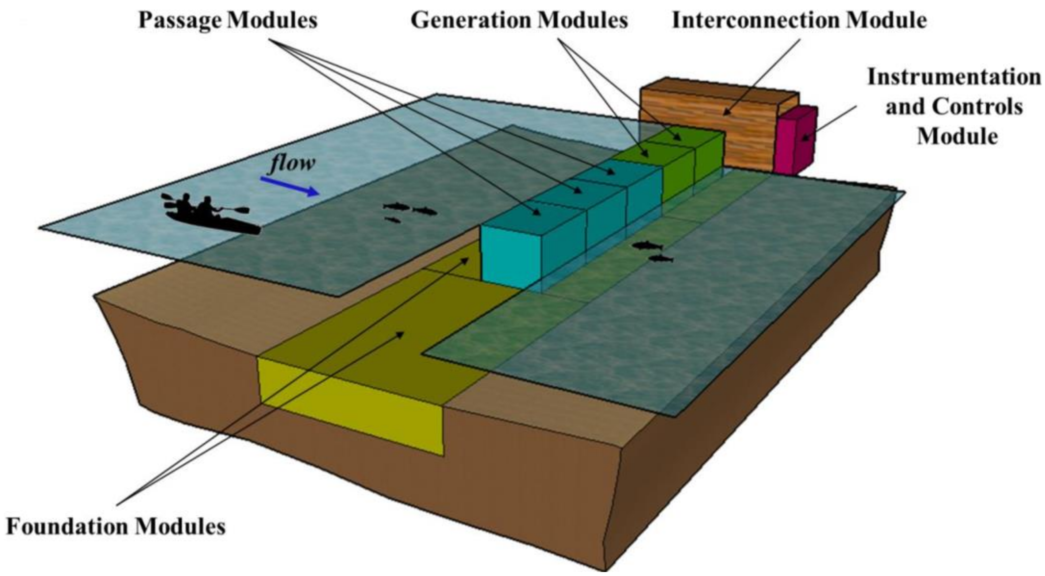

Figure 1. Conceptual schematic of a SMH facility with modules represented as "black boxes."
Reprinted from Witt et al. [5].

The report is organized as follows:

- Section 1 provides background information about the overall model philosophy and includes directions on how to use the model.
- Section 2 describes how to download and use the waterSHED model and related features.
- Section 3 provides a brief description for each of the inputs needed to run the model.
- Section 4 describes how the inputs are used to create, simulate, and evaluate a virtual module hydropower facility.
- Section 5 describes the two options for selecting modules for the facility—optimization and enumeration—and the purpose of dynamic modules.
- Section 6 describes possible use cases for the waterSHED model and potential features for future versions.
- Section 7 provides references.
- Appendix A provides detailed descriptions of the attributes for each object in the model.
- Appendix B provides the background literature and equations that are used in the calculation of the facility performance metrics.
- Appendix C describes the models used to provide input recommendations with the tool tips.
- Appendix D describes the attributes and the controlling variables that can be used to dynamically design technologies.
- Appendix E provides a list of the major assumptions that are made throughout the model.

1.1 THE waterSHED MODEL SCOPE

The waterSHED model allows users to virtually design, simulate, and evaluate a modular, run-of-river (ROR) hydropower facility. The waterSHED model aims to inform two main design questions related to the design of modular facilities:

- **Technology selection:** What combination of modular technologies will optimize performance objectives?

- **Flow allocation:** What distribution of flow between modular technologies over time will optimize performance objectives?

These design questions are tailored to the development challenges that SMH targets. As discussed, NSD hydropower potential in the United States is located primarily at low-head sites [1]. These sites face many environmental, social, and technical constraints that limit the ability of new hydropower facilities to change the conditions at the site. ROR hydropower is one option to limit flow alteration or land use change by limiting the amount of active water storage. ROR operation assumes that the flow coming into the facility equals the flow leaving the facility within a short time step. The current version of the waterSHED model uses a daily time step, so it is assumed that the average daily inflow equals the average daily outflow. In the literature, ROR facilities are often assumed to be at high-head sites where smaller flows are sent through long diversions before returning to the stream. These diversion schemes take advantage of large slopes to capture the economic benefits of high-head designs but at the expense of dewatering significant portions of the stream-reach, which has ecological consequences [8]. Low-head sites have lower stream slopes, so creating long diversions (the cost per length of diversion exceeds the benefits per head increase) is not typically economical. Therefore, modular facilities will likely use low-head, instream, ROR designs. These schemes have much different design considerations than high-head ROR or large storage reservoirs, which have expansive literature on dispatch scheduling and diversion design optimization [9–11]. The performance of instream ROR schemes is based primarily on how technologies transform flow into value and how flow is allocated across these technologies (i.e., technology selection and flow allocation). Literature on these design decisions is limited, particularly for modular design approaches, so this model serves as an early investigation of the related design trade-offs.

Another unique feature of this model is the inclusion of non-power (e.g., social, environmental) benefits as performance objectives. A recent review of hydropower design literature showed that design models primarily aim to optimize economic objectives, such as net present value [12]. When environmental objectives are included, they typically involve impacts that are less relevant in low-head, instream, ROR hydropower, such as environmental flows and water quality changes from reservoir stratification. Barrier effects, such as the blockage of fish and sediment passage, are also often excluded from performance. Following the principles of SMH, the waterSHED model incorporates non-power benefits into the design process and attributes environmental and economic functions to module classes. The environmental functions included in the current waterSHED model, which have corresponding module classes, are sediment passage, fish passage, recreation, and water passage (i.e., spillway). Generation, Foundation, and Non-Overflow modules are also included in the facility design.

The waterSHED model is designed for desktop-level information, which means that inputs can be gathered from publicly available internet resources, and in-person site visits are not required to reasonably determine inputs. Thus, this model is meant to aid users during feasibility/pre-feasibility assessments or high-level techno-economic analyses that have limited site-specific information. The waterSHED model can be set up quickly (<1 h), which provides users with a fast way of estimating project performance and sensitivity across economic, environmental, and social domains. The model can support multiple use cases, including site selection, feasibility/sensitivity analysis, and academic studies. Furthermore, the waterSHED model offers several purposes, including evaluating the trade-offs among design decisions and multi-dimensional performance metrics, determining the sensitivity of project performance to project parameters, and identifying optimal module configurations and operations. However, this model should not be used for detailed engineering design, which requires extensive site investigation and teams of engineers. The scope of the waterSHED model is summarized as follows.

Summary of Scope

- **Prefeasibility stage site evaluation tool:** The model is best used in early development stages to estimate project feasibility and design trade-offs.
- **Low-head sites:** The current model version is meant to be used in the design evaluation of low-head (<30 ft) sites, where modular design practices are especially beneficial.
- **Daily ROR operation:** The model is designed to model daily ROR operation of facilities and does not feature storage or scheduling optimization.
- **Instream designs:** Modular facilities created in this model do not have long diversions that can dewater significantly long portions of the downstream reach.
- **Non-power benefits:** In addition to quantifying power generation, this model also quantifies sediment passage, fish passage, recreation, and flood safety performance.

1.2 AN OBJECT-ORIENTED APPROACH

The waterSHED model uses an object-oriented approach to reflect the principles of standardization and modularity. Object-oriented programming (OOP) is a concept in computer science in which classes provide the blueprint for the attributes of an object. Instances of the class (i.e., objects) are created by providing input values for each attribute in the class. The object-oriented approach provides two main benefits: (1) it simplifies complex technologies into a simple, representative set of attributes, and (2) it creates "black-box" objects where the internal mechanisms do not need to be understood to determine the relationships between inputs and outputs. These benefits allow new technologies to be quickly integrated into the model, which is an important feature since low-head, modular technologies are still emerging.

The classes used in waterSHED are outlined in Table 1. Throughout this report, the user interface, and the waterSHED Workbook, the module classes are color-coordinated according to the scheme used in Table 1. Module classes reflect hydropower technologies that have consistent characteristics regardless of the specific technology. For example, a Generation module class has the attributes of the design flow, design head, and efficiency curve. Francis, Pelton, and Kaplan turbines are distinct technologies but can be described using similar attributes in the Generation module class. In addition to attributes, classes can have functions that are used in the simulation process. Generation modules, for example, can determine power output for a given head and flow value. OOP allows the model to compute power without knowing internal technology specifications such as the speed of the runner or the gate setting. However, users must input values to describe these attributes; the inputs are outlined in Section 3 and fully documented in Appendix A. Multiple module objects are combined to create a Facility object. Facility objects can be created by hand using the *Enumerate* option, where the user selects the module counts, or through an automated *Optimize* option, which uses a genetic algorithm to search for the optimal combination of modules intelligently. To simulate the operation of a facility, users must use the simulation classes, including the Site, Preference, Cost Tables, and Species classes. The backend classes are created within the code to facilitate internal processes during the simulation. Users do not interact with these backend classes and thus the class structures and related attributes are not presented in this report. Users should refer to the commented code on Github for this information. The performance models in Appendix B describe the relevant model outputs generated by the backend classes.

Table 1. Outline of waterSHED classes

Class	Description
Module classes	
Generation	Uses flow to produce electrical power; includes all required electro-mechanical equipment and water conveyance structures
Water Passage	Passes water from upstream to downstream. Spillway modules are Water Passage modules that operate in either controlled or uncontrolled spillway mode. Each Facility must have at least one Spillway module.
Sediment Passage*	Passes bed load and suspended load sediment through the facility. Sediment Passage modules may be one of the following subclasses: sediment bypasses, sediment sluice gates, or drawdown flushing gates.
Recreation*	A safe passageway for recreation crafts, such as boats, kayaks, and canoes
Fish Passage*	Facilitates the passage of fish across the facility in upstream and downstream directions
Foundation	Connects modules to the streambed, providing structural support, watertight seals, and safe operation of the facility
Non-Overflow	Inhibits the flow of water past the facility, similar to a conventional dam
Screen	Technologies, such as fish exclusion screens and trash racks, that are placed in series with passage modules
Simulation classes	
Site	Hydrologic and hydraulic characteristics that describe the stream-reach of interest
Preferences	Design and simulation parameters used to represent the goals of the developer and evaluate the performance of a facility
Cost Tables	Parameters used to convert module performance into simulated cost and benefit outcomes
Species*	A species of interest in the fish passage performance model
Backend classes	
Facility	A combination of module objects used to represent a complete SMH facility
SMH Project	The combination of Site, Preference, Cost Tables, Module Library, and Species objects used to simulate and optimize an SMH facility
Module Library	The collection of Module objects that can be chosen during the design optimization process.

*Indicates an optional class that does not need to be created to run a simulation.

As described in Figure 2, once the user creates the required objects, the objects are compiled into an SMH Project object. Then, the user can either use the *Enumerate* option or the *Optimize* option to create a facility for the SMH Project. The facility can be evaluated using a simulation based on the provided flow data. The simulation process uses a system of hydraulic and operation models to determine the headwater elevation, tailwater elevation, and allocation of flow between modules during each daily time step. The simulation process is described in Section 4.

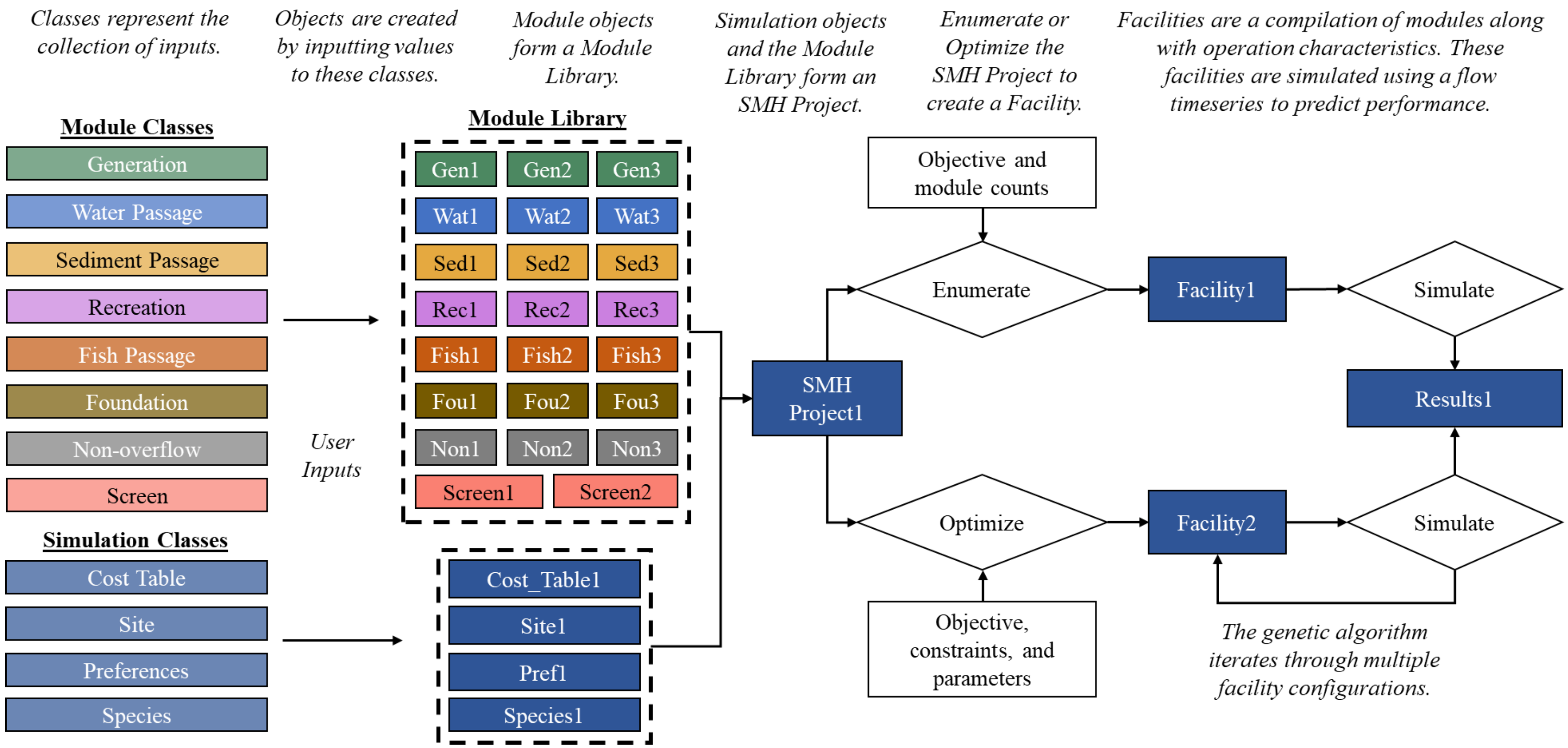

Figure 2. Flow diagram of waterSHED model processes. Numbers indicate instantiated objects rather than classes. The lighter colors for the left boxes under Module Classes and Simulation Classes headers reflect that the classes are not created as objects until the user input process.

The object-oriented approach is also expressed in the coding of waterSHED, which allows different operation and performance models to be quickly interchanged between versions. The SMH Exemplary Design Envelope Specification Report [5], an extensive review of scientific literature, and several hydropower design textbooks and manuals [13] helped to form the current structure of classes. The reasoning behind the structure of the current version of the model is described in the accompanying doctoral dissertation [7]. This report describes the first public version of the waterSHED model, and future versions will continue to use academic literature, user feedback, and the latest technology trends to integrate more complex models and class structures. Therefore, feedback is highly valuable, so please reach out to watershed.model.ornl@gmail.com with any comments.

2. INSTRUCTIONS

The waterSHED model is a Python application that uses a graphical user interface (GUI) to guide the user through the design process of an SMH facility. The following sections discuss several relevant questions a waterSHED model user may have, including how to download the model, how to use the GUI, and how to use some of the notable features in the waterSHED model.

2.1 HOW TO DOWNLOAD THE waterSHED MODEL

The waterSHED model comprises several Python scripts that work together to create a GUI. The GUI facilitates the collection, analysis, and visualization of the SMH Project data. However, the current version requires users to be able to run Python scripts on their computer. No coding is required to run the model, but users must be able to download the code, open an integrated development environment (IDE) for Python, import required packages and run the main script file.

Step 1. Download the waterSHED files from the GitHub repository. The repository can be downloaded by clicking the following link, selecting the green *Code* button, and then selecting the *Download ZIP* option. The *.zip* file must be exported into the desired directory, making sure not to change the names of the *Images Workbooks* directories within the main folder because they are used for uploading default data to the GUI.

GitHub link: https://github.com/waterSHED-Model-ORNL/waterSHED-Model.git

Step 2. Open a Python (version 3.7 or later) IDE. The model was built using Spyder (version 4.1.5), which can be accessed through the Anaconda Distribution. Downloading the Anaconda Navigator via the following link will enable access to Spyder and other IDEs and command-line programs that can run Python scripts. Spyder can also be downloaded directly from the Spyder website, but other IDEs such as Jupyter Notebooks could also work.

Anaconda download link: https://www.anaconda.com/products/distribution

Spyder download link: https://www.spyder-ide.org/

Step 3. Import the required packages. The waterSHED scripts rely on commonly used packages from the Python library. The required packages are listed below. If downloading Spyder for the first time, these packages will have to be downloaded to ensure that the waterSHED scripts can access them. If using Anaconda, the packages can likely be installed using the Anaconda Navigator as described in the package installation guide link. Otherwise, the packages will have to be installed from the command line using the *python -m pip install Package* command to install each package, as described in the pip installation guide link below. The waterSHED model will likely result in errors on start-up if the packages are not installed.

Anaconda package installation guide:
https://docs.anaconda.com/anaconda/navigator/tutorials/manage-packages/

Pip installation guide: https://docs.python.org/3/installing/index.html

List of required Python packages: *tkinter, webbrowser, pandas, queue, threading, Pillow (PIL), matplotlib, tksheet, numpy, os, openpyxl, time, math, copy, random, statistics, itertools, requests, io,* and *scipy*.

Step 4. **Run the main waterSHED script**. Within the selected IDE, users must open the main waterSHED script (*waterSHED_main.py*) and run the script by selecting the *play* button or using the *run waterSHED_main.py* command in the command prompt. This should open the GUI interface and allow for inputting, analyzing, and visualizing the project data.

2.2 HOW TO PROGRESS THROUGH THE MODEL

There are several possible end goals for the waterSHED model that revolve around creating facilities and simulating them to obtain results. Optimization and sensitivity analysis features iteratively create and simulate facilities to generate insights. The following steps to create and simulate SMH facilities are guided by the GUI. Optional steps are marked with an asterisk (*). The GUI provides entry forms for all the steps described in this section, such as the creation of module objects, the simulation of SMH facilities, and the visualization of results. Steps 3 through 7, described in this section, must be conducted within the GUI. However, the waterSHED model also includes a functionality called the *waterSHED Workbook*, which is a Microsoft Excel file that can be used to input and upload information in Steps 1 and 2. The waterSHED Workbook is an optional feature and is useful for saving information between model runs. More information on how to use the waterSHED Workbook is provided later in this section. The seven main steps for using the waterSHED model are described in Figure 3. The creation of the Site, Cost Tables, Preferences, and modules can happen in any order, but they must be created before adding screens and species or enumerating/optimizing the facility. These steps roughly correspond to the menu buttons on the left bar in the GUI, so users can intuitively progress down through the pages.

Step 1. Input Site, Cost Tables, and Preferences information

First, the user must gather and input values for the Site, Cost Tables, and Preferences objects. Optional inputs are marked with an asterisk (*). The inputs are described in Section 3.1 in the waterSHED Workbook, and in the tool tips that accompany the inputs within the GUI.

There are several ways to input information, which are described later in this section. Use of the GUI is recommended for initial entry, and the waterSHED Workbook is useful for saving runs. Once the values have been entered for a given class, the object can be created by selecting the *Create* button. If the object is successfully created, the model will create a pop-up indicating success.

Step 2. Create static modules

The user can incorporate technologies into the model by creating module objects. The types of module objects are described in Section 3.2. Modules can be added in the *Add Modules* page in the GUI by selecting the *Add Module* button. This will create a pop-up that lists the inputs for each module class, and the module class can be selected from the top option menu. In some cases, the inputs will change based on the prior inputs. For example, if a Water Passage module is operated as an uncontrolled spillway, then an entry for weir coefficient and crest height will also appear. Successfully created modules can be viewed in tabular form in the Module Library section of the *Add Modules* page. These modules can be exported as a .csv file describing the list of inputs by selecting the *View* button in the Module Library section, selecting the *Export* option at the top of the window, and providing a file name. Select modules can be deleted by selecting the *Delete* button on the module box, or all modules can be deleted by selecting the *Clear Library* button. Modules can be imported from the waterSHED Workbook by selecting the *Import Workbook* button on the *Add Module* page and inputting the waterSHED Workbook file name. The instructions in the waterSHED Workbook section provide more information.

Step 3. Create dynamic modules*

Dynamic modules are technologies that can be custom-designed using controlling variables, which are the project or site conditions that likely determine module designs. For example, the height of a Non-Overflow module can be parameterized as a function of the normal operating headwater level to ensure that they are sufficiently tall when changing the headwater level. The controlling variables differ between attributes and can be selected to reflect common relationships. The dynamic module classes and attributes are the same as the static modules, but instead, certain attributes can be input as constants or equations based on common variables. The creation of dynamic modules is optional if the required Foundation, Non-Overflow, and Spillway modules (a type of Water Passage module based on the operating mode) are created on the static module page. Alternatively, all modules can be created as dynamic modules.

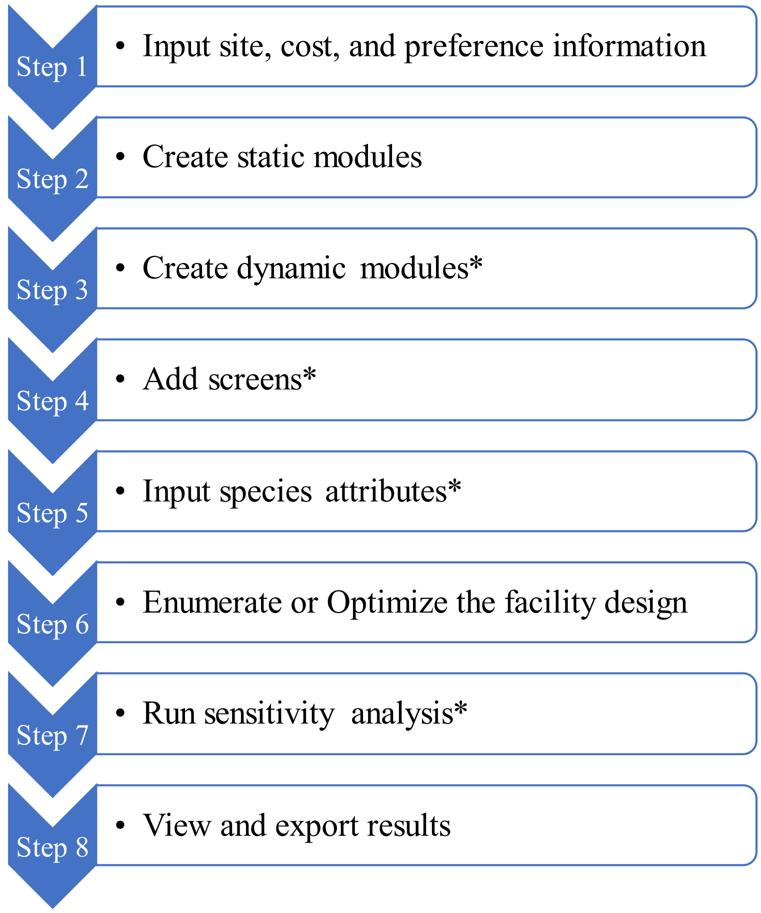

Figure 3. The waterSHED model steps. Asterisks (*) indicated optional steps.

Static modules, described in Step 2, do not change attributes during the creation or optimization of the facility. However, dynamic modules can be parameterized using equations to change attributes during design, thus allowing the enumeration and optimization processes to test a continuous range of attributes. The creation of equations is summarized in Section 2.3. For each attribute that can be set as an equation, the user will use a drop-down menu to select where the attribute should be a constant value or a function of select controlling variables. Otherwise, the creation of the module follows the procedure from Step 2. Default dynamic modules from Case Study A in the accompanying dissertation can be selected using the option menu at the top of the *Add Dynamic Module* window to prepopulate the data fields [7]. Once the dynamic module has been created, it will create a corresponding box in the Dynamic Module Library. These boxes will allow the user to view attributes, delete the module, and input values for the controlling variables to see how the attributes are recalculated. Certain controlling variables, such as depth to bedrock, can only be set using this input method or in the sensitivity analysis process, so the correct values must be input into these entries if they are not set directly in the *Enumerate* or *Optimize* pages.

Step 4. Add screens*

Screens are modules that are placed in front of passage modules to reflect factors such as head losses and fish passage mitigation from in-line technologies, such as fish screens or trash racks. They can be created on the *Add Screen* page but are not required for facility simulation. One of the attributes of the Screen module is the list of passage module types that it is covering (i.e., in front of), so screens must be added after modules have been created. However, screens are optional and can alternatively be integrated into the respective passage module performance through their attributes. For example, head losses from trash racks could be incorporated into Generation module head efficiency equations rather than as a separate screen object.

The screen object is created very similarly to the dynamic modules. A default menu allows the user to prepopulate values from the example fish screen in Case Study B from the accompanying dissertation [7]. The controlling variables for each attribute are specified in the option menu for the respective field, so the attributes can be set as constants or functions of other controlling variables. Under the *Covered Modules* header, the checkboxes are used to indicate the module objects that the screen should encompass. Whenever there are multiple covered modules, the screen can be parameterized to change size according to the combined width of the covered modules. Once a screen has been created, it can be seen in the *Screen Library,* which lets the user view the attributes or delete the screen. For the downstream fish passage model in Section B.4.1, the order of the screens from upstream to downstream is important, so the screens must be created in order from furthest upstream to closest to the dam. Screens can currently only be placed on the upstream side of the dam.

Step 5. Input Species attributes*

The waterSHED model provides a novel model for estimating the upstream and downstream fish passage performance of an SMH facility, which uses Species objects as an index. This functionality is not required for the simulation of the facility. To begin inputting Species attributes, go to the *Species Passage* page on the user interface. Species objects can be created by inputting a species name, entering the fish passage parameters, selecting the upstream and downstream migratory months using checkboxes, and selecting the *Add* button. Users should read the upstream fish passage models in Section B.4.2 or look at the corresponding support tool for more information about these inputs. Entries will then appear in the *Input Module Attributes* section describing how well the modules are able to attract and pass fish upstream and downstream. Then, the user can select a species using the drop-down menu, input values for the four module characteristics (defined in Section 3.2), and select the *Submit* button. This must be done for each species to simulate fish performance for each species properly. The related models are described further in Section B.4.

Step 6. *Enumerate* or *Optimize* the facility

A facility is created by filling the stream width with modules from the Module Library, which is the collection of created modules. The facility must contain at least one Non-Overflow module to create a headpond, one spillway (a subclass of the Water Passage module) to pass excess water, and one Foundation module to provide structural support. A facility can be created in one of two ways: enumeration or optimization.

Option 1: Facility Enumeration

The facility enumeration process allows the user to specify the number of each passage module within the facility, as well as any dynamic module attribute values. In the case of Foundation and Non-Overflow modules, the program automatically determines these module counts using the facility footprint and required dam length (discussed in Section 5.1). This method allows the user to test one facility design by setting constant values for all inputs or test multiple facilities by setting iteration limits for each input. Iterations require the user to select a minimum value, a maximum value, and a step size. For example, setting iteration values of min = 1, max = 3, and step = 1 for a module count will simulate facilities with one module, two modules, and three modules. The step size determines the change in value between iterations and must be an integer for the module count attribute, but other attributes, like design head, can have decimal step sizes. If the steps are not evenly divisible within the bounds (e.g., min = 1, max = 4, step = 2), then the maximum value will be added to the iterations. Each combination of the provided iterations will be created and evaluated if the resulting facility is valid. An objective function must be provided using the checkboxes in the top left corner when testing multiple facilities to select the best performer. The user can select the *Run Enumeration* button to start testing facilities, which can be viewed by selecting the *Show Iterations* checkbox. Results are shown beneath the configuration inputs in the *Simulation Results* section of the *Enumerate* tab. The data saved in the results table can be selected from the *Select Data to Save* section in the top right.

Option 2: Facility Optimization

The facility optimization process allows the user to determine the optimal configuration of modules by specifying optimization parameters, inputting attribute ranges and an objective function metric, and then running a genetic algorithm program. The methodology and optimization parameters are discussed further in Section 5.2. The genetic algorithm creates and tests different module configurations and tries to converge on the configuration with the best objective function according to the user-specified parameters. The optimization process may take several minutes depending on the number of modules, the optimization parameters, and the length of the simulation. Rather than setting iterations like in the enumeration method, the optimization method requires the user to specify attribute ranges (a minimum and maximum allowed value), which act as constraints in the optimization that can be optimized as continuous or discrete variables depending on the attribute. The user can select the *Run Optimization* button to start testing facilities, which can be viewed by selecting the *Show Iterations* checkbox. Results are shown beneath the configuration inputs in the *Simulation Results* section of the *Optimize* page.

Step 7. Run sensitivity analysis*

Sensitivity analysis is a feature that allows the user to run an enumeration process multiple times for different values of a project input. For example, the facility could be run multiple times with different energy prices to see the impact of the energy price on net present value. This method only works with the enumeration method and requires the enumeration inputs (attribute iterations, objective function, and save data) to be selected before running. Then, the user can select the *Run sensitivity analysis* button to open a window that will allow the user to select the object of interest, attribute of interest, iteration range, and unit. Selecting the *Run Analysis* button will run multiple enumeration procedures for each value of the attribute of interest. Each iteration will only save the highest-performing facility. The results of the enumeration will be shown at the bottom of the *Enumerate* page. These results include line plots of the sensitivity variable and the project outcomes and tables with the saved data.

Step 8. View and export inputs and results

The waterSHED model has a host of results and data visualizations for simulation runs. When an *Enumerate* or *Optimize* procedure is completed, the optimal facility can be plotted in the *Optimal Facility Configuration* section by selecting the *View Specifications* button to see the facility characteristics. Additionally, the *Simulation Results* section will provide a host of figure options to describe the results, which can be changed in the option menu. Each figure has a corresponding data table that can be viewed in a separate window using the *View Table* button. Any table window can be exported as a *.csv* or *.xlsx* file using the export menu option. Figures with a *Pop-out* button will create the figure in a separate window that has additional functionalities for editing and saving the figure. The results of repeated enumeration or optimization procedures can be viewed in tabular form by selecting the *View Runs* button. The results include only the optimal facilities from each run, and they can be exported or cleared using corresponding buttons. The *Show Animation* button also creates a useful window that lets the user animate the flow allocations, head and tailwater elevations, and plant outputs at each time step in the simulation by selecting the *Play* button or by selecting a time step on the slider. The *Sleep* input sets the time between time steps in milliseconds for the animation.

2.3 HOW TO USE THE waterSHED GUI

Users can gather and input data in several ways to expedite site assessment and enable certain use cases. These methods include GUI inputs, waterSHED Workbook upload, automated data retrieval, and support tools, which are all discussed here. For each type of input, users must pay close attention to the entry type and units, which are provided alongside each input in the waterSHED Workbook and the GUI via the tool tip buttons.

GUI inputs

There are several input types within the user interface, as described in Table 2.

Table 2. The waterSHED model input types

Input type	Example picture	Description
Entry	381.0 ft	Type the text or number into the box. Make sure to note the units and limit extra spaces.
Tool tip (button)	!	Select the box to see more information about the input and gain access to support tools (for select inputs).
Option menu	Horizontal Kaplan	Click on the box and select an option from the drop-down menu.
Checkbox	Diversion (Y/N) Diversion (Y/N)	Click on the checkbox to toggle it ON and OFF. The check mark indicates ON. In the example, an ON checkbox corresponds to Yes, so the module is a diversion and will not be included in the stream.
Equation	Efficiency vs. Flow Create Equation	Select the *Create Equation* button to open an Equation Creator window that will facilitate the entry of the equation form, coefficients, and bounds.
Dynamic attribute	Constant $ or Function of Design Head Width as a Function of Design Head ft Create Equation	Select the type of equation from the option menu. If a constant value is desired, then enter the numeric value in the entry. Otherwise, select the equation type relating to the desired controlled variable and create an equation with that controlled variable as the independent variable (x).

Equations

Throughout the model, several inputs are in the form of equations. This model uses a custom *Equation* object to enter and use equations. Therefore, limited equation forms are available, as shown in Table 3. To create an equation, the type of equation must be selected, followed by the coefficients (a through e), as shown by the equation forms, and the *Create Equation* button must be selected.

Table 3. List of available equation forms

Constant	$y = a$
Linear	$y = ax + b$
Power	$y = ax^b + c$
Polynomial-2	$y = ax^2 + bx + c$
Polynomial-3	$y = ax^3 + bx^2 + cx + d$
Multi-linear	$y = ax^b + cz^d + e$
Multi-power	$y = ax^b z^c + d$
Binomial	$y = a(bx + c)^d + e$

The *Equation Creator* window has two other special options to provide added flexibility—a linear regression option and a piecewise option. The linear regression option takes data uploaded from a *.csv* file and transforms it into the constant, linear, power, polynomial-2, or polynomial-3 forms using a custom linear regression method described in the following section. To do this, the user can select the *Linear Regression* in the equation type option menu of the *Equation Creator* window. However, this method may not be available for all attributes. The *.csv* file or Excel sheet that is uploaded must be structured in the form shown in Table 4. There can only be two columns, the first being the *X* header and values, the second being the *Y* header and values. The regression procedure is managed internally, as described in the Automated Regression section in Section 2.6.

Table 4. Example of data input format for the data regression function

***X* label**	***Y* label**
x_1	y_1
x_2	y_2
x_3	y_3

Users can also create piecewise equations that use the available forms to specify sections of a function. The *Equation Creator* window takes the user through the process of creating two equations at a time. The equations must have a middle bound that describes where the equations change domains. The component equations are created using their own *Equation Creator* windows. Users must make the equations valid across the range of possible independent variable values to ensure proper operation of the equation.

2.4 HOW TO USE THE waterSHED WORKBOOK

To better save inputs and information between runs, the waterSHED Workbook allows users to input values into an Excel file and import them into the GUI. Directions to fill out the waterSHED Workbook are located on each page within the workbook itself. Users must format the inputs as directed and limit additional columns or rows, which may otherwise cause errors in the upload process. Users can then select the *Import from Workbook* button in the GUI to upload a particular input sheet or can upload all data from the workbook by selecting the *Import waterSHED Workbook* button on the *Start* page. Users must provide the name of the waterSHED Workbook Excel file without the extension (*.xlsx*). If the files are saved in a subfolder in the location of the main script file, then users should input the subfolder name folder followed by a backslash. For example, if the workbook is saved in the Workbooks folder, then the user should input “Workbooks/waterSHED_workbook”.

2.5 HOW TO USE THE SUPPORT TOOLS IN THE waterSHED MODEL

Throughout the GUI, tool tips are available to provide information about the inputs, such as the units, definitions, and additional descriptions. Several inputs have support tools that provide further guidance using equations or models from the literature. These support tools can be found within the *Tool Tip* windows. The list of available support tools is provided in Table 5, and descriptions of the underlying models are provided in Appendix C. In some cases, the support tool has an export function that will automatically place the resulting value from the support tool into the input of the main page.

Table 5. List of available support tools and related sections

Object	Input	Support tool section
Site	Stage–storage curve	C.1
Site	Trap efficiency parameter	C.2
Generation module	Head efficiency curve	C.3
Sediment Passage module	Operating flow	C.4
Species	Relative discharge parameter and attraction sensitivity parameter	C.5

2.6 HOW TO USE THE AUTOMATED DATA RETRIEVAL AND REGRESSION TOOLS IN THE waterSHED MODEL

For specific inputs, the GUI provides the ability to automatically download and process data from the US Geological Survey (USGS) website. The USGS data retrieval function is available for the daily flow and peak flow inputs via the *USGS Download* button and for the stage–discharge curve attribute via the corresponding support tool. Selecting the button will open a window asking for a USGS gage number, a start date, and an end date. The gage number can be found using the USGS National Water Information System (NWIS) mapper.[1] The waterSHED GUI uses the USGS NWIS[2] to retrieve and parse the relevant data automatically, if available. Internet connection is required for this process, and data may not be available for all sites. These data can also be exported as a *.csv* file and saved for later uses by selecting the *Export Data* button on the *Site* page. For the stage–discharge input, the information can be uploaded via the support tool or by selecting the *USGS Download* button in the *Equation Creator* window that pops up from the stage–discharge curve input. The data will be downloaded using an application programming interface from USGS and then automatically regressed using a custom data regression functionality.

Automated regression

The automated regression functionality takes in a data table, formatted according to Table 4 with *X* and *Y* data in the first two columns, and then applies linear regression to create an equation object. This function can be accessed through the *Equation Creator* window of some equation inputs and through the stage–discharge support tool. The tool uses a custom linear regression method designed with USGS flow data types in mind. Before linear regression is conducted, the data are cleaned by removing outliers with z-scores (the number of standard deviations away from the mean) higher than three and, in the case of stage–discharge curves, removing negative data. The input data must have a sample size greater than two, or else an error will be created. The data regression tool developed for this tool applies scipy's *curve_fit* function to four equation forms (linear, power, polynomial-2, and polynomial-3) to find the optimal

[1] https://maps.waterdata.usgs.gov/mapper/index.html
[2] https://waterdata.usgs.gov/nwis/sw

equation parameters and then selects the equation form with the highest R^2 (the coefficient of determination) value [14]. An R^2 threshold of 0.97 is applied so that the least complex equation is used when the R^2 is above the threshold. For example, a linear equation requires fewer parameters than a polynomial-2 equation, so this threshold ensures that the model does not over-fit the data. If successful, the generated equation will automatically be added to the selected input, and the user will be able to plot the regressed curve along with a scatter plot of the data by selecting the *View* button in the equation input.

2.7 GENERAL TIPS AND NOTATION

This section provides some useful tips to have the best user experience. First, the current version of the waterSHED model exclusively uses Imperial units for most inputs. Users should pay close attention to units whenever listed. Metric units are only used in this report when describing models or values from other sources. Second, when changing inputs in the user interface, users must remember to press the *Submit* button prior to simulation. If this is not done, then the new values will not be updated with the associated objects. Third, throughout this report, the user interface, and the waterSHED Workbook, the module classes are color-coordinated according to the scheme provided in Table 1.

Finally, variables are used to connect the simulation and module inputs to the relevant mathematical models used to determine facility design and performance. Table 6 describes the common notations used in mathematical formulations. When a variable has one or more of the subscripts listed in Table 6, then the value is indexed by the subscript, meaning the value applies to a specific instance of the index. For example, the variable $Q_{m,t}$ refers to the flow allocated to module m at time step t in the simulation. In addition, set notation is used to describe processes that apply to all objects of a given class. For example, when summing the widths of all modules in the facility, the notation would show $\sum_m^{Fa} Y_m$, which adds the widths of each module (Y_m) that are in the set of modules comprising the facility (Fa). The axis directions used in this notation system are illustrated in Figure 4.

Table 6. Description of variable notations

Variable	Description
X	The streamwise dimension (length)
Y	The lateral dimension parallel to the dam axis (width)
Z	The vertical dimension parallel to the water column (height)
C	A cost input
R	A revenue input
B	A Boolean input (True/Yes or False/No)
T	Time or a period of time; when T is without a subscript, it refers to the total number of time steps in the simulation
Q	A flow rate
Common indices	
m	A module
t	A time step
s	A species
Set notations	
Fa	The set of all modules in the facility
Wp	The set of all Water Passage modules in the facility.
Fi	The set of all Fish Passage modules in the facility
Gn	The set of all Generation modules in the facility
Rc	The set of all Recreation modules in the facility
Sd	The set of all Sediment Passage modules in the facility
Sp	The set of all species of interest

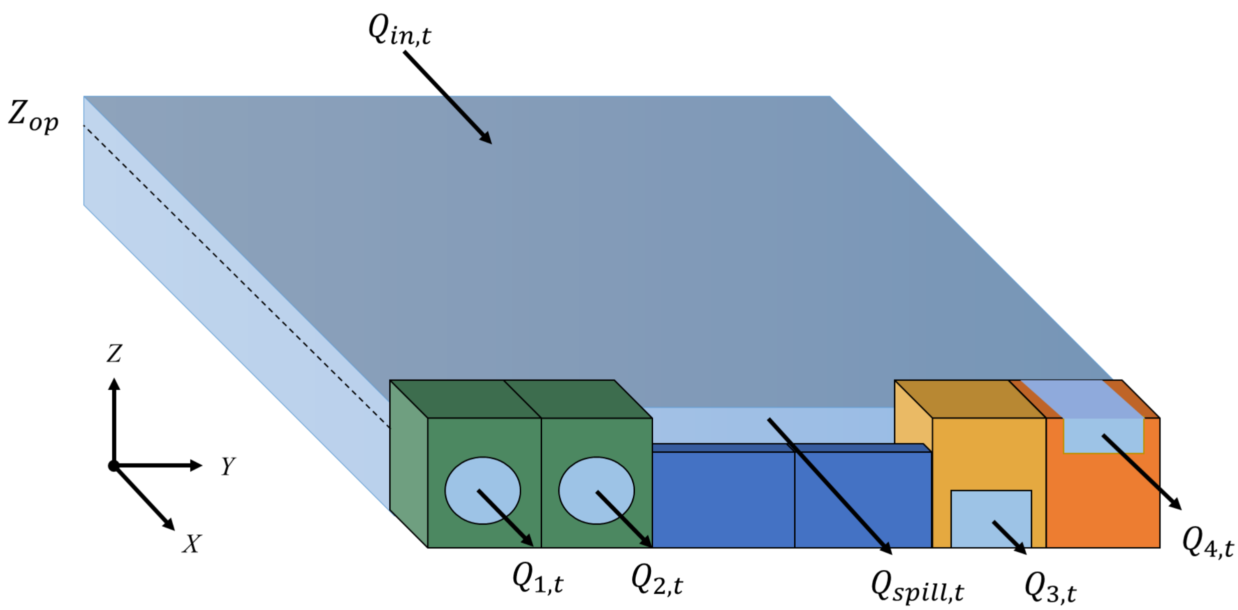

Figure 4. Three-dimensional illustration of axis directions and example modular facility.

3. INPUTS

The waterSHED model relies on user-input data for the module and simulation classes. Inputting the data properly with correct units and formatting is essential. Error checking is available for most inputs but may not be able to catch all errors. For the purposes of this report, the inputs are categorized into module inputs and simulation inputs. The simulation inputs are used to create the Site, Preferences, Cost Tables, and Species objects. To clarify the distinction between inputs and attributes, inputs are values provided by the user, and attributes are characteristics of the created object. In many cases, the inputs directly describe the module, such as design flow, so the inputs and attributes are the same. However, a module may use the inputs to create other attributes. For example, if the max power of a Generation module is not input, then it is calculated automatically from the other head and flow inputs.

The inputs are defined briefly in the section, along with the variable identifiers that are used throughout the model formulations in the following sections. Appendix A provides more detailed descriptions of how the inputs are used in the model. The waterSHED Workbook and GUI also contain information on units, entry types, definitions, and additional descriptions to accompany each of the inputs, so users should refer to these for more information. Inputs marked with an asterisk (*) are optional. Users should leave optional inputs blank (or with "N/A" in the waterSHED Workbook) when they are not in use. The objects defined in this section are often given names that are used to populate figures throughout the model, but these inputs are not reflected in the tables here.

3.1 SIMULATION INPUTS

Simulation inputs are used to characterize the site and the operation/performance of the facility during the simulation. The four simulation classes that can be constructed into objects during the input process are Site, Preferences, Cost Tables, and Species. The Species object is optional and is used solely in the calculation of upstream and downstream fish passage performance, discussed in Section 2. Table 7 defines the inputs (the descriptive characteristics) for each of these four simulation classes.

Table 7. Simulation input descriptions by class

Input	Variable	Description
Site class inputs		
Stream width	Y_{river}	The distance between the left and right banks along the dam axis at the height corresponding to the defined normal operating level (Z_{op}) (ft)
Bed elevation*	Z_{bed}	The bed elevation at the dam axis in reference to mean sea level (ft above mean sea level)
Stream slope*	S_{river}	The average stream slope prior to development (ft/ft)
Trap efficiency parameter*	β_{trap}	A dimensionless sedimentation factor used with the Siyam [15] formulation of the Brune model [16] to reflect the reduction in reservoir storage capacity due to sedimentation
Inflows	$Q_{in,t}$	The daily flow time series data for the site (time series: date and cfs)
Peak flood flows*	$Q_{flood,t}$	The peak flows and corresponding dates for the site (time series: date and cfs)
Stage–discharge equation	$Z_{stage}(Q)$	The water depth in the stream as a function of inflow prior to development (equation: ft vs. cfs)
Stage–storage equation*	$V_{res}(Z)$	The reservoir volume as a function of the headwater elevation (equation: ft^3 vs. ft)

Table 7. Simulation input descriptions by class (continued)

Input	Variable	Description
Preferences class inputs		
Normal operating headwater level	Z_{op}	The headwater elevation with respect to the bed elevation (Z_{bed}) at the dam axis that is maintained during normal operation (ft)
Test data start date	T_{start}	The start date of the simulation period (date)
Test data end date	T_{end}	The end date of the simulation period (date)
Generation dispatch model	N/A	The method used to allocate flows across the Generation modules: The four dispatch models are design ramping, peak ramping, simple greedy, and advanced greedy. The advanced greedy will likely provide the most optimal dispatch but will have longer run times. The peak ramping method will perform slightly worse in most scenarios but will compute much faster
Allow turbine overrun	B_{over}	The input to determine whether the Generation modules can be allocated flow greater than the design flow when excess flow is available (yes or no)
Spillway notch flow	Q_{notch}	The flow allocated to the spillway before passage module allocation that does not affect the headwater level (cfs)
Spillway minimum flow	$Q_{min,spill}$	The flow requirement for the spillway that must be met before passage module allocation; affects the headwater level (cfs)
Operational priorities	P_{op}	The ranking of module classes by priority level in the flow allocation procedure (1–5): The module classes are operated in order of rank (1: first, 2: second, etc.). Section 4 provides more information
Cost Tables class inputs		
Energy price	R_{kwh}	The average price of electricity ($/kWh)
Additional capital costs	C_{cap}	The one-time, fixed expenses incurred on capital assets that are not covered by the module capital costs ($)
Additional non-capital costs	C_{non}	The one-time expenses incurred during the development process that do not involve capital assets ($)
Excavation rate	C_{exc}	The cost to excavate overburden material as a function of dam foundation area ($/ft^2)
Overhead cost	C_{ov}	The cost of overhead activities such as licensing and administration ($ or % of initial capital costs [ICC])
Engineering cost	C_{eng}	The cost of engineering activities ($ or % of ICC)
Contingency allowance	C_{con}	The cost of unexpected expenditures ($ or % of ICC)
Annual O&M cost	C_{om}	The annual cost to operate and maintain the facility ($ or % of ICC)
Value of recreation	R_{rec}	The revenue associated with each Recreation module as a function of availability ($/h)
Flood cost	C_{flood}	The cost per unit of flow exceeding the facility hydraulic capacity during a given time step ($/cfs)
Discount rate	d	The rate used to discount future cash flows and determine the present value of those cash flows; used in the calculation of the net present value (Section B.1.4) (%)
Project life	T_{life}	The expected duration of project operation before plant retirement; used in the calculation of the net present value (Section B.1.4) (years)

Table 7. Simulation input descriptions by class (continued)

Input	Variable	Description
Species class inputs		
Species name	s	The identifier of the migratory species of concern
Relative discharge parameter	a_s	The coefficient used in the attraction efficiency function to set the relative discharge threshold required to prevent attraction efficiency losses: The higher the value, the higher the module flow must be to attract fish
Attraction sensitivity parameter	b_s	The coefficient used in the attraction efficiency function to set the slope of the attraction efficiency function: Higher values tend to create steeper step-functions so that smaller changes in relative discharge will lead to larger changes in attraction
Upstream migration months	$T_{up,s}$	The months during which the species travels upstream across the facility (from tailwater to headwater) (months)
Downstream migration months	$T_{down,s}$	The months during which the species travels downstream across the facility (from headwater to tailwater) (months)

3.2 SMH MODULE INPUTS

The module classes and the required inputs are summarized here in the class hierarchy. A useful feature of OOP is the ability for inheritance in which "child" classes (the subclasses linked hierarchically below another class) inherit the attributes of the "parent" class (the class linked hierarchically above another class). Inheritance condenses the formulation and represents the conceptual structure of information. In Figure 5, all modules have an installed cost, an annual operating cost, a streamwise length, and a lateral width. Passage modules are the child class of modules and have the same cost and dimension attributes in addition to the design flow attributes in its box. The SMH Module and Passage Module classes are "abstract" classes (marked by dotted line borders) that cannot be constructed as an object but are instead used to group characteristics for the child classes. For example, the Passage Module class is abstract because a user must choose a specific Passage Module subclass (e.g., a Fish Passage module). Water Passage and Sediment Passage modules can be created either as an object by selecting the *Continuous* operating mode or as one of the subclasses by selecting the corresponding operating mode. This report may refer to modules based on the operating mode subclass. The continuous operating mode can be used for Water Passage or Sediment Passage modules that operate with consistent design flows, such as minimum flow units or sediment bypasses/siphons. Water Passage modules can also operate in uncontrolled spillway or controlled spillway modes, so they can be referenced as Spillway modules. Each facility must have at least one Spillway module to pass flood overflows. Additionally, Sediment Passage modules may operate in flushing or sluicing modes and are referenced as Flushing or Sluicing modules when appropriate.

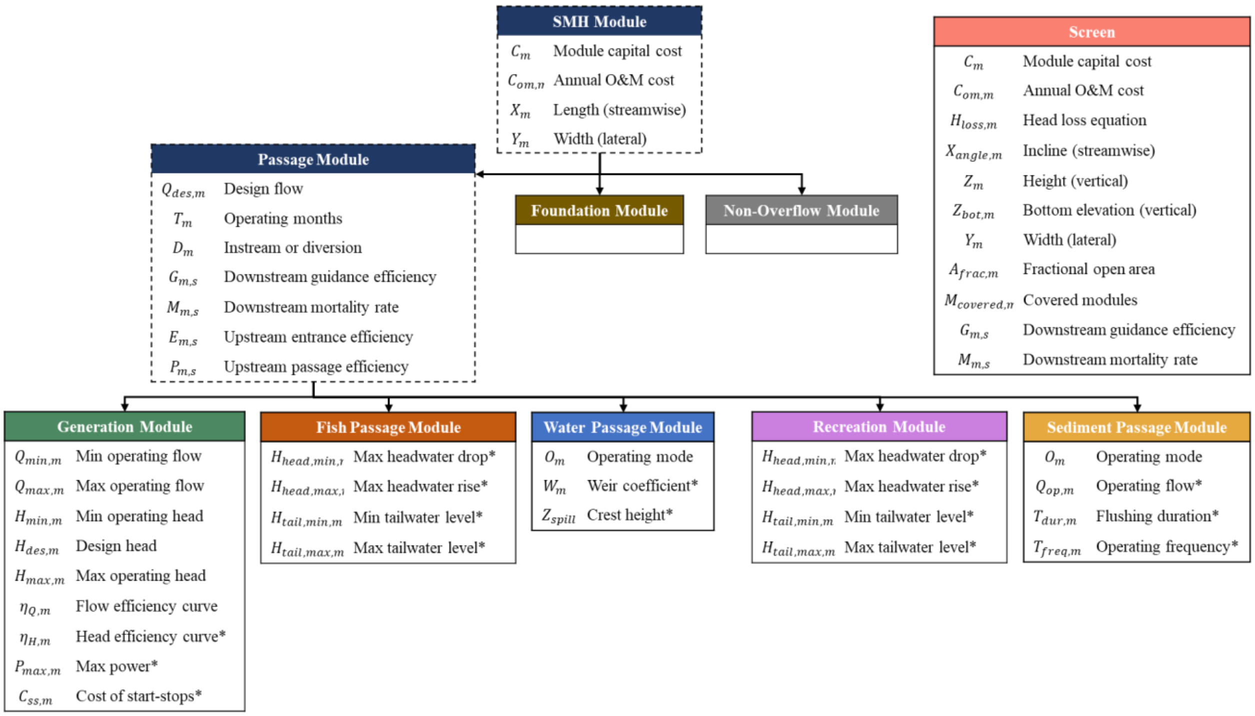

Figure 5. Class hierarchy structure for module objects. Asterisks (*) indicate optional attributes.

Table 8 summarizes the inputs according to the described hierarchy. In some cases, such as design flow, the definition differs depending on the module class. The individual module classes are described in Section A.1.

Table 8. Module input descriptions based on module class hierarchy

Input	Variable	Description
SMH module class inputs		
Module capital cost	$C_{cap,m}$	The capital cost for a module, which should include all fixed, one-time costs to prepare a module for operation ($)
Annual O&M cost	$C_{om,m}$	The annual operating costs for a module, which should include all annualized expected costs for maintaining and operating the module ($)
Width	Y_m	The module dimension along the dam axis from bank to bank, perpendicular to streamflow (ft)
Length	X_m	The module dimension parallel to streamflow (ft)
Passage module class inputs		
Design flow	$Q_{des,m}$	The flow rate through the module at design conditions (cfs): Definitions differ between module classes, as described in Appendix A.
Operating months	T_m	The months during which the module is on and is allocated flow (months)
Instream or diversion	D_m	Whether the module should be included as an instream module in the dam axis or as a diversion/bypass around the dam axis (yes for diversion or no for instream)

Table 8. Module input descriptions based on module class hierarchy (continued)

Input	Variable	Description
Downstream guidance efficiency*	$G_{m,s}$	The percentage of species s individuals entrained in the flow allocated to module m that are excluded from flow into the module (%): A guidance efficiency of 0% means all fish that attempt to enter the module will enter, whereas an efficiency of 100% means that all fish will be excluded and guided to another structure. The downstream mortality model in Section B.4 provides more information. *Can be entered in the Species Passage page of the GUI*
Downstream mortality rate*	$M_{m,s}$	The percentage of species s individuals that are killed or unable to reproduce after passage through the module (%): A mortality rate of 0% means that no fish that pass through the module are harmed, whereas a mortality rate of 100% means that no fish can safely pass. The effective mortality model in Section B.4 provides more information. *Can be entered in the Species Passage page of the GUI*
Upstream entrance efficiency*	$E_{m,s}$	The percentage of species s individuals that can successfully enter the module after being attracted to the entrance (%): An entrance efficiency of 0% means that no fish can enter the module, whereas an entrance efficiency of 100% means that all fish can enter safely. The effective upstream passage model in Section B.4 provides more information. *Can be entered in the Species Passage page of the GUI*
Upstream passage efficiency*	$P_{m,s}$	The percentage of species s individuals that can successfully ascend the module after entering (%). A passage efficiency of 0% means that no fish can ascend, whereas a passage efficiency of 100% means that all fish can ascend safely. The effective upstream passage model in Section B.4 provides more information. *Can be entered in the Species Passage page of the GUI*
Fish and Recreation module class inputs		
Max headwater drop*	$H_{head,min,m}$	The maximum decrease in headwater elevation with respect to the normal operating headwater level (Z_{op}) allowed during module operation (ft)
Max headwater rise*	$H_{head,max,m}$	The maximum increase in headwater elevation with respect to the normal operating headwater level (Z_{op}) allowed during module operation (ft)
Min tailwater level*	$H_{tail,min,m}$	The minimum tailwater level required for operation, in reference to the bed elevation (Z_{bed}) (ft)
Max tailwater level*	$H_{tail,max,m}$	The maximum allowable tailwater level for operation, in reference to the bed elevation (Z_{bed}) (ft)
Generation module class inputs		
Min operating flow	$Q_{min,m}$	The minimum flow required to operate the module (cfs)
Max operating flow	$Q_{max,m}$	The maximum flow that can be allocated to the module (cfs)
Min operating head*	$H_{min,m}$	The minimum gross head required to operate the module (ft)
Design head	$H_{des,m}$	The gross head at which the module operates at peak efficiency (ft)
Max operating head*	$H_{max,m}$	The maximum gross head allowable during module operation (ft)
Flow efficiency curve	$\eta_{Q,m}$	The power output efficiency coefficient as a function of the relative discharge, which is the flow allocated to the module divided by the design flow (i.e., design flow = 100%) (equation: % efficiency vs. % design head)

Table 8. Module input descriptions based on module class hierarchy (continued)

Input	Variable	Description
Head efficiency curve*	$\eta_{H,m}$	The power output efficiency coefficient as a function of the relative head, which is the gross head across the module divided by the design head (i.e., design head = 100%) (equation: % efficiency vs. % design head)
Max power*	$P_{max,m}$	The maximum possible power output of the unit (kW)
Cost of start-stops*	$C_{ss,m}$	The attributed cost of damages for one ramping cycle of the turbine ($/start-stop)
Water Passage and Spillway module classes inputs		
Operating mode	O_m	The effect of spillway flow on the headwater elevation (continuous, controlled spillway, or uncontrolled spillway)
Weir coefficient*	C_{spill}	A constant based on the shape of the weir ($ft^{1/2}/s$)
Crest height*	Z_{spill}	The height of the top of the weir in reference to the bed elevation (Z_{bed}) (ft)
Sediment Passage module class inputs		
Operating mode	O_m	The conditions under which the module is allocated flow (continuous, sluicing, or flushing)
Operating flow*	$Q_{op,m}$	The minimum inflow threshold required to mobilize bed-load sediments and open the sluice gate (cfs)
Flushing duration*	$T_{dur,m}$	The number of time steps required to flush the reservoir (days)
Operating frequency*	$T_{freq,m}$	The number of flushing events per year (flushes/yr)

4. SIMULATION

Once the module and simulation inputs have been entered, then the user can use the *Enumerate* or *Optimize* options to create an SMH facility and simulate operation. These processes are handled internally, but it is important for the user to understand the assumptions made about how the modules are configured and operated. Section 4.1 describes how the modules are created to form an SMH facility, and Section 4.2 describes the simulation procedure. These procedures are used to output performance metrics, which are presented in Section 4.3.

4.1 CREATING A FACILITY

An SMH facility, as exemplified in Figure 6, is created by placing a combination of modules within a site. A facility must consist of at least one Foundation module, one Non-Overflow module, and one Spillway module, which can be a Water Passage module operating in either controlled or uncontrolled spillway mode. If any existing structures comprise one of these components or the user wishes to include foundation costs in a different way, the user can input a default module with capital and operating costs of $0. Additional modules to be included in the site are either input from the user in the *Enumerate* function or automatically generated in the *Optimize* function. Once these modules are included, a theoretical facility schematic will be generated. The facility requires enough modules to be placed in the dam axis (a conceptual line across the river from bank to bank) to fill the stream width (Y_{river}) to create a watertight barrier between the headwater and tailwater. The current version of the model allows passage modules to be placed within the dam axis or as diversions around the dam, depending on the diversion or instream input (D_m). Although modules are displayed as diversions, they are assumed to be relatively short and operate according to the headwater and tailwater elevations at the dam axis.

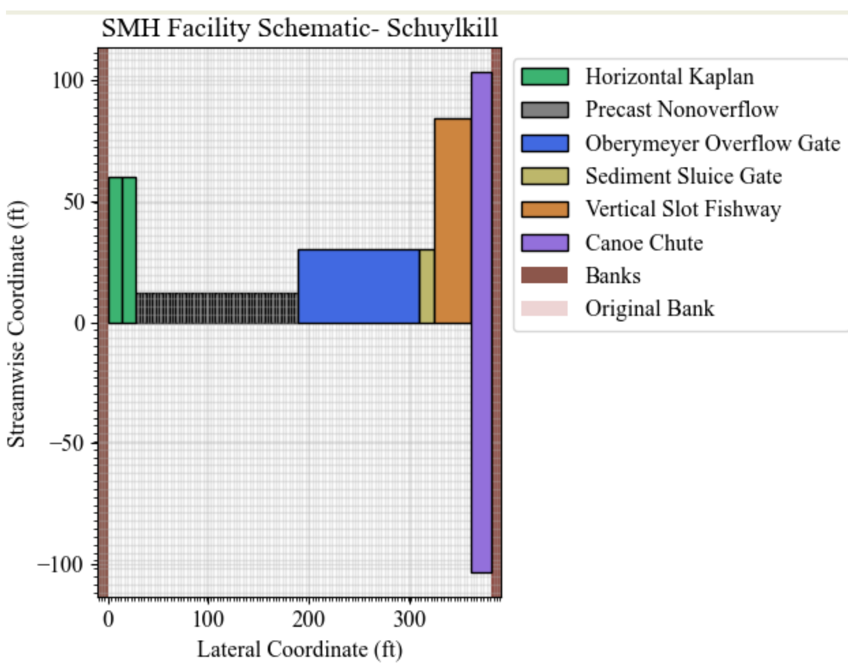

Figure 6. Example SMH facility schematic output.

The width of the facility is calculated by summing the widths of the modules placed on the dam axis. If the width of the facility is not greater than the stream width (Y_{river}), then additional Non-Overflow modules are added. Thus, the user cannot control the number of Non-Overflow modules explicitly, except by changing the stream width. The width of the modules in the dam axis can be larger than the stream width. In these cases, the original bank is represented as a pink region adjacent to the new bank line, but this does not affect performance.

$$If: (Total\ width\ of\ modules\ in\ dam\ axis) < Stream\ width$$

$$Then: Add\ Non\text{-}Overflow\ modules\ until\ Total\ width > Stream\ width$$

Research into Foundation modules for hydropower is ongoing, and the engineering design process for these modules is still unclear. The current waterSHED model approach requires Foundation modules to provide support beneath all modules, so the Foundation modules are represented as rectangular blocks under the other modules. The number of Foundation modules required is based on the total area of modules (i.e., the facility footprint) divided by the area of a single Foundation module. This value does not account for the shape or placement of the modules. This number is automatically calculated, and the user cannot explicitly set the number of Foundation modules. If the user has a particular foundation cost in mind, then the user should include a Foundation module with capital and operating costs of $0 and then input foundation costs in the Additional Capital Costs input of the Cost Tables.

$$Module\ area = Module\ width \times Module\ length$$

$$Facility\ footprint = \sum Module\ areas$$

$$Number\ of\ Foundation\ modules = \frac{Facility\ footprint}{Foundation\ module\ area}$$

Each facility must have one and only one type of Spillway module within the facility. There may be more than one Spillway module, but they must be of the same type. Spillway modules are aggregated together to form one spillway that operates in sync, thus creating a larger spillway with a higher design flow. The spillway design flow ($Q_{spill,des}$) is created by multiplying the design flow of the Spillway module ($Q_{des,m}$) by the number of Spillway modules in the facility. The spillway width (Y_{spill}) is calculated in a similar way by multiplying the width of the Spillway module (Y_m) by the number of Spillway modules.

$$Q_{spill,des} = Q_{des,m}\ of\ the\ Spillway\ module \times Number\ of\ Spillway\ modules$$

$$Y_{spill} = Y_m\ of\ the\ Spillway\ module \times Number\ of\ Spillway\ modules$$

Because the waterSHED model does not model 2D or 3D hydraulics, the placement of the modules along the dam axis or in bypasses does not affect the simulated operation. The modules are placed in the following order from left to right in the facility figures for aesthetic purposes, but the order does reflect design principles: Generation, Water Passage, Sediment Passage, Fish Passage, and Recreation. Generation modules should be located close to the bank to facilitate maintenance activities. Sediment Passage modules should be located toward the center or the lowest elevation in the streambed to facilitate lateral sediment transport. Recreation modules should be located close to the bank for easy access and for the safety of recreationalists. Fish Passage modules should be located wherever the target species is expected to swim. Williams et al. [17] suggest that upstream migrants move along the riverbanks where high-velocity gradients exist, whereas downstream migrants tend to follow high velocities in the center of the river.

Assumption: The facility width must equal or exceed the stream width to create a watertight barrier between the headwater and tailwater.

Assumption: Bypasses are relatively short and operate according to the headwater and tailwater elevations at the dam axis.

4.2 SIMULATING FACILITY OPERATION

Simulating the operation of the SMH facility utilizes a numerical method to predict performance. Numerous hydropower design models in the literature use analytical models to predict energy generation using coarse representations of flow duration curves. These models may neglect the operational relationships between technologies over time, such as the changes in headwater elevation. The waterSHED model aims to represent realistic daily operation by simulating flow allocation across daily time steps. This procedure, however, must balance the level of detail available to the user with the accuracy of the prediction. Given that inputs are limited to high-level site dimensions, the model uses 1D hydraulic relationships provided by the user and the rule-based programming procedure to allocate flow across modules and determine facility performance. Section 4.2.1 describes the inputs for hydraulic relationships that are used during the simulation, and Section 4.2.2 describes the rule-based programming operation model, which determines how the modules are operated.

4.2.1 Hydraulics Models and Assumptions

The operation of the facility requires operators to adapt to the hydraulic conditions of the site. If flood flows enter the reservoir, then the dam must be prepared to spill flows exceeding the module design flows. If flows are low and the gross head across the site causes cavitation or other safety concerns, then modules may need to be turned off. The waterSHED model aims to represent these hydraulic conditions through a stage–discharge curve, a stage–storage curve, and weir equations. These relationships are input by the user, so the level of accuracy is dependent on the user's desired level of detail and available information. Standard procedures and inputs are recommended where users do not have information.

Tailwater-level model

The tailwater level of the facility will change based on the flow out of the facility and the hydraulics of the channel. The tailwater level affects the net head across Generation modules, as well as the minimum flow depths needed for Recreation and Fish Passage modules. A full understanding of the stage–discharge relationship requires knowledge of the flow fields out of the modules, the geometry of the tailrace channel, and the roughness of the channel. This would require 2D or 3D hydraulic modeling and the ability to predict the geomorphic changes of the tailrace over time, which is difficult even with complete information. To maintain simplicity, the assumption of the previous waterSHED model [6] is employed, which is that the tailwater elevation at a given time step can be represented by the stage–discharge curve of the stream prior to development, i.e., $Z_{tail,t} = Z_{stage}(Q_{in,t})$. This assumption ignores geomorphic changes but employs site-specific data to preclude the need for information about the module hydraulics.

Assumption: The stage–discharge curve in the tailwater reach is the same before and after the development of the facility.

Headwater-level model: Controlled spillway

Headwater elevation is an important contributor to the head used for power generation and to the environmental impacts connected to reservoir size. ROR headponds are operated to provide consistent submergence for intakes, but the headwater level may fluctuate depending on the selected technologies and operations. Headwater fluctuations are particularly important for low-head sites because small changes in head represent a larger percentage of the total head compared with higher-head sites. Headwater elevation changes can be caused by changes in usable reservoir storage and by the hydraulics of modules, particularly spillways. This contribution is small for low-head ROR facilities compared with storage projects. This model assumes strict daily ROR operation where mean daily flows are passed evenly throughout the day, and there is no significant inter-day storage. Any sub-daily variation in flow that could change the reservoir storage volume is assumed negligible. However, the effects of hydraulics on headwater elevation must be considered. Because of the black-box approach, there is limited information about the hydraulics of the passage modules. Generalizable information is available on the hydraulics of weirs and spillways, so this headwater elevation model only focuses on the hydraulics of Spillway modules and ignores the effects of non-Spillway modules on headwater elevation. The two main categories of spillways used in this model, controlled and uncontrolled, are described here.

Assumption: Sub-daily inflow variation is minimal and does not contribute to significant headwater level variation.

Assumption: Headwater elevation is controlled primarily by the operation and hydraulics of the spillway.

Controlled spillways, such as Obermeyer gates and overflow structures with radial gates, can mechanically control the amount of flow. In the case of Obermeyer gates, as shown in Figure 7, the structures are pneumatically adjusted to control flow. The benefit of these structures is that they can regulate the headwater level of the headpond by controlling the invert elevation (i.e., crest height) of the structure. In ROR schemes, the crest height of these structures can be set at the normal headwater operating level, and gates can be controlled to pass different flow rates and maintain a constant headwater elevation. This model assumes that if the Water Passage module is a controlled spillway, then the headwater elevation is constant throughout the simulation, except in the case of flushing events. Thus, the headwater elevation at a given time step is equal to the constant normal headwater operating level from the Preferences object (Section A.2.3), i.e., $Z_{head,t} = Z_{nol}$.

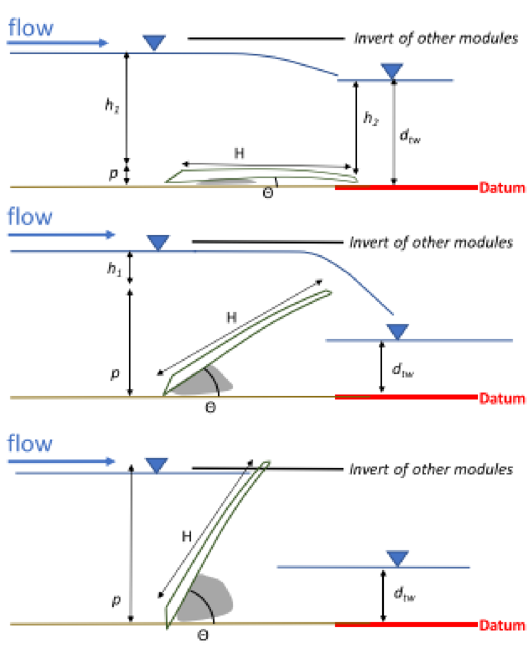

Figure 7. Profile view of conceptual Obermeyer overshot spillway. Reprinted from Witt (2018) [6].

Assumption: If the spillway provides head control, the headwater level is maintained at the normal operating level.

Headwater-level model: Uncontrolled spillway

For uncontrolled spillways, the headwater-level model focuses on weirs, which are static overflow structures that pass water based on head. Weirs are the focus because they are typically the lowest cost options for low-head sites compared with siphons, morning glories, or diversion tunnels. These structures cannot regulate headwater level, but they do provide predictable head and flow relationships. The Water Passage module provides a variety of options that can be used to model this head and flow relationship. Typically, weir equations are used to determine head from a measured flow. In this case, the model allocates extra flow to the Spillway module, so head must be back-calculated from a given flow.

The basic rectangular weir equation is shown in Equation 1. This equation relies on a weir coefficient (C; i.e., the effective coefficient of discharge), which corresponds to the module input (C_{spill}). The weir coefficient must be entered in $ft^{\frac{1}{2}}/s$, typically has a range of 2.6 to 4, and is described in depth in the US Bureau of Reclamation Water Measurement Manual.[3] The weir coefficient depends on the type of weir and the dimensions of the weir features. This formulation assumes a constant weir coefficient for different head values but allows the model to represent unique weir types. The weir coefficient is different from the discharge coefficient (C_d), which is a dimensionless constant that can be converted to a weir coefficient, as shown in Equation 1 below. When more than one of the same Spillway module type are in a facility, they are treated as a single structure with a total length (Y_{spill}) equal to the sum of each module.

Weir equation	$Q = CLH^{\frac{3}{2}}$	Equation 1
Flow over weir (cfs)	Q	
Weir length (ft)	L	
Head over weir (ft)	H	
Weir coefficient ($\frac{ft^{\frac{1}{2}}}{s}$)	$C = \frac{2}{3}C_d\sqrt{2g}$	
Discharge coefficient (dimensionless)	C_d	

By transforming this weir equation, we can derive an expression Equation 2 for headwater elevation based on the parameters used in this model. The corresponding dimensions are given in Figure 8.

Modified weir equation	$Z_{head,t} = \left(\frac{Q_{spill,t}}{C_{spill}Y_{spill}}\right)^{\frac{2}{3}} + Z_{spill}$	Equation 2
Flow through spillway (cfs)	$Q_{spill,t} = \sum_{m}^{W} Q_{m,t}$	
Total weir length (ft)	$Y_{spill} = \sum_{m}^{W} Y_m$	
Weir coefficient ($\frac{ft^{\frac{1}{2}}}{s}$)	C_{spill}	
Height of weir crest (ft)	Z_{spill}	

[3] https://www.usbr.gov/tsc/techreferences/mands/wmm/index.htm

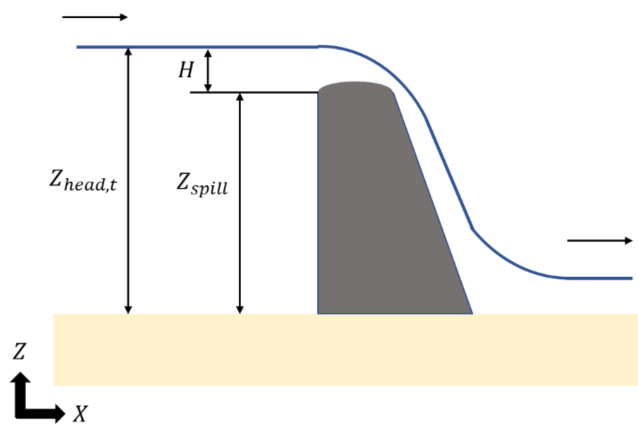

Figure 8. Conceptual profile schematic for a weir with dimension labels.

Assumption: The weir coefficient for uncontrolled spillways is constant for different head values.

Reservoir size model

Reservoir size is an important factor in sedimentation, water quality changes, and flood risk. The reservoir volume is a function of the normal operating level and the topography of the site. For typical site investigations, digital elevation models can be used to digitize the topography and evaluate the volume and surface area relationships for a given site. However, elevation models may not be available with sufficient resolution for the small reservoirs involved. This relationship is parameterized through a stage–storage equation ($V_{res,z}$) that is an attribute of the site. Models for the storage (volume) estimation have been created specifically for small dams where geographical information system tools may be limited. The support tool described in Section C.1 describes a geometric approach based on Lawrence and Cascio [18] that can be used to estimate the stage–storage relationship. Currently, this relationship is primarily used for the calculation of the sediment trap efficiency of the reservoir (described in Section B.3.3). However, reservoir size is qualitatively associated with several negative environmental and social outcomes, so it is generally recommended to minimize the impoundment size [19]. For example, larger reservoirs can be correlated with more displaced communities, greater chances for lacustrine water quality conditions, and more significant modification of the flow regime [19].

4.2.2 Rule-based Operation

The operation of the facility is critical to the selection of modules. The waterSHED model assumes that facilities are operated in daily ROR mode, meaning that the flow rates allocated to modules during a time step must equal the average daily inflow rate. There are several reasons for this assumption: (1) ROR operation limits impacts on the hydrologic regime, which can cause significant ecological impact [20]; (2) maintaining the natural flow regime requires a daily or sub-daily ROR time step (the time period over which flow in equals flow out) [21]; (3) recent regulations show an increase in ROR operating requirements for new licenses [4]; and (4) the most widely available flow information from USGS gages is daily average discharge. Future model features may address sub-daily time steps, but the current version requires daily flow information. Daily ROR operation also assumes that the sub-daily inflow variation is negligible so that changes in storage throughout the time step do not substantially affect head. This means that at the beginning of each day, the headwater elevation will be calculated based on the daily average inflow and spillway characteristics, and the facility will be operated at this headwater throughout the day.

The operation model uses rule-based programming to determine how the flow should be allocated across modules. The user can identify the priority order for module classes (P_{op}) by ranking the passage module classes from 1 (highest priority) to 5 (lowest priority). Modules with the highest priority will be allocated flow first, and modules with lower priority will be allocated flow if there is flow remaining. When allocating flow between non-Generation modules within the same class, it is assumed that the modules with the smallest design flow get allocated first since they require the smallest amount of flow to be operational. Generation modules will be allocated flows according to the dispatch models described in Section 4.3. The priority rankings create a rule curve that describes the order of allocation, as exemplified in Figure 9. All time steps (days) are treated as individual flow allocation problems with no links between time steps. However, flow can only be allocated to a module if it is ON, which can be a function of several inputs, including the operating months and head constraints. The pseudocode for each module class is described in Table 9. Although an optimized flow allocation procedure is feasible, this rule-based method was selected because it reflects the existing reservoir rule curves methods and simplifies the simulation process, leading to faster run times. Additionally, in a modular facility where units are standardized, design flows will likely be equal, thus reducing expected performance loss from non-optimized performance.

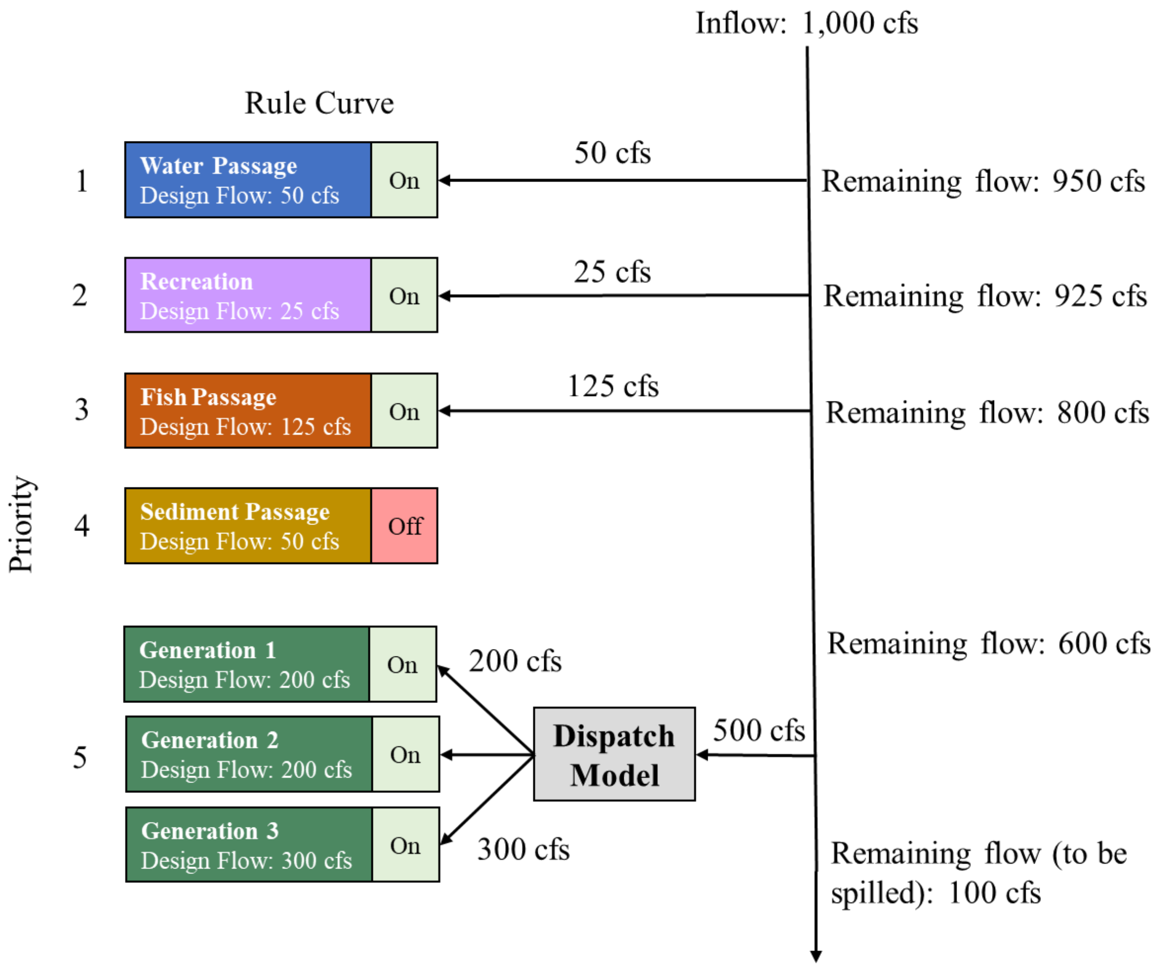

Figure 9. Example flow allocation for one time step given a prioritized module rule curve.

Table 9. Pseudocode for the operation of each module class

Module class	Operation pseudocode (Note: if no flow is allocated then the module is not turned on)

Sediment passage	For each module from smallest to largest:
	• If the time step is during an operating month, then:
	  • If Operating Mode = Continuous, then:
	    • If available flow > design flow, then:
	      • Allocate design flow
	  • Else if Operating Mode = Sluicing, then:
	    • If inflow > operating flow, then:
	      • If available flow > design flow, then:
	        • Allocate design flow
	  • Else if Operating Mode = Flushing, then:
	    • If the time step is during a flushing event, then:
	      • Allocate all inflow to sediment module

Recreation and Fish passage	For each module from smallest to largest:
	• If the time step is during an operating month, then:
	  • If headwater and tailwater within acceptable limits, then:
	    • If available flow > design flow, then:
	      • Allocate design flow

Water passage	For each module from smallest to largest:
	• If the time step is during an operating month, then:
	  • If Operating Mode = Continuous, then:
	    • If available flow > design flow, then:
	      • Allocate design flow
	  • Else if Operating Mode = Controlled or Uncontrolled Spillway, then:
	    • If inflow > operating flow, then:
	      • If available flow > design flow, then:
	        • Allocate design flow

Generation	Generation modules are treated as a singular powerhouse and operated according to a dispatch model.
	• If available flow > minimum powerhouse flow, then:
	  • If at least one generation module is operating this month, then:
	    • If the gross head is within the design range, then:
	      • Allocate flows using dispatch model to ON modules

There are exceptions to this rule-based procedure, which are captured in the high-level procedure that surrounds the rule-based flow allocation, as described in Figure 10. First, prior to flow allocation, if a sediment flushing module is included in the facility, then the schedule of flushing events is determined. The start of flushing events is assumed to be the first possible time step, and then flushing events occur every $365/T_{freq,m}$ time steps (rounded up) from the beginning of the first time step. The flushing events last for $T_{dur,m}$ time steps and during this time, all modules are turned off, the reservoir is drawn down, and all flow is allocated to the sediment flushing module.

Next, the model must consider the headwater and tailwater elevations. The Recreation, Fish Passage, and Generation modules can be turned off if the headwater elevation, tailwater elevation, or gross head (headwater − tailwater) are outside of user-specified bounds. The tailwater elevation is determined based on the stage–discharge curve and the inflow ($Z_{head,t} = Z_{stage}(Q_{in,t})$), and the headwater elevation is based on the spillway characteristics. In the case of controlled spillways, the headwater elevation is assumed constant, so flow is allocated based on known headwater and tailwater elevations. In the case of facilities with uncontrolled spillways and head-constrained modules, head is dependent on the spillway flow, and the spillway flow is dependent on head via the flow allocation to other modules. This situation requires a nonlinear solution and is addressed with an iterative solution, as described in Figure 10. The first step in this nonlinear solution process is to allocate flow to the modules while disregarding head limitations (including the headwater and tailwater limitations of the Recreation and Fish Passage modules and the head constraints of the Generation modules). This temporary flow allocation provides an estimate of the headwater elevation using the flow allocated to the spillway. The flow allocation is performed again with the estimated headwater and including the head limitations. The calculated headwater level is then computed using the new flow allocation. If the estimated and calculated headwater levels match (i.e., no modules are constrained by head limits), then the iteration ends. Otherwise, the constrained modules are turned off, and the iteration repeats. The estimated and calculated headwater levels must match to terminate the procedure because the calculated flow allocation is based on the estimated headwater level. If the module is unable to terminate after all modules are turned off, then the simulation reports an error. This would likely be caused by module head constraints being too tight, so the user should ensure that modules can operate within expected head conditions.

Finally, any flow remaining after rule-based flow allocation and turbine overrun is allocated to the spillway. If the remaining flow exceeds the spillway design flow (the sum of $Q_{des,m}$ for all Spillway modules), then the spillway design flow is allocated to the spillway, and the remaining is counted as overflow. This flow would overtop the facility and cause damage captured by the cost of flood damages parameter (C_{flood}).

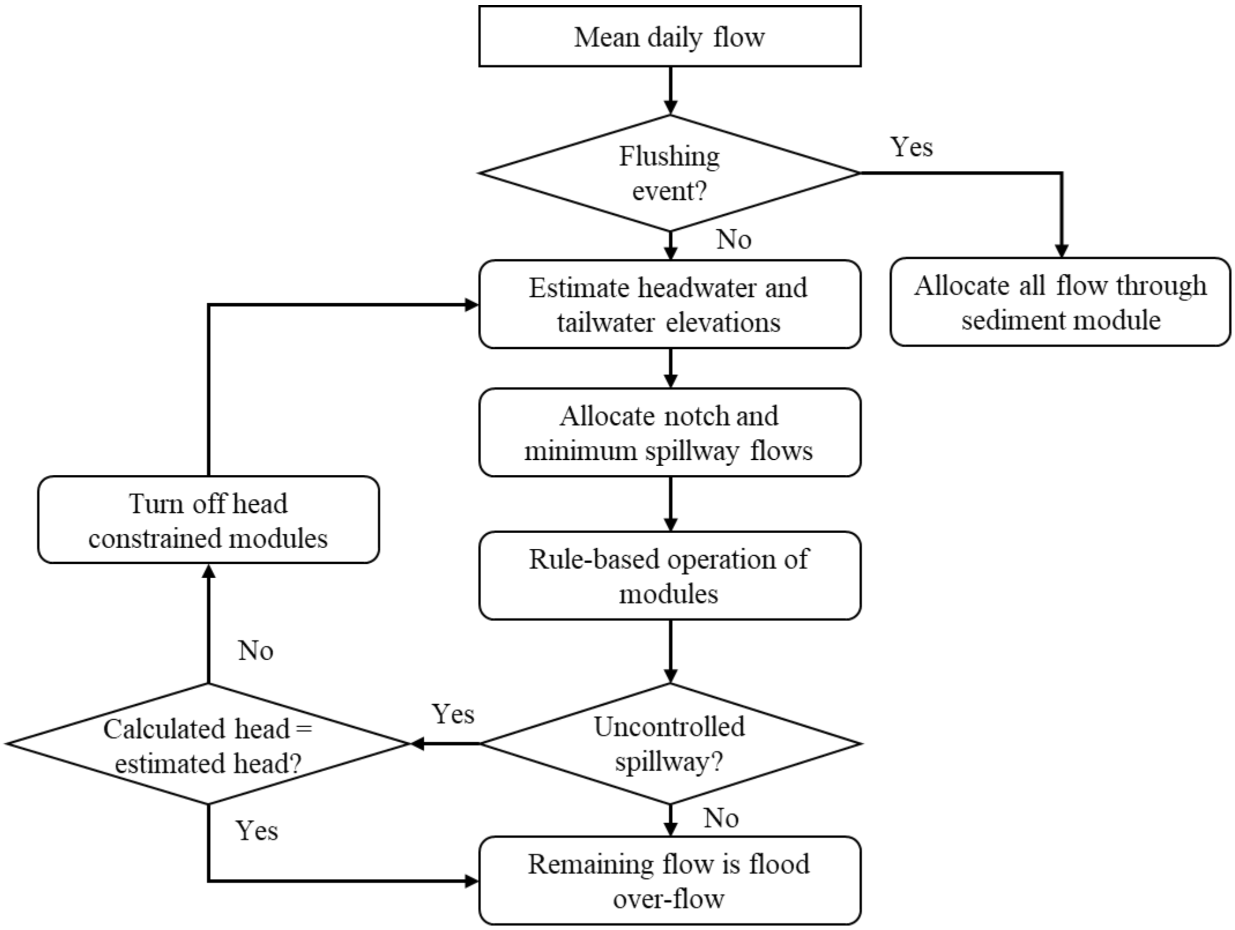

Figure 10. Operational flow chart.

Assumption: When allocating flow between non-Generation modules of the same class, the modules are ramped in order of smallest to largest design flow.

4.3 DISPATCH MODELS

The generation dispatch models are algorithms that aim to determine the flow allocation across Generation modules that maximizes the plant power output within realistic operating regimes. The main constraint for this daily dispatch model is termed a ramping constraint, which means that once a turbine has been turned on at a given amount of flow, it should not be turned off at higher generation flows. Turning turbines on and off can damage the units because off-design hydraulic conditions can lead to cavitation and other forms of wear [48]. Ramping turbines too quickly can also be damaging; however, given the daily timescale of operation, it is assumed that the turbines can be ramped safely within the operating flow range. Algorithms must balance accuracy and computation time since dispatch is required at every time step within the simulation, and multiple simulations may be needed for analyses in the waterSHED model. The context of SMH may provide benefits for simplifying dispatch. For example, the turbines will often have the same operating flows and efficiency characteristics. Four dispatch models were created in the waterSHED model to solve the optimal dispatch problem in different use cases, which have trade-offs regarding computation time and performance. These methods are design ramping, peak ramping, simple greedy, and advanced greedy. As described here, the peak ramping and advanced greedy methods are the most useful, and the other models were created for comparison purposes in the accompanying dissertation [7].

The algorithms have several inputs, including the available generation flow provided by the rule-based operation, the attributes of the Generation modules within the powerhouse, and the turbine overrun input (B_{over}) that determines whether turbines can be allocated past their design flows. Overrunning the turbine may allow the turbine to produce more power, but this does not occur at peak efficiency and may incur damages from operating outside of the design flow. Turbine overrun may be useful with the peak and design ramping models when the turbine power output increases past the design flow. However, when the power output decreases at flows higher than the design flow, then the turbine overrun option should not be used. The greedy algorithms are not affected by this option. This can only occur if there is flow remaining after allocating flow to the other modules. If turbine overrun is allowed, then the Generation module flow efficiency curves must cover the upper design range.

The design ramping and peak ramping methods are simpler and faster than the greedy algorithms but do not guarantee optimal allocations. When provided a powerhouse flow, the algorithm ramps the turbines in order from smallest to largest design flow. The difference between the design and peak ramping methods is that the peak ramping method will try to ramp all turbines first to their peak efficiency flows before ramping to their design flows, whereas the design ramping method ramps each turbine all the way to the design flow. In each case, once a turbine is ramped to the specified flow, the next turbine is turned on if there is sufficient flow to meet the minimum flow requirements. If the peak efficiency occurs at the design flow, then the methods do not differ. When turbine overrun is allowed and all modules are ramped to their design flows, the modules are ramped to the max design flow from smallest to largest. Ramping in this order ensures that low flows can be captured by operating the smallest module first. However, turbines in an SMH design are often the same size, so the size order may be arbitrary. The design ramping model is appropriate for fast solution times when the peak efficiency occurs at the design flow for the Generation modules. The peak ramping model is appropriate for fast solution times when the peak efficiency occurs before the design flow.

The simple greedy and advanced greedy models use an iterative process to allocate flow during the ramping process. The process starts with the minimum turbine flow and iterates by 1 cfs until the maximum powerhouse flow (the sum of maximum operating flows for all modules). For each flow increment, the algorithm calculates the increase in power for each possible flow allocation and then chooses the allocation with the maximum increase in power. The flow unit is not allocated to any modules above their design flow (max operating flow if turbine overrun is allowed), and new modules are not turned on unless the flow unit exceeds the minimum operating flow. If the unit of flow cannot be allocated at an iteration, then it is accumulated for the next iteration until it is large enough to turn on the next turbine. Additionally, if there is no increase in power, then the flow is not allocated and is accumulated for the next iteration. The flow allocation is saved between runs so that the dispatch of the next unit of flow is dependent on the previous dispatch. This process simulates the real-world scenario in which turbines are online, and operators must allocate incremental changes in flow. The simple greedy approach uses this method without modification and behaves very similarly to the design ramping method when turbines are the same size. This method is not effective for turbines with flat efficiency curves, such as Kaplan turbines. The advanced greedy method was modified to use a nested greedy approach in which the outer loop determines whether a new turbine should turn on or flow should be allocated across the modules that are already on and the inner loop allocates flow optimally across the on modules. Once a module is turned on, then it must stay on during the following iterations. However, the allocation of flow resets during each increment allowing the algorithm to ramp down turbines to bring new turbines online. The computational speed depends on the powerhouse flow range and the number of Generation modules, but the advanced greedy approach typically takes far longer than the other approaches. However, in the case studies in the accompanying dissertation, the advanced greedy performed the best in terms of maximizing energy generation [7]. The advanced greedy method should be used when longer run times are appropriate and the Generation modules are either different sizes or have flat efficiency curves. The simple greedy method should be used for faster run times when modules are different sizes.

4.4 MEASURES OF PERFORMANCE

The waterSHED model provides a suite of performance metrics that can be used to evaluate a facility across economic, social, and environmental objectives. Some metrics are well researched, whereas others are novel metrics that aim to represent objectives that are commonly neglected in RHDMs. The accuracy of these calculations depends on the detail of the inputs. However, an advantage of the model is the ability to represent the complex relationships between design decisions and performance metrics. Thus, users can learn about the associated sensitivity and performance trends with even coarse estimations.

The performance metrics can be viewed in the Simulation Results section of the *Enumerate* or *Optimize* page that populates when a simulation is completed. When possible, the novel metrics were formulated as percentages so that the user can better interpret the metric's scale. For the holistic performance ratios plot in the Simulation Results section of the GUI, the metrics are adjusted so that 0% represents poor performance and 100% represents good performance, although elsewhere, the metrics are kept in the original forms. The performance metrics are summarized in Table 10 and described in Appendix B.

Table 10. List of available performance metrics with descriptions and links to mathematical formulations

Category	Performance metric	Description (unit, suggested goal [i.e., maximize or minimize])
Economic	Annual energy generation	The annualized sum of energy generation for all Generation modules in the simulation (MWh/yr, maximize)
	ICC	The one-time expenses used to purchase or construct capital assets, such as buildings, land, and equipment ($, minimize)
	Total cost	All the one-time costs required to begin operation ($, minimize)
	Net present value	The current value of the project based on the total cost, expected revenue, annual maintenance expenditures, and discount rate ($, maximize)
	Levelized cost of energy	The average net present cost to produce energy over the life of the project ($/kWh, minimize)
Fish passage	Effective downstream mortality	A novel metric describing the expected time-averaged mortality rates for a species over the simulation (% [0–100], minimize)
	Effective upstream passage	A novel metric describing the expected time-averaged upstream passage success rates (% [0–100], maximize)
Sediment passage	Sediment flow ratio	The average ratio of flow allocated to Sediment Passage modules compared with the total inflow at each time step (% [0–100], maximize)
	Sediment passage frequency	The number of time steps in which Sediment Passage modules are operating divided by the total number of time steps (% [0–100], maximize)
	Average trap efficiency	The average percentage of incoming sediment that accumulates in the reservoir (% [0–100], minimize)
Social	Recreation availability	The percentage of simulation time in which recreation features are available (% [0–100], maximize)
	Spillway flood return period	The flood year capable of being passed through the spillway (year, maximize)
	Average impoundment volume	The average volume of the reservoir over the simulation period (ft^3, minimize)
Operational	Module availability factor	The number of time steps that the module is operating divided by the total time that the module could be on given operating months (% [0–100], maximize or minimize)
	Module flow ratio	The percentage of total simulation inflow allocated to the module (% [0–100], maximize or minimize)

5. OPTIMIZATION FEATURES AND METHODS

The goal of optimization is to select the facility configuration that best meets the objectives of the user. Selecting a configuration consists of choosing the required modules (Foundation, Non-Overflow, and Spillway modules), specifying the module counts for each passage module in the Module Library, and selecting a design point for any dynamic module attribute. The Module Library represents the design space that the model can pull from to create a facility. The waterSHED model provides two methods for searching that design space: enumeration and optimization. The enumeration procedure is best for small design spaces, meaning that there are not many possible facility configurations. The enumeration works by testing all possible configurations within a range and ranking their performance objectives. This functionality can be used along with the sensitivity analysis functionality to conduct trade-off analyses. When there are many possible module configurations (>300 or so), then the design space is large, and an intelligent search procedure is needed. The optimization feature uses a custom genetic algorithm to test a population of facilities and evolve toward the global optimal facility. This feature is best for scenarios with continuous, rather than discrete, design variables within the dynamic modules. This section discusses the procedures for these module selection features.

5.1 ENUMERATION

The enumeration option lets the user explicitly create one or more facility configurations and test all of them. On the *Enumerate* page, whenever a module is added to the Module Library, it will be added to the *Select Module Iterations* section. There, the module will have a row for each of the variables that can be selected using enumeration. Each passage module will have a module count row, and dynamic modules will have a row for each controlling variable that can be selected. Each row will have an option menu that allows the user to set it as a *Constant* value or as an *Iteration*, which will have a minimum value, maximum value, and step value. During the enumeration, the facility will be tested at each point within this iteration range (inclusive of the bounds), as described in Section 2.2. When multiple variables are specified as iterations, then each combination will be tested (the number of configurations is multiplicative).

Some special cases for certain module types limit the possible configurations. As discussed in Section 4.1, a facility must have one and only one type of Foundation and Non-Overflow modules, so these modules must be selected with check boxes and cannot be selected as an iteration range. The facility must have one and only one type of Spillway module, although that type of Spillway module may have more than one module. When using a Sediment Passage module in flushing mode, only one module can be added, so it is included as a checkbox rather than an iteration range.

In addition to selecting the module iterations, the user must select an objective metric used to compare configurations, as well as the data types that should be saved between runs. The saved data can be viewed by selecting the *View Runs* button in the *Simulation Results* window. Using this enumeration functionality, the user can specify a single facility configuration by setting constant values for the desired module counts and attributes. If the user wants to test multiple configurations, then the user can input a range of values, and the enumeration process will simulate all configurations and output a performance table for all configurations, as well as in-depth results of the best-performing configuration. Testing multiple configurations enables trade-off analyses between the multiple variables. However, certain variables, such as the economic and site conditions, cannot be changed in the typical enumeration process, so a sensitivity analysis functionality was added.

5.2 SENSITIVITY ANALYSIS

After constructing the enumeration ranges, the user can select the *Run Sensitivity Analysis* button on the top right of the *Enumerate* page to open a sensitivity analysis window. As described in Section 2.2, the user can select an object, an attribute of that object, a unit for the attribute, and an iteration range for that attribute, similar to the enumeration iteration process. The attributes can be changed depending on the selected object. Most sensitivity class attributes can be varied and can have static and dynamic module attributes. The accompanying dissertation provides examples of sensitivity analysis on various attributes, including the fish passage metrics and foundation depth [7]. By selecting the *Run Analysis* button, the model will run the enumeration procedure for each value of the sensitivity variable and output the optimal facility results for each value. This enables trade-off analyses between a wider subset of variables in the model than in the enumeration process alone.

5.3 OPTIMIZATION

The optimization option allows the user to run a genetic algorithm that programmatically tests module configurations to determine an optimal facility. Genetic algorithms are heuristic optimization methods based on evolutionary principles. These algorithms do not guarantee optimality but can efficiently search large design spaces for complex problems. The genetic algorithm was selected because it works by interchanging bits within a bit string, much like interchanging modules within an SMH facility. Optimization should be used when there are many modules to choose from and running all feasible options in the enumeration procedure would take too long. The algorithm can take several minutes depending on the population size and the number of iterations.

The inputs in the *Optimize* page are the objective function, module attribute ranges, performance constraints, and algorithm parameters. The objective function is the performance metric that is used to compare candidate facilities. The algorithm aims to maximize or minimize the objective function of the recommended facility depending on the selected metric. The levelized cost of energy (LCOE) metric is recommended because it does not require constraints to ensure the inclusion of Generation modules, and it balances long-term costs and energy production.

Similar to the enumeration process, each module in the Module Library will be present in the *Select Module Parameter Constraints* section of the *Optimize* page, where the user can select a range of values for the module counts and dynamic module attributes. Rather than setting the iteration limits, the user can specify a range (minimum and maximum value) of attribute values, and the genetic algorithm will treat it as a continuous or discrete range depending on the attribute. For example, module counts will be optimized as discrete variables, whereas Generation module design flow will be a continuous range. These ranges act as constraints within the selection of modules within facility configurations.

The two types of constraints available are facility design parameters and performance requirements. The facility design parameters cover characteristics that cannot be directly set using the attribute constraints, including characteristics like facility capacity, design flood, footprint, and spillway width. The performance requirements relate to the minimum/maximum values required for the performance metrics described in Table 10. For each of these constraints, if a facility generated in the genetic algorithm does not meet these constraints, then it is penalized using a large penalty factor in the objective function, which generally precludes it from becoming the optimal facility in the population. Within the *Input Module Selection Optimization Constraints* section, there are option menus for the constraint type, the objective/parameter to constrain, and the operator (e.g., >, <, =). The user must select the desired menu options, input a value into the entry, and select the *Add* button. The constraint can be seen within the table of constraints by selecting the *View Constraints* button and can be removed by selecting the *Clear* button, although this will clear all constraints from the list.

The genetic algorithm parameters are used to control the genetic algorithm procedure itself. Figure 11 illustrates how the genetic algorithm works at a high level. First, an initial population of facilities is generated by randomly creating facilities within the module range constraints. The number of facilities in the population is set by the *Population Size* parameter on the *Optimize* page. These facilities are possible solutions to the optimization problem. Second, the facilities are each tested by simulating operation and calculating the objective function metric. Third, the facilities are ranked according to their objective function metric. Iterations are counted every time a population is created or evolved. If the iteration equals the number of iterations set by the user input, then the program ends, and the facility with the best objective function metric is output. If the iterations have not reached the maximum iteration, then the algorithm proceeds to Step 4 (Figure 11), which evolves the population of facilities.

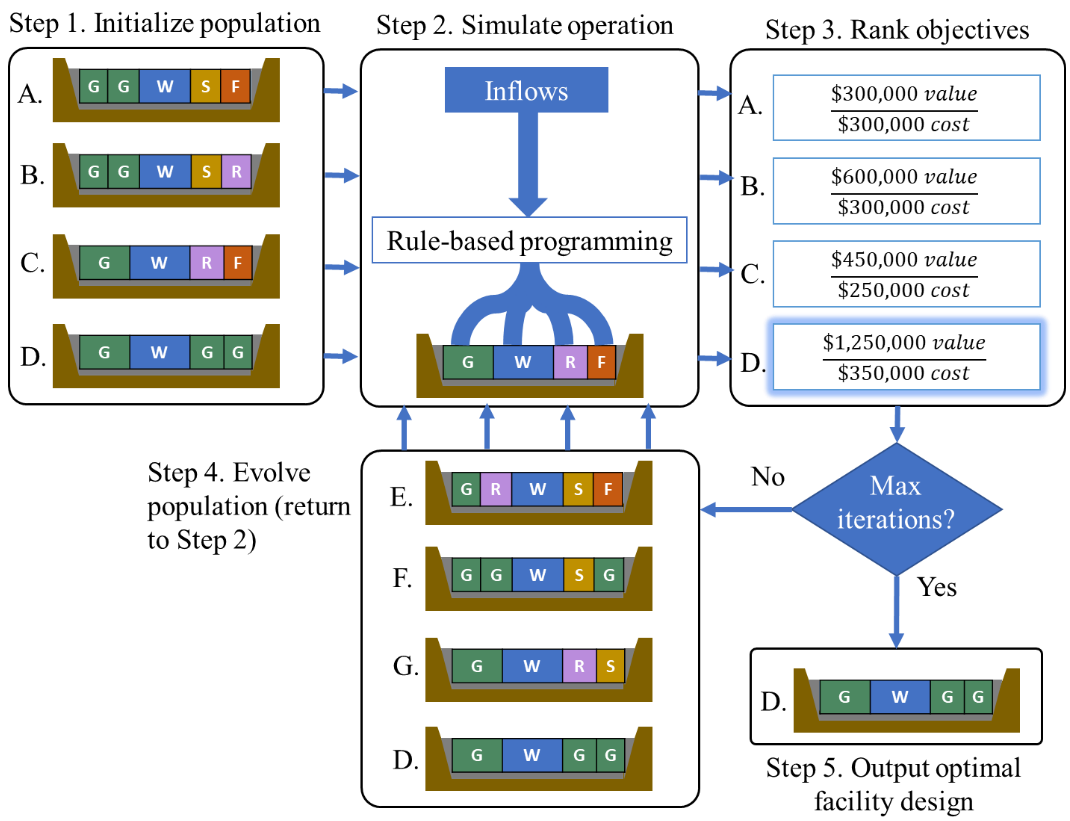

Figure 11. Illustration of genetic algorithm procedure for module selection and evolution.

The evolution process changes the population of facilities in intelligent and random ways to expand the search. Each evolution performs four functions to create a new facility from the existing facility, and these correlate to the genetic algorithm parameters (number of best solutions kept, number randomized, number of crossovers, and number mutated). The parameters each correlate to an individual in the new population, so the sum of these parameters must equal the population size. The number of best solutions kept determines how many of the best-performing facilities are kept between populations without changes. For each random facility, a new facility is added to the next population using randomized module counts and attributes. For each mutation, a random facility from the population is selected, and a random number of module attributes are randomized. The module attributes selected for mutation must have been specified as a range rather than a constant value during the *Select Module Parameter Constraints* step in the *Optimize* page. In the crossover function, a random facility is selected, and randomly selected attributes from one of the best solutions in the current population are transferred to the random facility. Additional research is needed to understand the optimal values for these genetic algorithm parameters, so default values are suggested in the GUI.

5.4 DYNAMIC MODULES

Dynamic modules are technologies that can be custom-designed for certain conditions. These allow the user to optimize across a range of design points (e.g., turbine design flow) rather than only module count. To include dynamic modules in the enumeration or optimization processes, the user must go to the *Dynamic Modules* page and select the *Add Dynamic Module* button. Modules are created similarly to static modules, except that select attributes can be set as equations that are functions of other controlling variables. The controlling variables are hard-coded values that were selected to represent the common drivers of module design. For example, the normal operating headwater level is a controlling variable for Non-Overflow modules and spillways because they are likely to change costs and dimensions to meet different headwater elevations. This functionality enables several trade-off and sensitivity analyses that are unique to the waterSHED model. The controlling variables may be attributes of the module or simulation class. Module attributes that are controlling variables can be changed during the enumeration or optimization processes. For example, Generation modules have design flow and design head as controlling variables. The capital cost attribute can be set as a function of the design head and flow so that the capital cost changes when the design head and flow change during optimization. When controlling variables are the attributes of the simulation classes, they must be changed using the sensitivity analysis function. For example, the normal operating headwater level is a Preferences attribute that cannot be selected during enumeration/optimization. The sensitivity analysis feature allows the user to run enumeration with multiple headwater levels, which will then change spillway and Non-Overflow module heights, for example, if the modules are parameterized according to this controlling variable.

Certain dynamic module classes have additional dynamic module attributes to help facilitate the custom design process. For example, recreation and fish passage technologies are often created using a series of steps or pools, so the related dynamic modules have attributes that enable technologies to be based on the number of steps. The additional attributes and relevant controlling variables are described in Appendix D.

6. CONCLUSIONS

The waterSHED model is a powerful tool for rapid prototyping of modular hydropower facilities. The model is built to help make decisions regarding the design and feasibility of these plants with a holistic focus rather than a purely economic focus. Potential use cases for a variety of stakeholders include the following:

- Hydropower developers for site feasibility assessment (i.e., identify sites with a low expected LCOE)
- Hydropower developers for determining mitigation requirements (i.e., identify the technologies required to meet environmental performance standards at a site)
- Technology developers for prototype modeling (i.e., identify sites where technologies perform well and simulate expected performance)
- Technology developers for cost analysis (i.e., determine the technology price points that make site development worthwhile)
- Researchers for determining environmental trade-offs (i.e., determine the relationships among economic, social, and environmental performance through sensitivity analysis of module selection and flow allocation)

The waterSHED model is a first attempt at incorporating the principles of standardization and modularity into the hydropower design process. Feedback is important for the continued development of the model. Please refer any comments or questions to watershed.model.ornl@gmail.com. Some features that may be integrated in future versions include the following:

- Water quality performance parameterization and modeling
- Long-term sediment performance estimation
- Variable and sub-daily time step simulations
- Improved weir coefficient methods
- Inclusion of non-powered dam components and development considerations
- Environmental flow methods for minimum flow requirements
- Modeling of diversion systems
- Additional dynamic modules and support tools
- Integrated sensitivity analysis functionality
- Improved equation entry

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APPENDIX A. INPUTS

This appendix describes the waterSHED inputs along with the attribute variables, names, entry types, units, and links to relevant support tools. Full definitions for each input, along with additional descriptions, can also be found in the tool tips accompanying the inputs in the GUI or in the waterSHED Workbook. Like Section 3, this appendix is categorized into SMH module classes and simulation classes.

Note about inputting percentages:

- Percentages should be entered as values between 0-100, as indicated by the units of "% (0-100)." In other words, 25% should be input as "25", rather than "0.25." However, when creating equations that have a percentage-based y-axis, such as the Generation module head and flow efficiency curves, the percentage should be calculated as a decimal between 0-1.0, as indicated by units of "% (0-1.0)." For example, an equation resulting in 25% for a given *x* value should output "0.25."

A.1 SMH MODULE CLASSES

For each module class, the relevant attributes are represented in tables. In addition to the tables, a brief discussion about the purpose and examples of the modules is included. As discussed in Section 3.2, the Screen class is not a part of the SMH Module classes and is implemented as a dynamic module, so it is described in Section APPENDIX AD.1.

All modules have the following five attributes:

> ***Name:*** the name used to identify the module in figures
>
> ***Capital cost:*** the capital cost for a module, which should include all fixed, one-time costs to prepare a module for operation. These can include material, equipment, installation, transportation, and so on ($C_{cap,m}$, $)
>
> ***Annual operating cost:*** the annual operating costs for a module, which should include all annualized expected costs for maintaining and operating the module. Annual operating costs can also be set at the plant level in the *Cost Tables* page ($C_{op,m}$, $/yr)
>
> ***Width:*** the module dimension along the dam axis from bank to bank, perpendicular to streamflow (Y_m, ft)
>
> ***Length:*** the module dimension parallel to streamflow (X_m, ft)

Passage modules (Generation, Water Passage, Fish Passage, Sediment Passage, and Recreation) additionally have these attributes in common:

> ***Design flow:*** the flow rate through the module at design conditions ($Q_{des,m}$, cfs). Definitions differ between module classes and are included in the respective sections
>
> ***Operating months:*** the months during which the module is on and is allocated flow (T_m, months). During the operating months, modules are modeled to operate continuously
>
> ***Instream or diversion:*** instream modules will be placed along the dam axis and will count toward the dam width; diversion modules are placed on the banks in the facility schematic and can be used to represent bypasses. Used to calculate the number of required Non-Overflow modules

The novel fish passage performance models described in Section B.4 require inputs to describe how well the modules can safely pass and attract fish. The following four metrics must be entered for each module in the facility to calculate performance. The fish passage attributes are not input along with the other module inputs and can only be input using the *Species Passage* page of the GUI. Example values from the literature for each of the following metrics can be found in Section B.4.

Downstream guidance efficiency: the percentage of species individuals entrained in the flow allocated to the module safely excluded from flow into the module ($G_{m,s}$, %). A guidance efficiency of 0% means all fish that attempt to enter the module will enter, whereas an efficiency of 100% means that all fish will be excluded and guided to another structure. This metric is normally measured for fish guidance structures such as bar racks and louvers and is parameterized for each species. The value depends on many factors, including species physiology, structure dimensions, and flow velocity. Efficiencies can vary from 0% to 100% depending on the technology. Modules without upstream fish guidance structures should assume a guidance efficiency of 0%.

Downstream mortality rate: the percentage of species individuals killed or unable to reproduce after passage through the module ($M_{m,s}$, %). A mortality rate of 0% means that no fish that pass through the module are harmed, whereas a mortality rate of 100% means that no fish can safely pass. This metric is normally measured for turbines and spillways and is parameterized by species. The value depends on many factors, including species physiology, technology dimensions (e.g., blade length), and flow characteristics. Rates can vary from 0% to 100% depending on the technology. Modules without fish safety features should assume a mortality rate of 100%, and low-head overflow spillways may assume a low mortality rate since low-head spillways were shown to have an inconsequential impact on fish passage [22].

Upstream entrance efficiency: the percentage of species individuals that can successfully enter the module after being attracted to the entrance ($E_{m,s}$, %). An entrance efficiency of 0% means that no fish can enter the module, whereas an entrance efficiency of 100% means that all fish can enter safely. This metric is normally measured for volitional fishways and is parameterized by species. The value depends on the swimming preferences of species of interest and the hydraulics of the entrance. Efficiencies can vary from 0% to 100% depending on the technology. Modules without fish passage capabilities should assume a value of 0% unless there is a chance of species entering the module from the downstream side.

Upstream passage efficiency: The percentage of species individuals that can successfully ascend the module after entering ($P_{m,s}$, %). A passage efficiency of 0% means that no fish can ascend, whereas a passage efficiency of 100% means that all fish can ascend safely. This metric is normally measured for volitional fishways. The value depends on the species of interest and the hydraulics of the entrance. Efficiencies can vary from 0% to 100% depending on the technology, although 100% passage rates can be difficult to achieve. Modules without species passage capabilities should assume an efficiency of 0%.

A.1.1 Generation Module

Generation modules use flow to produce electrical power and include all the electro-mechanical equipment and water conveyance structures required to produce that power. Modular turbines are emerging as viable low-head options, although deployment is relatively limited in the United States [23]. Conceptually, the module should include all electro-mechanical equipment required to generate and distribute power, but switchyards, powerhouses, or other supporting structures are likely needed for grid interconnection. It is recommended to include any additional costs for these structures in either the cost of the Generation module or the additional capital cost input (C_{cap}) in the Cost Tables object (Section B.2.2).

Table A.1. Generation module inputs

Generation module class				
Attribute variable	**Description**	**Entry types**	**Unit**	**Relevant sections**
—	Name	Text entry	—	
$C_{cap,m}$	Capital cost	Numeric	$	B.1
$C_{om,m}$	Annual operating cost	Numeric	$	B.1
Y_m	Width (dam-axis)	Numeric	ft	4.1
X_m	Length (streamwise)	Numeric	ft	4.1
$Q_{des,m}$	Design flow	Numeric	cfs	4.2.2
T_m	Operating months	List	Months	4.2.2
D_m	Instream or diversion	Yes or no	—	4.1
$Q_{min,m}$	Minimum operating flow	Numeric	cfs	4.2.2
$Q_{max,m}$	Maximum operating flow	Numeric	cfs	4.2.2
$H_{min,m}$	Minimum operating head	Numeric	ft	4.2.2
$H_{des,m}$	Design head	Numeric	ft	4.3
$H_{max,m}$	Maximum operating head	Numeric	ft	4.2.2
$\eta_{Q,m}\left(\frac{Q_{m,t}}{Q_{des,m}}\right)$	Flow efficiency curve	Equation	% (0.0-1.0) vs. cfs	4.3
$\eta_{H,m}\left(\frac{H_t}{H_{des,m}}\right)$	Head efficiency curve*	Equation	% (0.0-1.0) vs. ft	C.2
$P_{max,m}$	Max power*	Numeric	kW	B.1.1
$C_{ss,m}$	Cost of start-stops*	Numeric	$	B.1
$G_{m,s}$	Downstream guidance efficiency*	Numeric	% (0–100)	B.4.1
$M_{m,s}$	Downstream mortality rate*	Numeric	% (0–100)	B.4.1
$E_{m,s}$	Upstream entrance efficiency*	Numeric	% (0–100)	B.4.2
$P_{m,s}$	Upstream passage efficiency*	Numeric	% (0–100)	B.4.2

Several inputs may require further explanation, so they are discussed as follows and in the additional descriptions in the waterSHED Workbook and GUI.

Design flow: the set point used to indicate the peak power flow and is used in the dispatch models and the flow efficiency equation ($Q_{des,m}$, cfs). The Generation modules can be operated at any flow between the minimum and maximum operating flow. The turbine is operated at this design flow at normal conditions.

Minimum operating flow: the minimum flow required to operate the module ($Q_{min,m}$, cfs)

Maximum operating flow: the maximum flow that can be allocated to the module ($Q_{max,m}$, cfs). If the turbine-overrun option is allowed, then the excess flow will be allocated to increasing allocated flow above the design flow prior to spill allocation. If the turbine-overrun option is off, then design flow acts as the maximum allocated flow.

Minimum operating head: the minimum gross head required to operate the module ($H_{min,m}$, ft)

Design head: the gross head at which the module operates at peak efficiency ($H_{des,m}$, ft); used with the head efficiency equation to calculate head turbine efficiency

Maximum operating head: the maximum gross head allowable during module operation ($H_{max,m}$, ft)

Flow efficiency equation: the power output efficiency coefficient as a function of the relative discharge, which is the flow allocated to the module divided by the design flow (i.e., design flow = 100%) ($\eta_{Q,m}\left(\frac{Q_{m,t}}{Q_{des,m}}\right)$, flow efficiency [%] as a function of relative discharge [%]). The *x* (relative discharge) should be given as decimals, with 1.0 referring to 100% efficiency. The upper and lower bounds of *x* should at least span the operating range specified by the minimum and maximum operating limits. The *y* value (power efficiency) should be calculated as a decimal, where 1.0 is 100% efficiency. This efficiency curve should include all loss components along the powertrain, except for head losses.

Head efficiency equation: the power output efficiency coefficient as a function of the relative head, which is the gross head across the module divided by the design head (i.e., design head = 100%) ($\eta_{H,m}\left(\frac{H_t}{H_{des,m}}\right)$, head efficiency [%] as a function of relative head [%]). The *x* (relative head) should be given as decimals, with 1.0 referring to 100% efficiency. The upper and lower bounds of *x* should at least span the operating range specified by the minimum and maximum operating limits. The *y* value (power efficiency) should be calculated as a decimal, where 1.0 is 100% efficiency.

Max power: the maximum possible power output of the unit ($P_{max,m}$, kW); is used to calculate generation capacity factors and to cap power output during the simulation. If the calculated power output is higher than the designated max power during a given time step, then the power output is set to the maximum power. This input is optional and can be used to account for capacity limitations of the generator or other electrical equipment. If an input is not given, then the maximum power is set to the calculated power at the maximum operating head and flow.

Cost of start-stops: the attributed cost of damages for one ramping cycle of the turbine ($C_{ss,m}$, $/start-stop). A ramping cycle consists of turning the module on and off. Turbines often accumulate damage during these cycles as the flow rate passes through cavitation ranges. More frequent start/stops reduce the expected life of the turbine, which can increase maintenance costs. This metric is optional and is one way of calculating turbine operating costs as a function of operation, as opposed to the fixed annual module or annual plant O&M costs.

A.1.2 Water Passage Module

Water Passage modules control or enable the flow of water from upstream to downstream. Spillways are a type of Water Passage module and are required structures that can be either controlled or uncontrolled. As described in Section 4.2.1, controlled spillways enable the assumption of constant headwater elevations, whereas uncontrolled spillways create a relationship between headwater level and spillway flow using weir equations. Examples of Water Passage modules include Obermeyer spillway gates (illustrated in Figure 7) that use pneumatically actuated inflatable tubing to raise and lower an overshot gate.

Table A.2. Water Passage module inputs

Water Passage module class				
Attribute variable	**Description**	**Entry types**	**Unit**	**Relevant sections**
—	Name	Text entry	—	—
$C_{cap,m}$	Capital cost	Numeric	$	B.1
$C_{om,m}$	Annual operating cost	Numeric	$	B.1
Y_m	Width (dam-axis)	Numeric	ft	4.1
X_m	Length (streamwise)	Numeric	ft	4.1
$Q_{des,m}$	Design flow	Numeric	cfs	4.2.2
T_m	Operating months	List	Months	4.2.2
D_m	Instream or diversion	Yes or no	—	4.1
O_m	Operating mode	Continuous, controlled spillway, or uncontrolled spillway	—	4.2.1
C_{spill}	Weir coefficient*	Numeric	$ft^{1/2}/s$	4.2.1
Z_{spill}	Crest height*	Numeric	ft	4.2.1
$G_{m,s}$	Downstream guidance efficiency*	Numeric	% (0–100)	B.4.1
$M_{m,s}$	Downstream mortality rate*	Numeric	% (0–100)	B.4.1
$E_{m,s}$	Upstream entrance efficiency*	Numeric	% (0–100)	B.4.2
$P_{m,s}$	Upstream passage efficiency*	Numeric	% (0–100)	B.4.2

Several inputs may require further explanation, so they are discussed as follows and in the additional descriptions in the waterSHED Workbook and GUI.

Design flow: the definition of design flow depends on the operating mode ($Q_{des,m}$, cfs). If the mode is continuous, then the design flow means the flow required by the module during normal operation. In this case, the module will not be operated if there is not sufficient flow to meet the design flow (like other modules). If the mode is either an uncontrolled or controlled spillway, then the design flow represents the maximum passable flood flow for the module, which is used to calculate the total spillway design flow of all combined Spillway modules. The Spillway modules can be allocated flow up to the spillway design flow. Any flow exceeding spillway design flow will be counted as overflow and incur a flooding penalty, which is a cost equal to the exceeding flow times the flood cost (C_{flood} included in the Cost Tables class in Section A.2.2).

Operating mode: the effect of spillway flow on the headwater elevation. Water Passage modules can operate in one of three modes:

- Continuous: pass a constant discharge during the simulation time step
- Controlled spillway: can regulate the amount of flow through the module to maintain a constant headwater elevation
- Uncontrolled spillway: pass flow but cannot regulate headwater elevation (e.g., weirs)

Weir coefficient: a constant based on the shape of the weir; only required in uncontrolled spillway mode (C_{spill} – $ft^{1/2}/s$)

Crest height: the height of the top of the weir in reference to the bed elevation; only required in uncontrolled spillway mode (Z_{spill}, ft). The crest height should be at least higher than the normal operating level.

A.1.3 Sediment Passage Module

Sediment Passage modules pass bedload and suspended load sediment through the facility. The operating mode of the Sediment Passage module, which can be continuous, sluicing, or flushing, is an important attribute that controls how the module is operated in the rule-based operation. Continuous operation reflects sediment bypasses that divert sediment around a dam using a constant design flow. Examples include tunnels, siphons, and canals. Sediment sluicing is an operation in which sediment-laden waters are passed through a low-level outlet during high-flow events when sediment is likely mobilized, thus limiting accumulation. Sediment sluice gates are a common example and typically have larger openings and higher design flows than bypasses to pass significantly more sediment during operation. For modules operating in sluice mode, the user must additionally specify the operational inflow trigger ($Q_{op,m}$), which is the flow at which the sluice gate turns on and is allocated the design flow. This value can be informed by the sediment entrainment probability model (Support Tool C.4). Smaller flow triggers would cause the module to operate more frequently and lead to higher cumulative flow and less sediment accumulation. Sediment flushing (i.e., drawdown flushing) is a sediment management strategy in which the headpond is evacuated through a low-level outlet in a short time period to create high shear forces that pass large amounts of sediment. Flushing causes the headwater level to be drawn down, which typically requires turbines and other technologies to be turned off. When using flushing operation, the user must specify the flushing frequency $\left(T_{freq,m}\right)$ and flushing duration $\left(T_{dur,m}\right)$. Flushing events are assumed to be scheduled at the first available time step for the user-defined frequency. For example, if the flushing frequency is monthly, then the flushing will occur on the first day of every month. If the flushing frequency is monthly, but only two operating months are selected, then flushing will occur twice in the given year. The flushing event spans consecutive time steps according to the duration. During this time, all modules are turned off, and all flow is either assumed to pass through either the sediment gate or the spillway or used to refill the headpond. The minimum duration is one time step or one day. The duration of the flush event should depend on the size of the reservoir, the expected accumulation between events, the size of the sediment gate, and expected maintenance operations. To improve sediment continuity, it is suggested to select more frequent flushing events with short durations [24,25]. The attributes for Sediment Passage modules are shown in Table A.3.

Table A.3. Sediment Passage module inputs

Sediment Passage module class				
Attribute variable	**Description**	**Entry types**	**Unit**	**Relevant sections**
—	Name	Text entry	—	—
$C_{cap,m}$	Capital cost	Numeric	$	B.1
$C_{om,m}$	Annual operating cost	Numeric	$	B.1
Y_m	Width (dam-axis)	Numeric	ft	4.1
X_m	Length (streamwise)	Numeric	ft	4.1
$Q_{des,m}$	Design flow	Numeric	cfs	4.2.2
T_m	Operating months	List	Months	4.2.2

Table A.3. Sediment Passage module inputs (continued)

Sediment Passage module class				
Attribute variable	**Description**	**Entry types**	**Unit**	**Relevant sections**
D_m	Instream or diversion	Yes or no	—	4.1
O_m	Operating mode	Continuous, Sluicing, or Flushing	—	4.2.2
$Q_{op,m}$	Operating flow*	Numeric	cfs	C.4
$T_{dur,m}$	Flushing duration*	Numeric	Days	4.2.2
$T_{freq,m}$	Operating frequency*	Numeric	Flushes/yr	4.2.2
$G_{m,s}$	Downstream guidance efficiency*	Numeric	% (0–100)	B.4.1
$M_{m,s}$	Downstream mortality rate*	Numeric	% (0–100)	B.4.1
$E_{m,s}$	Upstream entrance efficiency*	Numeric	% (0–100)	B.4.2
$P_{m,s}$	Upstream passage efficiency*	Numeric	% (0–100)	B.4.2

Several inputs may require further explanation, so they are discussed as follows and in the additional descriptions in the waterSHED Workbook and GUI.

Design flow: the flow required by the module during normal operation ($Q_{des,m}$, cfs). The module will not be operated if there is not sufficient flow to meet the design flow. In the case of the flushing operating mode, the design flow is not used because all flow is allocated to the module during flushing events where the reservoir is drawn down.

Operating mode: the conditions under which the module is allocated flow. Sediment Passage modules can operate in one of three modes:

- Continuous: operate at consistent design flows throughout the operating months
- Sluicing: operate whenever a designated inflow threshold is met
- Flushing: used for drawdown flushing where the headpond level is decreased, and sediment is passed through low-level outlets at high velocity

Operating flow: the minimum inflow threshold required to mobilize bed-load sediments and open the sluice gate ($Q_{op,m}$, cfs). Sediment sluices will only be allocated flow if the total inflow is greater than the operating flow. This input is only used in the sluicing operating mode.

Flushing duration: the number of time steps (days) required to flush the reservoir; only required when the module operates in flushing mode ($T_{dur,m}$, days). During flushing events, all passage modules except for Spillway and Sediment Passage modules are turned off.

Operating frequency: the number of flushing events per year; only required when the module operates in flushing mode ($T_{freq,m}$, flushes/yr). During flushing events, all passage modules except for Spillway and Sediment Passage modules are turned off. Flushing events occur at the first available time step. Flushing events outside of the simulation time are not considered.

A.1.4 Recreation Module

Recreation modules provide a safe passageway for recreation crafts, such as boats, kayaks, and canoes. Recreation modules can be useful for providing social values to stakeholders and maintaining connectivity between recreational areas. An example of a Recreation module is a canoe chute described by Caisley, Bombardelli, and Garcia [26]. Recreational features that do not require water for operation, like boat launches or picnic areas, can be included in the facility cost via the additional capital cost input (C_{cap}) in the Cost Tables object (Section A.2.2).

Table A.4. Recreation module inputs

Recreation module class				
Attribute variable	**Description**	**Entry types**	**Unit**	**Relevant sections**
—	Name	Text entry	—	—
$C_{cap,m}$	Capital cost	Numeric	$	B.1
$C_{om,m}$	Annual operating cost	Numeric	$	B.1
Y_m	Width (dam-axis)	Numeric	ft	4.1
X_m	Length (streamwise)	Numeric	ft	4.1
$Q_{des,m}$	Design flow	Numeric	cfs	4.2.2
T_m	Operating months	List	Months	4.2.2
D_m	Instream or diversion	Yes or no	—	4.1
$H_{head,min,m}$	Max headwater drop*	Numeric	ft	4.2.1
$H_{head,max,m}$	Max headwater rise*	Numeric	ft	4.2.1
$H_{tail,min,m}$	Min tailwater level*	Numeric	ft	4.2.1
$H_{tail,max,m}$	Max tailwater level*	Numeric	ft	4.2.1
$G_{m,s}$	Downstream guidance efficiency*	Numeric	% (0–100)	B.4.1
$M_{m,s}$	Downstream mortality rate*	Numeric	% (0–100)	B.4.1
$E_{m,s}$	Upstream entrance efficiency*	Numeric	% (0–100)	B.4.2
$P_{m,s}$	Upstream passage efficiency*	Numeric	% (0–100)	B.4.2

Several inputs may require further explanation, so they are discussed as follows and in the additional descriptions in the waterSHED Workbook and GUI.

Design flow: the flow required by the module during normal operation ($Q_{des,m}$, cfs). The module will not be operated if there is not sufficient flow to meet the design flow.

Maximum headwater drop: the maximum decrease in headwater elevation with respect to the normal operating headwater level allowed during module operation ($H_{head,min,m}$, ft)

Maximum headwater rise: the maximum increase in headwater elevation with respect to the normal operating headwater level allowed during module operation ($H_{head,max,m}$, ft)

Minimum tailwater level: the minimum tailwater elevation required for module operation ($H_{tail,min,m}$, ft)

Maximum tailwater level: the maximum tailwater elevation allowable for module operation ($H_{tail,max,m}$, ft)

A.1.5 Fish Passage Module

Fish Passage modules facilitate the passage of fish across the facility in upstream and downstream directions. Fish passage technologies are typically either volitional or non-volitional depending on whether the target species pass under their own control or by manual/mechanized technologies. Volitional passageways are typically more common at low-head sites than high head sites since passage is more manageable for target species. These volitional technologies require continuous flows to attract species and create hydraulic conditions conducive to safe passage. Technical fishways are often modular in nature because they use repeatable series of pools, slots, and other structures to create the desired hydraulic conditions. Examples of conventional fishway types include Denil, vertical slot, and nature-like. Examples of innovative Fish Passage modules include Alden Laboratory's modular Silver American Eel Passageway [27], Whooshh Innovation's Passage Portal [28], and BK-Riverfish's Kynard Alternating Side Baffle Fish Ladder [29].

Table A.5. Fish Passage module inputs

Fish Passage module class				
Attribute variable	**Description**	**Entry types**	**Unit**	**Relevant sections**
—	Name	Text entry	—	—
$C_{cap,m}$	Capital cost	Numeric	$	B.1
$C_{om,m}$	Annual operating cost	Numeric	$	B.1
Y_m	Width (dam-axis)	Numeric	ft	4.1
X_m	Length (streamwise)	Numeric	ft	4.1
$Q_{des,m}$	Design flow	Numeric	cfs	4.2.2
T_m	Operating months	List	Months	4.2.2
D_m	Instream or diversion	Yes or no	—	4.1
$H_{head,min,m}$	Max headwater drop*	Numeric	ft	4.2.1
$H_{head,max,m}$	Max headwater rise*	Numeric	ft	4.2.1
$H_{tail,min,m}$	Min tailwater level*	Numeric	ft	4.2.1
$H_{tail,max,m}$	Max tailwater level*	Numeric	ft	4.2.1
$G_{m,s}$	Downstream guidance efficiency*	Numeric	% (0–100)	B.4.1
$M_{m,s}$	Downstream mortality rate*	Numeric	% (0–100)	B.4.1
$E_{m,s}$	Upstream entrance efficiency*	Numeric	% (0–100)	B.4.2
$P_{m,s}$	Upstream passage efficiency*	Numeric	% (0–100)	B.4.2

Several inputs may require further explanation, so they are discussed as follows and in the additional descriptions in the waterSHED Workbook and GUI.

Design flow: the flow required by the module during normal operation ($Q_{des,m}$, cfs). The module will not be operated if there is not sufficient flow to meet the design flow.

Maximum headwater drop: the maximum decrease in headwater elevation with respect to the normal operating headwater level allowed during module operation ($H_{head,min,m}$, ft)

Maximum headwater rise: the maximum increase in headwater elevation with respect to the normal operating headwater level allowed during module operation ($H_{head,max,m}$, ft)

Minimum tailwater level: the minimum tailwater elevation required for module operation ($H_{tail,min,m}$, ft)

Maximum tailwater level: the maximum tailwater elevation allowable for module operation ($H_{tail,max,m}$, ft)

For descriptions of the fish passage efficiency metrics, Section B.4 describes the fish passage performance model.

A.1.6 Foundation Module

Foundation modules connect modules to the streambed, providing structural support, watertight seals, and safe operation of the facility. Modular foundations are likely the most novel type of technology since dam foundations are typically custom-designed depending on the site-specific subsurface conditions [30]. Modular foundation technologies are currently in development [31], and to the best of the authors' knowledge, no modular foundation technologies are currently deployed. A potential example of Foundation modules includes precast concrete structures. The model represents the Foundation modules as blocks that are placed under the overlying passage and Non-Overflow modules. If the user does not wish to include Foundation modules in this way, alternatives exist. The first alternative is to create a default 1 × 1 ft Foundation module with a capital cost equal to the expected costs per square foot of creating the foundation. Because the number of Foundation modules is based on the facility footprint, this method provides a way to parameterize foundation costs as a function of the facility footprint. The second alternative is to incorporate the expected foundation costs in the Cost Tables parameters. The available parameters include the additional capital cost (C_{cap}), additional non-capital cost (C_{non}, which is not factored into the initial capital costs), and the excavation rate (C_{exc} , which is a cost per unit of the facility footprint).

Table A.6. Foundation module inputs

Foundation module class				
Attribute variable	**Description**	**Entry types**	**Unit**	**Relevant sections**
—	Name	Text entry	—	—
$C_{cap,m}$	Capital cost	Numeric	$	A.1
$C_{om,m}$	Annual operating cost	Numeric	$	A.1
Y_m	Width (dam-axis)	Numeric	ft	4.1
X_m	Length (streamwise)	Numeric	ft	4.1

A.1.7 Non-Overflow Module

Non-Overflow modules inhibit the flow of water past the facility. These modules are analogous to conventional dams, which are typically earthfill, rockfill, or concrete. Conventional dams are typically custom-designed for each site using locally sourced fill materials. Innovative modular technologies may look to precast concrete structures and ship them to the site to reduce construction time and costs. To the best of the authors' knowledge, no non-overflow technologies are currently deployed. Low-head dams may not include non-overflow sections and instead create weirs or spillway structures that span the facility. For cases in which non-overflow sections are not needed—such as in the case of non-powered dams, where the costs of the dams are already incurred—users should specify a default Non-Overflow module with zero capital or operating costs. Non-Overflow module costs should include abutments, but there is currently no distinction between abutments and in-stream modules.

Table A.7. Non-Overflow module inputs

Non-Overflow module class				
Attribute variable	**Description**	**Entry types**	**Unit**	**Relevant sections**
—	Name	Text entry	—	—
$C_{cap,m}$	Capital cost	Numeric	$	A.1
$C_{om,m}$	Annual operating cost	Numeric	$	A.1
Y_m	Width (dam-axis)	Numeric	ft	4.1
X_m	Length (streamwise)	Numeric	ft	4.1

A.2 SIMULATION CLASSES

This section provides attribute definitions and additional descriptions and context for the simulation classes. Definitions can also be found in the waterSHED Workbook or tool tips of the GUI.

A.2.1 Site Class

The Site object is the collection of hydrologic and hydraulic characteristics describing the stream-reach of interest. Sites of interest can be found using the SMH explorer tool.[4] The GUI provides useful tools for gathering flow information from the USGS NWIS[5] database. Other site characteristics can be gathered from satellite imagery, such as from Google Earth.[6]

Table A.8. Site class inputs

Site class				
Attribute variable	**Description**	**Entry types**	**Unit**	**Relevant sections**
—	Site name	Text entry	—	—
Y_{river}	Stream width	Numeric	ft	4.1
Z_{bed}	Bed elevation*	Numeric	ft amsl	—
S_{river}	Stream slope*	Numeric	ft/ft	C.4
β_{trap}	Trap efficiency parameter*	Numeric	— (0.0–1.0)	B.3.3
$Q_{in,t}$	Inflows	Table	Date and cfs	4.2.2
$Q_{flood,t}$	Peak flood flows*	Table	Date and cfs	B.2.2
$Z_{stage}(Q)$	Stage–discharge equation	Equation	—	4.2.1
$V_{res}(Z)$	Stage–storage equation*	Equation	—	C.1

The input definitions and additional descriptions concerning how the input is used and how it can be determined are as follows.

[4] https://smh.ornl.gov/tools/
[5] https://waterdata.usgs.gov/nwis
[6] https://earth.google.com/web/

Stream width: the distance between the left and right banks along the dam axis at the height corresponding to the defined normal operating level; used as a minimum for the total width of instream modules (Y_{river}, ft)

Bed elevation: the bed elevation above mean sea level at the dam axis; solely used for graphics and is set to a default of 100 ft amsl (Z_{bed}, ft amsl)

Stream slope: the average stream slope of the stream-reach prior to development; used in several places, including the sediment entrainment and reservoir volume model support tools (S_{river}, ft/ft)

Trap efficiency parameter: a dimensionless sedimentation factor (Beta) used with the Siyam (2000) formulation of the Brune model to reflect the reduction in reservoir storage capacity due to sedimentation (β). A value of 1 resembles a mixer tank where all sediment is kept in suspension, whereas a value close to 0 resembles a desilting basin where all sediment falls out of suspension. Thus, smaller values indicate a greater likelihood of sedimentation, which can result from many factors, including larger sediment sizes. The original Brune curve illustrated upper, median, and lower curves with values of 0.0055, 0.0079, and 0.015, respectively [16].

Inflows: the mean daily discharge time series data that will be used as facility inflows during the simulation ($Q_{in,t}$, cfs). The data must include the date (MM/DD/YYYY) and the flow (cfs). These can be historical data from stream gages, modified historical data, or predicted future flows. The GUI provides functionality to gather the historical USGS gage data if provided a gage number, a start date, and an end date. This automated data retrieval functionality uses the USGS application programming interface [32], and data are not guaranteed for every gage number.

Peak flood flows: the time series of peak flood events is used in a flood frequency analysis to calculate the return period of the spillway design flood flow ($Q_{flood,t}$, cfs). The flood frequency analysis procedure is described in Section B.2.2. USGS records peak flow data on the NWIS. The GUI provides an automated data retrieval function that can automatically grab data from NWIS and conduct the flood frequency analysis.

Stage–discharge equation: the water depth in the stream prior to development as a function of inflow ($Z_{stage}(Q)$, ft as a function of cfs). The *y* value is the river stage (ft), and the *x* value is the inflow (cfs). This input is used to determine the tailwater elevation after development, which is assumed to maintain similar hydraulic properties.

Stage–storage equation: the reservoir volume as a function of the headwater elevation ($V_{res}(Z)$, ft^3 as a function of ft). The *y* value is the reservoir volume (ft^3), and the *x* value is the headwater elevation (ft). This input is used to calculate the sediment trapping efficiency.

A.2.2 Cost Tables Class

The Cost Tables class is the collection of parameters used to convert module performance into simulated cost and benefit outcomes. The structure of the cost model is based on previous cost assessments of a reference SMH facility but is designed to be flexible for different use cases. Users should look through the economic performance models in Section B.1 to get a better understanding of how the inputs are used. When these inputs are not used, users should input a zero rather than leaving inputs blank.

Table A.9. Cost Tables class inputs

Cost Tables class				
Attribute variable	**Description**	**Entry types**	**Unit**	**Relevant sections**
R_{kwh}	Energy price	Numeric	\$/kWh	B.1
C_{cap}	Additional capital costs	Numeric	\$	B.1
C_{non}	Additional non-capital costs	Numeric	\$	B.1
C_{exc}	Excavation rate	Numeric	\$/ft^2	B.1
C_{ov}	Overhead cost	Numeric	\$ or % of initial capital costs [ICC]	B.1
C_{eng}	Engineering cost	Numeric	\$ or % of ICC	B.1
C_{con}	Contingency allowance	Numeric	\$ or % of ICC	B.1
C_{om}	Annual O&M cost	Numeric	\$ or % of ICC	B.1
R_{rec}	Value of recreation	Numeric	\$/h	B.1
C_{flood}	Flood cost	Numeric	\$/cfs	B.1
d	Discount rate	Numeric	% (0–100)	B.1
T_{life}	Project life	Numeric	Years	B.1

The input definitions and additional descriptions concerning how the input is used and how it can be determined are as follows.

> ***Energy price:*** the average price of energy per megawatt hour (R_{kwh}, \$/MWh). The energy price determines the generation revenue and is assumed constant throughout the simulation to reflect a constant power purchase agreement price.
>
> ***Additional capital costs:*** the one-time, fixed expenses incurred on capital assets that are not covered by the module capital costs (C_{cap}, \$). This can be used to include the costs for buildings, property, electrical equipment, and so on that retain value after commissioning. This cost category is included in the initial capital costs (ICC) calculation.
>
> ***Additional non-capital costs:*** the one-time expenses incurred during the development process that do not involve capital assets; can include the costs for the care of water, parking, recreational features, and so on that do not retain value after commissioning (C_{non}, \$). This cost category is not included in the ICC calculation.
>
> ***Excavation rate:*** the cost to excavate overburden material as a function of the dam foundation area (C_{exc}, \$/ft^2). This is one option for pricing excavation. The cost to excavate is this value times the total area of all modules. These costs can also be incorporated into the module capital costs or in the additional cost categories above.
>
> ***Overhead cost:*** the cost of overhead activities such as licensing and administration; can be input as either a lump sum or as a percentage of ICC (C_{ov}, \$ or % of ICC). The recommended value is 6% of ICC.
>
> ***Engineering cost:*** the cost of engineering activities; can be input as either a lump sum or as a percentage of ICC (C_{eng}, \$ or % of ICC). The recommended value is 4% of ICC.

Contingency allowance: the cost of unexpected expenditures; can include things like the cost from construction delays, material cost increases, and capital reserves (C_{con}, $ or % of ICC). It can be input as either a lump sum or as a percentage of ICC. The default value is 10% of ICC.

Annual O&M cost: the annual cost to operate and maintain the facility; can be input as either a lump sum or as a percentage of ICC (C_{om}, $ or % of ICC). This is one option for including annual operating costs that are not incorporated into the module O&M costs.

Value of recreation: the revenue associated with each Recreation module as a function of availability (R_{rec}, $/h). Although recreation may not be monetized in practice, this is one option for incorporating the value of recreational features to the public.

Flood cost: the cost per unit of flow exceeding the facility's hydraulic capacity during a given time step (C_{flood}, $/cfs). Any flow exceeding the flow capacity of all modules will be recorded as overflow and will incur a flood cost equal to this value times the amount of excess flow. This is particularly useful for the optimization option to ensure facilities without significant spillway capacity are penalized. If the user desires the facility not to be overtopped, then a high flood cost ($100/cfs or greater) is recommended.

Discount rate: the rate used to discount future cash flows and determine the present value of those cash flows; used in the calculation of the net present value (d, %). The recommended range of discount values is 6% to 14%.

Project life: the expected duration of project operation before plant retirement; used in the calculation of the net present value (T_{life}, years). Projects are typically licensed for 50-year terms but may be relicensed for additional time.

A.2.3 Preferences Class

The Preferences class is the collection of design and simulation parameters used to evaluate the performance of a facility. These represent design choices about how the facility is operated rather than the selection or design of modules.

Table A.10. Preferences class inputs

Preferences class				
Attribute variable	**Description**	**Entry types**	**Unit**	**Relevant sections**
Z_{op}	Normal operating headwater level	Numeric	ft	4.2.1
T_{start}	Test data start date	Date	MM/DD/YYYY	4.2
T_{end}	Test data end date	Date	MM/DD/YYYY	4.2
N/A	Generation dispatch model	List	Design ramping, peak ramping, simple greedy, or advanced greedy	4.3
B_{over}	Allow turbine overrun	Yes or no	—	4.3
Q_{notch}	Spillway notch flow	Numeric	cfs	4.2.2
$Q_{min,spill}$	Minimum spillway flow	Numeric	cfs or % of inflow	4.2.2
P_{op}	Operational priorities	List	— (1–5)	4.2.2

The input definitions and additional descriptions concerning how the input is used and how it can be determined are as follows. Similar information can be found in the waterSHED Workbook and GUI next to the corresponding input.

Normal operating headwater level: the headwater elevation with respect to the bed elevation at the dam axis that is maintained during normal operation (Z_{op}, ft). If the spillway is controlled, then the headwater level is assumed constant at the normal operating level. If the spillway is uncontrolled, then the crest height must be at least as high as the normal operating level, and any flow allocated to the spillway causes the headwater level to increase.

Test data start date: the start date for the simulation period; must be within the range of dates in the inflow time series data (T_{start}, date)

Test data end date: the end date for the simulation period; must be within the range of dates in the inflow time series data (T_{end}, date). The recommended length of the simulation is 1 year, or 365 days; however, all performance metrics are annualized, so running simulations with shorter or longer simulation times is possible.

Generation dispatch model: the method used to allocate flows across the Generation modules. The four dispatch models are as follows:

- Design ramping: turbines are ramped from smallest to largest. When flow is available, modules are ramped to the design flow before turning on the next module. This method is the fastest and is best used when peak efficiencies occur at the design flow.

- Peak ramping: turbines are ramped from smallest to largest. When flow is available, modules are ramped to the peak efficiency flow before ramping the next module. Once all modules are ramped to the peak efficiency, they are ramped to the design flow. If turbine overrun is allowed, then they are also ramped to the maximum operating flow from smallest to largest. This method is similar in speed to design ramping and should be used for turbines where the peak efficiency is not close to the design flow (e.g., Kaplan turbines).

- Simple greedy: determines the distribution of flows across modules. As the turbines are ramped, the algorithm sequentially allocates the next unit of flow to the turbine with the largest increase in power output. This method should be used instead of the design ramping method when using modules of different sizes.

- Advanced greedy: combines the peak ramping and simple greedy models. Modules are first ramped to the peak efficiency flow. Then, the flow is allocated to turn on modules if flow is available. Then, a greedy algorithm allocates the remaining flow between turbines that are on. This method is most likely to find the optimal dispatch of modules but takes more time than the peak ramping approach, which has similar performance for most turbines.

Allow turbine overrun: whether the Generation modules can be allocated flow greater than the design flow when excess flow is available. If overrun is allowed, then all modules will first be allocated their design flow and then will be ramped up to their max flow if flow is available. This allows the modules to generate more power but at lower efficiencies. If overrun is not allowed, then the module cannot be allocated flow above the design flow.

Spillway notch flow: the flow allocated to the spillway before passage module allocation that does not affect the headwater level; optional and can represent cuts or notches in weirs or spillways (Q_{notch}, cfs)

Spillway minimum flow: the flow requirement for the spillway that must be met before passage module allocation; affects the headwater level, is optional, and can be used to meet minimum flow requirements, which are flows that must be passed downstream without passage through turbines ($Q_{min,spill}$, cfs). The value can be set as a constant flow or a percentage of the inflow. Any notch flows also count toward this minimum flow constraint.

Operational priorities: the module class priority ranking used to determine the order of modules in the rule curve. Module classes are ranked from 1 (highest priority) to 5 (lowest priority). As described in Section 4, the modules with the highest priority are allocated flow first, and modules with lower priorities are then allocated flow if there is sufficient flow remaining to turn on the module. Module types within the same class are prioritized from smallest design flow (highest priority) to largest design flow (lowest priority).

A.2.4 Species Class

The Species class is used to represent a species of interest in the fish passage performance model. Fish passage systems are often designed with targeted species in mind, which have species-specific swimming behaviors, migratory patterns, and biomechanics. The current Species class allows the user to quantify the migratory timeline during which the fish passage performance metrics are calculated. The fish passage model, described in Section B.4, is unique because it calculates passage performance based on more than one species through cross-species metrics that average novel passage performance metrics. This class is not required for simulation of the facility but is required to estimate fish passage performance. For examples of common North American species found at small hydropower sites, please refer to Table 1 in the International Energy Agency report on fish passage at small hydropower sites [33].

Table A.11. Species class inputs

Species class				
Attribute variable	**Description**	**Entry types**	**Unit**	**Relevant sections**
N_{sp}	Species name	Text entry	—	—
a_s	Relative discharge parameter	Numeric	— (~0–10)	B.4.2
b_s	Attraction sensitivity parameter	Numeric	— (~0–10)	B.4.2
$T_{up,s}$	Upstream migratory months	List	Months	B.4.2
$T_{down,s}$	Downstream migratory months	List	Months	B.4.1

The input definitions and additional descriptions concerning how the input is used and how it can be determined are as follows.

Species name: the name used for species in calculations and figures

Relative discharge parameter: the coefficient used in the attraction efficiency function to set the relative discharge threshold required to prevent attraction efficiency losses (a_s). The higher the value, the higher the module flow must be to attract fish. The midpoint of the attraction efficiency curve is calculated by multiplying the relative discharge parameter by the attraction sensitivity parameter. For example, a relative discharge parameter of 0.2 and an attraction sensitivity parameter of 0.1 create a curve with close to 100% attraction at 3% relative discharge, a 50% attraction at 2% relative discharge, and close to 0% attraction at 1% relative discharge.

Attraction sensitivity parameter: the coefficient used in the attraction efficiency function to set the slope of the attraction efficiency function (b_s). Higher values tend to create steeper step-functions so that smaller changes in relative discharge will lead to larger changes in attraction. The midpoint of the attraction efficiency curve is calculated by multiplying the relative discharge parameter by the attraction sensitivity parameter. For example, a relative discharge parameter of 0.2 and an attraction sensitivity parameter of 0.1 create a curve with close to 100% attraction at 3% relative discharge, a 50% attraction at 2% relative discharge, and close to 0% attraction at 1% relative discharge.

Upstream migration months: the months during which the species travels upstream across the facility (from tailwater to headwater) ($T_{up,s}$, months). The effective upstream passage for the species is only calculated during these months.

Downstream migration months: the months during which the species travels downstream across the facility (from headwater to tailwater) ($T_{down,s}$, months). The effective downstream passage for the species is only calculated during these months.

APPENDIX B. PERFORMANCE MODELS

This appendix documents the mathematical formulations, background literature, and conceptual reasoning for each of the performance metrics used in this model. This appendix is divided into performance categories, including economic, fish passage, sediment, social, and operational. The performance metric formulations are described in the corresponding sections and are denoted with either *Minimize* or *Maximize* to reflect goal of the performance metric. Newly introduced variables are described with the corresponding equation. Previously introduced variables, such as module parameters, are described in Appendix A. When referring to a group of objects within the SMH Project, such as a class of modules, set notation, as outlined in Table 6, is used to refer to the group of objects as described here. The accompanying dissertation provides full documentation of the literature review that inspired the following models [7].

B.1 ECONOMIC PERFORMANCE MODELS

The economic performance models describe the cost of the facility and the expected revenue from generation. Economic benefits can also be created from recreation features through the value of recreation input. The cost models employed are based on industry-conducted cost estimates for exemplary low-head modular hydropower projects.

B.1.1 Annual Energy Generation Model

Annual energy generation is the annualized sum of energy generation for all Generation modules in the simulation (MWh/yr). The primary source of revenue for hydropower plants is the sale of electricity, so accurate estimation is vital. Literature on energy generation modeling is well established for hydropower. A variety of analytical and simulation-based models have been created to estimate hydropower generation potential. Equation 3 is used to determine the instantaneous power output of a module based on the flow allocated to the module and gross head at a given time step.

Instantaneous module power output (kW)	$P_{m,t} = (\frac{1kW}{737\frac{lb_f ft}{s}})\gamma(Q_{m,t})(H_{m,t})\eta_{Q,m}\left(\frac{Q_{m,t}}{Q_{m,des}}\right)\eta_{H,m}\left(\frac{H_{m,t}}{H_{des,m}}\right)$	Equation 3
Gross module head (ft)	$H_{m,t} = Z_{head,t} - Z_{tail,t} - H_{loss,m}(Q_{m,t})$	
Specific weight of water (lb_f/ft^3)	γ = 62.4	

If the Generation module has a maximum power input, then the instantaneous power output is capped at the maximum power. This maximum power can be used to account for limitations of generating equipment. The following pseudocode describes this feature.

$$If: P_{m,t} > Max\ power\ (P_{max,m})$$

$$Then: P_{m,t} = P_{max,m}$$

Once the instantaneous power output is determined, the daily energy generation in kilowatt-hours is calclated by multiplying the value by 24 h. This model in Equation 4 assumes that modules are operated at a constant flow throughout the time step. Then, the annual energy generation can be calculated by summing the daily energy generation from each module throughout the time step and annualizing the value by multiplying the sum by the ratio of simulation time to 365 days. This annualization factor is used throughout the performance models to account for varying simulation times.

Annual energy generation (kWh/yr)	$E_{ann} = \left(\sum_t^T \sum_m^{Gn} P_{m,t} * 24\ h\right) * \left(\frac{T}{365}\right)$	Equation 4 (Maximize)

B.1.2 ICC Model

The ICC (i.e., hard costs) represent the one-time expenses used to purchase or construct capital assets, such as buildings, land, and equipment. In the scope of this model, the main components are the module capital costs, which include the one-time costs to prepare a module for operation, such as materials, equipment, installation, and transportation. The user can also add additional capital costs in the *Cost Tables* page that are incorporated in the ICC. The ICC are different from the total initial costs of the project because they do not include soft costs, such as the overhead, engineering, contingency, and additional non-capital costs that can be input in the *Cost Tables* object (Section A.2.2). The ICC can be used to calculate several of the soft costs by setting them as a percentage of the ICC. The following equation shows the ICC as the sum of module capital costs plus the additional capital costs from the Cost Tables. The summation (Equation 5) inherently includes the module capital costs times the number of modules in the facility. The numbers of Non-Overflow and Foundation modules are automatically calculated as described in Section 4.1.

ICC ($)	$C_{icc} = C_{cap} + \sum_m^{Fa} C_m$	Equation 5 (Minimize)

B.1.3 Total Cost Model

The total cost of the project describes all the one-time costs required to begin operation. This value does not include any operating or maintenance costs that are incurred after commissioning. As shown by the following equations, this value sums the ICC and the soft costs that are input into the *Cost Tables* page. Several of the soft costs, including overhead, engineering, and contingency costs, can be input as either a lump sum or as a percentage of ICC, as shown in Equation 6 and Equation 7, respectively.

Total cost: all inputs as lump sums ($)	$C_{tot} = C_{ICC} + C_{over} + C_{eng} + C_{cont} + C_{non}$	Equation 6 (Minimize)
Total: all inputs as percentage of ICC ($)	$C_{tot} = C_{ICC}\left(C_{over} + C_{eng} + C_{cont}\right) + C_{non}$	Equation 7 (Minimize)

B.1.4 Net Present Value Model

Net present value is the current value of the project based on the total cost, expected revenue, annual maintenance expenditures, and discount rate assumptions. The formulation first calculates the annual benefits and annual costs of the project based on the simulation results and then incorporates them into the standard net present value equation. The two sources of benefits in the model are energy generation (Section B.1.1) and recreation availability (Section B.2.1). The plant annual operating cost input in the *Cost Tables* page can be input as either a lump sum or as a percentage of ICC. Both forms are shown here. There are also two unique sources of costs that require a further calculation based on the simulation performance, the flooding cost, and the start-stop cost. The flood cost (C_{flood}) is included to penalize facility designs that do not have enough flood capacity and are overtopped during high floods. Often, earthen dams cannot be overtopped safely, so the flood cost should be large, whereas concrete dams may be designed for overtopping, in which case the flood cost may be relatively low. The annualized total overflow volume ($Q_{flood,ann}$) is calculated by summing the total overflow from the simulation, which occurs when inflows cannot be distributed through active modules. Section 4.2 describes the allocation of flood overflow in more detail. The cost of start-stops (C_{ss}) is an alternative way of accounting for the damages caused by ramping turbines. Implementation of start-stop costs is growing but not yet standardized, so the cost of start-stops is applied equally to all turbines in the facility [34]. The number of start-stops ($P_{ss,m}$) is calculated by counting the number of time steps, where each Generation module is ramped from zero to non-zero flow. The calculation of net present value is standard across the literature, as described in Equation 8.

Net present value ($)	$P_{npv} = \sum_{y}^{T_{life}} \frac{(B_{ann} - C_{ann})}{(1+d)^y}$	Equation 8 (Maximize)
Annual benefits ($/yr)	$B_{ann} = E_{tot}R_{kwh} + P_{rec,h}R_{rec}$	
Annual costs: inputs as a lump sum ($/yr)	$C_{ann} = C_{om} + C_{flood}Q_{flood,ann} + C_{ss}\sum_{m}^{Gn} P_{ss,m} + \sum_{m}^{Fa} C_{om,m}$	
Annual costs: input as a % of ICC ($/yr)	$C_{ann} = C_{om}C_{ICC} + C_{flood}Q_{flood,ann} + C_{ss}\sum_{m}^{Gn} P_{ss,m} + \sum_{m}^{Fa} C_{om,m}$	
Annual flood overflow volume (ft^3)	$Q_{flood,ann}$	
Annual number of start-stops for module *m*	$P_{ss,m}$	

B.1.5 LCOE Model

The LCOE is the average net present cost to produce energy over the life of the project. This is a useful metric for comparing the project to other energy sources. The formulation (Equation 9) takes the ratio of the net present costs of the project and the discounted energy generation over the life of the project. The formulations for annual costs, ICC, and annual energy generation are described earlier in this section.

LCOE ($/MWh)	$P_{LCOE} = \frac{\left(C_{ICC} + \sum_{y}^{T_{life}} \frac{C_{ann}}{(1+d)^y}\right)}{\sum_{y}^{T_{life}} \frac{E_{ann} * \left(\frac{1\ MWh}{1000\ kWh}\right)}{(1+d)^y}}$	Equation 9 (Minimize)

B.2 SOCIAL PERFORMANCE MODELS

B.2.1 Recreation Availability

Recreation modules must be designed with hydraulics that ensure the safe passage of recreationalists. This includes safe drop heights, large recovery pools, and the exclusion of hydraulic rollers that can entrain passengers. The internal module hydraulics likely depend on the headwater and tailwater elevations, so users may specify minimum and maximum headwater and tailwater elevation limits that ensure passenger safety. These operating limits impact the availability of the passage module, which is the primary performance metric of Recreation modules. The availability is quantified using the number of hours that the Recreation modules are operating, as described in Equation 10. The on function is used to determine the number of time steps that the module is on and is allocated flow.

Annual recreation hours (h)	$P_{rec,h} = \left(\sum_{t}^{T}\sum_{m}^{Rc} f_{on}\left(Q_{m,t}\right) * 24\right) * \left(\frac{T}{365}\right)$	Equation 10 (Maximize)
On function	$f_{on}(Q) = \begin{cases} 1\ ;\ Q > 0 \\ 0\ ;\ Q \leq 0 \end{cases}$	

In addition to the annual recreation hours, the model calculates an average recreation availability factor that measures the ratio of the time steps that the Recreation modules are on to the time steps that the modules should be on. This helps determine the effect of head limitations on the module operation. The formulation is similar to the module availability factor formulation described in Section B.5.1. The availability function is used to determine the number of time steps that the module should be on given the operating months set by the user.

Recreation availability factor (%)	$P_{rec,avail} = \frac{\sum_{m}^{Rc}\sum_{t}^{T} f_{on}\left(Q_{m,t}\right)}{\sum_{m}^{Rc}\sum_{t}^{T} f_{avail}\left(Q_{m,t}\right)}$	Equation 11 (Maximize)
On function	$f_{on}(Q) = \begin{cases} 1\ ;\ Q > 0 \\ 0\ ;\ Q \leq 0 \end{cases}$	
Availability function	$f_{avail}(Q_t) = \begin{cases} 1\ ;\ t\ \in\ T_m \\ 0\ ;\ else \end{cases}$	

B.2.2 Spillway Flood Return Period

The spillway return period ($P_{floodyr}$) is the flood year capable of being passed through the spillway. Hydropower facilities are typically required to have spillways to pass excess flows in the case of flooding or outages. When designing the spillway, designers must balance the cost of the spillway with the risk of flooding. This is often discussed using the design flood of the spillway, which describes the maximum flow that can safely pass through the spillway. The design flood can also be described by its return period, which is the expected time between flood events. Standards suggest that small hydropower facilities should design for at least the 50-year flood, although up to the 100-year flood is recommended [13]. Calculating the return period requires conducting a flood frequency analysis that uses historical peak flow data to estimate a curve relating flows to the likelihood of occurrence ($f_{flood}(Q)$). The spillway return period is thus calculated by entering the spillway design flow in the flood frequency function, i.e., $P_{floodyr} = f_{flood}\left(Q_{spill,des}\right)$. The analysis is automatically conducted when uploading peak flow data on the *Site* page.

The following flood frequency analysis methodology and assumptions were adapted from Witt et al.'s case study report [6] and the Oregon State University streamflow evaluations online toolkit [35], as recommended by USGS Bulletin 17B [36]. When peak flow data are not uploaded via .csv, they can automatically be gathered from USGS's NWIS, which has data for more than 29,000 sites in the United States [32]. The peak flows are fit to a Log-Pearson Type III distribution, as shown in Equation 12. In the following formulation, the set of flows (*x*) is a set of *N* flows indexed by *n*. The flows are transformed into log space, and then the mean and standard deviation (described here) are used along with an empirically derived frequency factor to form the distribution. The frequency factor (*K*) is determined from a discrete table of values [35] based on the skewness coefficient (C_s) and the flood return period (T_{return}), which is the estimated number of years between flood events of a given size. The table only provides return periods of 1, 2, 5, 10, 25, 50, 100, and 200 years, so linear interpolation was used to determine flood return periods for flows between these years. This allows the model to approximate the flood return period of a spillway design flow. The linear interpolation may introduce error into the process, and the estimated curve is only as accurate as the flood data available, but it provides a suitable approximation for the purposes of this model.

Log-Pearson Type III Distribution	$\log(x) = \overline{\log(x)} + K\sigma_{logx}$	Equation 12
Mean	$\overline{\log(x)} = \frac{\sum_n^N \log(x_n)}{N}$	
Standard deviation	$\sigma_{logx} = \sqrt{\sum_n^N \frac{\left(\log(x_n) - \overline{\log(x)}\right)^2}{N-1}}$	
Frequency factor	$K = f(C_s, T_{return})$	
Skewness coefficient	$C_s = \frac{N\sum_n^N \left(\log(x_n) - \overline{\log(x)}\right)^3}{(N-1)(N-2)\left(\sigma_{logx}\right)^3}$	

B.2.3 Average Impoundment Volume

The average impoundment volume is an important factor in the social and ecological performance of the facility. The reservoir size plays a role in the sedimentation behind the dam, limnological impacts on the water quality, and potential impacts on displaced communities. It is typically recommended to minimize the size of the reservoir to limit environmental and social concerns [19]; however, research on the impact thresholds or quantitative trade-offs relating consequences to impoundment volume is limited since those relationships are site-specific. The average impoundment volume metric is an optional output that relies on the stage–storage curve input by the user. The formulation is shown in Equation 13.

Average impoundment volume (ft^3)	$V_{ave} = \frac{\sum_t^T V_{res}\left(Z_{head,t}\right)}{T}$	Equation 13 (Minimize)

B.3 SEDIMENT PASSAGE PERFORMANCE MODELS

Sediment is an important component of riverine ecosystem health and project performance. The goal of an SMH facility is to maintain sediment continuity in which the pre-development quantity, timing, and composition of sediment flows are maintained after development. Sediment continuity supports ecosystem function, limits geomorphic change, and limits economic impacts via sediment accumulation. Sediment transport is a well-studied field but is immensely complex because of unpredictable hydrological, hydraulic, biological, and sedimentological relationships. A host of empirical and theoretical models have been created to predict sediment flows in river systems [37]. User-driven 1D and 2D sediment transport models require detailed information about the stream bathymetry, sediment flows, and sediment composition. At the desktop level, this information is limited spatially and temporally in the United States, so these models are typically used during site investigation or during the operation of a facility. These models also require numerous assumptions and complex tuning to represent a river system realistically. The assumptions and accuracies of the models can lead to significant errors at each step of the modeling process, which include the determination of suspended sediment inflow, suspended sediment composition, bed sediment composition, bed-material inflow, reservoir sedimentation, sediment passage at the dam, and downstream armoring or deposition. These models are often used for decadal simulations in which errors from short-term calculations can be averaged out to reflect accurate long-term predictions. After a thorough investigation of existing methods, the authors determined that modeling volumetric sediment flow through a modular facility is outside the scope of the existing waterSHED model. Instead, the waterSHED model aims to capture the high-level design trade-offs that impact sediment continuity through the allocation of water. This model is not meant to be used in place of more detailed models. The performance metrics used to reflect expected trends in sediment continuity include the Sediment Passage module flow ratio, sediment passage frequency, and headpond trap efficiency.

B.3.1 Sediment Passage Module Flow Ratio

The Sediment Passage module flow ratio is the average ratio of flow allocated to Sediment Passage modules compared to the total inflow at each time step. Assuming sediment passage technologies work as intended, clearly, the more flow allocated to Sediment Passage modules, the better the sediment continuity performance. There are likely diminishing returns after certain flow conditions are met but determining this would require in-depth models of the sediment inflow, the bedforms, and the hydraulics during passage. Thus, this model should be used in conjunction with the other two sediment performance metrics to judge whether the facility is likely to deposit sediment qualitatively. In the case of flushing modules, all flows during the flushing period are allocated to the Sediment Passage module. The formulation below (Equation 14) is a simple ratio of the total flow allocated to Sediment Passage modules divided by the total inflow. The Sediment Passage module flow ratio is a percentage that should be maximized in conjunction with the other objectives.

Sediment Passage module flow ratio (%)	$P_{sed,mfr} = \sum_{t}^{T} \sum_{m}^{Sd} \frac{Q_{m,t}}{Q_{in,t}}$	Equation 14 (Maximize)

The primary disadvantage of this approach is that the ratio between Sediment Passage module flow and volumetric sediment flow is rarely constant. Different passage technologies may be able to pass more (or less) sediment per unit of flow than others. In addition, sediment transport can become supply limited, particularly at high flows, so transport rates may change based on inflow and the amount of accumulated sediment. Future versions of the waterSHED model may include modeling of volumetric sediment flows.

B.3.2 Sediment Passage Frequency

Sediment passage frequency is the ratio of sediment passage events to total time steps. The timing of sediment passage is important to consider, along with the quantity of sediment flows. The goal of sediment continuity means that the sediment passage frequency is 100%, assuming sufficient transport capacity. Studies have shown that more frequent but smaller flushing events are environmentally preferred to larger flushing events less frequently [24,25]. Therefore, users should aim to maximize sediment passage frequency if sediment continuity is desired. However, continuous sediment flows are likely not needed to limit sediment accumulation since sediment inflows are often caused by high flow events that occur seasonally. Acceptable frequencies should be determined by the user in accordance with any available sediment inflow data and the other sediment performance metrics. This metric is particularly helpful when using sluicing operation, in which the frequency of operation is not explicitly defined. The formulation below (Equation 15) is a simple approach that counts the number of time steps in which the flow allocated to all Sediment Passage modules is greater than zero and divides by the number of total time steps. If there is more than one Sediment Passage module, then only one of the Sediment Passage modules must be on to count as sediment passage.

Sediment passage frequency (%)	$P_{sed,freq} = \frac{1}{T}\sum_{t}^{T} f_{on}\left(\sum_{m}^{Sd} Q_{m,t}\right)$	Equation 15 (Maximize)
On function	$f_{on}(Q) = \begin{cases} 1\ ;\ Q > 0 \\ 0\ ;\ Q \leq 0 \end{cases}$	

B.3.3 Average Trap Efficiency Model

The average trap efficiency is the average percentage of incoming sediment that accumulates in the reservoir. Over the life of the project, accumulated sediments can reduce storage capacity, impact water quality, and lead to service interruptions. Smaller ROR impoundments have been shown to have limited sediment trapping [38], so this metric may not apply well to low-head projects with small headponds and minimal sediment inflow. In these cases, the estimated trap efficiency will be negligible. The true trap efficiency of a reservoir is based on the sediment composition, the reservoir shape, the modes of sediment passage, climate, and many other variables [39]. This metric is only a first-order approximation, and further investigation is required to determine the likelihood of significant sediment accumulation better.

The model for trap efficiency (Equation 16) is based on the trap efficiency equation from Siyam [15] as reported by Eizel-Din [40]. Siyam [15] created the equation using empirical evidence to generalize the Brune model [16], which asserts that the trap efficiency is a function of the capacity-inflow ratio (i.e., the reservoir volume divided by the average annual inflow). The Brune model was selected because of its simplicity, its accuracy in comparison to other models [39], and its compatibility with the variables defined in the waterSHED model. The sedimentation parameter β used in this model captures the reduction in reservoir storage due to sedimentation [41]. Higher β values (range between 0 and 1) indicate that the reservoir is less likely to deposit sediment for a given capacity-inflow ratio, like in the case of semi-arid reservoirs with small particle sizes. According to Siyam [15], the β values of 0.0055, 0.0079, and 0.015 are related to the upper, median, and lower curves on the Brune model. The model is adjusted per the procedure in Lewis [42] to calculate daily trap efficiencies by annualizing daily inflows (converting $Q_{in,t}$ from cfs to ft^3/yr) and then summing the daily trap efficiencies using a flow weighted summation. According to Lewis [42], the flow weighting accounts for the fact that the majority of sediment is transported during higher inflows.

Average trap efficiency (%)	$P_{trap,ave} = \frac{\sum_{t}^{T} P_{trap,t} Q_{in,t}}{\sum_{t}^{T} Q_{in,t}}$	Equation 16 (Minimize)
Annualized daily trap efficiency (%)	$P_{trap,t} = 100e^{-\frac{365\times 60\times 60\times 24\beta Q_{in,t}}{V_{res}(Z_{head,t})}}$	

This model does not reflect the effects of Sediment Passage modules and only quantifies the expected effects of reservoir sedimentation on sediment continuity. Reservoir sedimentation allows suspended sediments to settle and become part of the bed, which are typically more difficult to pass. Smaller reservoirs have lower hydraulic residence times, which increases the likelihood of particles passing downstream before settling. In addition, this trap efficiency model has been shown to overpredict sediment trapping in certain climates [42]. Users should aim to minimize the trap efficiency of the reservoir, which is primarily determined by design decisions affecting reservoir size (i.e., normal operating level and spillway type). To achieve better sediment passage performance, users should either allocate more flow to Sediment Passage modules in cases of high trap efficiencies or decrease the normal operating level to decrease trap efficiency.

B.4 FISH PASSAGE PERFORMANCE MODELS

Fish, especially diadromous species, must be able to cross the facility, upstream and downstream, to find suitable habitats or reproduction areas. The goal of an environmentally focused hydropower facility is to provide “transparent” passage of species, which indicates successful passage across the facility with negligible delays, injuries, or energetic losses that could impede survival or reproduction [43]. Fish passage studies often involve testing full-scale bypass and exclusion systems or modeling the hydrodynamics of these structures. Only recently have these studies been used to predict passage performance given bypass design variables, such as in the Fish-Net model created by Wilkes et al. [44], which uses empirical data to make fishway design decisions. To the best of the authors’ knowledge, no models in the literature can predict fish passage performance at the facility scale given the black-box scope of the waterSHED model, which does not provide internal module hydraulic or design information. Thus, the following performance models are novel formulations that employ metrics and qualitative knowledge from the literature. The reasonings and literature behind the formulations are provided in the following sections.

B.4.1 Effective Downstream Mortality

Effective downstream mortality is a novel metric describing the expected time-averaged mortality rates for a species over the simulation. This value is based on the flow allocation, module guidance efficiencies, and module mortality rates. These metrics are common in the literature but are typically used with different technology classes. For example, mortality rate is commonly measured for turbines and sometimes spillways [45], whereas guidance efficiencies are measured for fish guidance structures (e.g., bar racks, louvers, bubble screens) [46]. Mortality rate and guidance efficiency represent the two main steps in downstream fish passage. First, fish are guided by physical barriers or behavioral devices away from unintended pathways and toward safe bypasses. These deterrents are rarely 100% effective for all species, so some individuals may still travel through unintended pathways (i.e., modules). Then, fish must pass through the modules. Turbines and other conveyances can injure fish via several modes, including rapid decompression, blade strike, cavitation, turbulence, and shear forces [45]. The risk of injury is often quantified by the mortality rate because it provides a clearer distinction than other measures of trauma [45]. Fish bypasses are designed for low mortality rates by providing gradual descents. The other main step in this process is refusal, which is when individuals decide not to pass the facility and remain upstream. The rate of refusal is more difficult to determine from empirical evidence, so this model assumes that refusal indicates an inability to pass safely and should be included in the mortality rate. This novel formulation uses guidance efficiency and mortality rate as inputs and multiplies them to indicate that these processes occur in series. The following two subsections introduce the inputs and provide example values from the literature.

B.4.1.1 Downstream guidance efficiency

Downstream guidance efficiency is the percentage of species individuals entrained in the flow allocated to the module that is safely excluded from flow into the module. A guidance efficiency of 0% means all fish that attempt to enter the module will enter, whereas an efficiency of 100% means that all fish will be excluded and guided to another structure. This metric is normally measured for fish guidance structures like bar racks and louvers. The value depends on many factors, including species physiology, structure dimensions, and flow velocity. Efficiencies can vary from 0% to 100% depending on the technology. Modules without upstream fish guidance structures should assume a guidance efficiency of 100%. Efficiencies for various example fish guidance structures bar racks are provided in Table B.1. In several sources, such as Albayrak et al. [46], guidance efficiency can also be termed bypass efficiency. The sources in Table B.1, Beck et al. [47], and Linnansaari et al. [48] provide more information about guidance efficiencies.

Table B.1. Example downstream guidance efficiencies for a variety of fish guidance structures

Source	Technology	Angles (α, β)	Spacing (mm)	Velocity (m/s)	Species	Guidance efficiency (%)
Albayrak et al. [46]	Louver	(15,90)	50	0.3	Barbel	78.6
Albayrak et al. [46]	Louver	(15,90)	50	0.6	Barbel	65.2
Albayrak et al. [46]	Modified bar rack	(15,45)	50	0.3	Barbel	95
Albayrak et al. [46]	Modified bar rack	(15,45)	50	0.6	Barbel	82.6
Albayrak et al. [46]	Modified bar rack	(15,45)	50	0.8	Barbel	100
Albayrak et al. [46]	Modified bar rack	(30, 45)	50	0.3	Barbel	86.4
Albayrak et al. [46]	Modified bar rack	(30, 45)	50	0.6	Barbel	100
Albayrak et al. [46]	Louver	(15,90)	50	0.3	Spirlin	81
Albayrak et al. [46]	Louver	(15,90)	50	0.6	Spirlin	10
Albayrak et al. [46]	Modified bar rack	(15,45)	50	0.3	Spirlin	100
Albayrak et al. [46]	Modified bar rack	(15,45)	50	0.6	Spirlin	85
Albayrak et al. [46]	Modified bar rack	(30, 45)	50	0.3	Spirlin	75
Albayrak et al. [46]	Modified bar rack	(30, 45)	50	0.6	Spirlin	75
Scruton et al. [49]	Louver	(18,90)	100	0.75	Atlantic Salmon smolts	77.1
Amaral et al. [50]	Bar rack	(45, 45)	25	0.3	American eel	64.8
Amaral et al. [50]	Bar rack	(45, 45)	25	0.6	American eel	56.5
Amaral et al. [50]	Bar rack	(45, 45)	25	0.9	American eel	65.9
Amaral et al. [50]	Bar rack	(45, 45)	50	0.3	American eel	72.5
Amaral et al. [50]	Bar rack	(45, 45)	50	0.6	American eel	57.8
Amaral et al. [50]	Bar rack	(45, 45)	50	0.9	American eel	53.3
Amaral et al. [50]	Louver	(45, 90)	50	0.3	American eel	33.3
Amaral et al. [50]	Louver	(45, 90)	50	0.6	American eel	62.1
Amaral et al. [50]	Louver	(45, 90)	50	0.75	American eel	45.4
Amaral et al. [50]	Bar rack	(15, 75)	50	0.3	American eel	95.1
Amaral et al. [50]	Bar rack	(15, 75)	50	0.6	American eel	95.2
Amaral et al. [50]	Bar rack	(15, 75)	50	0.9	American eel	88.9
Amaral et al. [50]	Louver	(15, 90)	50	0.3	American eel	88.7
Amaral et al. [50]	Louver	(15, 90)	50	0.6	American eel	95.2
Amaral et al. [50]	Louver	(15, 90)	50	0.9	American eel	90.3

B.4.1.2 Downstream mortality rate

Downstream mortality rate is the percentage of species individuals that are killed or unable to reproduce after passage through the module. A mortality rate of 0% means that no fish that pass through the module are harmed, whereas a mortality rate of 100% means that no fish can safely pass. This metric is normally measured for turbines and spillways. The value depends on many factors, including species physiology, technology dimensions (e.g., blade length), and flow characteristics. Rates can vary from 0% to 100% depending on the technology. Modules without fish safety features should assume a mortality rate of 100%, whereas low-head overflow spillways may assume a low mortality rate since low-head spillways were shown to have an inconsequential impact on fish passage [22]. Pracheil et al. [51] compiled mean mortality rates for a variety of species and turbine types from studies in the literature, as described in Table B.2. Therrien and Bourgeois [33], Calles and Greenberg [52], and Schilt [53] provide more information.

Table B.2. Compilation of mean mortality rates from turbine mortality studies. Reprinted from Pracheil et al. [51]

Turbine type	Family	Genus	Number of studies	Mean mortality rate (%)	Standard deviation (%)
Francis	*Anguillidae*	*Anguilla*	5	10.9	13
Francis	*Catostomidae*	*Catostomus*	20	16.3	23
Francis	*Centrarchidae*	*Ambloplites*	1	96	
Francis	*Centrarchidae*	*Lepomis*	22	14.8	19.8
Francis	*Centrarchidae*	*Micropterus*	8	14	9.6
Francis	*Centrarchidae*	*Pomoxis*	1	100	
Francis	*Centrarchidae*	Unspecified	7	29.4	32.5
Francis	*Clupeidae*	*Alosa*	11	24.3	2.3
Francis	*Cyprinidae*	*Notemigonius*	2	13.1	9.8
Francis	*Cyprinidae*	*Notropis*	3	31.8	7.2
Francis	*Cyprinidae*	Unspecified	7	12.5	4.5
Francis	*Esocidae*	*Esox*	5	22.7	15.5
Francis	*Ictaluridae*	*Ictalurus*	1	6	
Francis	*Percidae*	*Perca*	9	31	26.6
Francis	*Percidae*	*Sander*	7	39.4	28.5
Francis	*Percidae*	Unspecified	11	45.5	24.2
Francis	*Salmonidae*	*Anguilla*	47	26.2	21
Francis	*Salmonidae*	*Lepomis*	8	30.1	26.9
Francis	*Salmonidae*	*Micropterus*	1	57	
Francis	*Salmonidae*	Unspecified	17	31.3	28.3
Kaplan	*Anguillidae*	*Anguilla*	3	25.7	10.6
Kaplan	*Centrarchidae*	*Lepomis*	6	8.3	5.9
Kaplan	*Centrarchidae*	*Micropterus*	3	2.7	0.6
Kaplan	*Centrarchidae*	Unspecified	6	4.7	2.1
Kaplan	*Clupeidae*	*Alosa*	12	7.2	6
Kaplan	*Cyprinidae*	*Notemigonius*	1	8	
Kaplan	*Esocidae*	*Esox*	2	22.5	4.9
Kaplan	*Ictaluridae*	*Ictalurus*	4	10.8	5.7
Kaplan	*Percidae*	*Perca*	4	5	2.9
Kaplan	*Percidae*	*Sander*	4	13.8	2.8
Kaplan	*Salmonidae*	*Oncorhyncus*	68	8.6	16.5
Kaplan	*Salmonidae*	*Salmo*	8	9.2	6.9
Kaplan	*Salmonidae*	Unspecified	6	5.3	4.6
Crossflow	*Clupeidae*	*Alosa*	1	10	
Crossflow	*Moronidae*	*Morone*	4	15.9	2.4
Crossflow	*Salmonidae*	*Oncorhyncus*	17	32.4	23.4
Crossflow	*Salmonidae*	*Salmo*	4	12.1	7.3

B.4.1.3 Formulation

The effective downstream mortality employs these two metrics along with some assumptions about fish behavior. Although technology characteristics determine the mortality and guidance performance, the allocation of flow plays a role in the likelihood of an individual to approach a given technology. Migratory fish aim to minimize energy expenditure while swimming downstream, so they tend to follow the bulk flow [17]. Although swimming behavior is species-specific, for the sake of this black-box model, the proportion of fish approaching a given module was assumed to be proportional to the relative discharge (module flow divided by total flow) of the module. With this assumption, the expected "fish flow" to each module can be calculated by multiplying the module flows by the inverse of the guidance efficiency, which represents the percentage of fish that enter a module despite guidance structures. Each module should have a guidance efficiency for each species. This formulation is lossless, meaning that all fish that enter the facility will go through one of the modules (since refusals are incorporated as mortalities). Therefore, if a fish is initially guided away from module A, then it may return after being excluded from module B. Thus, the probability of fish going through a given module is represented as the proportion of the module's adjusted fish flow to the sum of adjusted fish flow across the facility. This captures the desired behavior because although module A has a 60% guidance efficiency, if module B has an 80% guidance efficiency, then more fish will likely go through module A despite high guidance efficiencies. Fish bypasses with 0% guidance efficiency will thus collect most of the fish excluded from other modules. Then, the mortality rates of each module are multiplied by the percentage of fish flow through that module. This enables the calculation of the effective mortality across the facility at a given time step for a given species, shown in Equation 17.

Assumption: The proportion of entrained fish through a given module is proportional to the relative discharge through the module (i.e., fish follow the bulk flow [17]).

Assumption: Over time, the rate of refusal (the number of fish who refuse to descend the facility) is negligible, and the impact of refusals is captured as fish mortality.

Effective mortality at a time step (%)	$\mathrm{M}_{\mathrm{eff,s,t}} = \sum_{m}^{Fa} \frac{(1 - G_{m,s}) Q_{m,t} M_{m,s}}{\sum_{m}^{Fa} (1 - G_{m,s}) Q_{m,t}}$	Equation 17 (Minimize)

Screen objects add another layer of complexity to implementing this model. The effective mortality model allocates fish flow across modules at the same "level" of the facility. However, screens create separate levels since lateral mobility is limited. For example, if a fish passes a fish screen, it is assumed that the hydraulic and physical barriers limit the ability of the fish to leave the facility upstream. Therefore, the fish that pass the screen can only be distributed across modules within the screen. This process resembles a decision tree where the fish make a series of choices as they encounter screens and modules. To solve this problem, when a facility has a screen object, it is turned into a tree structure, which creates a hierarchy with the most upstream screens/modules at the top and branches to indicate modules within the screen coverage. The model is then applied iteratively through each branch to allocate fish within the same branch level. An example tree structure for an example facility is illustrated in Figure B.1.

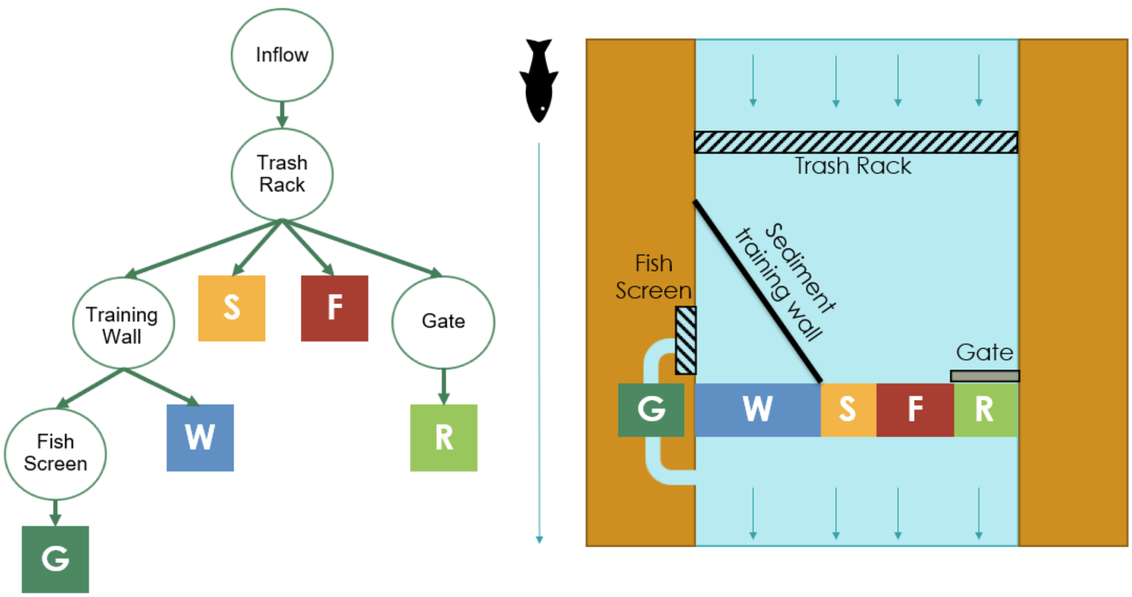

Figure B.1. Example screen tree implementation for an example facility layout. Reprinted from Sasthav [7].

To determine the effective mortality across the simulation time and across multiple species, the average across the simulation time and the number of species can be taken as shown in Equation 18. The goal of users should be to minimize this value in coordination with the other objectives.

Cross-species effective downstream mortality (%)	$\mathrm{M_{eff}} = \sum_{t}^{T} \sum_{s}^{Sp} \frac{M_{eff,s,t}}{SpT}$	Equation 18 (Minimize)

This model simplifies an extremely complex process; however, it considers the trade-offs among flow allocation over time and technology selection, which are not considered in existing studies. Furthermore, the proportional approach to fish flow should be validated using real-world data and facilities with multiple pathways. Despite the lack of real-world validation, this formulation captures the expected trade-offs, including modules without exclusion measures and larger flows will attract more fish, and turbine mortality rates can be reduced with exclusion measures but are rarely zero, especially for modules with high relative discharge.

B.4.2 Effective Upstream Passage

Similar to downstream fish passage, facilities should be "transparent," and fish should be able to traverse over the dam with minimal delay, injury, or energetic losses. Volitional fishways have been used at hydropower facilities to provide safe upstream passage routes. Volitional structures are designed to create hydraulic conditions that attract and pass different species that move on their own accord, but they require flow to create these conditions. A large body of literature exists on upstream fish passage. However, many of the studies assess the effectiveness of a specific technology for a specific fish species. There are no existing approaches for modeling multi-species passage across a facility with more than one passage structure. The proposed model pulls technology-specific metrics and general knowledge about fish passage into a novel approach for predicting fish passage effectiveness and the trade-offs among flow allocation and technology selection.

Upstream fish passage effectiveness is typically measured by total passage efficiency or the number of fish that can successfully ascend a facility compared to the number of migratory fish that approach the facility. Total passage efficiency is widely considered the product of three efficiencies related to the steps that occur during passage [43]: the attraction, entrance, and passage. These efficiencies have been computed for a variety of fishway types and can vary widely depending on numerous factors, such as species physiology and flow conditions [54]. Fishways are typically designed to accommodate the swimming behavior of a target species, so the entrance and passage efficiency inputs are species-specific. The attraction efficiency is computed internally based on the flow allocation as described in the following section.

B.4.2.1 Attraction efficiency

Attraction efficiency is the percentage of migratory fish within the project boundary that approach a given module within a certain distance. Swimming behavior is not often random because migratory fish aim to follow signals that will lead to suitable habitat [17]. Fish tend to follow the mainstem river, so they are signaled by flow allocation. The flow through fish passage structures must be sufficient compared with the total inflow to attract fish to the entrance [55]. In several cases, low passage efficiencies are related to insufficient attraction flows [54]. The higher the attraction flow, the better, but industry standard says that 10% of the total inflow is recommended, although 1%–5% can be sufficient if entrances are properly placed entrances, and total flow is relatively high [55,56]. Although attraction efficiency is likely a function of the relative discharge, studies often record an average attraction efficiency for a given technology rather than model attraction as a function of relative discharge.

Using this knowledge, the attraction efficiency was formulated in Equation 19 as a sigmoid function that penalizes the effective passage metric if the relative discharge to the module falls below a user-defined threshold. The shape of the sigmoid function (i.e., a logistic curve or S-curve) is parameterized by the relative discharge parameter (a_s) attraction sensitivity parameter efficiency (b_s), which are set for each Species object. As an example, an a_s value of 0.8 and a b_s value of 0.05 creates a curve that reaches an efficiency factor of 100% at relative discharges above 10% and a factor close to 0% at relative discharges less than 1%. Figure B.2 provides an example of the attraction efficiency function for different parameter combinations [7]. The product of a_s and b_s reflect the midpoint of the curve. The a_s and b_s parameters, as well as the shape of the curve, should be validated using real data, but the estimated form does represent qualitative expectations from the literature.

Attraction efficiency (%)	$A_{m,s,t} = \dfrac{1}{1 + e^{-100\left(\left(\frac{1}{a_s}\right)Q_{m,t}/\sum_m^{Fa} Q_{m,t} - b_s\right)}}$	Equation 19 (Maximize)
Relative discharge parameter (dimensionless)	a_s	
Attraction sensitivity parameter (dimensionless)	b_s	

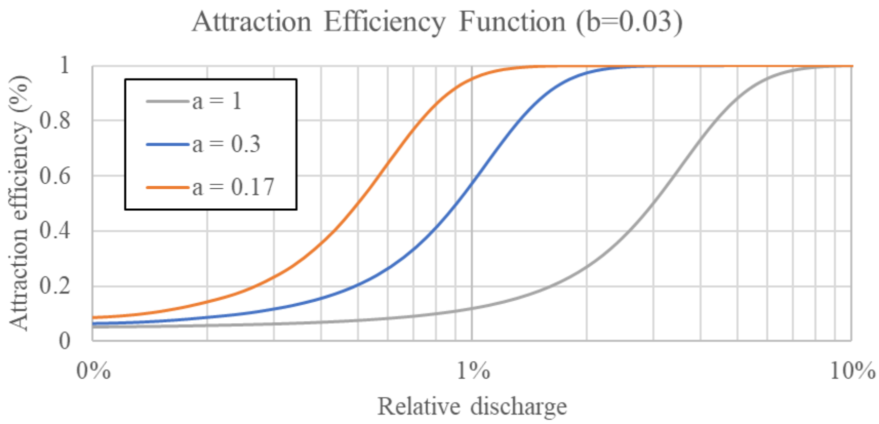

Figure B.2. Attraction efficiency function for upstream fish passage. Reprinted from Sasthav [7].

B.4.2.2 Upstream entrance efficiency

The upstream entrance efficiency is the percentage of species individuals that can successfully enter the module after being attracted to the entrance. An entrance efficiency of 0% means that no fish can enter the module, whereas an entrance efficiency of 100% means that all fish can enter safely. This metric is normally measured for volitional fishways. The value depends on the species of interest and the hydraulics of the entrance. Efficiencies can vary from 0% to 100% depending on the technology. Modules without fish passage capabilities should assume a value of 0% unless there is a chance of species entering the module from the downstream side.

Entrance efficiencies are determined primarily by the hydraulics created from the structure, so they are incorporated as a module input. Flow and velocity fields are designed to attract specific species of fish. The entrance area is also important and represents trade-offs among design flow, velocity, and module cost. The most effective modules would span the entire length of the river, but this would increase costs and limit the inclusion of other modules. Because entrance efficiencies are primarily a function of module hydraulics, entrance efficiency was set as a parameter to be provided by any modules capable of upstream passage. This formulation ignores the effect of the entrance area since no research has been found specifically on the relationship between the entrance area and efficiency. The effect of the entrance area can be conceptually incorporated into the entrance efficiency parameter. Bunt, Castro-Santos, and Haro [54] provide a very useful review of 19 fishway monitoring surveys and documents the attraction (matches the definition of entrance efficiency) and passage efficiencies for a variety of fishway types, as shown in Table B.3. The review paper also lists the fishway designs in the appendix, which can be used as examples of Fish Passage modules [54].

Table B.3. Summary of entrance and passage efficiencies from Bunt, Castro-Santos, and Haro [54] based on 19 fishway monitoring surveys.

Fishway type	Slope (%)	Entrance efficiency* mean (range)	Passage efficiency mean (range)
Pool and weir	7	77 (29–100)	40 (0–100)
Vertical slot	10.7	63 (0–100)	45 (0–100)
Denil	15.7	61 (21–100)	51 (0–97)
Nature-like	3	48 (0–100)	70 (0–100)

*Bunt, Castro-Santos, and Haro [54] only define attraction and passage efficiencies, so the attraction efficiency was redefined here as entrance efficiency.

B.4.2.3 Upstream passage efficiency

Upstream passage efficiency is the percentage of species individuals that can successfully ascend the module after entering. A passage efficiency of 0% means that no fish can ascend, whereas a passage efficiency of 100% means that all fish can ascend safely. This metric is normally measured for volitional fishways. The value depends on the species of interest and the hydraulics of the entrance. Efficiencies can vary from 0% to 100% depending on the technology, although 100% passage rates can be difficult to achieve. Modules without species passage capabilities should assume an efficiency of 0%.

Passage efficiency is primarily determined by the internal hydraulics of the structure, so it is incorporated as a module input. Pool and weir fishways have large, slow pools that allow fish to rest between jumps, whereas others like Denil fishways aim to create attractive velocities for strong swimmers. The hydraulics are designed for specific species; however, generally, the lower the slope, the better the performance. Lower slopes allow for more gradual energy expenditure at the expense of longer structures, which have higher costs. Passage and entrance efficiencies have been studied for a variety of fishway designs, and average passage efficiencies for select fishways are described in Table B.3 [54].

B.4.2.4 Formulation

Formulation relies on the conceptual understanding of attraction, entrance, and passage efficiencies to create an effective upstream fish passage metric that captures technology selection and flow allocation trade-offs. The first step is to estimate attraction efficiency using Equation 19 and the flow allocation at the given time step. Similar to the downstream passage model, the next step is to estimate the probability of fish entering a given module. To simplify the calculation, fish were assumed to be able to only make one attempt to pass through the facility. Energy used in unsuccessful attempts may preclude fish from making second attempts. Based on this assumption and the fact that fish can only enter one module at a given time, the entrance probability is treated as lossless, meaning that the sum of probabilities to enter each module is 100%. Therefore, the probability of a fish selecting a given module is calculated by multiplying the module’s entrance efficiency and attraction efficiency factor and dividing it by the sum of these products for all modules. Thus, modules with high attraction and entrance efficiencies will attract the most fish but competing flows from other modules with non-zero entrance efficiencies can detract from entrance probabilities. Once the percentage of fish flow is allocated to each module, the value is multiplied by the entrance, attraction, and passage efficiencies, as shown in Equation 20.

Assumption: Fishway modules are placed in the ideal locations for each type of fish, and the effects of location are not included in the model.

Assumption: Fish only make one attempt to pass through a module.

Effective upstream passage at a time step (%)	$U_{m,s,t} = \frac{E_{m,s}A_{m,s,t}}{\sum_{m}^{Fa} E_{m,s}A_{m,t}} E_{m,s}A_{m,s,t}P_{m,s}$	Equation 20 (Maximize)

Summing the effective passage for each module gives the percentage of a species that can ascend the facility at a given time step. These values can then be averaged over the simulation time and across species to get a metric that describes the performance of the facility over the simulation time, as shown in Equation 21.

Cross-species effective upstream passage (%)	$U_{eff} = \sum_{t}^{T} \sum_{s}^{Sp} \frac{\sum_{m}^{Fa} U_{m,s,t}}{SpT}$	Equation 21 (Maximize)

Attraction and entrance efficiencies are also significantly influenced by the location of the entrance. Fish tend to swim along the banks of the rivers where considerable velocity gradients exist and proceed as far upstream before entering structures, although the behavior is species-dependent [17]. The spatial component of fish attraction is outside the modeling capabilities of the waterSHED model, so the proposed model assumes that Fish Passage modules are placed in the appropriate locations along banks at the most upstream point. Thus, the losses in attraction and entrance efficiency from placement are negligible. Other factors can also influence overall passage effectiveness, such as fallback rate, delay, and any trauma resulting from passage. These factors are not well studied in existing studies, so they are excluded from the proposed formulation.

B.5 OPERATIONAL PERFORMANCE MODELS

The operational performance metrics provide details about how the module performed during the simulation and can be used for diagnostics. The two metrics included here are the module availability factor and the module flow ratio. Similar formulations are used in the other performance models for objective-specific metrics. These metrics apply to all passage modules.

B.5.1 Module Availability Factor

The module availability factor is the number of time steps that the module is operating divided by the total time that the module could be on given operating months. Some module classes, such as Generation modules, may want to maximize the availability, whereas others, such as Spillway modules, may want to minimize the availability. This metric can indicate the impact of operating constraints such as head and flow limits or the sediment sluice operating flow threshold. For example, facilities with highly variable headwater and tailwater stage–discharge curves and tight head constraints might lead to low module availability factors. Two functions are used in this formulation (Equation 22) to determine the number of time steps that the module is on and the number of time steps that the module should be on without constraints.

Module availability factor (%)	$P_{m,avail} = \frac{\sum_t^T f_{on}\left(Q_{m,t}\right)}{\sum_t^T f_{avail}\left(Q_{m,t}\right)}$	Equation 22 (Maximize or minimize)
On function	$f_{on}(Q) = \begin{cases} 1 \; ; \; Q > 0 \\ 0 \; ; \; Q \leq 0 \end{cases}$	
Availability function	$f_{avail}(Q_t) = \begin{cases} 1 \; ; \; t \in T_m \\ 0 \; ; \; else \end{cases}$	

B.5.2 Module Flow Ratio

The module flow ratio is the percentage of total simulation inflow allocated to the module. This metric can be a diagnostic to ensure that modules are operating as expected and can show which modules are receiving the most flow. Because modules typically require flow to provide value, the flow acts as a sort of currency that is allocated across the modules. The formulation (Equation 23) is a simple ratio of the total flow allocated to the module divided by the total inflow during the simulation.

Module flow ratio (%)	$P_{m,flow} = \frac{\sum_t^T Q_{m,t}}{\sum_t^T Q_{in,t}}$	Equation 23 (Maximize or minimize)

APPENDIX C. SUPPORT TOOLS

Support tools are supplementary models that help the user determine inputs throughout the waterSHED model. These features are implemented through the tool tips adjacent to the corresponding input. Support tools allow features to be added to the waterSHED model without the need to integrate directly into the main simulation functions. This appendix describes the background literature, assumptions, and model formulations for the following support tools:

- Geometric Stage–Storage Support Tool (Section C.1)
- Trap Efficiency Support Tool (Section C.2)
- Gordon Head Efficiency Support Tool (Section C.3)
- Probability of Sediment Entrainment Support Tool (Section C.4)
- Fish Attraction Efficiency Support Tool (Section C.5)

C.1 GEOMETRIC STAGE–STORAGE SUPPORT TOOL

This support tool is used to provide a default option for the stage–storage equation, $V_{res}(Z)$, in the Site object. This tool is based on a paper from Lawrence and Cascio [18], which describes a geometric approach that has been used by several authors as a direct method of small reservoir capacity estimation [57]. This approach represents the reservoir valley cross-section as a pyramid with the base as the dam cross-section and extends upstream. The model described in Lawrence and Cascio [18] uses two constants that describe the shape of the valley-cross section, the maximum water depth at the dam, the width of the dam, and the throwback (distance from the dam to the entrance of the reservoir). All terms are multiplied together to determine the volume of the weight pyramid. This formulation combines the two constant terms to simplify the inputs and assumes that the throwback length is the headwater level divided by the stream slope. Figure C.1 illustrates how these parameters are used to represent the reservoir control volume.

Assumption: The throwback of the reservoir is approximately the headwater level divided by the average stream slope.

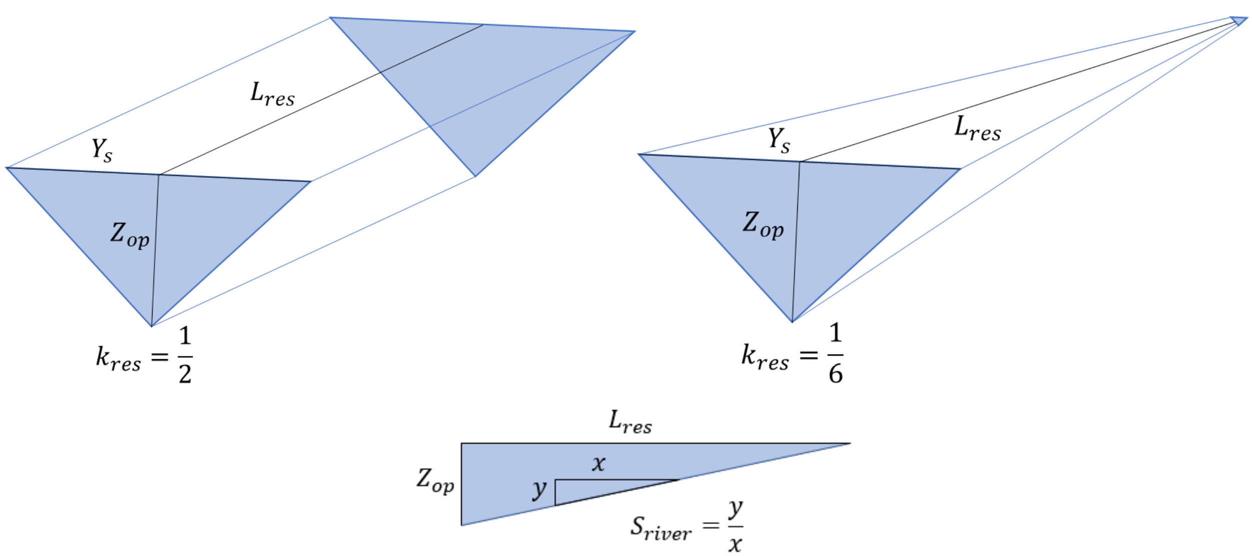

Figure C.1. Illustrations of geometric reservoir approach with representative dimensions.

Lawrence and Cascio [18] reviewed four methods for identifying the k_1 and k_2 constants and compared them with nine surveyed reservoir volumes. The results are shown in Table C.1. In this formulation, the combined constants, k_{res}, should range from 0.5 to 0.16 with a recommended value of 0.26. Larger coefficients represent larger volume to stage ratios.

Table C.1. Results of reservoir capacity estimation models from Lawrence and Cascio [18]

Method	k_1	k_2	k_{res}	Ratio of predicted to surveyed volume
USAID (1982)	0.4	1	0.4	1.36
Fowler (1977)	0.25	1	0.25	0.86
1/6 rule	0.167	1	0.167	0.57
Nelson (1986)*	0.22	1.22	0.26	0.9

* In the Nelson method, k_2 is dependent on the valley cross-section. Lawrence and Cascio [18] assumed a value of 1.22 in their comparison.

The following formulation (Equation 24) creates a function that determines the reservoir volume for a given headwater level. Through the course of the simulation, the reservoir volume and length may change depending on the headwater elevation, in which case Z_{op} is replaced by $Z_{head,t}$.

Reservoir volume (ft^3)	$V_{res} = k_{res} Z_{op} Y_s L_{res}$	Equation 24
Reservoir length i.e., throwback (ft)	$L_{res} = \dfrac{Z_{op}}{S_{river}}$	
Reservoir size factor (dimensionless)	$k_{res} \sim \left[\dfrac{1}{6}, \dfrac{1}{2}\right]$	

C.2 TRAP EFFICIENCY SUPPORT TOOL

The trap efficiency support tool allows the user to test different values of the trap efficiency parameter β (part of the Site object) used in the average trap efficiency model, as described in Section B.3.3. The model takes in a trap efficiency parameter, a stage–storage curve, a normal operating level, and a mean daily inflow to calculate the trap efficiency. If this information is already incorporated in the model, then it will be uploaded into the support tool; otherwise, default information is provided. This support tool does not use the flow weighted average or the varying headwater levels that are used in the simulation process, but it does provide a helpful way of showing how the trap efficiency parameter affects average trap efficiency. Section B.3.3 provides a description of the model.

C.3 GORDON HEAD EFFICIENCY SUPPORT TOOL

This support tool is used to provide a default option for the Generation module head efficiency equation, $\eta_{H,m}$. Turbines are typically designed for a particular design head and flow. Adjustable blade turbines may have a wider range of peak operating conditions than fixed blade turbines, but higher heads and flow are generally preferred for more power. Thus, turbines may lose efficiency if the operating head and flow differ from the design point. Efficiency equations as a function of flow, but the effects of changing head on flow are much less studied. The head efficiency input allows the user to incorporate this relationship, but it is an optional input that will default to a constant head efficiency of 100%. Gordon [58] provides one of the only quantitative estimations for head efficiency losses, which is parameterized by the relative deviation from the design head. The Gordon [58] equation, modified to fit the notation of this manual, is presented in Equation 25. Gordon [58] noted that this equation is meant for Kaplan and Francis turbines, which have relatively minor efficiency losses at heads 25% above or below the design head, whereas propeller turbines should not be operated in sites with highly variable heads.

Head efficiency equation adapted from Gordon [58] (%)	$\Delta\eta_{H,m}(H_t) = -0.5\left(\frac{H_t - H_{des,m}}{H_{des,m}}\right)^2$	Equation 25

The head efficiency equation input is parameterized by the relative head (operating head divided by the design head) in terms of decimals (0.0–1.0), where the design head corresponds to 1.0. After adapting the head efficiency equation to this parameterization, the following default head efficiency equation (Equation 26) was created.

Default head efficiency equation (%)	$\eta_{H,m}\left(\frac{H_t}{H_{des,m}}\right) = -0.5x^2 + x + 0.5$	Equation 26

C.4 PROBABILITY OF SEDIMENT ENTRAINMENT SUPPORT TOOL

This support tool is used to provide guidance on the selection of the operating flow for sediment sluice gates, $Q_{op,m}$. The tool uses a probability of entrainment model from Elhakeem et al. [59] to select the inflow that will likely cause mobility of bedload particles. To prevent sediment accumulation, sediment sluice gates should be operated whenever there is significant sediment mobilization that would otherwise deposit in the reservoir. The entrainment model uses information about the target sediment size, stream slope, and stage–discharge curve to determine the operating flow for a user-input probability of entrainment. This model has been used in the previous case study report [6] and in the system dynamics model by Dowda [60].

In this approach, particles have a condition of incipient motion that is probabilistic in nature and depends on the bed shear forces [6]. By estimating the bed shear force at a given time step, the probability of entrainment for a representative particle size can be approximated, which is the likelihood that the particle is mobilized, separating from the active bed layer and moving downstream. The shear force can be estimated using the stage–discharge relationship of the upstream reach. The resulting probability vs. flow curve can be used to provide information about the sediment transport properties of the stream to aid in the selection of a design flow. Use of this model requires two additional inputs: a representative particle size (d_{50}) in millimeters and a probability of entrainment threshold $\left(P_{op,m}\right)$. In this notation, d_{50} indicates the particle size in which 50% of bed material is finer; however, other particle sizes may be used as allowed by the Elhakeem et al. [59] model. The reference particle sizes included in the GUI are referred to as the Wentworth scale by Bunte and Abt [61]. Larger particle sizes would lead to higher operating flow triggers since larger flows are needed to mobilize the larger particles. Similarly, higher probability of entrainment thresholds would lead to higher operating triggers since the probability threshold indicates the minimum probability of entrainment that must be met to open the sluice gate. Higher operating triggers likely lead to less frequent operation, higher sediment accumulation between flushes, and less cumulative flow for the same design flow. Selection of the threshold is based on user-preference, but testing multiple values (e.g., 10%, 50%, and 90%) is recommended to evaluate trade-offs.

The Elhakeem et al. [59] model improves on existing probabilistic models in several ways, including the consideration of both bed surface irregularity and near-bed turbulence. The model was derived analytically and validated/calibrated using several lab-scale data sets that studied a variety of sediment types. The following procedure has been adapted to use the variables used in this model. This model requires five main steps.

Step 1. Determine the minimum critical shear stress

First, the minimum critical shear stress required to mobilize the target particle class must be determined. Any shear stresses below this threshold have a 0% probability of mobilizing the target particle size class. Following the methodology of Witt et al.'s case study report [6], two methods were used for calculating the critical shear stress: one for coarse (gravel) beds and one for fine (sand) beds. The bed is assumed fine if the representative grain size (d_{50}) is less than 2 mm and coarse otherwise.

For fine (sand) beds, the formula for critical shear stress (Equation 27) is provided by Brownlie [62].

Minimum critical shear stress: fine beds	$\tau_{*c} = 0.22R_p^{-0.6} + 0.06 \times 10^{-7.7R_p^{-0.6}}$	Equation 27
Particle Reynolds number	$R_p = \frac{d_{50}}{\upsilon}\left(\left(\frac{\gamma_s}{\gamma_w} - 1\right) g d_{50}\right)^{0.5}$	
Kinematic viscosity of water at 10°C	$\upsilon = 1.31e^{-6}\frac{m^2}{s}$	
Specific weight of sediment	$\gamma_s = 2650g\frac{N}{m^3}$	
Specific weight of water	$\gamma_w = 1000g\frac{N}{m^3}$	

For coarse beds, the equation for the critical shear stress (Equation 28) is derived from Elhakeem [59] and based on the assumptions used in the case study report [6]. Per the recommendations in Elhakeem [59], several coefficients are assumed for coarse beds. $\beta = 15$ describes particle-flow interaction and accounts for the effects of particle protrusion and packing density. $C_D = 0.4$ is the drag coefficient and $C_L = 0.12$ is the lift coefficient. $R_r = 1.5$ is the relative roughness of the bed compared to a value of 1 for fine beds. By inserting the assumed coefficients, the following equation can be simplified using the stream slope.

Minimum critical shear stress: coarse beds	$\tau_{*c} = \frac{\cos(S_s)}{0.75(r_m C_D + C_L)f^2} = \frac{\cos(S_s)}{0.75(3.84 \times 0.4 + 0.12)8.50^2} = \frac{\cos(S_s)}{89.8}$	Equation 28
where	$r_m = \sqrt{3(R_r + 1)^2 - 4} = \sqrt{3(1.5 + 1)^2 - 4} = 3.84$ $f = 2.5\ln(\beta R_r + 7.5) = 2.5\ln(15 \times 1.5 + 7.5) = 8.50$	

Step 2. Determine the maximum critical bed shear stress

The next step is to identify the maximum critical bed shear stress where there is a 100% probability of entrainment for the representative particle. Again based on Elhakeem [59], the form of the equation is the same for both fine and coarse beds, but the assumed coefficients are different, as illustrated in Table C.2. Incorporating these assumed coefficients into the equation, maximum dimensionless shear stresses can be calculated for fine (Equation 29) and coarse (Equation 30) beds.

Maximum critical shear stress: fine beds	$\tau_{*max,fine} = nCa((R_r+1)^2 - 1.333)^{-0.5}$ $= 5 \times 0.6 \times 0.94((1+1)^2 - 1.333)^{-0.5}$ $= 1.727$	Equation 29
Maximum critical shear stress: coarse beds	$\tau_{*max,coarse} = nCa((R_r+1)^2 - 1.333)^{-0.5}$ $= 3 \times 0.4 \times 0.94((1.5+1)^2 - 1.333)^{-0.5}$ $= 0.509$	Equation 30

Table C.2. Assumed shear stress coefficients from Elhakeem [59] that are used to calculate maximum critical shear stress

Coefficient	Description	Fine	Coarse
n	Number of particles defining the thickness of the active layer	5	3
C	Volumetric fraction of sediment particles in the active layer	0.6	0.4
a	Constant describing the dynamic fraction angle of sand and gravel (between 0.8 and 1.4)	0.94	0.94
R_r	Relative roughness, or the ratio of mobile particles to bed particles	1	1.5

Step 3. Define a probability function between the minimum and maximum critical shear stresses

Equation 31 from Elhakeem [59] defines the probability of entraining the target particle size class as a function of the bed shear stress. The formula uses the minimum critical shear stress value to determine m_c and applies to the range of shear stresses between the minimum and maximum critical shear stresses.

Probability of entrainment	$P = \left[1 + e^{-0.07056m^3 - 1.5976m}\right]^{-1} - \left[1 + e^{-0.07056m_c^3 - 1.5976m_c}\right]^{-1}$	Equation 31

where

$$m = \frac{X - \bar{X}}{\sigma_x}$$

$$m_c = \frac{X_c - \bar{X}}{\sigma_x}$$

$$X = \ln(\tau_*)$$

$$X_c = \ln(\tau_{*c})$$

Step 4. Determine the bed shear stress for a given flow value

The previous equations set the dimensionless shear stresses that correspond to the minimum and maximum shear stresses. In this step, shear stress must be connected to river flow to identify the probability of entrainment for the range of inflows. Equation 32 below is a basic particle shear stress equation that uses the user-input stage–discharge curve to determine the water depth.

Bed shear stress	$\tau_* = \frac{\tau}{(\gamma_s - \gamma)d_{50}} = \frac{\gamma S_s Z_{stage}(Q)}{(\gamma_s - \gamma)d_{50}}$	Equation 32

Step 5. Solve for the recommended flow given a probability of entrainment

The equation in Step 3 describes the probability of entrainment as a function of shear stress, and the equation in Step 4 describes the shear stress as a function of flow. Given the complex form of the probability of entrainment equation, linear interpolation is used to relate the probabilities to flow values. This is done by iterating through flow values, calculating the shear stresses for each flow value, and then using the calculated shear stress to a corresponding list of probabilities. The user-input probability of entrainment is compared with the list of probabilities and computed using a linear interpolation between the nearest two probabilities in the list.

C.6 FISH ATTRACTION EFFICIENCY SUPPORT TOOL

This support tool allows the user to visualize how the relative discharge parameter (a_s) and the attraction sensitivity parameter (b_s) from the Species object form the attraction efficiency function, as described in Section B.4.2. The model takes each parameter as an input and simply plots the resulting sigmoid curve. This allows the user to understand better where the relative discharge threshold is and how steep the drop-off is. Section B.4.2 provides more information about the attraction efficiency model.

APPENDIX D. DYNAMIC MODULES

Dynamic modules are module objects that can be custom-designed for different site conditions. These modules can change attributes depending on one or more controlling variables, which can be select module attributes or simulation class attributes. The controlling variables for each module class are described in Table D.1. The attributes for dynamic modules differ slightly from their static module counterparts, some having additional inputs or attributes calculated from the inputs (i.e., intermediate attributes) that can be used as controlling variables. For example, the Dynamic Foundation module class has an additional depth attribute that is used to calculate the foundation volume by multiplying the length, width, and depth. The foundation volume is an intermediate attribute that allows the user to set cost equations as a function of foundation volume, which was useful for the case studies in the accompanying dissertation [7]. The use of control variables is not error-checked, so users should make sure not to parameterize attributes in a way that self-references or creates a loop in which one or more attributes are based on itself or each other. The additional attributes and intermediate attributes for each dynamic module class that differs from the static module version in Appendix A are also described in Table D.1. Notable differences are the addition of height and depth attributes to the Non-Overflow and Foundation modules, respectively, so that the cost attribute can be parameterized as a function of module volume. Additionally, the number of steps and step type attributes were added to the Recreation and Fish Passage modules to reflect the modular nature of volitional fishway and boat chute designs, which typically consist of a series of steps and pools. The step functionality allows the user to determine the number of steps required based on controlling variables, such as the normal operating headwater level, and then parameterize costs based on the number of steps.

Table D.1. Dynamic module controlling variables by module class

Module class	Controlling variables	Additional attributes
Generation	Design flow; Design head; Nominal power;	—
Non-Overflow	Normal operating level; Volume;	Volume: the product of the length, width, and height of the module (ft^3) Height: the vertical distance from the bed elevation to the top of the module (ft)
Foundation	Volume; Depth;	Volume: the product of the length, width, and depth of the module (ft^3) Depth: the vertical distance from the top of the riverbed to the bottom of the Foundation module (ft)
Recreation	Mean daily flow; Normal operating level; Number of steps;	Mean daily flow: the average daily inflow for the simulation (cfs) Number of steps: a discretized unit of measuring the size of a module (integer) Step type: whether the number of steps should be a continuous value or rounded the nearest integer (continuous, round up, or round down)
Fish Passage	Mean daily flow; Normal operating level; Number of steps;	Mean daily flow: the average daily inflow for the simulation (cfs) Number of steps: a discretized unit of measuring the size of a module (integer) Step type: whether the number of steps should be a continuous value or rounded to the nearest integer (continuous, round up, or round down)
Water Passage	Normal operating level	—
Sediment Passage	Mean daily flow;	Mean daily flow: the average daily inflow for the simulation (cfs)
Screen	Screen area; screen flow; normal operating level; stream width; covered module width;	—

D.1 SCREEN MODULE

The Screen module represents technologies that are placed in series with SMH modules. Examples include trash racks, fish exclusion screens, and booms. These technologies are typically designed to protect other technologies and species from damage by excluding them from the flow. The Screen module was not included in the SMH Exemplary Design Envelope Specification [5] and is not a subclass of the SMH Module parent class. The Screen module required greater design flexibility than standardized modules since screen technologies are often sold by screen area rather than discrete modules. Thus, screens were created as a dynamic class, which provides several options for parameterizing the module. Screen objects can be created with constant attributes that do not change with the facility design or with attribute functions that change the costs and dimensions according to controlling variables, such as screen area and design flow. In addition to having the following attributes, the Screen module also has the downstream guidance efficiency ($G_{m,s}$) and downstream mortality rate ($M_{m,s}$) attributes with the same definitions previously list for the Passage Modules class. The mortality rate can be used to factor in screen impingement; however, the mortality rate is currently applied after the guidance step. For example, a 10% mortality rate on an 80% guidance efficiency screen means that the 10% mortality rate only applies to the 20% of fish that make it through the screen.

Table D.2. Screen module inputs

Screen module class				
Attribute variable	**Description**	**Entry types**	**Unit**	**Controlling variables**
—	Name	Text entry	—	—
$C_{cap,m}$	Capital cost	Equation	$	Screen area (ft^2) or screen flow (cfs)
$C_{om,m}$	Annual operating cost	Equation	$	Screen area (ft^2) or screen flow (cfs)
$H_{loss,m}$	Head loss equation	Equation	ft	Screen area (ft^2) or screen flow (cfs)
$X_{angle,m}$	Incline	Numeric	° (0–90)	—
Z_m	Height	Equation	ft	Normal operating level (ft)
$Z_{bot,m}$	Bottom elevation	Numeric	ft	
Y_m	Width	Equation	ft	Stream width (ft), covered module width (ft)
$A_{frac,m}$	Fractional open area	Numeric	% (0–100)	—
$M_{covered,m}$	Covered modules	List	—	—
$G_{m,s}$	Downstream guidance efficiency*	Numeric	% (0–100)	—
$M_{m,s}$	Downstream mortality rate*	Numeric	% (0–100)	—

The definitions for each of these attributes are listed as follows. The screen attribute dimensions are illustrated conceptually using the profile view in Figure D.1.

Name: the name used to identify the screen

Capital cost: should include all fixed, one-time costs to prepare the screen for operation; can include material, equipment, installation, transportation, and so on, and can be constant or parameterized as a function of the total area or design flow ($C_{cap,m}$, $)

Annual operating cost: the annualized expected costs for maintaining and operating the screen; can be constant or parameterized as a function of the total area or design flow ($C_{op,m}$, $/yr)

Head loss equation: the equation that determines the total head loss to the covered modules as a function of either the active area (the submerged screen area times the fractional open area), the operating flow (the flow allocated to the covered modules), or a combination of both ($H_{loss,m}$, % as a function of ft^2 or cfs)

Incline: the angle of the screen from horizontal in the streamwise direction ($X_{angle,m}$, °). At a 90° incline, the module would be perpendicular to the streamwise direction, whereas a 0° angle would be flat along the bed. The incline is used to determine the active area.

Height: the screen dimension in the vertical dimension to streamflow; can be constant or a function of the normal operating level (Z_m, ft)

Bottom elevation: the vertical distance from the bed to the bottom of the screen; can account for raised screens and impact the active area ($Z_{bot,m}$, ft)

Width: the module dimension along the dam axis from bank to bank, perpendicular to streamflow; can be constant or parameterized as a function of the stream width or the width of the covered modules (Y_m, ft)

Fraction open area: the percentage of the total screen area that flow can pass through (i.e., the total screen area minus the material area) ($A_{frac,m}$, %)

Covered modules: the set of SMH passage module objects in series with the screen ($M_{covered,m}$, set of module names). The design flow of the screen and other parameters will be determined by the number of covered modules in the facility.

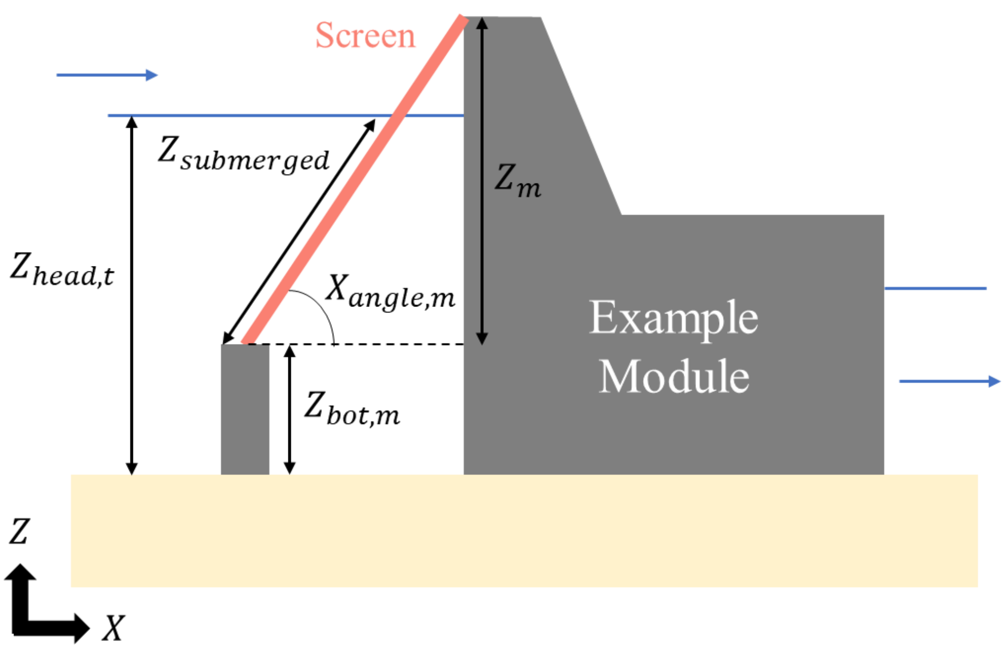

Figure D.1. Example schematic of screen profile view with attribute labels.

Because the Screen is a dynamic module that resizes depending on the site conditions, several internal processes must redesign the screen before each simulation. The redesign process occurs once the facility is constructed but before operation. The following redesign steps only apply if the inputs are parameterized as functions and are not constant. First, the screen height is calculated based on the normal operating level and the provided height equation. Second, the screen width is calculated by summing the widths of covered modules in the facility, if necessary, and applying the provided width equation. In Case Study B in the accompanying dissertation, the width equation uses a screen angle of 40° to convert the module width to the screen width. Third, the total screen area is calculated by multiplying the screen height and width. Fourth, the design screen flow is calculated by summing the design flows of the covered modules. Finally, the capital and operating costs are calculated using the relative variables and equations.

Several processes are also conducted during the simulation to determine screen head losses based on the flow allocation. The head loss equation can be set as a function of the screen operating flow and or the active area. The operating flow is the flow through the screen and to the covered modules during a given time step. The active area is the total area of the flow passing through the screen, which can be calculated as the submerged screen area times the fractional open area. To calculate the active area, the model calculates the submerged screen height by subtracting the headwater elevation at the time step by the bottom elevation and multiplying it by the sine of the incline ($Z_{submerged} = \sin\left(X_{angle,m}\right) \times \left(Z_{head,t} - Z_{bot,m}\right)$). The active area then becomes a product of the submerged height, the screen width, and the fraction open area, which accounts for the width of the bars ($A_{active} = X_m Z_{submerged} A_{frac,m}$). This allows the head loss to be calculated according to the velocity through the screen.

APPENDIX E. LIST OF ASSUMPTIONS

This section documents the major assumptions made throughout the waterSHED model. This list does not include the assumptions made in the support tools or dynamic modules because these features are not required for operation of the model.

The waterSHED model scope:

- **Prefeasibility stage site evaluation tool:** the model is best used in the early development stages to estimate project feasibility and design trade-offs.
- **Low-head new stream-reach sites:** the current model version is meant to be used in the design evaluation of low-head (<30 ft) NSD sites where modular design practices are especially beneficial.
- **Daily ROR operation:** the model is designed to model daily ROR operation of facilities and does not feature storage or scheduling optimization.
- **Instream designs:** modular facilities created in this model do not have long diversions that can dewater significantly long portions of the downstream reach.
- **Non-power benefits:** in addition to quantifying power generation, this model also quantifies sediment passage, fish passage, recreation, and flood safety performance.

Assumption: The facility width must equal or exceed the stream width to create a watertight barrier between the headwater and tailwater.

Assumption: Bypasses are relatively short and operate according to the headwater and tailwater elevations at the dam axis.

Assumption: The stage–discharge curve in the tailwater reach is the same before and after the development of the facility.

Assumption: Sub-daily inflow variation is minimal and does not contribute to significant headwater level variation.

Assumption: Headwater elevation is controlled primarily by the operation and hydraulics of the spillway.

Assumption: If the spillway provides head control, then the headwater level is maintained at the normal operating level.

Assumption: When allocating flow between modules of the same class, the modules are ramped in order of smallest to largest design flow.

Assumption: Fishway modules are placed in the ideal locations for each type of fish, and the effects of location are not included in the model.

Assumption: Fish only make one attempt to pass through a module.