

Penn State Integrated Hydrologic Model(PIHM)

Technical Documentation

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1 Overview

This is the technical documentation of the PIHM system (PIHM and PIHMgisR).

PIHM The Penn State Integrated Hydrologic Model (PIHM) is a multiprocess, multi-scale hydrologic model where the major hydrological processes are fully coupled using the semi-discrete Finite Volume Method.

PIHMGIS The model itself is “tightly-coupled” with PIHMgis, an open-source Geographical Information System designed for PIHM. The PIHMgis provides access to the digital data sets (terrain, forcing and parameters) and tools necessary to drive the model, as well as a collection of GIS-based pre- and post-processing tools.

Collectively the system is referred to as the **Penn State Integrated Hydrologic Modeling System (PIHMS)**.

The PIHM is an open source software, freely available for download at PIHM website or Github Page along with installation and user guides.

1.1 Why PIHM?

It is our intention to begin a debate on the role of *Community Models* in the hydrologic sciences. Our research is a response to recent trends in US funding for *Observatory Science* that have emerged at NSF over the last few years, namely, the NSF-funded **CUAHSI** program (Consortium of Universities for Advancing Hydrologic Sciences).

PIHM represents our strategy for the synthesis of *multi-state, multiscale* distributed hydrologic models using the integral representation of the underlying physical process equations and state variables.

Our interest is in devising a concise representation of watershed and/or river basin hydrodynamics, which allows interactions among major physical processes operating simultaneously, but with the flexibility to add or eliminate states/processes/constitutive relations depending on the objective of the numerical experiment or purpose of the scientific or operational application.

To satisfy the objectives, the PIHM

- is distributed hydrologic model, based on the semi-discrete **Finite Volume Method (FVM)** in which domain discretization is an unstructured triangular irregular network (e.g. Delaunay triangles) generated with constraints (geometric,

and parametric). A local prismatic control volume is formed by the vertical projection of the Delaunay triangles forming each layer of the model. Given a set of constraints (e.g. river network support, watershed boundary, altitude zones, ecological regions, hydraulic properties, climate zones, etc), an “optimal” mesh is generated. River volume elements are also prismatic, with trapezoidal or rectangular cross-section, and are generated along or cross edges of Delaunay triangles. The local control volume contains all equations to be solved and is referred to as the model kernel.

- is a physically-based model, in which all equations used are describing the physics of the hydrological processes which control the catchment. The physical model is able to predict the water in the ungage water system, to estimate the sediment, pullutants, and vegetation, etc, such that it is practical to be coupled with biochemistry, geomorphology, limnology, and other water-related research. The global ODE system is assembled by combining all local ODE systems throughout the domain and then solved by a state-of-the-art parallel ODE solver known as CVODE developed at the Lawrence Livermore National Laboratory.
- is a fully-coupled hydrologic model, where the state and flux variables in the hydrologic system are solved within the same time step and conserve the mass. The fluxes are infiltration, overland flow, groundwater recharge, lateral groundwater flow, exchange of river and soil/groundwater and river discharge.
- is of an adaptable temporal and spatial resolution. The spatial resolution of the model varies from meters to kilometers based requirement of modeling and computing resources. The internal time step of the iteration step is adjustable; it is able to export the status of the catchment in less 1 second to days. Also, the time interval for exporting results is configured flexibly. The flexible spatial and temporal resolution is rather valuable for community model coupling.
- is an open source model, anyone can access the source code, use and submit their improvement.
- is a long-term yield and single-event flood model.

An important partnership and motivation for this work was the Project Leaders participation in two community-science research activities over the last few years: The University of Arizona-led Science and Technology Center (SAHRA: Sustainability of Water Resources in Semi-Arid Regions), and the Chesapeake Community Modeling Project (CCMP). Each of these research programs has been essential in supporting the concept of **Community Models** for environmental prediction and helping to make it happen.

1.2 History of PIHM system

- 2005 PIHM v1.0

Dr. Yizhong Qu (Qu and Duffy, 2007) developed and verified the first version of PIHM in 2001-2005 during his Ph.D. in Pennsylvania State University, following the blueprint

of Freeze and Harlan (1969). This version of PIHM is the soul of the PIHM model.

- 2009 PIHMgis

Dr. Gopal Bhartt (Bhatt, 2012) developed the PIHMgis with support of C++, Qt GUI library, TRIANGLE library, and QGIS developing kit. The development of PIHMgis makes the learning curve of PIHM moderate and benefits the developing, modeling and coupling.

- 2015 MM-PIHM

Dr. Yuninh Shi led and developed the MM-PIHM (Multi-Module PIHM), which embedded all modules from PIHM family, such as RT-PIHM, LE-PIHM, flux-PIHM, BGC-PIHM, etc. together. The sophisticated design and coupling of the MM-PIHM is the summit of the PIHM as a *Community Model* that combined all water-related modules together.

- 2019 PIHM++

Based on the accumulated contribution of PIHM modeling and coupling with related researches, it is necessary to solve the known bugs and limitations, improve the performance of the model with parallel methods, and adopt new updates from SUNDIALS solver and programming strategy.

Several publications that may helps:

- (Qu, 2004)
- (Qu and Duffy, 2007)
- (Li, 2008)
- (Kumar et al., 2004)
- (Kumar et al., 2009)
- (Yu et al., 2015)
- (Yu et al., 2014)
- (Li and Duffy, 2011)
- (Shi et al., 2015a)
- (Shi et al., 2015b)
- (Bhatt et al., 2014)

1.3 Steps of PIHM modeling

1.3.1 Essential Terrestrial Variables?

- Atmospheric forcing (precipitation, snow cover, wind, relative humidity, temperature, net radiation, albedo, photosynthetic atmospheric radiation, leaf area index)
- Digital elevation model (DEM)
- River/stream discharge

1 Overview

- Soil (class, hydrologic properties)
- Groundwater (levels, extent, hydro-geologic properties)
- Lake/Reservoir (levels, extent)
- Land cover and land use (biomass, human infrastructure, demography, ecosystem disturbance)
- Water use

Most data reside on federal serversmany petabytes

1.3.2 A-Priori Data Sources

Feature/Time-Series	Property	Source
Soil	Porosity; Sand, Silt, Clay Fractions; Bulk Density	CONUS, SSURGO and STATSGO
Geology	Bed Rock Depth; Horizontal and Vertical Hydraulic Conductivity	http://www.dcnr.state.pa.us/topogeo/ , http://www.lias.psu.edu/emsl/guides/X.html
Land Cover	LAI	UMC, LDASmapveg;
Land Cover	Manning's Roughness;	Hernandez et. al., 2000
River	Manning's Roughness;	Dingman (2002)
River	Coefficient of Discharge	ModHms Manual (Panday and Huyakorn, 2004)
River	Shape and Dimensions;	Derived from regression using depth, width, and discharge data from USGS data
River	Topology: Nodes, Neighboring Elements;	Derived using PIHMgis (Bhatt et. al., 2008)
Forcing	Prec, Temp. RH, Wind, Rad.	National Land Data Assimilation System: NLDAS-2
Topography	DEM	http://seamless.usgs.gov/
Streamflow		http://nwis.waterdata.usgs.gov/nwis/sw

1.3 Steps of PIHM modeling

Feature/Time-Series	Property	Source
Groundwater		http://nwis.waterdata.usgs.gov/nwis/gw

2 Workflow of PIHM System

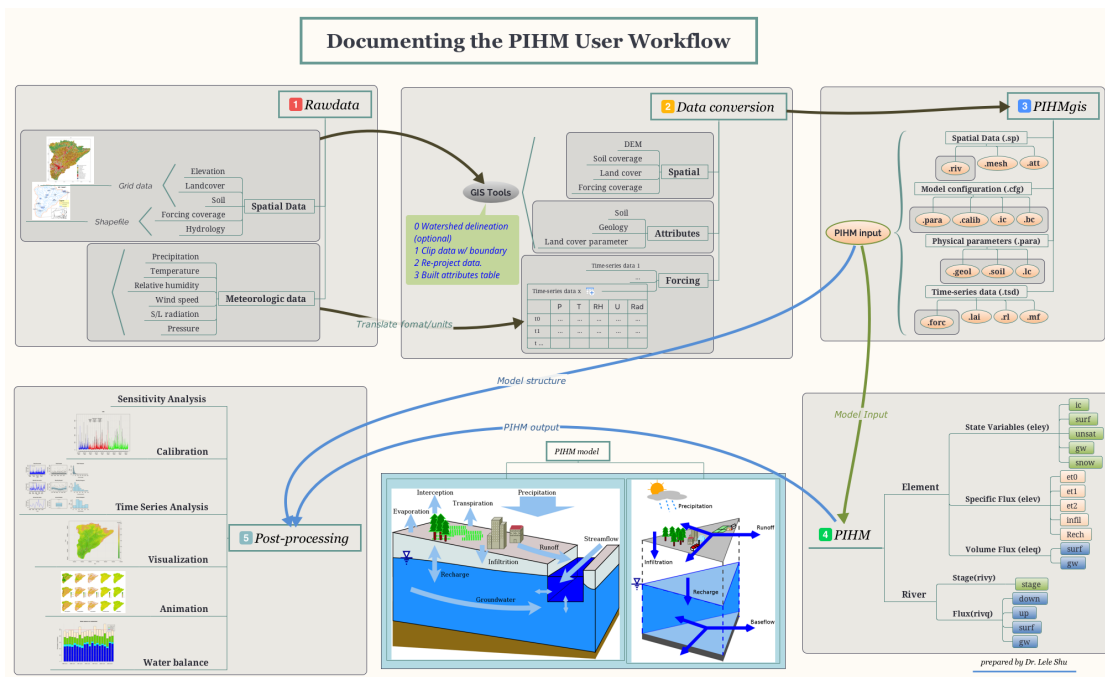


Figure 2.1: The workflow of modeling with PIHM System

1. Prepare raw Essential Terrestrial Variables (ETV)
2. Convert and crop raw data with the research area boundary.
3. Build the PIHM modeling domain with PIHMgis or PIHMgisR (Recommended for PIHM++)
4. Run PIHM on desktop or cluster.
5. Analysis the PIHM results with PIHMgisR or your hydrologic analysis tools.

3 Install PIHM and PIHMgisR

3.1 SUNDIALS/CVODE

The PIHM model requires the support of SUNDIALS or CVODE library. **SUNDIALS** is a SUite of Nonlinear and Differential/ALgebraic equation Solvers, consists of six solvers. **CVODE** is a solver for stiff and nonstiff ordinary differential equation (ODE) systems (initial value problem) given in explicit form $y' = f(t, y)$. The methods used in CVODE are variable-order, variable-step multistep methods. You can install the entire SUNDIALS suite or CVODE only.

Since the SUNDIALS/CVODE keeps updating periodically and significantly, the function names and structure are changed accordingly, we suggest to use the specific version of the solver, rather than the latest solver.

PIHM Version	SUNDIALS/CVODE version
PIHM v1.x	v2.2 ~ v2.4
PIHM v2.x	v2.2 ~ v2.4
PIHM v3.x	v2.2 ~ v2.4
MM-PIHM v1.x	v2.4
PIHM++ v4.x	v3.x

SUNDIALS/CVODE is available in LLNL: <https://computation.llnl.gov/projects/sundials/sundials-software>

The installation of CVODE v3.x:

1. Go to your Command Line and enter your workspace and unzip your CVODE source code here.
2. make directories for CVODE, including *builddir*, *instdir* and *srcdir*

```
mkdir builddir
mkdir instdir
mkdir srcdir
cd builddir/
```

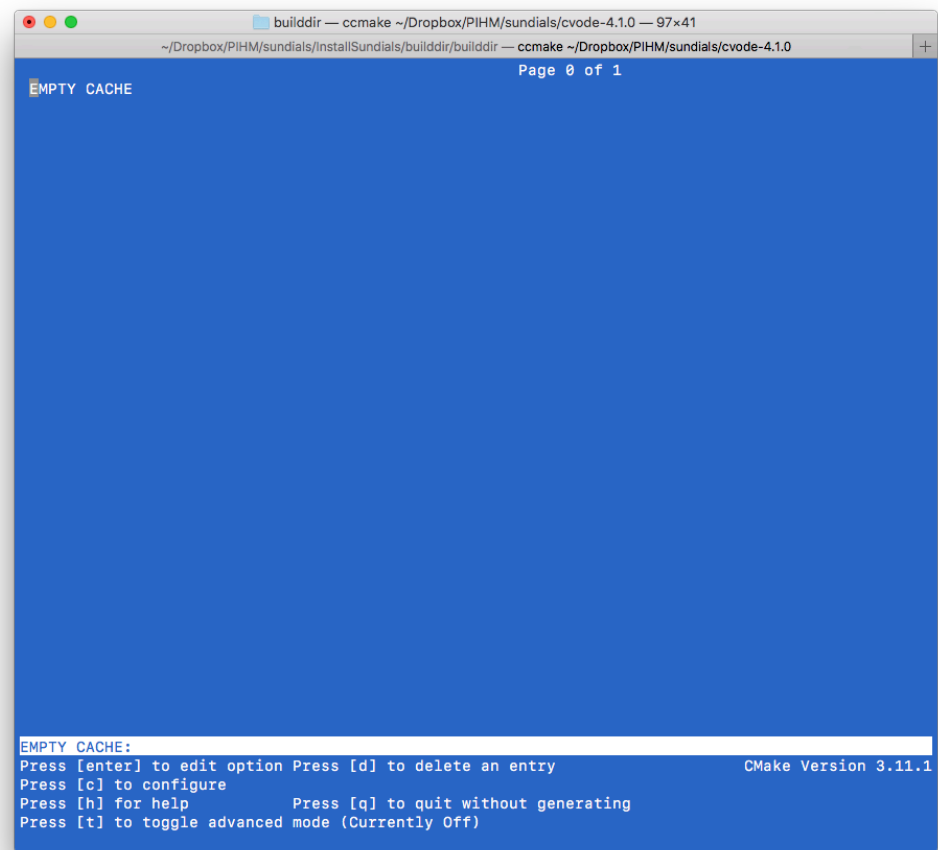
3. Try cmake. Install **cmake** if you don't have one.

```
cmake
```

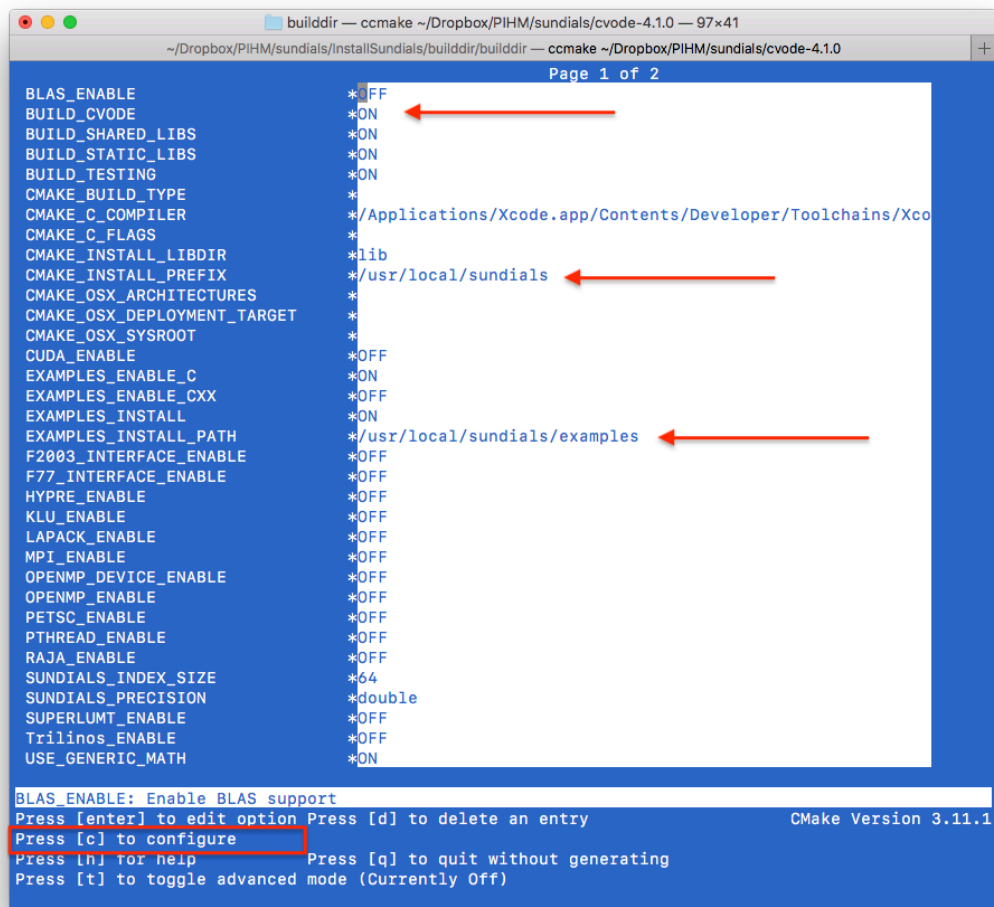
3 Install PIHM and PIHMgisR

4. Run cmake to configure your compile environment.

```
ccmake /Users/leleshu/Dropbox/PIHM/sundials/cvode-4.1.0
```



This is an empty configure. Press **c** to start the configuration.

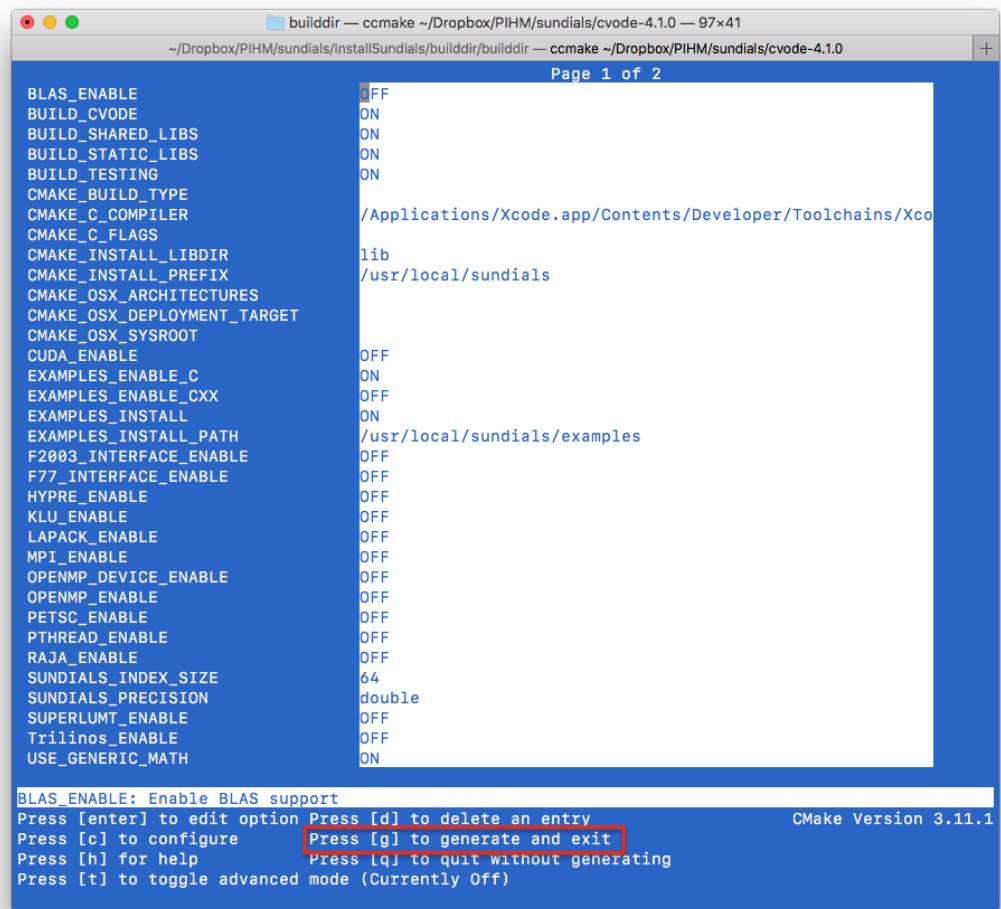


The default configuration. Make sure the value for three lines:

```
BUILD_CVODE = ON
CMAKE_INSTALL_PREFIX = /usr/local/sundials
EXAMPLES_INSTALL_PATH = /usr/local/sundials/examples
```

After the modification of values, press **c** to confirm configuration.

3 Install PIHM and PIHMgisR



The cmake configures the environment automatically. When the configuration is ready, press **g** to generate and exit.

1. Then you run commands below:

```
make
make install
```

2. Optional library copy Sometimes, the code might not find the right library support in your system, try to copy the library in sundials folder to your system library folder.

```
cp /usr/local/sundials/lib/* /usr/local/lib/
```


3.2 PIHM

Configuration in *Makefile*:

1. Path of *SUNDIALS_DIR*. [**CRITICAL**]
2. Path of OpenMP if the parallel is preferred.
3. Path of *SRC_DIR*, default is *SRC_DIR* = .
4. Path of *BUILT_DIR*, default is *BUILT_DIR* = .

After updating the SUNDIALS path in the *Makefile*, user can compile the PIHM with:

```
make clean
make pihm
```

There are more options to compile the PIHM code:

- `make all` - make both `pihm` and `pihm_omp`
- `make pihm` - make `pihm` executable
- `make pihm_omp` - make `pihm_omp` with OpenMP support
- `make calib_mpi` - make `calib_mpi` with MPI support
- `make calib_omp` - make `calib_omp` with OpenMP support

3.2.1 OpenMP

If parallel-computing is preferred, please install OpenMP. For mac:

```
brew install llvm clang
brew install libomp
compile flags for OpenMP:
-Xpreprocessor -fopenmp -lomp
Library/Include paths:
-L/usr/local/opt/libomp/lib
-I/usr/local/opt/libomp/include
```

3.2.2 Run pihm executables.

After the successful installation and compile, you can run PIHM models using

```
./pihm <projectname>
```

3 Install PIHM and PIHMgisR

```
#####  #### ##  ##  ##  ##  #
##  ##  ##  ##  ##  ###  ###  #
##  ##  ##  ##  ##  ###  ###  # #####
#####  ##  #####  ##  ###  ##  #  #
##  ##  ##  ##  ##  ##  #####  #
##  ##  ##  ##  ##  ##  #  #
##  #####  ##  ##  ##  ##  # Verion 4.0

      The Penn State Integrated Hydrologic Model v4.0

openMP disabled.

Usage: ./pihm [-p projectfile] [-o output_folder] [-n Num_Threads] <project name>

-o output folder. Default is output/projname.out
-p projectfile, which include the path for each input and output path.
-n Number of threads to run with OpenMP for pihm++ or calib_omp.
```

Command line pattern is:

```
./pihm [-p projectfile] [-o output_folder] [-n Num_Threads] <project name>
```

- <project name> is the name of the project
- [-p projectfile]
- [-o output_folder] is to write all model output variables in the specified output directory
- [-n Num_Threads] is number of OpenMP threads, which works with `pihm_omp` only.

When the `pihm++` program starts to run, the screen should look like this:

```

#####  #####  ##      ##  ##      ##      #
##      ##  ##  ##      ##  #####  #####  #
##      ##  ##  ##      ##  #####  #####  #  #####
#####  ##  #####  ##  ##  ##  #  #
##      ##  ##  ##  ##  ##  ##  #####  #
##      ##  ##  ##  ##  ##  ##  #
##      #####  ##  ##  ##  ##  # Verion 4.0

The Penn State Integrated Hydrologic Model v4.0

openMP disabled.
* Project name: sh
* Project input folder: input/sh
* Project output folder: output/sh.out
1 Reading file: input/sh/sh.cfg.para
2 Reading file: input/sh/sh.sp.riv
The downstream of RIV 3 is negtive
3 Reading file: input/sh/sh.sp.rivchn
4 Reading file: input/sh/sh.sp.mesh
5 Reading file: input/sh/sh.sp.att
6 Reading file: input/sh/sh.para.soil
7 Reading file: input/sh/sh.para.geol
8 Reading file: input/sh/sh.para.lc
9 Reading file: input/sh/sh.tsd.forc
10 Reading file: input/sh/sh.tsd.lai
11 Reading file: input/sh/sh.tsd.rl
12 Reading file: input/sh/sh.tsd.mf
13 Reading file: input/sh/sh.cfg.calib

Initializing data structure ...

```

3.3 PIHMgisR

This PIHMgisR is an R package. What you need is to install the package as a source code package. For example:

```
install_github('shulele/PIHMgisR')
```

That is all you need to deploy the PIHMgisR.

4 Input files

List of input files:

File	Category	Comments	Header	# of column
.mesh	sp	Domain element (triangular mesh)	Yes	
.att	sp	Attribute table of triangular elements	Yes	
.riv	sp	Rivers	Yes	
.rivchn	sp	Topologic relation b/w River and Element	Yes	
.calib	cfg	Calibration on physical parameters	Yes	
.para	cfg	Parameters of the model configurature	Yes	
.ic	cfg	Intial conditions	Yes	
.geol	para	Physical parameters for Geology layers	Yes	
.soil	para	Physical parameters for Soil layers	Yes	
.lc	para	Physical parameters for Land cover layers	Yes	
.forc	tsd	List of files to the Time-series forcing data	Yes	
.csv	tsd	Time-series forcing data	Yes	
.lai	tsd	Time-series LAI data	Yes	
.obs	tsd	Time-series observational data for calibration purpose only	Yes	
.mf	tsd	Time-series Melt Factor data	Yes	
.rl	tsd	Time-series Roughness Length data	Yes	
gis/domain	Shapefile	Shapefile of .mesh file	x	x
gis/river	Shapefile	Shapefile of .riv file	x	x
gis/seg	Shapefile	Shapefile of .rivchn file	x	x

The files in folder *gis* and *fig* are not involved in PIHM modeling, but they are very useful for your data pre- and post-processing.

4 Input files

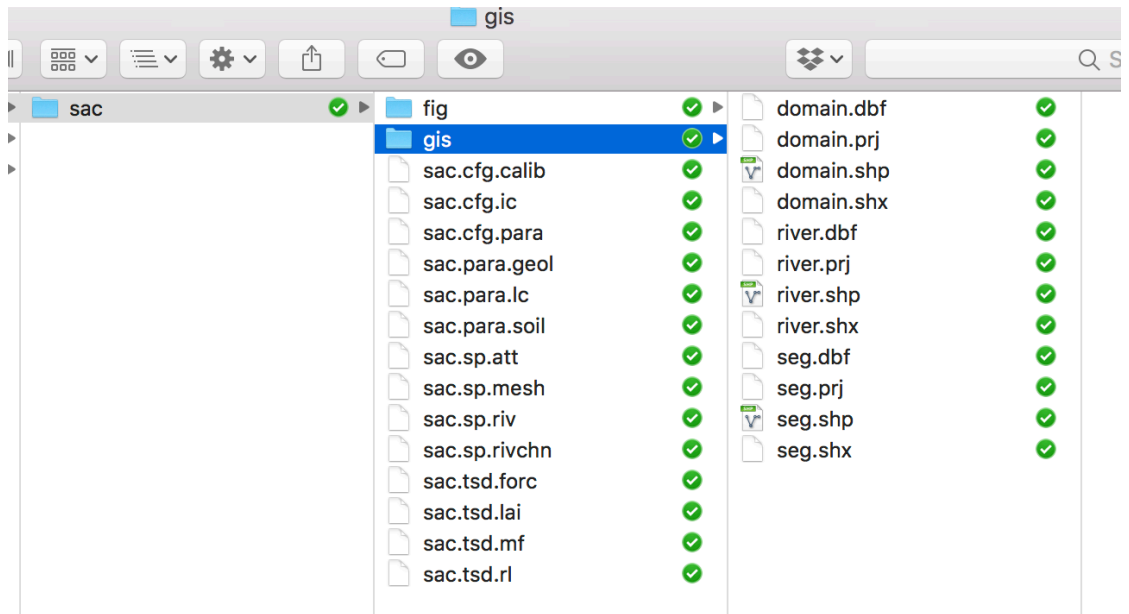


Figure 4.1: The screenshot of input files for PIHM++

4.1 Spatial data

4.1.1 .sp.mesh file

```

1 854 8
2 ID Node1 Node2 Node3 Nabr1 Nabr2 Nabr3 Zmax
3 1 278 340 342 595 594 563 22.22
4 2 86 84 88 93 77 68 71.47
5 3 429 23 428 760 758 757 16
6 4 427 465 429 756 820 757 12.83
7 5 113 10 103 140 0 116 63.35
8 6 458 453 457 825 802 812 9.31
9 7 107 73 105 129 143 142 15.16
10 8 67 102 122 23 175 596 15.84
11 9 28 98 471 0 835 798 9
12 10 120 123 122 176 178 138 20.09
13 11 5 65 66 34 13 78 77.09
14 12 55 274 470 466 834 833 61.72
15 13 60 66 65 56 11 87 75.81
16 14 467 71 466 828 827 829 48.95
17 15 453 443 451 817 130 802 11.42
18 16 337 339 123 590 597 177 21.11
19 17 19 17 320 18 559 843 32.24
20 18 17 19 18 17 0 0 31.98
21 19 211 217 201 363 356 325 34.39
22 20 15 294 299 369 510 523 40.58
23 21 58 62 64 58 72 79 55.77
24 22 324 476 320 844 843 565 30.6
sac.sp.mesh #8 12/1339,19-20

```

```

853 851 481 446 220 854 690 793 33.44
854 852 222 479 480 849 691 853 37.78
855 853 222 480 481 852 854 374 40.01
856 854 481 480 446 853 775 851 32.63
857 481 5
858 ID X Y AqDepth Elevation
859 1 -2148535 2026400 10 79.6
860 2 -2149051 2026052 10 80.56
861 3 -2149290 2025092 10 76.43
862 4 -2148601 2024449 10 79.74
863 5 -2148443 2023801 10 83.92
864 6 -2148465 2023205 10 85.65
865 7 -2148942 2023055 10 83.07
866 8 -2150163 2023900 10 76.78
867 9 -2150502 2024515 10 69.32
868 10 -2152400 2024476 10 67.83
869 11 -2152934 2024748 10 67.81
870 12 -2154154 2024355 10 62.43
871 13 -2155368 2024743 10 54.51
872 14 -2156738 2023986 10 49.59
873 15 -2157421 2024186 10 43.81
874 16 -2158244 2023679 10 38.29
875 17 -2159475 2023821 10 37.47
876 18 -2159973 2023448 10 31.28
877 19 -2160090 2023786 10 34.45
878 20 -2162853 2023462 10 23.74
879 21 -2163895 2023654 10 21.95
880 22 -2164733 2023156 10 20.59
881 23 -2166519 2023723 10 15.99
sac.sp.mesh #1 856/1339,33

```

There are two tables in the .mesh file, the one is a table of elements and the other is a table of nodes of elements.

- Block 1 (Element information)
- Pre-table

4 Input files

Value1	Value2
Number of rows ($N_{element}$)	Number of columns (8)

- Table

Colname	Meaning	Range	Unit	Comments
ID	Index of element i	$1 \sim N_{element}$	-	
Node1	Node 1 of element i	$1 \sim N_{node}$	-	
Node2	Node 2 of element i	$1 \sim N_{node}$	-	
Node3	Node 3 of element i	$1 \sim N_{node}$	-	
Nabr1	Index of Neighbor 1 of element i	$1 \sim N_{element}$	-	
Nabr2	Index of Neighbor 2 of element i	$1 \sim N_{element}$	-	
Nabr3	Index of Neighbor 3 of element i	$1 \sim N_{element}$	-	
Zmax	Surface elevation of element i	$-9999 \sim +\text{inf}$	m	

- **Block 2 (node information)**

- Pre-table:

Value1	Value2
Number of rows (N_{node})	Number of columns (5)

- Table

Colname	Meaning	Range	Unit	Comments
ID	Index of node i	$1 \sim N_{element}$	-	
X	X coordinate of node i	$1 \sim N_{node}$	-	
Y	Y coordinate of node i	$1 \sim N_{node}$	-	
AqDepth	Thickness of aquifer i	$0 \sim +\text{inf}$	m	
Elevation	Surface elevation of node i	$-9999 \sim +\text{inf}$	m	

4.1.2 .sp.att file

- Pre-table

Value1	Value2
Number of rows ($N_{element}$)	Number of columns (7)

- Table


```

1 854 7
2 INDEX SOIL GEOL LC FORC MF BC
3 1 48 48 4 3 1 1
4 2 50 50 5 5 1 1
5 3 48 48 5 1 1 1
6 4 49 49 6 1 1 1
7 5 54 54 4 4 1 1
8 6 48 48 5 1 1 1
9 7 47 47 4 3 1 1
10 8 43 43 3 3 1 1
11 9 48 48 3 3 1 1
12 10 53 53 3 3 1 1
13 11 53 53 4 5 1 1
14 12 24 24 3 5 1 1
15 13 39 39 5 5 1 1
16 14 24 24 5 4 1 1
17 15 48 48 5 1 1 1
18 16 49 49 5 3 1 1
19 17 50 50 5 4 1 1
20 18 50 50 5 4 1 1
21 19 50 50 5 4 1 1
22 20 50 50 4 4 1 1
23 21 24 24 3 4 1 1
24 22 50 50 4 4 1 1
sac.sp.att #7 1/856,1

```

Figure 4.2: Example of .sp.att file

Colname	Meaning	Range	Unit	Comments
ID	Index of element i	$1 \sim N_{element}$	-	
SOIL	Index of soil type	$1 \sim N_{soil}$	-	
GEOL	Index of geology type	$1 \sim N_{geol}$	-	
LC	Index of land cover type	$1 \sim N_{lc}$	-	$N_{lc} = N_{lai}$
FORC	Index of forcing site	$1 \sim N_{forc}$	-	
MF	Index of melt factor	$1 \sim N_{mf}$	-	
BC	Index of boundary condition	$1 \sim N_{bc}$	-	

4.1.3 .sp.riv file

```

1 77 5
2 Index Down Type Slope Length
3 1 4 2 0.001807047 127.2792
4 2 1 2 0.0002208611 271.6616
5 3 6 2 0.002740643 474.3416
6 4 3 2 -0.000380952 210
7 5 8 2 6.979145e-05 573.1492
8 6 5 2 0.002156285 630.7139
9 7 22 2 -8.753545e-05 456.9464
10 8 7 2 0.004173992 469.5743
11 9 12 2 0.001366666 300
12 10 9 2 0.00542115 424.2641
13 11 2 2 0.002221881 342.0526
14 12 11 2 -0.0001863362 268.3282
15 13 16 2 0.0009596092 573.1492
16 14 13 2 0.0006666692 300
17 15 18 2 0.0003528645 680.147
18 16 15 2 0.004442536 456.9464
19 17 20 2 0.001503557 611.8823
20 18 17 2 0.002286204 258.0698
21 19 62 2 -6.237773e-05 480.9366
22 20 19 2 0.001573566 1194.738
23 21 24 2 0 241.8677
24 22 21 2 0 254.5584
sac.sp.riv #9 1/83,1

```

Figure 4.3: Example of .sp.riv file

- Pre-table

Value1

Value2

4 Input files

Colname	Meaning	Range	Unit	Comments
DOWN	Index of downstream river	$1 \sim N_{river}$	-	Negative vlaue indicates outlet
Type	Index of river parameters	$1 \sim N_{rivertype}$	-	
Slope	Slope of river bed	$-10 \sim 10$	m/m	Height/Length
Length	Length of the river i	$0 \sim \text{inf}$	m	

4.1.4 .sp.rivchn file

- Pre-table

Value1	Value2
Number of rows ($N_{segment}$)	Number of columns (4)

- Table

Colname	Meaning	Range	Unit	Comments
ID	Index of segments i	$1 \sim N_{segment}$	-	
iRiv	Index of river	$1 \sim N_{river}$	-	
iEle	Index of element	$1 \sim N_{element}$	-	
Length	Length of the segments i	$0 \sim \text{inf}$	m	

4.2 Model configuration files

4.2.1 .cfg.para file

- Table

Colname	Meaning	Range	Unit	Comments
VERBOSE	Verbose mode	-	-	
DEBUG	Debug mode	-	-	
INIT_MODE	Initial condition mode	1,2,3	-	1=Dry condition, 2=Relief conditon, 3=Warm start
ASCII_OUTPUT	ASCII ouput	1/0	-	
Binary_OUTPUT	Binary output	1/0	-	
NUM_OPENMP	Number of threads for OpenMP	$0 \sim N_{threads}$	-	

Colname	Meaning	Range	Unit	Comments
ABSTOL	Abosolute tolerance for CVMODE solver	1e-6 ~ 0.1	-	
RELTOL	Relative tolerance for CVMODE solver	1e-6 ~ 0.1	-	
INIT_SOLVER_STEP	Initial time step for CVMODE solver	?	-	
MAX_SOLVER_STEP	Maximum time step for CVMODE solver	?	-	
ET_STEP	Time step of Evapotranspiration	1~360	<i>min</i>	
START	Start Time	0 ~ inf	<i>day</i>	
END	End Time	-	<i>day</i>	
dt_ye_snow	Time step of output snow storage	0 ~ inf	<i>min</i>	
dt_ye_surf	Time step of output surface storage	0 ~ inf	<i>min</i>	
dt_ye_unsat	Time step of output unsaturated storage	0 ~ inf	<i>min</i>	
dt_ye_gw	Time step of output groundwater head	0 ~ inf	<i>min</i>	
dt_Qe_surf	Time step of output surface element flux	0 ~ inf	<i>min</i>	
dt_Qe_sub	Time step of output subsurface element flux	0 ~ inf	<i>min</i>	
dt_qe_et0	Time step of output element flux, interception	0 ~ inf	<i>min</i>	
dt_qe_et1	Time step of output element flux, transpiration	0 ~ inf	<i>min</i>	
dt_qe_et2	Time step of output element flux, evaporation	0 ~ inf	<i>min</i>	
dt_qe_etp	Time step of output element flux, potential ET	0 ~ inf	<i>min</i>	
dt_qe_prcp	Time step of output element flux, interception	0 ~ inf	<i>min</i>	

4 Input files

Colname	Meaning	Range	Unit	Comments
dt_qe_infil	Time step of output element flux, interception	0 ~ inf	<i>min</i>	
dt_qe_rech	Time step of output element flux, interception	0 ~ inf	<i>min</i>	
dt_yr_stage	Time step of output river stage	0 ~ inf	<i>min</i>	
dt_Qr_down	Time step of output river flux, downstream	0 ~ inf	<i>min</i>	
dt_Qr_surf	Time step of output river flux, surface flow	0 ~ inf	<i>min</i>	
dt_Qr_sub	Time step of output river flux, base flow	0 ~ inf	<i>min</i>	
dt_Qr_up	Time step of output river flux, upstream	0 ~ inf	<i>min</i>	

4.2.2 .cfg.calib file

- Table

Colname	Meaning	Range	Unit	Comments
GEOL_KSATH	Horizontal conductivity of ground water	?	-	
GEOL_KSATV	Vertical conductivity of ground water	?	-	
GEOL_KMACSATH	Horizontal conductivity of macropore	?	-	
GEOL_DMAC	Macropore depth		-	
GEOL_THETAS	Porosity, saturated soil moisture		-	
GEOL_THETAR	Residual soil moisture		-	
GEOL_MACVF	Vertical macropore areal fraction		-	
SOIL_KINF	Vertical conductivity of top soil	?	-	
SOIL_KMACSATV	Vertical conductivity of soil macropore	?	-	
SOIL_DINF	Infiltration depth	?	-	
SOIL_DROOT	Root depth		-	
SOIL_ALPHA	α value in van Genuchten equation		-	
SOIL_BETA	β value in van Genuchten equation		-	
SOIL_MACHF	Horizontal macropore areal fraction		-	
LC_VEGFRAC	Vegetation fraction		-	
LC_ALBEDO	Emissive reflection ratio		-	
LC_ROUGH	Manning's roughness of element surface		-	

Colname	Meaning	Range	Unit	Comments
LC_SOILDGD	Soil degradation		-	
LC_IMPAF	Impervious areal fraction		-	
LC_ISMAX	Maximum interception		-	
AQ_DEPTH+	Thickness of aquifer		m	
TS_PRCP	Precipitation		-	
TS_SFCTMP+	Temperature		C	
ET_ETP	Transpiration		-	
ET_IC	Interception		-	
ET_TR	Evaporation		-	
ET_SOIL	Evaporation		-	
RIV_ROUGH	Manning's roughness of river		-	
RIV_KH	Conductivity of river bed		-	
RIV_DPTH+	Depth of river cross section		m	
RIV_WDTH+	Width of river cross section		m	
RIV_SINU	Sinuosity of river path		-	
RIV_CWR	C_{wr} in Chezy equation		-	
RIV_BSLOPE+	Slope of river bed		m/m	
IC_GW+	Initial condition of groundwater		m	
IC_RIV+	Initial condition of river stage		m	

4.2.3 .cfg.ic file

- **Block 1 (Element initial condition)**
- Pre-table

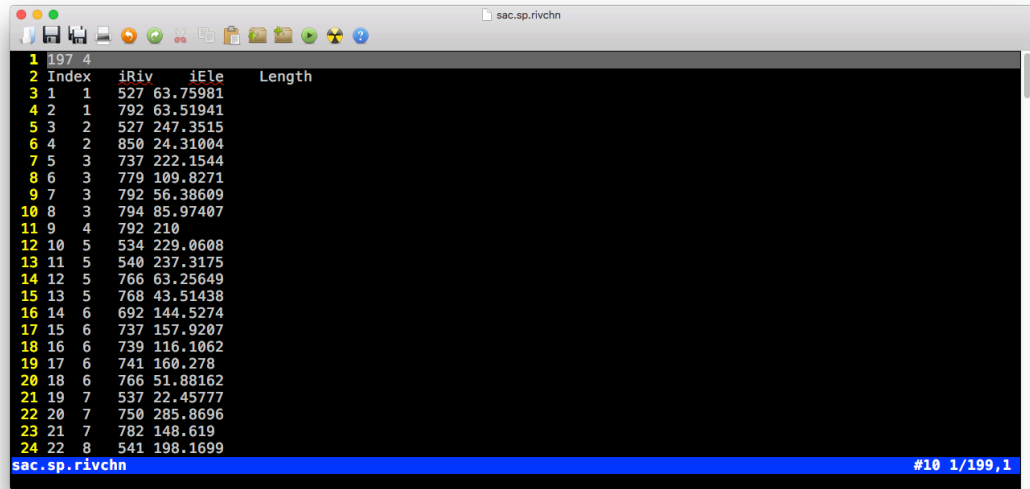
Value1	Value2
Number of rows ($N_{element}$)	Number of columns (6)

- Table

Colname	Meaning	Range	Unit	Comments
ID	Index of element i	$1 \sim N_{element}$	-	
Canopy	Canopy storage of element i	$0 \sim \text{inf}$	m	
Snow	Snow storage of element i	$0 \sim \text{inf}$	m	
Surface	Surface storage of element i	$0 \sim \text{inf}$	m	
Unsat	Unsaturated storage of element i	$0 \sim \text{inf}$	m	
GW	Groundwater head of element i	$0 \sim \text{inf}$	m	

- **Block 2 (river initial condition)**

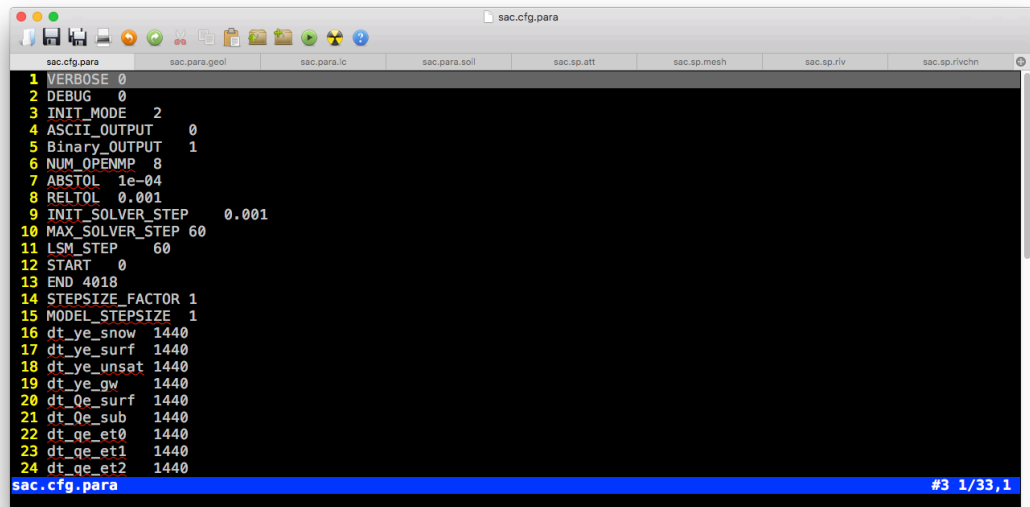
4 Input files



The screenshot shows a text editor window titled "sac.sp.rivchn". The file contains a table with 4 columns: Index, iRiv, iEle, and Length. The table has 24 rows of data. The status bar at the bottom indicates "sac.sp.rivchn" and "#10 1/199,1".

Index	iRiv	iEle	Length
1	1	527	63.75981
2	1	792	63.51941
3	2	527	247.3515
4	2	850	24.31004
5	3	737	222.1544
6	3	779	109.8271
7	3	792	56.38609
8	3	794	85.97407
9	4	792	210
10	5	534	229.0608
11	5	540	237.3175
12	5	766	63.25649
13	5	768	43.51438
14	6	692	144.5274
15	6	737	157.9207
16	6	739	116.1062
17	6	741	160.278
18	6	766	51.88162
19	7	537	22.45777
20	7	750	285.8696
21	7	782	148.619
22	8	541	198.1699

Figure 4.4: Example of .sp.rivchn file



The screenshot shows a text editor window titled "sac.cfg.para". The file contains a list of parameters and their values. The status bar at the bottom indicates "sac.cfg.para" and "#3 1/33,1".

```
1 VERBOSE 0
2 DEBUG 0
3 INIT_MODE 2
4 ASCII_OUTPUT 0
5 Binary_OUTPUT 1
6 NUM_OPENMP 8
7 ABSTOL 1e-04
8 RELTOL 0.001
9 INIT_SOLVER_STEP 0.001
10 MAX_SOLVER_STEP 60
11 LSM_STEP 60
12 START 0
13 END 4018
14 STEPSIZE_FACTOR 1
15 MODEL_STEPSIZE 1
16 dt_je_snow 1440
17 dt_je_surf 1440
18 dt_je_unsat 1440
19 dt_je_gw 1440
20 dt_je_surf 1440
21 dt_je_sub 1440
22 dt_je_et0 1440
23 dt_je_et1 1440
24 dt_je_et2 1440
```

Figure 4.5: Example of .cfg.para file

4.2 Model configuration files

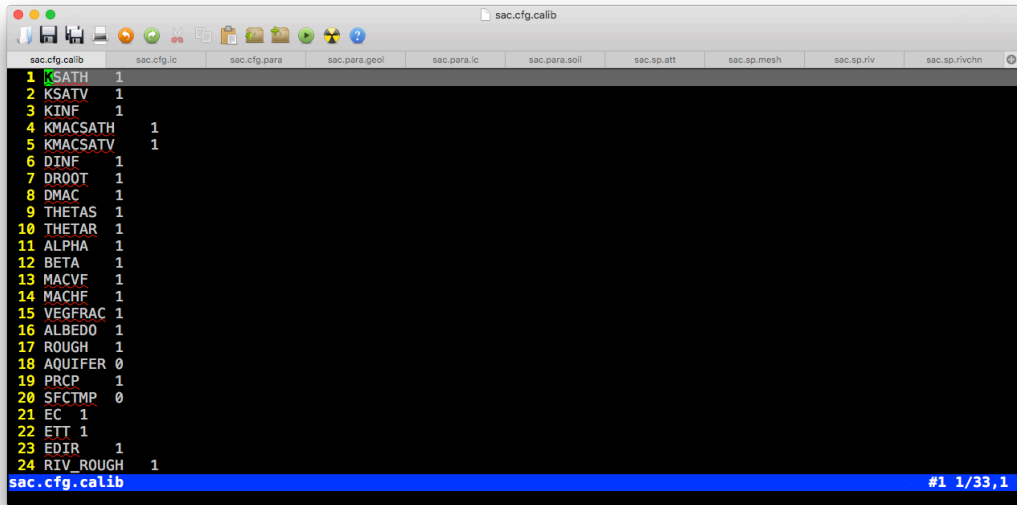


Figure 4.6: Example of .cfg.calib file

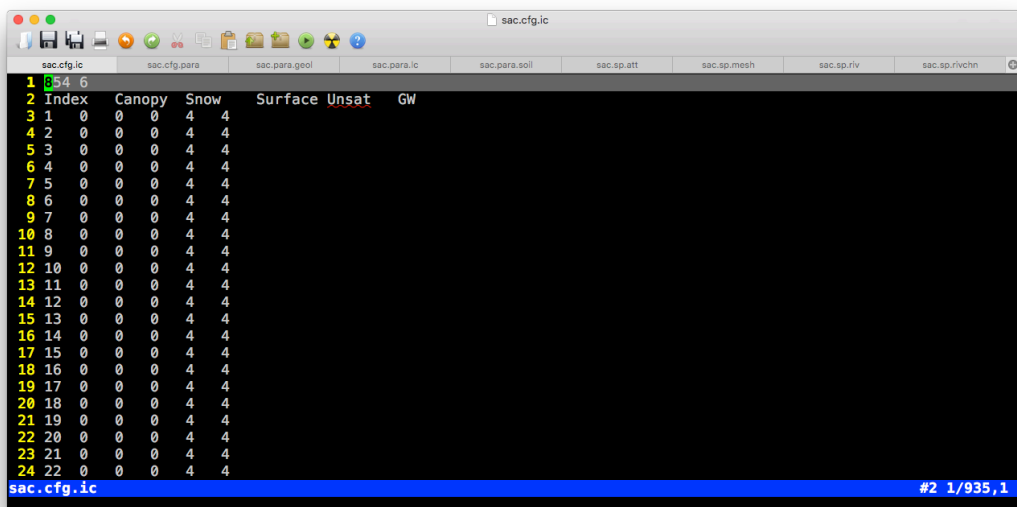


Figure 4.7: Example of .cfg.ic file

4 Input files

- Pre-table:

Value1	Value2
Number of rows (N_{riv})	Number of columns (2)

- Table

Colname	Meaning	Range	Unit	Comments
ID	Index of river i	$1 \sim N_{riv}$	-	
Stage	Stage of river i	$0 \sim \text{inf}$	m	

4.3 Time-series data

4.3.1 .tsd.forc file

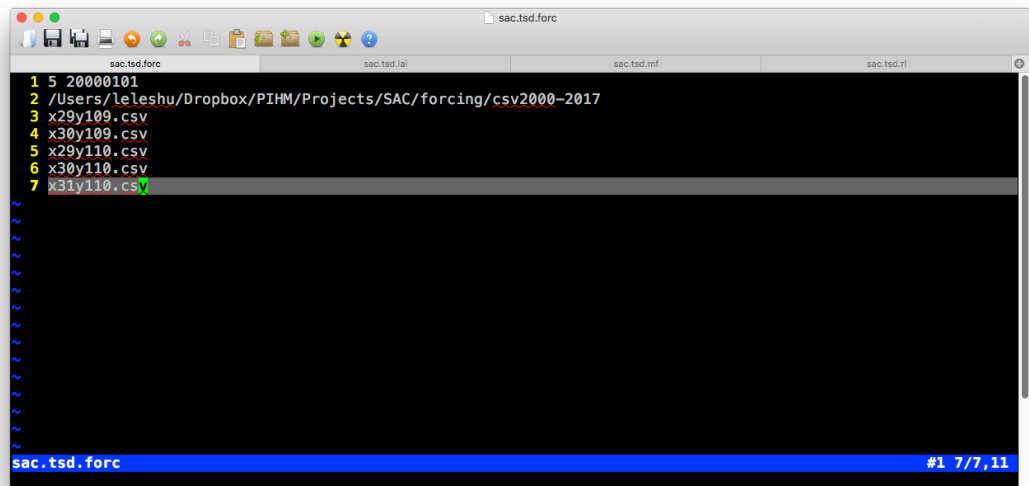


Figure 4.8: Example of .tsd.forc file

- Line 1: Number of forcing sites | Start day (YYYYMMDD)
- Line 2: Directory to the spreadsheet
- Line 3~N: Filenames of spreadsheet

- Pre-table:

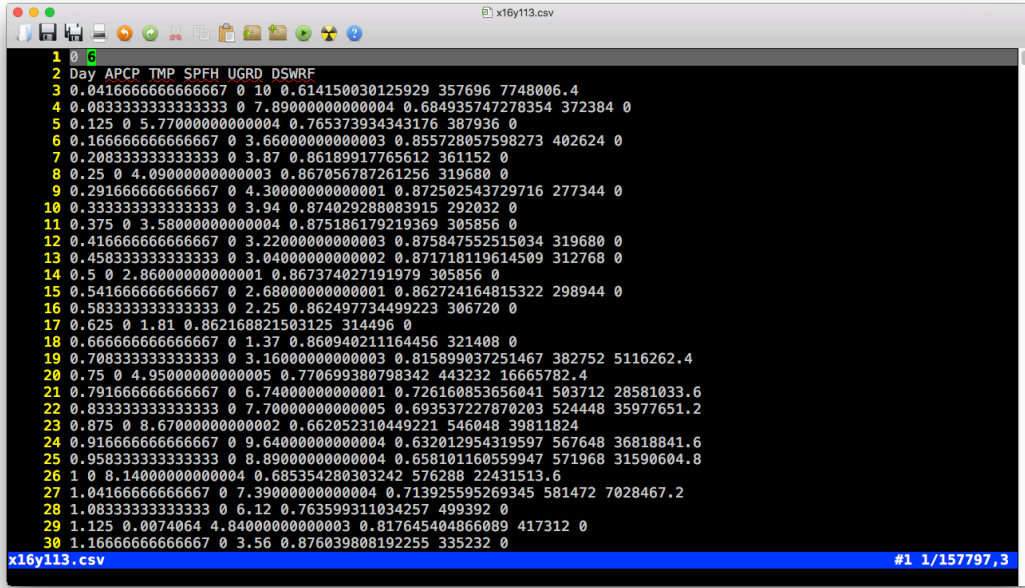


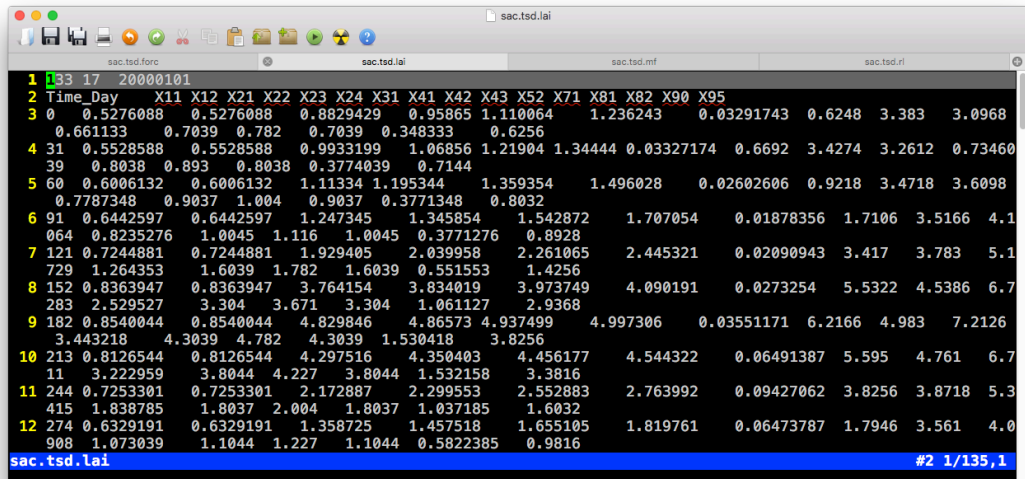
Figure 4.9: Example of .csv forcing file

Value1	Value2
(0)	Number of columns (6)

- Table

Colname	Meaning	Range	Unit	Comments
Day	Time	$0 \sim N_{day}$	day	
PRCP	Precipitation	$0 \sim 1$	m/day	
TEMP	Temperature	$-100 \sim 70$	$^{\circ}C$	
RH	Relative Humidity	$0 \sim 1$	—	
wind	Wind Speed	$0 \sim \text{inf}$	m/day	
Rn	Solar (shortwave) radiation	?	J/day/m ²	

4.3.2 .tsd.lai file



4 Input files

Colname	Meaning	Range	Unit	Comments
TIME	Time	$0 \sim N_{time}$	day	
Column 2	LAI of land cover 1	$0 \sim \text{inf}$	m^2/m^2	
Column i	LAI of land cover $i - 1$	$0 \sim \text{inf}$	m^2/m^2	
...	

4.3.3 .tsd.rl file

```

1 183 17 20000101
2 Time_Day X11 X12 X21 X22 X23 X24 X31 X41 X42 X43 X52 X71 X81 X82 X90 X95
3 0 0.07602524 0.07602524 0.1011028 0.1186548 0.153759 0.1830124 0.01326339 0.34308 1.62288 0.5
4 2068 0.06492916 0.07105 0.0777 0.07105 0.03384916 0.06216
5 31 0.07551426 0.07551426 0.1010668 0.118517 0.1534173 0.1825008 0.01326371 0.34312 1.62292 0.5
6 1802 0.06499535 0.07114 0.0778 0.07114 0.03387535 0.06224
7 60 0.07772204 0.07772204 0.1039028 0.1234799 0.1626342 0.1952627 0.01312691 0.43072 1.62292 0.5
8 5732 0.06446723 0.07114 0.0778 0.07114 0.03334723 0.06224
9 91 0.08250124 0.08250124 0.1090171 0.132355 0.1790306 0.217927 0.01292203 0.57716 1.62296 0.6
10 2876 0.06374124 0.07123 0.0779 0.07123 0.03258124 0.06232
11 121 0.0846955 0.0846955 0.1113892 0.1365811 0.186965 0.2289515 0.01292171 0.64972 1.62292 0.6
12 6322 0.06367505 0.07114 0.0778 0.07114 0.03255505 0.06224
13 152 0.08449668 0.08449668 0.11089 0.1362326 0.1869176 0.2291551 0.01292005 0.65724 1.62264 0.66444
14 0.06323401 0.07051 0.0771 0.07051 0.03239401 0.06168
15 182 0.08471342 0.08471342 0.1097965 0.1352189 0.1860637 0.2284343 0.01291854 0.65556 1.62216 0.6
16 6486 0.06252889 0.06943 0.0759 0.06943 0.03216889 0.06072
17 213 0.08496604 0.08496604 0.1105409 0.1359966 0.186908 0.2293341 0.01343009 0.65284 1.62244 0.6
18 6544 0.06496246 0.07006 0.0766 0.07006 0.03432246 0.06128
19 11 244 0.08514252 0.08514252 0.111731 0.1371793 0.1880758 0.2304895 0.01362346 0.65272 1.62292 0.6
20 6652 0.06647241 0.07114 0.0778 0.07114 0.03535241 0.06224
21 12 274 0.08299022 0.08299022 0.1093748 0.1329809 0.180193 0.2195365 0.01353003 0.58136 1.62296 0.6
22 3266 0.06608844 0.07123 0.0779 0.07123 0.03492844 0.06232
sac.tsd.rl #4 1/135,1

```

Figure 4.11: Example of .tsd.rl file

- Pre-table:

Value1	Value2	Value3
Number of day (N_{time})	Number of columns (N_{lc})	Start day (YYYYMMDD)

- Table

Colname	Meaning	Range	Unit	Comments
TIME	Time	$0 \sim N_{time}$	day	
Column 2	Roughness length of land cover 1	$0 \sim \text{inf}$	m	
Column i	Roughness length of land cover $i - 1$	$0 \sim \text{inf}$	m	
...	

4.3.4 .tsd.mf file

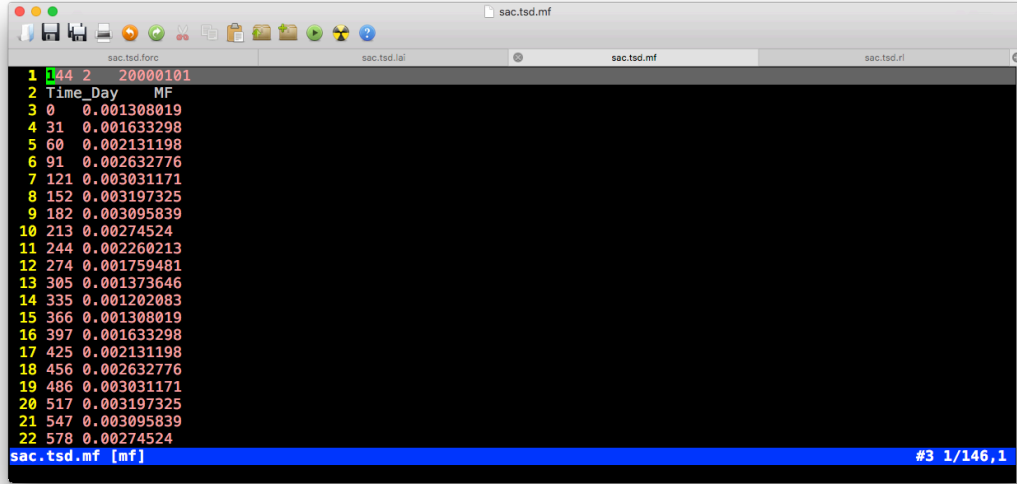


Figure 4.12: Example of .tsd.mf file

- Pre-table:

Value1	Value2	Value3
Number of day (N_{time})	Number of columns (N_{mf})	Start day (YYYYMMDD)

- Table

Colname	Meaning	Range	Unit	Comments
TIME	Time	$0 \sim N_{time}$	day	
Column 2	Melt factor 1	$0 \sim \text{inf}$	-	
Column i	Melt factor $i - 1$	$0 \sim \text{inf}$	-	
...	

4.3.5 .tsd.obs file

- Pre-table:

Value1	Value2	Value3
Number of day (N_{time})	Number of columns (N_{obs})	Start day (YYYYMMDD)

4 Input files

```

1 1827 2 20000101
2 Time_Day rbind.x.
3 0 846515.1
4 1 839175.4
5 2 839175.4
6 3 812263.1
7 4 829389.1
8 5 792690.5
9 6 787797.4
10 7 778011
11 8 785350.8
12 9 880767.2
13 10 5162274
14 11 3033754
15 12 3890055
16 13 24294495
17 14 17028166
18 15 25689043
19 16 12012686
20 17 8293891
21 18 11621234
22 19 17028166
23 20 9804165
24 21 721739.8
25 22 6825946
26 23 9419316
sac.tsd.obs #1 24/1829, 10-11

```

Figure 4.13: Example of .tsd.obs file

- Table

Colname	Meaning	Range	Unit	Comments
TIME	Time	$0 \sim N_{time}$	day	
Column 2	Observational data 1	?	?	
Column i	Observational data $i - 1$?	?	
...	

5 Output files

5.1 Output file names

Format of output file names:

[Project Name].[Identifier].[Format]

-The *[Project Name]* is user defined name of the project, so every input and output files must start with the *[Project Name]*. -The *[Format]* is one of *csv* or *dat*. *csv* is spreadsheet format and *dat* is binary format.

The *[Identifier]* is a combination of variables features, that in format of: **[Model Unit][Variable Type][Variable Name]**. *[Model Unit]* is one of three options of *ele* (element), *riv* (river) or *lak* (lake). Variable type includes *y*, *v* and *q* that are state variable (in L), specific flux (in $L^3/L^2/T$) and flux (in L^3/T) respectively.

The list of output files is in following table.

Identifier	Mod unit	Type	Var Name	Meaning	Unit	Old name in PIHM v.2.2
<i>.eleyic.</i>	ele	y	ic	Storage of Interception	m	.ic
<i>.eleysnow.</i>	ele	y	snow	Storage of snow equivalence	m	.snow
<i>.eleysurf.</i>	ele	y	surf	Storage of surface	m	.surf
<i>.eleyunsat.</i>	ele	y	unsat	Storage of vados zone	m	.unsat
<i>.eleygw.</i>	ele	y	gw	Groundwater head	m	.GW
<i>.elevetp.</i>	ele	v	etp	Potential ET	$\frac{m^3}{m^2d}$	-
<i>.eleveta.</i>	ele	v	eta	Actual ET	$\frac{m^3}{m^2d}$	-
<i>.elevetic.</i>	ele	v	etic	Evap of interception	$\frac{m^3}{m^2d}$	.ET0
<i>.elevettr.</i>	ele	v	ettr	Transpiration	$\frac{m^3}{m^2d}$	.ET1
<i>.elevetev.</i>	ele	v	etev	Soil Evaporation	$\frac{m^3}{m^2d}$	.ET2
<i>.elevprcp.</i>	ele	v	prcp	Precipitation	$\frac{m^3}{m^2d}$	-
<i>.elevnetprcp.</i>	ele	v	netprcp	Net Precipitation	$\frac{m^3}{m^2d}$	-
<i>.elevinfil.</i>	ele	v	infil	Infiltration Rate	$\frac{m^3}{m^2d}$	.infil
<i>.elevexfil.</i>	ele	v	infil	Exfiltration Rate	$\frac{m^3}{m^2d}$	-
<i>.elevrech.</i>	ele	v	rech	Recharge Rate	$\frac{m^3}{m^2d}$	.Rech
<i>.elegsurf.</i>	ele	q	surf	Overland flow	m^3/d	.fluxsurf
<i>.elegsub.</i>	ele	q	sub	Subsurface flow	m^3/d	.fluxsub
<i>.rivystage.</i>	riv	y	stage	River Stage	m	stage

5 Output files

Identifier	Mod unit	Type	Var Name	Meaning	Unit	Old name in P
<i>.rivqup.</i>	riv	q	up	Flux to upstream	m^3/d	.rivflx
<i>.rivqdown.</i>	riv	q	down	Flux to downstream	m^3/d	.rivflx
<i>.rivqsurf.</i>	riv	q	surf	Flux to landsurface	m^3/d	.rivflx1
<i>.rivqsub.</i>	riv	q	sub	Flux to subsurface	m^3/d	.rivflx4

5.2 Data format in ASCII (.csv) file

N - Number of column of output data, excluding the time column. m - Number of time-step. StartTime - String of date/time (YYYYMMDD or YYYYMMDD.hhmmss)

N	StartTime				
T_1	$v_{1.1}$	$v_{1.2}$	...	$v_{1.N}$	
T_2	$v_{2.1}$	$v_{2.2}$	...	$v_{2.N}$	
T_3	$v_{3.1}$	$v_{3.2}$	...	$v_{3.N}$	
...	
T_m	$v_{m.1}$	$v_{m.2}$	...	$v_{m.N}$	

5.3 Data format in binary (.dat) file

The value saved in binary file are identical from ASCII format, but different data structure.

ID	i	Value	Format	Length
1	-	N	double	8
2	-	StartTime	double	8
3	0	T_1	double	8
4	1	$v_{1.1}$	double	8
5	2	$v_{1.2}$	double	8
...	...	...	double	8
$(N + 1) * (T - 1) + i + 3$	N	$v_{1.N}$	double	8
$(N + 1) * (T - 1) + i + 3$	0	T_2	double	8
$(N + 1) * (T - 1) + i + 3$	1	$v_{2.1}$	double	8
$(N + 1) * (T - 1) + i + 3$	2	$v_{2.2}$	double	8
$(N + 1) * (T - 1) + i + 3$	...	...	double	8
$(N + 1) * (T - 1) + i + 3$	N	$v_{2.N}$	double	8
$(N + 1) * (T - 1) + i + 3$	0	T_3	double	8
$(N + 1) * (T - 1) + i + 3$	1	$v_{3.1}$	double	8
$(N + 1) * (T - 1) + i + 3$	2	$v_{3.2}$	double	8

5.3 Data format in binary (.dat) file

ID	i	Value	Format	Length
$(N+1) * (T-1) + i + 3$	...	...	double	8
$(N+1) * (T-1) + i + 3$	N	$v_{3 \cdot N}$	double	8
$(N+1) * (T-1) + i + 3$	...	...	double	8
$(N+1) * (T-1) + i + 3$	...	...	double	8
$(N+1) * (T-1) + i + 3$	...	...	double	8
$(N+1) * (T-1) + i + 3$	...	...	double	8
$(N+1) * (m-1) + i + 3$	0	T_m	double	8
$(N+1) * (m-1) + i + 3$	1	$v_{m \cdot 1}$	double	8
$(N+1) * (m-1) + i + 3$	2	$v_{m \cdot 2}$	double	8
$(N+1) * (m-1) + i + 3$	...	...	double	8
$(N+1) * (m-1) + i + 3$	N	$v_{m \cdot N}$	double	8

6 Applications

Some *significant* applications are demonstrated in this chapter.

6.1 Best practice suggestions

1. Derive and QC all inputs (time mean, accumulation, screen for anomalies ...)
2. Conduct offline simulations ...
3. Start with ‘idealized’ forcing (Option FORC_debug=1 in .cfg.para file). Which will use uniform forcing data to drive the hydrologic simulations.
4. Run with short time period, load the outputs and examine whether results are in expectation
5. If all above works, then hook all modules and run with your forcing data.

6.2 Example 1: Vauclin Experiment

6.3 Example 2: Shall Hill CZO

6.4 Example 3: Conestoga Watershed, Pennsylvania

7 Calibration

File	Comments	Header	# of columns
.cfg.cmaes	Configuration of CMA-ES method	No	-

Values in .calib.cmaes file:

Item	Meaning	Default value	Range	Unit
lambda	Number of children in each generation	48		-
stopfitness	Threshold to accept the <i>best</i> solution	0.3		-
maxgen	Maximun generations	48		-
sigma		0.8		-
updateic	Whether to update initial condition after each generation	0	0/1	-
walltime	Walltime to kill the modeling thread	86400	0-inf	second
nspingup	Number of days for spinup	0	0-inf	day
				-

Values in .calib.range file:

Rows: Values in .cfg.calib file.	Column: | Item | Meaning | Default value | Range | Unit
| :—:| :—:| :—:| :—:| | On/off | On or Off | 0 | 0/1 | -	
| log | Whether logarithm | 0 | 0/1 | - | | min | Minimum value | - | - | - | | max | Maximum value | - | - | - |	

8 Automatic hydrologic modeling with PIHM system

Automatic deployment of PIHM System

9 Course code and program design

The source code of PIHM++ and PIHMgisR are available via Github: <https://github.com/shulele/PIHM-4.0> and <https://github.com/shulele/PIHMgisR>.

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