Penn State Integrated Hydrologic Model(PIHM)

Technical Documentation

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2019-05-03

Contents

1 Overview

This is the technical documentation of 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 the 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 Advanicing 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 vertical projection of the Delauney 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 Delauney triangles. The local control volume contains all equations to be solved and is referred to as the model kernel.

- is physically-based model, in which all equations used is descibing the physics of the hydrological processes which control the catchment. The physical model is ablr to predict the water in 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 fully-couple hydrologic model, where the state and flux variables in the hydrologic system are solved within 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 adaptable temporal and spatial resolution. The spatial resolution of model varies from meters to kilometers based requirement of modeling and computing resources. Internal time step of iteration step are adjustable; it is able to export the status of catchment in less 1 sencond to days. Also the time interval for exporting results is configured flexiblly. The flexible spatial and temporal resolution is rather valueable for community model coupling.
- is open source model, anyone can access the source code, use and submit their improvement.
- is 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 activites 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 to 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 PhD in Pennsylvania State Unversity, 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 developmemnt of PIHMgis make 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 embeded the all modules from PIHM family, such as RT-PIHM, LE-PIHM, flux-PIHM, BGC-PIHM etc. together. The sophysiticated design and coupling of the MM-PIHM is the summit of the PIHM as a *Community Model* that combined all water-related module together.

- 2019 PIHM++

Based on the accumulated contribution of PIHM modeling and coupling with related researches, it is neccessary to solve the known bugs and limitation, improve the performance of model with parrellel methods, and adopt new update 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, photosynthestic atmospheric radiation, leaf area index)
- Digital elevation model (DEM)

- River/stream discharge
- 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 servers ….many 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/

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

2 Workflow of PIHM System

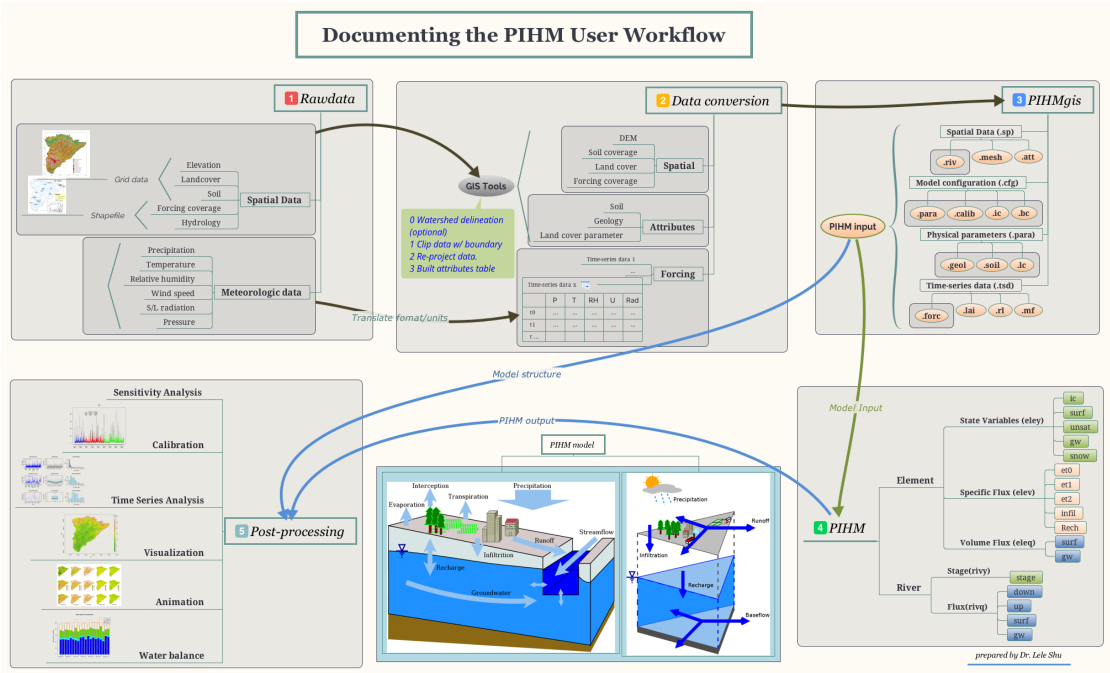


Figure 2.1: The workflow of modeling with PIHM System

1. Prepare raw Essential Terrestrial Variables (ETV)
2. Convert and crop raw data with 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.

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*

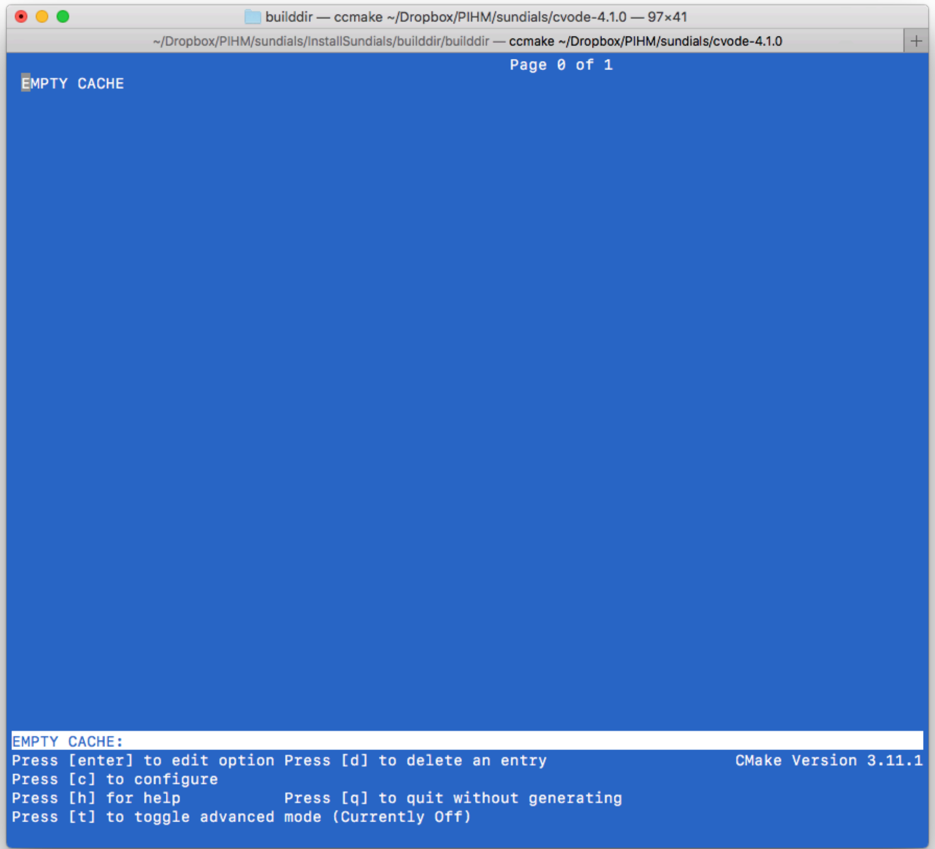
```
mkdir builddir
mkdir instdir
mkdir srcdir
cd builddir/
```

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

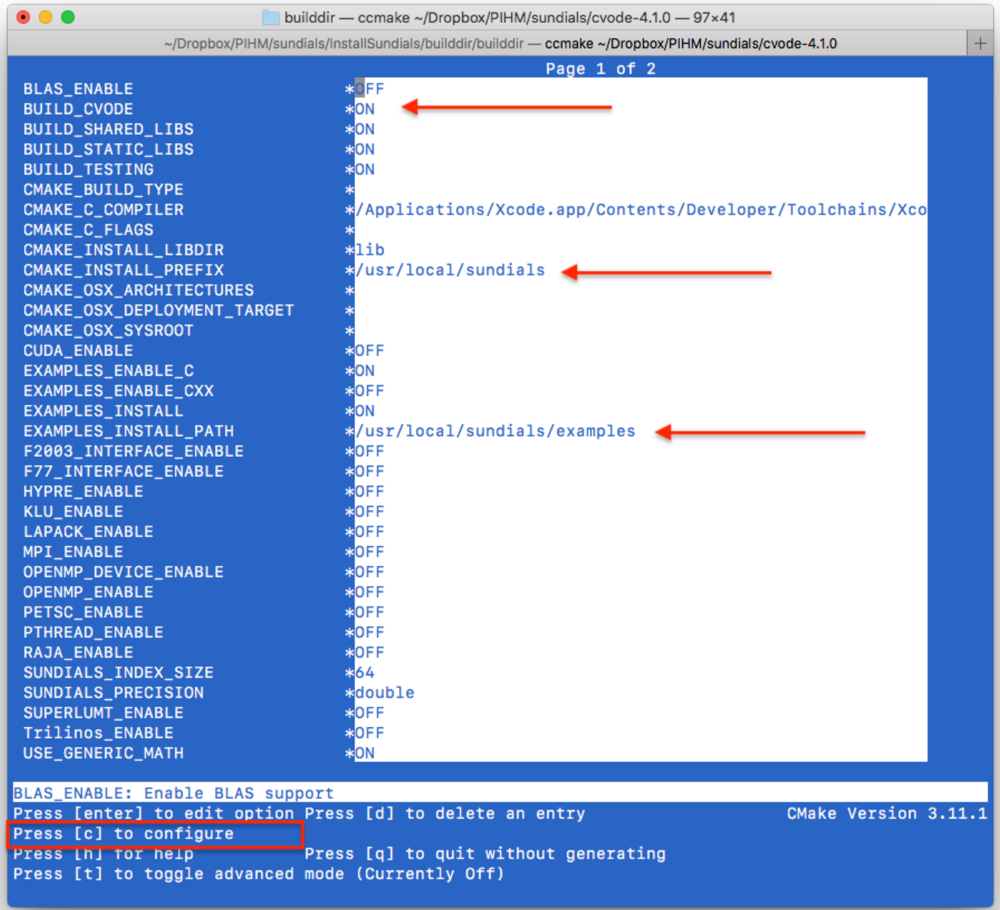
```
ccmake
```

4. Run ccmake to configure your compile environment.

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



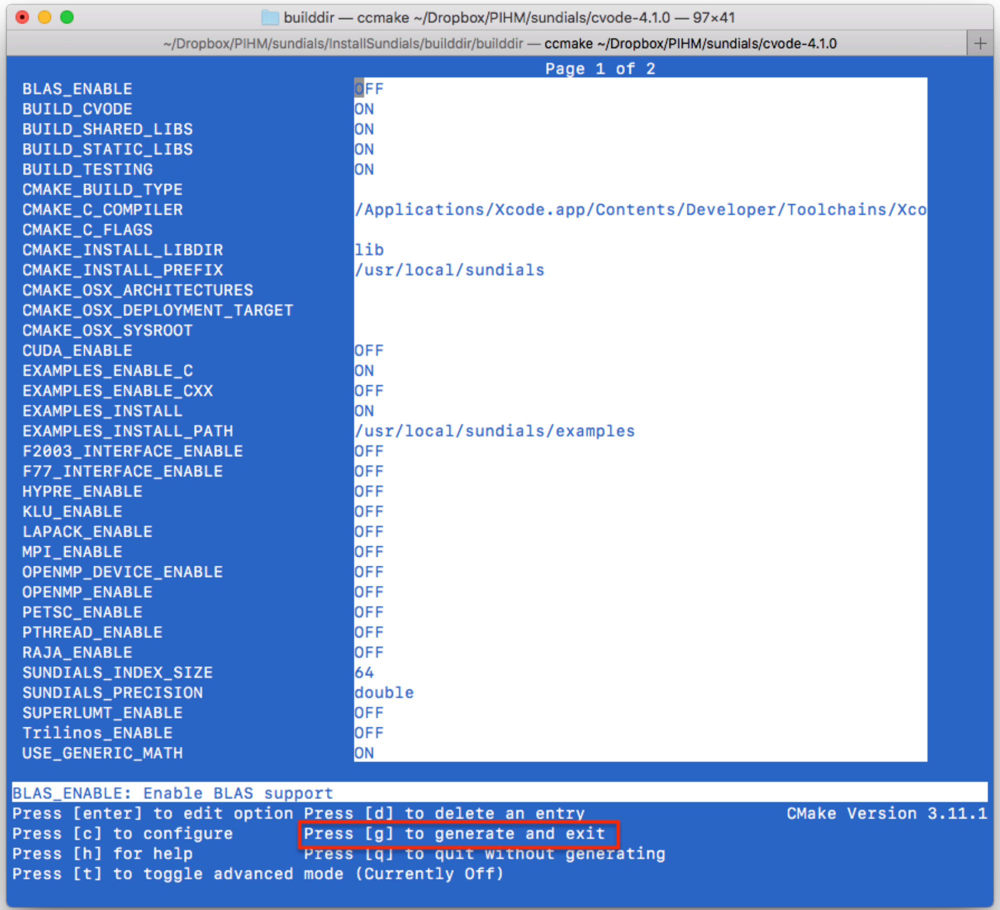
This is a empty configure. Press `c` to start the configuration.



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.



The ccmake configures the environment automatically. When the configuration is ready, press g to genrate 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

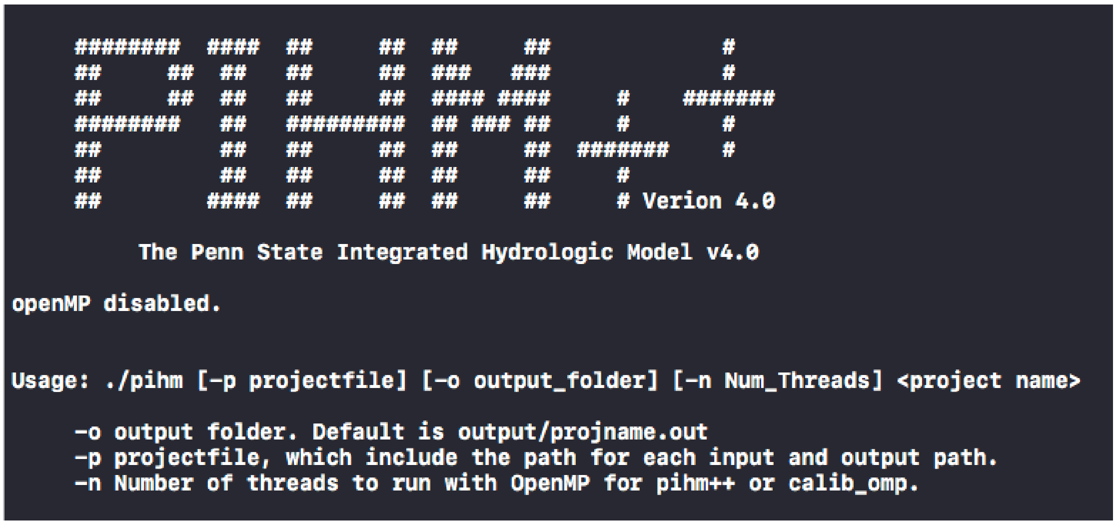
If parallel-computing is prefered, please install OpenMP. For mac:

```
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>
```



```
########  ####  ##     ##  ##     ##            #
##     ##  ##   ##     ##  ###   ###            #
##     ##  ##   ##     ##  #### ####     #    #######
########   ##   #########  ## ### ##     #       #
##         ##   ##     ##  ##     ##  #######    #
##         ##   ##     ##  ##     ##     #
##        ####  ##     ##  ##     ##     # 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 and output

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.

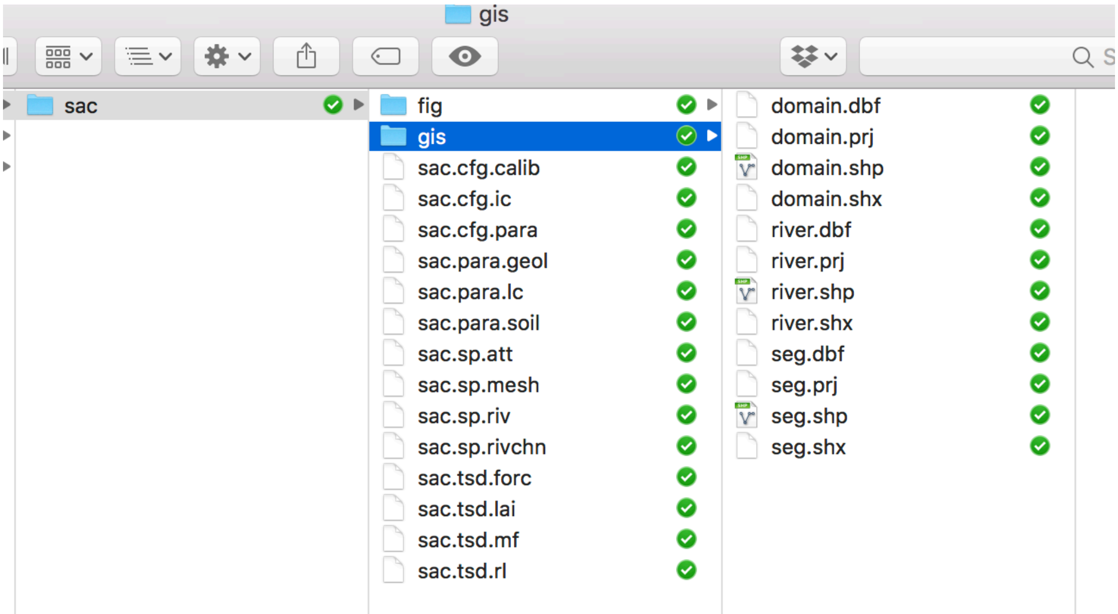
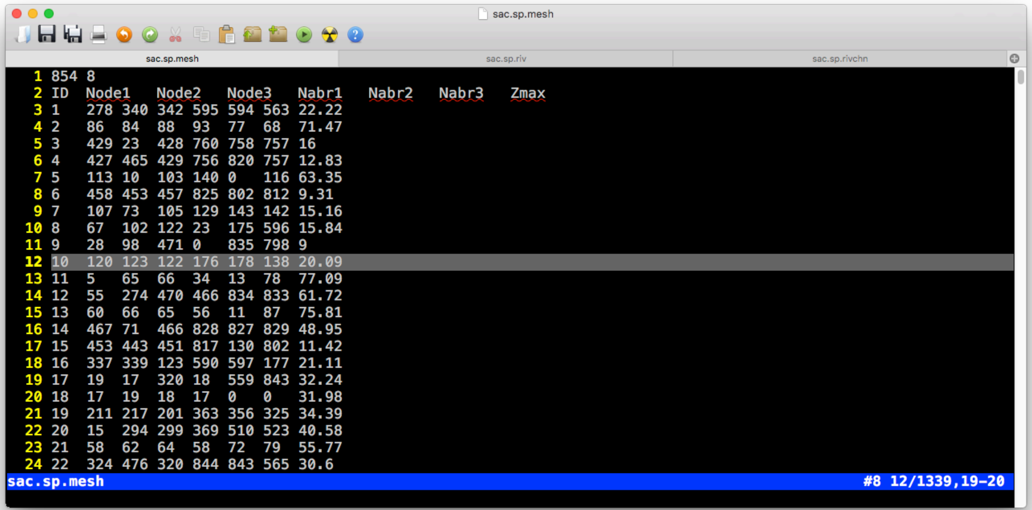


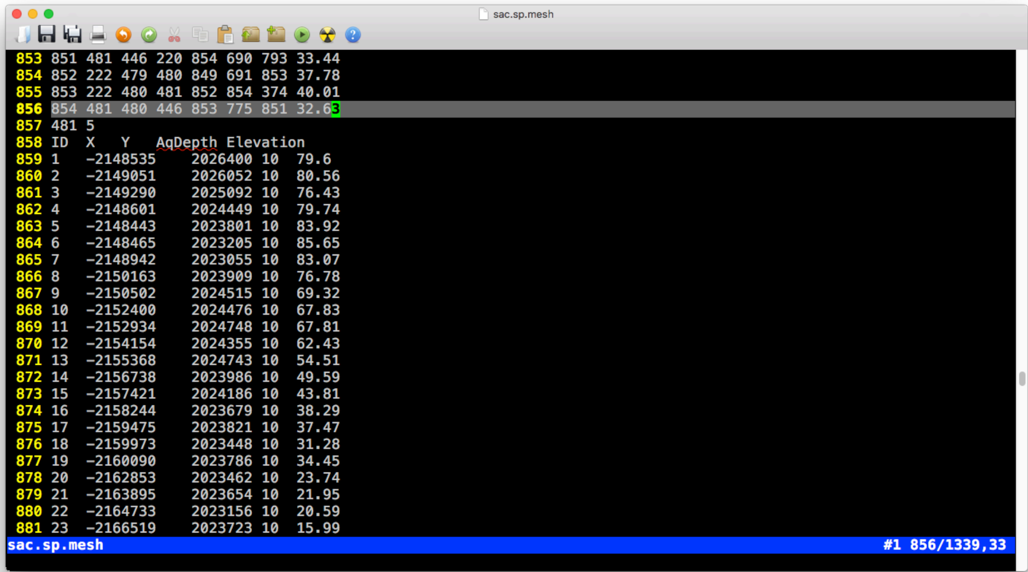
Figure 4.1: The screenshort of input files for PIHM++

4.1 Spatial data

4.1.1 .sp.mesh file



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



```
sac.sp.mesh
851 481 446 220 854 690 793 33.44
852 222 479 480 849 691 853 37.78
853 222 480 481 852 854 374 40.01
854 481 480 446 853 775 851 32.63
481 5
ID  X   Y   AqDepth Elevation
1   -2148535    2026400 10  79.6
2   -2149051    2026052 10  80.56
3   -2149290    2025092 10  76.43
4   -2148601    2024449 10  79.74
5   -2148443    2023801 10  83.92
6   -2148465    2023205 10  85.65
7   -2148942    2023055 10  83.07
8   -2150163    2023909 10  76.78
9   -2150502    2024515 10  69.32
10  -2152400    2024476 10  67.83
11  -2152934    2024748 10  67.81
12  -2154154    2024355 10  62.43
13  -2155368    2024743 10  54.51
14  -2156738    2023986 10  49.59
15  -2157421    2024186 10  43.81
16  -2158244    2023679 10  38.29
17  -2159475    2023821 10  37.47
18  -2159973    2023448 10  31.28
19  -2160090    2023786 10  34.45
20  -2162853    2023462 10  23.74
21  -2163895    2023654 10  21.95
22  -2164733    2023156 10  20.59
23  -2166519    2023723 10  15.99
sac.sp.mesh                                        #1 856/1339,33
```

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

- **Block 1 (Element information)**

- Pre-table

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 ~ +inf	m	

- **Block 2 (node information)**
- Pre-table:

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

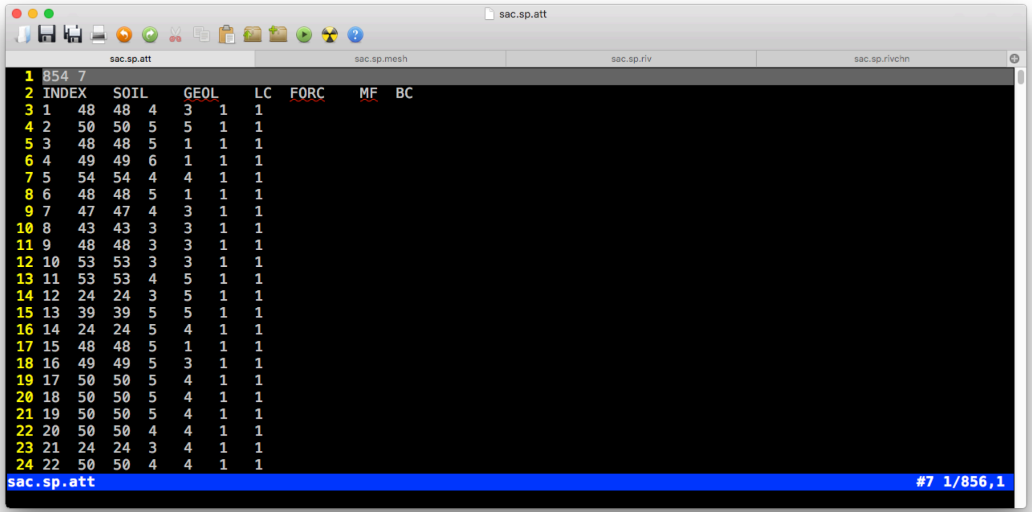
- Table

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 ~ +inf	m	
Elevation	Surface elevation of node i	-9999 ~ +inf	m	

4.1.2 .sp.att file

- Pre-table

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



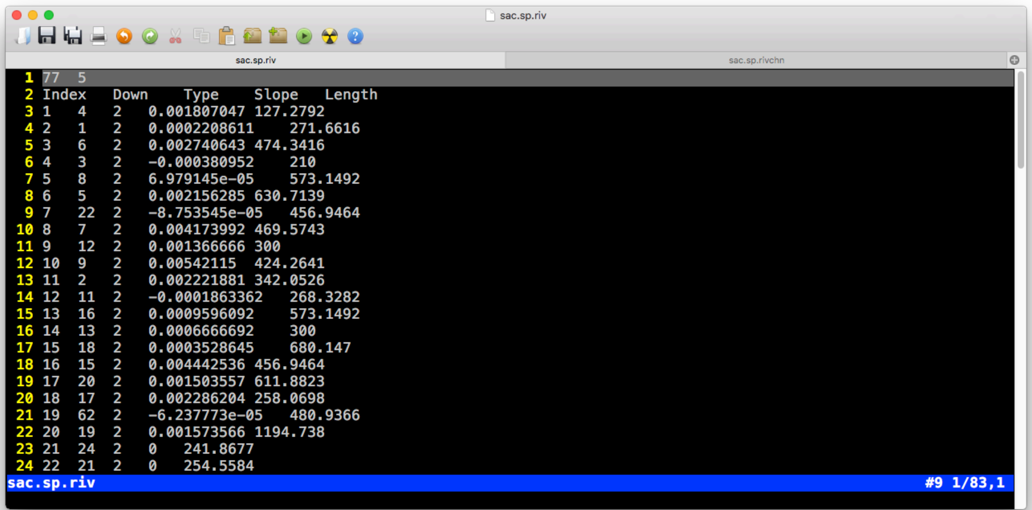

```
854 7
INDEX   SOIL    GEOL    LC  FORC    MF  BC
1   48  48  4   3   1   1
2   50  50  5   5   1   1
3   48  48  5   1   1   1
4   49  49  6   1   1   1
5   54  54  4   4   1   1
6   48  48  5   1   1   1
7   47  47  4   3   1   1
8   43  43  3   3   1   1
9   48  48  3   3   1   1
10  53  53  3   3   1   1
11  53  53  4   5   1   1
12  24  24  3   5   1   1
13  39  39  5   5   1   1
14  24  24  5   4   1   1
15  48  48  5   1   1   1
16  49  49  5   3   1   1
17  50  50  5   4   1   1
18  50  50  5   4   1   1
19  50  50  5   4   1   1
20  50  50  4   4   1   1
21  24  24  3   4   1   1
22  50  50  4   4   1   1
```

Figure 4.2: Example of .sp.att file

- Table

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



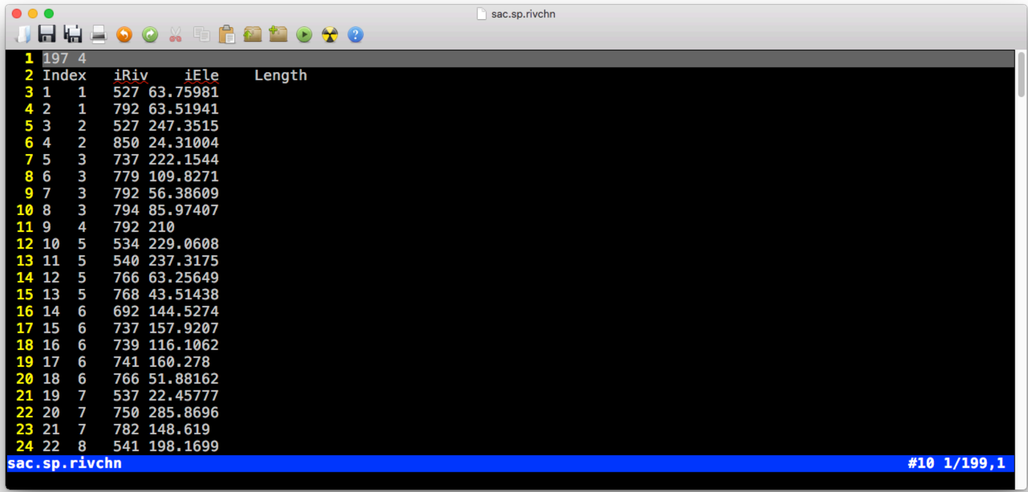

```
77  5
Index   Down    Type    Slope   Length
1   4   2   0.001807047 127.2792
2   1   2   0.0002208611    271.6616
3   6   2   0.002740643 474.3416
4   3   2   -0.000380952    210
5   8   2   6.979145e-05    573.1492
6   5   2   0.002156285 630.7139
7   22  2   -8.753545e-05   456.9464
8   7   2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

Figure 4.3: Example of .sp.riv file

- Pre-table

Colname	Meaning	Range	Unit	Comments
ID	Index of river i	$1 \sim N_{river}$	-	
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 ~ 10	m/m	Height/Length
Length	Length of the river i	0 ~ inf	m	

4.1.4 .sp.rivchn file



```
197 4
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
sac.sp.rivchn                                    #10 1/199,1
```

Figure 4.4: Example of .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	$1 \sim N_{river}$	-	

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

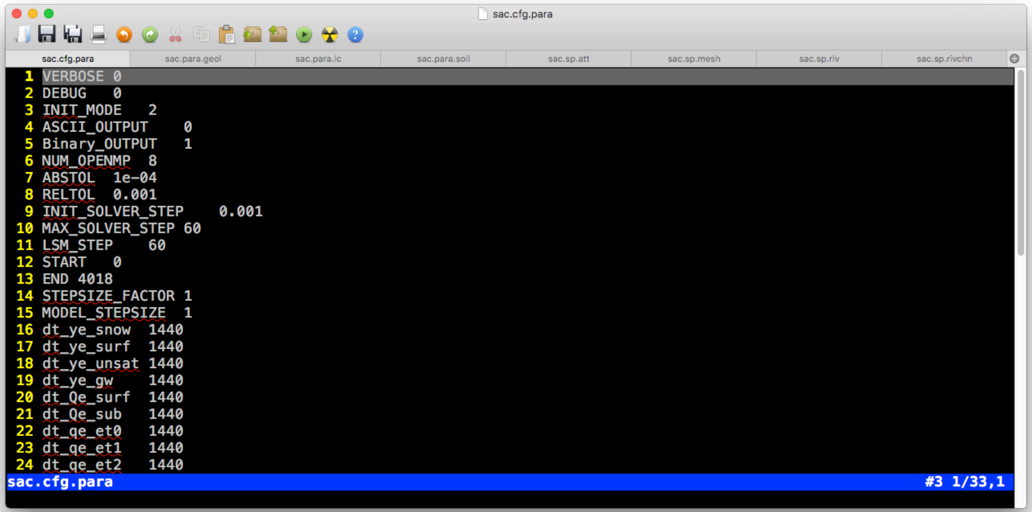
4.2 Model configuration files

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	$0 \sim N_{threads}$	-	
ABSTOL	Abosolute tolerance for CVODE solver	1e-6 ~ 0.1	-	
RELTOL	Relative tolerance for CVODE solver	1e-6 ~ 0.1	-	
INIT_SOLVER_STEP	Initial time step for CVODE solver	?	-	
MAX_SOLVER_STEP	Maximum time step for CVODE solver	?	-	
LSM_STEP	Time step of Evapotranspiration	1~360	min	
START	Start Time	-	day	
END	End Time	-	day	
STEPSIZE_FACTOR	Step size factor	-	-	Temporary value
MODEL_STEPSIZE	Model step size	-	min	
dt_ye_snow	Time step of output snow storage	$0 \sim$ inf	m	
dt_ye_surf	Time step of output surface storage	$0 \sim$ inf	m	
dt_ye_unsat	Time step of output unsaturated storage	$0 \sim$ inf	m	

Colname	Meaning	Range	Unit	Comments
dt_ye_gw	Time step of output groundwater head	0 ~ inf	m	
dt_Qe_surf	Time step of output surface element flux	0 ~ inf	m^3/day	
dt_Qe_sub	Time step of output subsurface element flux	0 ~ inf	m^3/day	
dt_qe_et0	Time step of output element flux, interception	0 ~ inf	m/day	
dt_qe_et1	Time step of output element flux, transpiration	0 ~ inf	m/day	
dt_qe_et2	Time step of output element flux, evaporation	0 ~ inf	m/day	
dt_qe_etp	Time step of output element flux, potential ET	0 ~ inf	m/day	
dt_qe_prcp	Time step of output element flux, interception	0 ~ inf	m/day	
dt_qe_infil	Time step of output element flux, interception	0 ~ inf	m/day	
dt_qe_rech	Time step of output element flux, interception	0 ~ inf	m/day	
dt_yr_stage	Time step of output river stage	0 ~ inf	m^3/day	
dt_Qr_down	Time step of output river flux, downstream	0 ~ inf	m^3/day	
dt_Qr_surf	Time step of output river flux, surface flow	0 ~ inf	m^3/day	
dt_Qr_sub	Time step of output river flux, base flow	0 ~ inf	m^3/day	
dt_Qr_up	Time step of output river flux, upstream	0 ~ inf	m^3/day	



```
VERBOSE 0
DEBUG   0
INIT_MODE   2
ASCII_OUTPUT    0
Binary_OUTPUT   1
NUM_OPENMP  8
ABSTOL  1e-04
RELTOL  0.001
INIT_SOLVER_STEP    0.001
MAX_SOLVER_STEP 60
LSM_STEP    60
START   0
END 4018
STEPSIZE_FACTOR 1
MODEL_STEPSIZE  1
dt_ye_snow  1440
dt_ye_surf  1440
dt_ye_unsat 1440
dt_ye_gw    1440
dt_Qe_surf  1440
dt_Qe_sub   1440
dt_qe_et0   1440
dt_qe_et1   1440
dt_qe_et2   1440
```

Figure 4.5: Example of .cfg.para file

4.2.2 .cfg.calib file

- Table

Colname	Meaning	Range	Unit	Comments
KSATH	Horizontal conductivity of ground water	?	-	
KSATV	Vertical conductivity of ground water	?	-	
KINF	Vertical conductivity of top soil	?	-	
KMACSATH	Horizontal conductivity of macropore	?	-	
KMACSATV	Vertical conductivity of soil macropore	?	-	
DINF	Infiltration depth	?	-	
DROOT	Root depth		-	
DMAC	Macropore depth		-	
THETAS	Porosity, saturated soil moisture		-	
THETAR	Residual soil moisture		-	
ALPHA	α value in van Genuchten equation		-	
BETA	β value in van Genuchten equation		-	
MACVF	Vertical macropore areal fraction		-	
MACHF	Horizontal macropore areal fraction		-	
VEGFRAC	Vegetation fraction		-	
ALBEDO	Emissitive reflection ratio		-	
ROUGH	Manning's roughness of element surface		-	
AQUIFER	Thichness of aquifer		-	
PRCP	Precipitation		-	

Colname	Meaning	Range	Unit	Comments
SFCTMP	Temperature		-	
EC	Interception		-	
ETT	Transpiration		-	
EDIR	Evaporation		-	
RIV_ROUGH	Manning's roughness of river		-	
RIV_KH	Conductivity of river bed		-	
RIV_DPTH	Depth of river cross section		-	
RIV_WDTH	Width of river cross section		-	
RIV_SINU	Sinuosity of river path		-	
RIV_CWR	C_{wr} in Chezy equation		-	
RIV_BSLOPE	Slope of river bed		-	
SOIL_DGD	Soil degradation		-	
IMPAF	Impervious areal fraction		-	
ISMAX	Maximum interception		-	

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 ~ inf	m	
Snow	Snow storage of element i	0 ~ inf	m	
Surface	Surface storage of element i	0 ~ inf	m	
Unsat	Unsaturated storage of element i	0 ~ inf	m	
GW	Groundwater head of element i	0 ~ inf	m	

- **Block 2 (river initial condition)**
- Pre-table:

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

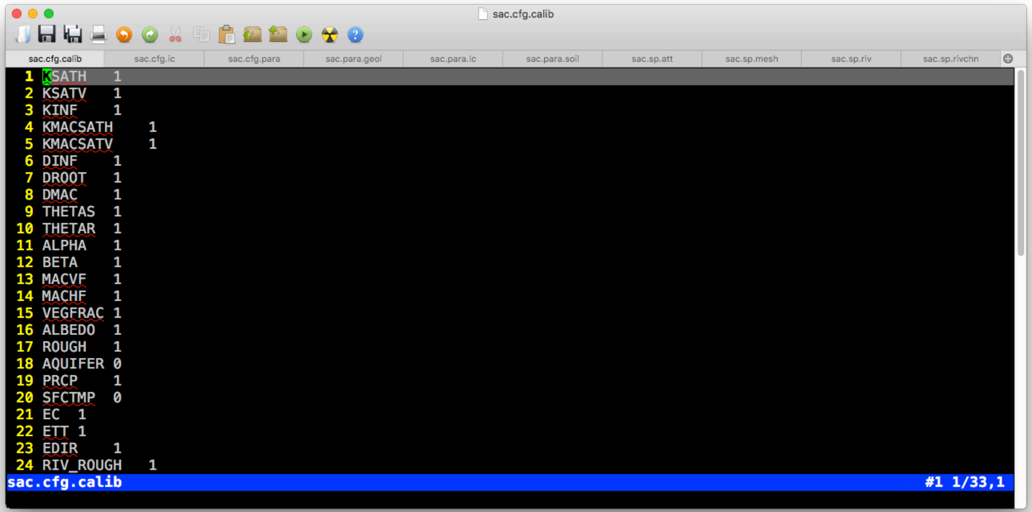


Figure 4.6: Example of .cfg.calib file

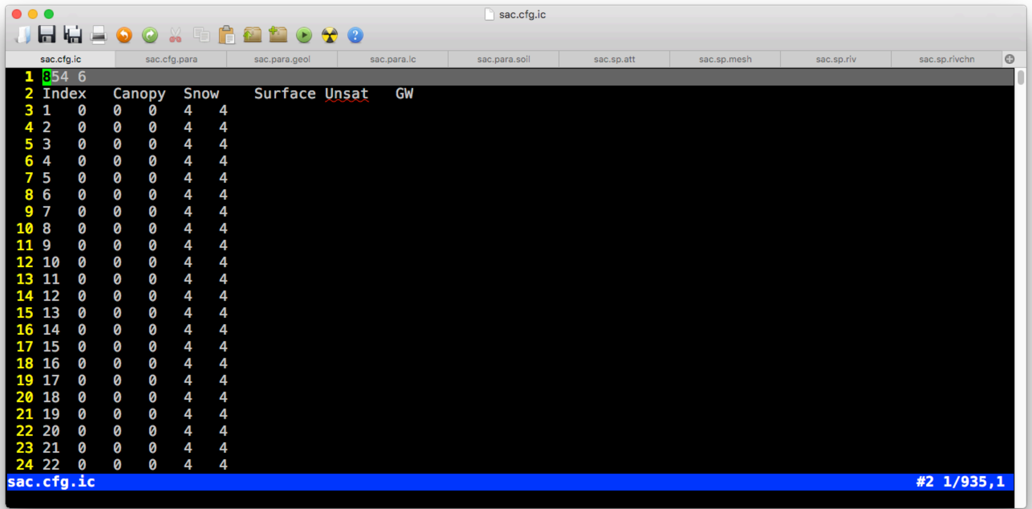


Figure 4.7: Example of .cfg.ic file

- Table

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

4.3 Time-series data

4.3.1 .tsd.forc file

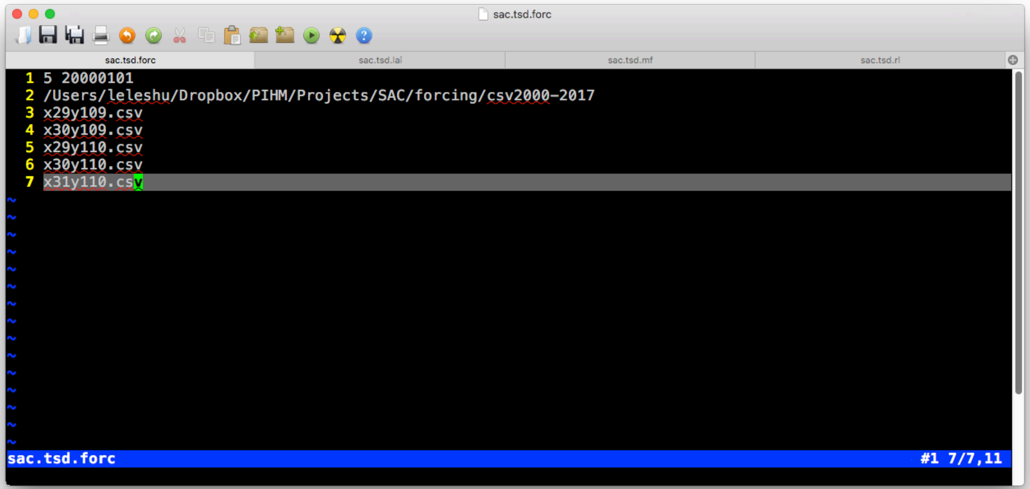


Figure 4.8: Example of .tsd.forc file

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

4.3.2 .tsd.lai file

- Pre-table:

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

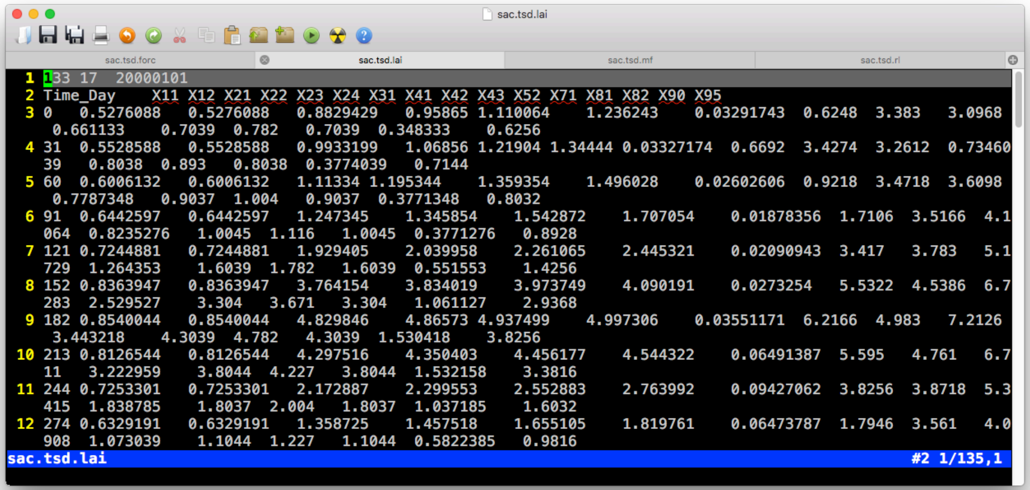


Figure 4.9: Example of .tsd.lai file

- Table

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

4.3.3 .tsd.rl file

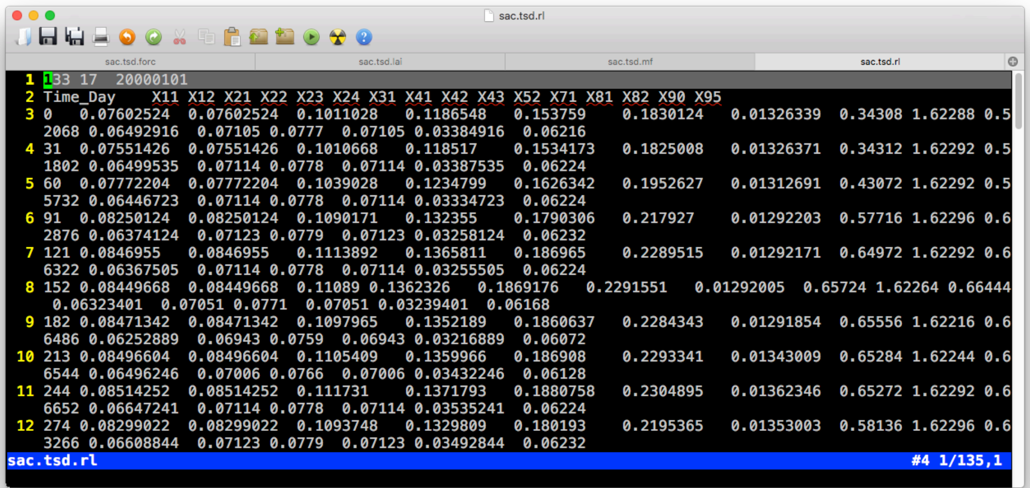


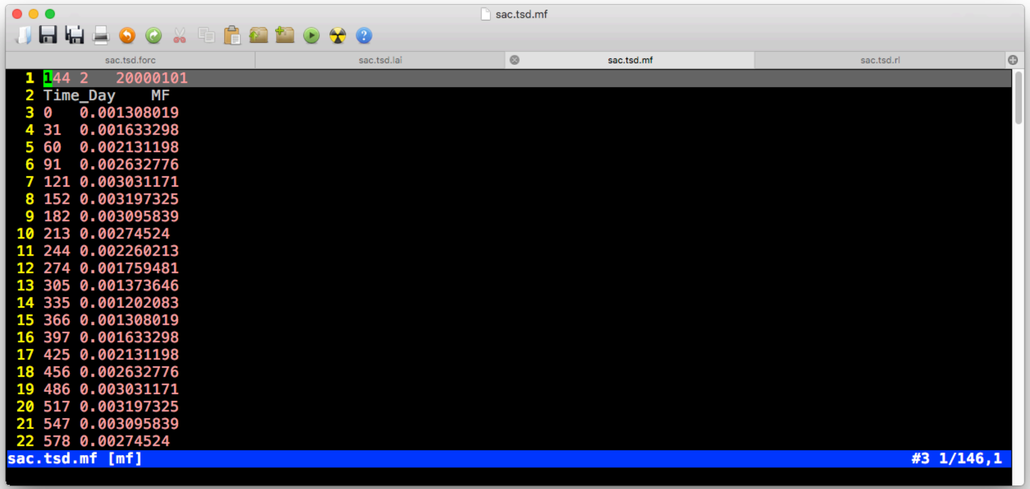
Figure 4.10: Example of .tsd.rl file

- Pre-table:

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

- Table

4.3.4 .tsd.mf file



```
144 2   20000101
Time_Day    MF
0   0.001308019
31  0.001633298
60  0.002131198
91  0.002632776
121 0.003031171
152 0.003197325
182 0.003095839
213 0.00274524
244 0.002260213
274 0.001759481
305 0.001373646
335 0.001202083
366 0.001308019
397 0.001633298
425 0.002131198
456 0.002632776
486 0.003031171
517 0.003197325
547 0.003095839
578 0.00274524
```

Figure 4.11: Example of .tsd.mf file

- Pre-table:

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

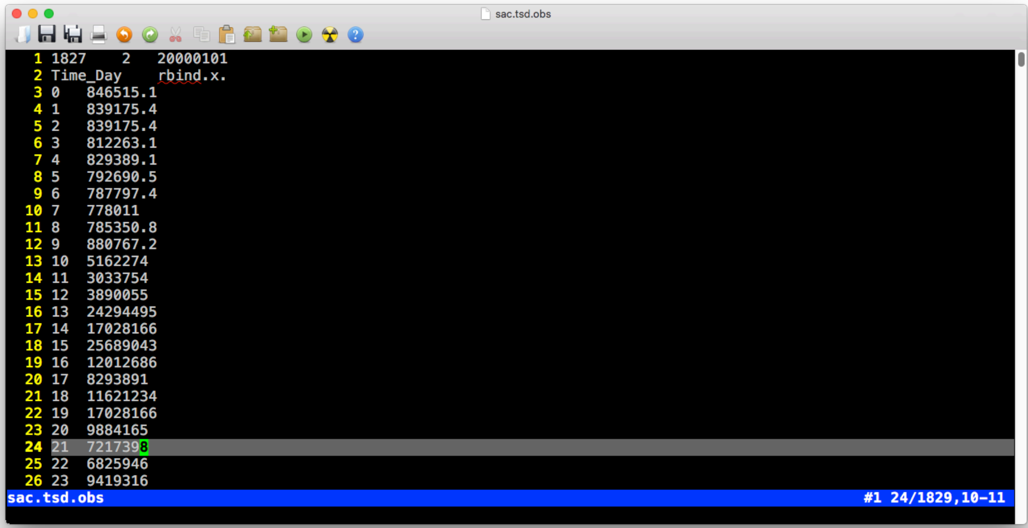
- Table

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



```
1827    2    20000101
Time_Day    rbind.x.
0    846515.1
1    839175.4
2    839175.4
3    812263.1
4    829389.1
5    792690.5
6    787797.4
7    778011
8    785350.8
9    880767.2
10   5162274
11   3033754
12   3890055
13   24294495
14   17028166
15   25689043
16   12012686
17   8293891
18   11621234
19   17028166
20   9884165
21   7217398
22   6825946
23   9419316
```

Figure 4.12: 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 Applications

Some *significant* applications are demonstrated in this chapter.

5.1 Example 1: Vauclin Experiment

5.2 Example 2: Shall Hill CZO

5.3 Example 3: Conestoga Watershed, Pennsylvanis

6 Automatic hydrologic modeling with PIHM system

Automatic deployment of PIHM System

7 Course code and program design

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

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