Hydropower Potential Assessment Tool (HPAT)

Tutorial and Case Study

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# Introduction

The Hydropower Potential Assessment Tool (HPAT) models run-of-river (ROR) hydropower potential at a single location or distributed over a study region (Mosier et al., 2016a). HPAT uses climate inputs to model streamflow and then estimates local ROR hydropower potential by calculating changes in elevation at the model spatial resolution (often 1 km). HPAT is designed to estimate ROR hydropower rather than reservoir-based system potential because the model does not contain functions to consider dam siting or reservoir operations.

A powerful feature of HPAT is the ability to estimate the spatial distribution of hydropower potential within a large region. This feature facilitates more objective planning of regional investments through being able to characterize and compare ROR potential using mapping and other forms of spatial analysis. HPAT is available at [GlobalClimateData.org](http://globalclimatedata.org/node/18) and [Thomas Mosier’s GitHub repository](https://github.com/thomasmosier).

HPAT is straightforward to apply across contexts because it bundles and abstracts multiple layers of the analyses. The only data input that is not globally-available is observation data for calibration and validation. The most basic type of calibration data are daily streamflow. For most implementations it is desirable to have streamflow data at multiple points to ensure the model assessment accounts for varying conditions across the area being studied. In general, additional streamflow data such as satellite imagery of snow covered area and glacier mass balance are also useful, depending on site characteristics. It is desirable to use many years of records in order to assess how well the model captures the inter-annual distribution of streamflow, but it is possible to use only a few years. These determinations require an “eyes wide open approach” and are best carried out by specialists. There is no definitive rule for how much observation data should be used, but except that more data is always better!

Climate data used as input to HPAT should be chosen carefully. The [Global Climate Data (GCD) package](https://github.com/thomasmosier/GCD) is designed to produce high-resolution (typically 1 km) monthly or daily climate data using only globally-available inputs (Mosier et al., 2014 and Mosier et al., 2018). The GCD package works equally with historical climate products (for example CRU monthly time-series or ERA-Interim daily time-series) and projected global climate model (GCM) simulations of climate change. As is done in Mosier et al., (2016a) it is recommended to establish a historic baseline of ROR hydropower and then consider possible impacts of climate change.

The core of HPAT is a spatially-distributed hydrologic model, the [Conceptual Cryosphere Hydrology Framework](https://github.com/thomasmosier/CCHF) (CCHF; Mosier et al., 2016b), which is designed for application in mountain environments. CCHF is highly configurable, which enables optimization of modelled process representation for a given setting (for example environments where snowpacks tend to be dry and low density versus those where snowpacks tend to be wet and high density). The configurability of CCHF may potentially seem foreboding for users without hydrologic expertise. HPAT can be implemented using a pre-configured CCHF implementation. Ultimately, though, it is recommended that users work in collaboration with a water resources specialist to ensure CCHF is configured suitably.

HPAT produces granular estimates of run-of-river hydropower potential by overlaying modelled streamflow with a digital elevation model (DEM). Flow output from the hydrologic model is used by two subroutines in the main script (“power\_potential” and “power\_quality”) to estimate run-of-river hydropower potential. Some representative statistics are automatically calculated and output, including mean power estimates and seasonal stability (characterized using the “stability metric” defined in Mosier et al. (2016a) and described in subsequent sections of this guide. Additional lines of code can be easily added to calculate and output additional statistics of interest for a specific application.

This document provides a general overview or HPAT and provides guidance on two associated case studies demonstrating implementations of HPAT. The “Oregon” case study is for a small watershed with significant forest cover, seasonal snowpack, and no glacier coverage located in Oregon, USA. The data generated for this case study have a monthly time resolution. The “Hunza” case study is for a medium-sized high elevation catchment in the Pakistan portion of the Upper Indus Basin (UIB) in the Karakoram Mountains. This region is above tree line, contains extremely steep slopes, seasonal snowpack, and significant glacier coverage. The Hunza case study uses daily data and extra inputs necessary to estimate glacier contributions to streamflow. In both cases snow processes are critical to the hydrology. In other respects, the case studies provide some contrasts, for example monthly versus daily time resolution and no glaciers vs. approximately 40% glacier cover.

# Obtaining HPAT

HPAT is open-source software written in Matlab and can be downloaded from [Thomas Mosier’s GitHub repository](https://github.com/thomasmosier) or [GlobalClimateData.org](http://globalclimatedata.org/node/18). The repository on GitHub is updated every time any edits are made to the underlying code and therefore is considered a “working copy” that is more likely to contain bugs. In contrast, the repository at GlobalClimateData is updated only periodically, typically when there is a new publication and a corresponding stable release of the software. Another difference is that if HPAT is downloaded from GitHub, the packages called “CCHF” and “subroutines\_Matlab” must also be downloaded and added to the Matlab search path. The releases stored at GlobalClimateData are sel-contained.

# Data Inputs

HPAT requires several input types (Table 1). Most of the inputs are straightforward to derive from globally-available sources. Expertise in GIS and data processing will be useful for obtaining several of the types of data. HPAT and the associated tools are designed to read multiple common data formats, such as ESRI ASCII files (common for data that are static in time or have a monthly time resolution), GEO Tiffs (common for data that are static in time), and NetCDF (common for temporally varying data with any time resolution). HPAT opens a pop-up data selection box for each of the inputs. Selecting “cancel” to any of the data inputs other than for observation data will terminate the model run.

A digital elevation model (DEM) and flow direction raster (FDR) must be supplied in ESRI ASCII format and must have the same grid size and spacing as the climate inputs used. In many cases the DEM will need to be conditioned in a program such as ArcMap. The main conditioning step is to “fill” the DEM, meaning to remove internal sinks, which can sometimes be a numeric artifact of the spatial sampling and can cause unrealistic streamflow results in HPAT. The FDR is then calculated from the sink-filled DEM using a program such as ArcMap.

Table 1: List of HPAT data inputs.

|  |  |  |  |
| --- | --- | --- | --- |
| **Input Type** | **Purpose** | **Notes** | **Example source** |
| Digital Elevation Model (DEM) | Used in hydrologic and hydropower calculations. | There are several DEMs available for all global land areas. Typically it is important to pre-process these using a “sink fill” tool, for example in ArcMap to ensure they are suitable for use in the hydrologic flow routing model. |  |
| Flow Direction Raster (FDR) | Used to set direction of streamflow between grid cells. | This is produced from the hydrologically-conditioned DEM in a GIS program, such as ArcMap, using the flow direction raster tool. HPAT contains a tool that can calculate this, but its performance is not as good as that produced using GIS software. |  |
| Climate data — gridded time-series | Calculating water inputs, seasonal storage as snow, and glacier melt. | The spatial grid must be the same as the DEM and FDR. The time step of the climate data determines the time step of the hydrologic model. Typically 30 arcseconds (approximately 1 km) daily data should be used.  Climate change simulations must be downloaded from a global repository. Typically an ensemble of climate data should be used. | The [Global Climate Data (GCD) package](https://github.com/thomasmosier/GCD) can be used to produce daily or monthly time-series at the same resolution as a reference grid. Input data for the GCD package must be obtained independently. A user guide for the GCD package is [available here](http://globalclimatedata.org/node/14).  Climate model simulations can be obtained from the [Earth System Grid Federation](https://esgf-node.llnl.gov/projects/esgf-llnl/). |
| Glacier outline | Calculating glacier melt | The glacier outline can be in shapefile or raster format. This input is not necessary in areas without glacier coverage. | [Randolph Glacier Inventory (RGI)](https://www.glims.org/RGI/) is the most globally complete glacier database. Other databases may be more accurate for specific locations. |
| Observation data — for example streamflow | Assessing model performance during calibration and validation stages. | While streamflow data are the most important and common, other types of observation data can be used, too. For example, snow covered area data from MODIS can improve model calibration in mountain areas where tree cover is minimal. Point or area estimates of glacier change can also be useful where available. | Streamflow data are typically only publically available in the USA ([through the USGS](https://waterdata.usgs.gov/nwis/rt)). In most instances, streamflow records must be obtained from local partners. |

# Generating Climate Data

The most involved aspect to implementing HPAT is gathering and generating the necessary input data. Most globally available sources of gridded climate data are relatively low-resolution. For example, Climate Research Unit (CRU) data, which have a monthly time step, have a spatial resolution of approximately 55 km. Hydrologic models typically use a spatial resolution of 1 km or finer. High resolution climate information can be extracted from low resolution information using a class of methodologies referred to as downscaling. The GCD package can be used to downscale gridded climate datasets using one of several methods. For example, monthly climate data can be downscaled using the “delta method” in the GCD package. Daily precipitation data can either be interpolated or can be downscaled using the “precipitable water method”. Daily temperature data can be downscaled based on known “lapse rates”. Documentation on the GCD package is distributed with the package.

Global Climate models (GCMs) are typically used to project how climate may change over the next several decades relative to historical patterns. Yet, GCMs contain biases that must be corrected to ensure that projections are consistent with the historical baseline. The GCD package integrates bias correction and downscaling methodologies. This means that historical baseline climate data can be downscaled in the GCD package using a particular downscaling methodology (with bias correction off) and then an ensemble of GCMs can also be processed using the GCM package with bias correction on. The GCD package contains multiple bias correction methods, but empirical quantile mapping appears to perform the best (Mosier et al., 2018).

# Running HPAT

HPAT is written in Matlab and is initiated by running the “main script”, e.g. “HPAT\_main\_vX.m”, where vX refers to the version of HPAT and therefore may change over time. Running HPAT requires generating several model inputs (Table 1). Additionally, there are several options within the main script that must be set (Table 2). Most of the options detailed herein must be edited for each instantiation of HPAT. There are also other options that typically do not need to be edited, which are not detailed here since they require expert knowledge of the program. The sub-sections “Oregon Case Study” and “Hunza Case Study” provide step-by-step guidance on running these HPAT examples.

Table 2: List of model configuration options. This list contains only those that typical users may want to consider.

|  |  |  |
| --- | --- | --- |
| **Name** | **Options** | **Description** |
| runType | 'default', 'calibration',  'validation', 'simulate' | Default uses “first-guess” parameter set; Calibration uses a built-in optimization routine to identify a “best performing” parameter set; Validation uses a parameter set file written during calibration and compares model output to observation data; Simulate uses a parameter set file written during calibration but does not compare model output to observation data. |
| region | String naming region being modelled. | This is a name chosen by the user to identify the model region |
| startDate | Numeric vector of format “[year, month, day of month]” | This vector sets the first day of the main model run. Climate data will be required for a period prior to the start date to “spin up” the model. The default spin up period is two years. |
| endDate | Numeric vector of format “[year, month, day of month]” | This vector sets the last day of the main model run. |
| nGage | Number | The number of files containing observation data to load. |
| moduleSet | Cell array of format provided. | The set of hydrologic process representations that will be implement. There is no one set of process representations that is uniformly “best”, but the default set is relatively common and robust. |
| modelTimeStep | 'day' or 'month' | Time step that the model should run at. “Day” is recommended. |
| dataRes | 'day' or 'month' | Time resolution of the input climate data. It is recommended (but not always necessary) for this to be the same as the model time step. |
| iceGrid | ‘same’, ‘fine’, or ‘none’ | This string sets whether or not glaciers are included in HPAT. “same” and “fine” both include glaciers, whereas “none” does not. “same” sets the glacier spatial grid to be the same as the main hydrologic grid. “fine” sets the glacier grid to be finer than the main hydrologic grid where the glacier spatial resolution is set based upon the loaded glacier grid. |

## Oregon Case Study

This section provides step-by-step guidance on implementing HPAT using input data provided for the catchment upstream of USGS streamgage 14158790 in Oregon, USA. The Oregon case study uses monthly climate data produced using the GCD package. The script used to produce these data is located at “./HPAT/test\_cases/Oregon\_test\_case/climate/GCD\_main\_v5\_HPAT\_test.m”. These climate inputs are stored in NetCDF format. The approximate run time for this case study is one minute.

This case study does not include glacier coverage or processes. USGS streamgage data are the only observations used for assessing model performance. MODIS snow covered area observations are not used in this case study because the area is heavily forested, which prevents observations of ground cover.

This case study uses monthly time steps. Monthly time steps cause HPAT to run very quickly. A byproduct of the coarse temporal resolution is that the output represents seasonal conditions but not events that deviate from the seasonal normals. For example, flows resulting from peak snowmelt events are not captured.

The Oregon test case can be run by following these steps:

**Step 1:** Run script “./HPAT/test\_cases/Oregon\_test\_case/HPAT\_main\_v3\_Oregon\_test\_case.m”.

**Step 2:** Select inputs as prompted (see selection prompt example in Figure 1). The full list of inputs and their respective file paths are provided in Table 3. Matlab will also prompt the user to enter observation data analysis details in the command window. The correct settings are provided as notes in Table 3.

**Step 3:** The script will run, display outputs, and write information to a unique folder at the path “./HPAT/test\_cases/Oregon\_test\_case/model\_runs”. Within the main output folder there will be subfolders for each region evaluated in the model instance. Statistics related to hydropower potential will be written to a subfolder named “hydropower\_stats”, which is within the region sub-folder.

**Step 4:** Edit the main script, “HPAT\_main\_v3\_Oregon\_test\_case.m”, and re-run in alternative configurations to improve model performance. For example, change the “runType” parameter to “calibrate” to optimize model parameters. Calibration requires approximately five hours of computation time on a machine with four cores.

Figure 1: Example input selection prompt. A file manager prompt loads after selecting “OK”.

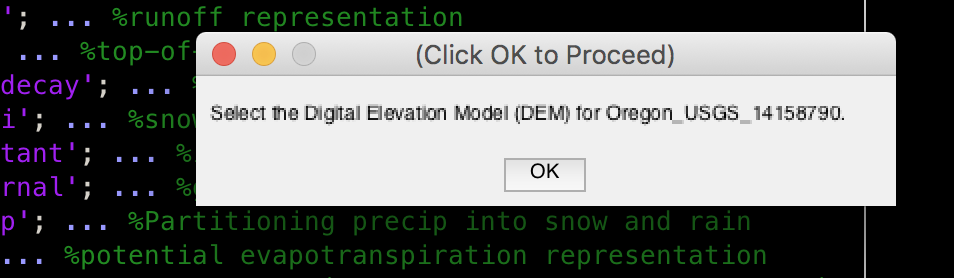
****

Table 3: Inputs required for Oregon test case. These correspond to entries in Table 1 relevant to the Oregon test case.

|  |  |
| --- | --- |
| **Input Type** | **Path** |
| DEM | ./HPAT/test\_cases/Oregon\_test\_case/terrain/SRTM\_CGIAR41\_USGS14158790\_dem.asc |
| FDR | ./HPAT/test\_cases/Oregon\_test\_case/terrain/SRTM\_CGIAR41\_USGS14158790\_fdr.asc |
| Climate – precipitation | ./HPAT/test\_cases/Oregon\_test\_case/climate/delta\_his\_pchip\_pre\_USGS14158790 |
| Climate – mean temperature | ./HPAT/test\_cases/Oregon\_test\_case/climate/delta\_his\_pchip\_tmp\_USGS14158790 |
| Climate – maximum temperature | ./HPAT/test\_cases/Oregon\_test\_case/climate/delta\_his\_pchip\_tmx\_USGS14158790 |
| Climate – minimum temperature | ./HPAT/test\_cases/Oregon\_test\_case/climate/delta\_his\_pchip\_tmn\_USGS14158790 |
| Observation data | ./HPAT/test\_cases/Oregon\_test\_case/observation\_data/USGS\_14158790-flow.txt  *Notes: The longitude is -122.046 and the latitude is 44.3314. The model will create a file called “*./HPAT/test\_cases/Oregon\_test\_case/observation\_data/*CCHF\_formatted\_observations-flow.txt” that can be selected in future model runs to avoid needing to enter the coordinates.* |

## Hunza Case Study

This section provides step-by-step guidance on implementing HPAT using input data provided for Hunza Catchment in the Pakistan portion of the UIB. The Hunza case study uses daily climate data produced by linearly interpolating daily ERA Interim reanalysis output. The approximate run time for this case study is 10 to 20 minutes.

This case study includes melt contributions from glaciers. The case study requires several additional glacier-relevant inputs to represent these contributions. Three types of observation data are used to assess model performance. These are streamgage measurements, MODIS snow covered area observations, and gridded glacier mass balance measurements.

It will be apparent after running HPAT for this case study that the default parameter set does not adequately represent conditions. The poor performance is mostly due to the choice of “default” parameters. No single set of parameters can represent conditions well for all locations. Therefore, location-specific calibration is recommended for all implementations for which results will be used for decision making. Another contributor to the poor performance is the choice of climate inputs. The climate inputs bundled with the test case are linearly interpolated ERA Interim data. The Hunza catchment contains terrain with extremely steep slopes. In such environments it is typically important to downscale the temperature inputs to account for orographic impacts.

The Hunza test case can be run by following these steps:

**Step 1:** Run script “./HPAT/test\_cases/Hunza\_test\_case/HPAT\_main\_v3\_Hunza\_test\_case.m”.

**Step 2:** Select inputs as prompted. The full list of inputs and their respective file paths are provided in Table 4. Matlab will also prompt the user to enter observation data analysis details in the command window. The correct settings are provided as notes in Table 4.

**Step 3:** The script will run, display outputs, and write information to a unique folder at the path “./HPAT/test\_cases/Hunza\_test\_case/model\_runs”. Within the main output folder there will be subfolders for each region evaluated in the model instance. Statistics related to hydropower potential will be written to a subfolder named “hydropower\_stats”, which is within the region sub-folder.

**Step 4:** Edit the main script, “HPAT\_main\_v3\_Hunza\_test\_case.m”, and re-run in alternative configurations to improve model performance. For example, change the “runType” parameter to “calibrate” to optimize model parameters. Calibration requires approximately two days of computation time on a high-end machine with four cores.

Table 4: Inputs required for Hunza test case. These correspond to entries in Table 1 relevant to the Hunza test case.

|  |  |
| --- | --- |
| **Input Type** | **Path** |
| DEM | ./HPAT/test\_cases/Hunza\_test\_case/terrain/hunza\_dainyor\_bridge\_dem.asc |
| FDR | ./HPAT/test\_cases/ Hunza\_test\_case/terrain/hunza\_dainyor\_bridge\_fdr.asc |
| Glacier outline | ./HPAT/test\_cases/ Hunza\_test\_case/RGI5\_Hunza/RGI\_5\_Hunza.shp |
| Ice thickness | ./HPAT/test\_cases/ Hunza\_test\_case/ice\_properties\_Hunza/ice\_thickness\_HKHK\_wmean\_Hunza.asc |
| Glacier debris cover thickness | ./HPAT/test\_cases/ Hunza\_test\_case/ice\_properties\_Hunza/debris\_thickness\_HKHK\_wmean\_Hunza.asc |
| Glacier pond fraction | ./HPAT/test\_cases/ Hunza\_test\_case/ice\_properties\_Hunza/glacier\_pond\_fraction\_HKHK\_wmean\_Hunza.asc |
| Climate – precipitation | ./HPAT/test\_cases/ Hunza\_test\_case/climate\_ERAi/hunza\_pr |
| Climate – mean temperature | ./HPAT/test\_cases/ Hunza\_test\_case/climate\_ERAi /hunza\_tmp |
| Climate – maximum temperature | ./HPAT/test\_cases/ Hunza\_test\_case/climate\_ERAi /hunza\_tmx |
| Climate – minimum temperature | ./HPAT/test\_cases/ Hunza\_test\_case/climate\_ERAi /hunza\_tmn |
| Observation data (3 inputs) | ./HPAT/test\_cases/ Hunza\_test\_case/observation\_data/CCHF\_gage\_Hunza-flow.txt  *Note: The longitude is 74.3716 and the latitude is 35.9279.*  ./HPAT/test\_cases/ Hunza\_test\_case/observation\_data/MOD10A2\_hunza\_area\_wgt/MOD10A2.A2000057.hunza.areawgt.nc  *Note: Set MODIS analysis method to “interp”.*  ./HPAT/test\_cases/ Hunza\_test\_case/observation\_data/ Bolch\_Aster\_KH9\_1999thru2009/dDEM\_AST-SRTM\_geo\_30.asc  *Note: Geodetic options include “interp”, “elev”, density of “850”, start date of “16/02/2000”, and end date of “30/09/2007”.*  *Note: The model will create a file called “*./HPAT/test\_cases/Hunza\_test\_case/observation\_data/*CCHF\_formatted\_observations-geodetic-flow-casi.txt” that can be selected in future model runs to avoid needing to enter the coordinates. When using only this observation file, set the parameter “nGage” to 1.* |

# Hydrologic Model Calibration

The internal hydrologic model used in HPAT – CCHF – must be calibrated before HPAT can be used to simulate run-of-river hydropower potential. Calibration is initiated by running HPAT with “runType” set to ‘calibrate’ in the user inputs section of the HPAT main script (Table 2). Calibration requires running CCHF many thousands of times and is therefore very computationally expensive. It is therefore recommended that calibration is performed on a small geographic area within the overall spatial domain of interest. For example, calibration performed on a high-end desktop computer with four cores using a daily time step for ten years and a grid that is 100 by 200 may take close to two days. The output of calibration is a file with the best performing parameter sets (“coefficients\_fittest.txt”) that can be used during subsequent simulation or validation model runs.

Multiple disjointed sites with observation data can be simultaneously used to calibrate the model by converting the user input “region” to a cell-array of site names (for example “region = {‘Site1’, ‘Site2’}”). This will cause the model to prompt the user to locate multiple sets of input data.

The default optimization routine is based on Adaptive Particle Swarm Optimization (APSO) (Zhi-Hui Zhan, 2009). When APSO is selected, Monte Carlo analysis is used to create a basic map of the parameter space. After Monte Carlo has completed, APSO is initiated to identify an optimum. APSO is more robust than many other stochastic optimization schemes.

Several outputs will be generated during calibration, which will be written to a subfolder called “./model\_runs”. The prefix of the output folder will be “calibrate\_”. Some of the outputs are:

* “coefficients\_fittest.txt”: text file containing the best-fitting set of model parameters. This file is used in any validation or simulation model runs to set the model parameters.
* “100\_parameter\_sets-stage\_[X].csv”: Text file containing the 100 best-fitting sets of model parameter values for stage X. This file can be used during simulation mode in order to simulate hydrologic and hydropower conditions for each of the sets of parameters (e.g. to assess equifinality or other uncertainties related to model parameter selection).
* “coefficients\_fittest\_parameter\_plot.png”: Graphical representation of best fitting model parameters with respect to the search space for each parameter.
* “parameter\_each\_gen.txt”: Text file containing the best-fitting set of model parameter values during each generation of calibration.
* “./[region name]/model\_performance.txt”: Hydrologic model performance relative to input calibration data for a specific region. Several metrics are computed, including the Kling-Gupta Efficiency (KGE) value (Gupta et al., 2009) and mean absolute error (MAE).
* “./mod\_v\_obs\_plots”: subfolder containing time-series and scatter plots comparing calibration data and model output.

*As noted above, the “coefficients\_\*\_fittest.txt” file is important because the user will be prompted to select it during any validation or simulation model runs.*

# Validation and Simulation Modes

HPAT can be run in validation or simulation modes if a file containing a calibrated set of model parameters is available. The primary difference between these two modes is that “validation” mode utilizes available observation data to assess model performance, while “simulation” mode does not. Therefore, simulation mode must be used for all future simulations or when the user does not possess observation data to assess model performance. Much larger spatial and temporal domains can be used during validation or simulation runs relative to calibration runs because the model only evaluates once instead of thousands of times (as is the case during calibration).

# Model Output and Custom Hydropower Statistics

HPAT outputs information to highlight various attributes of the site being modelled. For example, by default CCHF outputs plots showing spatially-averaged snowfall and rainfall for the evaluation period. HPAT outputs several gridded files related to run-of-river hydropower potential. The hydropower statistics that are calculated and written to file can be edited to meet needs of specific projects, as described below.

A few of the outputs and corresponding file locations are:

* “processing\_log\_[time stamp].txt”: Text file with all content written to the command window during the model run.
* “./model\_output\_plots”: Subfolder containing all time-series plots produced by the hydrologic sub-model.
* “./hydropower\_stats”: Subfolder containing all files related to hydropower statistics written by HPAT.

Estimation of run-of-river hydropower potential is conducted in the subroutines titled “power\_potential” and “power\_quality”, which are called within the function “HPAT\_implement”. By default, “power\_potential” calculates average power (Watts), power density (Watts / horizontal length along flow path), standard deviation of power (Watts), power stability (unitless).[[2]](#footnote-2) “power\_quality” simply multiplies power density and power stability (Watts / distance). “power\_quality” is therefore a weighting of the average power at a location and how stable the power is seasonally. Other statistics of interest to a user can be implemented by editing these functions or adding a new analysis function to this section of “HPAT\_implement”. For example, a user can program a statistic to estimate streamflow or run-of-river hydropower potential corresponding to a certain non-exceedance probability or could find the day of the year with peak streamflow.

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1. thomas.mosier@inl.gov [↑](#footnote-ref-1)
2. See Mosier et al. (2016a) for a description of the default hydropower statistics. [↑](#footnote-ref-2)