Raven:
User's and Developer's Manual v3.0

the Raven development team

Contributions to Raven, its utilities, documentation, testing, and source code, have been made by numerous students and faculty at the University of Waterloo and elsewhere, including Erfan Amiri, Richard Arsenault, Nandita Basu, Genevieve Brown, Rob Chlumsky, Sarah Grass, David Huard, Susan Huang, Ayman Khedr, Konhee Lee, Stuart Pearson, Silvie Spraakman, Graham Stonebridge, Connor Werstuck, and Cloud Zhang. Andrew P. Snowdon contributed much to the early library of hydrologic process algorithms, and to the global numerical solver. Juliane Mai has provided Mac/Linux compilation support and extensive NetCDF gridded data support. Martin Serrer from NRC contributed to the I/O design, code optimization, and interfacing tools. Wayne Jenkinson from NRC and Georg Jost from BC Hydro have provided debugging, benchmarking, and planning support, particularly for the UBCWM emulation. The base software architecture and much of the core program was developed by James R. Craig at the University of Waterloo, with support through multiple conversations with Drs. Eric Soulis and Bryan Tolson.

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Chapter 1

Introduction

This document describes the design and operation of the Raven hydrologic modelling framework, a software package for watershed modeling. The document is meant for both users of the software who wish to run the program and understand the multitude of model options and by new developers of the Raven software who wish to understand, customize, and/or upgrade the code (chapters and sections for developers are marked with an asterisk*).

Raven is a mixed lumped/semi-distributed model that can be used to understand the hydrologic behavior of a watershed and assess the potential impacts of land use, climate, and other environmental change upon watershed properties such as flood potential, soil water availability, or groundwater recharge. The model can be used to investigate individual storm events or develop long-term water, mass, and energy balances for resource management and water quality assessment. Raven's uniqueness primarily comes from its numerical robustness and its flexibility; Raven is able to use a wide variety of algorithms to represent each individual component of the water cycle and has a quite general treatment of every possible model option, from output access to numerical simulation algorithm. Because of its modular design, users have access to a number of different methods of interpolating meteorological forcing data, routing water downstream, representing evaporation, and any number of other model options. With this flexibility, a modeler can examine the wide range of possible outcomes that result from our uncertainty about a watershed model, and test hypotheses about watershed function.

In addition, Raven's flexibility and large library of user-customizable subroutines allow it to emulate (and augment) a number of existing hydrologic models. Raven has achieved level 1 (near-perfect) emulation of the UBC Watershed Model (Quick, 1995), Environment Canada's version of the HBV model (Bergstrom, 1995), HMETS (Martel et al., 2017), MOHYSE (Fortin and Turcotte, 2006), and GR4J (Perrin et al., 2003). Level 2 (conceptual) emulation is available for various algorithms used which are comparable to those found in (e.g.,) Brook90, SWAT, VIC, PRMS, HYMOD, and/or described within various hydrology texts, such as Dingman's *Physical Hydrology* (Dingman, 2002).

1.1 Model Abstraction

While much of Raven's operations are generic and flexible, they are all built up from critical assumptions about the organization and operation of a watershed. These collectively form the core structure of any Raven model, which is depicted in figure 1.1. A watershed is here assumed to be assembled from a number of subbasins, which in turn are assembled from a number of contiguous or non-contiguous hydrologic response units (HRUs), defined as areas with hydrologically unique responses to precipitation events.

Each HRU is defined by a single combination of land use/land type (LU/LT), vegetation cover, and terrain type and is underlain by a defined soil profile and stratified aquifer. Membership in these classification schemes, or property classes, is used to determine all or part of the physically-based properties of the response unit, such as soil conductivity or leaf area index. Each HRU is composed of a finite number of storage compartments, such as the soil, canopy, and snowpack, in which water and energy are stored (see table 1.1). Given some set of user-specified controlling hydrologic processes (see table 1.2), Raven builds and solves the resultant zero- and 1-dimensional water and energy balance problem for each HRU, redistributing water within the HRU in response to precipitation and other atmospheric forcings. Some of this water is redistributed to surface water channels associated with the subbasin, where it is routed downstream from subbasin to subbasin. During this simulation process, diagnostics about water/mass/energy storage distribution, cumulative flux, and instantaneous fluxes may be tracked.

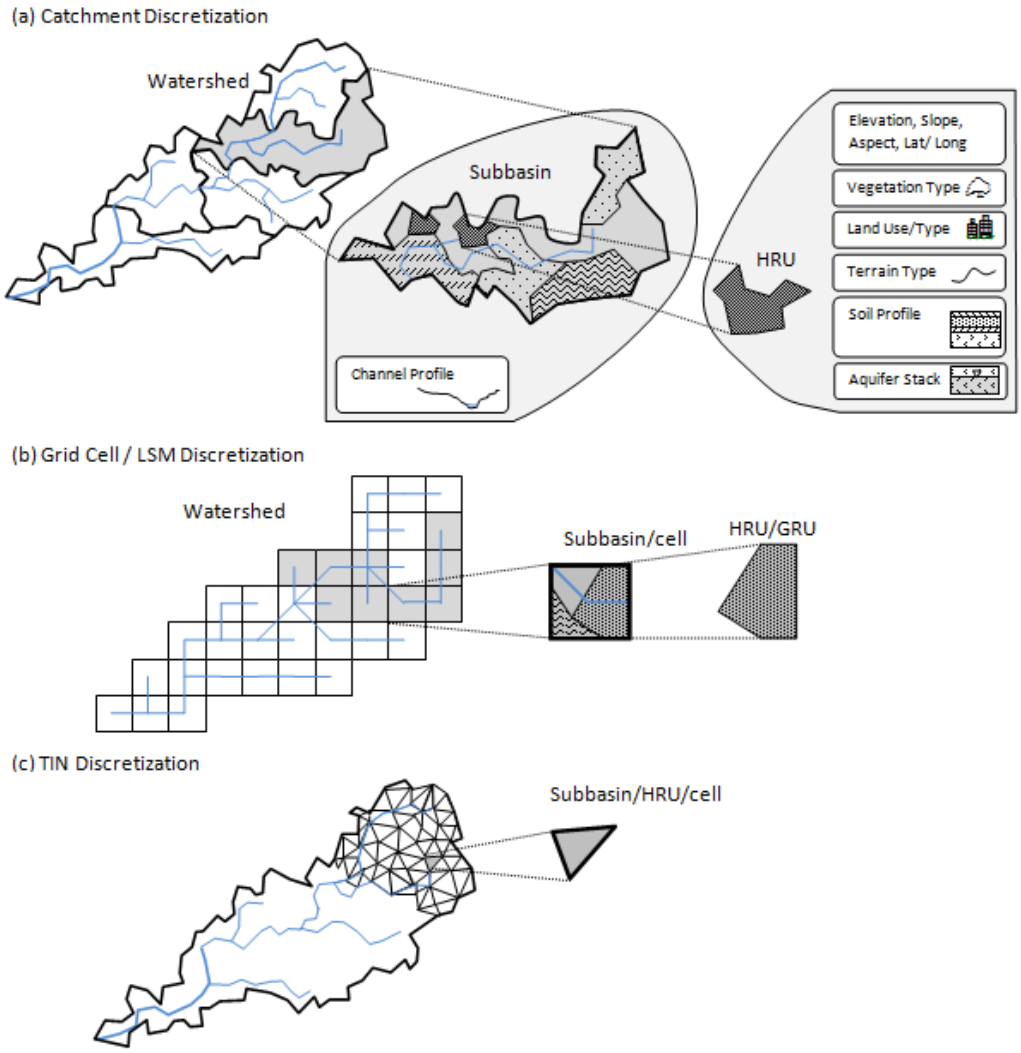

Figure 1.1: Land surface partitioning in Raven

Each HRU is wholly defined by its geometric properties (area, latitude, longitude, parent subbasin), topographic properties (slope, aspect), subterranean soil profile, and its property class membership (land use, vegetation, terrain). Each soil horizon in the soil profile and the aquifer in turn belong to a soil property class. All individual HRU properties are assigned based upon membership in these classes, i.e., most of the properties belong to the class, not the HRU, enabling the solution of a finely discretized model (>10,000 HRUs) without generating an equally large number of unknown parameters.

surface(ponded water)	surface(lakes and streams)	atmospheric
shallow soil	deep soil	groundwater aquifer
frozen snow	liquid snow	canopy
glacial ice	glacial melt	wetlands

Table 1.1: Common storage compartments that correspond to state variables in hydrologic models - each compartment can store both water and energy (a non-comprehensive list)

precipitation	runoff	evaporation	transpiration
drip	trunk drainage	canopy drainage	interflow
throughfall	infiltration	recharge	capillary rise
snowmelt	sublimation		glacial melt

Table 1.2: Common hydrologic processes that may be included in a Raven model

As a generalization of standard methods used to represent shallow soils in hydrologic models, the shallow subsurface may be represented by one or many discrete layers, which is generated from the specified soil profile, as shown in figure 1.2. The soil profile, specified for each HRU, describes the thickness and soil type of each constituent horizon. Soil parameters for the M-layer soil model (e.g., hydraulic conductivity) are then determined based upon soil class membership of each soil horizon, aggregated or disaggregated depending upon desired vertical model resolution. Alternatively, the soil layers may correspond to conceptual soil moisture stores not explicitly linked to physical soil horizon, as is done in many lumped watershed models.

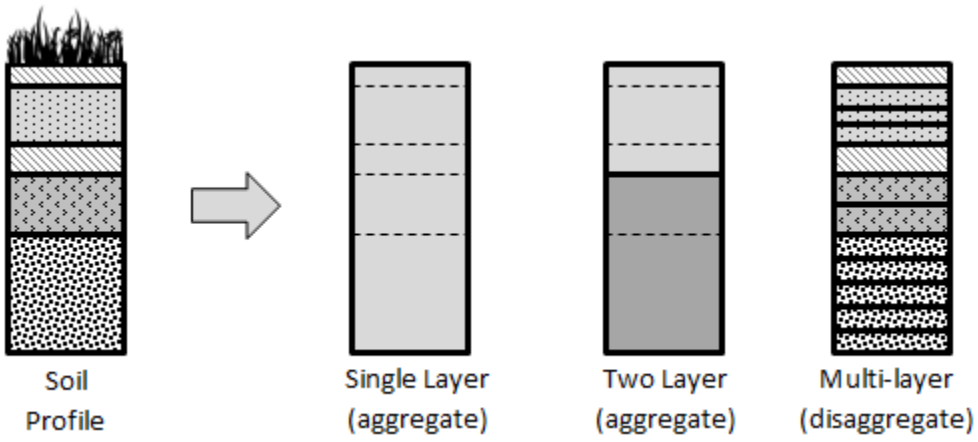

Figure 1.2: Translation of soil profiles to soil models. Properties are aggregated or disaggregated depending upon specified vertical resolution of soil model

Subbasins are similarly succinctly characterized by their channel characteristics, their topology with respect to other subbasins (i.e., their outlet basin) and their cross-sectional profile. Again, properties are linked to channel and profile types, so finely discretized distributed models may still be parsimonious in terms of parameters.

With Raven, unlike other models, the modeler determines the degree of model complexity. At the simplest, a watershed can be treated as a single giant HRU/subbasin where only daily precipitation and temperature are needed to provide predictions of streamflow. In the other extreme, the model could be composed of thousands of HRUs consisting of tens of individual storage compartments and forced using measured hourly longwave radiation, wind velocity, and air pressure. The complexity of the model is limited by the

user or (even more sensibly) the availability of data.

While the various components of the HRU water balance are user-specified, an example schematic of the flow of water in a single HRU can be seen in figure 1.3.

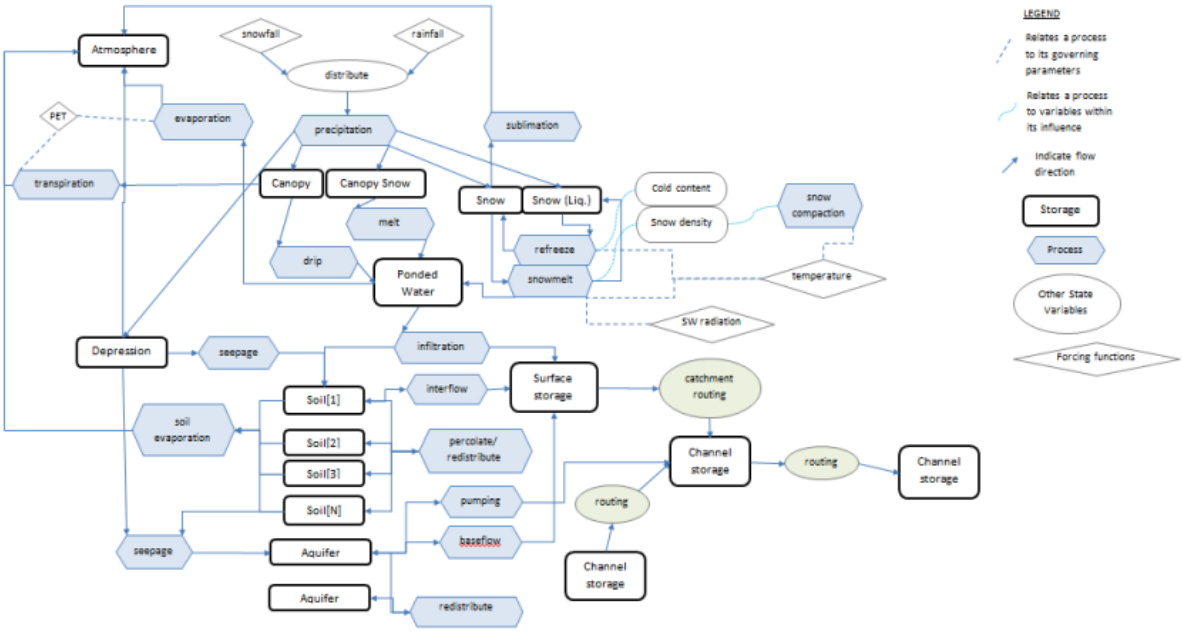

Figure 1.3: Example flowchart of the water balance in a Raven model. Note that individual processes and storage compartments may be added or subtracted from this schematic.

1.2 Global Numerical Algorithm

The operation of Raven is fundamentally simple. Starting from some initial state of the watershed, the model moves forward in time, updating the distribution of water, mass and energy both within and between HRUs in response to physical forcings such as precipitation, and laterally routing water and energy downstream to the watershed outlet. The entire system is simulated one timestep at a time. During each timestep, the following sequence of events occur:

1. The forcing functions are updated, i.e., the representative values of rain and snow precipitation, temperature, and perhaps wind velocity, longwave radiation, etc. are generated or extracted from user-specified time series at a (relatively small) number of gauge stations, then interpolated to every HRU in the model. Alternatively, these functions may be specified as a gridded model input from a regional climate or weather model.
2. All of the model parameters which change in response to the current state of the system are updated in each HRU (for example, canopy leaf area index may be updated with the seasons)
3. Using these updated forcing functions and parameters, the state of the system at the end of the timestep is determined from the state of the system at the start of the timestep by rigorously solving the coupled mass and energy balance equations in each HRU in the model. These mass and energy balances are assembled from the relevant hydrologic processes occurring in the HRU, which individually redistribute water and energy between different compartments (e.g., the evaporation process may move ponded water to the atmosphere).
4. If needed, advective and dispersive mass transport of constituents (contaminants or tracers) is simulated using the water fluxes over the time step.
5. Runoff from the HRUs (and mass/energy associated with this runoff) is routed into the surface water network in each subbasin, and concurrently routed downstream.
6. Mass/Energy balance checks are performed
7. Output is written to a number of continuous output files

The process is repeated until the model has been run for the specified duration.

1.2.1 The HRU Mass/Energy Balance

The problem being solved by Raven within each HRU is fundamentally that of a coupled system of ordinary and partial differential equations (ODEs and PDEs). These ODEs and PDEs individually describe either (1) the accumulation of mass or energy within a given storage compartment or continuum (i.e., a mass or energy balance) or (2) the temporal change in some auxiliary system property (e.g., snow density or albedo).

Here, each state variable in an HRU is subject to the influence of a number of hydrologic processes. Increases or decreases in a primary state variable are simply the additive combination of influx or outflux terms (i.e., the ODE or PDE corresponding to a primary state variable is built up from mass or energy balance considerations). Increases or decreases in auxiliary variables are likewise assumed to be written as the additive combination of terms. We can therefore write an individual differential equation for the change in the j^{th} state variable, ϕ_j, as:

$$\frac{\partial \phi_j}{\partial t} = \sum_{k=1}^{NP} \sum_{i=1}^{NS} M_{ij}^{k}(\vec{\phi}, \vec{P}, \vec{F}) \tag{1.1}$$

where M_{ij}^k is the change in state variable j due to process k (of NP processes), which is linked to another state variable i. This linkage typically communicates flow direction, e.g., a process M_{ij}^k moves mass or energy from storage compartment i to compartment j. A process M_{ii}^k (i.e., $i = j$) represents an independent rate of change for an auxiliary variable, and does not connotate exchange of mass or energy between compartments. The fluxes or rates-of-change returned by each process are a function of the current vector of state variables ($\vec{\phi}$), system parameters ($\vec{P}$), and forcing functions $\vec{F}$. For example, the mass balance for ponded water on the land surface (depression storage, DS) may be given as:

$$\frac{\partial \phi_{DS}}{\partial t} = P - E - I - R \tag{1.2}$$

where P is the precipitation input, E is the evaporation rate, I is the infiltration rate into the soil beneath, and R is the overflow rate of the depression. Each of these processes (M^k) may be a function of a number of forcings (e.g., precipitation and temperature), current state variables (e.g., ponding depth and soil saturation), and parameters (e.g., maximum depression storage and soil hydraulic conductivity).

The full system of equations describing the influence of all processes in an HRU can be written in matrix form:

$$\frac{\partial \vec{\phi}}{\partial t} = \mathbf{M}^G(\vec{\phi}, \vec{P}, \vec{F})\{1\} \tag{1.3}$$

where $\vec{\phi}$ is the complete vector of state variables, $\mathbf{M}^G$ is a NSxNS global symmetric matrix of composite rate-of-change functions, where NS is the number of state variables, and $\{1\}$ is a column vector filled with ones. The global process matrix is the sum of contributions from each individual symmetric process matrix, i.e., $\mathbf{M}^G = \sum \mathbf{M}^k$.

The above mathematical formulation enables the complete separation of individual hydrologic process algorithms, which may individually be very simple or quite complicated. It also enables the use of a variety of methods for solving the global system of equations defined by 1.3. Because of the approach used to solve this system, mass balance errors are typically on the order of machine precision.

1.2.2 Routing

Raven separately handles in-catchment routing (from the HRU to the major reach in the subbasin) and in-channel routing (in and between subbasin stream reaches). The concept is depicted in figure 1.4.

In-catchment routing to the primary basin channel is generally handled using a convolution or unit hydrograph (UH) approach, where the UH for each catchment is either user-specified or generated from basin characteristics. The immediate history of quickflow, interflow, and baseflow output to surface water is stored in memory as an array of time step-averaged outflow rates to off-channel tributaries, $\vec{Q}^{lat}$; the duration of this history is determined by the subbasins time of concentration, t_c. To transfer this water to either the channel segments within the subbasin or directly to the subbasin outflow, the pulse hydrograph is convolved with the unit hydrograph, represented as a piecewise linear function. Water and energy is transferred to the downstream ends of channel segments within the reach.

In-channel routing, for each time step, is assumed to be completely characterized by a finite history of upstream inflow (stored as a vector of flow values at fixed time intervals of Δt, $\vec{Q}^{in}$), and the outflow at the start of the time step; the duration of this history is determined by the minimum flood celerity and the length of the reach segment. During each time step, moving from upstream to downstream at both the watershed level (basin to basin) and subbasin level (reach segment to reach segment), a routing algorithm is used to generate the outflow from each reach based upon the time history of upstream inflows, i.e.,

$$Q_{out}^{n+1} = F_{route}(Q_{out}^n, \vec{Q}^{in}, \vec{P}_s) \tag{1.4}$$

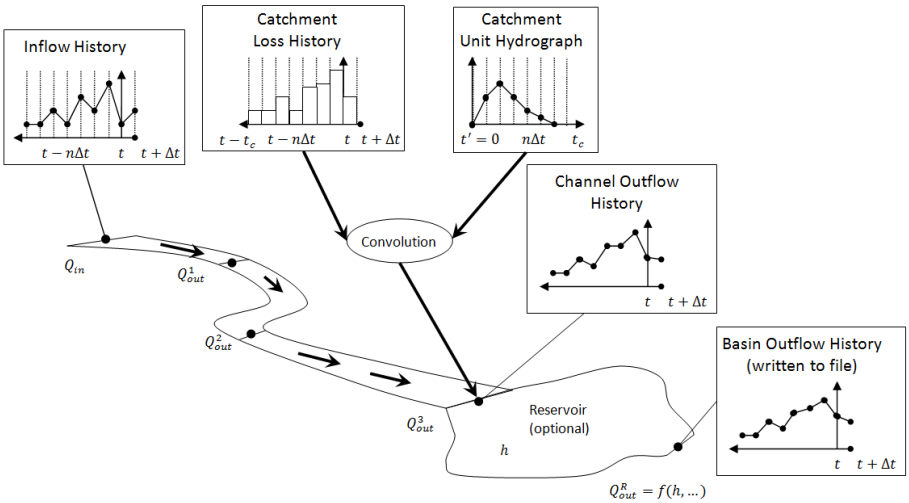

Figure 1.4: The general routing model of RAVEN

where F_{route} is the routing algorithm, $\vec{P}_s$ is a vector of channel parameters, typically a number of stored channel rating curves, primary channel and bank roughness, and, if applicable, weir or reservoir relationships. This formalization supports both common lumped and distributed flow routing methods depending upon the form of $F_{route}()$, including Muskingum-Cunge, lag-and-route, transfer function/unit hydrograph convolution, and, if desired, a more complex kinematic wave or diffusive wave approach (not currently implemented). Notably, sub-time-stepping for routing is also enabled with this formulation.

Reservoir/lake routing. At the outlet of each subbasin, the option exists to specify a managed reservoir or natural lake which mediates the outflow from the subbasin channel. This reservoir is characterized using specified volume-stage and surface area-stage relationship, and level-pool outflow from the reservoir may be calculated using a variety of methods, including simple weir formulae to complex reservoir management rules. The mass balance within the reservoir is calculated as

$$\frac{dV(h)}{dt} = Q_{in}(t) - Q_{out}(t,h) - ET(A(h)) + P(A(h)) \tag{1.5}$$

where $V(h)$ is the stage (h) dependent volume of the reservoir, Q_{in} is the inflow to the reservoir, $Q_{out}(t,h)$ is the outflow from the reservoir (a function of stage), and ET and P are the evapotranspiration from and precipitation to the reservoir surface, both functions of surface area.

Irrigation demand, diversions, and plant discharges Man-made extractions and injections of water are incorporated directly into the mass balance formulations at reach inflows, reach outflows, or reservoirs in the form of user-specified time series of discharge and/or rule curves. These can be constrained by environmental minimum flows.

1.3 Watershed Conceptual Model

The critical feature of RAVEN is that it does not make any assumptions about the functioning of the watershed. That is the modelers job. There is no single system conceptualization that is forced upon the modeler, other than those imposed by the Subbasin-HRU model framework. Rather, the modeler determines what processes to use, how to parameterize the watershed, how to discretize the watershed. All the while, RAVEN makes this easy to do by providing reasonable defaults, an intuitive file interface, and

a large library of hydrologic and algorithmic options. In addition, it allows users to assess the utility and appropriateness of their conceptual model and revise it as needed.

1.4 Citing Raven

The preferred citation for the Raven hydrological modelling framework in a research manuscript or technical report is the following paper in Environmental Modelling and Software:

> Craig, J.R., G. Brown, R. Chlumsky, W. Jenkinson, G. Jost, K. Lee, J. Mai, M.Serrer, M. Shafii, N. Sgro, A. Snowdon, and B.A. Tolson, Flexible watershed simulation with the Raven hydrological modelling framework, Environmental Modelling and Software, 129, 104728, doi:10.1016/j.envsoft.2020.104728, July 2020

To cite Raven technical details for technical reports, this manual may be cited as:

> Craig, J.R., and the Raven Development Team, Raven user's and developer's manual (Version 3.0), URL: http://raven.uwaterloo.ca/ (Accessed xxx, 2020).

If you are using a model emulation housed within Raven, then that model configuration should be explicitly cited to give credit where credit is due. For instance, if you use the unmodified UBC watershed model configuration from appendix D, the preferred citation format would be (e.g.,) "we used the UBC Watershed Model (Quick, 1995) as implemented in the Raven hydrologic modelling framework v3.0 (Craig et al., 2020)". If the base conceptual model was significantly revised and/or merged with other tools, then it may be acceptable to refer to the model as (e.g.,) UBCWM* or UBCWM-Raven. In all cases, it is recommended to provide the model version number and input files in supplementary material so the details and attribution of the model components may be identified.

Chapter 2

Running Raven

Much energy has been expended to ensure that the operation and use of Raven is as simple, convenient, intuitive, and user-friendly as possible. Model commands and file formats are in plain English, error messages are reasonably concise and explanatory, unnecessary restrictions or requirements are not forced on the user, and model input and output files can be read and understood with a minimal learning curve. There may be, however, a learning curve in familiarizing oneself with the large variety of modelling options and how they differ.

2.1 Installation

There is no formal installation package for Raven without NetCDF support, and no special programs are libraries are required to operate Raven. Simply download the Windows, Mac, or linux executable `Raven.exe` and unzip to a local drive. Mac users should note that despite the .exe extension, the program runs just like any other command line tool.

Only if you are using the Raven version with NetCDF support (i.e., for supporting gridded forcing data such as that generated in regional climate forecasts):

- For Windows users, you will have to install the NetCDF 4 Library (without DAP) from https://www.unidata.ucar.edu/software/netcdf/docs/winbin.html. You then must ensure that the the directory path of the installed NetCDF.dll file is in your PATH environment variable. Documentation for modifying the PATH environmental variable is readily found online for your specific version of windows.
- For MacOS and linux users, look to https://www.unidata.ucar.edu/software/netcdf/docs/getting_and_building_netcdf.html to download and build the NetCDF libraries, or run from CYGWIN.

2.2 Input Files

In order to perform a simulation using Raven, the following five input files are required:

- `modelname.rvi` - the primary model input file
  This is where the primary functioning of the RAVEN model is specified. This includes all of the numerical algorithm options (simulation duration, start time, time step, routing method, etc.) and model structure (primarily, how the soil column is represented). Critically, the list of hydrologic processes that redistribute water and energy between storage compartments is specified here, which define both the conceptual model of the system, the specific state variables simulated, and the parameters needed. Lastly, various options for output generation are specified.

- `modelname.rvh` - the HRU / basin definition file
  The file that specifies the number and properties of subbasins and HRUs, as well as the connectivity between subbasins and HRUs. Importantly, land use/land type, vegetation class, aquifer class, and soil classes are specified for each HRU in order to generate appropriate model parameters to represent the properties of each HRU.

- `modelname.rvt` - the time series/forcing function file
  This file specifies the temperature, precipitation, and possibly other environmental forcing functions at a set of observation points ("gauges") within the model domain. This information is interpolated to each HRU within the watershed based upon spatial location. The .rvt file typically "points" to a set of files storing information for each gauge or forcing type. If gridded forcing data is used, the details about the corresponding NetCDF gridded data file and connections between the grid and landscape are specified here.

- `modelname.rvp` - the class parameters file
  This is where most of the model parameters are specified, grouped into classes. Each HRU belongs to a single vegetation class, single land use, single aquifer class, and has a unique soil profile defined by a collection of soil horizons each of a single soil class. All model parameters, on a class by class basis, are specified here. The class formalism aids in the calibration process. Note that the `:CreateRVPTemplate` command can be used to generate an empty .rvp file given the model configuration specified in the .rvi file (see appendix for details).

- `modelname.rvc` - the initial conditions file
  This is where the initial conditions for all state variables in all HRUs and subbasins are specified. This may be generated from the output of a previous model run. If a blank file is provided, all storage initial conditions are assumed to be zero (i.e., no snow, dry soil, etc.) and a run-up period will be warranted.

Each of these files are described in detail in appendix A. While the .rvi (setup), .rvh (watershed geometry), .rvc (initial conditions) and .rvt(forcing data) files are typically unique to a particular model, the .rvp (properties) file may ideally be ported from one model to another. Figure 2.1 depicts the base input used by and output generated from Raven, where the default/mandatory files for all simulations are indicated in light blue.

To prepare the input files, it is recommended to first familiarize yourself with the format and various input options. A number of pre-processors have been or are being developed to generate the .rvt file(s) from alternative formats. For instance, Environment Canada stream gauge data may be imported with utilities in the RAVENR package. The .rvh file is likely best prepared with the assistance of a healthy GIS database which can be used to determine unique class combination and the topology of the watershed subbasins. Note that, if the size of .rvt or .rvh files becomes unwieldy, the `:RedirectToFile` command can be used to redirect the input from an 'extra' input file, so a model could, for instance, have a single master .rvt file that points to a number of meteorological forcing files (e.g., one or more .rvt file per gauge). A similar approach also enables the testing of multiple climate scenarios without having to overwrite data files.

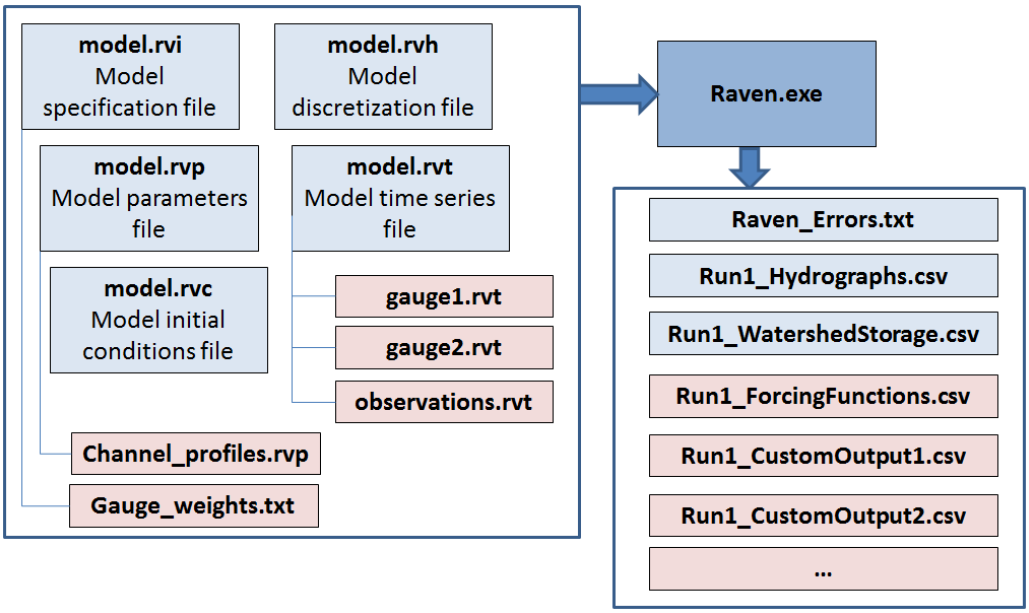

Figure 2.1: Standard input/output configuration of Raven. Light blue input files are required, light blue output files are the default output (which may be suppressed if desirable). The light red input files are files referred to by the primary input files, and are kept separate mostly for organization. The light red output files are generated only if specifically requested by the user in the .rvi file.

2.3 Running the Model

Once all of the necessary components of the above files have been created, the model may be called from the command line, e.g., in the windows command prompt,

```
> C:\Program Files\Raven\Raven.exe C:\Temp\model_dir\modelname
```

or, if the active directory is `C:\Temp\model_dir\`:

```
> C:\Program Files\Raven\Raven.exe modelname
```

where 'modelname' is the default predecessor to the .rvi, .rvh, .rvt, and .rvp extensions. There are no special flags needed, just the name of the model. The command line also supports the following flagged commands:

- `-o {output directory}` : specifies the directory for generated model output
- `-p {rvp_filename.rvp}` : specifies the rvp file location
- `-t {rvt_filename.rvt}` : specifies the rvt file location
- `-c {rvc_filename.rvc}` : specifies the rvc file location
- `-h {rvh_filename.rvh}` : specifies the rvh file location
- `-r {runname}` : specifies the run name for the simulation

Alternatively, the `:OutputDirectory` command in the .rvi file may be used to specify file output

location and the `:rv*_Filename` command may be used to specify the corresponding files (see the details in appendix A.1).

A useful application of the output directory flag is to specify an output directory in the folder directly beneath the working directory, for instance:

```
> C:\Program Files\Raven\Raven.exe modelname -o .\output\
```

RAVEN will create this specified output folder if it does not exist.

Note that while it is allowed that the input files from multiple models exist in a single folder, it is recommended that each model get its own output directory to avoid overwriting of outputs.

For MacOS users, note that the Raven.exe, despite its .exe extension, runs like any other command line tool. This can be run by opening the `terminal` application. The only difference then is the use of forward slashes rather than backward slashes, e.g.,:

```
machine:~ username$ Raven.exe modelname -o ./output/
```

2.4 Output Files

RAVEN generates a number of customizable outputs which contain model diagnostics. By default, RAVEN generates the following files:

- `Hydrographs.csv` - the hydrograph output file
  Contains the flow rates, $Q(t)$ [m^3/s], at the outlets of specified subbasins in the watersheds (usually corresponding to those with stream gauges). Which subbasin hydrographs are reported is specified in the .rvh file.
- `WatershedStorage.csv` - the watershed storage file
  Contains watershed-averaged water storage in all of the modeled compartments over the duration of the simulation. Also reports watershed-wide water mass balance diagnostics.
- `solution.rvc` - the solution file
  Stores the complete state of the system at the end of the simulation. This file can be used as initial conditions for a later model run. This file may also be generated at user-specified intervals during simulation as a defense against computer breakdown for massive computationally-demanding models.
- `RavenErrors.txt` - the errors file
  Includes all of the warnings and errors for a particular model run, including when the model may be making choices on behalf of the modeler (i.e., parameter autogeneration) or when model input is flawed.

The formats of these files are described in appendix B, and may be pre-appended with the runname if the `:RunName` command is used, generating (for example), `Alouette41_Hydrographs.csv` if the run name is Alouette41. `RavenErrors.txt` is never given a prefix.

In addition to the above, the following output files may be created on request:

- `WatershedMassEnergyBalance.csv` - the watershed flux diagnostics file
  Contains watershed-averaged water and energy fluxes from each hydrologic process over time. (enabled using the `:WriteMassBalanceFile` command)
- `ForcingFunctions.csv` - the forcing functions file
  Stores the complete time series of all watershed-averaged forcing functions over the domain (i.e., rainfall, snowfall, incoming radiation, etc.) (enabled using the `:WriteForcingFunctions` command)
- `Diagnostics.csv` - model quality diagnostics
  Reports metrics characterising of fit between the model results and any user-specified observations. This output is enabled using the `:EvaluationMetrics` command, and requires at least one set of observation data (`:ObservationData` in the .rvt file) to be generated.
- `ReservoirStages.csv` - reservoir stage history file
  Stores the time history of reservoir stages for all simulated reservoirs. Requires at least one reservoir in the model and is automatically generated if reservoirs are present.
- `ReservoirMassBalance.csv` - reservoir mass balance history file
  Stores the time history of reservoir inflows and outflows for all simulated reservoirs. Requires at least one reservoir in the model.
- `Demands.csv` - irrigation demands file
  Stores the time history of irrigation, environmental flow constraints, and unmet demand
- `ExhaustiveMB.csv` - exhaustive mass balance file
  Stores all state variables in all HRUs over time. Given the potential size of this file, this option should be used sparingly (enabled using the `:ExhaustiveMassBalance` command.)
- State (`.rvc`) files - model intermediate state files
  Similar to solution.rvc, except output at intermediate times specified using the `:OutputDump` or `:MajorOutputInterval` commands. The files are named using the output timestamp, e.g., `RunName_state_2001-10-01.rvc`, and may be used as initial conditions for later simulation runs.

Lastly, the extremely flexible `:CustomOutput` command can be used to indicate that Raven should track and store in .csv, NetCDF, or .tb0 flat files any user-specified parameter, state variable, or mass/energy flux in the model over time. This data may be aggregated either temporally or spatially, so that the user may generate files containing, e.g., basin-averaged hydraulic conductivity of the top soil layer at the daily timescale, or monthly averaged evaporation from the canopy in the 23rd HRU. The details of this custom output are in the discussion of the `:CustomOutput` command in the .rvi file (appendix A.1.5).

Additional output files generated by the transport routines are discussed in chapter 7.

2.4.1 Alternative .tb0 (Ensim) Output Format

For compatibility with the Green Kenue™ software interface, the option is also available to generate output in .tb0 (Green Kenue™ tabular) format. Custom output will be written to a .tb0 table output file if the `:WriteEnsimFormat` command is present in the .rvi file.

2.4.2 Alternative .nc (NetCDF) Output Format

For compatibility with software based on NetCDF files (e.g., the Deltares FEWS forecasting system) it is also possible to write outputs in that format. The `:WriteNetCDFFormat` command should be present in the .rvi file if the NetCDF output should be written instead of .csv files. Details are documented in appendix B.3.

2.5 Building a Model

Base model: rvi and rvp files
It is recommended that users initially start with an existing model template such as the UBCWM, HBV-EC, HMETS, MOHYSE, or Canadian Shield model configurations reported in appendix app:TemplateFiles. Once you get more experienced with Raven, you may have existing model configurations that you have found work well on similar landscapes to those you have modelled previously.

Template .rvp files can be generated by running the .rvi template file with the `:CreateRVPTemplate` command, which builds a hollow .rvp file with all of the parameters necessary for simulation using the particular model configuration specified in the .rvi file. Reasonable initial parameter values are reported in the appendix, but manual calibration will be required in pretty much all cases.

Landscape discretization: rvh files
The best approach for generating the subbasin delineation and HRU delineation (i.e., the .rvh file) is to use a GIS program such as ArcMap, SAGA, TauDEM or GRASS. These tools enable the generation of basin geometry from a hydrologically conditioned DEM and additionally enable the overlay of map layers to determine HRU areas. Basin outlets should at the very least correspond to locations of known streamgauges, but would also be added at the outlets of hydrologically important lakes and reservoirs, at major stream junctions, or at locations which divide the network into hydrologically similar landscapes (e.g., separating mountains from foothills). HRUs are commonly generated by reclassification of raster- or vector-based land use maps overlain with subbasin boundaries, though these may be additionally overlain with soil maps and/or elevation bands, where appropriate, using a union operation. Slope, aspect, elevation, latitude, longitude, and subbasin membership for each unique vegetation/land use/soil profile parcel would then be determined by spatial averaging and geometric operations within the GIS. Note that HRUs do not have to be spatially contiguous. The mechanics on how this is done vary from application to application. If the resultant HRU map is in vector format, its data table may be exported to a text file then rearranged using any number of text editing, spreadsheet, or scripting tools to be converted to .rvh format. Likely the hardest part to automate here is the specification of subbasin connectivity (i.e., the downstream subbasin ID for each subbasin), which typically would be done by eye.

Initial conditions: rvc file
The simplest initial conditions file can be empty. This can be modified later, but most storage compartments in the model when run in continuous (rather than event or forecasting) mode have a spin-up period that can compensate for an initially dry watershed. Groundwater storage and initial reservoir stage are two notable exceptions that may have to be modified.

Meteorological inputs and observations: rvt files
The populating of the time series (.rvt) file is generally a problem of finding appropriate and available data and converting it to the .rvt format, which is relatively straightforward. Of course, there are many complications arising in infilling missing forcing data, interpreting what data is useful, and determining how to interpolate spatial data. Users can start with a single meteorological gauge initially and readily add or remove meteorological gauges in a minimally invasive manner. The RavenR R library provides a number

of utilities for directly downloading Canadian meteorological and stream gauge data and converting them to .rvt format.

Iterative improvement
Once you get a base model created and running, then you can start swapping out individual processes, moving towards a landscape-appropriate model with complexity justified by the amount of data available at the site. A lot of meteorological data and hydrograph data can justify a quite complex model with finely discretized landscape and more complicated model configuration. Modifying model configuration should be assessed one step a time, confirming each process addition or swapout of forcing function representation lead to a more appropriate or otherwise more effective representation of watershed hydrology. Note that modifying and iteratively evaluating model structure in this way can be a time consuming and arduous process, so many users will choose to stick with a fairly standard model configuration with a few minor tweaks.

2.6 Calibration, Visualization, and Uncertainty Analysis

Unlike many hydrologic modeling tools, the Raven software package intentionally does not include any methods for calibration, uncertainty analysis, plotting, or complex statistical analysis. All of these tools are best addressed using flexible and generic pre-and post-processing tools. Some recommendations:

- RavenR
  A set of R utilities available from the Raven website. Requires the R open-source software environment. Available at: http://www.raven.uwaterloo.ca/RavenR.html
- Ostrich
  A model-independent multi-algorithm optimization and parameter estimation tool. Ostrich can be used to calibrate Raven models, generate Monte Carlo simulations, and much, much more... http://www.civil.uwaterloo.ca/envmodelling/Ostrich.html
- Green Kenue™
  An advanced data preparation, analysis, and visualization tool for hydrologic modellers, which supports some Raven features and provides useful post-processing tools for Raven output as well as direct access to Canadian hydrologic data repositories. Available at https://www.nrc-cnrc.gc.ca/eng/solutions/advisory/green_kenue_index.html
- R
  An open-source software environment for statistical computing and scientific graphics. Available at https://cran.r-project.org/
- mc-stan.org
  An open-source software environment for Bayesian inference and maximum likelihood estimation. Available at mc-stan.org

Note that the model quality diagnostics generated using the `:EvaluationMetrics` command may be utilised to support the calibration process.

2.7 Common Run Approaches

The following section describes suggested methods for running Raven in a mode other than straightforward simulation of a single model with a single set of inputs.

Automated Calibration
Multiple tools are provided within Raven for supporting automatic calibration by other software packages. It is encouraged to use the algorithms within the Ostrich software package, and an example Ostrich-Raven configuration is provided with the Raven documentation. To constrain the calibration, it is recommended to allow Raven to generate the diagnostics used to build the objective function using one or more of the diagnostics described in section 8.2, which supports the provision of observation weights to (1) include a spinup period (2) represent a calibration period (3) represent a validation period (4) discount seasonal (e.g., winter) data during diagnostic calculation.

Other useful commands for calibration support include the ability to suppress all output but the diagnostics file (`:SuppressOutput`) and suppress all console output (`:SilentMode`). This maximizes the speed of repeated model application (output generation can be more than 90 percent of computational cost). Users also have the ability to override historical stream and reservoir flows and replace modeled hydrographs with observed hydrographs at locations within the stream network (`:OverrideReservoirFlow` for reservoirs and `:OverrideStreamflow` for stream gauges). Lastly, portions of the model may be calibrated independently by disabling the remainder of the model using the `:DisableHRUGroup` command.

Large Models
For larger models with considerable data inputs and outputs, it is suggested to lean on the power of the `:RedirectToFile` command to organize the data. For instance, in a large basin model, it is useful to have folders to store the observation data, meteorological gauge data, reservoir, and channel data and keep it separate from the main body of Raven model files. A sample file structure might look like:

```
model folder/
 ./channels/
 ./observations/
 ./output/
    ./run1/
    ./run2/
    ./run3/
 ./metdata/
 ./reservoirs/
 modelname.rvi
 modelname.rvt
 modelname.rvh
 modelname.rvp
 modelname.rvc
```

Multiple Climate Scenarios
For running multiple climate scenarios using a single model, it is recommended to fix the .rvc, .rvp, and .rvh files. Different .rvt files should be generated for the specific climate scenarios. Individual runs would be generated by modifying the rvt filename (using the `:rvtFilename` command in the .rvi file) and the run name (using the `:RunName` command in the .rvi file).

Multiple Parameter Sets
It is common to run a model using multiple parameter sets in order to assess the uncertainty or sensitivity of its predictions to changes in input (as done in, e.g., Markov Chain Monte Carlo). For such an approach,

it is recommended (if not using software such as Ostrich), to generate multiple .rvp files, keeping the remainder of the data files fixed. Individual runs would be generated by modifying the rvp filename (using the `:rvpFilename` command in the .rvi file) and the run name (using the `:RunName` command in the .rvi file).

Forecasting
For forecasting, standard practice would be to hindcast / spin-up the model for a period of time, often prior to winter to properly account for snow depths. The state of the model would be saved at the current date and used as a 'warm start' .rvc file for short-term forecasts fueled by weather forecasts, rather than meteorological gauge data, thus only the .rvt files and .rvc files are changed when moving from spinup to forecast, plus the start date and end date in the .rvi file. The initial state of the model (for instance snow depth, soil moisture, or upstream flows) could be corrected if real-time data are available to compensate for model errors by revising the .rvc state file. Operational choices can be evaluated, for instance, using the `:OverrideReservoirFlow` time series to control reservoir flows.

2.8 Troubleshooting Raven

While Raven will generally try to tell you when a mistake in the input files will cause problems, there are times when the interface will "hang" or input will be noticeably erroneous without providing a warning or error in `RavenErrors.txt` (note that Raven is designed to produce significant errors when something goes wrong rather than subtle undetectable errors). These unchecked errors are most commonly due to missing or erroneous input forcing or parameter data, though it may occasionally be due to a genuine bug in the Raven code.

Always Check the RavenErrors.txt file in the output directory first. Often, the error messages and warnings will contain sufficient information to diagnose and repair the problem. This is always the best first step.

Use the Forum Posting questions and answers to the online Raven forum at (https://http://www.civil.uwaterloo.ca/raven_forum//) ensures the whole community can learn.

The following steps may be taken to diagnose and repair issues with Raven.

1. **If the model 'hangs' prior to the beginning of simulation.**
   Add the command `:NoisyMode` to the .rvi file. This must be after any call to `:SilentMode` (these commands toggle the same internal switch), but ideally at the top of the input .rvi file. Running the code in noisy mode generates detailed narrative output to the command prompt window, and is best for diagnosing errors in input parsing. By looking at where the code "hangs", the problematic input command can often be found. See if the model runs with the problematic command commented out. If it does, there may be (a) improper command syntax or (b) a missing input parameter for the chosen method/algorithm or (c) erroneous input data linked to this method/algorithm that Raven is not currently able to detect.
2. **If the model runs to completion but generates clearly erroneous output** (i.e., NaN or -#inf in the output)
   This type of error is likely due to (a) an error in input which Raven did not detect (e.g, a parameter

outside reasonable bounds like a porosity of 3.8); (b) a missing model parameter which RAVEN did not detect; or (c) an error in the RAVEN modelling library.

(a) Step 1: Open the `ForcingFiles.csv` output file and look for non-sensible numerical values (e.g., negative PET or NaN radiation). These errors in Forcing Functions will propagate through the model and generate hydrograph errors. Comment out or modify the corresponding forcing function commands (catalogued in section A.1.2 of the appendix) until the faulty forcing output not generated. For instance, if the PET is consistently negative, replace the PET estimation or PET orographic correction algorithm with another method. If the errors are fixed, then this may be due to poor parameters which drive this method. If the errors remain, then data which is used to drive PET estimation may be faulty OR one of the other forcing functions which drives PET (such as shortwave radiation, temperature, etc.) is faulty. The latter would also be obvious from a cursory inspection of the `ForcingFiles.csv` output.

(b) Step 2: If the forcing functions are not the culprit, then examine the WatershedStorage.csv file and check for clearly erroneous estimates of watershed-averaged water storage. If, for example, glacial storage looks faulty but everything else is OK, comment out the algorithms which operate on glacial storage in the `:HydrologicProcesses` block in the .rvi file and re-run until the glacial storage results are feasible (perhaps monotonically growing or shrinking, but not NaN or hugely negative). This narrows us down to the problematic process algorithm. Check the documentation to make sure that the proper parameters are provided for this algorithm in the .rvp file for all glacier HRUs. If you still cannot diagnose the problem, first ask questions on the Raven forum (https://http://www.civil.uwaterloo.ca/raven_forum//), then (if needed) send the problematic input files with a short description to jrcraig@uwaterloo.ca.

3. **If the model is providing odd/unexpected output.**
Sometimes generated hydrographs are not completely broken, but are at odds with our expectations. For example, outflows are 10 times larger or smaller than they should be when compared to the observed hydrographs. These issues are much thornier, as they can arise from individually reasonable (but collectively unreasonable) combinations of parameter inputs. They are also quite possible if you are building a model from scratch with RAVEN, and have done so improperly (e.g., RAVEN technically allows you the flexibility to have two evapotranspiration processes, but it is physical nonsense to implement this). There are some general approaches you may take towards debugging this kind of model issue.

(a) Look at the `WatershedStorage.csv` file for clues. Most watersheds should have a quasi-steady state behaviour from year to year; there may be wet years and dry years, but storage in general oscillates and repeats a relatively consistent water balance from month to month. If your model is a continuous model of three or more years, you should expect this type of oscillatory behavior. If you find that one storage compartment is steadily increasing or decreasing in storage, it may be worthwhile to investigate the cause. In many cases, the inflow/outflow processes are not properly matched, e.g., a middle soil storage unit may be filled due to percolation at a much faster rate than it depletes due to baseflow losses, even at the annual scale. Another possible symptom that may be seen in the `WatershedStorage.csv` file is a storage compartment which always fills but never drains (or the opposite). Some storage units are intended to have this behavior, such as `ATMOS_PRECIP` (which is always a water source, and is a proxy for cumulative precipitation) and `ATMOSPHERE` (which is always a water sink, and is a proxy for cumulative evapotranspiration losses). Others, such as deep `GROUNDWATER`, may be used to represent external losses from the system. However, any other storage unit should have means of decreasing and increasing in storage, as determined by the hydrologic process list (each storage unit should act as a "To" and "From" storage unit), and the parameter

lists.

(b) Look at the ForcingFunctions.csv file for clues. Again, poor parameter choices can lead to significant underestimates or overestimates of system forcings, which propagate through to hydrographs and other model outputs. Look for reasonable values for radiative, precipitation, and temperature forcings to the watershed. What constitutes "reasonable" is specific to the climate and landscape, and is up to you to define.

(c) Check your stream network topology. The surface water network is fully defined by the list of `DOWNSTREAM_ID`s in the :SubBasins command. If this is improperly constructed, or if the entirety of an upstream watershed is not included in the model, you may need to either correct the stream network or add user-specified inflows to account for upstream parts of the watershed not explicitly included in the model.

(d) Check your cumulative watershed area. The area of each subbasin, and therefore also the total drainage area of each subbasin, is dependent upon the areas of its constituent HRUs. If these areas are incorrect, or if certain HRUs are not included in the model, this can lead to mass balance errors.

(e) Check the units of your forcing functions. A common mistake for subdaily flow information is to supply precipitation in mm rather than as a precipitation intensity in mm/d, leading you to be off by a factor of 24.

4. **Turn on :NoisyMode**
   If the issue is prior to simulation, or if the RavenErrors.txt warnings and errors are difficult to comprehend, adding the `:NoisyMode` and `:EndPause` command to the top of the .rvi file writes an extensive stream of information to the command prompt/console. Occasionally, this can direct you to a bad input command.

2.9 Version Notes

2.9.1 Major Changes from v2.9.1 to v3.0 (May 2020)

The following features have been added:

1. addition of `SW_CLOUD_CORR_ANNANDALE` algorithm for shortwave cloud cover correction
2. competitive ET now supported by all ET algorithms (can suppress for backward compatibility with `:SuppressCompetitiveET` command. AET magnitudes are now directly accessible as state variable in custom outputs. Additional option `:SnowSuppressesPET` can be used to suppress ET when snow is on the ground. New `PET_LINACRE` algorithm for PET estimation.
3. support for simple insertion data assimilation of streamflow with `:AssimilateStreamflow` command
4. new reservoir regulatory support:
   - `:ReservoirMinFlow`
   - `:ReservoirMaxFlow`
   - `:ReservoirDownstreamFlow`
   - `:ReservoirMaxQDecrease`

    - :ReservoirOverflowMode
5. support for irrigation demand and flow diversions:
    - :IrrigationDemand
    - :ReservoirDownstreamDemand
    - :FlowDiversion
    - :FlowDiversionLookupTable
    - :DemandMultiplier
    - :UnusableFlowPercentage
6. support for stage-volume and stage-area curves for lake-type reservoirs and groundwater seepage from reservoirs
7. the :LatFlush command now supports inter-basin lateral water transfer
8. support for period-ending NetCDF inputs using :PeriodEndingNC command and proper handling of NetCDF time zones, offset, and scale attributes
9. support for reference elevations for gridded forcings
10. improved and optimized support for massive stream/lake networks
11. writing of interpolation weights to external file using :WriteInterpolationWeights command
12. major bug fixes: correct handling of diffusive wave hydrograph for basins with very small travel times; using open water ET for reservoir mass balance; glitch in the determination of day-switching which impacts some sub-daily models using daily min/max temperature for estimation of melt energy/PET
13. minor bug fixes; improved QA/QC of inputs

The following backwards compatibility issues were introduced:

1. None

2.9.2 Major Changes from v2.9 to v2.9.1 (May 2019)

The following features have been added:

1. support of user-specified NetCDF attributes
2. support for non-standard calendars
3. support for non-midnight start time with NetCDF forcing
4. minor bug fixes; improved QA/QC of inputs

2.9.3 Major Changes from v2.8.1 to v2.9 (Feb 2019)

The following features have been added:

1. Support for level 1 (exact) emulation of the MOHYSE model (Fortin and Turcotte, 2006); multiple processes added.
2. Support for level 1 emulation of the HMETS model (Martel et al., 2017); multiple processes added.
3. Support for the PAVICs platform
4. Added `PET_OUDIN` PET estimation method and `:DirectEvaporation` support.
5. Added `:AnnualCycle` method for inputting cyclical time series.
6. Integrated multiple algorithms from the Cold Regions Hydrological Model (CRHM) (Pomeroy et al., 2007), including the PET approach of Granger and Gray (1989), the rain snow partitioning approach of Harder and Pomeroy (2013), two snow albedo evolution algorithms, a energy balance potential melt routine and a simple snow balance approach.
7. Support for model simulation start times other than midnight

The following backwards compatibility issues were introduced:

1. Due to a bug in the calculation of UTM zone from HRU latitudes and longitudes, the interpolation schemes for large models with multiple meteorologic gauges had an anisotropic bias (e.g., long, thin nearest-neighbor zones). This has been fixed, leading to a discrepancy between old and new model precipitation and temperature interpolation. This will not impact Raven models using single gauges, NetCDF gridded inputs, or user-specified gauge weights, only those using inverse distance or nearest neighbor interpolation.

2.9.4 Major Changes from v2.8 to v2.8.1 (Jul 2018)

The following features have been added:

1. FEWS-compliant NetCDF custom and standard output (Hydrographs.nc and WatershedStorage.nc)
2. support of deaccumulation of NetCDF input data
3. RAINSNOW_HARDER Rain/snow discrimination
4. fixes to relative file path handling, :VegetationChange/:LandUseChange/lake crest height/target stage bugs introduced in v2.8,

The following backwards compatibility issues were introduced:

1. relative file paths are now (correctly and consistently) with reference to the file specified rather than the model working directory

2.9.5 Major Changes from v2.7 to v2.8

The following features have been added:

1. Documentation improvements/Bug fixes/Improved QA/QC on model inputs
2. Significant speed improvements, particularly with NetCDF processing
3. Wetlands - new wetland HRU type; support for lateral flow to and from geographically-isolated and riparian wetlands; new depression flow and seepage routines for wetland depression storage

4. Lakes and Reservoirs - lake-type reservoirs for natural (unmanaged) run-of-river lakes; time-dependent weir control and rule curves (maximum, minimum, and target stages); spillway and underflow stage-discharge curve specification; advective transport of constituents and tracers through reservoirs; reservoir inflow and net inflow diagnostics; reservoir outflow override; reservoir mass balance reporting;
5. Inter-HRU Flow and Transport - generalized lateral flow support of water between HRUs and lateral advective transport of constituents;
6. Shortwave radiation on sloping surfaces - the default method now uses the robust analytical calculation approach of Allen et al. (2006) for estimating clear sky solar radiation
7. Improved Input/Output - custom flux reporting between/to/from any state variable, mixed gauge interpolation support (i.e., when temperature and precipitation reported at different gauges)
8. Other - HRU/subbasin disabling (only model a subset of the model); subbasin-specific Manning's n and slope; automated HRU group population; optimization and speed improvements (particularly for NetCDF input); running average NSE diagnostics; basin inflow hydrographs at downstream end of subbasin; vegetation-based PET correction; support of date-based net shortwave radiation input forcings;

The following backwards compatibility issues were introduced:

1. None

2.9.6 Major Changes from v2.6 to v2.7 (May 2017)

The following features have been added:

1. Documentation improvements/Bug fixes/Improved QA/QC on model inputs
2. Significantly improved support for flexible reservoir simulation and calibration - time-varying reservoir curves, unevenly spaced reservoir curves,
3. Support for gridded data in NetCDF format (see appendix A.4.6)
4. Improved place- and time-specific control over application of processes using the `:->Conditional` command, `:LandUseChange` command, and `:VegetationChange` command.
5. `:CreateRVPTemplate` command can be used to generate a template .rvp file from specified .rvi model configuration
6. Added a number of new diagnostics (`LOG_NASH`, `NASH_DERIV`, `KLING_GUPTA`)
7. Addition of the GAWSER-style snow balance and consolidation routine
8. Addition of US Army Corps snowmelt model
9. `RunName` can be specified from the command line

The following backwards compatibility issues were introduced:

1. None

2.9.7 Major Changes from v2.5 to v2.6 (May 2016)

The following features have been added:

1. Significant improvements to the Raven Documentation
2. Support for additional model quality diagnostic (R2)
3. Improved support for sub-daily emulation of the UBC watershed model
4. New elevation-based gauge interpolation algorithm (`INTERP_INVERSE_DISTANCE_ELEVATION`)
5. New two-layer snow melt model (`SNOBAL_TWO_LAYER`)
6. Improved support for blank observation values and non-zero observation weights in model diagnostics

The following backwards compatibility issues were introduced:

1. The hydrograph observations file is now written in period-starting (rather than period-ending) format, meaning that the single time step correction to the start date of a continuous observation hydrograph time series is no longer needed. **ACTION**: Existing observation .rvt files will have to be amended with a simple date shift.
2. For models with more than one subbasin where the reference or initial stream discharges were not user-specified, the algorithm used to estimate basin initial and reference flows has been significantly modified. Automatic estimation of network flows now requires the specification of the :AnnualAvgRunoff command in the .rvp file. **ACTION**: Recalibration of existing models will likely be required if `Q_REFERENCE` was not user-specified for all basins and a celerity-dependent routing algorithm was used (e.g., a Muskingum variant, plug flow, or diffusive wave).
3. For models with more than one gauge and gauge-specific `:SnowCorrections` and `:RainCorrections`, the interpolation algorithm has been modified to more appropriately handle the spatial handling of these corrections. **ACTION**: Recalibration of existing models may be required.

Chapter 3

The Hydrologic Process Library

The following chapter outlines the many process algorithms available for modelling the water cycle in Raven.

3.1 Precipitation Partitioning

The precipitation partitioning process moves water, in the form of snow and rain, to the appropriate storage compartment. The order of application is depicted in figure 3.1. The specific distribution of rainfall and snowfall to the canopy, and ground surface (in the form of ponded water) depends upon the existence of particular storage compartments and a number of model parameters.

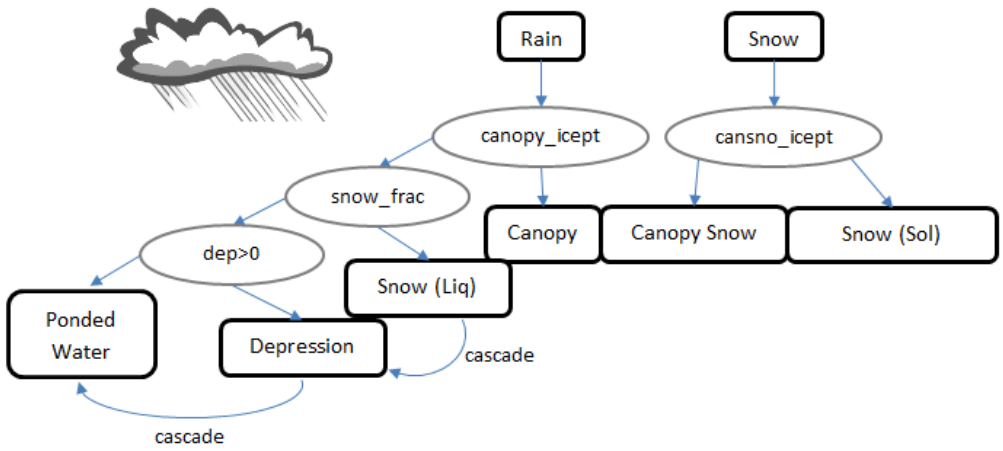

Figure 3.1: Partitioning of rainfall/snowfall to the appropriate surface storage compartments

The partitioning of precipitation proceeds as follows (for non-lake HRUs):

1. The amount of rain and snow captured by the vegetation canopy is controlled by the precipitation interception rate (calculated as described below) and the storage capacity of the canopy. If the canopy exists as a storage state variable (i.e., `CANOPY` or `CANOPY_SNOW`) are present in the model, these storage compartments are filled at the calculated interception rate until filled. The remainder (if any) is allowed to proceed onward, with a correction included for the percent forest cover, (land use parameter `FOREST_COVER`). If canopy water/snow storage is not explicitly modeled, the

amount of available canopy storage is not considered and the amount of snow and rain that would be captured by the canopy is "evaporated" to the atmosphere.

2. If there is a snow state variable in the model (determined usually by the presence of some kind of snow balance or snow melt algorithm), the snow as SWE is increased by an amount corresponding to snowfall. If rain hits the snowpack, it fills the unripe pores in the snowpack and is allowed to proceed onward. If required by the model, cold content, and snow density may also be updated. Some of the snow balance algorithms override the details of this process, instead moving all snowfall to NEW_SNOW and all rainfall to PONDED_WATER where it waits to be handled by the snow balance algorithm.

The water in the PONDED_WATER storage compartment, which typically also includes meltwater from snow melt, waits to be distributed to the shallow subsurface or surface water storage through subsequent application of an infiltration or abstraction algorithm.

Special HRU types for open water, exposed rock, glaciers, and wetlands (determined by WATER, ROCK, GLACIER and WETLAND prefixes on HRU soil profiles) are treated a bit differently than the default land HRU. In these HRUs, top soil is not active; therefore precipitation partitioning works a bit differently and (e.g.,) infiltration and soil evaporation routines are inactive.

For lake HRUs, all snow and rain is converted to liquid water and added directly to the SURFACE_WATER store ready to be routed downstream via in-catchment routing. Alternately, water can be sent to the LAKE_STORAGE store (if specified using the :LakeStorage command), where water release is delayed to the surface water network as controlled using (e.g.,) the :LakeRelease process (section 3.13). This latter approach is likely preferred for systems dominated by small lake features. Lake HRUs are defined as those with a zero-layer soil profile whose name begins with LAKE.

For wetland HRUs, all rain is converted to liquid water and added directly to the DEPRESSION store. Wetland HRUs are defined as those with a soil profile whose name begins with WETLAND. Snow which falls on a wetland is allowed to accumulate, assuming that the wetland is frozen. When it melts, it turns to ponded water and must be flushed to depression storage via proper commands in the :HydrologicProcesses block within the .rvi file.

For exposed rock HRUs, all throughfall and snowmelt is stored as PONDED_WATER. Since infiltration schemes don't function with rock-type HRUs, the user must provide an alternate mechanism to reach SURFACE_WATER (usually via a conditional :Flush process).

Example usage in the .rvi file:

```
:Precipitation RAVEN_DEFAULT ATMOS_PRECIP MULTIPLE
```

3.1.1 Canopy Interception Algorithms

The canopy interception algorithms, specified by the model command :PrecipIceptFract are used to determine the percent rain or snow captured by a full forest/crop canopy. In all cases, the maximum interception rates are given as

$$\begin{aligned} R_{int} &= \theta_{rain} \cdot R \\ S_{int} &= \theta_{snow} \cdot S \end{aligned}$$

where R and S are snowfall rates, in [mm/d], R_{int} and S_{int} are interception rates, in mm/d, and $\theta_{rain}/\theta_{snow}$ are the interception percentages (values between 0 and 1). These maximum interception rates may be limited (as mentioned above) by the current amount of water stored in the canopy. Many of these rates are controlled by leaf area index, LAI, and stem area index, SAI, calculated as follows:

$$\begin{aligned} \mathrm{LAI} &= (1-s)\cdot \mathrm{LAI_{max}} \cdot \mathrm{f_{LAI}(m)} \\ \mathrm{SAI} &= (1-s)\cdot \beta \cdot h_{veg} \end{aligned} \tag{3.1}$$

where s is the land use parameter FOREST_SPARSENESS, LAI_{max} is the maximum LAI (vegetation parameter MAX_LAI, $f_{LAI}(m)$ is the relative LAI correction by month m, specified by the :SeasonalRelativeLAI command for each vegetation type, and β is the vegetation parameter SAI_HT_RATIO. Note that FOREST_COVERAGE should be interpreted as the percentage of land covered in representative vegetation, and FOREST_SPARSENESS should be interpreted as a land use-based correction factor for vegetation density. The height of vegetation, h_{veg} is calculated as

$$h_{veg} = h_{max} \cdot f_{veg}(m)$$

where h_{max} is the maximum vegetation height (vegetation parameter MAX_HT) and $f_{veg}(m)$ is the relative vegetation height correction by month m, specified using the :SeasonalRelativeHeight command in the .rvp file.

The following algorithms are used to determine the percentages of rain and snow that will be intercepted by the vegetative canopy:

User-specified throughfall fraction (PRECIP_ICEPT_USER)

The interception percentages are directly specified by the user θ_{rain} is the vegetation parameter RAIN_ICEPT_PCT and θ_{rain} is the vegetation parameter SNOW_ICEPT_PCT.

Linear LAI-based method (PRECIP_ICEPT_LAI)

From Dingman (2002), the interception percentages are given as a linear function of the LAI:

$$\begin{aligned} \theta_{rain} &= \alpha_{rain} \cdot (\mathrm{LAI} + \mathrm{SAI}) \\ \theta_{snow} &= \alpha_{snow} \cdot (\mathrm{LAI} + \mathrm{SAI}) \end{aligned}$$

where α_{rain} and α_{snow} are the vegetation parameters RAIN_ICEPT_FACT and SNOW_ICEPT_FACT, respectively. The leaf area index LAI and stem area index SAI are calculated as indicated above.

Exponential LAI-based method (PRECIP_ICEPT_EXPLAI)

The interception percentages are given as:

$$\begin{aligned} \theta_{rain} &= 1 - \exp(-0.5(\mathrm{LAI} + \mathrm{SAI})) \\ \theta_{snow} &= 1 - \exp(-0.5(\mathrm{LAI} + \mathrm{SAI})) \end{aligned}$$

Hedstrom-Pomeroy method for snow (PRECIP_ICEPT_HEDSTROM)

If this method is chosen, the rain interception is the same as for PRECIP_ICEPT_EXPLAI, but the snow interception is handled as documented in Hedstrom and Pomeroy (1998).

3.2 Infiltration

Infiltration refers to the partitioning of ponded water (the residual rainfall and/or snowmelt) between the shallow surface soil (infiltrated water) and surface water (runoff). Infiltration is typically controlled by the saturation of the soil and its hydraulic properties (e.g., hydraulic conductivity, infiltration capacity).

Infiltration always moves water from `PONDED_WATER` to `SOIL[0]` (the top soil layer), and depending upon the soil structure model specified by the `:SoilModel` command, may additionally push water to lower soil moisture stores. The remaining ininfiltrated water is typically treated as runoff and moved to `SURFACE_WATER`.

Infiltration is limited by the availability of soil/aquifer storage. Many of the following algorithms use the quantities of maximum soil storage (ϕ_{max} [mm]), maximum tension storage (ϕ_{tens} [mm]), and field capacity storage (ϕ_{fc} [mm]) in a layer, always calculated as:

$$\begin{aligned} \phi_{max} &= Hn(1-SF) \\ \phi_{tens} &= \phi_{max}(S_{fc}-S_{wilt}) \\ \phi_{fc} &= \phi_{max}S_{fc} \end{aligned} \tag{3.2}$$

where H is the soil layer thickness [mm], n is the porosity (soil property `POROSITY`), SF is the stone fraction (soil property `STONE_FRAC`), S_{fc} is the saturation at field capacity (soil parameter `FIELD_CAPACITY`), and S_{wilt} is the saturation at the wilting point (soil parameter `SAT_WILT`).

Example usage in the .rvi file:

```
:Infiltration INF_GREEN_AMPT PONDED_WATER MULTIPLE
```

Infiltration Algorithms

Partition coefficient method (`INF_PARTITION`)

A simple linear relationship between precipitation and runoff (e.g., Chow et al. (1988)), characterized by:

$$M_{inf} = R \cdot (1 - P_c)$$

where M_{inf} is the infiltration rate [mm/d], R is the rainfall/snowmelt rate [mm/d] (alternately, the current amount of ponded water divided by the model timestep), and P_c is the partition coefficient, specified as the land use parameter `PARTITION_COEFF`. The remainder of rainfall is routed to surface water.

SCS method (`INF_SCS`)

The standard Soil Conservation Society (SCS) method (Soil Conservation Service, 1986), where infiltration is a function of the local curve number:

$$M_{inf} = R \cdot \left(1 - \frac{(R-0.2S)^2}{R+0.8S}\right)$$

where M_{inf} is the infiltration rate [mm/d], R is the rainfall/snowmelt rate [mm/d] (alternately, the current amount of ponded water divided by the model timestep), and S [mm] is the retention parameter

$$S = 25400/CN - 254$$

where CN is the SCS curve number (land use parameter `SCS_CN`. The curve number for moderate antecedent moisture content (condition II) is user-specified with land use parameter `SCS_CN` and corrected for dry or wet conditions based upon 5-day precipitation history and whether or not it is growing season. The SCS method should only be used for daily simulations.

Explicit Green Ampt method (`INF_GREEN_AMPT`)

The explicit calculation of Green-Ampt cumulative (Green and Ampt, 1911) infiltration

$$M_{inf} = \min\left(R, k_{sat}\left(1 + \frac{|\psi_f|(\phi_{max} - \phi_{soil})}{F}\right)\right)$$

where R is the rainfall/snowmelt rate [mm/d], F uses the n^{th} recursive approximation of the Lambert W_{-1} function (Barry et al., 2005). The variables ψ_f [-mm], ϕ_{max} [mm], and ϕ_{soil} [mm], are the Green-Ampt wetting front suction (soil parameter `WETTING_FRONT_PSI`), maximum soil moisture content (defined in equation 3.2), and soil moisture at the start of the time step, a state variable. k_{sat} is the saturated conductivity of the soil [mm/d], soil parameter `HYDRAUL_COND`. All parameters used are those associated with the top soil.

Simple Green Ampt method (`INF_GA_SIMPLE`)

The quick-and-dirty version of the Green-Ampt (Green and Ampt, 1911) analytical solution for discrete time-stepping schemes:

$$M_{inf} = \min\left(R, k_{sat}\left(1 + \frac{|\psi_f|(\phi_{max} - \phi_{soil})}{F}\right)\right)$$

where R is the rainfall/snowmelt rate [mm/d]. F [mm], the cumulative infiltration, is accumulated as a state variable during simulation, and reverts to zero after prolonged periods without precipitation. The variables ψ_f [-mm], ϕ_{max} [mm], and ϕ_{soil} [mm], are the Green-Ampt wetting front suction (soil parameter `WETTING_FRONT_PSI`), maximum soil moisture content (defined in equation 3.2), and soil moisture at the start of the time step. k_{sat} is the saturated conductivity of the soil [mm/d], soil parameter `HYDRAUL_COND`. All parameters used are those associated with the top soil.

VIC method (`INF_VIC`)

From the variable infiltration capacity model (Wood et al., 1992):

$$M_{inf} = R \cdot K_1\left(\gamma\alpha z_{max} + z_{min} - \frac{\phi_{soil}}{\phi_{max}}\right)^{\gamma}$$

where R is the rainfall/snowmelt rate [mm/d], ϕ_{soil} [mm] is the soil moisture content, ϕ_{max} is the maximum soil storage capacity as defined using equation 3.2, α is the soil parameter `VIC_ALPHA`, z_{min} and z_{max} are the soil parameters `VIC_ZMIN` and `VIC_ZMAX`, and K_1 is given by:

$$K_1 = ((z_{max} - z_{min})\alpha\gamma)^{-\gamma}$$

VIC/ARNO method (`INF_VIC_ARNO`)

The VIC/ARNO model as interpreted by (Clark et al., 2008).

$$M_{inf} = R \cdot \left(1 - \left(1 - \frac{\phi_{soil}}{\phi_{max}}\right)^{b}\right)$$

where R is the rainfall/snowmelt rate [mm/d], b is the soil parameter `B_EXP`, ϕ_{soil} is the top soil layer water content [mm], and ϕ_{max} is the maximum topsoil storage [mm] calculated using equation 3.2.

HBV method (`INF_HBV`)

The standard HBV model approach (Bergstrom, 1995).

$$M_{inf} = R \cdot \left(1 - \left(\frac{\phi_{soil}}{\phi_{max}}\right)^{\beta}\right)$$

where β is the soil parameter `HBV_BETA`, ϕ_{soil} is the soil layer water content [mm], and ϕ_{max} is the maximum soil storage [mm] calculated using equation 3.2.

PRMS method (`INF_PRMS`)

The PRMS model (Leavesley and Stannard, 1995) as interpreted by Clark et al. (2008):

$$M_{inf} = R \cdot \left(1 - F_{sat}^{max} \min\left(\frac{\phi_{soil}}{\phi_{tens}}, 1\right)\right)$$

where ϕ_{soil} is the soil layer water content [mm], ϕ_{tens} is the maximum tension storage [mm] calculated using equation 3.2, and F_{sat}^{max} is the maximum saturated area fraction (land use parameter `MAX_SAT_AREA_FRAC`).

UBC Watershed Model method (`INF_UBC`)

As documented in Quick (2003), the UBCWM infiltration algorithm partitions ponded water to surface water, interflow, and two groundwater stores. The infiltration rate into the shallow soil is calculated as

$$M_{inf} = R \cdot (1 - b_2)$$

where M_{inf} is limited by the soil storage deficit and b_2, the effective impermeable area percentage, is calculated using a deficit-based estimate corrected with a special term for flash floods (corresponding to higher rainfall/melt rates):

$$b_2 = b_1 + (1 - b_1) \cdot FF$$

here b_1, the unmodified effective impermeable area percentage, calculated as

$$b_1 = F_{imp} \cdot 10^{\left(-\frac{\phi_{max} - \phi_{soil}}{\text{P0AGEN}}\right)}$$

where ϕ_{soil} and ϕ_{max} are as defined in equation 3.2 and FF, the flash factor (which is constrained to vary between 0 and 1) is calculated as:

$$FF = \cdot \left(1 + \log\left(\frac{\phi_{pond}}{\text{V0FLAX}}\right) / \log\left(\frac{\text{V0FLAX}}{1800}\right)\right)$$

here, F_{imp} [-] is the land use parameter `IMPERMEABLE_FRAC`, V0FLAX [mm] is the global ponding parameter `UBC_FLASH_PONDING`, and P0AGEN [mm] is the soil property `UBC_INFIL_SOIL_DEF`, the reference soil deficit used at which 10 percent of the soil surface generates runoff.

The remaining rainfall/snowmelt is distributed to groundwater (at rate M_{perc}), interflow (at rate M_{int}, and runoff M_{run} using the following expressions

$$\begin{aligned} M_{perc} &= \min\left(M_{max}^{perc}, R - M_{inf}\right) \cdot (1 - b_2) \\ M_{int} &= (R - M_{inf} - M_{perc}) \cdot (1 - b_2) \\ M_{run} &= b_2 \cdot R \end{aligned}$$

To summarize, a percentage b_2 of the rainfall/snowmelt runs off directly. The remainder first infiltrates into the shallow soil, until the deficit is filled. Any remaining water then percolates into the groundwater at a maximum rate M_{max}^{perc} [mm/d], specified using the `MAX_PERC_RATE` parameter of the groundwater soil layers. This component will be partitioned such that a certain percentage, `UBC_GW_SPLIT`, a global parameter specified using the `:UBCGroundwaterSplit` command, goes to the lower groundwater storage, whereas the remainder goes to upper groundwater storage The final remaining water (if any) goes to interflow storage, where it will be routed to the surface water network.

GR4J infiltration method (`INF_GR4J`)

From the GR4J model (Perrin et al., 2003):

$$M_{inf} = \phi_{max} \cdot \left(\frac{\alpha \cdot (1 - \left(\frac{\phi_{soil}}{\phi_{max}}\right)^2}{1 + \alpha\phi_{soil}}\phi_{max}\right)$$

where $\alpha = \tanh(\phi_{pond}/\phi_{max})$, ϕ_{pond} [mm] is the ponded water storage after rainfall/snowmelt, ϕ_{soil} is the top soil layer water content [mm], and ϕ_{max} is the maximum topsoil storage [mm] calculated using equation 3.2.

HMETS infiltration method (`INF_HMETS`)

From the HMETS model (Martel et al., 2017):

$$M_{inf} = R \cdot \left(1 - \alpha \cdot \frac{\phi_{soil}}{\phi_{soil}^{max}}\right)$$

where R is the rainfall/snowmelt rate [mm/d], α is the unitless land use parameter `HMETS_RUNOFF_COEFF`, ϕ_{soil} is the topsoil layer water content, and ϕ_{max} is the maximum soil storage [mm] calculated using equation 3.2.

3.3 Baseflow

Baseflow refers to the flow of water from an aquifer or deeper soil horizon to surface water, typically due to a head gradient between fully saturated soil and stream. It may be considered the sum of the contribution of deep groundwater exchange with a river and delayed storage in the streambank.

Baseflow moves water from either `SOIL[m]` or `AQUIFER` state variables, depending upon the soil structure model specified by the `:SoilModel` command. The water is always moved to `SURFACE_WATER`. Baseflow is rate-limited by the availability of soil/aquifer storage. Example usage in the .rvi file:

```
:Baseflow BASE_LINEAR SOIL[4] SURFACE_WATER
```

Available Algorithms

Constant baseflow (`BASE_CONSTANT`)

A constant, specified rate of baseflow:

$$M_{base} = M_{max}$$

where M_{max} [mm/d] is the maximum baseflow rate, soil parameter `MAX_BASEFLOW_RATE`.

Linear storage (`BASE_LINEAR_STORAGE` or `BASE_LINEAR_ANALYTIC`)

A very common approach used in a variety of conceptual models. The baseflow rate is linearly proportional to storage:

$$M_{base} = k\phi_{soil}$$

Where k [1/d] is the baseflow coefficient (soil parameter `BASEFLOW_COEFF`), and ϕ_{soil} is the water storage [mm] in the soil or aquifer layer. An alternate version, `BASE_LINEAR_ANALYTIC` may be used to simulate the same condition, except using a closed-form expression for integrated flux over the time step (Δt):

$$M_{base} = \phi_{soil} \cdot (1 - \exp(-k\Delta t))/\Delta t$$

The two methods are effectively equivalent for sufficiently small time steps, but the second is preferred for large values of k.

Non-linear storage (`BASE_POWER_LAW`)

A very common approach used in a variety of conceptual models, including HBV Bergstrom (1995). The baseflow rate is non-linearly proportional to storage:

$$M_{base} = k\phi_{soil}^{n}$$

Where k [1/d] is the baseflow coefficient (soil parameter `BASEFLOW_COEFF`), and ϕ_{soil} is the water storage [mm] in the soil or aquifer layer, and n is the user-specified soil parameter `BASEFLOW_N`.

VIC baseflow method (BASE_VIC)

From the VIC model Wood et al. (1992) as interpreted by (Clark et al., 2008):

$$M_{base} = M_{max} \left(\frac{\phi_{soil}}{\phi_{max}} \right)^n$$

where M_{max} [mm/d] is the maximum baseflow rate at saturation (soil parameter MAX_BASEFLOW_RATE), ϕ_{soil} is the water storage [mm] in the soil or aquifer layer, ϕ_{max} is the maximum soil storage capacity , and n is the user-specified soil parameter BASEFLOW_N.

GR4J baseflow method (BASE_GR4J)

From the GR4J model Perrin et al. (2003):

$$M_{base} = \frac{\phi_{soil}}{\Delta t} \cdot \left(1 - \left(1 + \left(\frac{\phi_{soil}}{\phi_{ref}} \right)^4 \right)^{\frac{1}{4}} \right)$$

where ϕ_{ref} [mm] is the reference soil storage, the user-specified soil parameter GR4J_X3, which can be interpreted as a baseflow reference storage, ϕ_{soil} is the water storage [mm] in the soil or aquifer layer.

Topmodel baseflow method (BASE_TOPMODEL)

From TOPMODEL (Beven and Kirkby, 1979)as interpreted by (Clark et al., 2008):

$$M_{base} = M_{max} \cdot \frac{\phi_{max}}{n} \cdot \frac{1}{\lambda^n} \cdot \left(\frac{\phi_{soil}}{\phi_{max}} \right)^n$$

where M_{max} [mm/d] is the maximum baseflow rate at saturation (soil parameter MAX_BASEFLOW_RATE), ϕ_{soil} is the water storage [mm] in the soil layer, ϕ_{max} is the maximum soil storage capacity, λ is the mean of the power-transformed topographic index [m] (terrain parameter LAMBDA), and n is the user-specified soil parameter BASEFLOW_N.

Threshold-based baseflow method (BASE_THRESH_POWER)

Here, baseflow doesn't commence until a threshold saturation of the soil layer is met. Above the threshold, the outflow rate is controlled by saturation up to a maximum rate.

$$M_{base} = M_{max} \cdot \left(\frac{\frac{\phi_{soil}}{\phi_{max}} - S_{th}}{1 - S_{th}} \right)^n$$

where S_{th} [-] is the threshold saturation at which baseflow begins (soil parameter BASEFLOW_THRESH), M_{max} is the soil parameter MAX_BASEFLOW_RATE [mm/d], and the power law coefficient n is the soil parameter BASEFLOW_N.

Threshold-based baseflow method (storage) (`BASE_THRESH_STOR`**)**

Here, baseflow doesn't commence until a threshold storage amount of the soil layer is met. Above the threshold, the outflow rate is linearly related to storage excess above the threshold.

$$M_{base} = K_2 \cdot \max\left(\phi_{soil} - \phi_{thresh}, 0\right)$$

where ϕ_{th} [mm] is the threshold soil storage at which baseflow begins (soil parameter `STORAGE_THRESHOLD`), K_2 is the soil parameter `BASEFLOW_COEFF2` [1/d].

3.4 Percolation

Percolation refers to the net downward flow of water from one soil/aquifer unit to another. This process is physically driven by a moisture gradient, but this is often simplified in conceptual percolation models.

Percolation moves water between `SOIL[m]` or `AQUIFER` units, depending upon the soil structure model specified by the `:SoilModel` command. The user typically has to specify both the 'from' and 'to' storage compartments. Percolation is rate-limited by the availability of soil/aquifer storage and by the capacity of the receptor 'to' compartment. Example usage in the .rvi file:

```
:Percolation PERC_LINEAR SOIL[0] SOIL[1]
:Percolation PERC_LINEAR SOIL[1] SOIL[2]
```

Available Algorithms

Constant percolation (`PERC_CONSTANT`)

A constant, specified rate of percolation from one soil layer to the next:

$$M_{perc} = M_{max}$$

where M_{max} is the soil parameter `MAX_PERC_RATE` of the 'from' soil compartment.

Linear percolation (`PERC_GAWSER`)

As used in the GAWSER hydrologic model, (Schroeter, 1989).

$$M_{perc} = M_{max} \left(\frac{\phi_{soil} - \phi_{fc}}{\phi_{max} - \phi_{fc}} \right)$$

where M_{max} is the soil parameter `MAX_PERC_RATE`, ϕ_{soil} [mm] is the moisture content of the soil layer, and the other moisture contents are defined in equation 3.2. All parameters refer to that of the 'from' soil compartment.

Linear percolation (`PERC_LINEAR`)

Percolation is proportional to soil water content:

$$M_{perc} = k\dot{\phi}_{soil}$$

where k [1/d] is the soil parameter `PERC_COEFF` and ϕ_{soil} [mm] is defined in equation 3.2. All parameters refer to that of the 'from' soil compartment.

Power law percolation (`PERC_POWER_LAW`)

Percolation is proportional to soil saturation to a power:

$$M_{perc} = M_{max} \left(\frac{\phi_{soil}}{\phi_{max}} \right)^{n}$$

where M_{max} [mm/d] is the soil parameter `MAX_PERC_RATE`, n is the soil parameter `PERC_N` and ϕ_{soil} [mm] and ϕ_{max} [mm] are defined in equation 3.2. All parameters refer to that of the 'from' soil compartment.

PRMS percolation method (`PERC_PRMS`)

Percolation is proportional to drainable soil saturation to a power, as done in the PRMS model (Leavesley and Stannard, 1995):

$$M_{perc} = M_{max} \left(\frac{\phi_{soil} - \phi_{tens}}{\phi_{max} - \phi_{tens}} \right)^{n}$$

where M_{max} [mm/d] is the soil parameter `MAX_PERC_RATE`, n is the soil parameter `PERC_N` and ϕ_{soil}, ϕ_{tens}, and ϕ_{max} [mm] are defined in equation 3.2. All parameters refer to that of the 'from' soil compartment.

Sacramento percolation method (`PERC_SACRAMENTO`)

Percolation is given by the following expression:

$$M_{perc} = M_{max}^{base} \left(1 + \alpha \left(1 - \frac{\phi_{soil}^{to}}{\phi_{max}^{to}} \right)^{\psi} \right) \left(\frac{\phi_{soil} - \phi_{tens}}{\phi_{max} - \phi_{tens}} \right)$$

where M_{max}^{base} is the saturated baseflow rate (soil parameter `MAX_BASEFLOW_RATE`), α is soil parameter `SAC_PERC_ALPHA`, γ is the soil parameter `SAC_PERC_EXPON`, and ϕ_{soil} and ϕ_{max} are defined in equation 3.2. All parameters refer to that of the 'from' soil compartment, unless they have the ^{to} superscript.

GR4J percolation method (`PERC_GR4JEXCH` and `PERC_GR4JEXCH2`)

Percolation (really here exchange between a conceptual soil store and a groundwater store) is calculated as consistent with the original GR4J model (Perrin et al., 2003):

$$M_{perc} = -x_2 * (\min(\phi_{soil}/x_3, 1.0))^{3.5}$$

where x_2 is the soil parameter `GR4J_X2` and x_3 is the soil parameter `GR4J_X3` (both properties of the soil from which the water is percolating). In the case of `PERC_GR4JEXCH2`, the soil water content ϕ_{soil} refers to the topsoil storage (in SOIL[0]) rather than the soil from which percolation is being taken.

To do (1)

3.5 Interflow

Interflow refers to subsurface flow moving laterally through a shallow unsaturated soil horizon until it enters a stream channel.

Interflow moves water between SOIL and SURFACE_WATER units, and is typically used in conjunction with a (slower) baseflow algorithm. The user typically has to specify the 'from' storage compartment (i.e. a specific soil layer); the 'to' storage compartment is always SURFACE_WATER. Interflow is rate-limited by the availability of soil/aquifer storage. Example usage in the .rvi file:

```
:Interflow INTERFLOW_PRMS SOIL[1] SURFACE_WATER
```

Available Algorithms

PRMS interflow method (INTERFLOW_PRMS)

Interflow is proportional to drainable soil saturation, as done in the PRMS model (Leavesley and Stannard, 1995):

$$M_{inter} = M_{max} \cdot \left(\frac{\phi_{soil} - \phi_{tens}}{\phi_{max} - \phi_{tens}} \right)$$

where M_{max} is the maximum interflow rate (soil parameter MAX_INTERFLOW_RATE), ϕ_{soil} is the moisture content (in mm) of the draining soil, and ϕ_{tens}, and ϕ_{max} are defined in equation 3.2. All parameters refer to that of the 'from' soil compartment.

3.6 Soil Evaporation

Soil evaporation (really evapotranspiration) involves converting water from the soil layers to water vapour in the atmosphere via both evaporation and transpiration. The rate of evapotranspiration depends on soil moisture, plant type, stage of plant development and weather conditions such as solar radiation, wind speed, humidity and temperature.

Soil evaporation always moves water between `SOIL[m]` and `ATMOSPHERE` units. Which soil layers are subjected to evaporation depend on the soil structure model specified by the `:SoilModel` command and the particular evaporation algorithm. Soil evaporation is rate-limited by the availability of soil/aquifer storage and by the capacity of the atmosphere to absorb water vapour. Example usage in the .rvi file:

```
:SoilEvaporation SOILEVAP_VIC SOIL[0] ATMOSPHERE
```

In all notation below, PET refers to the potential evapotranspiration determined by one of the forcing function estimators of section 5.4. In all cases, this PET may be modified by the soil parameter `PET_CORRECTION`, which only modifies PET in these algorithms.

Available Algorithms

Uncorrected evaporation algorithm (`SOILEVAP_ALL`)

Water is removed from soil at the maximum rate until there is no water remaining:

$$M_{evap} = \text{PET}$$

VIC soil evaporation algorithm (`SOILEVAP_VIC`)

Soil ET is proportional to the topsoil saturation to a power, as done in the VIC model (Wood et al., 1992):

$$M_{evap} = \text{PET} \cdot \left(1 - \left(1 - \frac{\phi_{soil}}{\phi_{max}}\right)^{\gamma}\right)$$

where PET is the potential evapotranspiration rate, γ is the soil parameter `VIC_EVAP_GAMMA`, and ϕ_{soil}, and ϕ_{max} are defined in equation 3.2.

Linear evaporation-storage (`SOILEVAP_LINEAR`)

Actual evapotranspiration is linearly proportional to topsoil storage, up to a maximum of PET:

$$M_{evap} = \min\left(\alpha \cdot \phi_{soil}, \text{PET}\right)$$

where PET is the potential evapotranspiration rate [mm/d], and ϕ_{soil} [mm] is defined in equation 3.2, and α is the land use parameter `AET_COEFF`. This is used in the MOHYSE model Fortin and Turcotte (2006).

Linear evaporation-saturation (`SOILEVAP_HBV` or `SOILEVAP_TOPMODEL`)

Soil ET is at PET if storage exceeds the tension storage, then is linearly proportional to the soil saturation:

$$M_{evap} = \text{PET} \cdot \min\left(\frac{\phi_{soil}}{\phi_{tens}}, 1\right)$$

where PET is the potential evapotranspiration rate [mm/d], and ϕ_{soil} [mm] and ϕ_{tens} [mm] are defined in equation 3.2. The HBV model uses an additional snow correction, such that ET is zero in non-forested areas if snow depth is non-zero.

Root-distributed 2-layer evaporation (`SOILEVAP_ROOT`)

Soil ET [mm/d] is linearly proportional to the soil saturation, but distributed by root fraction, ξ_m. Soil ET is at $\xi_m \cdot$ PET if storage exceeds the tension storage.

$$M^U_{evap} = \text{PET} \cdot \xi_U \cdot \min\left(\frac{\phi^U_{soil}}{\phi^U_{tens}}, 1\right) \tag{3.3}$$

$$M^L_{evap} = \text{PET} \cdot \xi_L \cdot \min\left(\frac{\phi^L_{soil}}{\phi^L_{tens}}, 1\right) \tag{3.4}$$

where U and L refer to the upper and lower layers, respectively, and ϕ_{soil} [mm] and ϕ_{tens} [mm] are defined in equation 3.2. Currently, ξ_L and ξ_U are hardcoded as 0.3 and 0.7, respectively.

Sequential 2-layer evaporation (`SOILEVAP_SEQUEN`)

Daily soil ET [mm/d] is linearly proportional to the soil saturation; the top layer storage is exhausted first, then ET can be withdrawn from the lower layer.

$$M^U_{evap} = \text{PET} \cdot \left(\frac{\phi^U_{soil}}{\phi^U_{tens}}\right) \tag{3.5}$$

$$M^L_{evap} = (\text{PET} - M^U_{evap}) \cdot \left(\frac{\phi^L_{soil}}{\phi^L_{tens}}\right) \tag{3.6}$$

where U and L refer to the upper and lower layers, respectively, and ϕ_{soil} [mm] and ϕ_{tens} [mm] are defined in equation 3.2.

UBCWM approach (`SOILEVAP_UBC`)

Evaporation is controlled by the soil moisture deficit, $\phi_{max} - \phi_{soil}$, where ϕ_{max} is defined in equation 3.2, and is corrected for effective saturated area.

$$M_{evap} = \text{PET} \cdot (1 - \beta_{fast}) 10^{\left(-\frac{\phi_{max} - \phi_{soil}}{\gamma_e}\right)}$$

where γ_e is the soil parameter `UBC_EVAP_SOIL_DEF` (the soil deficit at which the actual ET depletes to 0.1 PET), and β_{fast}, a proxy for the effective impermeable fraction is calculated as

$$\beta_{fast} = F_{imp} \cdot 10^{\left(-\frac{\phi_{max} - \phi_{soil}}{\gamma_a}\right)}$$

where F_{imp} is the impermeable fraction (land use parameter `IMPERMEABLE_FRAC`) and γ_a is the soil parameter `UBC_INFIL_SOIL_DEF`.

GR4J soil evaporation method (SOILEVAP_GR4J)

From the GR4J model Perrin et al. (2003):

$$M_{evap} = \alpha\phi_{soil}\frac{2.0 - \frac{\phi_{soil}}{\phi_{max}}}{1.0 + \alpha\left(1.0 - \frac{\phi_{soil}}{\phi_{max}}\right)}$$

where $\alpha = \tanh(\text{PET}'/\phi_{max})$, PET′ is the PET remaining after ponded water storage is depleted, ϕ_{soil} is the water storage [mm] in the topsoil, ϕ_{max} is the maximum storage in the top soil.

HYPR soil/wetland evaporation method (SOILEVAP_HYPR)

From the HYPR model for representing prairie landscapes (Ahmed et al., 2020), intended to be used in conjunction with the ABST_PDMROF abstraction routine, which represents depression storage as a probability distribution on the landscape. This process algorithm is unique in that it handles both evaporative losses from the soil and the losses from the depression storage. The soil evaporation rate is calculated in the same manner as the HBV model, where soil ET is at PET if storage exceeds the tension storage, then is linearly proportional to the soil saturation:

$$M^*_{evap} = \text{PET} \cdot \min\left(\frac{\phi_{soil}}{\phi_{tens}}, 1\right)$$

where PET is the potential evapotranspiration rate [mm/d], and ϕ_{soil} [mm] and ϕ_{tens} [mm] are defined in equation 3.2. The percentage of the landscape covered by depression storage is calculated as in Mekonnen et al. (2014):

$$F_p = F_{max} \cdot \left(\frac{\phi_{dep}}{\phi_{dmax}}\right)^n$$

where F_{max} is the land use parameter MAX_DEP_AREA_FRAC, n is the land use parameter PONDED_EXP, ϕ_{dep} is the depression storage in mm, and ϕ_{dmax} is the maximum depression storage on the landscape, DEP_MAX (mm).

$$\begin{aligned} M^d_{evap} &= (1 - F_p) \cdot M^*_{evap} \\ M^s_{evap} &= F_p \cdot \text{PET}_{OW} \end{aligned}$$

where PET_{OW} is the open water evaporation rate determined from the :OW_Evaporation-specified method. The first term is evaporation from the soil, the second term is evaporation from depression storage.

3.7 Capillary Rise

Capillary rise is the rise of groundwater above the water table due to surface tension. The capillary zone extends up from the water table to the limit of capillary rise, and varies based on pore size and surface tension. In conceptual watershed models, the capillary rise term often refers to a process that moves water from lower to higher soil water stores, which may also implicitly include lateral groundwater flow processes in a sloping domain.

Capillary rise occurs between `SOIL` and `AQUIFER` units, depending upon the soil structure model specified by the `:SoilModel` command. The user typically has to specify the 'to' and 'from' storage compartments. Capillary rise is rate-limited by the availability of soil/aquifer storage and by the capacity of the receptor 'to' compartment. Example usage in the .rvi file:

```
:CapillaryRise CRISE_HBV SOIL[1] SOIL[0]
```

Available Algorithms

HBV model capillary rise (`CRISE_HBV`)

Capillary rise rate is linearly proportional to soil saturation of the recipient soil, as done in the HBV model (Bergstrom, 1995):

$$M_{crise} = M_{max}^{cr} \left(1 - \frac{\phi_{soil}}{\phi_{max}}\right)$$

where M_{max}^{cr} is the maximum interflow rate (soil parameter `MAX_CAP_RISE_RATE`), and ϕ_{soil} and ϕ_{max} are defined in equation 3.2. All parameters refer to that of the 'to' soil compartment.

3.8 Canopy Evaporation

Canopy evaporation converts water from the vegetated canopy to water vapour in the atmosphere. The rate of evaporation depends on plant type, stage of plant development and weather conditions such as solar radiation, wind speed, humidity and temperature. Canopy evaporation always occurs between `CANOPY` and `ATMOSPHERE` units. Canopy evaporation is rate-limited by the availability of canopy storage. Example usage in the .rvi file:

```
:CanopyEvaporation CANEVP_RUTTER CANOPY ATMOSPHERE
```

Available Algorithms

Maximum canopy evaporation (`CANEVP_MAXIMUM`)

Moisture on the canopy evaporates at the potential ET rate, provided storage is available.

$$M_{evap} = \text{PET} \cdot F_c \cdot (1 - f_s)$$

where PET is the potential evapotranspiration rate, F_c is the forest cover of the HRU (land use parameter `FOREST_COVERAGE`, and f_s is the vegetation sparseness factor (land use parameter `FOREST_SPARSENESS`.

Complete canopy evaporation (`CANEVP_ALL`)

All moisture on the canopy evaporates instantaneously, i.e., all intercepted precipitation is sent back to the atmosphere. This is also the default behaviour if no canopy is present.

Rutter canopy evaporation (`CANEVP_RUTTER`)

From (Rutter et al., 1971):

$$M_{evap} = \text{PET} \cdot F_c \cdot (1 - F_t) \left(\frac{\phi_{can}}{\phi_{cap}} \right)$$

where PET is the potential evapotranspiration rate, F_c is the forest cover of the HRU (land use parameter `FOREST_COVERAGE`), F_t is the trunk fraction (vegetation parameter `TRUNK_FRACTION`), ϕ_{can} [mm] is the storage in the canopy over the forested region, ϕ_{cap} [mm] is the storage capacity of the canopy over the forested region.

3.9 Canopy Drip

Canopy drip is the loss of liquid water from canopy to land surface, typically due to the impacts of wind. Canopy drip always occurs between CANOPY and PONDED_WATER units and is rate-limited by the availability of canopy storage. Example usage in the .rvi file:

```
:CanopyDrip CANDRIP_RUTTER CANOPY PONDED_WATER
```

Available Algorithms

Rutter canopy drip (CANDRIP_RUTTER**)**

Moisture on the canopy which exceeds storage (given by vegetation parameter MAX_CAPACITY, mm) falls instantaneously to the ground.

Slowdrain canopy drip (CANDRIP_SLOWDRAIN**)**

Moisture on the canopy which exceeds storage falls instantaneously to the ground, but the remaining drip is proportional to storage:

$$M_{drip} = \alpha \cdot \left(\frac{\phi_{can}}{\phi_{cap}} \right)$$

where α is the vegetation parameter DRIP_PROPORTION, and ϕ_{can} [mm] and ϕ_{cap} [mm] are the canopy storage and capacity (vegetation parameter MAX_CAPACITY) in the forested region, respectively. Drip only occurs in the forested region.

3.10 Abstraction

Abstraction refers to the redirection of rainfall to surface impoundments, such as swales, ponds, and puddles. In Raven, these are collectively referred to as DEPRESSION storage.

Abstraction always moves water from the PONDED_WATER state variable to the DEPRESSION storage state variable, but in some cases may also generate runoff (e.g., the ABST_PDMROF algorithm. Example usage in the .rvi file:

```
:Abstraction ABST_PERCENTAGE PONDED_WATER DEPRESSION
#or
:Abstraction ABST_PDMROF PONDED_WATER MULTIPLE
```

Available Algorithms

SCS method (ABST_SCS)

The abstraction rate is determined from the Soil Conservation Service method based upon SCS curve number.

$$M_{abst} = \frac{1}{\Delta t} \max \left(f_{SCS} \cdot 25.4 \left(\frac{1000}{\text{CN}} - 10 \right), \phi_{pond} \right)$$

Where CN is the curve number corrected for antecedent precipitation conditions, where the type II (moderate wetness) curve number is given by the land use parameter SCS_CN. The fraction f_{SCS} is the land use parameter SCS_IA_FRACTION, and is 0.2 for the standard SCS approach (i.e., $I_a = 0.2S$)

Percentage method (ABST_PERCENTAGE)

The abstraction rate is a given fraction of the ponded water accumulation rate,

$$M_{abst} = \alpha M_{pond}$$

where α is the land use parameter ABST_PERCENT

Fill method (ABST_FILL)

In this approach, all ponded water (the cumulative contribution of rainfall and snowmelt) is redirected to depression storage until it is filled, then the remainder is available for infiltration/runoff. The maximum depression storage amount is given by land use parameter DEP_MAX

PDMROF method (ABST_PDMROF)

This approach, which has been shown to be successful in prairie and wetland systems, is documented in (Mekonnen et al., 2014), and assumes a probability distribution of storage capacity within the HRU represented with the Pareto distribution parameter b (land use parameter PDMROF_B). A maximum local depression storage capacity, c_{max} is calculated as

$$c_{max} = \phi_{max} \cdot (b + 1)$$

where ϕ_{max} is the maximum total average depression storage in the HRU, land use parameter DEP_MAX [mm]. From this, the current critical capacity c^* may be calculated from the depression storage ϕ_{dep}:

$$c^* = c_{max} \left(1 - \left(1 - \frac{\phi_{dep}}{\phi_{max}} \right)^{\frac{1}{b+1}} \right)$$

The total amount of abstraction during a time step may be determined from ϕ_{pond}, the available ponded water ready to be abstracted:

$$M_{abst} = \frac{\phi_{max}}{\Delta t} \left[\left(1 - \frac{c^*}{c_m ax} \right)^{b+1} - \left(1 - \frac{c^* + \phi_{pond}}{c_{max}} \right)^{b+1} \right]$$

where the term $c^* + \phi_{pond}$ in the square brackets is constrained to be less than c_{max} (corresponding to the entire landscape shedding water). The amount of water not abstracted is moved to SURFACE_WATER storage as runoff.

3.11 Depression/Wetland Storage Overflow

Depression overflow refers to water lost from ponds and wetlands to the main surface water network. Depression overflow moves water from the DEPRESSION storage variable and is always moved to SURFACE_WATER. Depression overflow is rate-limited by the availability of water in depression storage. Usage in .rvi file:

```
:DepressionOverflow DFLOW_THRESHPOW DEPRESSION SURFACE_WATER
```

Available Algorithms

Power-law threshold (DFLOW_THRESHPOW)

The overflow to surface water is controlled by the amount of water in depression storage past a certain threshold:

$$M_{dflow} = M_{max} \cdot \left(\frac{\phi_{dep} - \phi_{th}}{\phi_{max} - \phi_{th}} \right)^n$$

where M_{max} [mm/d] is the maximum overflow rate, landuse parameter DEP_MAX_FLOW, ϕ_{dep} is the current depression storage [mm], ϕ_{th} is the given threshold storage level [mm] (landuse parameter DEP_THRESHHOLD, ϕ_{max} is the maximum depression storage DEP_MAX [mm], and n is the landuse parameter DEP_N (unitless).

Linear depression overflow(DFLOW_LINEAR)

The overflow to surface water is controlled by the amount of water in depression storage past a certain threshold:

$$M_{dflow} = k_d \cdot (\phi_{dep} - \phi_{th})$$

where ϕ_{dep} is the current depression storage [mm], ϕ_{th} is the given threshold storage level [mm] (landuse parameter DEP_THRESHHOLD), and k_d is the linear storage coefficient [1/d] (landuse parameter DEP_K). If $\phi_{dep} < \phi_{th}$, $M_{dflow} = 0$.

3.12 Seepage from Depressions/Wetlands

Seepage overflow refers to water lost from ponds and wetlands to lower soil units, including groundwater.

Seepage moves water from the DEPRESSION storage variable and is always moved to SOIL, subject to the availability of water in depression storage and remaining room in the soil. Seepage is rate-limited by the availability of water in depression storage. Example usage in the .rvi file:

```
:Seepage SEEP_LINEAR DEPRESSION SOIL[1]
```

Available Algorithms

Linear seepage (SEEP_LINEAR)

The seepage to surface water is controlled by the amount of water in depression storage:

$$M_{dflow} = k_{seep} \cdot \phi_{dep}$$

where ϕ_{dep} is the current depression storage [mm], and k_{seep} is the linear seepage coefficient [1/d] (landuse parameter DEP_SEEP_K).

3.13 Lake Release

Lake release refers to delayed release of water from lake storage, and is only used when a specific LAKE_STORAGE storage compartment is specified using the :LakeStorage command (alternately, all water falling on LAKE-type HRUs will be directed directly to the surface water network after accounting for open water evaporation, which may lead to a flashier-than-expected hydrograph). Lake storage is intended to represent lakes which are connected to the surface water network either directly or indirectly via groundwater. Exchange can be bidirectional such that low lake levels may extract water from surface water storage. Lake release is disabled for LAKE-type HRUs when they are linked to surface water reservoirs; for these (usually larger) lakes, the delayed release from storage is completely controlled by the reservoir outflow structure.

Lake release typically moves water from the LAKE_STORAGE storage variable to SURFACE_WATER; Lake storage may go below zero, which corresponds to a disequilibrium with the surface water network such that lakes will extract water. Lake release is not rate-limited except for when excess negative lake storage will dry out the surface water. Example usage in the .rvi file:

```
:LakeRelease LAKEREL_LINEAR DEPRESSION SOIL[1]
```

Available Algorithms

Linear release (LAKEREL_LINEAR)

The rate of release to/from surface water is controlled by the amount of water in depression storage:

$$M_{lrel} = k_{lrel} \cdot \phi_{lake}$$

where ϕ_{lake} is the current (positive or negative) net lake storage [mm], and k_{lrel} is the linear storage coefficient [1/d] (landuse parameter LAKE_REL_COEFF). Note that lake seepage can be negative (increasing lake storage) if the net lake storage is negative.

3.14 Snow Balance

Snow balance algorithms are used to simulate the strongly coupled mass and energy balance equations controlling melting and refreezing of snow pack and the liquid phase in the snow pores.

Most snow balance algorithms consists of multiple coupled equations, and there are also many 'to' and 'from' compartments, depending on which algorithm is selected. 'From' compartments include SNOW (as SWE), SNOW_LIQ and SNOW_DEPTH. 'To' compartments include SNOW, ATMOSPHERE, SNOW_LIQ, SNOW_DEPTH and SURFACE_WATER. Snow balance is rate-limited by the storage in 'from' and 'to' compartments. Example usage in the .rvi file (note that most snow balance models are manipulating multiple storage compartments):

```
:SnowBalance SNOBAL_SIMPLE_MELT SNOW PONDED_WATER
```

or

```
:SnowBalance SNOBAL_TWO_LAYER MULTIPLE MULTIPLE
```

Most of the snowmelt algorithms that explicitly simulate liquid water content within the snowpack use the global parameter SNOW_SWI to determine the maximum possible liquid water storage of the snowpack:

$$\phi_{max}^{sl} = SWE \cdot SWI$$

where ϕ_{max}^{sl} [mm] is the maximum liquid water storage of the snowpack, SWE is the snow water equivalent of the snowpack [mm], and SWI is the global parametre SNOW_SWI, which defaults to 0.05 if not specified.

Available Algorithms

Simple melt (SNOBAL_SIMPLE_MELT)

The melt rate (in [mm/d]) is simply calculated by applying the potential melt rate to the snowpack until it is gone.

$$M_{melt} = M'_{melt}$$

where the potential melt rate, M'_{melt} [mm/d], is calculated using one of the methods described in section 5.8.1. The melt rate is constrained such that only available snow will melt (i.e., the maximum melt rate is $SWE/\Delta t$) . This is the same as using :SnowMelt MELT_POTENTIAL.

HBV snow balance (SNOBAL_HBV)

The HBV snow balance (Bergstrom, 1995) represents both melt and liquid water storage in the pore space of the snow. The melt rate is determined by the potential melt rate algorithm (POTMELT_HBV for true HBV emulation), while refreeze is calculated using:

$$M_{refreeze} = K_a \cdot \max(T_f - T, 0)$$

where K_a is the land use parameter REFREEZE_FACTOR [mm/d/ °C].

Meltwater fills the snow pore space first (with the maximum fillable pore space determined by the global parameter SNOW_SWI), then is allowed to overflow. All overflow percolates into SOIL[0] by default, but may be redirected to PONDED_WATER using the :Redirect command if desired.

UBCWM snow balance (SNOBAL_UBCWM)

As described in the UBC Watershed model documentation (Quick, 1995). Potential melt is typically calculated using the POTMELT_UBCWM method described in section 5.8.1. If the land use/land type parameter SNOWPATCH_LIMIT is zero, the method is relatively straightforward - SWE is melted at a rate equivalent to the potential melt, with some of the water melted first filling up the Liquid holding capacity of the snow, the remainder becoming ponded water. During melt of ripened snowpack, the liquid water is released along with the corresponding SWE melted. The user is referred to the UBCWM documentation for the full description of the snowmelt algorithm with snow patching.

Cema Neige snow balance (SNOBAL_CEMA_NEIGE)

Often used with the GR4J model configuration, the Cema Neige snow balance uses the potential melt rate calculated using the methods of section 5.8.1, but corrected with a snow cover factor,

$$M_{melt} = \left(0.1 + 0.9 \cdot \min\left(\frac{\phi_{SWE}}{S_{Ann}}, 1\right)\right) \cdot M'$$

where M' is the potential melt rate, ϕ_{SWE} is the snow amount as snow water equivalent, S_{Ann} is the average annual snow amount, specified as the global parameter AVERAGE_ANNUAL_SNOW.

Two-layer snow balance (SNOBAL_TWO_LAYER)

A two-layer snowmelt model that simulates accumulation of cold content, changes in surface snow temperature, and evolution both liquid and solid snow stores. Available energy (supplied as potential melt) is first used to bring the temperature of the surface snowpack to freezing, then the remainder is used to melt the frozen snow, which is allocated to liquid snow until the pack is ripe, at which point it then drains into PONDED_WATER storage. Ripeness is controlled by the global parameter SNOW_SWI, which represents the maximum liquid snow storage capacity as a fraction of snowpack SWE. The second (bottom) layer is only applied when the snow as SWE exceeds the global parameter MAX_SWE_SURFACE, in mm.

HMETS snow balance (SNOBAL_HMETS)

A snowmelt model documented in Martel et al. (2017). This is a simple single layer snowmelt model with degree day freezing, which tracks liquid water content in the snowpack in addition to SWE. The refreeze rate (constrained by water availability) is given by:

$$M_{rf} = K_f \cdot (T_{rf} - T_{di})^f$$

where K_f is the land use property REFREEZE_FACTOR, T_rf is the degree day refreeze factor (land use property DD_REFREEZE_TEMP, and f is the land use parameter REFREEZE_EXPONENT. The

water retention capacity (upper limit of liquid water content in snow) varies over the course of the year based upon cumulative snowmelt:

$$\text{SWI} = \max\left(\text{SWI}_{min}, \text{SWI}_{max} \cdot (1 - \alpha \cdot M_{cumul})\right)$$

where SWI_{min} and SWI_{max} are the land use parameters `SNOW_SWI_MIN` and `SNOW_SWI_MAX`, α is the land use parameter `SWI_REDUCT_COEFF`, and M_{cumul} is the cumulative melt since the last period of zero snow depth.

CRHM EBSM snow balance (`SNOBAL_CRHM_EBSM`)

A snowmelt model based upon that of Marks and Dozier (1992) as implemented within the CRHM hydrological model Pomeroy et al. (2007). The single-layer energy-balance-based snow model tracks liquid water content, SWE, and energy content of the snowpack.

3.15 Snow Sublimation

Sublimation is the process of snow transforming to water vapour without passing through the intermediate liquid phase. It can be a significant part of the snow balance at high elevations, windy regions, and when atmospheric water conent is low.

Sublimation always occurs between SNOW and ATMOSPHERE units and is limited by the availability of snow. Example usage in the .rvi file:

```
:Sublimation SUBLIM_KUZMIN SNOW ATMOSPHERE
```

Available Algorithms

Kuzmin (1972) method (SUBLIM_KUZMIN)

The sublimation rate (in [mm/d]) is calculated using the following empirical relationship (Kuzmin, 1972; Kutchment and Gelfan, 1996):

$$M_{subl} = (0.18 + 0.098 \cdot v_{ave}) \cdot (P_{sat} - P_{vap})$$

where v_{ave} [m/s] is the wind velocity at 10m, P_{sat} and P_{ave} [mb] are the saturated vapour pressure and vapour pressure, respectively.

CRHM method (SUBLIM_CRHM)

The sublimation rate (in [mm/d]) is calculated using a variation of the (Kuzmin, 1972) approximation:

$$M_{subl} = 0.08 \cdot (0.18 + 0.098 \cdot v_{ave}) \cdot (P^0_{sat} - P_{vap})$$

where v_{ave} [m/s] is the wind velocity at 10m, P^0_{sat} is the saturation pressure at zero degrees, and P_{ave} [mb] is the atmospheric vapour pressure, respectively.

Central Sierra method (SUBLIM_CENTRAL_SIERRA)

The sublimation rate (in [mm/d]) is calculated using the following empirical relationship (U.S. Dept. of Commerce, 1956):

$$M_{subl} = 0.0063 \cdot (h_w \cdot h_v)^{-\frac{1}{6}} \cdot (P_{sat} - P_{vap}) \cdot v_{ave}$$

where v_{ave} [m/s] is the wind velocity at reference height h_w [ft], P_{sat} and P_{ave} [mb] are the saturated vapour pressure and vapour pressure, respectively, and h_v is the elevation of the vapour pressure reference height [ft].

3.16 Snow Refreeze

Snow refreeze algorithms are used if the full `:SnowBalance` algorithms are not applied, and simply convert `SNOW_LIQ` to `SNOW`

Snow refreeze always occurs between `SNOW_LIQ` and `SNOW` units. Snow refreeze is limited by the availability of liquid water in the snowpack. Refreeze rates must be positive. In most cases, snow refreeze should be handled using the `:SnowBalance` routines. Example usage in the .rvi file:

```
:SnowRefreeze FREEZE_DEGREE_DAY SNOW_LIQ SNOW
```

Available Algorithms

Degree day method (`FREEZE_DEGREE_DAY`)

The refreeze rate (in [mm/d]) is calculated using the following degree-day relationship (much like the degree-day melt approaches for calculating potential melt):

$$M_{frz} = K_f \cdot \min(T_f - T_a, 0)$$

where K_f [mm/d/ °C] is the refreeze parameter (land use parameter `REFREEZE_FACTOR`, T_f is the freezing temperature (0 °C) and T_a is the air temperature.

3.17 Snow Albedo Evolution

Snow albedo evolution is the process through which snow albedo changes due to snow compaction, snowpack aging, or fresh snow accumulation. The snow albedo evolution algorithms have no sources or sinks, it simply models the rate of change of albedo over time. Snow albedo is constrained to be in the range 0-1. Example usage in the .rvi file (note that there is no 'to' and 'from' state variable, since this is not changing the water/energy balance):

```
:SnowAlbedoEvolve SNOALB_UBC
```

Available Algorithms

UBC Watershed Model approach (SNOALB_UBC)

The albedo, α, increases with accumulating snow and decreases as the season progresses. It is bounded by the global parameters MIN_SNOW_ALBEDO MAX_SNOW_ALBEDO, defined in the :UBC–SnowParams command in the .rvp file.

$$M_{snalb} = -\alpha \cdot \frac{1-K}{\Delta t} + \frac{(\alpha_{max} - \alpha)}{\Delta t} \min\left(\frac{SN}{SN_{alb}}, 1\right) \qquad \text{if } \alpha > \alpha_b$$

$$M_{snalb} = -\alpha_b \exp\left(-\frac{S_{cum}}{S_{max}}\right) \frac{dS_{cum}}{dt} + \frac{(\alpha_{max} - \alpha)}{\Delta t} \min\left(\frac{SN}{SN_{alb}}, 1\right) \qquad \text{if } \alpha < \alpha_b$$

where α_{max} is the global parameter MAX_SNOW_ALBEDO, α_b is a threshold albedo value (ALBASE), SN [mm/d] is the daily snowfall, SN_{alb} [mm/d] is the total daily snowfall required to bring albedo to that of new snow (global param ALBSNW), K is the global parameter ALBREC (a recession constant), S_{cum} is the cumulative snow deposited in the current winter season and S_{max} is an estimate of the maximum cumulative snowfall in a year (MAX_CUM_MELT). All of these global parameters are specified using the command :UBCSnowParams in the .rvp file.

CRHM Essery Approach (SNOALB_CRHM_ESSERY)

A simple albedo evolution algorithm developed by Richard Essery, now at the University of Edinburgh. The albedo decays as follows:

$$M_{snalb} = -\beta \qquad \text{if } T_{snow} < 0$$

$$M_{snalb} = -\beta_2 \cdot (\alpha - \alpha_{min}) \qquad \text{if } \alpha < \alpha_b$$

where β is he global parameter ALB_DECAY_COLD [1/d], β_2 is the global parameter ALB_DECAY_MELT [1/d], and α_{min} is the global parameter MIN_SNOW_ALBEDO [-]. The albedo also increases due to fresh snow using the following

$$M_{snalb} = (\alpha_{max} - \alpha) \cdot \min(S/S_{thresh}, 1.0) \cdot \Delta t$$

where α_{max} is the global parameter MAX_SNOW_ALBEDO [-], S is the snowfall rate [mm/d], and S_{thresh} is the global parameter SNOWFALL_ALBTHRESH [mm/d].

Baker Approach (`SNOALB_BAKER`)

A simple albedo evolution algorithm from Baker et al. (1990), as ported from CRHM (Pomeroy et al., 2007). The albedo decays as follows:

$$\alpha = 0.9 - 0.0473 \cdot A_{snow}^{0.1}$$

where A_{snow} is the age of the snow in days. The snow age reboots to zero if the snowfall rate exceeds the global parameter `SNOWFALL_ALBTHRESH` [mm/d].

3.18 Glacier Melt

Glacier melt refers to the process of melting of glacier ice. It is typically only applied to those HRUs treated as glaciers.

Glacier melt algorithms move water from GLACIER_ICE to either GLACIER (liquid water storage in or on the glacier itself) or SURFACE_WATER. They may also modify the cold content of the glacier, GLACIER_CC. Glacial melt is not limited by the available glacier ice, which is assumed to be abundant. Example usage in the .rvi file:

```
:GlacierMelt GMELT_SIMPLE_MELT GLACIER_ICE SURFACE_WATER
```

Available Algorithms

Simple melt approach (GMELT_SIMPLE_MELT)

The melt rate is equal to the potential melt rate, calculated using the methods described in section 5.8.1.

HBV approach (GMELT_SIMPLE_MELT)

The melt rate is equal to the potential melt rate, calculated using the methods described in section 5.8.1. A glacial melt correction factor may be used to modify the melt rate (land use parameter HBV_MELT_GLACIER_CORR), which is 1 by default. No glacial melt occurs if there is any snow cover, i.e., the snow must melt first.

UBC Watershed Model approach (GMELT_UBC)

The potential melt rate is applied to melt the glacier, but modified by the snow cover (i.e., no glacial melt occurs if there is 100% snow cover).

3.19 Glacier Release

Glacier release refers to the release of meltwater stored within a glacier to surface water, and is typically used in conjunction with the glacier melt process, i.e., melt is released from the surface and is temporarily stored or delayed before reaching the surface water network.

Glacier release algorithms move water from GLACIER to SURFACE_WATER. Glacial release is limited by the available glacier liquid water storage. Example usage in the .rvi file:

```
:GlacierRelease GRELEASE_LINEAR_STORAGE GLACIER SURFACE_WATER
```

Available Algorithms

Linear storage (GRELEASE_LINEAR_STORAGE**)**

A simple linear storage coefficient approach:

$$M_{grelease} = -K\phi_{glac}$$

where ϕ_{glac} [mm] is the total glacial storage, and K [1/d] is a linear storage coefficient (land use parameter GLAC_STORAGE_COEFF)

Linear storage (analytical) (GRELEASE_LINEAR_ANALYTIC**)**

A simple linear storage coefficient approach, but analytically solved for and integrated over the timestep:

$$M_{grelease} = \frac{\phi_{glac}}{\Delta t}(1 - exp(-K\Delta t))$$

where ϕ_{glac} [mm] is the total glacial storage,Δt is the model time step and K [1/d] is a linear storage coefficient (land use parameter GLAC_STORAGE_COEFF)

HBV-EC approach (GRELEASE_HBV_EC**)**

A simple linear storage coefficient approach:

$$M_{grelease} = -K^*\phi_{glac}$$

where ϕ_{glac} [mm] is the total glacial storage, and K^* [1/d] is a linear storage coefficient which is corrected for snow cover, such that the glacier releases more water at times of less snow cover, calculated as:

$$K^* = K_{min} + (K - K_{min})\exp(-AG(SN + SN_{liq}))$$

where K_{min} [1/d] is a linear storage coefficient (land use parameter HBV_GLACIER_KMIN), K [1/d] is a linear storage coefficient (land use parameter GLAC_STORAGE_COEFF), AG [1/mm] is the land use parameter HBV_GLACIER_AG, and SN and SN_{liq} [mm] are the SWE and liquid snow content of the snowpack on top of the glacier, respectively.

3.20 Crop Heat Unit Evolution

Crop heat units (CHUs) are used by some organizations in Ontario, Canada in order to assess soil evaporation. ET is maximized when CHUs meet their maturity level. To be used in conjunction with the soil evaporation algorithm `SOILEVAP_CHU`. The crop heat units grow in magnitude over the course of a growing season based upon the daily temperature profiles.

Crop heat unit evolution algorithm does not move water between storage compartments. The method only revises the magnitude of the `CROP_HEAT_UNITS` state variable. Crop heat units are zero outside of the growing season. Example usage in the .rvi file:

```
:CropHeatUnitEvolve CHU_ONTARIO
```

Available Algorithms

Ontario method (`CHU_ONTARIO`)

The growing season is determined to begin when the minimum temperature over a 3-day period is 12.8 $^{\circ}$C, at which time the crop heat units are set to zero. It ends when the temperature dips below -2 $^{\circ}$Cor after September 30th. During the growing season, CHUs are incremented using the following expressions Brown and Bootsma (1993):

$$\begin{aligned} \text{CHU}_d &= 3.33 \cdot (T_{max} - 10) - 0.084 \cdot (T_{max} - 10)^2 \\ \text{CHU}_n &= 1.8 \cdot (T_{min} - 4.4) \\ \text{CHU}_{new} &= \text{CHU}_{old} + 0.5 \cdot (\text{CHU}_d + \text{CHU}_n) \end{aligned}$$

where T_{min} and T_{max} are the minimum and maximum daily temperatures

3.21 Special Processes

The flush, lateral flush, split, and overflow processes are used in conceptual models to represent the 'instantaneous' movement of water from one water storage compartment to another. The convolution process allows for a time lag of storage. As these are wholly conceptual in nature, they are most often included in order to emulate the functioning of existing hydrologic models. These processes may not work as intended when using a numerical method other than the ordered series approach.

- The Flush process instantaneously moves all of the water storage from one storage to another.
- The Lateral Flush process instantaneously moves all of the water storage from one storage in one or more HRUs in a basin to another storage unit in another HRU within the basin.
- The Overflow process moves the excess water storage (more than the maximum capacity of the water storage unit) to another compartment.
- The Split process instantaneously moves all of the water storage from one storage compartment into two, with the proportion specified in the input command.
- The convolution process temporarily stores water in a convolution storage compartment, to be released using a transfer function approach. The output fluxes from a convolution process are typically an attenuated and delayed version of the input fluxes.

The flush, lateral flush, overflow, and split processes may move water from any water storage compartment to any other. The convolution process (`:Convolve` command in the input) releases water added to a convolution storage structure buy any other process to any storage compartment. Example usage in the .rvi file:

```
# moves all ponded water to surface water
:Flush RAVEN_DEFAULT PONDED_WATER SURFACE_WATER

# moves liquid snow in excess of maximum liquid snow storage
#to surface water
:SnowBalance SNOBAL_SIMPLE_MELT SNOW SNOW_LIQ
:-->Overflow RAVEN_DEFAULT SNOW_LIQ SURFACE_WATER

# moves 60% of ponded water to surface water, the rest infiltrates
:Split RAVEN_DEFAULT PONDED_WATER SURFACE_WATER SOIL[0] 0.6

# delays release of surface water to outlet through convolution
:Flush RAVEN_DEFAULT      SURFACE_WATER   CONVOLUTION[0]
:Convolve CONVOL_GR4J_1   CONVOLUTION[0]  SURFACE_WATER

# moves all runoff from upland HRUs to wetlands
# requires definition of Uplands and Wetlands HRU groups
:LateralFlush RAVEN_DEFAULT Uplands SURFACE_WATER To Wetlands DEPRESSION
```

Available Algorithms (Convolution)

Since convolution methods store the time history of inputs to convolution storage of a duration consistent with the longest time delay in the convolution, it is not suggested to use convolution with a time constant

in days with an hourly time step. Typically the order of the time delay should be on the order of the model time step.

The below convolution methods are available. All of them perform a discrete version of the following convolution:

$$M_{conv} = \int_0^\infty UH(\tau) I(t-\tau) d\tau$$

where $I(t)$ is the input flux history (in mm/d) to the convolution storage unit and $UH(t)$ is the transfer function; the area under the transfer function is always equal to one to ensure mass balance.

GR4J transfer function 1 (`CONVOL_GR4J_1`**)**

The transfer function used is

$$UH(t) = \begin{cases} \frac{5}{2x_4}\left(\frac{t}{x_4}\right)^{\frac{3}{2}} & \text{for } t \leq x_4 \\ 0 & \text{for } t > x_4 \end{cases}$$

where x_4 is the land use parameter `GR4J_X4`.

GR4J transfer function 1 (`CONVOL_GR4J_2`**)**

The transfer function used is

$$UH(t) = \begin{cases} \frac{5}{4x_4}\left(\frac{t}{x_4}\right)^{\frac{3}{2}} & \text{for } t \leq x_4 \\ \frac{5}{4x_4}\left(2 - \frac{t}{x_4}\right)^{\frac{3}{2}} & \text{for } x_4 < t \leq 2x_4 \\ 0 & \text{for } t > 2x_4 \end{cases}$$

where x_4 is the land use parameter `GR4J_X4`.

Gamma transfer function 1 (`CONVOL_GAMMA`**)**

The transfer function used is

$$UH(t) = \frac{1}{t}\frac{(\beta t)^a}{\Gamma(a)}\exp(-\beta t)$$

where a and β are the land use parameters `GAMMA_SHAPE` and `GAMMA_SCALE`.

Gamma transfer function 2 (`CONVOL_GAMMA2`**)**

The transfer function used is

$$UH(t) = \frac{1}{t}\frac{(\beta t)^a}{\Gamma(a)}\exp(-\beta t)$$

where a and β are the land use parameters `GAMMA_SHAPE2` and `GAMMA_SCALE2`. The purpose of this is to be able to support two convolution processes in serial or parallel.

Chapter 4

Routing

The following chapter outlines the routing algorithms available for modelling the downstream migration of water through a terrain/channel/reservoir network in Raven. As briefly summarized in section 1.2.2, the routing process in Raven has two components: at the sub-basin level, rainfall and snowmelt from all HRUs is released to surface water via overland runoff, interflow, and base flow. There is some delay and/or redistribution of the timing of the release of this water to the subbasin river reach, then again a delay before the water reaches the outlet. This delay is handled in Raven typically using a linear transfer function (e.g., Unit Hydrograph) approach, and is termed in-catchment routing. The second form of routing is the hydraulic/hydrologic routing between subbasins within the main channel of each subbasin. This is referred to as in-channel routing. The distinction between the two is shown in figure 1.4. In addition to in-catchment and in-channel routing, a separate routine is used to route waters through reservoirs/lakes at the end of subbasins.

While this chapter addresses the primary catchment-channel-reservoir routing progression in Raven, Raven supports alternate means of influencing the timing characteristics of a basin. For instance, some lateral routing between HRUs may be performed prior to delivery to the stream network (e.g., see section 3.21 for discussion of the Lateral Flush process which can be used to route water laterally). This lateral transfer is separate from the landscape routing described in this chapter, but may therefore impact propagation of water downstream, for instance by sending landscape runoff to a riparian wetland. Other conceptual models (e.g., those in HBV) route water through conceptual routing stores; this is supported in Raven by using 'artificial' soil horizons as routing stores, as can be seen in the HBV-EC and GR4J model evaluations in appendix D.

4.1 In-Catchment Routing

4.1.1 Overview

It is important to note that the rate of release of water from storage within an HRU is treated as constant over a given time step. This is the most appropriate, since water storage state variables are stored as snapshots in time (at the end of each time step). However, in the channel, the state variable is no longer storage, but flow rates, as is consistent with the majority of routing algorithms developed in the literature. Therefore, in addition to impacting the timing of the flows, in-catchment routing is used to map flow rates which are constant over a time step (losses from the HRU) to those which are varying linearly over a time step (in-channel flows).

In all cases, in catchment routing is treated using a discrete transfer function approach, i.e.,

$$Q(t+\Delta t) = \sum_{n=0}^{N} Q_{lat}(t - n\Delta t) \cdot UH_n \tag{4.1}$$

where $Q(t)$ [m^3/s] is the flow rate into the channel from the subbasin at time t, $Q_{lat}(t)$ [m^3/s] is the constant lateral release flow rate from the HRU surface over the time step from t to $t + \Delta t$, and $\vec{UH}$ is a unitless vector which describes the distribution of arrival times to the channel. The sum of values of the $\vec{UH}$ vector equal 1, and the magnitude of UH_n may be interpreted as the percentage of the flow appearing in the channel n time steps after its release from the HRU. This is the discrete generalization of a convolution:

$$Q(t) = \int_0^{\infty} Q_{lat}(t - \tau) \cdot UH(\tau) d\tau \tag{4.2}$$

Either of these may be interpreted as providing a distributed delay between when water is released from the HRU and when it appears in the channel. There are numerous approaches in the literature for estimating unit hydrograph characteristics. While the unit hydrographs below are reported as continuous, they are internally converted to a discrete version via the following relation:

$$UH_n = \frac{1}{\Delta t} \int_{n\Delta t}^{(n+1)\Delta t} UH(t) dt \quad n = 0...\infty \tag{4.3}$$

Only non-zero $\vec{UH}$ vector elements are retained.

4.1.2 Algorithms

The following algorithms may be used for in-catchment routing. The sole difference between the various catchment routing algorithms is the shape of the unit hydrograph used.

Dump method (`ROUTE_DUMP`)

In the "dump" method of catchment routing, all of the water released from the HRUs to surface water over a time step appears in the channel at the end of the time step. This is generally valid for small subbasins (those with small times of concentration) or large time steps. This is equivalent to $\vec{UH} = \{1, 0, 0, 0, ...\}$, and is an approximation of

$$UH(t) = \delta(t)$$

where δ is the Dirac delta function.

Gamma unit hydrograph (`ROUTE_GAMMA_CONVOLUTION`)

Here, a Gamma distribution is used to represent the unit hydrograph, i.e.,

$$UH(t) = \frac{1}{t} \frac{(\beta t)^a}{\Gamma(a)} \exp(-\beta t)$$

where $\Gamma(a)$ is the Gamma function and a and β are the subbasin parameters GAMMA_SCALE and GAMMA_SHAPE. If not provided, a defaults to a reasonable value of 3. if the GAMMA_SCALE parameter is not provided but the time to peak subbasin parameter TIME_TO_PEAK (t_p) is provided, then β is calculated as follows:

$$\beta = \frac{a-1}{t_p}$$

Note that this automatic calculation can lead to issues when a<1.0, because the peak value occurs at $t = 0$ for this distribution when $a < 1.0$.

Triangular unit hydrograph (ROUTE_TRI_CONVOLUTION)

A triangular unit hydrograph is used with a peak time of t_p, specified as the subbasin property TIME_TO_PEAK and total duration specified by the time of concentration, t_c, specified using the subbasin property TIME_CONC. Note that variations in the time of concentration smaller than the model time step will have no impact on model solution.

$$UH(t) = \begin{cases} \frac{2}{t_c}\frac{t}{t_p} & \text{for } t < t_p \\ \frac{2}{t_c}\left(\frac{t_c - t}{t_c - t_p}\right) & \text{for } t \geq t_p \end{cases}$$

Nash unit hydrograph (ROUTE_RESERVOIR_SERIES)

The Nash unit hydrograph is used with a linear reservoir constant (k) specified using the subbasin property RES_CONSTANT and the number of reservoirs (N) equal to NUM_RESERVOIRS.

$$UH(t) = t^{N-1}k^N e^{-kt}$$

To do (2)

4.2 In-Channel Routing

4.2.1 Overview

In Raven, in-channel routing is the only means by which water, mass, and energy are exchanged laterally between subbasins. It is assumed that this movement is unidirectional, i.e., water moves downstream only through a one-dimensional branching stream network fully described by the succession of subbasins defined in the .rvh file. Each subbasin can have a single outlet and is conceptualized as having a single primary channel running through it, which may or may not have a reservoir at the end of the channel. Headwater subbasins (those without an upstream subbasin) are assumed to have no corresponding channel, but may have a reservoir which is fed purely via in-catchment routing and releases water to the next downstream basin.

This routing formalization leads to some implicit guidelines for subbasin discretization.

- Subbasin outlets should typically occur at stream network junctions.
- Surface water reservoirs should be located at the outlet of a subbasin (or themselves embody an entire subbasin)
- All stream gauges used for calibration or model evaluation should be located at the outlet of a subbasin
- For lumped (single subbasin) models, channel routing is usually disabled entirely.

In-channel routing may be treated by a number of algorithms. However, as indicated in section 1.2.2, all of these algorithms may be generalized as

$$Q_{out}^{n+1} = F_{route}(Q_{out}^{n}, \vec{Q}^{in}, \vec{P}_s) \tag{4.4}$$

where F_{route} is the routing algorithm, $\vec{Q}^{in}$ is the recent time history of upstream (and upbasin) inflows to the channel, $\vec{P}_s$ is a vector of channel parameters, typically a number of channel rating curves, primary channel and bank roughness, and weir or reservoir relationships. Figure 1.4 indicates the meaning of these major parameters. The descriptions of the channel inputs are detailed in section A.2.2 of the appendix, and specified using the `:ChannelProfile` command.

4.2.2 Algorithms

While more rigorous hydraulic routing algorithms (which handle backwater effects, etc.) may be implemented in future incarnations of Raven, for the most part, the algorithms currently in Raven are considered hydrologic routing methods based upon simple storage relationships, rather than complete solution of the Saint-Venant equations for momentum and mass conservation. They fall roughly into two categories: convolution approaches, which function in a manner nearly identical to that of the unit hydrograph approach used for in-catchment routing, and mass-balance approaches, which solve for outflow through a discrete form of the mass balance equation. Both sets of approaches are mass-conservative.

As with the in-catchment methods, the convolution-based methods (`ROUTE_DIFFUSIVE_WAVE`) and (`ROUTE_PLUG_FLOW`), use a discrete transfer-function approach:

$$Q_{out}^{n+1} = \sum_{i=0}^{N} Q_{in}^{n-i+1} \cdot UH_i' \tag{4.5}$$

where Q_{out}^{n+1} [m^3/s] is the flow rate from the subbasin at the end of the time step, Q_{in}^{n} [m^3/s] is the inflow rate from upstream sources at the end of time step n, and $\vec{UH'}$ is a unitless vector which describes the distribution of arrival times to the channel. The sum of values of the $\vec{UH'}$ vector equal 1, and the magnitude if UH_i' may be interpreted as the percentage of the flow leaving from the channel i time steps after its arrival in the channel from upstream sources.

Many of the in-channel routing routines require the reference celerity for the channel reach:

$$c_{ref} = \left.\frac{dQ}{dA}\right|_{Q_{ref}} \tag{4.6}$$

c_{ref} is the reference celerity for the reach, the velocity corresponding to the reference flow, Q_{ref} [m^3/s] in the reach, usually specified as the bank full flow using the subbasin parameter `Q_REFERENCE`. The slope of the Q vs. A relationship at Q_{ref} is interpolated from that generated for the specific channel.

No routing (`ROUTE_NONE`)

All inflows (both lateral and upstream), are instantly routed to the channel outlet, i.e.,

$$Q_{out}^{n+1} = Q_{in}^{n+1} + Q_{lat}^{n+1}$$

This option is mostly used for single subbasin models.

Simple plug flow (`ROUTE_PLUG_FLOW`)

Here, there is a delay between water entering and exiting the channel dictated by the celerity of the channel reach, but there is no smearing out of the hydrograph as it migrates along the channel.

$$UH'(t) = \delta\left(t - \frac{L}{c_{ref}}\right)$$

where $\delta(t)$ is the Dirac delta function, L is the reach length within the subbasin (specified from the subbasin property `REACH_LENGTH`, and c_{ref} is the reference celerity of the channel, as determined from the channel profile characteristics and the subbasin's reference flow rate, Q_{ref} specified as the subbasin parameter `Q_REFERENCE`. The reference celerity c_{ref} is calculated using 4.6.

Diffusive wave model (`ROUTE_DIFFUSIVE_WAVE`)

Here, an analytical solution to the diffusive wave equation is used to smear out the flood wave as it propagates through the reach. As with the simple plug flow approach, the reference celerity is used to determine the mean travel time of the wave, and the channel diffusivity, D [m^{2}d^{-1}] controls the smearing out of the wave signal prior to exiting the reach.

$$UH'(t) = \frac{1}{2\sqrt{\pi D t}} \exp\left(-\frac{(L - c_{ref}t)^2}{4Dt}\right)$$

where L [m] is the channel reach length, c_{ref} is calculated using 4.6, and the channel diffusivity, D, is estimated from the channel reference flow Q_{ref} (subbasin parameter `Q_REFERENCE`) using the following relationship: **To do** (3)

$$D = \frac{Q_{ref}}{2S \cdot d(Q_{ref})}$$

where S is the channel bedslope and $d(Q)$ is the relationship between flow depth, d and flow rate, Q, in the channel, determined from the channel geometry. The diffusive wave model is currently the preferred routing method for transport simulation.

Storage coefficient method (ROUTE_STORAGE_COEFF)

The storage coefficient method evaluates outflow using a discrete approximation of the water balance for the channel over the time step Williams (1969):

$$Q_{out}^{n+1} = c_1 \cdot Q_{in}^{n+1} + c_2 \cdot Q_{in}^{n} + c_3 \cdot Q_{out}^{n} \tag{4.7}$$

here, the weights c_1, c_2, and c_3 are calculated from the storage coefficient, k, given as:

$$k = \min\left(\frac{1}{\frac{K}{\Delta t} + 0.5}, 1\right) \tag{4.8}$$

where K is the representative travel time for the reach (also the Muskingum K parameter, calculated as $\Delta x / c_{ref}$ where Δx is the reach segment length). Here, $c_1 = k/2$, $c_2 = k/2$, and $c_3 = 1 - k$. Caution should be used with this method on long reaches without finely discretizing the reach, as water will arrive at the outlet immediately after entering, even with a large representative travel time in the reach.

Muskingum-Cunge method (ROUTE_MUSKINGUM)

The standard Muskingum-Cunge approach also evaluates outflow using a discrete approximation of the water balance for the channel over the time step:

$$Q_{out}^{n+1} = c_1 \cdot Q_{in}^{n+1} + c_2 \cdot Q_{in}^{n} + c_3 \cdot Q_{out}^{n} \tag{4.9}$$

here, the weights c_1, c_2, and c_3 are calculated from the Muskingum X and K parameters as

$$\begin{aligned} c_1 &= \frac{\Delta t - 2KX}{2K(1-X) + \Delta t} \\ c_2 &= \frac{\Delta t + 2KX}{2K(1-X) + \Delta t} \\ c_3 &= \frac{-\Delta t + 2K(1-X)}{2K(1-X) + \Delta t} \end{aligned}$$

The Muskingum algorithm is well-documented in the literature. **To do** (4) The Muskingum parameters X and K are calculated using the following relations:

$$K = \frac{\Delta x}{c_{ref}}$$

$$X = \frac{1}{2}\left(1 - \frac{Q_{ref}}{S w_{ref} c_{ref} \Delta x}\right)$$

where c_{ref} is the reference celerity for the reach (calculated using equation 4.6), S is the channel bedslope, w_{ref} is the channel width at the reference flow Q_{ref} (basin parameter Q_REFERENCE), and Δx is the reach segment length (or reach length, L, if only one segment is used per reach). Care must be taken to ensure that X and K fall within a reasonable range of values, notably that $2KX < \Delta t < 2K(1-X)$. If the time step is too large, Raven automatically employs local time stepping for the routing algorithm. However, the case where the time step is too small (a warning will be thrown to RavenErrors.txt) must be handled via user intervention, by increasing the number of segments in the reach.

Iterative hydrologic routing approach (`ROUTE_HYDROLOGIC`)

Here, the routing is performed using an iterative application of Newton's root-finding algorithm to the following discretization of the storage relationship for the reach,

$$\frac{V(Q_{out}^{n+1}) - V(Q_{out}^{n})}{\Delta t} = \frac{1}{2}(Q_{in}^{n} + Q_{in}^{n+1}) - \frac{1}{2}(Q_{out}^{n} + Q_{out}^{n+1})$$

Given that the channel volume, $V(Q)$ may be written as a function of outflow from the reach if a level-pool assumption is used, this may be expressed as a root-finding problem for Q_{out}^{n+1}. This method is very stable, fast, accurate, and mass-conserving. It avoids the numerical pitfalls of the non-iterative Muskingum algorithm. Right now, it can only be applied to reaches which constitute a single reach segment.

4.3 Lake and Reservoir Routing

4.3.1 Overview

Lakes or reservoirs may be specified using a `:Reservoir-:EndReservoir` command in the .rvh file (see appendix A.3), and are always located a the outlet of a subbasin, i.e., a reservoir linked to a given subbasin receives its water from that basin's in-channel routing routine, then releases it downstream. Raven supports a range of methods for determining the outflow from a reservoir or lake using either stage-discharge relationships or operational constraints such as flow and stage targets. Each reservoir may have two stage-discharge curves to represent, for example, combined tunnel underflow and spillway overflow. For simple natural lakes, stage-discharge curves can be calculated by Raven, only the estimated crest width of the lake overflow is specified by the user. A schematic of two common reservoir configurations, one for a prismatic single-parameter lake and one for a general managed reservoir are shown in figure 4.1

Iterative reservoir routing approach

Only one algorithmic option is available for routing water in a reservoir. In this approach, a Newton solver is used to iteratively calculate the reservoir stage using the following time discretization of the reservoir level-pool mass balance:

$$\begin{aligned} \frac{dV(h)}{dt} &= Q_{in} - Q(h) - E \cdot A(h) - S(h) \\ \frac{V(h^{n+1}) - V(h^{n})}{\Delta t} &= \frac{1}{2}(Q_{in}^{n} + Q_{in}^{n+1}) - \frac{1}{2}\left(Q(h^{n}) + Q(h^{n+1})\right) \\ &\quad -\frac{E}{2}\left(A(h^{n}) + A(h^{n+1})\right) - \frac{1}{2}\left(S(h^{n}) + S(h^{n+1})\right) \end{aligned}$$

where h is the stage and $Q(h)$, $V(h)$, and $A(h)$ are the stage-discharge, stage-volume, and stage-area relations defined in the `:Reservoir` command (appendix A.3.2). E is the timestep-averaged open-water evaporation rate for the reservoir calculated as determined by the `:OWEvaporation` command for the reservoir-linked open water HRU. $S(h) = k \cdot (h - h_{gw})$ is the groundwater seepage rate of the reservoir, calculated from a seepage coefficient k [m^3/d] and groundwater reference head h_{gw} (specified using the `:SeepageParameters` command). Reservoir evaporation may be modified by the `LAKE_PET_CORR` land surface parameter. Note that the reservoir should be included as an HRU with the average reservoir area. All precipitation falling on this HRU gets added to the Q_in component, where evaporation from the

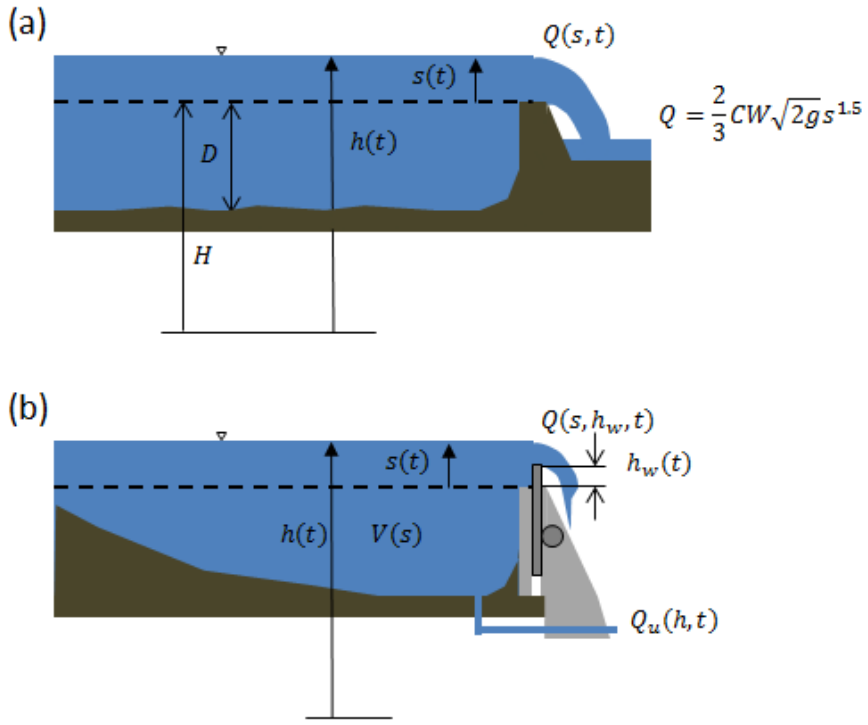

Figure 4.1: Example reservoir configurations in RAVEN. (a) a lake-type reservoir and (b) a general managed reservoir. $h(t)$ is the absolute stage height and $s(t)$ is the height of the water level above the minimum crest height. For the lake-type reservoir, D is the `:MaxDepth` parameter, H is the optional `:AbsoluteCrestHeight` parameter, C is the `:WeirCoefficient`, and W is the `:CrestWidth`. For operated reservoirs, typically the stage-volume ($V(h)$) and stage-discharge ($Q(h)$) curves are provided, with optional support for underflow $Q_u(h)$ if desired. The gate shift $h_w(t)$ may be specified to represent the operation of a stop-log weir or similar.

surface of the reservoir is only included in the above expression. If no HRU is linked to the reservoir in the reservoir command, evaporation is considered negligible and not included in the mass balance.

It is critical that the entire range of likely stage elevations are included when specifying the stage-discharge ($Q(h)$) and stage-volume ($V(h)$) curves. The outflow from the reservoir is determined solely from the stage-discharge curve unless overridden by operational rules.

Operational controls that can be applied to determine reservoir outflow include:

- Maximum Stage constraints - the maximum stage may be provided as a time series using the `:ReservoirMaxStage` command in an .rvt file. The maximum stage constraint overrides all other controls.
- Minimum Stage constraints - the minimum stage may be provide as a time series using the `:ReservoirMinStage` command in an .rvt file. The minimum stage must be less than the maximum stage; if the minimum stage constraint is hit, then the outflow is set to zero or to the minimum flow as proscribed in the `:ReservoirMinStageFlow` time series command.
- Target Stage constraints - the target stage may be provides as a time series using the `:ReservoirTargetStage` command in an .rvt file. The target stage must be between the minimum and maximum stage. When supplied, the required outflow at the end of the time step Q^{n+1} needed to maintain the target stage (i.e., such that $h^{n+1} = h^{n+1}_{target}$) will be determined. If there are no

maximum flow change constraints, this will be applied and the target stage will always be met. However, if a maximum flow change constraint is met, then the change in discharge over the time step ($Q^{n+1} - Q^n$) will be limited by the flow constraint, which is expressed as the maximum positive rate of change in outflow, in m^3/s. This maximum flow change constraint is supplied as a time series via the `:ReservoirMaxQDelta` command. There can also be a maximum negative rate of change in outflow specified using the `:ReservoirMaxQDecrease` command.

- Variable weir height - the datum of the stage-discharge curve may be shifted over time by specifying the relative weir height as a time series with the `:VariableWeirHeight` command. This can emulate the operation of a stop-log weir or similar weir structure where the crest height is controlled by operators.
- Outflow override - the outflow from the reservoir may be completely specified by the user if the `:OverrideReservoirFlow` time series command is supplied for the modeled reservoir.
- Minimum flow constraints - the minimum flow may be provided as a time series using the `:ReservoirMinFlow` command in an .rvt file. This specified minimum flow may increase to satisfy downstream target flows specified using the `:ReservoirDownstreamFlow` command, if present.
- Maximum flow constraints - the maximum flow may be provided as a time series using the `:ReservoirMaxFlow` command in an .rvt file.
- The DZTR (Dynamic Zoned Target Release) model of Yassin et al. (2019) - the discharge is calculated using a time-variable volume-discharge curve generated via matching historical observations occurring under unknown reservoir operational rules using the `:DZTRResservoirModel` command in the .rvh `:Reservoir` block.

Advice

If any of these reservoir constraints are constant in time or annually cyclical, use the `:AnnualCycle` time series command so you don't have to specify a long redundant time series in the .rvt file.

The combination of maximum, minimum, and target stage constraints may be used, for instance, to emulate historical application of rule curves during the model calibration/validation process. The override reservoir outflow control can be used to replace modeled outflows from a reservoir with observed outflows during model calibration/validation or it can be used in short-term forecasting to examine the influence of operational decisions on reservoir stage and downstream flows. Lastly, approximate rule curves may be used in forecasting for systems where actual operational rules are unknown. It is worth noting the order of priority of these different constraints when multiple operational controls are specified for a reservoir (from highest priority to lowest priority):

1. Maximum stage constraint has highest priority (`:ReservoirMaxStage`)
2. Minimum flow and maximum flow constraints (`:ReservoirMinFlow` and `:ReservoirMaxFlow` (and also downstream target flows from `:ReservoirDownstreamDemand` influencing minimum flow))
3. Overridden flow (`:OverrideReservoirFlow`)
4. Minimum stage with Min stage specified flow (which is zero if not specified) (`:ReservoirMinStage` and `:ReservoirMinStageFlow`)*
5. Qdelta constraints (`:ReservoirMaxQDelta` and `:ReservoirMaxQDecrease`)
6. Target stage (`:ReservoirTargetStage`)

7. Natural weir flows has lowest priority

*The minimum stage constraint can be moved to the top of this list (i.e., get highest priority) by using the `:MinStageConstraintDominant` command in the `:Reservoir` block.

Note that there are a number of different approaches available for discretizing and representing lakes and reservoirs in Raven. For small lakes, we may not wish to explicitly represent their outflow characteristics and only wish to represent their role in influencing the basin water balance. In this case, water HRUs would be included in the basin, but a reservoir would not be used. For smaller lakes or reservoirs that still have a notable influence on downstream flows, a single water HRU would be included in the subbasin and linked to the reservoir. For natural lakes, it is suggested to use the 'lake-type' reservoir input structure described in appendix A.3.2. For large reservoirs (especially those with multiple subbasins draining into them), it is suggested to treat the reservoir as its own single-HRU subbasin with zero reach length.

Known inflows or outflows from the reservoir (e.g., irrigation diversions) may be considered in the above mass balance using the `:ReservoirExtraction` time series command in the .rvt file.

If reservoirs are present in the model, the file `ReservoirStages.csv` file is automatically created (with the runname prefix if specified). A full reporting of reservoir mass balance for all gauged subbasins is provided in the file `ReservoirMassBalance.csv` if the `:WriteReservoirMBFile` command is included in the .rvi file.

Observations of reservoir inflow, reservoir net inflow, and/or reservoir stage may be supplied to Raven and be evaluated against simulated values using the full set of diagnostics indicated in section 8.2.

4.4 Water Demand and Flow Diversions

4.4.1 Overview

Raven supports user-specified time series of water demand (e.g., irrigation or water treatment withdrawals) and flow diversions from one part of the watershed to another. It also supports simplified management constraints upon reservoirs based upon downstream demand. The key tools for representing these management-driven influences on river discharge include the following commands, described in details in appendix A.4.4:

- `:IrrigationDemand` (.rvt): a time series of desired withdrawals from the outlet of a subbasin, constrained such that stream discharge must be greater than zero or the environmental minimum flow.
- `:EnvironmentalMinFlow` (.rvt): used to constrain irrigation demand to maintain environmental minimum flows. If flows are less than environmental minimum flows, irrigation demand goes unmet.
- `:FlowDiversion` (.rvt): moves water from the outlet of one subbasin to the inlet of another basin. A simple percentage of simulated discharge may be used, or a user-specified lookup table may be used with the `:FlowDiversionLookupTable` command.
- `:ReservoirDownstreamDemand` (.rvt): ensures that the minimum outflow from reservoirs satisfies irrigation demand downstream. This can be specified on a case-by-case basis where (e.g.) a single reservoir meets a percentage of demand at a single location. Alternately, multi-reservoir systems may support multiple downstream demands as is controlled by the `:ReservoirDeman-`

dAllocation command in the .rvi file. Percentages of downstream demand may be determined by reservoir contributing area or by maximum reservoir capacity.

- :ReservoirExtraction (.rvt): supports both extraction from a reservoir or (if negative) injection of water into a given reservoir.
- :BasinInflowHydrograph (.rvt): can be used to add water to (or remove water from, if negative) a subbasin at its reach outlet. If negative, this command does not respect positivity constraints, so the :IrrigationDemand command is preferred.
- :BasinInflowHydrograph2 (.rvt): can be used to add water to a subbasin at its reach inlet.

Because extractions are applied at the inlet (upstream end of basin main reach) or outlet (downstream end of main reach), users may wish to consider discretizing the watershed into subbasins in such a way that demand or supply locations correspond to basin outlets. Unmet irrigation demand is reported in the output file demands.csv when the :WriteDemandsFile command is included.

4.4.2 Reservoir Demand Allocation

Reservoirs are often managed in such a way to support downstream irrigation needs. Raven supports emulation of this management practice by modifying the minimum flow targets for individual reservoirs based upon the instantaneous flows at irrigation demand locations downstream. The :ReservoirDownstreamDemand command implements this functionality, and can support individual demands (e.g., Reservoir A is expected to meet 80% of irrigation demand at location 1) or multiple demands (e.g., the 3 reservoirs upstream of demand location 2 share the responsibility of satisfying the minimum flow at that location. The impact of multiple controls simultaneously applied are best demonstrated via example. Consider the watershed in figure 4.2.

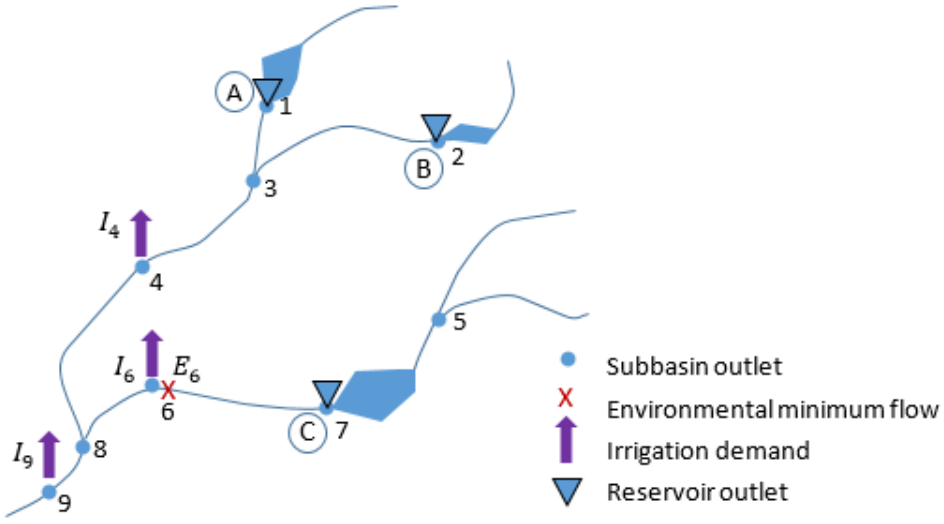

Figure 4.2: An example reservoir routing configuration

This system is represented using the following setup:

In the .rvi file:

```
:ReservoirDemandAllocation DEMANDBY_CONTRIB_AREA
```

In the .rvt file:

```
:IrrigationDemand 4
  :AnnualCycle 0 0 0 0 20 20 20 20 20 10 0 0 #monthly flows [m3/s]
:EndIrrigationDemand
:IrrigationDemand 6
  :AnnualCycle 0 0 0 0 10 10 10 10 10 0 0 0
:EndIrrigationDemand
:IrrigationDemand 9
  :AnnualCycle 0 0 0 0 5 5 30 5 5 5 0 0
:EndIrrigationDemand
:EnvironmentalMinFlow 6
  :AnnualCycle 22 22 22 22 22 22 22 22 22 22 22 22
:EndEnvironmentalMinFlow

# 20% of irrigation demand in subbasin 4 is supported by
# reservoir A (in subbasin 1)
:ReservoirDownstreamDemand 4 1 0.2
# 90% of irrigation demand in subbasin 6 is supported by
# reservoir C (in subbasin 7)
:ReservoirDownstreamDemand 6 7 0.9
# 50% of irrigation demand in subbasin 9 is supported
# by upstream reservoirs
:ReservoirDownstreamDemand 9 _AUTO 0.5
```

In the .rvp file, the global demand multiplier, α_G is set with the command `:GlobalParameter RESERVOIR_DEMAND_MULT`. In the .rvh file, in the `:Reservoir` command blocks, the local demand multipliers α_i are set using the `:DemandMultiplier` property.

Because these reservoir demand constraints are additive, the minimum outflow from each reservoir can be calculated as follows:

$$\begin{aligned} Q^A_{min} &= \alpha_A \cdot \alpha_G \cdot \left((0.2 \cdot I_4) + \frac{A_1}{A_1 + A_2 + A_7} \cdot (0.5 \cdot I_9) \right) \\ Q^B_{min} &= \alpha_B \cdot \alpha_G \cdot \left(\frac{A_2}{A_1 + A_2 + A_7} \cdot (0.5 \cdot I_9) \right) \\ Q^C_{min} &= \alpha_C \cdot \alpha_G \cdot \left((0.9 \cdot I_6) + \frac{A_7}{A_1 + A_2 + A_7} \cdot (0.5 \cdot I_9) \right) + E_6 \end{aligned}$$

where A_i, I_i and E_i are the contributing area, irrigation demand, and environmental minimum flow of basin i, respectively. Note that the α_i terms locally correct the influence of each dam; by setting to zero, the influence of this demand constraint can be turned off. The global modifier α_G can evaluate different management scenarios (e.g., determine the impact of not modifying reservoir flows to support downstream demand). It can be seen that if the local and global demand multipliers are equal to one, the minimum flows of all three reservoirs will satisfy 50% of the demand in subbasin 9. It should also be noted that if an environmental minimum flow is specified at a downstream demand location, then it must be respected by the reservoir outflow, without any multiplier used.

Chapter 5

Forcing Functions

In Raven, forcing functions, such as rainfall or incoming radiation, are calculated from meteorological information specified at gauge stations in the watershed or, alternatively, from gridded weather/climate data. This information is interpolated between gauge stations or grid cells to each hydrologic response unit (HRU), where it may be corrected for orographic or other effects. Forcing functions are calculated at the beginning of each computational time step, and are always constant over individual time steps. Many forcing functions may be estimated by Raven if field data is unavailable.

Note that the basic data from which forcing functions are generated (often daily precipitation, minimum/maximum daily temperature, etc.) must be reported in terms of rates (e.g., mm/d or MJ/m^2/d) for precipitation and radiation data, not total quantities for the time period. For example, if hourly rainfall information is stored in mm, it must be converted to mm/d prior to simulation. Missing data in the gauge information is currently not allowed. The time periods of available forcing data must fully overlap the simulation duration, but they do not have to be identical.

The minimum required forcing data for fueling a Raven simulation is daily precipitation and daily maximum and minimum temperature. From this, Raven can partition precipitation into snowfall and rainfall, estimate subdaily temperatures and PET, and provide estimates of incoming shortwave and longwave radiation. Alternately, these parameters may be specified if available. Raven has the ability to estimate the following forcings from simple records of total precipitation and daily min/max temperatures:

- Snowfall/Rainfall
- Potential ET (or reference ET)
- Shortwave and longwave net radiation
- Cloud cover
- Potential melt
- Wind speed, relative humidity, and air pressure
- Orographic corrections to temperature, precip, and potential ET rates
- Sub-daily corrections to daily ET, SW radiation, and potential melt rates

Refer to section A.1.2 of Appendix A for more details about each of the available processes that will be discussed in this chapter.

5.1 Spatial Interpolation

Spatial interpolation of forcing functions from gauge stations to HRUs is based upon the lat-long locations of the gauges and HRUs as specified in the .rvt and .rvh files, respectively. These coordinates are internally converted into the most appropriate local Universal Transverse Mercator (UTM) coordinate system (as determined by Raven) to calculate distances between points. Raven currently supports nearest neighbor and inverse distance weighting interpolation, as documented under the `:Interpolation` command in appendix A.1. It also supports the provision of a user-specified gauge weighting file, such that gauges may be assigned specifically to individual HRUs or alternate interpolation schemes may be used external to the program.

In general, any interpolated field value (e.g., temperature), is calculated for each HRU using a relatively general weighted averaging scheme:

$$V_k = \sum_{g=1}^{NG} w_{kg} \cdot V_g$$

i.e., any value V_k for HRU k is generated by weighting the values from all gauges V_g, using an HRU-specific weighting factor w_{kg}. Note that $\sum_{g=1}^{NG} w_{kg} = 1$ is required. Different interpolation schemes differ only in the means by which they generate the weights, usually based upon the relative geographic position of the HRUs and gauges.

For gridded data, the contributions to each HRU to each grid cell is similarly specified using a weighting scheme, though in this case the most intuitive weighting scheme is to use an area-weighted average of the cells that overlap each HRU, i.e.,

$$V_k = \sum_{g=1}^{NC} w_{kg} \cdot V_g$$

where NC is the number of cells and $w_{kg} = (A_g \bigcap A_k)/A_k$, i.e., the weighting is determined by the area of intersection ($\bigcap$) between the grid cell (A_g) and HRU (A_k). The user must define these weights, typically using GIS.

As of v2.8, Raven supports two different sets of gauges interpolants, i.e., only a subset of gauges must have temperature or precipitation. If an automated interpolation technique (e.g., `INTERP_NEAREST_NEIGHBOR`) is used, only the gauges that have available temperature data will be used to interpolate temperature; all other gauges will be given a weight of 0.0; likewise with precipitation. However, if the interpolation is user-supplied (`INTERP_FROM_FILE`), all gauges must have precipitation and temperature data. If windspeed/radiation/humidity data is provided, it must be provided at the same gauges where precipitation is available.

Note that values are first spatially interpolated, then corrected for orography. Orographic corrections are based upon the interpolated gauge elevation. This ensures, for instance, that an HRU directly between two met stations at different elevations doesn't get doubly corrected for orography - the interpolation already handles this. The interpolated gauge reference elevation is calculated as:

$$\hat{z}_k = \sum_{g=1}^{NG} w_{kg} \cdot z_g \tag{5.1}$$

where z_g is the elevation of the g^{th} gauge. Note that for a nearest neighbor interpolation, this is equivalent to standard orographic corrections from the nearest meteorological gauge.

5.1.1 Interpolation for Gridded Data

If gridded data in NetCDF format is supplied using the `:GriddedForcing` command, then the user must provide a means of mapping grid cell meteorological data to HRUs. This is done in a similar fashion to the `INTERP_FROM_FILE` option for meteorological gauges. Usually, one would generate the relative area coverage of each cell i in each HRU k using a GIS tool. The proper weighting for each grid cell in each HRU is then $w_{ki} = A_{ki}/A_k$ where A_{ik} is the area of the HRU and A_{ik} is the area of NetCDF grid cell i which overlaps HRU k. With this (specified using the `:GridWeights` command structure explained in appendix A.4.6), the forcings for each HRU may be calculated as:

In general, any interpolated field value (e.g., temperature), is calculated for each HRU using a relatively general weighted averaging scheme:

$$V_k = \sum_{i=1}^{NC} w_{ki} \cdot V_i$$

i.e., any forcing (precip/temp/etc.) value V_k for HRU k is generated by weighting the values from all NC cells V_i, using an HRU-specific weighting factor w_{ki}. Note that $\sum_{i=1}^{NC} w_{ki} = 1$ is required. Different interpolation schemes differ only in the means by which they generate the weights, usually based upon the relative geographic position of the HRUs and gauges.

If cell representative elevations are provided, the representative elevation of the meteorological data in each cell is given as

$$\hat{z}_k = \sum_{i=1}^{NC} w_{ki} \cdot \hat{z}_i$$

where $\hat{z}_i$ is the representative cell elevation (usually the mean ground elevation in each climate model cell). If not provided, it is assumed that no orographic corrections are applied, i.e., $\hat{z}_k = z_k$, where z_k is the elevation of the HRU. This is fairly reasonable approximation if the grid cells are small enough such that there is relatively small variability of elevation within each cell.

5.2 Temperature

Daily average, sub-daily, and daily minimum and maximum temperatures are required for many hydrologic simulation algorithms. This forcing data is often used for partitioning of precipitation into rainfall and snowfall components, estimating potential and actual evapotranspiration, driving snow melt and refreezing, as a proxy for cloud cover, etc., etc. In Raven, one of three temperature data sets are needed at each gauge or grid cell. Ideally, sub-daily (typically hourly) data is specified, and daily minimum, maximum, and average temperatures are calculated directly. If daily minimum and maximum temperature data are provided, daily averages are calculated as the average of the two, and sub-daily temperatures (if needed) are specified using the approach dictated by the `:SubDailyCorrection` command. Lastly, in the worst case scenario where only daily average temperature is provided, the daily min, max, and sub-daily temperatures are also generated using the approach specified in the `:SubDailyCorrection` command, but with the max and min calculated as the mean daily temperature plus or minus 4 degrees.

5.2.1 Orographic Temperature Effects

Orographic effects may be applied to correct temperature estimates at each HRU based on the specified elevation of the HRU relative to the local meteorological gauge. The options available for orographic temperature adjustment are described below. The orographic temperature effect is set in the RVI file using the `:OroTempCorrect` keyword. Orographic corrections are typically only applied to gauged (not gridded) input data. Orographic corrections would typically not be applied when gridded temperature data is provided.

> **Advice**
>
> The `OROCORR_SIMPLELAPSE` is recommended for most applications, unless trying to emulate a specific model configuration (i.e., HBV or UBCWM). The UBCWM algorithm performs well on the western face of the Rockies.

Simple method (`OROCORR_SIMPLELAPSE`)

The simple method for orographic temperature correction estimates the HRU through the application of a lapse rate correction to the associated gauge temperature:

$$T = T_k - \alpha(z - \hat{z}_k) \tag{5.2}$$

where T is the estimated HRU temperature after correction, T_k is the temperature in the HRU interpolated from the gauge data, z and $\hat{z}_k$ are the elevation of the HRU and reference elevation at the gauge respectively, where $\hat{z}_k$ is calculated from equation 5.1, and α is the specified adiabatic lapse rate. Equation 5.2 is applied to all temperature forcing variable time series, including: daily average, minimum and maximum; and monthly average, minimum and maximum. The adiabatic lapse rate is set with the `:AdiabaticLapseRate` keyword in the RVP file. Note that this correction is equivalent to the standard interpretation of lapse rates for nearest neighbor interpolation, i.e., 5.2 simplifies to:

$$T = T_g - \alpha(z - z_g) \tag{5.3}$$

where z_g is the elevation of the nearest gauge and T_g is the temperature at the nearest gauge.

HBV method (OROCORR_HBV)

The HBV model method from Bergstrom (1995) employs the simple orographic temperature correction method described above employing Equation 5.2, except that the monthly average temperatures are not lapsed to be consistent with their treatment in the standard HBV model.

UBCWM method 1 (OROCORR_UBC)

The UBC watershed model orographic temperature correction method 1 employs a series of lapse rates and inflection points describing the orographic correction profile. The UBC method 1 calculates four temperature lapse rates: above and below 2000 m elevation for both daily maximum and daily minimum temperatures. The parameters are set in the .rvp file using the following keyword and parameter sequence:

```
:UBCTempLapseRates A0TLXM A0TLNM A0TLXH A0TLNH P0TEDL P0TEDU
```

The parameters listed above are described in Table 5.1.

Table 5.1: UBC Watershed Model temperature lapse rate parameters

Parameter	Description	Units
A0TLNH	Lapse rate for minimum temperatures when the station elevation is greater than 2000 m	C / 1000 m
A0TLNM	Lapse rate for minimum temperatures when the station elevation is less than 2000 m	°C/ 1000 m
A0TLXH	Lapse rate for maximum temperatures when the station elevation is greater than 2000 m	°C/ 1000 m
A0TLXM	Lapse rate for maximum temperatures when the station elevation is less than 2000 m	°C/ 1000 m
P0TEDL	Lapse rate of maximum temperature range for elevations below 2000 m	°C/ 1000 m
P0TEDU	Lapse rate of maximum temperature range for elevations above 2000 m	°C/ 1000 m

$$V = \begin{cases} \min\left(\frac{P}{\text{A0PPTP}}, 1.0\right), & \text{if A0PPTP} > 0 \\ 0, & \text{if A0PPTP} \leq 0 \end{cases} \tag{5.4}$$

where P is the precipitation rate, A0PPTP is the threshold precipitation for temperature lapse rate in mm and V is a rainfall correction factor that transition a lapse rate from a dry to wet adiabatic lapse rate based on current precipitation rate. A corrected adiabatic lapse α_c is determined by providing a weighted average between the specified dry adiabatic lapse rate α_d and the wet adiabatic lapse rate α_w as shown in Equation 5.5. The wet and dry adiabatic lapse rates are specified in the RVP file using the `:WetAdiabaticLapse` and `:AdiabaticLapseRate` respectively.

$$\alpha_c = V\alpha_w + (1 - V)\alpha_d \tag{5.5}$$

A daily temperature range factor w_t is calculated as the current daily temperature range divided by the maximum temperature range parameter A0TERM shown in Equation 5.6.

$$w_t = \frac{T_{max} - T_{min}}{\text{A0TERM}} \tag{5.6}$$

The final equation for the maximum daily temperature lapse rate α_{max} and the minimum daily temperature lapse rate α_{min} are shown in Equations 5.7 and 5.8 respectively. The lapse rates have an inflection point at 2000 m in all cases, and as the daily temperature range approaches zero the lapse rates approach the corrected adiabatic lapse rate.

$$\alpha_{max} = \begin{cases} w_t \mathrm{A0TLXM} + (1 - w_t)\alpha_c, & \text{if elevation} \geq 2000 \text{ m} \\ w_t \mathrm{A0TLXH} + (1 - w_t)\alpha_c, & \text{if elevation} < 2000 \text{ m} \end{cases} \tag{5.7}$$

$$\alpha_{min} = \begin{cases} w_t \mathrm{A0TLNM} + (1 - w_t)\alpha_c, & \text{if elevation} \geq 2000 \text{ m} \\ w_t \mathrm{A0TLNH} + (1 - w_t)\alpha_c, & \text{if elevation} < 2000 \text{ m} \end{cases} \tag{5.8}$$

To do (5)

UBCWM method 2 (`OROCORR_UBC2`)

The UBC Watershed Model method 2 for estimating orographic temperature effects is to dynamically derive the lapse rate from the measured temperature data collected at the meteorological gauges. This routine uses only the first two meteorological gauges (the first two listed in the RVT file) to derive the lapse rate relationships. The relationship for the maximum daily temperature lapse rate is shown in Equation 5.9 and the relationship for the minimum daily temperature lapse rate is shown in Equation 5.10.

$$\alpha_{max} = \frac{T_{max2} - T_{max1}}{z_2 - z_1} \tag{5.9}$$

$$\alpha_{min} = \frac{T_{min2} - T_{min1}}{z_2 - z_1} \tag{5.10}$$

where T_{min1} and T_{min2} are the minimum daily temperatures at stations 1 and 2 respectively, T_{max1} and T_{max2} are the maximum daily temperatures at stations 1 and 2 respectively, and z_1 and z_2 are the elevations at stations one and two respectively.

This method requires two stations configured in the RVT file and subsequent stations are ignored in the calculations.

5.3 Precipitation

Precipitation forcings (rainfall and snowfall) are interpolated directly from gauges or gridded data. At the very minimum, total daily precipitation and daily average temperature is required to generate required time series of rainfall and snowfall everywhere in the watershed.

Measured total precipitation, snow precipitation, or rain precipitation may be corrected on a gauge-by-gauge basis by using gauge-dependent rainfall and snowfall corrections to correct for observation bias. This is handled using the `:RainCorrection` and `:SnowCorrection` commands outlined in appendix A.4.1. Rainfall and snowfall may further be corrected for bias on a subbasin-by-subbasin basis using the subbasin properties `RAIN_CORR` and `SNOW_CORR`.

5.3.1 Snow-Rain Partitioning

If only total precipitation is specified at a gauge station or grid cell, then this total precipitation is partitioned into rain and snow, based upon the approach specified in the `:RainSnowFraction` command. All of the provided algorithms calculate the snow fraction α_s, and rain and snow are determined from:

$$\begin{aligned} R &= (1-\alpha_s)P \\ S &= \alpha P \end{aligned}$$

where R [mm/d], S [mm/d], and P are rainfall, snowfall, and total precipitation rates, respectively. The following algorithms for α_s are available:

Determine From Data (`RAINSNOW_DATA`)

To be used if snowfall (or the snow fraction) is explicitly reported in the gauge/gridded data.

Temperature range approach (`RAINSNOW_DINGMAN`)

In the temperature range approach, the snow fraction, α, is calculated from the maximum and minimum daily temperatures:

$$\alpha_s = \frac{T_{trans} - T_{min}}{T_{max} - T_{min}} \tag{5.11}$$

where T_{trans} is the rain/snow transition temperature (global parameter `RAINSNOW_TEMP`) [default: 0 °C], and T_{min} and T_{max} are the min and max daily temperatures. If T_{trans} is outside of this temperature range, the precipitation is either all snow ($\alpha_s = 1$) or all rain ($\alpha_s = 0$), accordingly. This snow fraction is applied for the entire day.

Linear approaches (`RAINSNOW_UBC` or `RAINSNOW_HBV`)

In these approaches, a linear transition between all snow and all rain is determined from the average daily temperature, T_{ave}:

$$\alpha_s = 0.5 + \frac{T_{trans} - T_{ave}}{\Delta T} \tag{5.12}$$

in the range from $T_{trans} - \Delta T/2$ to $T_{trans} + \Delta T/2$, where T_{trans} is the rain/snow transition temperature (global parameter `RAINSNOW_TEMP`, [°C]) and ΔT is the global parameter `RAINSNOW_DELTA`

[°C]. If T_{ave} is outside of this temperature range, the precipitation is either all snow ($\alpha_s = 1$) or all rain ($\alpha_s = 0$), accordingly. This snow fraction is applied for the entire day.

Harder and Pomeroy Approach(RAINSNOW_HARDER)

Using the method of (Harder and Pomeroy, 2013) as implemented in CRHM Pomeroy et al. (2007). The fraction of snow is given by:

$$\alpha_s = 1 - \frac{1}{1 + 2.503 \cdot 8^{-T_{ib}}} \tag{5.13}$$

where T_{ib} is the ice bulb temperature, as determined from the relative humidity and air temperature.

HSPF Approach(RAINSNOW_HSPF)

Using the empirical formula as documented in the HSPF manual Bicknell et al. (1997) (here converted to Celsius). A reference temperature T^* is determined using

$$T^* = T_{trans} + (T_{ave} - T_{dp})(0.5808 + 0.0144 * T_{ave}) \tag{5.14}$$

where T_{trans} is the is the rain/snow transition temperature (global parameter RAINSNOW_TEMP), T_{dp} is the dew point temperature, calculated from the relative humidity. If $T^* > T_{ave}$, α_s is one, zero otherwise.

5.3.2 Orographic Precipitation Effects

Orographic effects may be applied to correct total interpolated precipitation at each HRU based upon HRU elevation. The fraction of precipitation in the form of snow or rain is not modified by these corrections.

Simple method (OROCORR_SIMPLELAPSE)

The simple precipitation lapse rate method employs a simple linear adiabatic method as outlined in Equation 5.15 below:

$$P = P_k + \alpha(z - \hat{z}_k) \tag{5.15}$$

where P is the total precipitation rate [mm/d], P_k is the interpolated precipitation at the HRU [mm/d], z is the elevation of the HRU, $\hat{z}_k$ is the reference elevation calculated from equation 5.1 at the HRU, and α [mm/d/km]is the precipitation correction lapse rate specified using the :PrecipitationLapseRate key word in the RVP file. Checks are included to ensure positivity of the precipitation rate. Note that this simplifies to the traditional interpretation of gauge orographic corrections for a single gauge or nearest neighbor interpolation algorithm, i.e.,

$$P = P_g + \alpha(z - z_g) \tag{5.16}$$

where z_g is the elevation of the nearest gauge and P_g is the total precipitation rate at the nearest gauge [mm/d].

HBV method (`OROCORR_HBV`**)**

From the HBV model Bergstrom (1995):

$$P = P_k \cdot (1.0 + \alpha(z - \hat{z}_k)) \tag{5.17}$$

where P is the total precipitation rate [mm/d], P_k is the interpolated precipitation at the HRU [mm/d], z is the elevation of the HRU, $\hat{z}_k$ is the reference elevation calculated from equation 5.1 at the HRU, and α, the precipitation correction lapse rate, is 0.00008 m^{-1} below 5000 masl, 0 above this elevation.

UBCWM method 1(`OROCORR_UBC`**)**

The UBC Watershed Model method 1 for orographic correction of precipitation estimates employs a temperature-corrected lapse rate with two inflection points (Quick, 2003). The base orographic correction equation is shown in Equation 5.18:

$$P = P_g \cdot (1 + \alpha F_t)^{\frac{z - z_g}{100}} \tag{5.18}$$

where P is the total applied precipitation rate, P_g is the measured gauge precipitation, z and z_g are the elevation of the HRU and gauge, respectively, and α, the precipitation correction lapse rate. F_t is a temperature correction factor shown in equation 5.19:

$$F_t = \begin{cases} 1, & \text{if } t_{band} \leq 0 \text{ C} \\ 1 - \text{A0STAB}\,(t_{band})^2, & \text{if } t_{band} > 0 \text{ C} \end{cases} \tag{5.19}$$

where $A0STAB$ is the precipitation gradient modification factor, and t_{band} is the temperature at the first listed elevation band in the model. F_t is constrained between 0 and 1.

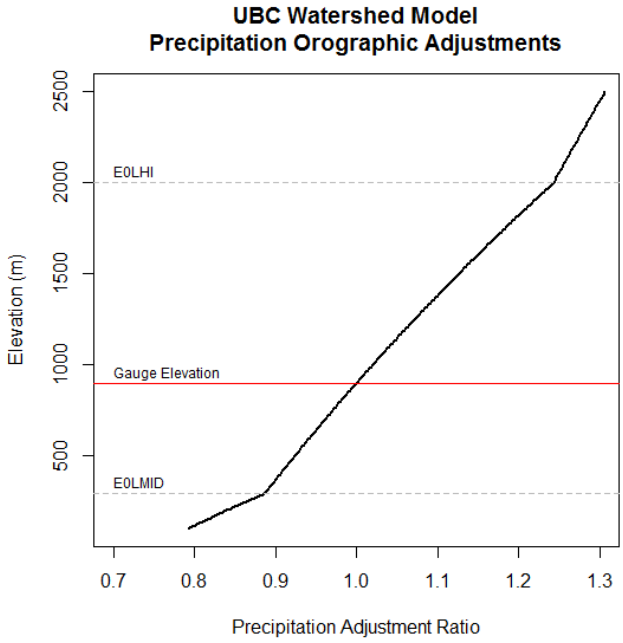

Figure 5.1: UBC Watershed Model Orographic Correction

5.4 Potential Evapotranspiration (PET)

A variety of potential evapotranspiration (PET) estimation algorithms of varying complexity are available for calculating PET within an HRU. These PET algorithms use many of the same relationships, including those for the saturated vapor pressure as a function of temperature,

$$e_s(T) = 0.6108 \cdot \exp\left(\frac{17.23T}{T + 237.3}\right) \tag{5.20}$$

and the slope of this curve, $\Delta(T) = de_s/dT$,

$$\Delta = \frac{4098}{(T + 237.3)} \cdot e_s(T) \tag{5.21}$$

where T is in $^\circ$C. The latent heat of vaporization of water, λ_v [MJ/kg], is estimable by:

$$\lambda_v = 2.495 - 0.002361 * T \tag{5.22}$$

where T is the temperature [$^\circ$C], and the psychrometric constant, γ is here treated as varying with atmospheric pressure, p [kPa],

$$\gamma = \frac{c_a}{0.622 \cdot \lambda_v} p \tag{5.23}$$

where c_a is the specific heat of air, equal to 1.012x10^{-3} MJ/kg/K.

Note that most of the algorithms below estimate daily PET. Methods are required to downscale these daily estimates to sub-daily time steps, as discussed in 5.10. If the `:DirectEvaporation` command is used, rainfall is automatically reduced by PET, with a corresponding decrease in the available potential evapotranspiration.

5.4.1 PET Estimation

Constant PET (`PET_CONSTANT`)

The daily PET value used is constant and uniform rate of 3 mm/d.

From file (`PET_DATA`)

The daily PET is explicitly specified at each gauge or grid cell (see section A.4 for details) and interpolated in-between. This enables any measured ET or user-specified means of calculating PET to be used.

From monthly (`PET_FROMMONTHLY`)

Used in the HBV Model Bergstrom (1995). Monthly PET and temperature norms are provided at the gauge using the `:MonthlyAveEvaporation` and `:MonthlyAveTemperature` commands. These estimates are assumed not to vary year-to-year. Daily estimates of PET may then be obtained from:

$$\text{PET} = \text{PET}_{mon} \cdot \min(1 + \tfrac{1}{2}(T_{ave} - T_{mon}), 2)$$

where PET_{mon} and T_{mon} are the daily PET [mm/d] and temperature norms for the current month, and T_{ave} is the average daily temperature spatially and temporally interpolated from the gauge values for `:MonthlyAveEvaporation` and `:MonthlyAveTemperature`. Checks are used to ensure PET is positive and doesn't exceed twice the average representative monthly PET.

Penman Monteith (`PET_PENMAN_MONTEITH`)

From Monteith (1965). The standard Penman-Monteith equation estimates daily reference evapotranspiration over a reference vegetation,

$$\text{PET} = \frac{1}{\lambda_v \rho_w} \cdot \left[\frac{\Delta}{\Delta + \gamma^*} R_n + \frac{\rho_a C_a c_a}{\Delta + \gamma^*} (e_s - e) \right]$$

where λ_v [MJ/kg] is the latent heat of vaporization of water, ρ_w [kg/m^3] is the density of water, $\Delta = de_s/dT$ is the slope of the saturated vapor pressure curve, $R_n = S_n + L_n$ [MJ/m^2/d] is the net radiation to the system, ρ_a is the air density, C_a [MJ/kg] is the specific heat of air, c_{atm} [md^{-1}] is the atmospheric conductance, e is the vapor pressure of the atmosphere, $e_s(T)$ [kPa] is the current saturated vapor pressure of the atmosphere, a function of temperature, and γ^* [kPa/ °C] is the corrected psychrometric constant,

$$\gamma^* = \left(1 + \frac{c_a}{c_{can}}\right) \gamma$$

where c_{can} [m/d] is the canopy conductance, and γ [kPa/ °C] is calculated using 5.23. The final expression is converted from m/d to mm/d. The atmospheric conductance is calculated using the following relationships Dingman (2002):

$$c_{atm} = v \cdot \frac{\kappa^2}{\ln\left(\frac{z_{ref} - z_0}{z_{rough}}\right) \ln\left(\frac{z_{ref} - z_0}{z_{vap}}\right)}$$

where κ is the Von Karman Constant (0.42), z_{ref} is the reference height [m] at which the wind velocity v [m/d] is reported, z_0 [m] is the zero-plane displacement height, z_{rough} is the roughness height [m], and z_{vap} is the vapour roughness height [m]. These parameters are predominantly calculated from the ground roughness and canopy heights. The canopy conductance is calculated as a function of vegetative leaf area index Dingman (2002):

$$c_{can} = 0.5 \cdot c_{leaf} \cdot \text{LAI}$$

where c_{leaf} is the leaf conductance [m/d], calculated using the expressions detailed in Dingman (2002) and LAI is calculated from equation 3.1.

Penman combination (`PET_PENMAN_COMBINATION`)

From Penman (1948). A similar expression to the Penman Monteith equation, daily reference ET is calculated from the following equation:

$$\text{PET} = \frac{1}{\lambda_v \rho_w} \cdot \left[\frac{\Delta}{\Delta + \gamma} R_n \right] + \left[\frac{\gamma \epsilon_v v}{\Delta + \gamma} (e_s - e) \right]$$

i.e., here the deficit-driven evapotranspiration (the second term) is treated using the wind velocity, v [m/s] and a vertical transport efficiency factor, ϵ_v, calculated as

$$\epsilon_v = \frac{0.622 \rho_a}{6.25 \cdot e \rho_w} \cdot \left(\ln\left(\frac{z_{ref} - z_0}{z_{rough}}\right)^{-2} \right)$$

terms are defined as defined above in the description of the `PET_PENMAN_MONTEITH` algorithm.

Priestley-Taylor (`PET_PRIESTLEY_TAYLOR`)

From Priestley and Taylor (1972). A simplified version of the Penman-Monteith approach where only net radiation explicitly drives daily ET, with an additional correction factor for the unmodeled ET driven by vapor deficit. The Priestley-Taylor equation is given by:

$$\text{PET} = 1.26 \cdot \frac{1}{\rho_w \lambda_v} \cdot \left[\frac{\Delta}{\Delta + \gamma} R_n \right]$$

where R_n is the net radiation [MJ/m^2/d], and other terms are defined as above in the description of the `PET_PENMAN_MONTEITH` algorithm. The factor of 1.26 is used to scale the radiation-driven ET to account for the (unmodeled) vapor deficit-driven ET. Priestley Taylor is predominantly used to estimate evaporation from open water.

Hargreaves (`PET_HARGREAVES`)

From Hargreaves and Samani (1982).

$$\text{PET} = \frac{1}{\rho_w \lambda_v} \cdot S_{ET} \cdot 0.000938 \cdot \left(\sqrt{T^{mon}_{max,F} - T^{mon}_{min,F}} \right) T_{ave,F}$$

where S_{ET} [MJ/m^2/d] is the extraterrestrial shortwave radiation, the temperatures $T^{mon}_{max,F}$ and $T^{mon}_{min,F}$ are the maximum and minimum monthly temperatures in Fahrenheit, and $T_{ave,F}$ is the daily temperature in Fahrenheit (converted internally within the code). The temperature factors attend to the impact of cloud cover and atmospheric interference with the extraterrestrial radiation.

Hargreaves 1985 (`PET_HARGREAVES_1985`)

From Hargreaves and Samani (1985). The 1985 Hargreaves equation, an empirical approach based solely on temperature and incoming solar radiation. Similar to `PET_HARGREAVES`, but it metric units.

$$\text{PET} = \frac{1}{\rho_w \lambda_v} \cdot S_{ET} \cdot 0.0023 \cdot \sqrt{T_{max} - T_{min}} \, (T_{ave} + 17.8)$$

where T_{ave}, T_{max}, and T_{min} are the average, maximum, and minimum daily air temperature, and S_ET [MJ/m^2/d] is the extraterrestrial shortwave radiation.

Monthly factor method (`PET_MONTHLY_FACTOR`)

Method used in the UBC Watershed Model (Quick, 1995). PET is calculated using the following formula:

$$\text{PET} = \max(E_{mon} \cdot T_{ave} - \epsilon, 0) \cdot \delta_{forest}$$

where E_{mon} [mm/d/K] is a monthly PET factor (specified using the `:MonthlyEvapFactor` command in the .rvt file, on the order of 0.2), T_{ave} is the daily average temperature in Celsius, and δ_{forest} is the land use parameter `FOREST_PET_CORR`), applied only to forested regions. The factor ϵ is an orographic correction factor, given as

$$\epsilon = 0.009 \cdot (z - \hat{z}_k)$$

where z is the HRU elevation, and $\hat{z}_k$ is the reference elevation for the HRU calculated using equation 6.1, respectively. Note that, unlike with most other ET approaches, the orographic correction is

necessarily fused with the PET calculation and therefore the orographic PET correction should be set to OROCORR_NONE. In previous versions (prior to 3.0), $\hat{z}_k$ was the elevation of the first gauge in the .rvt file.

Hamon (PET_HAMON)

From Hamon (1961). PET is calculated using the following relationship:

$$\text{PET} = 1115 \cdot \frac{e_{sat} L_d^2}{T_{ave}}$$

where e_{sat} is the saturated vapor pressure [kPa], T_{ave} is the average daily temperature [K], L_d is the day length [d], and the PET is in mm/d. The constant 1115 includes both units conversion factors and an approximate relationship to convert saturated vapor pressure and temperature to absolute humidity.

Oudin PET (PET_OUDIN)

A simple method from Oudin et al. (2005). PET is calculated using the following relationship:

$$\text{PET} = \frac{S_{ET}}{\lambda_v \rho_w} \cdot \min\left(\frac{T_{ave} + 5.0}{100}, 0.0\right)$$

where S_{ET} is the shortwave extraterrestrial radiation [MJ/m^2/d], λ_v is the latent heat of vaporization, ρ_w is the density of water, and T_{ave} is the daily average temperature.

Turc 1961 (PET_TURC_1961)

From Turc (1961) as reported in Liu et al. (2005). This empirical PET estimation algorithm has no additional parameters required.

$$\text{PET} = \begin{cases} 0.013 \left(\frac{T_{ave}}{T_{ave}+15}\right) (23.88 * S_n + 50) \left(1 + \frac{50-RH}{70}\right) & \text{for RH}<50\% \\ 0.013 \left(\frac{T_{ave}}{T_{ave}+15}\right) (23.88 * S_n + 50) & \text{for RH}\geq 50\% \end{cases}$$

where the PET is in mm/d, T_{ave} is the average daily temperature [$^\circ$C], S_n is the daily net shortwave radiation [MJ/m^2/d], and RH is the relative humidity expressed as a percentage.

Makkink 1957 (PET_MAKKINK_1957)

From Makkink (1957) as reported in Liu et al. (2005).

$$\text{PET} = 14.57 \left(\frac{\Delta}{\Delta + \gamma}\right) \frac{S_n}{58.5} - 0.12$$

where Δ is the slope of the saturation vapor pressure-temperature curve [kPa/$^\circ$C], γ is the psychrometric constant, and S_n is the net incoming solar radiation [MJ/m^2/d].

MOHYSE (`PET_MOHYSE`)

From the MOHYSE model (Fortin and Turcotte, 2006):

$$\text{PET} = \frac{c}{\pi} \cdot \cos^{-1}\left(-\tan(\Lambda) * \tan(\delta)\right) * \exp\left(\frac{17.3 \cdot T}{238 + T}\right)$$

where c is the global parameter `MOHYSE_PET_COEFF`, Λ is the latitude in radians, δ is the solar declination, and T is the average daily temperature in °C.

Granger-Gray (`PET_GRANGERGRAY`)

From Granger and Gray (1989), as implemented in the Cold Regions Hydrologic Model (CRHM) Pomeroy et al. (2007):

$$\text{PET} = \frac{1}{\lambda_v \rho_w} \frac{\Delta \cdot 0.9 \cdot R_n + \gamma \cdot D^* \cdot (e_s - e_a)}{\Delta + \gamma / G}$$

where $\Delta = de_s/dT$ is the slope of the saturated vapor pressure curve, γ is the psychometric constant, $R_n = S_n + L_n$ [MJ/m^2/d] is the net radiation to the system, $e_s(T)$ is the saturated vapour pressure and e is the actual vapour pressure. The 0.9 correction for net radiation assumes that 10 percent of energy goes to ground heat flux. Here, the formulation uses a drying power, D^* [MJ/m^2/d/kPa], given as

$$D^* = \lambda_v \rho_w \left((8.19 + 22 z_0) + (1.16 + 8 z_0) \cdot v\right)$$

where z_0 is the vegetation roughness height [m] and v is the wind velocity [m/s]. The correction term G is given by

$$G = \frac{1.0}{0.793 + 0.2 \exp(4.902 D)} + 0.006 D$$

where

$$D = \frac{1}{1 + \frac{R_n}{D^* \cdot (e_s - e_a)}}$$

Note that in Granger and Gray (1989), this 'potential' evapotranspiration rate is an actual evaporation rate constrained by moisture availability. The formula for G is similar to that of Granger and Gray (1989) in trend, but not precisely the same.

Linacre (`PET_LINACRE`)

From Linacre (1977).

$$PET = \frac{a \frac{T_{ave}}{100 - \phi} + 15 \cdot (F_{ave} - T_{dew})}{80.0 - T_{ave}}$$

where T_{ave} is the average daily temperature, T_{dew} is the daily dew point temperature, ϕ is the latitude, in degrees. The parameter a is equal to 700 for open water evaporation, 500 otherwise.

5.4.2 PET Orographic Effects

Orographic effects are calculated using the following algorithms, specified using the `:OroCorrPET` command in the .rvi file. Note that these should typically only be applied if PET data is provided at the gauge; otherwise, temperature orographic corrections will already impact PET estimates.

HBV method (`OROCORR_HBV`)

From the HBV model (Bergstrom, 1995):

$$\mathrm{PET} = \mathrm{PET}_k \cdot \alpha \left(1 - \beta\right) \left(z - \hat{z}_k\right)$$

where PET_k is the interpolated gauge-provided PET rate [mm/d], α is the global PET correction factor (`GLOBAL_PET_CORR`), β is the HBV precip correction factor (`HBV_PRECIP_CORR`), z is the HRU elevation, and $\hat{z}_k$ is the reference elevation for the HRU calculated using equation 5.1, respectively.

PRMS method (`OROCORR_PRMS`)

This orographic correction factor is described in the users's manual of the PRMS model (Leavesley et al. (1983)). It uses the maximum saturated vapor pressure, e_{sat}^{max} [kPa] (calculated from the average August temperature) and the minimum saturated vapor pressure e_{sat}^{min} [kPa] (calculated from the average February temperature).

$$\mathrm{PET} = \mathrm{PET}_k \cdot \left(\frac{1}{68 - 0.0118z + \frac{650}{e_{sat}^{max} - e_{sat}^{min}}} \right)$$

where z is the HRU elevation [masl] and PET_k is the interpolated PET at the HRU (implicitly presumed to be calculated at an elevation of zero). Note that because this algorithm implicitly includes orographic temperature effects, it must be used with care in combination with orographic temperature corrections.

5.5 Shortwave Radiation

Solar radiation contributes to the earth surface's energy balance, and is important for estimating snow melt and evapotranspiration, amongst other things. Since solar radiation is not directly measured in many places, here the standard routines documented in (Dingman, 2002) are used to estimate critical terms needed to estimate extraterrestrial shortwave radiation. This can then be corrected using information about cloud cover and/or optical air mass. Used in many of these calculations is the day angle, Γ [rad], and the solar declination, δ [rad]:

$$\Gamma = \frac{2\pi J}{365} \tag{5.24}$$

$$\begin{aligned}\delta = \quad & 0.006918 - \quad 0.399912 \cdot \cos(\Gamma) + \\ & 0.070257 \cdot \sin(\Gamma) - \quad 0.006758 \cdot \cos(2 \cdot \Gamma) + \\ & 0.000907 \cdot \sin(2\Gamma) - \quad 0.002697 \cdot \cos(3 \cdot \Gamma) + \\ & 0.001480 \cdot \sin(3\Gamma)\end{aligned}$$

Day length is calculated as follows, with additional corrections for polar latitudes:

$$\text{Day Length} = \frac{\arccos(-\tan(\delta) \cdot \tan(\Lambda))}{\pi}$$

where Λ is the latitude of the location (in radians). In Raven, net shortwave is calculated as

$$S_n = (1 - \alpha) \cdot f_{can} \cdot f_{cloud} \cdot S_{cs} \tag{5.25}$$

where f_{can} and f_{cloud} [0..1] are correction factors for canopy cover and cloud cover, respectively, and the clear sky solar radiation is given as

$$S_{cs} = f_{atm} \cdot f_{asp} \cdot S_{ET} \tag{5.26}$$

where f_{atm} and f_{asp} [0..1] are a correction factors for atmospheric refraction and slope/aspect of the ground surface, S_{ET} is the extra terrestrial radiation. Section 5.5.1 details methods for calculating S_{ET}, section 5.5.2 details methods for handling f_{atm}, section 5.5.3 details methods for handling f_{cloud} and section 5.5.4 details methods for handling f_{can}. These individual terms may be visualized in figure 5.2.

5.5.1 Extraterrestrial Shortwave Generation

The following shortwave radiation estimation algorithms are available, and are specified using the `:SWRadiationMethod` command in the .rvi file.

Raven default (`SW_RAD_DEFAULT`)

Extraterrestrial radiation flux on a horizontal plane is calculated using Dingman (2002):

$$S_{ET} = I_{sc} \cdot E_0 \cdot [\cos(\delta) \cdot \cos(\Lambda) \cdot \cos(2\pi t) + \sin(\delta)\sin(\Lambda)] \tag{5.27}$$

where I_{sc} is the solar constant (118.1 MJm^{-2}d^{-1}), E_0 is an eccentricity correction (see Dingman (2002)), and t is the time of day in days (i.e., $t = 0$ is midnight, $t = 0.5$ is noon). Corrections are applied for radiation on a sloping surface (i.e., on HRUs with a non-zero slope). Aspects are corrected for in the default approach using the corrections put forth in Dingman (2002), and can handle the two sunset effect.

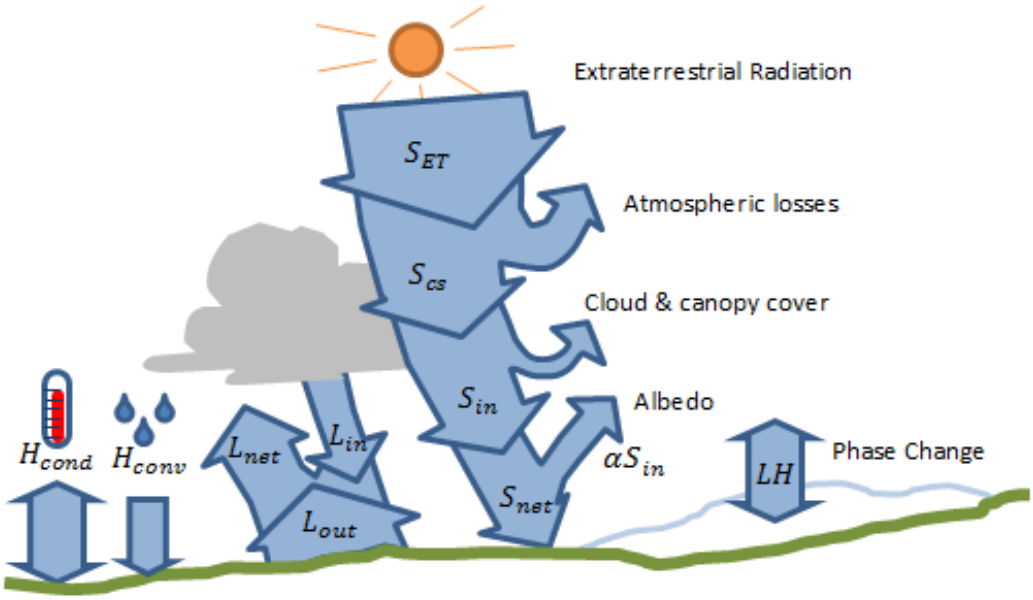

Figure 5.2: The surface energy balance in Raven. Important components include shortwave radiation (S), longwave radiation (L), conductive/convective heat transfer (H), and latent heat/phase change (LH).

UBCWM approach (`SW_RAD_UBCWM`)

Shortwave radiation is calculated using the same equations as the `SW_RAD_DEFAULT` approach (equation 5.27), but employs a correction to the day length to account for mountain barrier effects. Two sets of monthly correction parameters are employed in this method to correct for SW radiation for north- and south-facing slopes. The parameters are included in the `UBCNorthSWCorr` and `UBCSouthSWCorr` keywords in the RVP file with one parameter for each month (January to December). The HRU orientation factor is calculated as a function of the aspect of the HRU

$$O = 1 - \left| \frac{\theta}{\pi} - 1 \right|$$

where θ is the dominant aspect direction and O is the orientation (eg. north = 0 and south = 1, east/west = 0.5). The final SW radiation estimate is

$$f_{asp} = [O \cdot C_S + (1 - O) \cdot C_N]$$

where f_{asp} is the correction factor for shortwave radiation on an inclined plane, S_{ET} is the uncorrected shortwave radiation estimate based on equation 5.27, and C_S and C_N are the south and north correction factors respectively (from `UBC_S_CORR` and `UBC_N_CORR`).

Interpolate from data (`SW_RAD_DATA`)

The incident shortwave radiation is read from a file, specified at one or more gauge locations. The radiation could be either measured, generated from an atmospheric model, or estimated using an external preprocessor. If incident shortwave is provided directly, cloud cover corrections (but not aspect, or canopy corrections) are implicitly contained in this number. What is actually being input is

$$f_{cloud} \cdot f_{atm} \cdot S_{ET}$$

Additional algorithms are required to attend to slope/aspect and canopy corrections.

5.5.2 Clear Sky Radiation

As radiation passes through the earths atmosphere, energy is absorbed and scattered by particles and water vapor, both in cloudy and cloud-free areas. Corrections must be made to extraterrestrial radiation to account for this.

Dingman (`SW_RAD_DEFAULT`)

The approach outlined in Dingman (2002), total incident radiation is calculated as:

$$f_{atm} = (\tau_{dir} + 0.5(1 - \tau_{diff})) \cdot (1 + 0.5(1 - \tau_{diff})\alpha)$$

where α is the surface albedo, and the scattering correction factors for diffuse and direct solar radiation τ_{diff} and τ_{dir} are given by

$$\begin{aligned} \tau_{dir} &= \exp\left(-0.124 - 0.0207W_p - (0.0682 + 0.0248W_p)M_{opt}\right) \\ \tau_{diff} &= \exp\left(-0.0.363 - 0.0084W_p - (0.0572 + 0.0173W_p)M_{opt}\right) \end{aligned} \tag{5.28}$$

where the precipitable water vapor, W_p, is calculated as $W_p = 1.12\exp(0.0614T_d)$, where T_d is the dew point temperature, and the optical air mass, M_{opt}, is calculated using the methods of Yin (1997).

UBCWM approach (`SW_RAD_UBCWM`)

In the UBC watershed model, the corrections for atmospheric scattering and adsorption are given as

$$f_{atm} = \exp(-2.0 \cdot (0.0128 - 0.0234\ln(m_a))$$

where the air mass, m_a is given by

$$m_a = \frac{1 - 0.001 \cdot z}{[\cos(\delta) \cdot \cos(\Lambda) \cdot \cos(2\pi t) + \sin(\delta)\sin(\Lambda)]} \tag{5.29}$$

This product $f_{atm} \cdot S_{ET}$ is numerically integrated over the course of the day to estimate the daily clear sky radiation. The day length in this integration calculation is corrected for using a mountain barrier correction.

5.5.3 Cloud Cover Corrections

Additional corrections are required to handle cloud cover. While the algorithms for estimating actual cloud cover are included in section 5.7 below, the use of the cloud cover factor for estimating incident radiation is treated here.

UBC approach (`SW_CLOUDCOV_CORR_UBC`)

The UBC watershed model (Quick, 1995) corrects shortwave radiation due to cloud cover using the following equation

$$f_{cloud} = (1 - (1 - \mathrm{POCAST}) \cdot C_c)$$

where S_C is the shortwave radiation corrected for cloud cover, S is the uncorrected shortwave radiation, C_C is the cloud cover correction factor and POCAST is the cloud penetration factor specified in the RVP file with the `:UBCCloudPenetration` keyword.

Dingman approach (`SW_CLOUDCOV_CORR_DINGMAN`)

The cloud cover correction factor may also be estimated as outlined in Dingman (2002, Eq. 5-30):

$$f_{cloud} = (0.355 + 0.68 \cdot (1 - C_c)) \tag{5.30}$$

where C_c is cloud cover. This approach does not require any parameters to be set in the RVP file.

Annandale approach (`SW_CLOUDCOV_CORR_ANNANDALE`)

The cloud cover correction factor is generating using the approach from Annandale et al. (2002):

$$f_{cloud} = 0.16 * (1.0 + 0.00027z)\sqrt{(T_{max} - T_{min})} \tag{5.31}$$

where z is the elevation in masl, and T_{max}/T_{min} are the maximum and minimum daily temperature.

5.5.4 Canopy Cover Corrections

Calculates the ratio of solar radiation under forest canopy relative to open. The default canopy cover correction method is no correction (`SW_CANOPY_CORR_NONE`).

UBCWM method (`SW_CANOPY_CORR_UBC`)

To correct for shortwave correction due to canopy cover the UBC watershed model method employs the following equation

$$f_{can} = F_E$$

where S_C is the shortwave energy corrected for canopy cover, S is the uncorrected shortwave energy, and F_E is the forest cover correction factor specified using the `:UBCExposureFactor` command in the RVP file.

Bulk transmittance approach (`SW_CANOPY_CORR_STATIC`)

The Bulk transmittance approach provides a static canopy transmittance based on leaf-area index and stem-area index estimates to produce a "sky view" factor, or the fraction of the ground that receives sunlight (Dingman, 2002):

$$f_{can} = \exp(-k(\text{LAI} + \text{SAI}))$$

where k is the extinction coefficient, LAI is the leaf-area index and SAI is the stem-area index, both estimated as indicated in equation 3.1. The extinction coefficient, leaf-area index and stem-area index are supplied or calculated from parameters within the `:VegetationClasses` parameter structure in the .rvp file by the `SVF_EXTINCTION`, `MAX_LAI`, and `SAI_HT_RATIO` columns respectively.

5.6 Longwave Radiation

Longwave radiation is the electromagnetic radiation emitted by materials with near-earth-surface temperatures. The net longwave is the difference between the incident longwave emitted (or back scattered) by the atmosphere, clouds, and canopy and the outgoing radiation from the land surface (see figure 5.2).

Interpolate from data (`LW_RAD_DATA`)

The net longwave radiation (in $MJm^{-2}d^{-1}$) is read from a file, specified at one or more gauge locations or as a gridded climate product. The radiation could be either measured or estimated using an external preprocessor.

Raven Default method (`LW_RAD_DEFAULT`)

Net longwave radiation is treated using the Stefan -Boltzmann law, with a correction factor for the inefficiency of the land and atmospheres as black-body emitters.

$$L_n = \sigma \cdot \epsilon_s \cdot \left(\epsilon_{atm} \cdot T_{atm,K}^4 - T_{s,K}^4\right)$$

where σ is the Stefan Boltzmann constant (4.9x10^{-9} $MJm^{-2}d^{-1}K^{-4}$), $T_{atm,K}$ and $T_{s,K}$ [°K] are the effective temperatures of the atmosphere and ground surface (here presumed equal to the air temperature in Kelvin), and ϵ_s and ϵ_{atm} are the effective emissivities of the surface and atmosphere, respectively. In Raven, the surface emissivity is held constant as $\epsilon_s = 0.99$ and the atmospheric emissivity is calculated as Dingman (2002)

$$\epsilon_{atm} = (1 - F_c) \cdot 1.72 \cdot \left(\frac{e}{T_{a,K}}\right)^{1/7} \cdot (1 + 0.22 \cdot C_C^2) + F_c$$

where F_c [0..1] is the forest cover (treated as a blackbody), e is the vapor pressure, $T_{a,K}$ is the air temperature in Kelvin, and C_c is the cloud cover.

UBCWM method (`LW_RAD_UBC`)

The longwave radiation is estimated in the UBC Watershed model separately for open and forested covers. The open longwave radiation is estimated using

$$L_o = (1 - f_{cloud}) \cdot \lambda_f \rho_w \cdot (-20 + 0.94 T_{avg}) + f_{cloud} \cdot \lambda_f \rho_w \cdot (1.24 T_{min})$$

where L_o is the net longwave radiation estimate for open forest cover in mm/d, T_{avg} °Cis the daily average temperature, T_{min} °Cis the daily minimum temperature, f is the UBC cloud cover correction factor (see Section 5.7), and λ_f is the latent heat of fusion. The net longwave radiation estimate for forest covered areas is:

$$L_f = \lambda_f \rho_w f_{LW} T_{avg}$$

where L_f is the longwave radiation estimate for open forest cover in mm/d, t_{avg} is the daily average temperature, and f_{LW} is the temperature multiplier factor in mm/dK^{-1} which is set in the RVP file using the `:UBCLWForestFactor` keyword. If the forest cover for an HRU is greater than zero then the latter equation is employed. Note that this expression is a linearization of the Stefan-Boltzmann law.

HSPF method (LW_RAD_HSPF)

Net longwave radiation is given as a simple function of average daily temperature, T_{avg} [°C]

$$L_n = 0.361 * (T_{avg} - 6.6) \tag{5.32}$$

where L_n is in MJm^{-2}d^{-1}.

5.7 Cloud Cover

This section outlines the various method for the estimation of a cloud cover in the model and the associated cloud cover corrections for incident short wave radiation. The default cloud cover method is CLOUDCOV_NONE, implying no cloud cover estimation or cloud cover correction.

No cloud cover calculations (CLOUDCOV_NONE)

No cloud cover is the default approach to cloud cover for Raven and can be set explicitly in the RVI file using the :CloudCoverMethod keyword of NONE, or by excluding the keyword entirely.

Interpolate from data (CLOUDCOV_DATA)

The cloud cover data [0-1] may be incorporated from gauge data if available in which case the CLOUDCOV_DATA option for the CloudCoverMethod keyword should be employed in the RVI file. The cloud cover data is stored in the meteorological time series data files (see Section A.4 for details).

UBC approach (CLOUDCOV_UBC)

Cloud cover factor in the UBC watershed model are estimated by determining the daily temperature range as observed at the meteorological gauges that influence an HRU and comparing that range to specified cloud temperature range parameters. The observed temperature range for the HRU is calculated as

$$\Delta T = T_{max} - T_{min} \tag{5.33}$$

where T_{max} and T_{min} are the interpolated maximum and minimum temperatures and Δt is the temperature range at HRU. The cloud cover correction factor is

$$C_c = \begin{cases} 1, & \text{if } \Delta T \leq T_{cmin} \\ 1 - \frac{\Delta T - T_{cmin}}{T_{cmax} - T_{cmin}}, & \text{if } T_{cmin} > \Delta T > T_{cmax} \\ 0, & \text{if } \Delta t \geq T_{cmax} \end{cases} \tag{5.34}$$

where C_c is the cloud cover factor [0-1], and T_{cmin} and T_{cmax} are the cloud cover temperature ranges in °Cas specified for each gauge within the RVT file using the keyword :CloudTempRanges.

5.8 Energy

This section includes a number of processes that are involved in the energy balance in the Raven model, including the estimates of potential snowmelt

5.8.1 Potential Melt

Potential snow melt can be estimated using a number a methods in the Raven model. To set the appropriate process in the model the RVI must include the `:PotentialMeltMethod` keyword along with the appropriate value for the method selected.

Degree day method (`POTMELT_DEGREE_DAY`)

The degree day method estimates a potential snow melt using an temperature index approach as described in, e.g., Dingman (2002):

$$M_{melt} = M_a \cdot \max(T - T_f, 0)$$

where M_{melt} is the potential melt rate [mm/day], T is the atmospheric temperature of the HRU [deg C], T_f is the freeze/melt temperature [°C] (zero by default, but can be set with the land use parameter `DD_MELT_TEMP`), and M_a is the melt factor [mm/day/deg C], specified using the land use/land type parameter `MELT_FACTOR`.

UBC approach (`POTMELT_UBC`)

The UBC watershed model approach to calculating potential snowmelt is described below. The model requires a certain number of participating parameters defined in the RVP file: `FOREST_COVERAGE` supplied in the `:LandUseClasses` table, and `UBC_MIN_SNOW_ALBEDO`, `UBC_SW_S_CORR` and `UBC_SW_N_CORR` provided as global variables. The total snow melt is an accumulation of separate melt components:

$$M_{melt} = \frac{1}{\lambda_f \rho_w} \left((1 - \alpha_s) S + L_n + Q_c + Q_a + Q_r \right)$$

where M_{melt} is the total potential melt rate $[mm/d]$, S is the incoming shortwave radiation, α_s is the snow albedo, L_n [MJ/m^{2}2/d] is the long wave radiation, Q_c [MJ/m^{2}2/d] is the convective melt energy, Q_a [MJ/m^{2}2/d] is the condensation or advective melt energy and Q_r [MJ/m^{2}2/d] is the melt energy due to rainfall. The convective and advective melt energy is estimated using

$$Q_c = 0.113 \cdot p \cdot T_a \cdot V \cdot R_M$$
$$Q_a = 0.44 \cdot T_{min} \cdot V \cdot R_M \cdot [(1 - f_c)p + f_c]$$

where p is the air pressure T_a is the average air temperature, T_{min} is the minimum daily air temperature, V is the wind velocity, f_c is the fraction of forest cover and R_M is a reduction factor as described below,

$$R_M = 1.0 - 7.7 \cdot R_I$$
$$0 \leq R_M \leq 1.6$$

where R_I is a linearized estimate of Richardson's number:

$$R_I = \frac{0.095 \cdot T_{avg}}{V^2}$$

The rainfall related melt is estimated using the following equation:

$$Q_r = k \cdot T_a \cdot P_r$$

where k represents the heat content of the rain mm/C and P_r is the rainfall over the time step.

HBV method (`POTMELT_HBV`)

The potential melt in the HBV method (Bergstrom, 1995) is given by a corrected version of the degree day approach, with the corrected melt coefficient given by

$$M'_a = C_f \cdot C_a \left(M_{a.min} + (M_{a.max} - M_{a.min}) \cdot \frac{1.0 - \cos(\Gamma - \Gamma_s)}{2} \right) \tag{5.35}$$

where M'_a is the potential melt coefficient, C_f is the forest correction factor, C_a is the aspect correction factor, A_c is the aspect correction factor, $M_{a.max}$ and $M_{a.min}$ are the maximum and minimum potential melt rate parameters specified using the `MELT_FACTOR` and `MIN_MELT_FACTOR` keywords respectively, and are specified in the land use parameters. Γ is the day angle calculated using equation 5.24 and Γ_s is the winter solstice angle and is a model constant of 23.5°. The forest and aspect correction factors are described below:

$$C_f = (1.0 - F_c) \cdot (1.0 + (F_c) \cdot M_{RF}) \tag{5.36}$$

$$C_a = \max\left(1 - A_m \cdot C_s \cdot \cos(\theta), 0.0\right) \tag{5.37}$$

where F_c is the fraction of forest cover, M_{RF} is the forest melt correction parameter specified using `HBV_MELT_FOR_CORR`, A_m is the aspect melt correction parameter `HBV_MELT_ASP_CORR`, and θ is the landscape aspect angle. C_s is slope correction factor described below:

$$C_s = (1.0 - F_c) \cdot (1.0 + (F_c) \cdot \sin(\theta_s)) \tag{5.38}$$

where θ_s is the landscape slope.

Restricted method (`POTMELT_RESTRICTED`)

The potential melt rate is given by the degree day method plus a correction term due to net incoming radiation:

$$M_{melt} = M_a \cdot (T - T_f) + \frac{S_n + L_n}{\lambda_f \rho_w}$$

where S_n and L_n are the net incoming radiation, and the melt factor, M_a is the land surface parameter `MELT_FACTOR`. λ_f and ρ_w are the latent heat of fusion [MJ/kg] and density of water [kg/m^3], respectively. An additional factor in the latter portion of the equation converts from meters to millimeters.

Energy balance method (`POTMELT_EB`)

Similar to the `POTMELT_UBCWM` approach, except the estimates for Q_c, Q_a and Q_r are obtained using the methods of Dingman (2002). This approach requires no additional parameters: all energy estimates are taken from the current air and surface temperatures, and roughness heights of the land/vegetation.

U.S. Army Corps method (POTMELT_USACE)

The U.S. Army Corps of Engineers potential melt model (U.S. Army Corps of Engineers, 1998) takes into account various factors including solar radiation, wind, and long-wave radiation exchange. The equation combines several melt equations, depending on the physical characteristics of the hydrologic response unit (HRU) and precipitation. These melt estimates include shortwave radiation melt, long-wave radiation melt, convection (sensible heat) melt, condensation (latent heat) melt, rain melt, and ground melt. Requires the parameter WIND_EXPOSURE, which represents the mean exposure of the HRU to wind considering topographic and forest effects; for open areas this would be equal to 1.0, but may be as low as 0.3 for forested areas. Details may be found in U.S. Army Corps of Engineers (1998).

HMETS method (POTMELT_HMETS)

A revised degree day model from the HMETS model (Martel et al., 2017), which uses a degree day factor which varies with cumulative snowmelt. The degree day model is given as

$$M_{melt} = M_a \cdot (T - T_f)$$

where T is the daily average temperature. T_f is the melt temperature (zero by default, but can be set with the land use parameter DD_MELT_TEMP), and M_a [mm/d/ °C] is the degree day melt factor, calculated as a function of cumulative melt:

$$M_a = \min\left(M_a^{max}, M_a^{min} \cdot (1 + \alpha \cdot M_{cumul}\right)$$

where the following land use parameters are used: the maximum melt rate M_a^{max} [mm/d/ °C] (MAX_MELT_FACTOR), the minimum melt rate M_a^{min} [mm/d/ °C] (MIN_MELT_FACTOR), and α [1/mm] is the parameter DD_AGGRADATION.

CRHM EBSM method (POTMELT_CRHM_EBSM)

A parameter-free energy-based potential melt model from the Cold Regions Hydrologic Model (CRHM) (Pomeroy et al., 2007).

$$M_{melt} = \frac{1}{\lambda_v \rho_w}(S_n + L_n + Qh + Qp)$$

where convective/conductive heat transfer Q_h [MJ/m^2/d] is estimated from wind velocity, v [m/s], and maximum daily temperature, T_{max} [°C],

$$Q_h = -0.92 + 0.076 \cdot v + 0.19 \cdot T_{max}$$

and the energy content of the rainfall is given by the rainfall R [mm/d] and air temperature T [°C]:

$$Q_p = c_p \rho_w \cdot R \cdot \max(T, 0.0)/1000$$

where c_p and ρ_w are the specific heat capacity and density of water; the 1000 factor converts rainfall to m/d.

5.9 Atmospheric Variables

This section includes various methods for estimating wind speed, relative humidity, and air pressure.

5.9.1 Wind Speed

The following methods can be used to estimate the wind speed at 2 meters, as used for a number of ET and potential melt estimation algorithms.

Constant wind velocity (`WINDVEL_CONSTANT`)

Returns a constant value of 2.0 m/s (the global average).

Interpolate from data (`WINDVEL_DATA`)

Wind velocity is interpolated from data supplied at a gauge location, as specified in the .rvt file.

UBCWM approach (`WINDVEL_UBC`)

An algorithm adapted from the UBC Watershed model. The base wind speed, v_b [km/hr] is first estimated to be between a reasonable range using the temperature range for the day

$$v_b = (1-\omega)v_{max} + (\omega)v_{vmin}$$

where $v_{max} = 8$ km/hr, $v_{min} = 1$ km/hr, and $\omega = 0.04 \cdot \min(T_{max} - T_{min}, \Delta T_{max})$. Here T_{max} and T_{min} are the orographically corrected minimum and maximum daily temperature, ΔT_{max} is the global parameter `MAX_RANGE_TEMP`, which may be corrected for elevation. If the following maximum temperature range is smaller than `MAX_RANGE_TEMP`, it overrides `MAX_RANGE_TEMP`:

$$\Delta T_{max} = 25.0 - 0.001 \cdot \mathrm{P0TEDL} \cdot z_g - 0.001 \cdot \mathrm{P0TEDU}(z - z_g)$$

where P0TEDL and P0TEDU are global lapse rate parameters specified using the `:UBCTempLapseRates` command, and z_g and z are the elevation of the temperature gauge and HRU, respectively. The wind velocity is then converted to m/s, then corrected for forest cover and elevation,

$$v = \alpha_f \cdot (0.001 \cdot z)^{1/2} \cdot v_b$$

where α_f is equal to 1 for bare ground and 0.7 if `FOREST_COVER` is greater than zero.

5.9.2 Relative Humidity

The following algorithms may be used to estimate relative humidity in Raven:

Constant humidity (`RELHUM_CONSTANT`)

The relative humidity is (somewhat arbitrarily) estimated to be 0.5.

Interpolate from data (`RELHUM_DATA`)

Relative humidity is interpolated from data supplied at a gauge location or gridded data, as specified in the .rvt file.

Minimum daily temp as estimator of dew point (`RELHUM_MINDEWPT`)

The minimum daily temperature is assumed to be equal to the dew point, allowing relative humidity to be estimated as

$$RH = \frac{e_s(T_{min})}{e_s(T_{ave})}$$

where T_{min} and T_{ave} are the minimum and average daily temperatures and $e_s(T)$ is the saturated vapor pressure, a function of temperature.

5.9.3 Air Pressure

The following approaches may be used to estimate atmospheric pressure:

Constant air pressure (`AIRPRESS_CONSTANT`)

A constant air pressure of 101.3 kPa is used (air pressure at standard temperature of 25 °C).

Interpolate from data (`AIRPRESS_DATA`)

Air pressure is interpolated from data supplied at a gauge location, as specified in the .rvt file.

UBCWM approach (`AIRPRESS_UBC`)

From Quick (1995). Air pressure is corrected for elevation above mean sea level, z,

$$P = 101.3 \cdot (1 - 0.001z)$$

where P is in kPa.

Basic Approach (`AIRPRESS_BASIC`)

Air pressure is corrected for both temperature and pressure using the following relationship:

$$P = 101.3 \cdot \left(1 - 0.0065\frac{z}{T_{ave}^K}\right)^{5.26}$$

where T_{ave}^K is the average temperature for the time step in °K, and z is the HRU elevation.

5.10 Sub-daily Corrections

Many of the above algorithms estimate incoming radiation, potential melt, and/or ET on a daily timescale. When simulating at a sub-daily timescale, it is advantageous to be able to downscale these estimates for smaller time intervals. If a time step less than Δt=1.0 is used, the sub-daily corrections are used to modify the following quantities:

- potential melt

- shortwave radiation
- PET

No sub-daily correction (SUBDAILY_NONE)

No modification is used.

Simple method (SUBDAILY_SIMPLE)

The half-day length is used to scale a cosine wave which peaks at midday, is zero after sunset and before sunrise, and has a total area of 1.0 underneath; the average value of this sine wave over the time step is used as the subdaily correction.

$$\delta = \frac{1}{\Delta t} \int_{t}^{t+\Delta t} -\frac{1}{2} \cos\left(\frac{\pi t}{DL}\right) dt$$

where DL is the day length, in days.

UBC Watershed model approach (SUBDAILY_UBC)

To do (6)

5.11 Monthly Interpolation

Various methods to be used for interpolation and use of all monthly data.

Uniform method (MONTHINT_UNIFORM)

Monthly values are assumed to be uniform throughout the month, jumping abruptly when moving from month to month.

Relative to first day of month (MONTHINT_LINEAR_FOM)

Monthly values are linearly interpolated, assuming that the specified monthly values correspond to the first day of the month.

Relative to middle day of month (MONTHINT_LINEAR_MID)

Monthly values are linearly interpolated, assuming that the specified monthly values correspond to the middle of the month.

Relative to 21st day of the month (`MONTHINT_LINEAR_21`)

Monthly values are linearly interpolated, assuming that the specified monthly values correspond to the 21st day of the month (as done in the UBC Watershed model (Quick, 1995)).

Chapter 6

Forecasting and Assimilation

RAVEN has a number of built-in features to support short-term flood and reservoir inflow forecasting.

6.1 Streamflow Assimilation

RAVEN can integrate real-time observations of streamflow into its forecasting model via a simple and unique direct insertion algorithm. For more complicated applications of data assimilation (e.g., ensemble Kalman Filter or similar), it is recommended to use external tools.

When supplied with streamflow observations (using the `:AssimilateStreamflow` command in the .rvi file), RAVEN will override the stream discharge modeled at any point in the domain with streamflow observed at a subbasin outlet. In addition to overriding the flows during hindcasting (when observations are available), it can also propagate a scaled flow forward in time and upstream in space, with the key assumption that the ratio of the observed to modeled flow is more likely to be constant than not. The following scaling relationship is used:

$$\omega_i(t, x_i, t_i^{last}) = 1 + \alpha \cdot \left(\frac{Q^i_{obs}(t) - Q_{mod}(t)}{Q^i_{mod}(t)} \right) \cdot \exp(-\beta x_i) \cdot \exp(-\gamma t - t_i^{last})$$

where $\omega_i(t)$ is the weighting factor in subbasin i at time t, $Q^i_{obs}(t)$ is the observed flow at the nearest downstream observation location from basin i at time t, $Q^i_{mod}(t)$ is the modeled flow at the same location at time t (which may reflect the impact of upstream data assimilation in previous time steps), x_i is the downstream distance to the nearest downstream observed flow, and t_i^{last} is the time since the last observation was observed at this location (typically equal to t in hindcasting). The parameter α (global parameter `ASSIMILATION_FACT`) indicates the degree of assimilation, where $\alpha = 1$ corresponds to full insertion and $\alpha = 0$ corresponds to none. The parameter β (global parameter `ASSIM_UPSTREAM_DECAY`) determines how the scaling factor decreases with distance to the observation. For $\beta = 0$, the scaling factor persists to the headwater of the basin, scaling all upstream flows by the ratio of observed to modeled discharge at the downstream observation. The parameter γ (global parameter `ASSIM_TIME_DECAY`) determines how the scaling factor diminishes with time after the observations are unavailable, such that the assimilated flows converge upon the modeled unassimilated flows at some time forward in the forecast.

In all basins upstream of an observation point, the streamflows and rivulet flows in the basin are scaled using the following:

$$Q' = \omega_i \cdot Q_{mod}$$

For basins without a downstream observation point, the scaling factor ω_i is one, and no assimilation is performed.

In this algorithm, the closest downstream observation is always used for scaling.

6.2 Deltares FEWS support

Raven readily plugs into the Deltares Delft-FEWS forecasting environment https://www.deltares.nl/en/software/flood-forecasting-system-delft-fews-2/. An adaptor developed by NRC-OCRE (in the form of a a Python script) is available upon request.

Chapter 7

Tracer and Contaminant Transport

Raven can be used to track contaminants and/or tracers (referred to as constituents) through a watershed via advection. It also has the capacity to (in the future) simulate dispersion, turbulent dispersion, and single and multi-species chemical reactions, volatilization, and settling; these capabilities have yet to be implemented. Transport is now limited to single-subbasin models; mass cannot yet be routed downstream through the channel reach.

The advective transport capabilities of Raven are relatively simple in concept. During each time step, water exchange in the HRU is first calculated. Using the known water fluxes between storage compartments over a given time step, and the mass of a given constituent in each storage compartment, the net mass flux is calculated between all storage compartments for the time step. Internally, the mass density (in mg/m^2) is stored in each storage compartment (i.e., soils, surface water, snow, etc.), though concentrations of constituents are reported in more natural concentration units of mg/L. Advective fluxes between all water storage compartments are calculated as

$$J = M \cdot \left(\frac{m}{\phi}\right)$$

where J is the advective flux [mg/m^2/d], M is the water exchange rate between compartments [mm/d], m is the constituent mass [mg/m^2], ϕ is the water storage of the compartment which the mass is leaving [mm]. In any of the storage compartments, constituent concentration is calculated as

$$C = \frac{m}{\phi}$$

With the `ORDERED_SERIES` global numerical algorithm, mass balance errors for each constituent should be exactly zero. Because the transport module wraps around the hydrologic water balance model, the addition of new hydrologic processes and algorithms does not require the addition of new code for simulating mass transport.

For flow tracers, the option may be used to ignore the inherent units of mass density, and instead track the percent of flows sourced from particular sources. This can be useful, for example, in tracking snow vs. rain components of streamflow, or determining the timing of outflow coming from a given HRU. In the case of a tracer, the same expression as above is valid, though using an equivalent flux and equivalent mass, i.e.,

$$J' = M \cdot \left((\frac{m'}{\phi}\right)$$

where J' is the advective flux [mm/d], and m' is the effective mass [mm]. In this case, J'/M may be interpreted as the fraction of the flow which contains the tracer fluid; likewise, m'/ϕ, the tracer concentration

[unitless] can be interpreted as the fraction of storage which is marked by tracer. Tracer concentrations should range from 0 to 1.

The primary outputs from the transport simulation are the average concentrations of a given constituent in each of the various storage compartments and pollutographs at subbasin outlets.

7.1 Constituent Sources

Sources of constituents may be handled in one of two ways:

- As Dirichlet conditions, where the constituent concentration in a given compartment is fixed at a user-specified value
- As Neumann conditions, where a user-specified (dry) mass flux is applied to a given compartment

Other source types may be incorporated into Raven at a later date.

7.2 Catchment Routing

Constituents are routed through the catchment in a manner consistent with the catchment routing process described in section 4.1. A discrete transfer function approach is used,

$$QC(t+\Delta t) = \sum_{n=0}^{N} QC_{lat}(t - n\Delta t) \cdot UH_n \tag{7.1}$$

where QC [mg/d] is the mass loading, QC_{lat} is the loading released from the catchment at time t, and $\vec{UH}$ is a unitless vector which describes the distribution of arrival times to the channel, and is the same distribution used by the catchment routing for water, described in section 4.1.

7.3 In-channel Routing

Raven currently supports in-channel routing of transport constituents only with the diffusive wave, plug flow, and `ROUTE_NONE` methods of in-channel routing. Plans are to support the remaining methods before the end of 2018. For these methods, a discrete transfer function approach is used similar to that used in the in-catchment routing,

$$QC(t+\Delta t) = \sum_{n=0}^{N} QC_{in}(t - n\Delta t) \cdot UH'_n \tag{7.2}$$

where QC [mg/d] is the mass loading, QC_{in} is the loading from upstream at time t, and $\vec{UH'}$ is a unitless vector which describes the distribution of arrival times to the channel outlet, and is the same distribution used by the in-channel routing for water, described in section 4.2.

7.4 In-reservoir Routing

Constituent routing in the reservoir is based upon an explicit solution of the Crank-Nicolson discretized mass balance on the reservoir,

$$\frac{dM}{dt} = \sum_{i=1}^{N} Q_{in}^{i} C_{in}^{i} - Q_{out} C - \lambda M \tag{7.3}$$

where M is the reservoir mass (in mg), Q_{in}^{i} and Q_{out} are the N inflows and single outflow rates from the reservoir (in m^3/s), C_{in}^{i} are the concentrations [mg/m^3] from the multiple inflows, and λ is the decay rate of the constituent [1/d]. Note that evaporation is presumed not to carry the constituent from the reservoir surface. The discrete form of the equation, after summing all of the mass inflow terms together into a single effective mass inflow, $Q_{in}C_{in} = \sum_{i=1}^{N} Q_{in}^{i} C_{in}^{i}$, is:

$$\frac{M^{n+1} - M^{n}}{\Delta t} = \frac{1}{2}\left(Q_{in}^{n} C_{in}^{n} + Q_{in}^{n+1} C_{in}^{n+1}\right) + \frac{1}{2}\left(Q_{out}^{n} C^{n} + Q_{out}^{n+1} C^{n+1}\right) - \frac{\lambda}{2}\left(C^{n} + C^{n+1}\right) \tag{7.4}$$

where n indicates the time step, and the concentration C^n is evaluated as $M^n/V(h^n)$ where $V(h)$ is the volume of the reservoir for a stage of h. This expression may be directly rearranged to determine the mass in the reservoir at the end of the time step, M^{n+1}.

Chapter 8

Model Diagnostics

While Raven doesn't have built-in calibration functionality, it supports it's own assessment by internally comparing observation data to model output. The model diagnostic output can readily be used by model-independent optimization and parameter estimation tools (as briefly discussed in section 2.6). This chapter includes information about all of the available diagnostics.

8.1 Pointwise vs. Pulsewise comparison

Note that in all cases, Raven is comparing a time series of observations to a time series of model output. It is assumed that the observations are instantaneous observations at a point in time (e.g., a single soil moisture measurement or snow depth measurement). The key exception to this is observed hydrographs. Most observed hydrographs available from government or municipal agencies report averaged data over discrete time intervals, e.g., daily average flows. Raven is careful to treat this continuous data as is appropriate, and compares the modeled average flows over each time interval to the observed average flows.

For non-hydrograph data, the model output is interpolated to the exact time of observation.

The documentation for the relevant .rvi and .rvt input commands (`:ObservationData`, `:ObservationWeights`, and `:EvaluationMetrics`) can be found in appendix A.

8.2 Diagnostic Algorithms

In all of the algorithms below, ϕ_i is an observation of interest, $\hat{\phi}_i$ is the corresponding modeled value, w_i is the corresponding weight of the observation (1.0 by default, 0 for blank observation data) and N is the number of non-blank observations. Note that many of these diagnostics are useful for hydrographs but may not make particular sense for other observed state variables (even though we can calculate them anyhow).

Nash-Sutcliffe Efficiency (`NASH_SUTCLIFFE`)

$$\text{NS} = 1 - \frac{\sum_{i=1}^{N} w_i \left(\hat{\phi}_i - \phi_i\right)^2}{\sum_{i=1}^{N} w_i \left(\bar{\phi} - \phi_i\right)^2}$$

where $\bar{\phi}$ is the weighted mean of observations,

$$\bar{\phi} = \frac{1}{N} \sum_{i=1}^{N} w_i \phi_i$$

Log-transformed Nash-Sutcliffe Efficiency (`LOG_NASH`)

$$\text{NS} = 1 - \frac{\sum_{i=1}^{N} w_i \left(\ln(\hat{\phi}_i) - \ln(\phi_i)\right)^2}{\sum_{i=1}^{N} w_i \left(\ln(\bar{\phi}) - \ln(\phi_i)\right)^2}$$

where $\bar{\phi}$ is the weighted mean of observations,

$$\bar{\phi} = \frac{1}{N} \sum_{i=1}^{N} w_i \phi_i$$

Root-mean-squared Error (`RMSE`)

$$\text{RMSE} = \sqrt{\sum_{i=1}^{N} w_i \left(\hat{\phi}_i - \phi_i\right)^2}$$

Percentage Bias (`PCT_BIAS`)

Returns the percent bias. Non-zero weights have no effect on this calculation, but zero weights will force the corresponding data points to be ignored.

$$\text{PCT\_BIAS} = \frac{\sum_{i=1}^{N} \left(\hat{\phi}_i - \phi_i\right)}{\sum_{i=1}^{N} \left(\phi_i\right)}$$

Average Absolute Error (`ABSERR`)

Returns the weighted average absolute error.

$$\text{ABSERR} = \frac{1}{N} \sum_{i=1}^{N} w_i \left|\hat{\phi}_i - \phi_i\right|$$

Maximum Absolute Error (ABSMAX)

The maximum absolute error between observed and modeled data. Non-zero weights have no effect on this calculation, but zero weights will force the corresponding data points to be ignored.

$$\text{ABSMAX} = \max\left\{\left|\hat{\phi}_i - \phi_i\right|\right\}$$

Peak difference (PDIFF)

The difference between the peak modeled data and peak observed data. Non-zero weights have no effect on this calculation, but zero weights will force the corresponding data points to be ignored.

$$\text{PDIFF} = \max\left\{\hat{\phi}_i\right\} - \max\left\{\phi_i\right\}$$

Monthly Mean Squared Error (TMVOL)

Describes the total monthly mean error between modeled data and observed data.

$$\text{TMVOL} = \sum_{j=1}^{M}\left[\frac{1}{N}\sum_{i=1}^{N_j} w_i\left(\hat{\phi}_i - \phi_i\right)^2\right]$$

where M is the number of months in the simulation and N_j is the number of data points in month j.

Correlation of Error (RCOEF)

Describes the correlation of error between adjacent time steps. It represents the tendency for the error to remain constant from one time step to the next and should only be applied to continuous time series.

$$\text{RCOEF} = \frac{1}{\sigma_\phi \sigma_{\hat{\phi}}}\frac{1}{N^* - 1}\sum_{i=1}^{N-1}(\hat{\phi}_i - \phi_i)(\hat{\phi}_{i+1} - \phi_{i+1})$$

where σ_ϕ is the standard deviation of the observed data and $\sigma_{\hat{\phi}}$ is the standard deviation of the modeled data. N^* is the number of adjacent non-blank data entries. Non-zero observation weights are ignored.

Number of Sign Changes (NSC)

NSC describes the number of sign changes in the error from one data point to the next. A low NSC (as compared to the total number of data points) would imply that the modeled values are constantly above or below the observed values.

Kling Gupta Efficiency (KLING_GUPTA)

Kling-Gupta efficiency metric as defined in Gupta et al. (2009).

Chapter 9

Raven Code Organization*

This section is intended primarily for Raven software developers

The Raven code is fully object-oriented code designed to, as much as possible, separate the numerical solution of the coupled mass-balance and energy-balance ODEs and PDEs from the evaluation of flux-storage relationships, enabling the testing of various numerical schemes without having to dig into each subroutine for each hydrologic process.

9.1 Classes

The Class diagram for the Raven code is depicted in figure 9.1. The code operates by generating a single instance of the `CModel` class, which may be considered a container class for all of the model data, i.e. the arrays of basins, HRUs, land/vegetation classes, and meteorological gauges/gridded forcing data that define the entirety of the model.

9.1.1 CModel class

The `CModel` class is a container class for all of the hydrologic response units (HRUs), subbasins, hydrologic processes ("HydroProcesses") and measurement gauges/gridded data. It also has global information about all of the state variables. It has a few key functions called by the solver routines:

- `Initialize()` Called before the simulation begins to initialize all variables. This also calls all Subbasin, Gauge, HRU and other initialize functions.
- `IncrementBalance()`
- `IncrementLatBalance()`
- `IncrementCumulInput()`
- `IncrementCumOutflow()` increment the individual cumulative HRU water and energy balances, stored within the CModel class

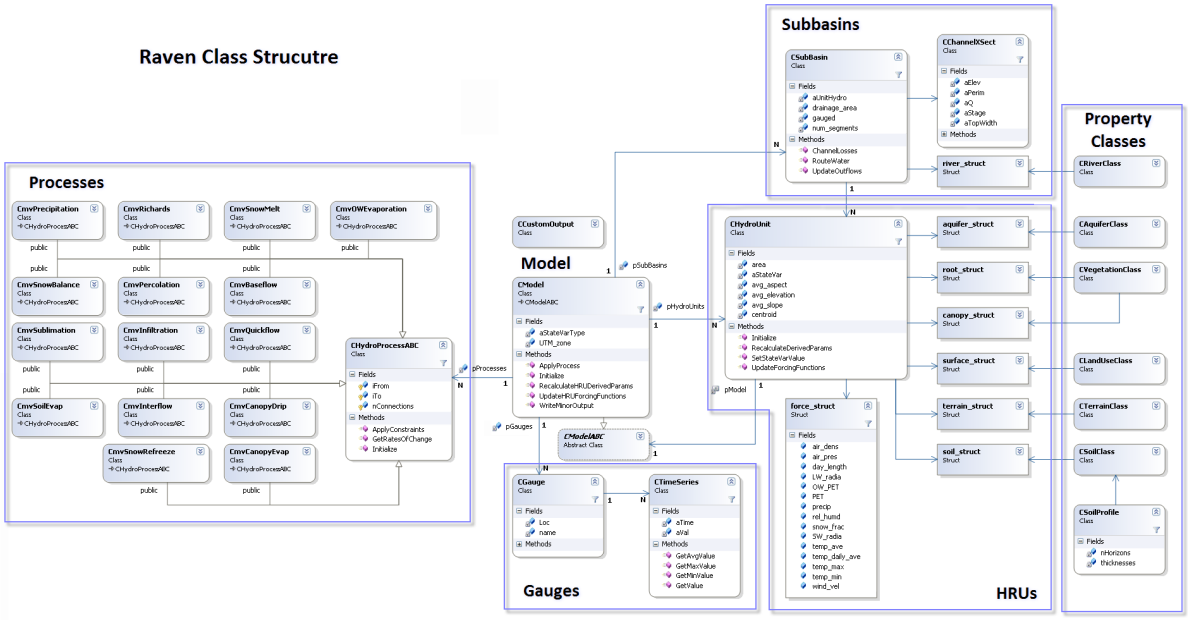

Figure 9.1: Raven class diagram

- `WriteMinorOutput()` Called at the end of each timestep, writes water and energy balance and watershed-scale storage information (i.e., total storage in snowpack, etc.), in addition to all custom output.
- `WriteMajorOutput()` Called at user-specified intervals, basically dumps a snapshot of all system state variables and derived parameters to an output file.
- `UpdateHRUForcingFunctions()` Called every time step - sifts through all of the HRUs and updates precip, temperature, radiation, and other (external) atmospheric forcing functions, interpolated from gauge/measurement data or gridded forcings. These values are then stored locally within each HRU. Called at the start of each time step.
- `RecalculateHRUDerivedParams()`, `UpdateTransientParams()` called every time step - updates derived and specified model parameters which change over time.
- `ApplyProcess()`, `ApplyLateralProcess()` Based upon some assumed current water storage/state variable distribution, returns a prediction of the rate of water (or energy) movement from one storage unit (e.g., canopy) to another (e.g., atmosphere) during the time step. This function DOES NOT actually move the water/energy - this is done within the solver. Basically returns $\mathbf{M}^k(\{\phi\},\{P\})$ in the above discussion for specified values of $\{\phi\}$
- `UpdateDiagnostics` Compares current modelled and observed output for the time step and updates diagnostic measures.

The CModel class has an abstracted parent class, CModelABC, that ensures the model can only provide information to, but cannot be modified by, other classes aware of its existence (e.g., any hydrologic processes (`CHydroProcess`), or subbasin (`CSubBasin`), etc.)

9.1.2 CGauge class

The CGauge class stores a set of time series (of class CTimeSeries) corresponding to observations of atmospheric forcing functions (precipitation, air temperature, radiation, etc.) at a single point in the watershed. The model interpolates these forcing functions from gauge information in order to determine forcing functions for individual HRUs at any given time step.

Interpolation is performed using the most appropriate local UTM coordinate system automatically calculated from the specified lat-long centroid of the watershed.

9.1.3 CSubBasin class

A container class for HRUs - only used for routing of water, as it stores information about the connectedness of itself to other subbasins in the modeled watershed(s). Conceptualized as a subbasin.

9.1.4 CHydroUnit class

An abstraction of an HRU - a homogeneous area of land to which the zero- or one-dimensional water and energy balances are applied. It is unaware of the CModel class. It stores the state of all local HRU-specific parameters that are valid for the current timestep, the values of the HRU forcing functions (e.g., precipitation, PET, radiation) averaged over the entirety of the current timestep, and the values of the state variables (water storage, energy storage, and snow parameters) that are valid at the start of the current timestep. It also stores its membership to the landuse and vegetation cover classes via pointers to those instances, so that it may be used to access properties shared by all measures of that class.

Key routines:

- `SetStateVarValue()` updates the values of a specific state variable. Called at the end of each time step by the main Raven solver
- `UpdateForcingFunctions()` updates the values of the forcing functions (rainfall, temperature, saturated water vapor, etc.) uniformly applied to the HRU at the beginning of each time step. The HydroUnit is unaware of the source of these values, but they are interpolated from measured data.
- `RecalculateDerivedParams()` Given some set of state variables and the current time of year, updates all derived parameters (e.g., Leaf area index) stored locally within the HRU. These are used within `GetRatesOfChange` functions

9.1.5 CHydroProcessABC class

An abstraction of any hydrologic process that moves water or energy from one or more storage units to another set of storage units (i.e., an abstraction of M_{ij} for one-to-one transfer of water/energy, or a summation of more than one M_{ij} that moves water through multiple compartments, as is required for PDE solution). Each CHydroProcess child class has five key subroutines:

- `Initialize()` initializes all necessary structures, etc. prior to solution
- `GetParticipatingStateVars()` returns the list of participating state variables for the model. This is used to dynamically generate the state variables used in the model. For example, snow will

not be tracked in the model until a process (e.g., snowmelt) is introduced that moves snow between storage compartments.

- `GetParticipatingParameters()` returns the list of algorithm-specific parameters needed to simulate this process with the specified algorithm. This is used to dynamically ensure that all parameters needed by the model are specified by the user within each HRU.
- `GetRatesOfChange()` calculates and returns rate of loss of one set of storage units to another set, in units of mm/d (for water), mg/m^2/d (for constituent mass) or MJ/m^2/d (for energy).
- `ApplyConstraints()` Corrects the rates calculated by rates of change to ensure that model constraints (e.g., state variable positivity) are met.

The CHydroProcessABC class is purely virtual - inherited classes each correspond to a single (or coupled set of) hydrologic process(es) as described in section 9.1.6

9.1.6 Hydrologic Processes

All hydrologic process algorithms are specified as individual child classes of `CHydroProcessABC`. Note that each HydroProcess may include multiple algorithms; distinction between classes is mostly based upon physical interpretation, i.e., baseflow and snowmelt are fundamentally different. While independent snow melt/snow balance algorithms may be very different, they are still grouped into one class.

9.2 Contributing to the Raven Framework*

Source code for Raven is available online, with file support for Microsoft Visual Studio, both 2013 and 2017 versions. Users are encouraged to develop custom-made algorithms for representing hydrologic processes, estimating forcing functions from gauge data, or interpolating gauge data. If a new algorithm is tested and found useful, feel free to submit your code to the Raven development team to be considered for inclusion into the main Raven code.

9.2.1 How to Add a New Process Algorithm

1. Make sure the process algorithm is not already included in the framework with a slightly different "flavour"
2. Determine whether the algorithm requires new state variable types to be added to the master list. The complete list of state variables currently supported may be found in the `enum sv_type` definition in `RavenInclude.h`. If a new state variable is required, follow the directions in section 9.2.2.
3. Determine whether the algorithm requires new parameters, and whether these parameters will be fixed for the model duration or depend upon transient factors. The lists of existing parameters (all linked to soils, vegetation, land use, or terrain types) are found in `Properties.h`. If a new parameter is needed, follow the directions in section 9.2.3
4. Determine whether the algorithm fits within an existing `CHydroProcess` class, i.e., is it a different means of representing one of the many processes already simulated within Raven? If so, you will be editing the code in 6 or 7 places, all within either the `CHydroProcess` header/source files or the main input parsing routine:

(a) Add a new algorithm type to the enumerated list of algorithms for that process. For example, if it is a new baseflow algorithm, you would add `BASE_MYALGORITHM` to the `enum baseflow_type` in `SoilWaterMovers.h`. Follow the apparent naming convention.

(b) Edit the `CHydroProcess` constructor. Constructors should be dynamic for all routines that have fixed input and output variables. Others, such as baseflow, can have user-specified input/output pairs declared. The `CmvBaseFlow` and `CmvSnowBalance` codes are excellent templates for class construction. Edit the if-then-else statement in the constructor, specifying the `iFrom` and `iTo` state variables manipulated by the algorithm connections. For example, most infiltration algorithms move water from ponded storage to both topsoil and surface water, requiring the following specification:

```
CHydroProcessABC::DynamicSpecifyConnections(2);
iFrom[0]=pModel->GetStateVarIndex(PONDED_WATER);
iTo  [0]=pModel->GetStateVarIndex(SOIL,0);
iFrom[1]=pModel->GetStateVarIndex(PONDED_WATER);
iTo  [1]=pModel->GetStateVarIndex(SURFACE_WATER);
```

This creates two connections, one from ponded water to the topmost soil (`SOIL[0]`) and one from ponded water to surface water. The corresponding rates of exchange will later be calculated in `GetRatesOfChange()` and stored in `rates[0]` and `rates[1]`. Note you shouldn't have to check for existence of state variables in the constructor - if they are later specified in `GetParticipatingStateVarList`, they will be generated in the master state variable list prior to instantiation of the class.

(c) Edit the if-then-else statement in the corresponding `GetParticipatingParamList` routine with the list of parameters needed by your new algorithm. This information is used for quality control on input data (ensuring that users specify all parameters needed to operate the model).

(d) Edit (if necessary) in `GetParticipatingStateVarList` the list of state variables required for your algorithm, within a conditional for your specific algorithm. See `CmvSnowBalance` for a good example.

(e) Add the actual flux calculation algorithm to the corresponding `GetRatesOfChange()` function for this `CHydroProcesss` class. Some key things to keep in mind:
(a) parameters may be obtained from the corresponding soil, vegetation, or land use structure via the HRU pointer, e.g.,

```
double lambda,K;
K     =pHRU->GetSoilProps(m)->max_baseflow_rate;
lambda=pHRU->GetTerrainProps()->lambda;
```

(b) the final result of the algorithm (rates of change of modeled state variables) are assigned to the `rates[]` array. The `rates[i]` array value corresponds to the flux rate of mass/water/energy from state variable `iFrom[i]` to `iTo[i]`, which you have defined in the constructor (step b).
(c) Try to follow the following code habits:

- unless required for emulation of an existing code, constraints should ideally not be used except later in the `ApplyConstraints` routine. A good rule of thumb is that the time

step should not appear anywhere in this code. This may not be strictly possible with some more complicated algorithms.

- each process algorithm longer than about 20-30 lines of code should be relegated to its own private function of the class
- all unit conversions should be explicitly spelled out using the provided global constants, defined in `RavenInclude.h`
- constants that might be used in more than one process subroutine should not be hard-coded, where at all possible.
- references should be provided for all equations, where possible. The full reference should appear in the back of this manual
- all variables should be declared before, not within, algorithm code
- All returned rates should be in mm/d or MJ/m^2/d for water storage and energy storage, respectively

(f) If needed, add special state variable constraints in the `ApplyConstraints()` function, conditional on the algorithm type.

(g) Lastly, add the process algorithm option to the corresponding command in the `ParseMainInputFile()` routine within `ParseInput.cpp`.

9.2.2 How to Add a New State Variable

1. Make sure the state variable is not already included in the framework with a slightly different name. Note that proxy variables should be used cautiously. For example, right now snow (as SWE) and snow depth are included in the variable list, while snow density is not (as it may be calculated from the other two).
2. Add the state variable type to the `sv_type` enumerated type in `RavenInclude.h`
3. Edit the following routines in the `CStateVariables` class (within `StateVariables.cpp`) (revisions should be self-evident from code):
   - `GetStateVarName()`
   - `StringToSVType()`
   - `IsWaterStorage()`
   - `IsEnergyStorage()`
4. Edit the `CHydroUnit::GetStateVarMax()` routine in `HydroUnits.cpp` if there is a maximum constraint upon the variable

9.2.3 How to Add a New Parameter

1. Make sure that the parameter is not included in the framework by examining the available parameters in the `soil_struct`, `canopy_struct`, `terrain_struct` defined in `Properties.h` and the global parameters currently defined within the `global_struct` (`RavenInclude.h`). If it is not, determine whether the parameter is (and should always be) global (i.e., not spatially or

temporally varying). If it is not global, determine whether the property is best tied to land use/land cover class, soil class, vegetation class, or terrain class.

2. Add the new global parameter to the `global_struct` structure, non-global parameters to the corresponding `soil_`, `veg_`, `terrain_`, or `surface_struct` (corresponding to land use). The units of the parameter should generally be consistent with those used throughout Raven, i.e., SI units, with fractions represented from 0 to 1 (not 1-100%), time units preferably in days, and energy in MJ.

3. Depending upon the type of parameter, different classes will have to be revised. As an example, if it is a soil parameter, the following code must be revised:

    - `CSoilClass::AutoCalculateSoilProps()` In most cases, the new parameter will be conceptual and therefore not autocalculable from the base parameters of soil composition. In this case, code may be replicated from other parameters (see, e.g., `VIC_zmin` code for an example).
    - `CSoilClass::InitializeSoilProperties()` (revisions evident from code)
    - `CSoilClass::SetSoilProperty()` (revisions evident from code)
    - `CSoilClass::GetSoilProperty()` (revisions evident from code)

    Similar functions exist in the alternate classes (e.g., `CVegetationClass, CGlobalParams`). With these revisions, the parameter is now accessible via (for soils)

    ```
    pHRU->GetSoilProps(0)->new_param_name
    ```

    where `pHRU` is a pointer to a specific instantiated HRU. New global parameters (which are not specific to an HRU) may be accessed via

    ```
    CGlobalParams::GetParams()->new_param_name
    ```

To do (7)

Appendix A

Input Files

A.1 Primary Input file (.rvi)

The primary input file stores the model simulation options and numerical options. An example .rvi file is shown below. Note that comments may be included on individual lines using the * or # characters as the first word on the line. An .rvi file is structured as follows:

```
# ----------------------------------------
# Raven Input (.rvi) file
# ----------------------------------------
:StartDate       2000-10-01 00:00:00
:EndDate         2001-09-30 00:00:00
:TimeStep        01:00:00
# -Options----------------------------------
:Routing         ROUTE_HYDROLOGIC
:CatchmentRoute  ROUTE_GAMMA_CONVOLUTION
:Evaporation     PET_PENMAN_MONTEITH
:SoilModel       SOIL_TWO_LAYER
# -Processes--------------------------------
:HydrologicProcesses
  :Precipitation   PRECIP_RAVEN     ATMOS_PRECIP    MULTIPLE
  :Infiltration    INF_GREEN_AMPT   PONDED_WATER    SOIL[0]
  :SoilEvaporation SOILEVAP_SEQUEN  SOIL[0]         ATMOSPHERE
  :Percolation     PERC_POWER_LAW   SOIL[0]         SOIL[1]
  :Percolation     PERC_POWER_LAW   SOIL[1]         GROUNDWATER
  :Baseflow        BASE_LINEAR      SOIL[1]         SURFACE_WATER
:EndHydrologicProcesses
# -Custom Output----------------------------
:CustomOutput Daily   Average SOIL[0]    BY_HRU
:CustomOutput Monthly Maximum SOIL[1]    BY_BASIN
```

Note that, for the most part, input commands in Raven are unstructured - spacing, tabs, etc., should not impact the ingestion of input. Most commands can be input in arbitrary order. The only exceptions to this are

1. The `:SoilModel` command must preceded the `:HydrologicProcesses` block.

2. The :HydrologicProcesses block must precede any :Transport command.
3. If HRU groups are to be used for conditional application of processes in the :HydrologicProcesses block, for :CustomOutput, for disabling HRUs, or for transport boundary conditions, they must be declared first using the :DefineHRUGroups command.

A.1.1 Required Commands

The .rvi file consists of the following required commands:

```
:StartDate [yyyy-mm-dd hh:mm:ss]
```

(Required) Starting time of the simulation.

```
:EndDate [yyyy-mm-dd hh:mm:ss]
```

(Required) Ending time of the simulation.

```
:Duration [days]
```

Duration of the simulation, in decimal days, beginning from the start date specified. An alternative to using the :EndDate command.

```
:TimeStep [time step in days]
# OR
:TimeStep [hh:mm:ss]
```

(Required) Time step for the simulation, expressed in days as a real-valued number (e.g., 0.4166667 for one hour) or using hh:mm:ss format (e.g., 01:00:00 for one hour). As Raven is intended for sub-daily calculations, the time step must be less than or equal to 1.0. It also must evenly divide into a day - 2 hours or 5 minutes is allowed, but 1 hour 40 minutes is not.

```
:SoilModel [soilmodel string] {(conditional) other_data}
```

(Required) Soil model used in the simulation, one of the following:

- SOIL_ONE_LAYER - Single soil layer
- SOIL_TWO_LAYER - Two soil layers
- SOIL_MULTILAYER [number of layers] - Any number of soil layers

This command must be placed before the :HydrologicProcesses block.

```
:DefineHRUGroups [HRUgrp1] {HRUgrp2} ... {HRUgrpN}
```

(Somewhat required) Declaration of HRU groups that may be used for (1) conditional application of hydrologic processes, (2) grouping of custom output, (3) disabling of groups of HRUs, or (4) . They must be defined prior to use in the .rvi file. They are populated in the .rvh file using the :HRUGroup-:EndHRUGroup command. Here, the HRUgrp is a unique string identifier for the group (e.g., OpenHRUs or ForestBurnSite)

```
:HydrologicProcesses
...
:EndHydrologicProcesses
```

(Required) These commands bracket the list of hydrologic processes to be modeled (see section A.1.6)

A.1.2 Model Operational Options

The following section discusses about the several hydrologic processes that are supported by Raven and their respective algorithms. Some of these algorithms require specific parameters to be entered by the users. Refer to section A.1.3 for more details about the required parameters.

```
:CatchmentRoute [method]
```

Catchment routing method, used to convey water from the catchment tributaries and rivulets to the subbasin outlets. Can be one of the following methods, discussed in section 4.1:

- `DUMP` (**default**) - water from the catchment is dumped directly to the basin outlet.
- `ROUTE_GAMMA_CONVOLUTION` - a Gamma distribution is used to represent the unit hydrograph
- `ROUTE_TRI_CONVOLUTION` - a triangular distribution is used for the unit hydrograph
- `ROUTE_RESERVOIRS_SERIES` - series of linear reservoirs (Nash Hydrograph)

```
:Routing [method]
```

Channel routing method which is used to transport water from upstream to downstream within the main subbasin channels. Can be one of the following methods, as described in section 4.2:

- `ROUTE_DIFFUSIVE_WAVE` (**default**) - analytical solution to the diffusive wave equation along the reach using a constant reference celerity
- `ROUTE_HYDROLOGIC` - iterative level-pool routing using channel characteristics and Manning's equation
- `ROUTE_NONE` - water is not routed from subbasin to subbasin. Intended for single-subbasin/single catchment models or numerical testing only.
- `ROUTE_STORAGE_COEFF` - From Williams (1969)
- `ROUTE_PLUG_FLOW` - water travels as a pulse of uniform celerity along the reach
- `ROUTE_MUSKINGUM` - reach storage is updated using the Muskingum-Cunge routing algorithm

```
:Method [method]
```

(Optional) Numerical method used for simulation. The method string be one of the following:

- `ORDERED_SERIES` (**default**) - Process ordering is defined as being the same as the order of hydrologic process in the input file
- `EULER` - uses the classical Euler method, with operator-splitting. Process order as specified in the input file does not matter

```
:InterpolationMethod [method]
```

(Optional) Means of interpolating forcing function data (e.g., precipitation, PET, etc.) between monitoring gauges. The centroid of the HRU is used as the interpolation point. The following methods, discussed in section 5.1 are supported:

- INTERP_NEAREST_NEIGHBOR (**default**) - the nearest neighbor (Voronoi) method
- INTERP_INVERSE_DISTANCE - inverse distance weighting
- INTERP_AVERAGE_ALL - averages all specified gauge readings
- INTERP_FROM_FILE [filename]- weights for each gauge at each HRU are specified in a file named filename with the following contents:

  ```
  :GaugeWeightTable
    [NG] [# of HRUs]
    {w_n1 w_n2 ... w_nNG} x {# of HRUs}
  :EndGaugeWeightTable
  ```

  where NG is the number of gauges. The sum of the weights in each row (i.e., for each HRU) should be 1. It is assumed that the number of HRUs is the same as in the current model .rvh file; the orders are also assumed to be consistent.

```
:RainSnowFraction [method]
```

(Optional) Means of partitioning precipitation into snow and rain, if these values are not specified as time series data. The following methods, discussed in detail in section 5.3.1, are supported:

- RAINSNOW_DINGMAN (**default**)
- RAINSNOW_DATA - gauge or gridded time series of snowfall used
- RAINSNOW_UBC
- RAINSNOW_HBV
- RAINSNOW_HSPF
- RAINSNOW_HARDER

```
:Evaporation [method]
```

PET calculation method for land surface. Can be one of the following methods, described in detail in section 5.4:

- PET_HARGREAVES_1985 (**default**)
- PET_CONSTANT - not recommended in practice
- PET_PENMAN_MONTEITH
- PET_PENMAN_COMBINATION
- PET_PRIESTLEY_TAYLOR - physically-based, but data requirements are intensive
- PET_HARGREAVES
- PET_FROMMONTHLY
- PET_DATA - gauge or gridded time series used
- PET_HAMON_1961
- PET_TURC_1961

- PET_MAKKINK_1957
- PET_MONTHLY_FACTOR
- PET_MOHYSE
- PET_OUDIN - works quite well in Canadian watersheds

Note that the evaporation algorithm will be influence by whether the :DirectEvaporation command is used.

```
:OW_Evaporation [method]
```

(Optional) PET calculation method for open water. Has the same options as :Evaporation command.

```
:DirectEvaporation
```

(Optional) If this command is added, rainfall is automatically reduced through evapotranspiration up to the limit of the calculated PET. PET is likewise reduced by the quantity of rainfall evaporated.

```
:SnowSuppressesPET
```

(Optional) If this command is added, presence of snow suppresses PET to zero.

```
:SuppressCompetitiveET
```

(Optional) If this command is added, competitive ET is disabled and ET routines independently remove water based upon PET, not PET corrected for other processes.

```
:OroPrecipCorrect [method]
```

(Optional) Method for correcting total precipitation for orographic (elevation) effects. The following methods, discussed in detail in section 5.3.2, are supported:

- OROCORR_NONE (**default**)
- OROCORR_HBV
- OROCORR_UBC
- OROCORR_UBC_2
- OROCORR_SIMPLE

```
:OroTempCorrect [method]
```

(Optional) Method for correcting estimated Temperatures for orographic (elevation) effects. The following methods are supported:

- OROCORR_NONE (**default**)
- OROCORR_HBV
- OROCORR_UBC

- OROCORR_UBC_2
- OROCORR_SIMPLE

```
:OroPETCorrect [method]
```

(Optional) Method for correcting estimated PET for orographic (elevation) effects. The following methods are supported, as discussed in section 5.3.2:

- OROCORR_NONE (**default**)
- OROCORR_HBV
- OROCORR_UBC
- OROCORR_UBC_2
- OROCORR_PRMS

Note: No specific parameter required for any of the methods mentioned above.

```
:SWRadiationMethod [method]
```

(Optional) Means of estimating shortwave radiation to the surface. The following methods, described in detail in section 5.5, are supported:

- SW_RAD_DEFAULT(**default**) - From Dingman (2002)
- SW_RAD_DATA - gauge or gridded time series used
- SW_RAD_UBCWM - From Quick (2003)

```
:SWCanopyCorrect [method]
```

(Optional) Means of correcting shortwave radiation to the surface due to canopy cover. The following methods, described in detail in section 5.5, are supported:

- SW_CANOPY_CORR_NONE(**default**)
- SW_CANOPY_CORR_STATIC
- SW_CANOPY_CORR_DYNAMIC
- SW_CANOPY_CORR_UBC - From Quick (2003)

```
:SWCloudCorrect [method]
```

(Optional) Means of correcting shortwave radiation to the surface due to cloud cover. The following methods, described in detail in section 5.5, are supported:

- SW_CLOUDCOV_CORR_NONE(**default**)
- SW_CLOUDCOV_CORR_DINGMAN
- SW_CLOUDCOV_CORR_UBC - From Quick (2003)

```
:LWRadiationMethod [method]
```

(Optional) Means of estimating longwave radiation. The following methods are supported, as discussed in section 5.6:

- `LW_RAD_DATA` - gauge or gridded time series used
- `LW_RAD_DEFAULT`(**default**) - From Dingman (2002)
- `LW_RAD_UBC` - From Quick (2003)
- `LW_RAD_HSPF` - From (Bicknell et al., 1997)

```
:CloudCoverMethod [method]
```

(Optional) Means of calculating cloud cover percentages, if used. The following methods, as described in section 5.7, are supported:

- `CLOUDCOV_NONE` (**default**)
- `CLOUDCOV_DATA` - gauge or gridded time series used
- `CLOUDCOV_UBC` - From Quick (2003)

```
:WindspeedMethod [method]
```

(Optional) Means of calculating wind speed at a reference height. The following methods are supported, as described in section 5.9.1:

- `WINDVEL_CONSTANT` (**default**) - constant wind velocity of 3 m/s
- `WINDVEL_DATA` - gauge or gridded time series used
- `WINDVEL_UBC` - From Quick (2003)

```
:RelativeHumidityMethod [method]
```

(Optional) Means of calculating relative humidity. The following methods are supported, as described in section 5.9.2:

- `RELHUM_CONSTANT` (**default**) - constant relative humidity of 0.5
- `RELHUM_DATA` - gauge or gridded time series used
- `RELHUM_MINDEWPT` - uses minimum dew point to estimate relative humidity

Note: No specific parameter required for any of the methods mentioned above.

```
:AirPressureMethod [method]
```

(Optional) Means of estimating air pressure. The following methods are supported, as described in section 5.9.3:

- `AIRPRESS_BASIC` (**default**)
- `AIRPRESS_CONST` - standard atm. pressure at 20 °C
- `AIRPRESS_DATA` - gauge or gridded time series used
- `AIRPRESS_UBC` - From Quick (2003)

```
:PrecipIceptFract [method]
```

(Optional) Means of estimating the precipitation interception fraction (i.e., what percentage of precip is intercepted by the canopy). The following methods are supported, as described in section 3.1.1:

- `PRECIP_ICEPT_USER` (**default**)
- `PRECIP_ICEPT_LAI`
- `PRECIP_ICEPT_EXPLAI`

```
:PotentialMelt [method]
```

(Optional) If used, estimates the potential melt. The following methods are supported , as discussed in section 5.8.1:

- `POTMELT_DEGREE_DAY` (**default**)
- `POTMELT_EB`
- `POTMELT_RESTRICTED`
- `POTMELT_UBCWM`
- `POTMELT_HBV`
- `POTMELT_CRHM`
- `POTMELT_HMETS`

```
:RechargeMethod [method]
```

(Optional) Typically used for coupling with other hydrologic models that independently calculate runoff and recharge, which is handled by Raven for routing and water management.

- `RECHARGE_NONE` (**default**)
- `RECHARGE_DATA` - gridded time series used

```
:MonthlyInterpolationMethod [method]
```

(Optional) If used, performs monthly interpolations. The following methods, as discussed in section 5.11, are supported:

- `MONTHINT_UNIFORM` - monthly variables are treated as constant during each month
- `MONTHINT_LINEAR_MID` (**default**) - the monthly variables are linearly interpolated from the midpoint of each month
- `MONTHINT_LINEAR_FOM` - the monthly variables are linearly interpolated from the 1st day of each month
- `MONTHINT_LINEAR_21` - the monthly variables are linearly interpolated from the 21st day of each month (yes, this seems very specific)

Note: No specific parameter is required for any of the methods mentioned above.

```
:SubDailyMethod [method]
```

(Optional) Used for sub-daily temporal downscaling of daily average PET and snowmelt. The supported methods are, as described in section 5.10:

- `SUBDAILY_NONE` (**default**)
- `SUBDAILY_UBC`
- `SUBDAILY_SIMPLE`

Note: No specific parameter required for any of the methods mentioned above.

```
:LakeStorage [lake storage variable]
```

Specifies the state variable to be used for rainfall on lake HRUs, typically `SURFACE_WATER` (default) or `LAKE_STORAGE`. If the lake storage state variable is used, it is critical that the user provide a hydrologic process mechanism which removes water from the lake in addition to accumulating it through precipitation. This is typically only used for HBV emulation, which uses a non-conventional lake evaporation routine.

```
:Calendar [calendar string]
```

(Optional) Specifies the calendar to be used. By default, Raven uses the standard proleptic Gregorian calendar which includes leap years. However, for compatibility with some climate model outputs for long-term forecasting, sometimes it is useful to be able to run with (e.g.,) 365 day calendars. Raven supports the following calendars (consistent with the NetCDF calendar convention):

- `PROLEPTIC_GREGORIAN` (**default**)
- `JULIAN` - ignores special leap years (every 100/400 years)
- `GREGORIAN` - ignores special leap years before 1583
- `STANDARD` - same as `GREGORIAN`
- `NOLEAP` - leap years ignored
- `365_DAY` - same as `NOLEAP`
- `ALL_LEAP` - every year gets a February 29
- `365_DAY` - same as `ALL_LEAP`

A.1.3 Required Parameters for Model Operation Options

The following table (Figure A.1) shows the required parameters in order to use the different model operation options that were listed in the previous section (Section A.1.2).

Option	Algorithms	Required Parameters
Interpolation		
:Interpolation	INTERP_FROM_FILE	:GaugeWeightsTable required
	INTERP_AVERAGE_ALL	-
	INTERP_NEAREST_NEIGHBOR*	-
	INTERP_INVERSE_DISTANCE	-
Routing		
:Routing	ROUTE_NONE ROUTE_DIFFUSIVE_WAVE* ROUTE_PLUG_FLOW ROUTE_STORAGE_COEFF ROUTE_MUSKINGUM ROUTE_MUSKINGUM_LAGGED ROUTE_MUSKINGUM_CUNGE ROUTE_HYDROLOGIC	Channel Geometry, Mannings n (ALL but ROUTE_NONE)
:CatchmentRoute	ROUTE_DUMP*	-
	ROUTE_GAMMA_CONVOLUTION	TIME_TO_PEAK
	ROUTE_TRI_CONVOLUTION	TIME_CONC, TIME_TO_PEAK
	ROUTE_RESERVOIR_SERIES	NUM_RESERVOIRS, RES_CONSTANT
	ROUTE_EXPONENTIAL	RES_CONSTANT
Evaporation		
:Evaporation	PET_CONSTANT	-
	PET_FROMFILE	[gridded data or time series at gauge]
	PET_FROMMONTHLY	:MonthlyAveEvaporation, :MonthlyAveTemperature
	PET_MONTHLY_FACTOR [HBV]	FOREST_PET_CORR, FOREST_COVERAGE, :MonthlyEvapFactor
	PET_PENMAN_MONTEITH	MAX_HEIGHT,RELATIVE_HT,MAX_LAI, RELATIVE_LAI SPARSENESS, MAX_LEAF_COND
	PET_PENMAN_COMBINATION	MAX_HEIGHT,RELATIVE_HT
	PET_HAMON	-
	PET_HARGREAVES	:MonthlyMaxTemperature and :MonthlyMinTemperature
	PET_HARGREAVES_1985*	-
	PET_TURC_1961	-
	PET_SIMPLE33 (Valiantzas et al 2006)	-
	PET_SIMPLE39 (Valiantzas et al 2006)	-
	PET_MAKKINK_1957	-
	PET_PRIESTLEY_TAYLOR	-
:OW_Evaporation	Same as :Evaporation	-
:OroPETCorrect	OROCORR_NONE*	-
	OROCORR_SIMPLELAPSE	
	OROCORR_HBV	
Radiation		
:SWRadiationMethod	SW_RAD_DATA	[gridded data or time series at gauge]
	SW_RAD_DEFAULT*	SLOPE, ASPECT
	SW_RAD_UBCWM	
:LWRadiationMethod	LW_RAD_DATA	[gridded data or time series at gauge]
	LW_RAD_DEFAULT*	FOREST_COVERAGE
	LW_RAD_UBC	FOREST_COVERAGE
:CloudCoverMethod	CLOUDCOV_NONE*	-
	CLOUDCOV_DATA	[gridded data or time series at gauge]
	CLOUDCOV_UBC	-

Table A.1: Required parameters for all model operation options. The asterisk* denotes the default algorithm for each method.

Option	Algorithms	Required Parameters
Precipitation		
:RainSnowFraction	RAINSNOW_DATA	[gridded data or time series at gauge]
	RAINSNOW_DINGMAN	RAINSNOW_TEMP
	RAINSNOW_HBV	RAINSNOW_TEMP, RAINSNOW_DELTA
	RAINSNOW_UBC	RAINSNOW_TEMP, RAINSNOW_DELTA
:PrecipIceptFract	PRECIP_ICEPT_USER	RAIN_ICEPT_PCT, SNOW_ICEPT_PCT
	PRECIP_ICEPT_LAI	RAIN_ICEPT_FACT,SNOW_ICEPT_FACT
	PRECIP_ICEPT_EXPLAI	-
:OroPrecipCorrect	OROCORR_NONE*	-
	OROCORR_UBC	:UBCPrecipLapseRates
	OROCORR_HBV	-
	OROCORR_SIMPLELAPSE	-
Temperature		
:OroTempCorrect	OROCORR_NONE*	-
	OROCORR_UBC	:UBCTempLapseRates,:ReferenceMaxTemperatureRange, ADIABATIC_LAPSE,WET_ADIABATIC_LAPSE
	OROCORR_HBV	ADIABATIC_LAPSE
	OROCORR_SIMPLELAPSE	ADIABATIC_LAPSE
Energy		
:PotentialMeltMethod	POTMELT_DEGREE_DAY*	MELT_FACTOR
	POTMELT_RESTRICTED	MELT_FACTOR
	POTMELT_DATA	[gridded data or time series at gauge]
	POTMELT_EB [Dingman]	-
	POTMELT_USACE	WIND_EXPOSURE
	POTMELT_HBV	MIN_MELT_FACTOR,HBV_MELT_ASP_CORR,HBV_MELT_FOR_CORR, FOREST_COVERAGE
	POTMELT_UBC	MIN_SNOW_ALBEDO, FOREST_COVERAGE,ASPECT,:UBCNorthSWCorr :UBCSouthSWCorr,F0ERGY,
:SubdailyMethod	SUBDAILY_NONE*	-
	SUBDAILY_SIMPLE	-
	SUBDAILY_UBC	-
Atmospheric Variables		
:WindspeedMethod	WINDVEL_CONSTANT*	-
	WINDVEL_DATA	[gridded data or time series at gauge]
	WINDVEL_UBC	:UBCTempLapseRates (P0TEDL,P0TEDU,MAX_RANGE_TEMP), FOREST_COVERAGE
:RelativeHumidityMethod	RELHUM_CONSTANT*	-
	RELHUM_DATA	[gridded data or time series at gauge]
	RELHUM_MINDEWPT	-
:AirPressureMethod	AIRPRESS_BASIC*	-
	AIRPRESS_UBC	-
	AIRPRESS_DATA	[gridded data or time series at gauge]
	AIRPRESS_CONST	-
Temporal Interpolation		
:MonthlyInterpolationMethod	MONTHINT_UNIFORM	-
	MONTHINT_LINEAR_FOM	-
	MONTHINT_LINEAR_MID*	-
	MONTHINT_LINEAR_21	-

Table A.2: Required parameters for all model operation options (cont'd)

A.1.4 Optional Input/Output Control Commands

```
:RunName [name]
```

The name of the model run. This acts as a prefix to all output files generated by the program. The default is no run name, and no prefix is appended to the file outputs.

```
:rvh_Filename [name]
```

The name of the *.rvh file. By default, the .rvh file has the same name as the .rvi file; this command allows the user to override this default behavior. If no directory is specified, it is assumed the file exists in the working directory. Equivalent to the command prompt argument `-h [name]`.

```
:rvc_Filename [rvc_name]
:rvp_Filename [rvp_name]
:rvt_Filename [rvt_name]
```

Same as `:rvh_Filename [name]` above, but for .rvc,.rvp, and .rvt files, respectively

```
:OutputDirectory [directory name]
```

Sets the output directory, which by default is the working directory from which the executable is called. Directory name is usually in a system independent format, using all forward slashes for folders, ending with a forward slash, e.g., `C:/Temp/Model Output/run 3/`. Equivalent to the (preferable) command line argument `-o [directory name]`. If used, this should be called as early as possible in the .rvi file. This command supports both absolute and relative pathnames.

```
:CreateRVPTemplate
```

Produces a template .rvp file in the same directory as the .rvi file based upon the hydrologic process list and model options in the .rvi file, so the user knows which parameters need to be specified for the given model configuration. NOTE: this turns off model operation, only the template file will be created.

```
:OutputInterval [frequency]
```

The frequency of printing output to the output files. Default of 1 (printing every time step). Typically used for simulations with small time steps (e.g., if frequency=60 for a model with a time step of 1 minute, standard output is printed hourly).

```
:WriteMassBalanceFile
```

The file runname_WatershedMassEnergyBalance.csv (or .tb0) is generated (see appendix B)

```
:WriteForcingFunctions
```

The file runname_ForcingFunctions.csv (or .tb0) is generated (see appendix B)

```
:WriteEnergyStorage
```

The file runname_WatershedEnergyStorage.csv is generated (see appendix B)

```
:WriteDemandFile
```

The file runname_Demands.csv is generated (see appendix B)

```
:WriteEnsimFormat
```

Specify that the output files generated by RAVEN should be in an EnSim (*.tb0) format instead of .csv. Used primarily for visualization with the Green Kenue software.

```
:WriteExhaustiveMB
```

The file runname_ExhaustiveMB.csv is generated (see appendix B)

```
:EndPause
```

This command forces the program output to stay on the screen (e.g., as a DOS window) until the user exits manually. Default behaviour is that the command prompt will close once execution finished.

```
:DebugMode
```

The equivalent of including `:WriteMassBalanceFile`, `:WriteForcingFunctions`, and `:WriteEnergyStorage`. Also generates the output file debug.csv.

```
:SilentMode
```

If this command is included, output to the command prompt is minimized. Useful during automated calibration or uncertainty analysis to speed program operation.

```
:SuppressOutput
```

Suppresses all standard output, including generation of Hydrograph, transport output, and watershed storage files. Does not turn off optional outputs which were requested elsewhere in the input file. Does not turn off creation of diagnostics.csv. Useful during automated calibration to speed program operation.

```
:WaterYearStartMonth [integer month]
```

Changes the start of the water year from October 1st (the default) to the 1st of another month (for example, `:WaterYearStartMonth 7 #July` for Australian application). The water year is only used for reporting of annual (`WATER_YEARLY`) budget reporting in the `:CustomOutput` command.

```
:OutputDump [YYYY-MM-DD hh:mm:ss]
```

Outputs snapshot of all state variables to file state_(timestamp).rvc, where timestamp is the indicated time in the command. The format of this file is the same as solution.rvc. This can later be used as an

initial condition file. Multiple calls to this command will cause snapshots to be written at all requested dump times. This is useful for long model operations where interruption could cause work to be lost. Alternately, it can be used to generate intermediate warm start states.

```
:SnapshotHydrograph
```

Hydrographs are reported using the values at the end of each time step. By default, hydrographs are reported as averaged over the time step, to be consistent with most available observation data, typically reported using time-averaged values. This is mostly used for direct comparison to emulated models, which typically do not report time step-averaged flows.

```
:EvaluationMetrics [metric1] {metric2} {metric3} ... {metricN}
```

If observation time series are provided (see `:ObservationData` command in appendix A.4.2), Raven will generate the evaluation metrics listed in this command. The metrics include:

- `NASH_SUTCLIFFE`
- `RMSE`
- `PCT_BIAS`
- `ABSERR`
- `ABSMAX`
- `PDIFF`
- `TMVOL`
- `RCOEF`
- `NSC`
- `RSR`
- `R2`
- `LOG_NASH`
- `KLING_GUPTA`

These metrics are defined in section 8.2.

```
:NetCDFAttribute [attribute name] [value]
```

Adds a user-specified attribute with name attribute name and arbitrary string value value. Commas are not allowed in the value string.

A.1.5 Custom Output

```
:CustomOutput [time_per] [stat] [variable] [space_agg] {filename}
```

This command is used to create a custom output file that tracks a single variable, parameter, or forcing function over time at a number of basins, HRUs, or across the watershed. Here, the `variable` is specified

using either the state variable name(for an exhaustive list, see table C.1), the forcing name (see table C.2), or parameter name. `time_per` refers to the time period, one of:

- `DAILY`
- `MONTHLY`
- `YEARLY`
- `WATER_YEARLY`
- `CONTINUOUS` (for output created every time step)

For the water year aggregation, a default water year of October 1-September 30 is used. The start month can be changed using the `:WaterYearStartMonth` command above. `stat` is the statistic reported over each time interval, one of:

- `AVERAGE`
- `MAXIMUM`
- `MINIMUM`
- `RANGE`
- `MEDIAN`
- `QUARTILES`
- `HISTOGRAM [min] [max] [num. of bins]`

If `HISTOGRAM` is selected, the command should be followed (in the same line) with the minimum and maximum bounding values of the histogram range and the number of evenly spaced bins.

`space_agg` refers to the spatial evaluation domain for reporting, and is either `BY_BASIN`, `BY_HRU`, `BY_HRU_GROUP`, or `ENTIRE_WATERSHED`. In all cases, the variable statistics will be determined using the area-weighted average, i.e., if `MONTHLY MAXIMUM SOIL[0] BY_BASIN` is chosen, it will report the maximum basin average soil moisture in the top soil layer in any given month, not the maximum HRU soil moisture found in the basin within that month.

If the state variable is not used in the model (it does not participate in any of the user-specified hydrologic processes), the output file will not be created; a warning will be generated.

As an example, the custom output command may be used as follows:

```
:CustomOutput DAILY MAXIMUM SNOW BY_BASIN
```

This would create the file `runname_DailyMaximumSnowByBasin.csv`, which would include a time series of daily maximum snow contents (as mm SWE) for all subbasins in the model. An optional specified filename may be appended to the end of any command to override the default filename.

There are also three special forms of custom output for tracking fluxes between modeled storage compartments. The first reports the cumulative flux from a single storage compartment, using the following syntax:

```
:CustomOutput DAILY AVERAGE From:SNOW BY_HRU
```

where the term after the From: command is a state variable from table C.1. This example returns the cumulative loss from snowpack in the form of snowmelt or sublimation (in mm).

```
:CustomOutput DAILY AVERAGE To:SNOW BY_HRU
```

where the term after the To: command is a state variable from table C.1. This example returns the cumulative gain of snow (in mm).

```
:CustomOutput DAILY AVERAGE Between:SOIL[0].And.ATMOSPHERE BY_HRU
```

where the terms after the Between: and .And. commands are both state variables from the table C.1. This example returns the cumulative loss of water from the top soil (SOIL[0]) to the atmosphere, i.e., the actual evapotranspiration rate from the top soil.

If the user requires this custom output file to be written as an Ensim (.tb0) or NetCDF (.nc) file, the :CustomOutput command must be preceded by the :WriteEnsimFormat or :WriteNetCDFFormat command, respectively.

A.1.6 Hydrologic Processes

In addition to the above commands, the .rvi file must include the list of all of the necessary hydrologic processes to be included in the model, which are bracketed by the :HydrologicProcesses and :EndHydrologicProcesses commands. The process commands are typically in some variation of the following format:

```
:ProcessName ALGORITHM {ProcessFrom} {ProcessTo}
```

where :ProcessName is the name of the process (e.g., :CanopyDrip), ALGORITHM refers to the particular algorithm used for simulation (e.g., CANDRIP_RUTTER corresponds to the (Rutter et al., 1971) model for loss of water from canopy to ground surface), and ProcessFrom and ProcessTo are the state variable code for the source and sink storage compartments, which are selected from the complete list of state variables in table C.1.

The state variables SURFACE_WATER, PONDED_WATER, ATMOS_PRECIP and ATMOSPHERE are automatically included in all models. The others will be dynamically included in the model as processes are added. For example, the SNOW variable will be automatically added if a snowmelt or sublimation hydrologic process is added to the list. Note that the computational cost of a model is directly related to the number of state variables and number of processes included in that model. Note that the SOIL variable is followed by the index of the soil layers in the model, with [0] corresponding to the topmost layer. The MULTIPLE tag is a placeholder, indicating that there are more than one compartments either receiving water/energy/mass, or more than one losing. The specific compartments are usually determined from the chosen algorithm, though there are certain routines (e.g., many baseflow or percolation algorithms) which require the user to specify the 'to' or 'from' compartment.

> Important: depending upon the numerical method chosen, the ordering of the processes in the input file may determine the accuracy and/or behavior of the solution. In general, processes should be ordered from fast to slow and precipitation and snowmelt should be applied prior to infiltration. This becomes less of an issue with decreasing time step size.

As shown in the template files in appendix D, the `:Alias` command may be used to give 'nicknames' to state variables which can be used instead of the Raven standard syntax. This is most often done to distinguish between actual storage compartments (e.g., `SOIL[1]`) and conceptual storage compartments (e.g., the alias `ROUTING_STORE`). For example,

```
:Alias FAST_RESERVOIR SOIL[1]
:Alias SLOW_RESERVOIR SOIL[2]
# SLOW_RESERVOIR now refers to SOIL[2] when used
```

Table A.3 includes a detailed description of the process commands available in Raven.

Process	Algorithms	"From" Storage Compartments	"To" Storage Compartments
Precipitation			
:Precipitation	PRECIP_RAVEN	ATMOS_PRECIP*	*All**
Evapotranspiration/Evaporation Processes			
:CanopyEvap	CANEVP_RUTTER	CANOPY	ATMOSPHERE
	CANEVP_MAXIMUM	CANOPY	ATMOSPHERE
:SoilEvaporation	SOILEVAP_VIC	SOIL[0]	ATMOSPHERE
	SOILEVAP_HBV	SOIL[0]	ATMOSPHERE
	SOILEVAP_CHU	SOIL[0]	ATMOSPHERE
	SOILEVAP_TOPMODEL	SOIL[0]	ATMOSPHERE
	SOILEVAP_SEQUEN	SOIL[0]	ATMOSPHERE
	SOILEVAP_ROOTFRAC	SOIL[0]	ATMOSPHERE
	SOILEVAP_GAWSER	SOIL[0]	ATMOSPHERE
:LakeEvaporation	LAKE_EVAP_BASIC	LAKE, SURFACE_WATER*	ATMOSPHERE
:OpenWaterEvaporation	OPEN_WATER_EVAP	DEPRESSION	ATMOSPHERE
Soil Processes			
:Infiltration	INF_RATIONAL	PONDED_WATER	SOIL[0], SURFACE_WATER
	INF_SCS	PONDED_WATER	SOIL[0], SURFACE_WATER
	INF_ALL_INFILTRATES	PONDED_WATER	SOIL[0], SURFACE_WATER
	INF_GREEN_AMPT	PONDED_WATER	SOIL[0], SURFACE_WATER
	INF_GA_SIMPLE	PONDED_WATER	SOIL[0], SURFACE_WATER
	INF_UPSCALED_GREEN_AMPT	PONDED_WATER	SOIL[0], SURFACE_WATER
	INF_HBV	PONDED_WATER	SOIL[0], SURFACE_WATER
	INF_UBC	PONDED_WATER	SOIL[0], SOIL[1], SOIL[2], SOIL[3],SURFACE_WATER
	INF_VIC	PONDED_WATER	SOIL[0], SURFACE_WATER
	INF_VIC_ARNO	PONDED_WATER	SOIL[0], SURFACE_WATER
	INF_PRMS	PONDED_WATER	SOIL[0], SURFACE_WATER
:Percolation	PERC_GAWSER	SOIL[m]/AQUIFER*	SOIL[m]/AQUIFER*
	PERC_LINEAR	SOIL[m]/AQUIFER*	SOIL[m]/AQUIFER*
	PERC_POWER_LAW	SOIL[m]/AQUIFER*	SOIL[m]/AQUIFER*
	PERC_PRMS	SOIL[m]/AQUIFER*	SOIL[m]/AQUIFER*
	PERC_SACRAMENTO	SOIL[m]/AQUIFER*	SOIL[m]/AQUIFER*
	PERC_CONSTANT	SOIL[m]/AQUIFER*	SOIL[m]/AQUIFER*
	PERC_GR4J	SOIL[m]/AQUIFER*	SOIL[m]/AQUIFER*
:CapillaryRise	CRISE_HBV	SOIL[m]/AQUIFER*	SOIL[m]/AQUIFER*
:Baseflow	BASE_LINEAR	SOIL[m]/AQUIFER*	SURFACE_WATER
	BASE_POWER_LAW	SOIL[m]/AQUIFER*	SURFACE_WATER
	BASE_CONSTANT	SOIL[m]/AQUIFER*	SURFACE_WATER
	BASE_VIC	SOIL[m]/AQUIFER*	SURFACE_WATER
	BASE_THRESH_POWER	SOIL[m]/AQUIFER*	SURFACE_WATER
	BASE_GR4J	SOIL[m]/AQUIFER*	SURFACE_WATER
	BASE_TOPMODEL	SOIL[m]/AQUIFER*	SURFACE_WATER
:Interflow	PRMS	SOIL[m]*	SURFACE_WATER
Wetland/Depression/Lake Processes			
:Seepage	SEEP_LINEAR	DEPRESSION	SOIL[m]*
:DepressionOverflow	DFLOW_THRESHPOW	DEPRESSION	SURFACE_WATER
	DFLOW_LINEAR	DEPRESSION	SURFACE_WATER
:LakeRelease	LAKEREL_LINEAR	LAKE	SURFACE_WATER
:Abstraction	ABST_PERCENTAGE	PONDED_WATER	DEPRESSION
	ABST_FILL	PONDED_WATER	DEPRESSION
	ABST_SCS	PONDED_WATER	DEPRESSION

Table A.3: Hydrologic process commands for the .rvi file. Compartments with an asterisk must be specified within the command.

Snow Processes			
:SnowMelt	MELT_POTMELT	SNOW	SNOW_LIQ,PONDED_WATER,SURFACE_WATER*
:Snow Refreeze	FREEZE_DEGREE_DAY	SNOW_LIQ	SNOW
:Snow Balance	SNOBAL_SIMPLE_MELT	SNOW	PONDED_WATER,SNOW_LIQ*
	SNOBAL_COLD_CONTENT	SNOW,SNOW_LIQ	SNOW, SNOW_LIQ,PONDED_WATER
	SNOBAL_HBV	SNOW,SNOW_LIQ	SOIL[0]
	SNOBAL_TWO_LAYER	SNOW[0,1],SNOW_LIQ[0,1]	SNOW[0,1],SNOW_LIQ[0,1],SURFACE_WATER
	SNOBAL_CEMA_NEIGE	SNOW	PONDED_WATER
	SNOBAL_GAWSER	SNOW_SNOW_LIQ	SNOW_LIQ,ATMOSPHERE,PONDED_WATER
	SNOBAL_UBC	SNOW,SNOW_LIQ	SNOW,SNOW_LIQ,SURFACE_WATER
:Sublimation	SUBLIM_SVERDRUP	SNOW	ATMOSPHERE
	SUBLIM_KUZMIN	SNOW	ATMOSPHERE
	SUBLIM_CENTRAL_SIERRA	SNOW	ATMOSPHERE
	SUBLIM_PSBM	SNOW	ATMOSPHERE
	SUBLIM_WILLIAMS	SNOW	ATMOSPHERE
:SnowAlbedoEvolve	SNOALB_UBC		
Vegetation			
:CanopyDrip	CANDRIP_RUTTER	CANOPY	PONDED_WATER
	CANDRIP_SLOWDRAIN		
:CropHeatUnitEvolve	CHU_ONTARIO		
Glacier Processes			
:GlacierMelt	GMELT_SIMPLE_MELT	GLACIER_ICE	GLACIER
	GMELT_HBV	GLACIER_ICE	GLACIER
	GMELT_UBC	GLACIER_ICE	GLACIER
:GlacierRelease	GRELEASE_LINEAR	GLACIER	SURFACE_WATER
	GRELEASE_HBV_EC	GLACIER	SURFACE_WATER
Special Processes			
:Flush	FLUSH_RAVEN	any*	any*
:Overflow	OVERFLOW_RAVEN	any*	any*
:Split	RAVEN_DEFAULT	any*	any*
:Convolution	CONVOL_GR4J1	any*	CONVOLUTION[m]*
	CONVOL_GR4J2	any*	CONVOLUTION[m]*
:LateralFlush	RAVEN_DEFAULT	any*	any*

Table A.4: Hydrologic process commands for the .rvi file. (cont'd)

The Lateral Flush process

Lateral flow processes may require the specification of the source and destination HRU groups as well as the state variables. The :LateralFlush process, for instance, uses the following syntax:

```
:LateralFlush RAVEN_DEFAULT [SourceGrp] [SourceSV] To [DestGrp] [DestSV]
```

Where the source and destination HRU group (SourceGrp and DestGrp, within a given basin) and source and destination state variable (water compartments SourceSV and DestSV, from table C.1), are specified. For instance,

```
:LateralFlush RAVEN_DEFAULT Uplands SURFACE_WATER To Wetlands DEPRESSION
```

The preceding command will drain all surface and subsurface runoff from the Uplands HRU group to depression storage in an HRU belonging to the Wetlands HRU group. Note that only one recipient HRU in the destination group is allowed in each subbasin (i.e., you couldn't have two HRUs belonging to the Wetlands group in a single subbasin).

Conditional Application of Processes

Note that application of any given process algorithm can be made conditional using the :-->Conditional command immediately after the process command. For example,

```
:Flush              RAVEN_DEFAULT PONDED_WATER   SURFACE_WATER
  :-->Conditional   HRU_TYPE IS_NOT GLACIER
:Flush              RAVEN_DEFAULT PONDED_WATER   GLACIER
  :-->Conditional   HRU_TYPE IS GLACIER
```

The above input file snippet moves ponded water to surface water, unless the HRU type is a glacier (as defined by its soil profile properties). Currently, the conditional command supports:

- conditionals based upon HRU type (HRU_TYPE), where the type is one of (GLACIER, LAKE, ROCK, WETLAND, or STANDARD)
- conditionals based upon land use type, e.g.,

  ```
  :-->Conditional LAND_USE IS PEATLAND
  ```

  where LAND_USE names are as defined in the :LandUseClasses command in the .rvp file
- conditionals based upon HRU group, e.g.,

  ```
  :-->Conditional HRU_GROUP IS_NOT BURNED_FOREST
  ```

  where the HRU_GROUPs are defined using the :HRUGroup command in the .rvh file.

The only available comparison operators are IS and IS_NOT.

To do (8)

A.1.7 Transport Commands

```
:Transport [const_name] {units}
```

(Optional) This command declares a new transport constituent named `const_name` which can be advected through the system. The optional units command should be either mg/l or none (for tracers).

```
:FixedConcentration [const_name] [compartment] [concent.] {HRUgrp}
```

(Optional) This command applies a type one boundary condition in all water storage compartment state variables of type `compartment` (taken from the state variable list of table C.1) in HRU group `HRUgrp`. All water passing through this storage compartment will be assigned the specified concentration (`concent.`)for the constituent named `const_name`. Note that the constituent name needs to be specified using the `:Transport` command prior to calling this command. If the optional `HRU_group` is omitted, then the condition applies to all storage compartments of this type throughout the watershed. For tracers, it is useful to specify a concentration of 1.0 (no units).

A.1.8 Other Control Commands

```
:DisableHRUGroup [HRUgrp]
```

(Optional) This command disables all of the HRUs in the group, meaning that the model will not simulate the mass/energy balance for any of the HRUs. For instance, if you had a large model and only wanted to simulate a single headwater basin, you would create an HRU group that included HRUs not within that basin, then apply the `:DisableHRUGroup` command to that single group of HRUs. In most cases, it is desirable to disable entire subbasins - the model will not provide comprehensible results if random assortments of individual HRUs are disabled.

```
:AssimilateStreamflow
```

(Optional) If this command is used, all available streamflow observations are assimilated into model predictions as indicated in section 6.1. Model output will then be a combination of data and model simulation; this is typically used only in a forecasting environment.

```
:ReservoirDemandAllocation [method]
```

This command indicates how irrigation demand addressed using the `:ReservoirDownstreamDemand` command is distributed to upstream reservoirs. Here, method = `DEMANDBY_CONTRIB_AREA` if demand is allocated proportionately to contributing area of each reservoir and method = `DEMANDBY_MAX_CAPACITY` if reservoir maximum storage capacity is used (to specify this, use the command below). This is only used if the `_AUTO` flag is used to determine the reservoirs supplying a single `:ReservoirDownstreamDemand` item.

```
:CallExternalScript [system command]
```

This calls an external script or system command at the start of every time step. If the system command includes the tags <model_time>, <date>, <version>, or <output_dir>, then these tags in the command will be replaced with the model time (time from the start of the model, in days), date string in ISO standard format, version number (e.g., 3.0.2), or output directory, respectively. This can be used, for instance, to assist in coupling multiple models, and would typically be used with the Raven live (.rvl) file.

```
:ReadLiveFile [frequency]
```

Reads externally-generated live file (see appendix A.6) every `frequency` time steps.

A.2 Classed Parameter Input file (.rvp)

The classed parameter input file stores a database of soil, vegetation, river, aquifer, and land class properties. Not all classes specified in the *.rvp file need to be included in the model. An example .rvp file is shown below.

```
# ----------------------------------------
# Raven Example Classed Parameter File
# ----------------------------------------
# Class definition --------------------------
:SoilClasses
  :Attributes, %SAND,  %CLAY, %SILT, %ORGANIC
  :Units,       none,   none,  none,     none
   SAND,           1,      0,     0,        0
   LOAM,         0.5,    0.1,   0.4,      0.4
:EndSoilClasses
:VegetationClasses
  :Attributes,       MAX_HT, MAX_LAI, MAX_LEAF_COND
  :Units,                 m,    none,      mm_per_s
  CONIFER_FOREST,        25,     6.0,           5.3
       BROADLEAF,        25,     5.0,           5.3
:EndVegetationClasses
:LandUseClasses
  :Attributes,  IMPERMEABLE_FRAC, FOREST_COVERAGE
  :Units     ,             fract,           fract
    GRASSLAND,                 0,               0
     SUBURBAN,               0.3,             0.3
:EndLandUseClasses
# Soil Profile definition -------------------
:SoilProfiles
#     name, #horizons, hor1, th1, hor2, th2
      LAKE,         0
   GLACIER,         0
  LOAM_SEQ,         2, LOAM, 0.5, SAND, 1.5
  ALL_SAND,         2, SAND, 0.5, SAND, 1.5
:EndSoilProfiles
# Parameter specification -------------------
:GlobalParameter WET_ADIABATIC_LAPSE 0.5
:LandUseParameterList
  :Parameters,  MELT_FACTOR, MIN_MELT_FACTOR
  :Units     ,       mm/d/K,          mm/d/K
    [DEFAULT],          3.2,            1.3
    GRASSLAND,          3.5,       _DEFAULT
:EndLandUseParameterList
```

As with the *.rvi file, ⋆ or # denotes a comment.

A.2.1 Required Commands

```
:SoilClasses
  :Attributes     ,%SAND,%CLAY,%SILT, %ORGANIC
  :Units          , none, none, none,    none
  {soil_class_name,%sand,%clay,%silt,%organic}x[NSC]
:EndSoilClasses
```

or

```
:SoilClasses
  {soil_class_name}x[NSC]
:EndSoilClasses
```

Defines each soil class and (optionally) specifies the mineral and organic composition of the soil which can be used to automatically generate some physical properties such as porosity or hydraulic conductivity. These parameters are defined as follows:

- `soil_class_name` is the code (less than 30 characters) used to identify the soil class within the .rvp file and in the .rvh file, discussed below. The name may not contain spaces or special characters.
- `%SAND,%CLAY,%SILT,%ORGANIC` [0..1] are the percent sand, clay, and organic matter of the soil, expressed in decimal form, between 0 and 1. The sand, silt, and clay fractions refer to the non-organic component of the soil, i.e., specifying %SAND=0.5, %CLAY=0.3, %SILT=0.2, %ORGANIC=0.1 indicates a soil composition of 45% sand, 27% clay, 18%silt, and 10% organic matter. The sum of the mineral components (%SAND, %CLAY, and %SILT) must be 1.

With the soil information provided, Raven can autogenerate many other physically-based (i.e., measurable) soil properties such as hydraulic and thermal conductivities, wilting pressure, etc. To override these autogenerated parameters or to specify other soil parameters, an additional command (`:SoilParameterList`), described below, may be added to the input file *after* the `:SoilProperties` command has been called. For conceptual models, the soil composition will generally not be specified.

```
:SoilProfiles
  {profile_name,#horizons,{soil_class_name,thick.}x{#horizons}}x[NP]
:EndSoilProflles
```

Defines all `NP` stored soil profiles, which is a collection of soil horizons with known depth and thickness, each belonging to a soil class. The soils should be specified from the top downward. Because the parameter `soil_class_name` is required, this command must come after the `:SoilClasses` command. The thickness (`thick.`) of each horizon is specified in meters.

The special cases of lakes, exposed rock, wetlands, and glaciers (land surface elements with 'no' surface soils, or where it is not appropriate to simulate using soil infiltration and evaporation routines, are represented with the special profile names `LAKE`, `ROCK`, `WETLAND`, and `GLACIER`, all with zero horizons. ANY soil profile that starts with these terms is not subject to soil-based process algorithms. Glaciers can have more than zero horizons to represent groundwater processes, but infiltration and evapotranspiration from the surface soil is disabled.

```
:VegetationClasses
  :Attributes    ,       MAX_HT,MAX_LAI,MAX_LEAF_COND
```

```
  :Units          ,            m,   none,     mm_per_s
  {veg_class_name,MAX_CANOPY_HT,MAX_LAI,MAX_LEAF_COND}x[NVC]
:EndVegetationClasses
```

Defines the basic parameters for each vegetation class, which are used to optionally autogenerate many canopy and root properties. Here,

- `veg_class_name` is the tag (less than 30 characters) used to identify the vegetation class within the .rvp file and in the .rvh file, discussed below.
- `MAX_CANOPY_HT` [m] is the maximum canopy height reached during the year.
- `MAX_LAI` [m^2/m^2] is the maximum leaf area index (LAI) of the vegetation.
- `MAX_LEAF_COND` [mm/s] is the maximum leaf conductance of the vegetation.

```
:LandUseClasses
  :Attributes   ,IMPERMEABLE_FRAC, FOREST_COVERAGE
  :Units        ,           fract,           fract
  {LU_class_name,IMPERMEABLE_FRAC, FOREST_COVERAGE}x[NLU]
:EndLandUseClasses
```

Defines all `NLU` land use/land type classes in the model. Land use is assumed to determine many of the surface roughness, albedo, and snow parameters. Here,

- `LU_class_name` is the tag (less than 30 characters) used to identify the land use class within the .rvp file and in the .rvh file, discussed below.
- `IMPERMEABLE_FRAC` [0..1] is the percentage of the land surface that is considered impermeable.
- `FOREST_COVERAGE` [0..1] is the percentage of the land surface that is covered with a vegetation canopy. It is recommended (but not required) to use either 0 (open) or 1 (fully forested), with partial coverage handled via HRU definition.

A.2.2 Optional Classes and Objects

Terrain classes and channel profiles do not need to be included in all models.

```
:TerrainClasses
  :Attributes        , HILLSLOPE_LENGTH, DRAINAGE_DENSITY
  :Units             ,                m,           km/km2
  {terrain_class_name, HILLSLOPE_LENGTH, DRAINAGE_DENSITY}x[NTC]
:EndTerrainClasses
```

Defines all `NTC` physiographic terrain classes in the model, ranging from flat to hilly to steep and mountainous. Here,

- `terrain_class_name` is the tag (less than 30 characters) used to identify the terrain class within the .rvp file and in the .rvh file, discussed below.
- `HILLSLOPE_LENGTH` [m] is the representative hillslope length within the terrain.
- `DRAINAGE_DENSITY` [km/km^2] is the terrain drainage density.

If no terrain classes are specified, the tag `[NONE]` should be placed in the `:HRUs` command under terrain class.

```
:ChannelProfile [channel_name]
  :Bedslope [slope]
  :SurveyPoints
    {[x]  [bed_elev]}x num survey points
  :EndSurveyPoints
  :RoughnessZones
    {[x_zone] [mannings_n]} x num roughness zones
  :EndRoughnessZones
:EndChannelProfile
```

Defines a channel profile with the unique name `channel_name`. The channel geometry is fully defined by a number of survey points (at least 2) along a transect. At the leftmost and rightmost points along the transect, it is assumed that the channel is bounded with infinitely steep sides. The x-coordinate system is arbitrary. In the same coordinate system, at least one zone with one Manning's n value must be specified. The coordinate x_{zone} is the leftmost boundary of the zone, and therefore the leftmost x_{zone} must be to the left of or equal to the leftmost (smallest) survey coordinate x. The channel configuration definitions are depicted in figure A.1. A representative bedslope (expressed as the slope ratio) is also needed: this is used to calculate flow rates using Manning's equation.

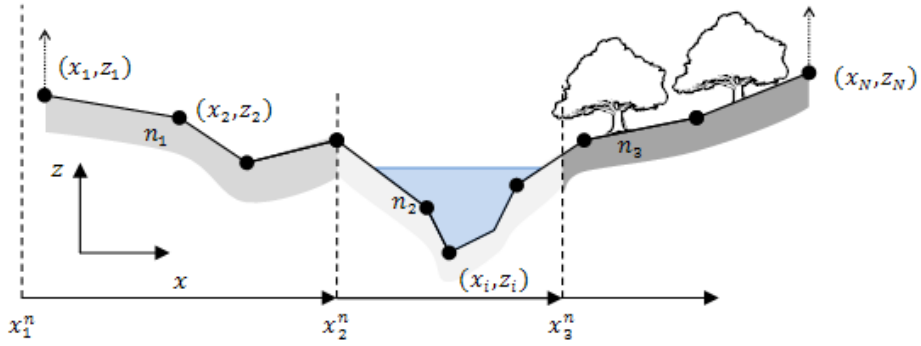

Figure A.1: Channel Profile definition. Each channel is defined by a cross sectional profile and a number of zones with different Manning's n values.

As an example, the following profile command generates the channel shown in figure A.2.

```
:ChannelProfile Reach3
  :Bedslope 0.08
  :SurveyPoints
    0.000 0.25
    1.000 0.00
    1.750 0.00
    2.000 0.25
  :EndSurveyPoints
  :RoughnessZones
    0.000 0.07
    0.500 0.02
    1.875 0.08
```

```
  :EndRoughnessZones
:EndChannelProfile
```

Note that it is undesirable to overly constrain the lateral extent of the channel, i.e., if there is any chance that the water levels reach the leftmost or rightmost channel point. Also note that Manning's n and slope may both be overwritten for a specific subbasin via the `:SubBasinProperties` command in the .rvh file.

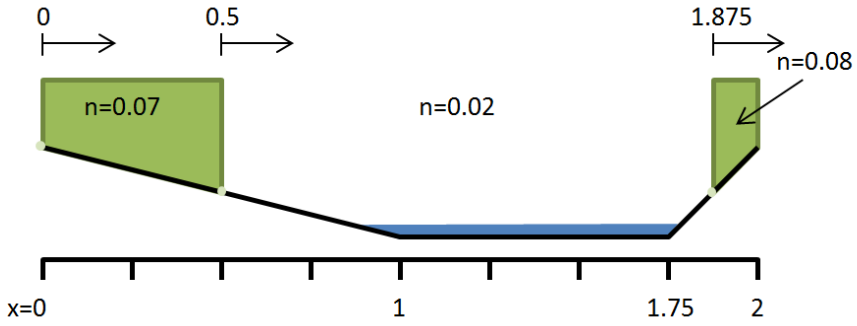

Figure A.2: Example channel profile generated using example command.

```
:ChannelRatingCurves [channel_name]
  :Bedslope [slope]
  :StageRelations
    {[stage] [area] [width] [flow]} x num curve points
  :EndStageRelations
:EndChannelRatingCurves
```

Defines a channel profile with the unique name `channel_name`, and is used as an alternative to `:ChannelProfile`. Here, the stage-area, stage-top width, and stage-flow rating curves are explicitly provided. The first data point should correspond to stage and flow equal to zero, with all values entered with increasing stage. The units are stage [m], area [m^2], width [m], flow [m^3/s].

A.2.3 Parameter Specification

In addition to the required terms above, the following optional commands may be used to override autogeneration of parameters and specify parameters that cannot be autogenerated. If these are not included, either for an entire class or individual parameter, it is assumed that the parameter is to be autogenerated.

Soil Parameter Specification

The following command is used to specify parameters linked to each soil class:

```
:SoilParameterList
  :Parameters     , { param_name1, param_name1,...,  param_nameNP}
  :Units          , {  unit_type1,  unit_type2,...,   unit_typeNP}
  {[DEFAULT]      , {default_val1,default_val2,..., default_valNP} [optional]
  {soil_class_name, {  param_val1,  param_val2,...,
param_valNP}}x[<=NSC]
:EndSoilParameterList
```

where available soil parameter names (`param_name`) are described in the table A.5 and the soil class names (with the exception of the special `[DEFAULT]` tag) must already have been declared in the `:SoilClasses` command.

The `[DEFAULT]` soil class name is used to specify parameter values for all classes not explicitly included as rows in the parameter list. Only soil classes which have parameters different from the default soil properties need to be specified in this list. If the user desires to autogenerate any of the parameters in the list (if Raven has the capacity to autogenerate these parameters), the `_AUTO` flag should be placed instead of a numerical value, as depicted in the example file. The `_DEFAULT` flag may be used if the default property (which can also be `_AUTO`) should be applied.

Note that the units must be consistent with the native units of each parameter indicated in table A.5 - this line is intended for user interface processing and readability; **units will not be automatically converted if alternative unit specifiers are used**.

While many watershed model and algorithm parameters have a physical basis (e.g., hydraulic conductivity), certain algorithms, particularly for lumped models, abstract a physical process so that coefficients in the relationships between storage and fluxes are completely artificial. These artificial parameters, which cannot be automatically generated based upon soil type, need to be specified directly by the user, and are often used as calibration (or 'tuning') parameters. These parameters are described in the second section of table A.5.

Vegetation Parameter Specification

```
:VegetationParameterList
  :Parameters     , { param_name1, param_name1,...,  param_nameNP}
  :Units          , {  unit_type1,  unit_type2,...,   unit_typeNP}
  [DEFAULT]       , {default_val1,default_val2,..., default_valNP} [opt.]
  {VEG_CLASS_NAME , {  param_val1,  param_val2,...,
param_valNP}}x[<=NVC]
:EndVegetationParameterList
```

The :VegetationParameterList command operates in the same fashion as the :SoilParameterList command described above. The available vegetation parameters in RAVEN are described in table A.7. Note that the [DEFAULT] vegetation type is optional.

```
:SeasonalCanopyLAI
   [DEFAULT]      ,  J, F, M, A, M, J, J, A, S, O, N, D {optional}
  { veg_class_name,  J, F, M, A, M, J, J, A, S, O, N, D}x[<=NVC]
:EndSeasonalCanopyLAI
```

The :SeasonalCanopyLAI command provides a monthly correction factor that can be used to adjust leaf area indices as the seasons change, i.e., $LAI = LAI_{max} \cdot f$, where $f(t)$ is the monthly correction factor for time t. By default, no correction factor is applied. This correction factor must be between zero and one for all months and will be interpolated based upon the specification of the :MonthlyInterpolationMethod command in the .rvi file.

```
:SeasonalCanopyHeight
   [DEFAULT]      ,  J, F, M, A, M, J, J, A, S, O, N, D {optional}
  { veg_class_name,  J, F, M, A, M, J, J, A, S, O, N, D}x[<=NVC]
:EndSeasonalCanopyHeight
```

The :SeasonalCanopyHeight command provides a monthly correction factor that can be used to adjust vegetation height as the seasons change, i.e., $h_{veg} = h_{max} \cdot f$, where $f(t)$ is the monthly correction factor for time t. By default, no correction factor is applied. This correction factor must be between zero and one for all months and will be interpolated based upon the specification of the :MonthlyInterpolationMethod command in the .rvi file.

Land Use / Land Type Parameter Specification

```
:LandUseParameterList
  :Parameters     , { param_name1, param_name1,...,  param_nameNP}
  :Units          , {  unit_type1,  unit_type2,...,   unit_typeNP}
   [DEFAULT]      , {default_val1,default_val2,..., default_valNP} [optional]
  {lult_class_name, {  param_val1,  param_val2,...,
param_valNP}}x[<=NSC]
:EndLandUseParameterList
```

The `:LandUseParameterList` command operates in the same fashion as the `:SoilParameterList` command described above. The available land use parameters in Raven are described in table A.6

Global Parameter Specification

The following global parameters can also be specified, anywhere in the .rvp file. Note that the preferred format for single-value parameters (i.e., not vectors of parameters) is to use the `:GlobalParameter` command. Many of the below commands are equivalent to this command, retained only for backwards compatibility with earlier versions of Raven.

```
:GlobalParameter [PARAM_NAME] [value]
```

Can be used to specify the value of any scalar global parameter, where the list of global parameter names is in table A.8.

> Please note that the `:GlobalParameter` command is the only one truly needed to specify single-valued global parameters in table A.8. The remainder of the commands shown below have been deprecated, and are only provided as a reference for those using older models which may include these commands. The only exception to this are the global parameters which include monthly sequences (e.g., `:UBCNorthSWCorr`)

```
:AdiabaticLapseRate [rate]
# is equivalent to (the preferred option)
:GlobalParameter ADIABATIC_LAPSE [rate]
```

The base adiabatic lapse rate [°C/km].

```
:PrecipitationLapseRate [rate]
# is equivalent to (the preferred option)
:GlobalParameter PRECIP_LAPSE [rate]
```

The simple linear precipitation lapse rate [mm/d/km], as used in the `OROCORR_SIMPLELAPSE` orographic correction algorithm.

```
:RainSnowTransition [rainsnow_temp] [rainsnow_delta]| \\ %
# equivalent to (the preferred option)
:GlobalParameter RAINSNOW_TEMP [rainsnow_temp]
:GlobalParameter RAINSNOW_DELTA [rainsnow_delta]
```

Specifies the range of temperatures (`rainsnow_delta`, [°C]) over which there will be a rain/snow mix when partitioning total precipitation into rain and snow components. The midpoint of the range is `rainsnow_temp`.

```
:IrreducibleSnowSaturation [saturation]
# equivalent to (the preferred option)
:GlobalParameter SNOW_SWI [saturation]
```

Maximum liquid water content of snow, as percentage of SWE [0..1]. Usually ~0.05.

```
:AvgAnnualRunoff [runoff]
# equivalent to (the preferred option)
```

```
:GlobalParameter AVG_ANNUAL_RUNOFF [runoff]
```

This parameter should be the average annual runoff for the entire modeled watershed, [mm/yr]. It is used to autogenerate initial flows and reference flows in the channel network. While the resultant estimates of initial flows will wash out with time, reference flows may be critical and modelers may wish to overwrite these by specifying the `Q_REFERENCE` parameter for each channel in the `:SubBasinProperties` command of the .rvp file.

```
:WetAdiabaticLapseRate [rate] [A0PPTP]
# equivalent to (the preferred option)
:GlobalParameter WET_ADIABATIC_LAPSE [rate]
:GlobalParameter UBC_A0PPTP [A0PPTP]
```

The wet adiabatic lapse rate [$^{\circ}$C/km] and the UBCWM threshold precipitation, A0PPTP, for temperature lapse rate [mm/d] (usually $\sim$5 mm/d).

```
:ReferenceMaxTemperatureRange [range]
# equivalent to (the preferred option)
:GlobalParameter UBC_MAX_RANGE_TEMP [range]
```

A parameter (A0TERM) used in the UBC watershed model orographic corrections for temperature [$^{\circ}$C].

```
:UBCTempLapseRates [A0TLXM A0TLNM A0TLXH A0TLNH P0TEDL P0TEDU]
```

Parameters used in the UBC watershed model orographic corrections for temperature. A0TLXM and A0TLXH [$^{\circ}$C/km] are the low and high elevation lapse rates of the maximum daily temperature; A0TLNM and A0TLNH [$^{\circ}$C/km] are the low and high elevation lapse rates of the minimum daily temperature; P0TEDL and P0TEDU [$^{\circ}$C/km] are the low and high elevation lapse rates of the maximum temperature range. Low and high elevation refer to below or above 2000 masl.

```
:UBCPrecipLapseRates [E0LLOW E0LMID E0LHI P0GRADL P0GRADM P0GRADU A0STAB]
```

Parameters used in the UBC watershed model orographic corrections for precipitation. E0LLOW E0LMID and E0LHI, are the low, medium, and high reference elevations [m]; P0GRADL, P0GRADM, and P0GRADU are the precipitation gradient factors (%) applied below E0LMID, between E0LMID and E0LHI, and above E0LHI, respectively; A0STAB is a precipitation gradient modification factor.

```
:UBCEvapLapseRates [A0PELA]
```

The PET lapse rate in the UBCWM PET orographic correction algorithm [$^{\circ}$C/km].

```
:UBCNorthSWCorr [J F M A M J J A S O N D]
```

Monthly correction factors (unitless) for shortwave radiation on north-facing slopes, used in the UBC shortwave generation routine.

```
:UBCSouthSWCorr [J F M A M J J A S O N D]
```

Monthly correction factors (unitless) for shortwave radiation on south-facing slopes, used in the UBC shortwave generation routine.

```
:UBCSnowParams [P0ALBMIN P0ALBMAX P0ALBREC P0ALBASE P0ALBSNW P0ALBMLX]
```

Parameters used in the UBCWM-style snow albedo evolution algorithm. `P0ALBREC` [-] is the recessional constant for albedo decay of new snow (∼0.9); `P0ALBSNW` [mm] is the daily snowfall required to bring albedo to that of new snow; `P0ALBMAX` is the albedo of fresh snow (∼0.95); `P0ALBMIN` is the albedo of an aged snowpack or glacier (∼0.30); `P0ALBMLX` [mm] is a constant on the order of total snowmelt in one year; `P0ALBASE` is the albedo initial decay value (∼0.65).

```
:UBCGroundwaterSplit [value]
```

The UBC watershed model deep zone share, which controls how much infiltration goes to deep vs. shallow storage.

```
:UBCExposureFactor [value]
```

The UBCWM sun exposure factor for forested areas (∼0.01), indicating the percentage of forested areas exposed to solar radiation. Used in the `SW_CANOPY_CORR_UBCWM` canopy correction algorithm.

```
:UBCCloudPenetration [value]
```

The UBCWM fraction of solar radiation penetrating cloud cover [0..1], as used in the `SW_CLOUD_CORR_UBCWM` cloud cover correction algorithm.

```
:UBCLWForestFactor [value]
```

The UBCMW Longwave correction factor for forests [mm/d/K](∼0.75), as used in the `LW_RAD_UBCWM` longwave radiation estimation routine.

```
:AirSnowCoeff [value]
```

This is the air/snow heat transfer coefficient in units of [1/d], as used in the `SNOTEMP_NEWTONS` snow temperature evolution routine.

```
:AvgAnnualSnow [value]
```

This parameter is the average annual snow for the entire watershed in mm SWE. It is used in the `CEMA_NEIGE` snowmelt algorithm.

Special Commands

The following special commands can be used for temporally variable landscape change (e.g., to simulate urbanization, forest fire impacts, or changes in agricultural practices).

```
:LandUseChange [HRU group] [new LULT tag] [YYYY-mm-dd]
```

The land use for the specified HRU group is changed to the new LULT type (as specified in the :LandUseClasses-:EndLandUseClasses block) on the specified date in ANSI YYYY-mm-dd format. The change occurs just after midnight of the night before. Note that all parameters from the new land use class are applied to all of the specified HRUs in the group. There is no limit to the number of land use changes in the model.

```
:VegetationChange [HRU group] [new vegetation tag] [YYYY-mm-dd]
```

The vegetation for the specified HRU group is changed to the new vegetation type (as specified in the :VegetationClasses-:EndVegetationClasses block) on the specified date in ANSI YYYY-mm-dd format. The change occurs just after midnight of the night before. Note that all parameters from the new vegetation class are applied to all of the specified HRUs in the group. There is no limit to the number of vegetation changes in the model.

```
:TransientParameter [PARAM_NAME] [class] {(optional) ClassName}
  [date yyyy-mm-dd] [time hh:mm:ss.0] [interval] [N]
  {double value} x N
:EndTransientParameter
```

This command may be used to replace any (usually fixed) parameter specified in the .rvp file with a time series of user-specified parameter values. This is often used to represent the influence of changing land use, seasonal impacts of agriculture, or unmodeled hydrologic processes such as frozen soils. Here, interval is the time interval of the supplied time series and N is the total number of entries. PARAM_NAME corresponds to one of the parameters included in tables A.5, A.6, A.7, or A.8. class is one of SOIL, VEGETATION, LANDUSE, TERRAIN or GLOBALS. The optional ClassName specifies the particular soil/vegetation/land use class to override; if not included, the parameter will be overridden for all soil/vegetation/land use classes. Note that the specified transient parameter completely overwrites the static value specified earlier in the .rvp file. It is common to put this time series in another file and point to it via the :RedirectToFile command.

```
:RedirectToFile [filename]
```

This treats the contents of file "filename" as if they were simply inserted into the .rvp file at the location of the :RedirectToFile command. This is useful for storing individual sets of commands in an organized format (e.g., the :TransientParameter time series). If no path is specified, the filename must be reported relative to the working directory. Note that this command cannot work within data blocks (e.g., a the entire :SoilParameters-:EndSoilParameters block would have to be in a single file, not just the tabular data in that block).

Table A.5: Soil Parameters. The top section described autocalculable parameters which may be generated automatically using only the base soil class information (sand, clay, silt, and organic content). The bottom section must be user-specified.

Name	Definition	Units	Range	
SAND_CON	percent sand content of mineral soil (sand+clay+silt=1)	[0..1]	0.0-1.0	
CLAY_CON	percent clay content of mineral soil	[0..1]	0.0-1.0	
SILT_CON	percent silt content of mineral soil	[0..1]	0.0-1.0	
ORG_CON	percent organic content of soil (mineral+org.=100%)	[0..1]	0.0-0.8	
POROSITY	effective porosity of the soil	[0..1]	0.1-0.6	Physical Parameters
STONE FRAC	stone fraction of the soil	[0..1]	0.0-0.5	
SAT_WILT	hydroscopic minimum saturation	[0..1]	0.0-0.9	
FIELD CAPACITY	field capacity saturation of the soil	[0..1]	0.0-1.0	
BULK_DENSITY	bulk dry density of the soil	[kg/m3]		
HYDRAUL_COND	saturated hydraulic conductivity of the soil	[mm/d]		
CLAPP_B	Clapp-Hornberger exponent	[-]		
CLAPP N,CLAPP M	Clapp-Hornberger transition parameters	[-],[mm]		
SAT_RES	residual saturation	[0..1]		
AIR_ENTRY_PRESSURE	(positive) air entry pressure (?ae)	[-mm]		
WILTING_PRESSURE	(positive) wilting pressure	[-mm]		
HEAT_CAPACITY	saturated volumetric heat capacity	[J/m3/K]		
THERMAL_COND	saturated soil thermal conductivity	[W/m/K]		
WETTING_FRONT_PSI	Green-Ampt wetting front pressure	[-mm]		
EVAP_RES_FC	soil evaporation resistance at Field capacity	[d/mm]		
SHUTTLEWORTH_B	Shuttleworth b expon. relating resistance to pressure	[-]		
ALBEDO_WET	albedo of the soil when fully saturated	[-]		
ALBEDO_DRY	albedo of the soil when dry	[-]		
VIC_ZMIN	Xinanjiang parameters for VIC model	[mm]		Conceptual Model Parameters
VIC_ZMAX	Xinanjiang parameters for VIC model	[mm]		
VIC ALPHA [-]	Xinanjiang parameters for VIC model	[-]		
VIC_EVAP_GAMMA	power law exponent for VIC soil evaporation	[-]		
MAX_PERC_RATE	VIC/ARNO/GAWSER percolation rate	[mm/d]	0.01 - 1000	
PERC N	VIC/ARNO percolation exponent	[-]	1.00 - 20	
SAC_PERC_ALPHA	Sacramento percolation multiplier	[-]	1.0 - 250.0	
SAC PERC EXPON	Sacramento percolation exponent	[-]	1.00 - 5.0	
MAX BASEFLOW RATE	maximum baseflow rate	[mm/d]	0.001 - 1000	
BASEFLOW_N	VIC/ARNO baseflow exponent	[-]	1.0 - 10.0	
BASEFLOW_COEFF	linear baseflow storage/routing coefficient	[1/d]		
BASEFLOW_THRESH	threshold saturation for onset of baseflow	[0..1]		
MAX_CAP_RISE_RATE	HBV max capillary rise rate	[mm/d]		
MAX_INTERFLOW_RATE	PRMS max interflow rate	[mm/d]		
INTERFLOW_COEFF	linear interflow storage/routing coefficient	[1/d]		
UBC_EVAP_SOIL_DEF	UBC model evaporation reference soil deficit	[mm]		
UBC_INFIL_SOIL_DEF	UBC watershed model infiltration reference soil deficit	[mm]		
GR4J_X2	GR4J Maximum groundwater exchange rate	[mm/d]		
GR4J_X3	GR4J reference storage for baseflow/GW exchange	[mm]		

Table A.6: Land use parameters. The parameters with an asterisk can be autogenerated by Raven or overriden by the model user.

Name	Definition	Units	Range	
FOREST_COVERAGE	fraction of land covered by vegetation canopy	[0..1]	0-1	Physical Parameters
IMPERMEABLE_FRAC	fraction of surface that is impermeable	[0..1]	0-1	
ROUGHNESS*	roughness of ground surface	[m]	0-10	
FOREST_SPARSENESS*	sparseness of canopy in land covered by forest	[0..1]	0-0.99	
DEP_MAX	maximum amount of water that can be stored in depressions	[mm]	0-5	
MAX_DEP_AREA_FRAC	percentage of landscape coverd by depressions when full	[0..1]	0-0.8	
MELT_FACTOR*	maximum snow melt factor used in degree day models	[mm/d/°C]	3.5	Conceptual Model Parameters
DD_REFREEZE_TEMP*	degree day reference (freezing) temperature	[°C]	0.0	
MIN_MELT_FACTOR*	minimum snow melt factor used in degree day models	[mm/d/°C]	2	
REFREEZE_FACTOR	maximum refreeze factor used in degree day models	[mm/d/°C]	3	
REFREEZE_EXP	exponent used in HMETS_SNOWBAL refreeze relationship	[-]	0.5	
DD_AGGRADATION	degree day increase rate with cumulative melt (HMETS pot. melt.)	[1/mm]	0.1	
SNOW_PATCH_LIMIT*	SWE limit below which snow does not completely cover ground	[mm]	0-100	
HBV_MELT_FOR_CORR*	HBV snowmelt forest correction (MRF in HBV-EC)	[-]	<1	
HBV_MELT_ASP_CORR*	HBV snowmelt aspect correction (AM in HBV-EC)	[-]	0-1	
GLAC_STORAGE_COEFF	maximum linear storage coefficient for glacial melt	[-]		
HBV_MELT_GLACIER_CORR	degree day correction factor for glacial melt (MRG in HBV-EC)	[-]		
HBV_GLACIER_KMIN	minimum linear storage coefficient for glacial melt	[-]		
HBV_GLACIER_AG	extinction coefficient for diminishing storage coefficient	[1/mm]		
CC_DECAY_COEFF	linear decay coefficient for decreasing cold content	[1/d]		
SCS_CN	SCS curve number (for antecedent wetness condition II)	[0-100]	1-100	
SCS_IA_FRACTION*	fraction of rainfall initially abstracted to depression storage	[0..1]	0-0.2	
PARTITION_COEFF	simple rational method partitioning coefficient	[0..1]	0.5	
MAX_SAT_AREA_FRAC	PRMS maximum saturated area (pct)-	[0-1]		
B_EXP	ARNO/VIC b exponent	[-]	0.001-3.0	
ABST_PERCENT	percentage of rainfall which is abstracted to depression storage	[0-1]		
DEP_MAX_FLOW	outflow rate with full depression storage	[mm/d]		
DEP_N	power law coefficient for depression outflow	[-]	0.5-3	
DEP_THRESHOLD	threshold storage at which flow commences	[mm]		
PONDED_EXP	exponent used in SOILEVAP_HYPR model	[-]	1-5	
OW_PET_CORR*	fraction of PET to apply to open water evaporation	[-]	0.1-1	
LAKE_PET_CORR*	fraction of PET to apply to lake evaporation	[-]	0.1-1	
FOREST_PET_CORR*	fraction of PET to apply to forest evapotranspiration	[-]	0.1-1	
GAMMA_SCALE(2)	Gamma unit hydrograph scale parameters	[1/d]	0.1-20	
GAMMA_SHAPE(2)	Gamma unit hydrograph shape parameters	[-]	0.5-5	
HMETS_RUNOFF_COEFF	HMETS runoff coefficient	[0..1]	0.3-1 (<1)	
AET_COEFF	SOILEVAP_LINEAR proportionality constant	[1/d]	0.05	
GR4J_X4	GR4J time routing parameter	[d]	0-100	
UBC_ICEPT_FACTOR*	UBC Interception factor	[-]		

Table A.7: Vegetation Parameters. The parameters with an asterisk can be automatically generated by Raven or overridden by the model user.

Name	Definition	Units	Range	
MAX_HEIGHT	maximum vegetation height	[m]		
MAX_LEAF_COND	maximum leaf conductance	[mm/s]		
MAX_LAI	maximum leaf area index	[m2/m2]		
SVF_EXTINCTION*	extinction coefficient used to calculate skyview factor	[-]	0.5	Physical Parameters
RAIN_ICEPT_PCT*	relates percentage of throughfall of rain to LAI+SAI	[-]	0.02-0.20	
SNOW_ICEPT_PCT*	relates percentage of throughfall of snow to LAI+SAI	[-]	0.02-0.20	
RAIN_ICEPT_FACT*	percentage of rain intercepted (maximum)	[0..1]	0.06	
SNOW_ICEPT_FACT*	percentage of snow intercepted (maximum)	[0..1]	0.04	
SAI_HT_RATIO*	ratio of stem area index to height	[m2/m3]		
TRUNK_FRACTION*	fraction of canopy attributed to tree trunk	[0..1]		
STEMFLOW_FRAC*		[0..1]	0.03	
ALBEDO*	visible/near-infrared albedo of leaf	[-]	0.15	
ALBEDO_WET*	albedo of wet leaf	[-]		
MAX_CAPACITY*	maximum canopy storage capacity	[mm]		
MAX_SNOW_CAPACITY*	maximum canopy snow (as SWE) storage capacity	[mm]		
ROOT_EXTINCT	extinction coefficient for roots, exp(-ext*z)	[]-		
MAX_ROOT_LENGTH	root length per unit canopy area	[mm/m2]		
MIN_RESISTIVITY	1.0/max_conductivity	[d/mm]		
XYLEM _FRAC	fraction of plant resistance in xylem	[0..1]		
ROOTRADIUS	average root radius (used to calculate cowan alpha)	[mm]		
PSI_CRITICAL	minimum plant leaf water potential	[-mm]		
DRIP_PROPORTION	drip proportion for bucket drip model	[1/d]		Conceptual Model Parameters
MAX_INTERCEPT_RATE	maximum rate of rainfall interception	[mm/d]		
CHU_MATURITY	crop heat unit maturity; level at which PET is maximized	[-]		

Table A.8: Available global parameters in Raven.

Name	Definition	Units	Range	
ADIABATIC_LAPSE	adiabatic temperature lapse rate	°C/km	0-7	Physical Parameters
WET_ADIABATIC_LAPSE	wet adiabatic temperature lapse rate	°C/km	0-7	
PRECIP_LAPSE	precipitation lapse rate for orographic correction	mm/d/km	0-100	
RAINSNOW_TEMP	rain/snow halfway transition temperature	°C	-1.0-1.0	
RAINSNOW_DELTA	range of rain-snow transition zone (about RAINSNOW_TEMP)	°C	0-4	
SNOW_SWI	water saturation fraction of snow	0..1	0.04-0.07	
SNOW_SWI_MIN	minimum water saturation fraction of snow	0..1	0.04-0.05	
SNOW_SWI_MAX	minimum water saturation fraction of snow	0..1	0.05-0.15	
SNOW_TEMPERATURE	default snow temperature if not explicitly modelled	°C	-2.0-0.0	
SNOW_ROUGHNESS	roughness height of snow	mm	0-5.0	
AVG_ANNUAL_SNOW	avg annual snow as SWE	mm	0-100	
AVG_ANNUAL_RUNOFF	avg annual runoff from basin	mm	0-1000	
MAX_SNOW_ALBEDO	albedo of fresh snow	0..1	0.95	
MIN_SNOW_ALBEDO	very old snow/glacier albedo	0..1	0.3	
BARE_GROUND_ALBEDO	bare ground albedo	0..1	0.1-0.4	
MAX_REACH_SEGLENGTH	maximum reach segment length	km		Conceptual/Numerical Model Parameters
MAX_SWE_SURFACE	maximum SWE in surface snow layer (SNOBAL_TWO_LAYER)	mm		
AIRSNOW_COEFF	air/snow heat transfer coefficient	1/d		
UBC_GW_SPLIT	UBC groundwater split parameter	0..1	0.4	
UBC_EXPOSURE_FACT	UBC Sun exposure factor of forested areas	0..1		
UBC_CLOUD_PENET	UBC Fraction of solar radiation penetrating cloud cover	0..1		
UBC_LW_FOREST_FACT	UBC temperature factor to estimate LW radiation in forests	mm/d/K		
UBC_FLASH_PONDING	UBC ponding threshold for flash factor	mm		
UBC_ALBASE	albedo exponential decay threshold value	-	0.65	
UBC_ALBREC	albedo decay constant	1/d	0.9	
UBC_ALBSNW	daily snowfall required to bring albedo to that of new snow	mm	15	
ALB_DECAY_COLD	linear albedo decay rate for cold conditions	1/d	0.008	
ALB_DECAY_MELT	linear albedo decay rate for melting conditions	1/d	0.12	
SNOWFALL_ALBTHRESH	threshhold snowfall rate to refresh albedo to fresh snow	mm/d	10	
UBC_MAX_CUM_MELT	estimate of maximum annual snowmelt	mm	4000	
SWI_REDUCT_COEFF	rate of SWI reduction with increasing cumulative melt	1/mm	0.02	
MOHYSE_PET_coeff	PET coefficient for MOHYSE PET algorithm	-	1.0	
ASSIMILATION_FACT	degree of assimilation (=0 for none, =1 for full insertion)	0..1	1	Alg Params
ASSIM_TIME_DECAY	controls degree of assimilation after observations end	1/d	0.2	
ASSIM_UPSTREAM_DECAY	controls degree of assimilation upstream of observation	1/km	0.1	
RESERVOIR_RELAX	relax. factor for reservoir simulation of target stage/flow	0..1	0.4	

A.3 HRU / Basin Definition file (.rvh)

The HRU/basin definition file describes the topology of the basin network and the class membership of all constituent HRUs. An example .rvh file is shown below:

Example File: `modelname.rvh`

```
# ------------------------------------------
# Raven HRU Input file
# TEST input
# ------------------------------------------
:SubBasins
 :Attributes,   NAME, DOWNSTREAM_ID, PROFILE, REACH_LENGTH, GAUGED
 :Units,        none,          none,    none,           km,   none
      1,  Downstream,            -1, DEFAULT,          3.0,      1
      2,    Upstream,             1, DEFAULT,          3.0,      0
:EndSubBasins
:HRUs
 :Attributes, AREA, ELEVATION, LATITUDE, LONGITUDE, BASIN_ID, LAND_USE_CLASS,
      ...VEG_CLASS,SOIL_PROFILE, AQUIFER_PROFILE, TERRAIN_CLASS, SLOPE, ASPECT
 :Units,      km2,          m,      deg,      deg,      none,
none, ...
                     none,        none,            none,
none,    deg,   degN
  101,  10,143, 43,-80,   1,FORESTED,BROADLEAF, ALL_SAND,SAND_AQ,
[NONE],0.0,0.0
  102,  10,145, 43,-80,   1,URBAN   ,BROADLEAF, ALL_SAND,SAND_AQ,
[NONE],0.0,0.0
  103,  10,143, 43,-80,   2,FORESTED,BROADLEAF,     TILL,SAND_AQ,
[NONE],0.0,0.0
  104,  10,147, 43,-80,   2,FORESTED,BROADLEAF,     TILL,SAND_AQ,
[NONE],0.0,0.0
:EndHRUs
:HRUGroup ForestedHRUs
 101,103,104
:EndHRUGroup
:RedirectToFile Reservoirs.rvh
:RedirectToFile SubBasinParams.rvh
```

Note that, as with the .rvi file, comments may be included on individual lines using the * or # characters as the first word on the line.

A.3.1 Required Commands

The .rvh file consists of the following required commands:

```
:SubBasins
  :Attributes,   ID, NAME, DOWNSTREAM_ID, PROFILE, REACH_LENGTH, GAUGED,
  :Units     , none, none,          none,    none,           km,   none,
  {ID,name,downstream_ID profile,reach_length,gauged}x[number of subbasins]
:EndSubBasins
```

To specify an array of SubBasins of the watershed and the connectivity between subbasins. Each subbasin may only have one outlet subbasin, specified by ID (a unique positive integer). The subbasin-specific parameters are defined as follows:

- `ID` - A positive integer unique to this subbasin. Used to refer to the subbasin in other parts of the input file.
- `name` - The nickname for the basin (cannot include commas or spaces)
- `downstream_ID` - The ID of the basin that receives this subbasins outflowing waters. If the drainage for this subbasin leaves the modeled watershed, a value of -1 for the downstream ID should be specified.
- `profile` - The representative channel profile code (channel profiles specified in the .rvp file)
- `reach_length` - The length of the primary reach channel in the basin (in km). If this is a headwater basin, in-channel routing can be avoided by setting `reach_length` to zero. If set to `_AUTO`, the reach length will be estimated from total subbasin area.
- `gauged` - Flag which determines whether modeled hydrographs for this subbasin are generated as output from the model (either 1 or 0, true or false)

```
:HRUs
  :Attributes,AREA,ELEVATION,LATITUDE,LONGITUDE,BASIN_ID,LAND_USE_CLASS,
     VEG_CLASS,SOIL_PROFILE,AQUIFER_PROFILE,TERRAIN_CLASS,SLOPE,ASPECT
  :Units     ,km2,         m,     deg,      deg,    none,          none,
          none,        none,           none,         none,  deg,  degN
  {ID,area,lat,long,basin_ID,...
     LU/LT,veg_class_name,soil_profile_name,...
         terrain_class_name,slope,aspect}x[number of HRUs]
:EndHRUs
```

To specify an array of HRUs within the subbasins defined above. Each HRU is defined by an ID (a unique positive integer), a total HRU area (in km^2), a mean HRU elevation (in m.a.s.l), a latitude-longitude location of the HRU centroid (in decimal degrees), the ID of the basin in which the HRU is located (as defined in the `:SubBasins` command), land use, terrain, aquifer classes and a soil profile (as defined in the .rvp file), an average slope (in degrees), and mean aspect (in degrees from north - i.e., a western aspect would be 90°).

If terrain classes or aquifer profiles are not used in the model (as is common), the flag `[NONE]` goes in the place of the class specifier.

A.3.2 Optional Commands

```
:SubBasinProperties
  :Parameters, {PARAM_1, PARAM_2, .. , PARAM_N}
  :Units     , {UNITS_1, UNITS_2, .. , UNITS_N}
  {[basin ID], [p_1]   , [p_2]  , .. , [p_N] }} x NSB
:EndSubBasinProperties
```

Subbasin properties are used to control the in-catchment routing behaviour of individual subbasins. Here, `PARAM_i` represents the name of a subbasin parameter (the full list of valid parameters can be found in table C.3), `UNITS_i` is the units tag (not used by Raven), `p_i` refers to numeric values of each parameter, `basin id` is the subbasin ID as defined in the `:SubBasins` command, and `NSB` is the number of subbasins in the model.

```
:HRUGroup [group_name]
  17,18,30-37
:EndHRUGroup
```

HRU Groups are used for a number of reasons: to generate custom output only for a select set of HRUs (or organize/aggregate output for multiple sets) or to control which processes are applied in what locations. Group names are typically specified using the `:DefineHRUGroups` command in the .rvi file; this command populates the memberships of these predefined groups. Individual HRUs are specified with their ID numbers (as defined in the `:HRUs` command), separated by commas. Ranges of HRUs can be specified using the hyphen, as shown above.

```
:PopulateHRUGroup [HRUgroup] With [con_base] [condition] [con_data]
```

An alternative to the `:HRUGroup` command which automatically populates the HRU group based upon certain criteria. The `cond_base` command indicates the basis for the criterion, one of (`HRUS`, `LANDUSE`, `VEGETATION`, or `ELEVATION`). The `condition` indicates the means of evaluating the criterion, one of (`NOTWITHIN`, `BETWEEN`, `EQUALS`, `NOTEQUALS`). The `con_data` is dependent upon the `condition`. For the `NOTWITHIN` condition, the condition data is another HRU group name and the criterion must be `HRUS`. For the `BETWEEN` condition, the condition data is a range of elevations, and the only currently valid criterion basis is the elevation. For the `EQUALS` and `NOTEQUALS` conditions, the vegetation or land use names are specified, to group HRUs based upon class membership (or non-membership). For example, the following commands are valid:

```
:PopulateHRUGroup CroplandHRUs    With LANDUSE EQUALS CROPLAND
:PopulateHRUGroup NonCroplandHRUs With LANDUSE NOTEQUALS CROPLAND
:PopulateHRUGroup BroadleafHRUs   With VEGETATION EQUALS BROADLEAF
:PopulateHRUGroup NotRock         With HRUS NOTWITHIN RockHRUGroup
:PopulateHRUGroup LowBand         With ELEVATION BETWEEN  0 500
```

A.3.3 Reservoirs and Lakes

```
# Man-made reservoir
:Reservoir [name]
  :SubBasinID [SBID]
  :HRUID [HRUID] # optional
  :StageRelations
    [number of points (N)]
    h_1, Q_1, V_1, A_1, {U_1}
    h_2, Q_2, V_2, A_2, {U_2}
    ...
    h_N, Q_N, V_N, A_N, {U_N}
  :EndStageRelations
  :MaxCapacity {capacity, in m^3} # optional
  :SeepageParameters [K_seep] [h_ref] # optional
:EndReservoir
```

This command creates a reservoir at the outlet of the subbasin referenced by `SBID` characterized by `N` points on the indicated stage-discharge, stage-volume, and stage-area curves. Here, stage (`h_i`) is in meters, flow (`Q_i`) and underflow (`U_i`, optional) are in m^3/s, volume stage (`V_i`) is in m^3, and area stage (`A_i`) is in m^2. The stage increments can be unevenly spaced but must be increasing from `h_1` to `h_N`. Area and volume both must be monotonically increasing with increasing stage. For numerical stability, it is expected that changes in volume with stage increments are approximately equal to the area times the change in stage (i.e., a useful test is to compare ΔV to $A\Delta h$).

Evaporation from the reservoir surface are obtained from the HRU referenced by `HRUID` (this is the only purpose for this; a special HRU for the reservoir is not strictly required, though often appropriate if the reservoir is relatively large). If no HRU ID is provided, evaporation from the reservoir is presumed negligible. The reservoir volume, outflow, and net precipitation to the reservoir surface are obtained by interpolating their value from the specified stage-discharge $Q(h)$, stage-area $A(h)$, and stage-volume $V(h)$ relations, defined here by `N` points along the rating curves. The underflow relation $Q_u(h)$ is optional, and is assumed to be zero if omitted; if included, the total flow from the reservoir will be $Q(h) + Q_u(h)$. Note that the minimum stage supplied in the `:StageRelations` should be the minimum expected stage (usually the bottom of the reservoir), and the maximum should be above the expected maximum stage. See figure 4.1b for additional clarification of terms. Note that multiple operational constraints upon stage and flow for reservoirs may be specified as time series in the .rvt file using commands such as the `:ReservoirMaxStage` command. The optional `:MaxCapacity` item the maximum storage capacity of the reservoir in m^3, but is only used to inform the `:ReservoirDemandAllocation` operation; it does not constrain the stage or outflow from the reservoir âĂŞ this should be handled via maximum stage constraints or via the stage-discharge curve of the reservoir.

Groundwater seepage parameters `K_seep` ($m^3/s/m$) and `h_ref` (m) can be used to represent groundwater seepage from the reservoir, where the losses are calculated as $Q_{loss} = K_{seep} \cdot (h - h_{ref})$. If the reference groundwater head (h_ref) is larger than the reservoir stage, the reservoir gains water, otherwise it loses water. By default, K_{seep} is zero, and no groundwater losses/gains are considered.

```
# Lake-like reservoir
:Reservoir [name]
  :SubBasinID [SBID]
  :HRUID [HRUID]
```

```
  :WeirCoefficient [C]
  :CrestWidth [width [m]]
  :MaxDepth [depth [m]]
  :LakeArea [area [m2]]
  :AbsoluteCrestHeight [elevation [masl]] {optional}
:EndReservoir
```

This command creates a **lake-like reservoir** at the outlet of the subbasin referenced by `SBID`, and is the preferred option for natural reservoirs. Evaporation from the reservoir surface are obtained from the HRU referenced by `HRUID`, as with the above `:Reservoir` command. Here, the discharge-stage, volume-stage, and area-stage relations are generated using the following overflow weir formulae for a prismatic lake:

$$\begin{aligned} Q(h) &= \frac{2}{3}\sqrt{2g}C \cdot L \cdot s^{3/2} \\ A(h) &= A \\ V(h) &= A \cdot (s + D) \end{aligned}$$

where s is the stage measured with reference to the crest height (which can be negative), D is the specified maximum lake depth (`:MaxDepth` [m]), g is the gravitational constant [m/s^2], C is the weir coefficient (`:WeirCoefficient`), A is the constant lake areas (`:LakeArea`), [m^2], and L is the crest width (`:CrestWidth`, [m]). See figure 4.1a for additional clarification of terms. Typically the weir coefficient is held fixed at a value of about 0.6, and the crest width is calibrated to represent the unknown crest width and overflow resistance. `:AbsoluteCrestHeight` may be supplied to reference stages to real lake stage; by default stage is with reference to the crest height, i.e., a zero stage would be just at the crest. Note that when many reservoirs and lakes are supplied, they would usually be kept in one or more separate files via the `:RedirectToFile` command. You can override the calculated area and volume relationships using the `:AreaStageRelation` and `:VolumeStageRelation` commands, respectively.

```
:MinStageConstraintDominant
```

Used within the `:Reservoir`-`:EndReservoir` block, this command is used to override the default ordering of outflow constraints for reservoirs. With this command, the minimum stage constraint (`:ReservoirMinSta` will override minimum flow, overrriden flow, and maximum flow constraints, changing the order of constraints indicated in section 4.3 but only in this reservoir. This will likewise override minimum demand flow calculated from the use of the `:ReservoirDownstreamDemand` command, such that the reservoir will not meet downstream demands if the stage is at minimum.

```
:DemandMultiplier [value]
```

Used within the `:Reservoir`-`:EndReservoir` block, this command is used to modify the percentage of downstream irrigation demand met by this reservoir. The `:ReservoirDownstreamDemand` command is used to allocate irrigation demand from downstream subbasins of a reservoir, thus increasing the minimum flow from that reservoir. The calculated minimum flow is multiplied by this demand multiplier. If set to 1.0, the reservoir completely respects the constraints from the downstream demand calculations. If set to 0.0, the reservoir will not be constrained in any way by downstream irrigation demand. This command may be used to help evaluate a range of water management strategies.

```
:DZTRResservoirModel
  :MaximumStorage           [Vmax]
```

```
  :MaximumChannelDischarge  [Qmax]
  :MonthlyMaxStorage        J F M A M J J A S O N D
  :MonthlyNormalStorage     J F M A M J J A S O N D
  :MonthlyCriticalStorage   J F M A M J J A S O N D
  :MonthlyMaxDischarge      J F M A M J J A S O N D
  :MonthlyNormalDischarge   J F M A M J J A S O N D
  :MonthlyCriticalDischarge J F M A M J J A S O N D
:EndDZTRReservoirModel
```

Used within the :Reservoir-:EndReservoir block, this command overrides the default stage-discharge relationship used to determine reservoir outflow with the time-variable volume-discharge relationship that is defined in Yassin et al. (2019). Historical volume-storage observations can be used to estimate these parameters to emulate historical (but unknown) reservoir outflow operational rules. All monthly storages (e.g., :MonthlyMaxStorage) are in m^3 and all flows (e.g., :MonthlyMaxDischarge) are in m^3/s; each row gets 12 monthly values. The order of the above commands must be respected and no comments are allowed between commands in this block. The details of operation are to be found in the ? paper. With this command, any stage-discharge curve indicated in the command structure is ignored.

```
:VolumeStageRelation
  [number of points (N)]
  h_1  V_1
  h_2  V_2
  ...
  h_N  V_N
:EndVolumeStageRelation
```

Used within the :Reservoir-:EndReservoir block, this command is used to override Raven's default calculation of the volume-stage relationship for a lake-like reservoir. The relationship is specified using N (h_i,V_i) pairs, which don't need to be evenly spaced. Stage is in units of meters, and volume is in cubic metres. Volumes must monotonically increase with increasing stage.

```
:AreaStageRelation
  [number of points (N)]
  h_1  A_1
  h_2  A_2
  ...
  h_N  A_N
:EndVolumeStageRelation
```

Used within the :Reservoir-:EndReservoir block, this command is used to override Raven's default calculation of the surface area-stage relationship for a lake-like reservoir. The relationship is specified using N (h_i,V_i) pairs, which don't need to be evenly spaced. Stage is in units of meters, and lake surface area is in square metres. Areas must monotonically increase with increasing stage.

A.4 Time Series Input file (.rvt)

The time series input file is used to store time series of forcing functions (precipitation, temperature, etc.). It also may include additional commands for handling irrigation and diversions (i.e., any control systems). An .rvt file is structured as follows:

```
#-----------------------------------------
# Raven Time Series Input file
#-----------------------------------------
:Gauge Stratford MOE (ID:6148105)
  :Latitude   43.37250
  :Longitude -80.55360
  :Elevation 53
  :RedirectToFile StratfordMOEData.rvt
:EndGauge
:Gauge WaterlooWeatherStation
  :Latitude   43.37
  :Longitude -80.55
  :Elevation 57
  :RedirectToFile WaterlooWeatherStationData.rvt
:EndGauge
:RedirectToFile UpstreamInflow.rvt
:RedirectToFile LandCoverChange.rvt
:RedirectToFile ObservedHydrograph.rvt
```

Note that standard practice is to have a single master `modelname.rvt` file that 'points to' a number of other .rvt files which contain unique data sets, i.e., an individual .rvt file for meteorological forcing data at a single meteorological gauge, another for observed stream flow at a stream gauge, and another reporting pumping from one reservoir. The 'pointing' is done using the `:RedirectToFile` command as shown in the above example file. All of the redirected files are treated as if their contents have been inserted into the master .rvt file.

Please note that all of Raven's inputs and internal calculations use the standard proleptic Gregorian calendar with leap years included. Any data which ignores leap years, is referenced from Jan 1, 1 AD, uses the Julian/Hebrew/Mayan calendar or is otherwise non-standard, will require pre-processing.
All hourly data referenced to GMT (Greenwich Mean Time) will need to be shifted to the local time zone to be consistent with the solar calculations, which assume solar noon is at 12:00PM.

A.4.1 Meteorological Gauge Data Commands

The entries in the .rvt file are predominantly meteorological gauge locations (either real or hypothetical) that provide time series of needed precipitation, temperature and other atmospheric forcings used by the model (see appendix A.4.6 for information about using gridded model inputs instead of gauges). This is supplemented by information about other time series needed for simulation. Each gauge entry is specified within a bracketed statement,

```
:Gauge [gaugename]
  :Latitude [latitude]
  :Longitude [longitude]
  :Elevation [elevation]
  [other gauge data and time series information here]
:EndGauge
```

and must contain the latitude/longitude (using the `:Latitude`, `:Longitude` commands) and typically contain a number of time series. Two formats, `:Data` (for a single time series) and `:MultiData` (for multiple time series), may be used to specify collections of forcing functions measured at the gauge. These are often stored in their own individual file and accessed via the `:RedirectToFile` command.

```
:Data [forcing type] {units}
  [date yyyy-mm-dd] [time hh:mm:ss.0] [time interval (d)] [N]
  v_1
  v_2
  v_3
  ...
  v_N
:EndData
```

where here, `v_i` are the ith time series values and the `forcing_type` term is one of the forcings listed in table C.2 (e.g., `PRECIP`, `TEMP_MIN`. etc.). `N` is the total number of data points provided, evenly spaced at the specified time interval. Note that this is the default format for most of the regularly spaced time series commands in Raven.

It is assumed that the array of values specified are time-averaged values over the specified time interval. All forcings are in period-starting format, so that if the start date is 2002-10-01 00:00:00 with a time interval of 1.0 days, then the first data item represents the average forcing value on October 1st. Note that the terms may be space-, comma-, or tab-delimited and would typically be entered as a single column. Multiple data points may be included on a single line, though the single-column format makes this easier to use in other program utilities. Also note that the time interval must be specified as a double, and cannot be specified using a format of 00:00:00.

IMPORTANT: The default units of the forcing functions (as tabulated in C.2) must be respected. Though non-intuitive to many hydrologists, precipitation intensity (in mm/d) must be specified even for hourly data intervals, e.g., 1 cm of rain in an hour would be specified as a rainfall rate of 240 mm/d.

```
:MultiData
  [date yyyy-mm-dd] [time hh:mm:ss.0] [time interval (d)] [N]
  :Parameters PARAMETER_1 PARAMETER_2 ... PARAMETER_J
  :Units      units_tag_1 units_tag_2 ... units_tag_J
  v_11, v_12, v_13
  v_21, v_22, v_23
  ...
  v_N1, v_N2, v_N3
:EndMultiData
```

This command is an alternate to the :Data approach, allowing multiple data to be included as a single data table using the :MultiData command, with columns corresponding to individual data types. Here, PARAMETER_i corresponds to the name of the input parameter (one of the forcing values in table C.2), and the units tags should be consistent with the actual desired units in table C.2.

Again, note that the time interval must be specified as a double, and cannot be specified using a format of 00:00:00. Raven will not perform units conversions for you if alternate units are specified in the :Units header.

Other additional terms may be associated with each gauge, contained between the :Gauge-:EndGauge brackets:

```
:Elevation [elevation]
```

The elevation of the gauge, typically in meters above mean sea level. This is used both in interpolation and in orographic correction of gauge data when mapped to HRUs at different elevations. Must be between the :Gauge–:EndGauge brackets

```
:Latitude [latitude]
```

The latitude of the gauge, in degrees. This is used in interpolation of gauged forcings.

```
:Longitude [longitude]
```

The longitude of the gauge, in degrees. This is used in interpolation of gauged forcings.

```
:MeasurementHeight [height]
```

The height of the gauge relative to the ground surface, in meters. This is particularly important for wind velocity measurements to calculate (e.g.) atmospheric conductance and other parameters dependent upon vertical wind speed distribution, but may typically be ignored in temperature-only gauges.

```
:RedirectToFile [filename]
```

This treats the contents of file "filename" as if they were simply inserted into the .rvt file at the location of the :RedirectToFile command. This is useful for storing individual time series at a gauge in separate files. If no path is specified, the filename must be reported relative to the working directory. Note that this command can work within a :Gauge-:EndGauge structure, but not within other structures (e.g., a :Multidata entry cannot be split into multiple files in this manner).

```
:RainCorrection [value]
```

A multiplier (hopefully near 1.0) applied to all reported rainfall rates at this gauge; often used as a correction factor for estimating proper rainfall volumes at gauges prone to undercatch or otherwise not expected to be representative of local conditions. Must be between the :Gauge–:EndGauge brackets.

```
:SnowCorrection [value]
```

A multiplier (hopefully near 1.0) applied to all reported snowfall rates at this gauge; often used as a correction factor for estimating proper snow volumes at gauges prone to undercatch or otherwise not

expected to be representative of local conditions. Must be between the :Gauge–:EndGauge brackets.

```
:MonthlyAveTemperature [J F M A M J J A S O N D]
```

A list of 12 representative monthly average temperatures at the gauge, from Jan to Dec, in °C. Must be between the :Gauge–:EndGauge brackets. Predominantly used for the PET_FROMMONTHLY PET estimation method, not otherwise needed.

```
:MonthlyMinTemperature [J F M A M J J A S O N D]
:MonthlyMaxTemperature [J F M A M J J A S O N D]
```

A list of 12 representative monthly minimum and maximum temperatures at the gauge, from Jan to Dec, in °C. Must be between the :Gauge–:EndGauge brackets. Predominantly used for the PET_HARGREAVES PET estimation method, not otherwise needed.

```
:MonthlyAveEvaporation  [J F M A M J J A S O N D]
```

A list of 12 representative monthly average potential evapotranspiration rates at the gauge, from Jan to Dec, in mm/d. Must be between the :Gauge–:EndGauge brackets. Predominantly used for the PET_FROMMONTHLY PET estimation method, not otherwise needed.

```
:MonthlyEvapFactor [J F M A M J J A S O N D]
```

A list of 12 monthly evaporation factors [mm/d/K]. This is used in the PET_MONTHLY_FACTOR estimation routine, not otherwise needed. Must be between the :Gauge–:EndGauge brackets.

```
:CloudTempRanges [cloud_temp_min] [cloud_temp_max]
```

Temperature ranges (in °C) used for estimation of cloud cover using the UBCWM model approach (CLOUDCOV_UBCWM not otherwise needed. Must be between the :Gauge–:EndGauge brackets.

```
:EnsimTimeSeries [filename]
```

A table of time series (similar to the :MultiData command) may be specified using the Ensim .tb0 format. The input parameter names are the same which are provided in table C.2. This must be between the :Gauge–:EndGauge brackets when providing gauge meteorological data. An example is provided below:

```
##########################################################################
:FileType tb0  ASCII  EnSim 1.0
#-------------------------------------------------------------------------
:ColumnMetaData
  :ColumnName  TEMP_MAX TEMP_MIN PRECIP
  :ColumnUnits DegC     DegC     mm/d
  :ColumnType  float    float    float
:EndColumnMetaData
#
:StartTime       1983/02/01 00:00:00.000
:DeltaT          24:00:00.000
```

```
#
:EndHeader
4.4 -0.6  0
5.0 -2.5  0.6
...
5.6 -3.0 0.3
4.4 -4.6 0.0
1.1 -4.4 0.0
```

Any individual time series can also be read from NetCDF files using a `:ReadFromNetCDF-:EndReadFromNetCDF` block. This command works with ALL of the time series in format similar to the `:Data-:EndData` block, and replaces the date/time/interval/data vector contents,e.g.,

```
:Data [forcing type] [unit]
  :ReadFromNetCDF
    :FileNameNC      [path/filename of .nc file]
    :VarNameNC       [name of variable in .nc file]
    :DimNamesNC      [stations_name] [time_name] # (2-D) or
    :DimNamesNC      [time_name] (1-D)
    :StationIdx      [ID of station of interest (starts with 1)]
    :TimeShift       [time stamp shift in days] #optional
    :LinearTransform [slope] [intercept] #optional
  :EndReadFromNetCDF
:EndData
```

This optional internal contents of the `:Data-:EndData` block can be used to generate forcing time series from NetCDF data. As indicated in documentation of the `:Data` command, the `forcing_type` is chosen from the options in table C.2. The NetCDF variables need to be either one-dimensional (time) or two-dimensional (time x stations or stations x time). If the data are two-dimensional, the user needs to specify which station should be read in using `:StationIdx`.

The `:ReadFromNetCDF` block also allows for the specification of a time shift `:TimeShift` in fractional days. For example, a time shift

```
:TimeShift -0.25
```

will shift all data earlier by 6 hours. Hence, a data point that was read for 8:00 am will be handled as 2:00 am in the model. The time shift only applies when the input data are sub-daily. Otherwise data can only be shifted by whole days.

The data read can also be linearly transformed using `:LinearTransform`. The slope and intercept specified will be applied to the data right after reading. The `:LinearTransform` can be used to apply unit conversions of the data. For example, the linear transformation

```
:LinearTransform 1.0 -273.15
```

would convert temperature data that were read in Kelvin into Celsius.

Advice

The `:LinearTransform` command is very useful for converting precipitation data that is natively in units of mm/data interval rather than mm/d, as Raven requires. If the NetCDF precipitation data is accumulated data, the `:Deaccumulate` command may be added to the `:ReadFromNetCDF` block, which will deaccumulate the data.

A.4.2 Observation Time Series

Time series of known flows and model parameters may also need to be specified to support the model. These are not linked to a specific Gauge, and would therefore not be included in an :Gauge...:EndGauge bracket. Most of these time series would be stored in a separate .rvt file and referred to in the main .rvt file using the :RedirectToFile command. Note that all of the below time series may be read from NetCDF by using the :ReadFromNetCDF-:EndReadFromNetCDF command from the previous section.

```
:ObservationData [data_type] [basin_ID or HRU_ID] {units}
  [date yyyy-mm-dd] [time hh:mm:ss.0] [time interval (d)] [N]
  v_1
  v_2
  v_3
  ...
  v_N
:EndObservationData
```

Similar to the :Data command above. This specifies a continuous time series of observations of type data_type with units units located either at the outlet of the basin specified with basin_ID or the HRU specified with HRU_ID. The data types correspond to state variables in the model, and the data_type therefore must be taken from table C.1, unless the data is (1) a hydrograph, in which case the HYDROGRAPH tag is used, (2) a reservoir stage, in which case the RESERVOIR_STAGE tag is used, (3) a reservoir inflow (the RESERVOIR_INFLOW tag) or (4) a reservoir net inflow (runoff+P-E, the RESERVOIR_NETINFLOW tag). For hydrographs, reservoir stage, and reservoir inflows, the basin ID is specified. For all other variables, the HRU ID is specified. With the exception of the hydrograph and inflow hydrographs, it is assumed that the observations correspond to instantaneous observations in time rather than time-averaged quantities. This command defines a time series of regularly spaced consecutive values. If the time series time interval doesn't match the model time step then the time series is re-sampled to match the model. For irregularly spaced observations, use the :IrregularObservations command.

Missing or unknown observations should be specified using the flag -1.2345. Note that the observation time series does not have to overlap the model simulation duration. All data outside the supplied time interval is treated as blank.

If an observed hydrograph is supplied, it will be output to the Hydrographs.csv file. Hydrographs should be specified in period-starting format, i.e., for a time series of daily discharges starting on October 1, 2006, the start time would be 2006-10-01 00:00:00, at the *start* of the first data period provided.

```
:ObservationWeights [data type] [ID]
  [date yyyy-mm-dd] [time hh:mm:ss.0] [time interval (d)] [N]
  wt_1
  wt_2
  wt_3
  ...
  wt_N
:EndObservationWeights
```

This command is used apply weights to observation data for the calculation of diagnostics. The data

type, ID, and number of entries all need to match an existing `:ObservationData` time series. Not all evaluation metrics can be weighted, in which case all weights are ignored except weights of zero.

```
:IrregularObservations [data type] [ID] [N] {(optional) units}
  [date yyyy-mm-dd] [time hh:mm:ss.0] v_1
  [date yyyy-mm-dd] [time hh:mm:ss.0] v_2
  ...
  [date yyyy-mm-dd] [time hh:mm:ss.0] v_N
:EndIrregularObservations
```

This command is used for time series where observations are discontinuous or irregularly spaced. Values in these time series are assumed to be instantaneous and modelled values are linearly interpolated to match the observation times for comparison.

Missing or unknown observations should be specified using the flag `-1.2345`. Note that the observation time series does not have to overlap the model simulation duration. All data outside the supplied time interval is treated as blank.

```
:IrregularWeights [data type] [ID] [N]
  [date yyyy-mm-dd] [time hh:mm:ss.0] wt_1
  [date yyyy-mm-dd] [time hh:mm:ss.0] wt_2
  ...
  [date yyyy-mm-dd] [time hh:mm:ss.0] wt_N
:EndIrregularWeights
```

This command is used apply weights to irregular observations, where `wt_i` is the weight for the i^{th} irregular data point in a corresponding `:IrregularObservations` time series. Weights must be between zero and one. If values in the time series are null or blank, the weights are automatically treated as zero. The data type, ID, and number of entries all need to match an existing `:IrregularObservations` time series.

A.4.3 Reservoir Control Time Series

The following time series commands deal with reservoir operational constraints.

```
:ReservoirExtraction [Basin ID]
  [date yyyy-mm-dd] [time hh:mm:ss.0] [time interval (d)] [N]
  Q_1
  Q_2
  ...
  Q_N
:EndReservoirExtraction
```

where `Q_i` is the ith inflow in m^3d^{-1}. Discharges are positive for reservoir extraction and negative for injection of water into the reservoir located at the outlet of the subbasin indicated by the basin ID. This command is usually used to represent diversion flow for irrigation or similar.

```
:VariableWeirHeight [Basin ID]
  [date yyyy-mm-dd] [time hh:mm:ss.0] [time interval (d)] [N]
```

```
  h_1
  h_2
  ...
  h_N
:EndVariableWeirHeight
```

where `h_i` is the ith height of the reservoir outflow weir in m. All weir heights should be positive and are relative to the minimum crest height of the stage-discharge curve (i.e., weir heights are not with reference to mean sea level). This minimum crest height is zero by default for a 'lake-like' reservoir (those specified using `:WeirCoefficient` and `:CrestWidth` parameters) and equivalent to the highest stage with zero discharge in reservoirs defined using the `:StageRelations` command. This time series of weir heights is only applied to the reservoir located at the outlet of the subbasin indicated by the basin ID.

```
:ReservoirMaxStage [Basin ID]
  [date yyyy-mm-dd] [time hh:mm:ss.0] [time interval (d)] [N]
  h_1
  h_2
  ...
  h_N
:EndReservoirMaxStage
```

where `h_i` is the ith maximum stage of the reservoir in m (usually with sea level as the datum), and Basin ID corresponds to the subbasin with the corresponding reservoir at its outlet. If the computed stage exceeds this stage during operation, the outflow from the reservoir will be adjusted so as to keep the stage at the specified maximum. This time series is often a constant value corresponding to the maximum flood pool level of a reservoir.

```
:ReservoirMinStage [Basin ID]
  [date yyyy-mm-dd] [time hh:mm:ss.0] [time interval (d)] [N]
  h_1
  h_2
  ...
  h_N
:EndReservoirMinStage
```

where `h_i` is the ith minimum stage of the reservoir in m (usually with sea level as the datum), and Basin ID corresponds to the subbasin with the corresponding reservoir at its outlet. If the simulated stage is below this stage during model operation, the outflow from the reservoir will be set to the minimum reservoir flow (as specified using the `:ReservoirMinStageFlow` command. This time series is typically used to represent reservoir rule curves.

```
:ReservoirMinStageFlow [Basin ID]
  [date yyyy-mm-dd] [time hh:mm:ss.0] [time interval (d)] [N]
  Q_1
  Q_2
  ...
  Q_N
:EndReservoirMinStageFlow
```

where Q_i is the ith specified minimum stage discharge from the reservoir in m^3/s, and Basin ID corresponds to the subbasin with the corresponding reservoir at its outlet. If the simulated stage is below the stage specified by the :ReservoirMinStage command during model operation, the outflow from the reservoir will be set to this flow, overriding the flow determined through stage-discharge relations. This time series is typically used to represent reservoir rule curves.

```
:OverrideReservoirFlow [Basin ID]
  [date yyyy-mm-dd] [time hh:mm:ss.0] [time interval (d)] [N]
  Q_1
  Q_2
  ...
  Q_N
:EndOverrideReservoirFlow
```

where Q_i is the ith overridden outflow rate from the reservoir in m^3/s, separated by the given time interval, and Basin ID corresponds to the subbasin with the corresponding reservoir at its outlet. Regardless of the stage-discharge relation for the reservoir, the flow will be overridden with this specified flow time series unless the value for Q_i is Raven's blank value of -1.2345, in which case the discharge will be calculated as normally done using the stage-discharge curve. This command is useful for replacing the calculated flow from a reservoir with observed flow during model calibration. It can also be used in short-term reservoir operations for evaluating discharge scenarios. The only time during which this specified flow is disregarded is if the maximum stage constraint for the reservoir (e.g., as specified using the :ReservoirMaxStage command) is exceeded.

```
:ReservoirTargetStage [Basin ID]
  [date yyyy-mm-dd] [time hh:mm:ss.0] [time interval (d)] [N]
  h_1
  h_2
  ...
  h_N
:EndReservoirTargetStage
```

where h_i is the ith target stage of the reservoir in m (usually with sea level as the datum), and Basin ID corresponds to the subbasin with the corresponding reservoir at its outlet. If the simulated stage is above or below this stage during model operation, the outflow from the reservoir will be adjusted to move towards this target stage subject to the constraint that the maximum increase rate of the discharge (specified using the :ReservoirMaxQDelta command) is respected. This time series is typically used to represent reservoir rule curves. This target stage must be between the minimum and maximum stages specified using the :ReservoirMaxStage and :ReservoirMinStage commands. If the target stage is given a blank value (-1.2345) for any time increment, the model will use the discharge as calculated from the stage-discharge relation.

```
:ReservoirMinFlow [Basin ID]
  [date yyyy-mm-dd] [time hh:mm:ss.0] [time interval (d)] [N]
  Q_1
  Q_2
  ...
  Q_N
:EndReservoirMinFlow
```

where Q_i is the i^{th} minimum flow of the reservoir in m^3/s, and Basin ID corresponds to the subbasin with the corresponding reservoir at its outlet. If the simulated/calculated desired flow from the reservoir is below this flow rate, the flow rate is corrected to this minimum flow value. If downstream reservoir demands are included, they will increase the specified value of this minimum flow rate to also meet downstream demand.

```
:ReservoirMaxFlow [Basin ID]
  [date yyyy-mm-dd] [time hh:mm:ss.0] [time interval (d)] [N]
  Q_1
  Q_2
  ...
  Q_N
:EndReservoirMaxFlow
```

where Q_i is the i^{th} maximum flow of the reservoir in m^3/s, and Basin ID corresponds to the subbasin with the corresponding reservoir at its outlet. If the simulated/calculated desired flow from the reservoir is above this flow rate, the flow rate is corrected to this maximum flow value. Only the maximum stage constraint associated with the :MaxReservoirStage command will override this maximum flow constraint (i.e., the outflow from the reservoir can exceed this max flow if the reservoir is full).

```
:ReservoirMaxQDelta [Basin ID]
  [date yyyy-mm-dd] [time hh:mm:ss.0] [time interval (d)] [N]
  QD_1
  QD_2
  ...
  QD_N
:EndReservoirMaxQDelta
```

where QD_i is the i^{th} maximum flow rate increase in $m^3/s/d$, and Basin ID corresponds to the subbasin with the corresponding reservoir at its outlet. If the simulated stage is above the target stage indicated by the :ReservoirTargetStage command during model operation, the outflow from the reservoir will be adjusted to move towards this target stage subject to the constraint that the maximum increase rate of the discharge (specified using this command) is respected. This time series is typically used to represent reservoir rule curves.

```
:ReservoirMaxQDecrease [Basin ID]
  [date yyyy-mm-dd] [time hh:mm:ss.0] [time interval (d)] [N]
  QD_1
  QD_2
  ...
  QD_N
:EndReservoirMaxQDelta
```

where QD_i is the i^{th} maximum flow rate decrease rate in $m^3/s/d$, and Basin ID corresponds to the subbasin with the corresponding reservoir at its outlet. If the simulated stage is above the target stage indicated by the :ReservoirTargetStage command during model operation, the outflow from the reservoir will be adjusted to move towards this target stage subject to the constraint that the maximum decrease rate of the discharge (specified using this command) is respected. This time series is typically used to represent reservoir rule curves.

A.4.4 Irrigation, demand, and diversions

```
:BasinInflowHydrograph [Basin ID]
  [date yyyy-mm-dd] [time hh:mm:ss.0] [time interval (d)] [N]
  Q_1
  Q_2
  ...
  Q_N
:EndBasinInflowHydrograph
```

where `Q_i` is the i^{th} inflow in m^3/s. This command is typically used to (1) specify inflows coming from an unmodeled portion of the domain; (2) override modeled inflow to a stream reach with observed inflows from a stream gauge, as might be done during calibration; or (3) add additional inflows to a stream reach from human activities, e.g., a wastewater treatment plant inflow. The discharge is introduced at the *upstream* end of a basin reach, therefore this should typically not be used in headwater basins (see `:BasinInflowHydrograph2`.

```
:BasinInflowHydrograph2 [Basin ID]
  [date yyyy-mm-dd] [time hh:mm:ss.0] [time interval (d)] [N]
  Q_1
  Q_2
  ...
  Q_N
:EndBasinInflowHydrograph2
```

where `Q_i` is the i^{th} inflow in m^3/s. This command is typically used to add (or subtract, if negative) inflows to or outflows from a stream reach from human activities, e.g., a wastewater treatment plant inflow or irrigation demand. The difference between this and `:BasinInflowHydrograph` is that it extracts/injects water from the downstream end of the basin stream reach rather than the upstream end. It may therefore be used in headwater basins.

```
:IrrigationDemand [SBID]
  [date yyyy-mm-dd] [time hh:mm:ss.0] [time interval (d)] [N]
  Qirr_1
  Qirr_2
  ...
  Qirr_N
:EndIrrigationDemand
```

This time series indicates the time history of irrigation demand, in m^3/s, from a subbasin, drawn from the outlet of the subbasin (downstream of the reservoir, if one is present). If there is sufficient water available (i.e., enough to satisfy positive flow and/or the environmental minimum flow), the water will be removed. This approach is preferred over using negative flows in a `:BasinInflowHydrograph` time series, which will not respect these constraints.

```
:ReservoirDownstreamDemand [down_ID] [res_ID] [percent_met] {j1} {j2}
```

This command modifies the minimum outflow from a reservoir or set of reservoirs upstream of a sub-

basin with irrigation demand (supplied using the :IrrigationDemand time series command) in order to satisfy some percentage of this downstream irrigation demand. Here, down_ID is the subbasin index referring to a subbasin with an irrigation demand time series, the res_ID is the upstream subbasin index of a reservoir which releases sufficient water to satisfy this demand (i.e., itâĂŹs minimum flow rate is modified to satisfy demand), and percent_met is the total percentage of the irrigation demand met by this reservoir, from 0 to 1, with 1 indicating 100% of demand is met by the specified reservoir. If the res_ID is _AUTO and percent_met is _AUTO, the method indicated by the :ReservoirDemandAllocation command in the .rvi file will be used to identify all of the upstream reservoirs and split the demand between them according to contributing area, maximum capacity, or other metrics. Note that the percent met will be globally corrected by the global parameter RESERVOIR_DEMAND_MULT, so if percent met=0.5 and RESERVOIR_DEMAND_MULT is 1.2, then 60% of the downstream demand will be satisfied by the specified reservoir.

Optional terms j1 and j2 are the start and end Julian dates on which this constraint will be applied. Both terms are integers ranging from 1 (Jan 1) to 365 (Dec 31 in a non-leap year). The date range is inclusive, i.e., using the range 233-235 would enable this demand constraint from August 21st to August 23rd inclusively in a non-leap year or August 20th to August 22nd in a leap year.

```
:FlowDiversion [fromSBID] [toSBID] [pct] [Qmin] {start_day} {end_day}

:FlowDiversionLookupTable [fromSBID] [toSBID] {start_day} {end_day}
  nPoints
  {Qsource_i Qdivert_i} x nPoints
:EndFlowDiversionLookupTable
```

These commands provide rules for flow diversions to move water from the outlet of one subbasin to the inlet of another subbasin. The amount of diversion can either be in the form of a percentage of source water discharge (the :FlowDiversion command) or using a lookup table (the :FlowDiversionRatingCurve command. In both cases, the fromSBID and toSBID are the source and target subbasin IDs; if the toSBID is -1, then the water is diverted outside of the model. The optional start_day and end_day command elements are the Julian start date of diversion and Julian end date of diversion; if these are omitted, it is assumed the diversion is year-round. In the case of the :FlowDiversion command, the diverted flow is a percentage of the discharge from the source subbasin at the start of each time step which is diverted, where pct is the decimal percentage (0..1) of flow in exceedance of the minimum flow Qmin (in m^3/s) which is diverted, i.e.,

$$Q_{divert} = \alpha \cdot \max((Q_{source} - Q_{min}), 0)$$

In the case of the :FlowDiversionLookupTable command, the diverted flow is linearly interpolated from a lookup table specified by nPoints pairs of flows, where Qsource is the source basin discharge (in m^3/s) at the start of the time step and Qdivert is the corresponding diversion flow (in m^3/s). The Qsource flows must be in ascending order where the first point is always a flow of zero. No negative diversions are allowed, and the diversion flow should always be less than the source flow (hopefully for obvious reasons!).

```
:EnvironmentalMinFlow [Basin ID]
  [date yyyy-mm-dd] [time hh:mm:ss.0] [time interval (d)] [N]
  Q_1
  Q_2
  ...
  Q_N
```

```
:EndEnvironmentalMinFlow
```

where `Q_i` is the i^{th} minimum flow constraint in m^3s^{-1}. This command is used in conjunction with the `:IrrigationDemand` time series at the same basin, and constrains the irrigation-based extraction such that the minimum flow is always respected. Note that modelled stream discharge can be less than this environmental minimum flow, but that irrigation cannot extract water such that this constraint is violated.

```
:UnusableFlowPercentage [Basin ID] [value]
```

This command is used to constrain the water available for irrigation demand, and would be used in conjunction with the `:IrrigationDemand` time series at the same basin (and perhaps also an `:EnvironmentalMinF` constraint). The value of this percentage (expressed as a fraction from 0.0 to 1.0) indicates the percentage of flow above the environmental minimum flow which is available for irrigation. For instance, if the discharge in a subbasin was 7 m^3/s and the environmental minimum flow was 3m^3/s and the unusable flow percentage was 0.3 =30%, the maximum amount of water that could be used to satisfy irrigation demand would be $(1 - 0.3) \cdot (7 - 3)$ =2.8 m^3/s. Most commonly, this would be used when there are regulatory constraints regarding allowable fractions of streamflow that may be used to satisfy water demand. The unusable flow percentage for all subbasins is zero by default, i.e., irrigation can draw down flows to the environmental minimum (or zero discharge, if the environmental minimum is not specified).

A.4.5 Special Commands

```
:AnnualCycle [J F M A M J J A S O N D]
# for instance:
:ReservoirTargetStage [Basin ID]
  :AnnualCycle 379 379 379 379 379 382 383 382 380 380 379 379
:EndReservoirTargetStage
```

This command may be used internal to any of the time series commands in this section (or any continuous single-data time series with a similar format), by replacing the date/time/interval/N and data vector contents between the `:Data` and `:EndData` (e.g.,) commands with the single `:AnnualCycle` command. The monthly values here will be interpolated using the method specified in the `:MonthlyInterpolationMethod` (section A.1.2) and used to populate a continuous cyclic time series.

```
:OverrideStreamflow  [Basin ID]
```

This command overrides the discharge at the outlet of the basin defined with this ID. For this to work, there must be a corresponding observation `HYDROGRAPH` data set provided using the `:ObservationData` command, and there cannot be blank values in the data record during the course of the simulation. This command is often used to replace modelled inflows with observed inflows during model calibration.

A.4.6 NetCDF Gridded Input Data

Raven supports gridded forcing inputs exclusively in NetCDF format (*.nc files). In case of gridded inputs, the user needs to define some information about the variables and structure of the gridded NetCDF input file; in addition, the mapping of grid cells to HRUs needs to be specified through a weighting table.

Example File: modelname.rvt

```
# ----------------------------------------
# Example Raven Gridded Input file
# ----------------------------------------
:GriddedForcing PRECIPITATION
  :ForcingType      PRECIP
  :FileNameNC       gridded_precip.nc
  :VarNameNC        pre
  :DimNamesNC       lon lat ntime   # must be in the order of (x,y,t)
  :GridWeights
    :NumberHRUs      3
    :NumberGridCells 24
     # HRU  GridCell  Weight
       1    15        0.4
       1    16        0.6
       2    14        1.0
       3    14        0.2
       3    15        0.3
       3    13        0.5
  :EndGridWeights
:EndGriddedForcing
#
:RedirectToFile UpstreamInflow.rvt
:RedirectToFile LandCoverChange.rvt
:RedirectToFile ObservedHydrograph.rvt
```

The forcing inputs like precipitation and temperature are traditionally given as time series per gauging station (see appendix A.4.1). This becomes inconvenient if you have inputs available for multiple gauging stations or you even have the forcings available on a grid covering your whole modeling domain. Hence, Raven supports gridded input in NetCDF format. Instead of specifying a time series per gauge or grid cell in the .rvt file, one can specify a single input grid inside a `:GriddedForcing-:EndGriddedForcing` command structure:

```
  :GriddedForcing [forcing name]
    :ForcingType       [type]
    :FileNameNC        [path/filename of .nc file]
    :VarNameNC         [name of variable in .nc file]
    :DimNamesNC        [long_name] [lat_name] [time_name]
    :TimeShift         [time stamp shift in days] #optional
    :LinearTransform   [slope] [intercept] #optional
    :Deaccumulate      #optional
    :GridWeights
      :NumberHRUs      [total number of HRUs]
```

```
      :NumberGridCells [total number of grid cells]
        [HRU ID] [Cell ID] [weight]
        ...
    :EndGridWeights
  :EndGriddedForcing
```

One has to specify the type of the forcing input in the :ForcingType command, e.g. PRECIP or TEMP_AVE (see Table C.2 for complete list). The name of the file containing the data has to be given :FileNameNC. The file can contain more data than only this specific forcing; only the data of the specified variable :VarNameNC will be read and used by Raven. Since the order of the dimensions in a NetCDF file is not unique, one has to specify the dimension names starting with the x-dimension (usually longitudes), y-dimension (usually latitudes) and at last the name of the time dimension. One can also specify a time shift :TimeShift to shift the data. For example, when data given in UTC need to be shifted to local time; positive time shifts make the time stamp later, negative make it earlier. A linear transformation can further be applied to the data. For example, when data are given in Kelvin but need to be provided in Celsius for Raven. For instance, the following shift could be used to convert Farenheit temperature gridded data to Celsius for Raven:

```
  :LinearTransform 0.555555 -17.77777
```

which is equivalent to $T_C = (T_F - 32)/1.8$. Note that the output is the desired raven units and the input to the linear transform is in the NetCDF units. The :Deaccumulate command, if included will take cumulative precipitation values stored in the NetCDF file (such as are output by some weather models) and convert these to precipitation rates, in mm/d.

To obtain the information about variable name :VarNameNC and dimension names :DimNamesNC, one can use the command line tool ncdump available with the NetCDF library. Running the command

```
> ncdump -h gridded_precip.nc
```

will display the header information of the NetCDF file gridded_precip.nc and provide all the necessary information. The last required information is the :GridWeights block specifying how much each grid cell is contributing to each HRUs. Only non-zero weights have to be given; missing pairs are automatically assumed to be zero. The HRU ID has to correspond to the numbering in the :HRUs block of the .rvh file. The numbering of the grid cells is linewise starting with zero in the upper left corner of the grid, i.e., the grid ID is $\mathrm{CELLID} = i_{row} * N_{col} + i_{col}$, where i_{row} and i_{col} are the row and column indices of the grid cell, and N_{col} is the number of grid columns. The weights per HRU ID have to sum up to 1.0 otherwise Raven raises an error message. The list of grid weights will get very long with large grids and multiple HRUs. In such a case, the :GridWeights block would typically be stored in a separate file then and the :RedirectFile functionality be used instead.

For NetCDF inputs that are not linked to a 2D grid, but rather store a vector of time series (e.g., from meteorological stations), the following alternate to :GriddedForcing is available:

```
  :StationForcing [forcing name]
    :ForcingType       [type]
    :FileNameNC        [path/filename of .nc file]
    :VarNameNC         [name of variable in .nc file]
    :DimNamesNC        [station_name] [time_name]
    :TimeShift         [time stamp shift in days] #optional
```

```
    :LinearTransform   [slope] [intercept] #optional
    :Deaccumulate      #optional
    :GridWeights
      :NumberHRUs      [total number of HRUs]
      :NumberStations  [total number of stations]
        [HRU ID] [station ID] [weight]
        ...
    :EndGridWeights
  :EndGriddedForcing
```

This differs only in the number of items in the `:DimNamesNC` command and the use of the `:NumberStations` command in the grid weights portion; the remaining components of the command are identical to that of `:GriddedForcings`, as defined above.

A.5 Initial Conditions Input file (.rvc)

The initial conditions input file is used to store the initial conditions for the model. By default, the initial conditions for all model state variables is zero, and there are no required commands in this file (it could even be completely empty).

Example File: modelname.rvc

```
# -----------------------------------------
# Raven Initial Conditions Input file
# -----------------------------------------
:HRUStateVariableTable
  :Attributes, SOIL[0], SNOW,
  :Units     ,      mm,   mm,
            1,      145,   33,
            2,      150,   13,
  ...
:EndHRUStateVariableTable
:UniformInitialConditions SOIL[3] 300

:BasinInitialConditions
  :Attributes,     Q
  :Units     ,  m3/s
           1 ,   3.6
:EndBasinInitialConditions
```

A.5.1 Optional Commands

```
:HRUStateVariableTable
  :Attributes, {SV_TAG_1, SV_TAG_2,...,SV_TAG_NSV}
  :Units     , {units_1, units_2,...,units_NSV}
  {HRUID, SV_value_1,SV_value_2,...,SV_value_NSV} x nHRUs
:EndHRUStateVariableTable
```

Provides initial conditions for state variables in each HRU within the model. Here, `NSV` is the number of state variables for which initial conditions are provided, and `nHRUs` is the number of HRUs in the model. `SV_TAG` refers to the state variable tag, with the complete list of state variable tags in table C.1. Note that initial conditions have to be provided for all HRUs in the model and initial conditions have to be entered in the same order as in the `:HRUs` command in the .rvh file.

```
:BasinInitialConditions
  :Attributes,     Q
  :Units     ,  m3/s
    {SBID, FLOWRATE} x nSubBasins
:EndBasinInitialConditions
```

A list of initial outflow rates from the subbasins, indexed by subbasin ID as specified within the :SubBasins command of the .rvh file.

```
:UniformInitialConditions [SV_TAG] [value]
```

Applies a uniform initial condition (value) to the state variable corresponding to SV_TAG, with the complete list of state variable tags in table C.1. If called after :HRUStateVariableTable, it will overwrite the initial conditions previously specified.

```
:BasinStateVariables
  :BasinIndex SBID, name
    :ChannelStorage [val]
    :RivuletStorage [val]
    :Qout [nsegs] [aQout x nsegs] [aQoutLast]
    :Qlat [nQlatHist] [aQlatHist x nQlatHist] [QlatLast]
    :Qin  [nQinHist] [aQinHist x nQinHist]
    {reservoir variables}
  :BasinIndex SBID, name
   ...
:EndBasinStateVariables
```

This command is usually generated only as part of the Raven solution file and would not typically be modified by the user. It fully describes the flow variables linked to the subbasin. Here, :ChannelStorage [m^3] is the volume of water in the channel, :RivuletStorage [m^3] is the volume of water waiting in catchment storage, Qout [m^3/s] the array of outflows at each reach segment, Qlat [m^3/s] is an array storing the time history of outflows to the channel, Qin [m^3/s] is the time history of inflows to the uppermost segment of the reach.

```
:InitialReservoirStage [SBID] [stage]
```

Specifies initial reservoir stage for the reservoir located in the subbasin indicated by subbasin ID SBID, in meters. Either initial stage or flow should be specified: if both are provided, only the last in the file is used.

```
:TimeStamp [YYYY-mm-dd] [00:00:00.0]
```

Specifies time stamp linked to the initial conditions file. This is generated automatically by Raven when it produces a snapshot of the state variables, such as when it generates the solution.rvc output file. The time stamp should be consistent with the start time of the model.

A.6 Live file (.rvl)

The live file is intended for direct synchronous coupling of Raven with another model or software tool which would require regular information exchange with Raven during operation. Examples of such tools include reservoir optimization tools, software which represents dynamic land use or forestry practices, hydraulic models, or glacier mass balance models. Typically used in conjunction with the `:CallExternalScript` command, the live file (*.rvl) is read if the `:ReadLiveFile` command is included in the .rvi file. By default this file will be read every time step and enables external codes to dynamically modify Raven state variables, simulated flows, parameters, and landscape classification.

An example .rvl file is shown below.

```
:LandUseChange 2402 URBAN
:LandUseChange 2417 URBAN
:LandUseChange 2483 URBAN
```

This file would change the land use of HRUs 2402, 2417, and 2483 from their previous land use to URBAN. The URBAN land use parameters will now be used to represent the hydrologic response of these HRUs.

A.6.1 Commands

```
:VegetationChange [HRU_ID] [new vegetation class name]
```

Converts HRU indicated by `HRU_ID` from its previous vegetation class to the one specified. Useful for representing agricultural management.

```
:LandUseChange [HRU_ID] [new land use class name]
```

Converts HRU indicated by `HRU_ID` from its previous land use class to the one specified.

```
:GroupLandUseChange [HRU_Group_Name] [new land use class name]
```

Converts all HRUs in the HRU group `HRU_Group_Name` from its previous land use class to the one specified.

```
:SetStreamflow [SBID] [Q]
```

Changes the outflow from subbasin with subbasin index `SBID` to the discharge Q in m^3/s.

```
:SetReservoirStage [SBID] [stage]
```

Changes the stage in the reservoir within subbasin `SBID` to the stage indicated (in m).

Appendix B

Output Files

B.1 Standard Output Files

By default, output files are in comma-delimited format, and can be readily opened up in Excel or R for post-processing, visualization, and analysis. Available output files include:

- `WatershedStorage.csv` (created by default)
  A comma-delimited file describing the total storage of water (in mm) in all water storage compartments for each time step of the simulation. Mass balance errors, cumulative input (precipitation), and output (channel losses) are also included. Note that the precipitation rates in this file are period-ending, i.e., this is the precipitation rate for the time step preceding the time stamp; all water storage variables represent instantaneous reports of the storage at the time stamp indicate. Created by default.

- `Hydrographs.csv` (created by default)
  A comma-delimited file containing the outflow hydrographs (in m^3/s) for all subbasins specified as 'gauged' in the .rvh file. If the `:SnapshotHydrograph` command is used, this reports instantaneous flows at the end of each time step (plus the initial conditions at the start of the first time step). Without, this reports period-ending time-averaged flows for the preceding time step, as is consistent with most measured stream gauge data (again, the initial flow conditions at the start of the first time step are included). If observed hydrographs are specified, they will be output adjacent to the corresponding modelled hydrograph. Created by default.

- `RavenErrors.txt` (always created)
  A text file outlining model input errors, warnings, and advisories for the user.

- `ForcingFunctions.csv` (optional)
  A comma-delimited file containing the time series of all watershed-averaged system forcing functions (e.g., rainfall, radiation, PET, etc.). The output is all period-ending, i.e., the values reported correspond to the time-averaged forcings for the time step before the indicated time stamp. Created if `:WriteForcingFunctions` command included in .rvi file.

- `WatershedMassEnergyBalance.csv` (optional)
  A comma-delimited file describing the total cumulative fluxes of energy and water (in MJ/m^2 or mm) from all energy storage compartments for each time step of the simulation. Created if `:WriteMassBalanceFile` command included in .rvi file.

- `Parameters.csv` (optional)
  A comma-delimited file containing the values for all static specified and auto-generated parameters for all soil, vegetation, land use, and terrain classes. Created if `:WriteParametersFile` command included in .rvi file.
- `ReservoirStages.csv` (optional)
  A comma-delimited file reporting the instantaneous stage of all modeled reservoirs where the corresponding subbasin is specified as 'gauged' in the .rvh file. Created automatically if reservoirs are present in the model.
- `Demands.csv` (optional)
  A comma-delimited file containing the time series of irrigation demand, environmental minimum flow, actual flow, and unmet demand for all subbasins =specified as 'gauged' in the .rvh file. The output is all instantaneous, i.e., the reported values refer to snapshots in time. Created if `:WriteDemandFile` command is included in .rvi file.
- `{constituent}concentrations.csv` (optional)
  A comma-delimited file reporting the instantaneous watershed-averaged concentration of the transport constituent in all water storage units. Created automatically if transport is included in the model.
- `{constituent}pollutograph.csv` (optional)
  A comma-delimited file reporting the instantaneous concentration of water flowing out from all gauged subbasins. Created automatically if transport is included in the model.
- `Diagnostics.csv` (optional)
  A comma-delimited file reporting the quality of fit between model and supplied observations. Created if observations are present and the `:EvaluationMetrics` command is used.

If the `:RunName` parameter is specified in the .rvi file, this run name is pre-appended to the above filenames.

B.2 Custom Outputs

A variety of custom outputs of any state variable or mass flux in the model may be generated using the `:CustomOutput` command. See section A.1.5 for details. Note that for `CONTINUOUS` time aggregation, these custom outputs report instantaneous fluxes/states, and the forcing function rates (e.g., rainfall) will be period-ending, i.e., the average precipitation rate for the time step preceding the time stamp is reported. If the aggregation is `MONTHLY`, `YEARLY`, or `WYEARLY`, the variables reported are calculated over the entire corresponding period.

B.3 NetCDF Output Format

The .nc output hydrographs, reservoir stages, forcing functions, and custom output files are generated if the `:WriteNetcdfFormat` command is used. Currently these are the only NetCDF-format outputs available; other outputs will still be generated in .csv format.

The NetCDF files written are compatiable with NetCDF version 4.0. The contain an unlimited dimension for time. Depending upon the output file, other dimensions may include the number of sub-basins with

simulated outflow `nbasin_sim` or the number of basins with observed outflows `nbasin_obs`. All floating-point variables are written in double precision. Multiple attributes are available for each output variable, such as `units`, `long_name`, `_FillValue`, and/or `missing_value`.

The header of an example `Hydrographs.nc` containing the results of a simulation with 2 sub-basins and streamflow observations for one sub-basin starting at Oct 1st, 1991 looks like:

```
netcdf Hydrographs {
dimensions:
  time       = UNLIMITED ;
  nbasin_sim = 2 ;
  nbasin_obs = 1 ;
variables:
  double time(time) ;
    time:units               = "days since 1991-10-01 00:00:00" ;
    time:calendar            = "gregorian" ;
  double precip(time) ;
    precip:units             = "mm d**-1" ;
    precip:long_name         = "Precipitation" ;
    precip:_FillValue        = -9999. ;
    precip:missing_value     = -9999. ;
  string basin_name_sim(nbasin_sim) ;
    basin_name_sim:long_name = "ID of sub-basins with simulated outflows" ;
  double q_sim(time, nbasin_sim) ;
    q_sim:long_name          = "Simulated outflows" ;
    q_sim:units              = "m**3 s**-1" ;
    q_sim:_FillValue         = -9999. ;
    q_sim:missing_value      = -9999. ;
  string basin_name_obs(nbasin_obs) ;
    basin_name_obs:long_name = "ID of sub-basins with observed outflows" ;
  double q_obs(time, nbasin_obs) ;
    q_obs:long_name          = "Observed outflows" ;
    q_obs:units              = "m**3 s**-1" ;
    q_obs:_FillValue         = -9999. ;
    q_obs:missing_value      = -9999. ;
}
```

Appendix C

Reference Tables

Table C.1: All state variables currently available in Raven. This list of state variables is supported by the `:HydroProcesses` commands and `:CustomOutput` commands, amongst others.

State Variable	[units] Description
Required Water Storage Variables	
SURFACE_WATER	[mm] streams/rivulets - routed to outlet via in-catchment routing
ATMOSPHERE	[mm] atmosphere : receives water only!!
ATMOS_PRECIP	[mm] atmosphere : provides water only!!
PONDED_WATER	[mm] water (melt & precip) waiting to infiltrate/runoff
Water Storage	
SOIL	[mm] shallow subsurface/vadose zone
GROUNDWATER	[mm] deep groundwater
CANOPY	[mm] liquid water on vegetation canopy
CANOPY_SNOW	[mm] snow on canopy
TRUNK	[mm] water stored in trunks of trees
ROOT	[mm] water stored in roots
DEPRESSION	[mm] depression/surface storage
WETLAND	[mm] deep depression storage
LAKE_STORAGE	[mm] lake storage
SNOW	[mm] frozen snow depth (mm SWE : snow water equivalent)
SNOW_LIQ	[mm] liquid snow cover
GLACIER	[mm] glacier melt/reservoir storage
GLACIER_ICE	[mm] glacier ice - typically assumed to be infinite reservoir.
Convolution storage	
CONVOLUTION	[mm] convolution storage - for conceptual models with convolution
CONV_STOR	[mm] convolution sub-storage - internal water mass for convolution
Temperature / Energy Storage	
SURFACE_WATER_TEMP	[C] temperature of surface water
SNOW_TEMP	[C] temperature of snow
COLD_CONTENT	[C or MJ/m2] Cold content of snowpack
GLACIER_CC	[C] cold content of glacier
SOIL_TEMP	[C] temperature of soil
CANOPY_TEMP	[C] temperature of canopy
Auxilliary Variables	
SNOW_DEPTH	[mm] snow depth - surrogate for density
PERMAFROST_DEPTH	[mm] depth of permafrost
SNOW_COVER	[0..1] fractional snow cover
SNOW_AGE	[d] snow age, in days
SNOW_ALBEDO	[-] snow surface albedo
CROP_HEAT_UNITS	[-] cumulative crop heat units
Memory Variables	
CUM_INFIL	[mm] cumulative infiltration to topsoil
CUM_SNOWMELT	[mm] cumulative snowmelt
Transport Variables	
CONSTITUENT	[mg/m2] chemical species or tracer
CONSTITUENT_SRC	[mg/m2] chemical species or tracer cumulative source
CONSTITUENT_SW	[mg/m2] chemical species dumped to surface water
CONSTITUENT_SINK	[mg/m2] chemical species or tracer cumulative sink (e.g., decay)

Table C.2: All forcing functions currently available in Raven. This list of forcing functions is supported by the `:Data`, `:GriddedForcing`, `:MultiData`, `:CustomOutput`, and `:GaugeMultiData` commands, amongst others.

Forcing Name	Definition
PRECIP	rain/snow precipitaiton rate over time step /data interval [mm/d]
PRECIP_DAILY_AVE	average rain/snow precipitaiton over day (0:00-24:00) [mm/d]
PRECIP_5DAY	precipitation total from previous 5 days [mm]
SNOW_FRAC	fraction of precip that is snow [0..1]
SNOWFALL	snowfall rate over time step [mm/d]
RAINFALL	rainfall rate over time step [mm/d]
RECHARGE	groundwater recharge rate over time step [mm/d]
TEMP_AVE	average air temp over time step/data interval [$^\circ$C]
TEMP_DAILY_AVE	average air temp over day (0:00-24:00) [$^\circ$C]
TEMP_MIN/TEMP_DAILY_MIN	minimum air temperature over day (0:00-24:00)[$^\circ$C]
TEMP_MAX/TEMP_DAILY_MAX	maximum air temperature over day (0:00-24:00)[$^\circ$C]
TEMP_MONTH_MAX	maximum air temp during month [$^\circ$C]
TEMP_MONTH_MIN	minimum air temp during month [$^\circ$C]
TEMP_MONTH_AVE	average air temp during month [$^\circ$C]
TEMP_AVE_UNC	uncorrected daily average air temp [$^\circ$C]
TEMP_MAX_UNC	uncorrected daily min air temp [$^\circ$C]
TEMP_MIN_UNC	uncorrected daily max air temp [$^\circ$C]
AIR_DENS	air density [kg/m^3]
AIR_PRES	air pressure [kPa]
REL_HUMIDITY	relative humidity [0..1]
ET_RADIA	uncorrected extraterrestrial shortwave radiation [MJ/m^2/d]
SHORTWAVE/SW_RADIA	Incoming shortwave radiation (uncorrected for albedo) [MJ/m^2/d]
SW_RADIA_NET	net shortwave radiation (albedo corrected) [MJ/m^2/d]
LW_RADIA_NET	net longwave radiation [MJ/m^2/d]
LW_INCOMING	incoming longwave radiation [MJ/m^2/d]
CLOUD_COVER	cloud cover [0..1]
DAY_LENGTH	day length [d]
DAY_ANGLE	day angle [0..2PI] (=0 for Jan 1, 2pi for Dec 31)
WIND_VEL	wind velocity [m/s]
PET	potential evapotranspiration [mm/d]
OW_PET	open water potential evapotranspiration [mm/d]
PET_MONTH_AVE	average PET during month [mm/d]
POTENTIAL_MELT	potential snowmelt rate [mm/d]
SUBDAILY_CORR	a subdaily correction factor to downscale daily average PET or snowmelt [-]

Table C.3: All subbasin parameters currently available in Raven. These parameters may be specified in the :SubBasinProperties command in the .rvh file.

Parameter	[units] Description
In-catchment Routing Parameters	
TIME_TO_PEAK	[d] The time to peak of the unit hydrograph
TIME_CONC	[d] The time of concentration of the unit hydrograph
TIME_LAG	[d] The time lage of the unit hydrograph
NUM_RESERVOIRS	[-] The number of reservoirs used in the ROUTE_RESERVOIR_SERIES method
RES_CONSTANT	[1/d] A linear reservor constant used to generate the unit hydrograph
In-channel Routing Parameters	
Q_REFERENCE	[m3/s] reference flow for the reach
MANNINGS_N	[-] Manning's coefficient for the reach; overrides channel profile value
SLOPE	[-] Slope for the reach; overrides channel profile value
Other Parameters	
RAIN_CORR	[0..1] rain correction factor for subbasin (multiplier)
SNOW_CORR	[0..1] snow correction factor for subbasin (multiplier)

Appendix D

Template Files

The following section provides template .rvi files. Note that for these files and for custom model configurations, the `:CreateRVPTemplate` command in the .rvi file (see section A.1.4) can be used to generate an empty rvp file which can be populated with parameter values by the user.

To do (9)

D.1 UBCWM Emulation

```
# ------------------------------------------------------------
# Raven Template Input File
# UBC Watershed Model v5 Emulation
# ------------------------------------------------------------
:StartDate    1991-10-01 00:00:00
:Duration     365
:TimeStep     24:00:00
#
:Method              ORDERED_SERIES
:Interpolation       INTERP_NEAREST_NEIGHBOR

:Routing             ROUTE_NONE
:CatchmentRoute      ROUTE_DUMP

:Evaporation         PET_MONTHLY_FACTOR
:OW_Evaporation      PET_MONTHLY_FACTOR
:SWRadiationMethod   SW_RAD_UBCWM
:SWCloudCorrect      SW_CLOUD_CORR_UBCWM
:SWCanopyCorrect     SW_CANOPY_CORR_UBCWM
:LWRadiationMethod   LW_RAD_UBCWM
:WindspeedMethod     WINDVEL_UBCWM
:RainSnowFraction    RAINSNOW_UBCWM
:PotentialMeltMethod POTMELT_UBCWM
:OroTempCorrect      OROCORR_UBCWM
:OroPrecipCorrect    OROCORR_UBCWM2
:OroPETCorrect       OROCORR_UBCWM
:CloudCoverMethod    CLOUDCOV_UBCWM
:PrecipIceptFract    PRECIP_ICEPT_USER
```

```
:MonthlyInterpolationMethod  MONTHINT_LINEAR_21

:SoilModel          SOIL_MULTILAYER 6
:SnapshotHydrograph

# --Hydrologic Processes-------------------------
:Alias TOP_SOIL      SOIL[0]
:Alias INT_SOIL      SOIL[1]
:Alias SHALLOW_GW    SOIL[2]
:Alias DEEP_GW       SOIL[3]
:Alias INT_SOIL2     SOIL[4]
:Alias INT_SOIL3     SOIL[5]
:HydrologicProcesses
   :SnowAlbedoEvolve  SNOALB_UBCWM
   :SnowBalance       SNOBAL_UBCWM     MULTIPLE      MULTIPLE
   # moves snowmelt to fast runoff
   :Flush             RAVEN_DEFAULT    PONDED_WATER  INT_SOIL2
     :-->Conditional    HRU_TYPE IS GLACIER
   :GlacierMelt       GMELT_UBC        GLACIER_ICE   PONDED_WATER
   :Precipitation     PRECIP_RAVEN     ATMOS_PRECIP  MULTIPLE
   :SoilEvaporation   SOILEVAP_UBC     MULTIPLE      ATMOSPHERE
   :Infiltration      INF_UBC          PONDED_WATER  MULTIPLE
   # from infiltration to routing
   :Flush             RAVEN_DEFAULT    SURFACE_WATER INT_SOIL2
   :GlacierInfiltration GINFIL_UBCWM   PONDED_WATER  MULTIPLE
   # soils really used as routing stores
   :Percolation       PERC_LINEAR_ANALYTIC INT_SOIL  INT_SOIL2
   :Percolation       PERC_LINEAR_ANALYTIC INT_SOIL2 INT_SOIL3
   :Baseflow          BASE_LINEAR      INT_SOIL3     SURFACE_WATER
   :Baseflow          BASE_LINEAR      SHALLOW_GW    SURFACE_WATER
   :Baseflow          BASE_LINEAR      DEEP_GW       SURFACE_WATER
   :GlacierRelease    GRELEASE_LINEAR  GLACIER       SURFACE_WATER
:EndHydrologicProcesses
```

See the Alouette tutorial example for a template .rvp file for UBCWM emulation, indicating all required parameters.

D.2 HBV-EC Emulation

```
# ------------------------------------------
# Raven Input file
# HBV-EC Emulation
# ------------------------------------------
# --Simulation Details ------------------------
:StartDate    1991-10-01 00:00:00
:Duration     365
:TimeStep     1.0
#
# --Model Details -----------------------------
:Method              ORDERED_SERIES
:Interpolation       INTERP_NEAREST_NEIGHBOR

:Routing             ROUTE_NONE
:CatchmentRoute      ROUTE_TRI_CONVOLUTION

:Evaporation         PET_FROMMONTHLY
:OW_Evaporation      PET_FROMMONTHLY
:SWRadiationMethod   SW_RAD_DEFAULT
:SWCloudCorrect      SW_CLOUD_CORR_NONE
:SWCanopyCorrect     SW_CANOPY_CORR_NONE
:LWRadiationMethod   LW_RAD_DEFAULT
:RainSnowFraction    RAINSNOW_HBV
:PotentialMeltMethod POTMELT_HBV
:OroTempCorrect      OROCORR_HBV
:OroPrecipCorrect    OROCORR_HBV
:OroPETCorrect       OROCORR_HBV
:CloudCoverMethod    CLOUDCOV_NONE
:PrecipIceptFract    PRECIP_ICEPT_USER
:MonthlyInterpolationMethod  MONTHINT_LINEAR_21

:SoilModel           SOIL_MULTILAYER 3

# an oddity unique to HBV:
:LakeStorage SLOW_RESERVOIR

# --Hydrologic Processes-------------------------
:Alias       FAST_RESERVOIR SOIL[1]
:Alias       SLOW_RESERVOIR SOIL[2]
:HydrologicProcesses
  :SnowRefreeze      FREEZE_DEGREE_DAY  SNOW_LIQ        SNOW
  :Precipitation     PRECIP_RAVEN       ATMOS_PRECIP    MULTIPLE
  :CanopyEvaporation CANEVP_ALL         CANOPY          ATMOSPHERE
  :CanopySnowEvap    CANEVP_ALL         CANOPY_SNOW     ATMOSPHERE
  :SnowBalance       SNOBAL_SIMPLE_MELT SNOW            SNOW_LIQ
    :-->Overflow     RAVEN_DEFAULT      SNOW_LIQ        PONDED_WATER
  :Flush             RAVEN_DEFAULT      PONDED_WATER    GLACIER
    :-->Conditional HRU_TYPE IS GLACIER
  :GlacierMelt       GMELT_HBV          GLACIER_ICE     GLACIER
  :GlacierRelease    GRELEASE_HBV_EC    GLACIER         SURFACE_WATER
  :Infiltration      INF_HBV            PONDED_WATER    MULTIPLE
  :Flush             RAVEN_DEFAULT      SURFACE_WATER   FAST_RESERVOIR
```

```
    :-->Conditional HRU_TYPE IS_NOT GLACIER
  :SoilEvaporation   SOILEVAP_HBV       SOIL[0]         ATMOSPHERE
  :CapillaryRise     RISE_HBV           FAST_RESERVOIR  SOIL[0]
  :LakeEvaporation   LAKE_EVAP_BASIC    SLOW_RESERVOIR  ATMOSPHERE
  :Percolation       PERC_CONSTANT      FAST_RESERVOIR  SLOW_RESERVOIR
  :Baseflow          BASE_POWER_LAW     FAST_RESERVOIR  SURFACE_WATER
  :Baseflow          BASE_LINEAR        SLOW_RESERVOIR  SURFACE_WATER
:EndHydrologicProcesses
#
:AggregatedVariable FAST_RESERVOIR AllHRUs
:AggregatedVariable SLOW_RESERVOIR AllHRUs
```

See the Alouette2 tutorial example for a template .rvp file for HBV-EC emulation, indicating all required parameters.

D.3 GR4J Emulation

```
# ------------------------------------------
# Raven Input file
# GR4J Emulation
# ------------------------------------------
:StartDate           2000-01-01 00:00:00
:Duration            365
:TimeStep            1.0

:Method              ORDERED_SERIES
:Interpolation       INTERP_NEAREST_NEIGHBOR

:Routing             ROUTE_NONE
:CatchmentRoute      ROUTE_DUMP

:Evaporation         PET_DATA
:RainSnowFraction    RAINSNOW_DINGMAN
:PotentialMeltMethod POTMELT_DEGREE_DAY
:OroTempCorrect      OROCORR_SIMPLELAPSE
:OroPrecipCorrect    OROCORR_SIMPLELAPSE

:SoilModel           SOIL_MULTILAYER  4

# --Hydrologic Processes-------------------------
:Alias PRODUCT_STORE      SOIL[0]
:Alias ROUTING_STORE      SOIL[1]
:Alias TEMP_STORE         SOIL[2]
:Alias GW_STORE           SOIL[3]
:HydrologicProcesses
 :Precipitation         PRECIP_RAVEN       ATMOS_PRECIP    MULTIPLE
 :SnowTempEvolve        SNOTEMP_NEWTONS    SNOW_TEMP
 :SnowBalance           SNOBAL_CEMA_NEIGE  SNOW             PONDED_WATER
 :OpenWaterEvaporation  OPEN_WATER_EVAP    PONDED_WATER    ATMOSPHERE
 :Infiltration          INF_GR4J           PONDED_WATER    MULTIPLE
 :SoilEvaporation       SOILEVAP_GR4J      PRODUCT_STORE   ATMOSPHERE
 :Percolation           PERC_GR4J          PRODUCT_STORE   TEMP_STORE
 :Flush                 RAVEN_DEFAULT      SURFACE_WATER   TEMP_STORE
 :Split          RAVEN_DEFAULT TEMP_STORE  CONVOLUTION[0]
CONVOLUTION[1] 0.9
 :Convolve              CONVOL_GR4J_1      CONVOLUTION[0]  ROUTING_STORE
 :Convolve              CONVOL_GR4J_2      CONVOLUTION[1]  TEMP_STORE
 :Percolation           PERC_GR4JEXCH      ROUTING_STORE   GW_STORE
 :Percolation           PERC_GR4JEXCH2     TEMP_STORE      GW_STORE
 :Flush                 RAVEN_DEFAULT      TEMP_STORE      SURFACE_WATER
 :Baseflow              BASE_GR4J          ROUTING_STORE   SURFACE_WATER
:EndHydrologicProcesses
```

See the Irondequoit tutorial example for a template .rvp file for GR4J emulation, indicating all required parameters.

D.4 Canadian Shield Configuration

A useful configuration in Canadian shield basins characterised by shallow soils atop rock, with ample exposed rock and lakes. Use the `:CreateRVPTemplate` command to generate the corresponding .rvp template file and determine what parameters are needed.

```
:StartDate           2003-10-01 00:00:00
:Duration            2192
:TimeStep            1.0

:Method              ORDERED_SERIES
:InterpolationMethod NEAREST_NEIGHBOR

:SoilModel           SOIL_MULTILAYER  3

:Routing             ROUTE_DIFFUSIVE_WAVE
:CatchmentRoute      ROUTE_TRI_CONVOLUTION
:Evaporation         PET_HARGREAVES_1985
:OW_Evaporation      PET_HARGREAVES_1985
:SWCanopyCorrect     SW_CANOPY_CORR_STATIC
:RainSnowFraction    RAINSNOW_DINGMAN
:PotentialMeltMethod POTMELT_DEGREE_DAY
:PrecipIceptFract    PRECIP_ICEPT_LAI

:MonthlyInterpolationMethod MONTHINT_LINEAR_MID

:LakeStorage LAKE_STORAGE

# --Hydrologic Processes-------------------------
:Alias       SOIL0 SOIL[0]
:Alias       SOIL1 SOIL[1]
:Alias       SOIL2 SOIL[2]
:HydrologicProcesses
    :SnowRefreeze       FREEZE_DEGREE_DAY SNOW_LIQ      SNOW
    :Precipitation      PRECIP_RAVEN      ATMOS_PRECIP  MULTIPLE
    :CanopyEvaporation  CANEVP_MAXIMUM    CANOPY        ATMOSPHERE
    :CanopySnowEvap     CANEVP_MAXIMUM    CANOPY_SNOW   ATMOSPHERE
    :SnowBalance        SNOBAL_TWO_LAYER  MULTIPLE      MULTIPLE
    :Abstraction        ABST_FILL         PONDED_WATER  DEPRESSION
    :OpenWaterEvaporation OPEN_WATER_EVAP DEPRESSION    ATMOSPHERE
    :Infiltration       INF_HBV           PONDED_WATER  MULTIPLE
    :LakeRelease        LAKEREL_LINEAR    LAKE_STORAGE  SURFACE_WATER
    :Baseflow           BASE_POWER_LAW    SOIL1         SURFACE_WATER
    :Baseflow           BASE_POWER_LAW    SOIL2         SURFACE_WATER
    :Interflow          INTERFLOW_PRMS    SOIL0         SURFACE_WATER
    :Percolation        PERC_GAWSER       SOIL0         SOIL1
    :Percolation        PERC_GAWSER       SOIL1         SOIL2
    :SoilEvaporation    SOILEVAP_ROOT     SOIL0         ATMOSPHERE
:EndHydrologicProcesses
```

D.5 MOHYSE Configuration

A simple educational model developed at the Université du Québec à Montréal (Fortin and Turcotte, 2006) . Use the `:CreateRVPTemplate` command to generate the corresponding .rvp template file and determine what parameters are needed.

```
:StartDate              1958-08-01 00:00:00
:EndDate                2003-09-30 00:00:00
:TimeStep               1.0
:Method                 ORDERED_SERIES

:Routing                ROUTE_NONE
:CatchmentRoute         ROUTE_GAMMA_CONVOLUTION

:PotentialMeltMethod    POTMELT_DEGREE_DAY
:Evaporation            PET_MOHYSE
:RainSnowFraction       RAINSNOW_DATA
:DirectEvaporation

:SoilModel              SOIL_TWO_LAYER

:HydrologicProcesses
  :SoilEvaporation  SOILEVAP_LINEAR    SOIL[0]       ATMOSPHERE
  :SnowBalance      SNOBAL_SIMPLE_MELT SNOW          PONDED_WATER
  :Precipitation    RAVEN_DEFAULT      ATMOS_PRECIP  MULTIPLE
  :Infiltration     INF_HBV            PONDED_WATER  SOIL[0]
  :Baseflow         BASE_LINEAR        SOIL[0]       SURFACE_WATER
  :Percolation      PERC_LINEAR        SOIL[0]       SOIL[1]
  :Baseflow         BASE_LINEAR        SOIL[1]       SURFACE_WATER
:EndHydrologicProcesses
```

See the MOHYSE model example file distributed with the Raven tutorials for a template .rvp file for MOHYSE emulation, indicating all required parameters.

D.6 HMETS Configuration

HMETS is a relatively simple model developed at the École de technologie supérieure (Martel et al., 2017). You may use the `:CreateRVPTemplate` command to generate the corresponding .rvp template file and determine what parameters are needed.

```
:StartDate 1953-01-01  00:00:00
:EndDate   2009-12-31 00:00:00
:TimeStep   24:00:00

:PotentialMeltMethod     POTMELT_HMETS
:RainSnowFraction        RAINSNOW_DATA
:Evaporation             PET_OUDIN

:CatchmentRoute          ROUTE_DUMP
:Routing                 ROUTE_NONE

:SoilModel               SOIL_TWO_LAYER

:HydrologicProcesses
 :SnowBalance     SNOBAL_HMETS   MULTIPLE     MULTIPLE
 :Precipitation   RAVEN_DEFAULT  ATMOS_PRECIP MULTIPLE
 :Infiltration    INF_HMETS      PONDED_WATER MULTIPLE
   :Overflow      OVERFLOW_RAVEN SOIL[0]      CONVOLUTION[1]
 :Baseflow        BASE_LINEAR    SOIL[0]      SURFACE_WATER #interflow
 :Percolation     PERC_LINEAR    SOIL[0]      SOIL[1]       #recharge
   :Overflow      OVERFLOW_RAVEN SOIL[1]      CONVOLUTION[1]
 :SoilEvaporation SOILEVAP_ALL   SOIL[0]      ATMOSPHERE      #AET
 :Convolve        CONVOL_GAMMA   CONVOLUTION[0] SURFACE_WATER #surf. runoff
 :Convolve        CONVOL_GAMMA_2 CONVOLUTION[1] SURFACE_WATER #delay. runoff
 :Baseflow        BASE_LINEAR    SOIL[1]      SURFACE_WATER
:EndHydrologicProcesses
```

See the Salmon model example file distributed with the Raven tutorials for a template .rvp file for HMETS emulation, indicating all required parameters.

D.7 HYPR Configuration

HYPR is a version of HBV revised to support simulation on the Canadian Prairies (Ahmed et al., 2020). You may use the `:CreateRVPTemplate` command to generate the corresponding .rvp template file and determine what parameters are needed.

```
:StartDate          2002-10-01 00:00:00
:EndDate            2015-08-31 00:00:00
:Duration           4718
:TimeStep           24:00:00

# Model options
#------------------------------------------------------------------------
:CatchmentRoute      TRIANGULAR_UH

:Evaporation         PET_FROMMONTHLY
:OW_Evaporation      PET_FROMMONTHLY
:SWRadiationMethod   SW_RAD_DEFAULT
:LWRadiationMethod   LW_RAD_DEFAULT
:RainSnowFraction    RAINSNOW_HBV
:PotentialMeltMethod POTMELT_HBV
:PrecipIceptFract    PRECIP_ICEPT_USER
:MonthlyInterpolationMethod  MONTHINT_LINEAR_21
:SoilModel           SOIL_MULTILAYER 3

# Soil Layer Alias Definitions
#------------------------------------------------------------------------
:Alias       FAST_RESERVOIR SOIL[1]
:Alias       SLOW_RESERVOIR SOIL[2]


# Hydrologic process order for HYPR Emulation
#------------------------------------------------------------------------
:HydrologicProcesses
  :SnowRefreeze      FREEZE_DEGREE_DAY  SNOW_LIQ        SNOW
  :Precipitation     PRECIP_RAVEN       ATMOS_PRECIP    MULTIPLE
  :CanopyEvaporation CANEVP_ALL         CANOPY          ATMOSPHERE
  :CanopySnowEvap    CANEVP_ALL         CANOPY_SNOW     ATMOSPHERE
  :SnowBalance       SNOBAL_SIMPLE_MELT SNOW            PONDED_WATER
  :Infiltration      INF_HBV            PONDED_WATER    MULTIPLE
  :Flush             RAVEN_DEFAULT      SURFACE_WATER   PONDED_WATER
  :Abstraction       ABST_PDMROF        PONDED_WATER    DEPRESSION
  :Flush             RAVEN_DEFAULT      SURFACE_WATER   FAST_RESERVOIR
  :SoilEvaporation   SOILEVAP_HYPR      MULTIPLE        ATMOSPHERE
  :Baseflow          BASE_LINEAR        FAST_RESERVOIR  SURFACE_WATER
  :Baseflow          BASE_THRESH_STOR   FAST_RESERVOIR  SURFACE_WATER
:EndHydrologicProcesses
```

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To do...

- ☐ 1 (p. 38): Add PERC ASPEN routine / parameter
- ☐ 2 (p. 65): Add unit hydrograph intercomparison figure
- ☐ 3 (p. 67): find RobertsonEtAl1995 reference
- ☐ 4 (p. 68): Muskingum citations
- ☐ 5 (p. 80): Sub-daily temperature orographic and lapsing temp ranges not yet described
- ☐ 6 (p. 101): SUBDAILY_UBC description
- ☐ 7 (p. 117): Forcing estimator code development section
- ☐ 8 (p. 137): Create a table for 'Required Parameters for Hydrologic Processes Options'
- ☐ 9 (p. 189): Report default Raven "vanilla" configuration