Solver for Hydrologic Unstructured Domain (SHUD)

User Guide

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Contents

1 Overview

This is a user guide or technical documentation of the SHUD modeling system.

The Solver for Hydrologic Unstructured Domain (SHUD - pronounced "SHOULD") is a multi-process, multi-scale hydrological model where major hydrological processes are fully coupled using the semi-discrete **Finite Volume Method** (FVM).

SHUD-tools is an open-source GIS and hydrological analysis toolkit designed for SHUD modeling system. The SHUDtools 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 **SHUD Modeling System**.

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

1.1 Standing on the shoulder of giant

SHUD is a descendent of **Penn State Integrated Hydrologic Model (PIHM)**, SHUD inherits the fundamental idea of solving hydrological variables in CVODE, but the model structure, compurational algorithm, programing laguage and input/out files are redesigned. The SHUD is imcompatible to PIHM.

It is our intention (me and previous PIHM group)to begin a debate on the role of *Community Models* in the hydrologic sciences.

SHUD and 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 SHUD

- 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.

1.2 Brief 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 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 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 modeling with SHUD

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
- 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/
Streamflow		http://nwis.waterdata.usgs.gov/nwis/sw
Groundwater		http://nwis.waterdata.usgs.gov/nwis/gw

1.4 Workflow of SHUD Modeling System

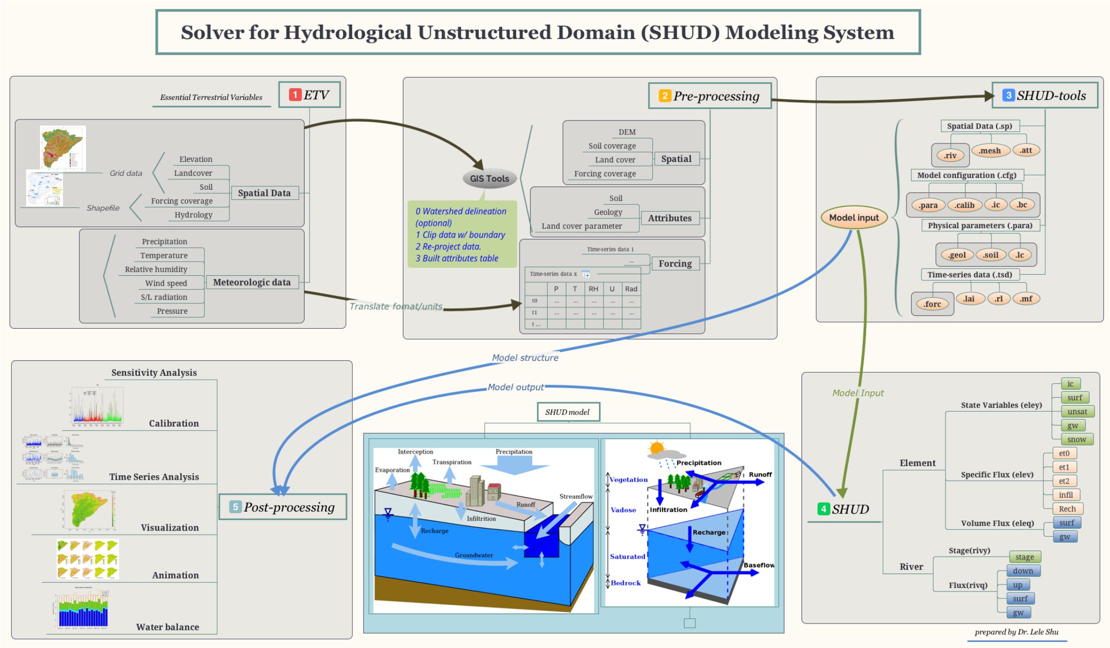


Figure 1.1: The workflow of modeling with SHUD Modeling System

1. Prepare raw Essential Terrestrial Variables (ETV)
2. Convert and crop raw data with the research area boundary.
3. Build the unstructued modeling domain with SHUD-tools
4. Run SHUD on desktop or cluster.
5. Analysis the SHUD model results with SHUD-tools or your hydrologic analysis tools.

2 Install SHUD and SHUD-tools

2.1 SUNDIALS/CVODE

The SHUD 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.

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*

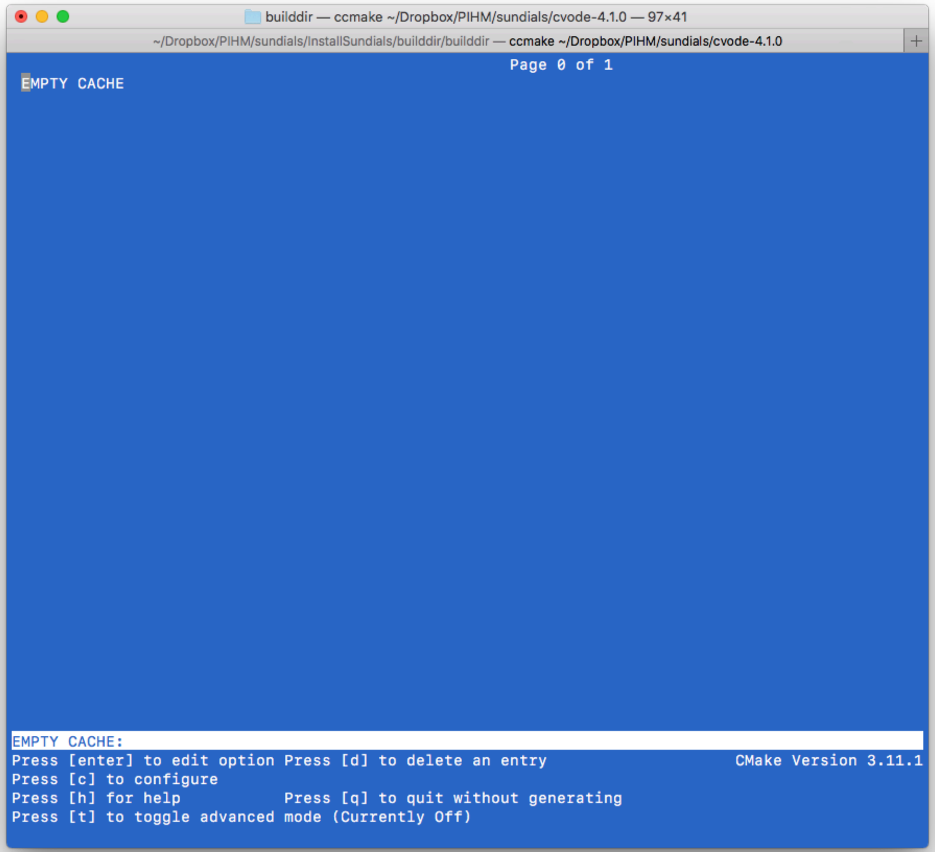
   ```
   mkdir builddir
   mkdir instdir
   mkdir srcdir
   cd builddir/
   ```

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

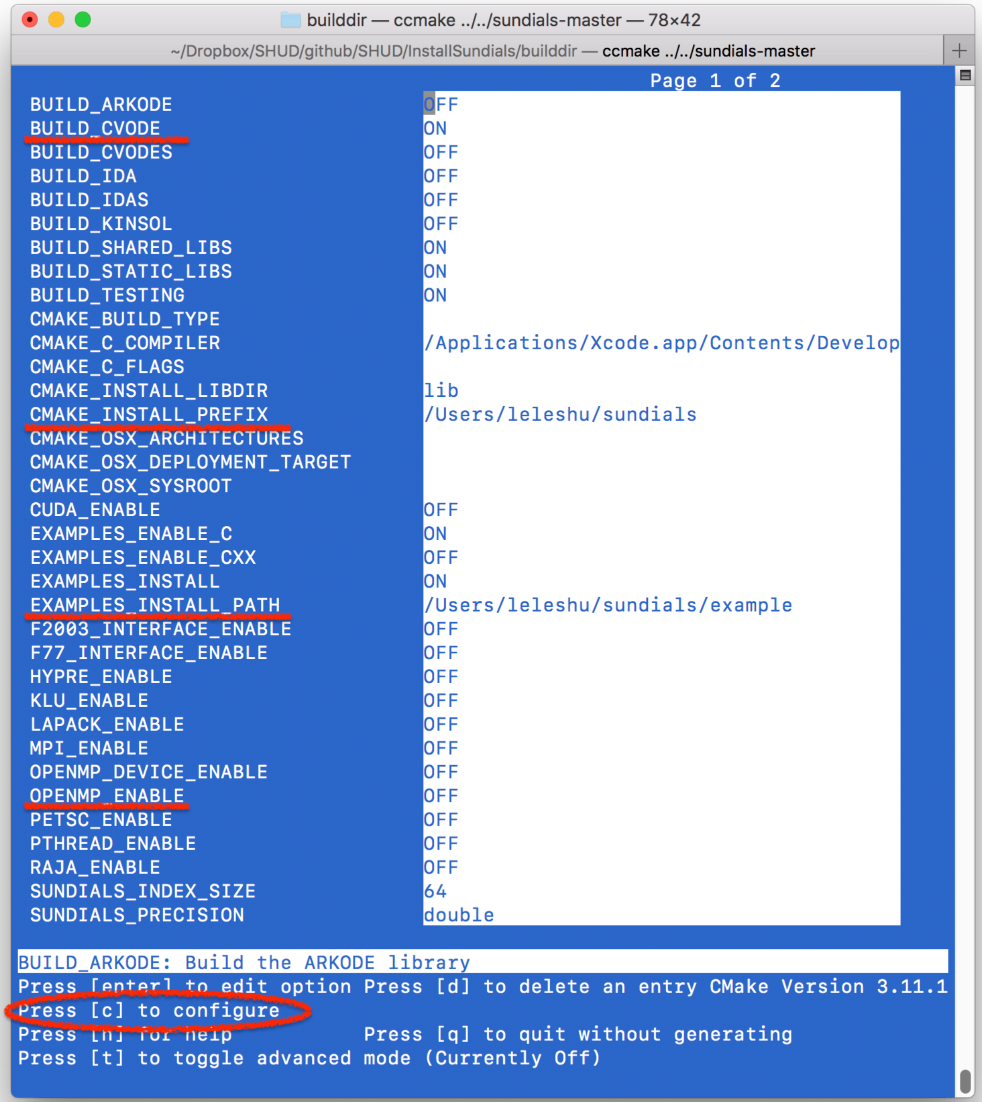
   ```
   ccmake
   ```

4. Run ccmake to configure your compile environment.

   ```
   ccmake ../sundials/cvode-5.0.0
   ```



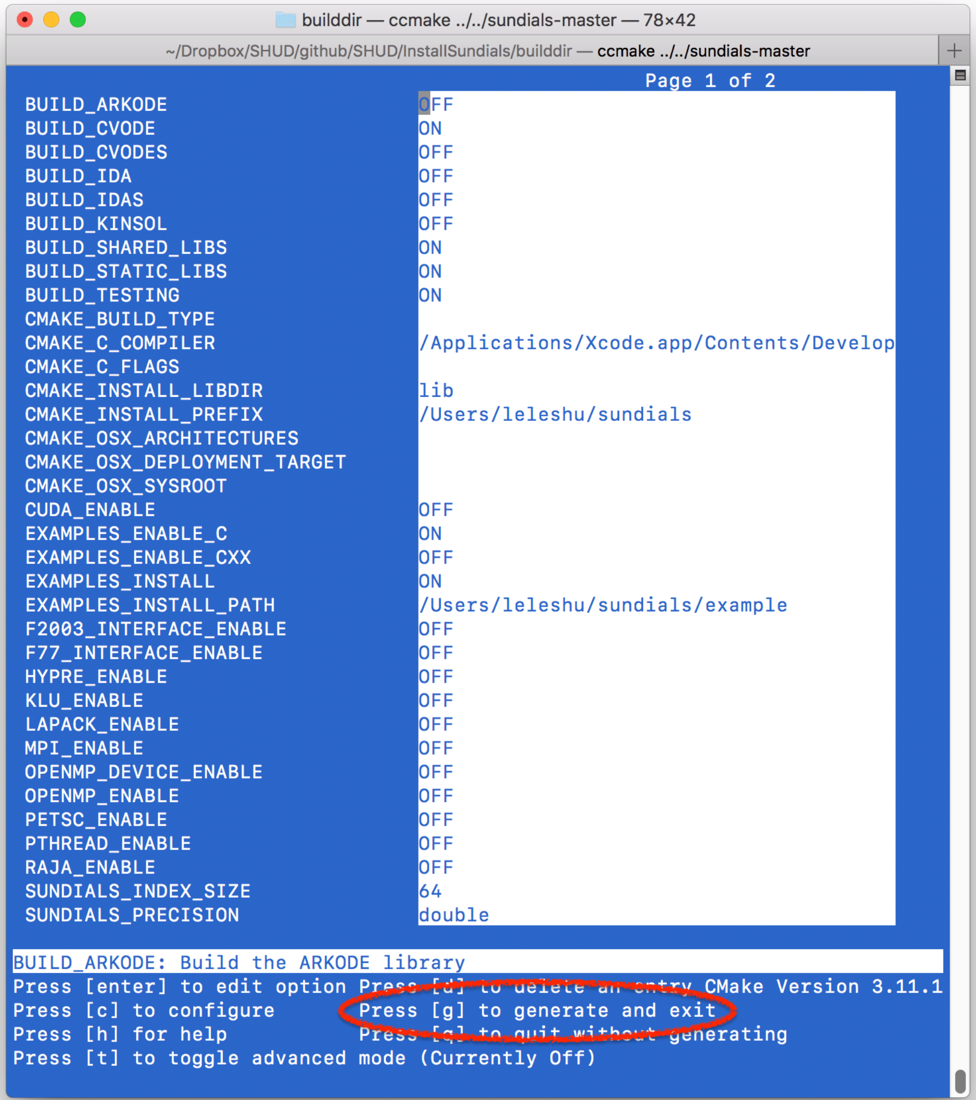
This is an empty configure. Press `c` to start the configuration.



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

```
BUILD_CVODE = ON
CMAKE_INSTALL_PREFIX = ~/sundials
EXAMPLES_INSTALL_PATH = ~/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 generate and exit.

1. Then you run commands below:

```
make
make install
```

2.2 SHUD

Configuration in *Makefile*:

1. Path of *SUNDIALS_DIR*. [**CRITICAL**]. If you install SUNDIALS into *~/sundials*, you don't change this line..
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 SHUD with:

```
make clean
make shud
```

There are more options to compile the SHUD code:

- `make all` - clean, then make both shud and shud_omp
- `make help` - help information
- `make SHUD` - make SHUD executable
- `make SHUD_omp` - make shud_omp with OpenMP support

2.2.1 OpenMP

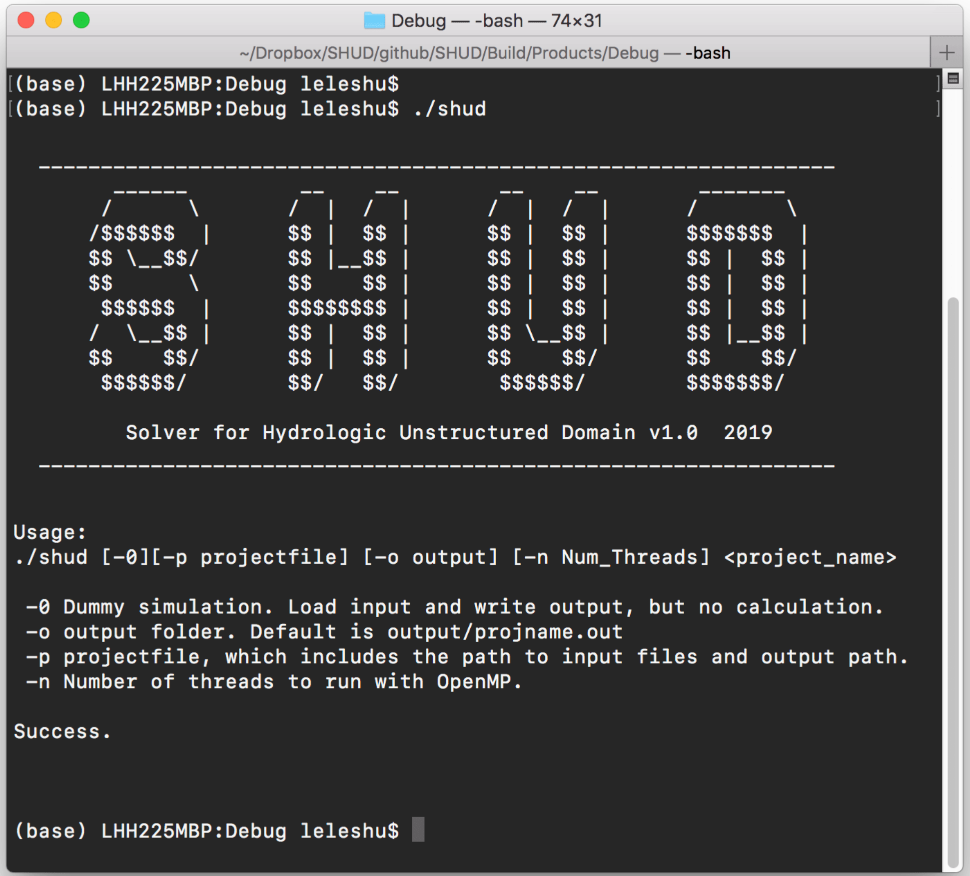
If parallel-computing is prefered, please install OpenMP. For mac:

```
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
```

2.2.2 Run SHUD executables.

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

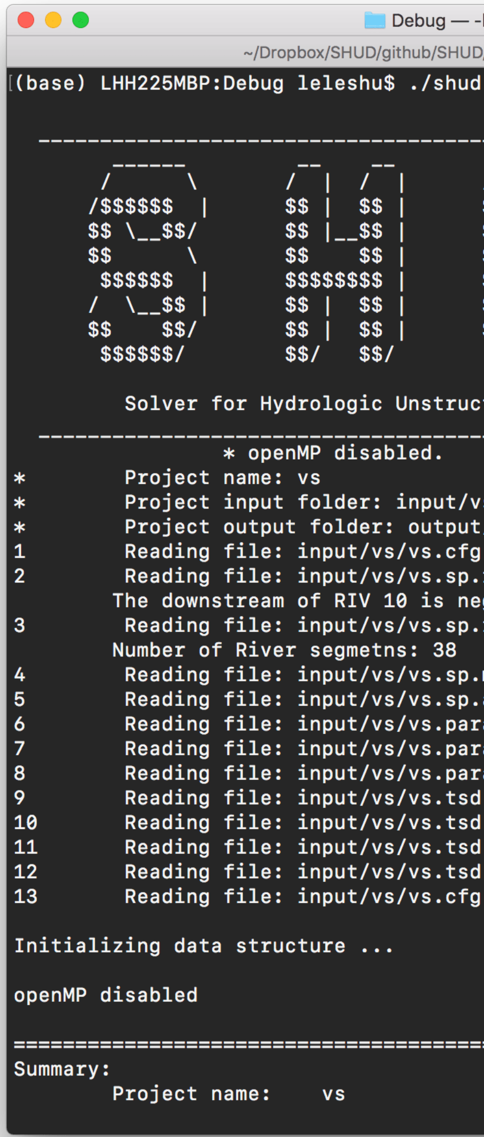
```
./shud <projectname>
```



Command line pattern is:

```
./shud [-0][-p projectfile] [-o output] [-n Num_Threads] <project_name>
```

- `-0` Dummy simulation. Load input and write output, but no calculation.
- `<project name>` is the name of the project.
- `[-p projectfile]` Specify the project file, which includes the path to input files and output path.
- `[-o output_folder]` Output directory. Default is output/projname.out
- `[-n Num_Threads]` Number of threads to run with OpenMP, which works with `pihm_omp` only. Usage:



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

2.3 SHUD-tools

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

```
install_github('SHUD-System/shud-tools')
```

That is all you need to deploy the SHUD-tools.

3 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 SHUD modeling, but they are very useful for your data pre- and post-processing.

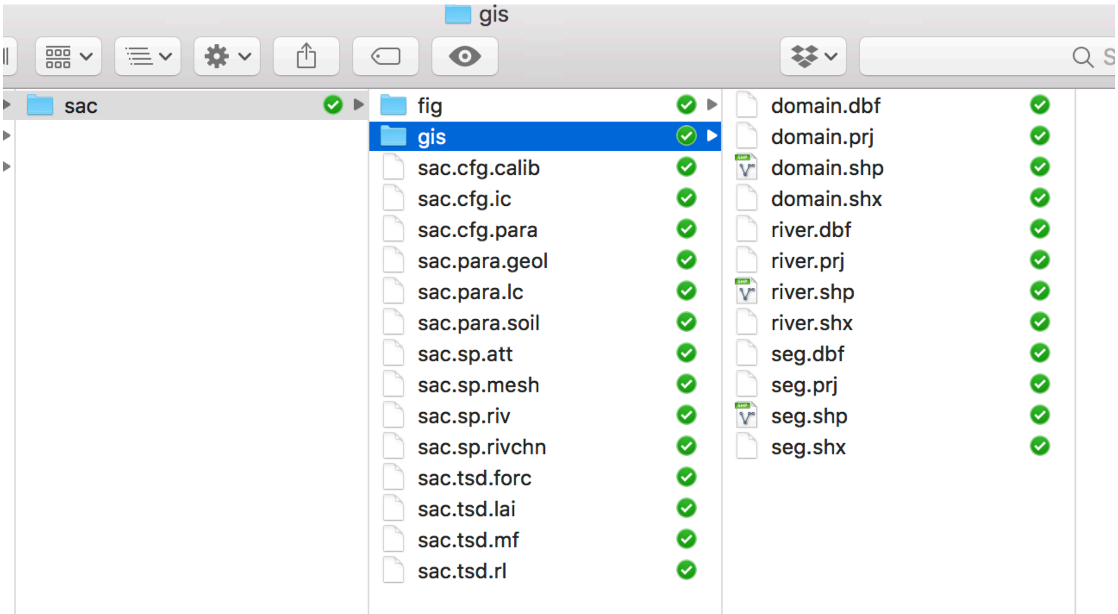
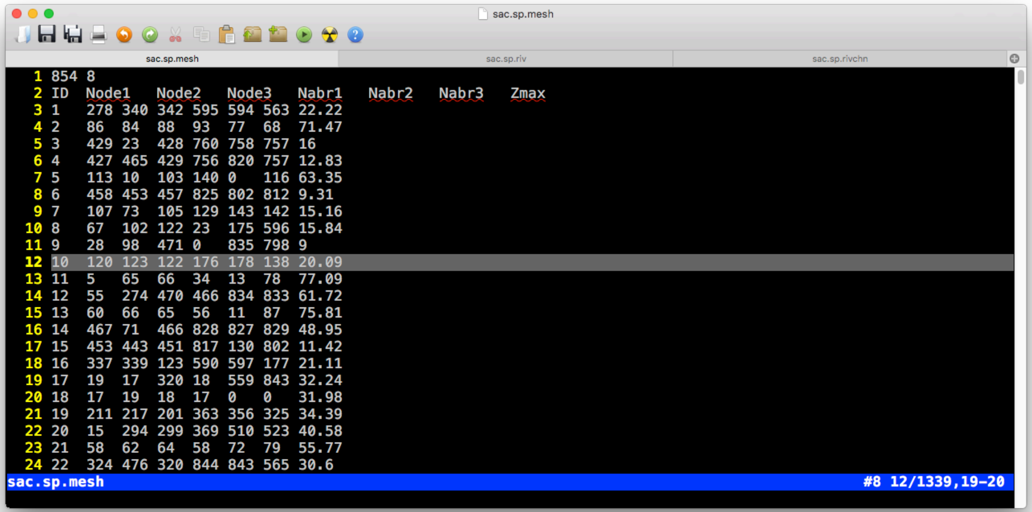


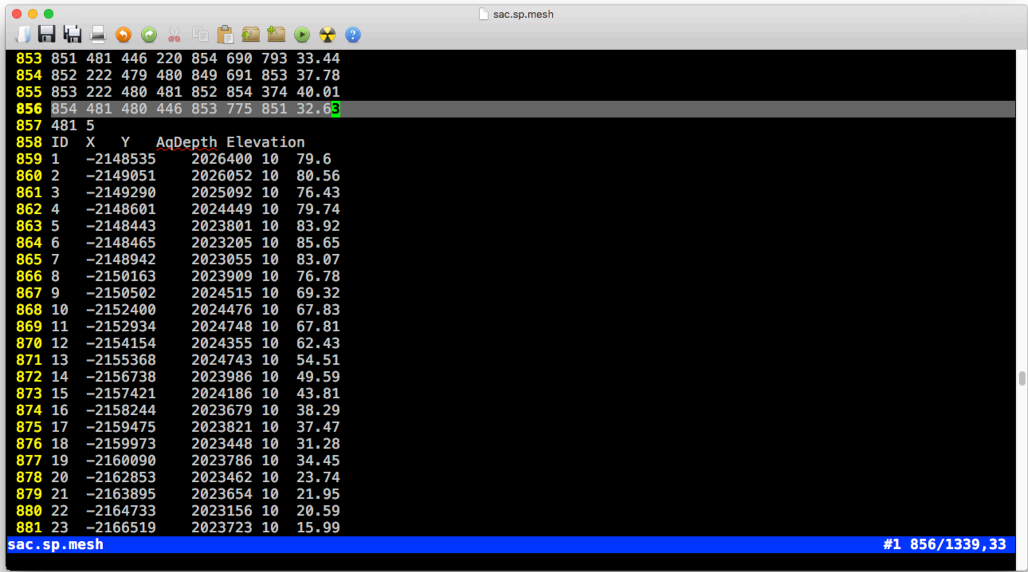
Figure 3.1: The screenshot of input files for SHUD

3.1 Spatial data

3.1.1 .sp.mesh file



```
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
```

```
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
```


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

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

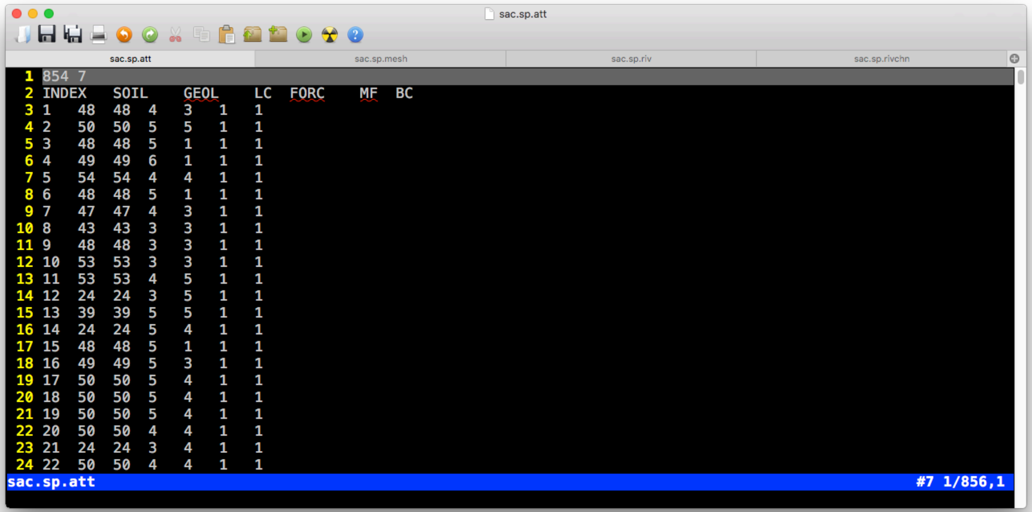
Colname	Meaning	Range	Unit	Comments
ID	Index of node i	$1 \sim N_{element}$	-	
X	X coordinate of node i	$1 \sim N_{node}$	-	
Y	Y coordinate of node i	$1 \sim N_{node}$	-	
AqDepth	Thickness of aquifer i	0 ~ +inf	m	
Elevation	Surface elevation of node i	-9999 ~ +inf	m	

3.1.2 .sp.att file

- Pre-table

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

- Table

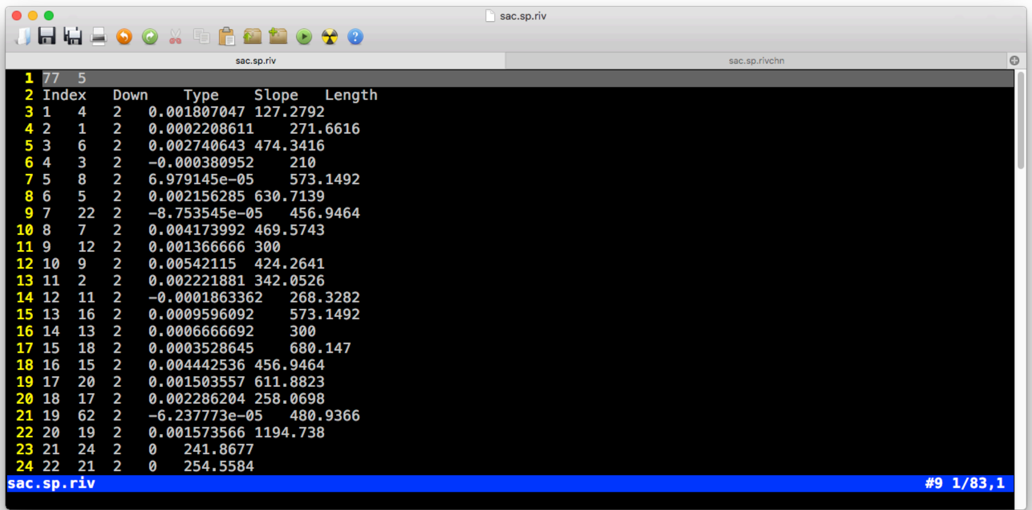


```
854 7
INDEX   SOIL    GEOL    LC  FORC    MF  BC
1   48  48  4   3   1   1
2   50  50  5   5   1   1
3   48  48  5   1   1   1
4   49  49  6   1   1   1
5   54  54  4   4   1   1
6   48  48  5   1   1   1
7   47  47  4   3   1   1
8   43  43  3   3   1   1
9   48  48  3   3   1   1
10  53  53  3   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 3.2: 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	$1 \sim N_{bc}$	-	

3.1.3 .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 3.3: Example of .sp.riv file

- Pre-table

Value1	Value2

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

3.1.4 .sp.rivseg 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 ~ $N_{segment}$	-	
iRiv	Index of river	1 ~ N_{river}	-	
iEle	Index of element	1 ~ $N_{element}$	-	
Length	Length of the segments i	0 ~ inf	m	

3.2 Model configuration files

3.2.1 .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 ~ $N_{threads}$	-	

Colname	Meaning	Range	Unit	Comments
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	?	-	
ET_STEP	Time step of Evapotranspiration	1~360	*min*	
START	Start Time	0 ~ inf	*day*	
END	End Time	-	*day*	
dt_ye_snow	Time step of output snow storage	0 ~ inf	*min*	
dt_ye_surf	Time step of output surface storage	0 ~ inf	*min*	
dt_ye_unsat	Time step of output unsaturated storage	0 ~ inf	*min*	
dt_ye_gw	Time step of output groundwater head	0 ~ inf	*min*	
dt_Qe_surf	Time step of output surface element flux	0 ~ inf	*min*	
dt_Qe_sub	Time step of output subsurface element flux	0 ~ inf	*min*	
dt_qe_et0	Time step of output element flux, interception	0 ~ inf	*min*	
dt_qe_et1	Time step of output element flux, transpiration	0 ~ inf	*min*	
dt_qe_et2	Time step of output element flux, evaporation	0 ~ inf	*min*	
dt_qe_etp	Time step of output element flux, potential ET	0 ~ inf	*min*	
dt_qe_prcp	Time step of output element flux, interception	0 ~ inf	*min*	

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

3.2.2 .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	Emissitive 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+	Thichness 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	

3.2.3 .cfg.ic file

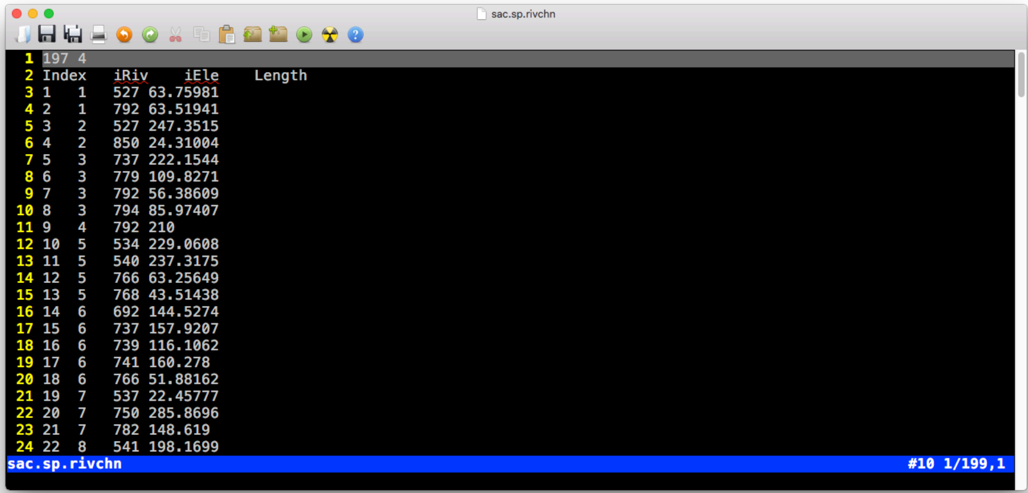
- **Block 1 (Element initial condition)**
- Pre-table

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

- Table

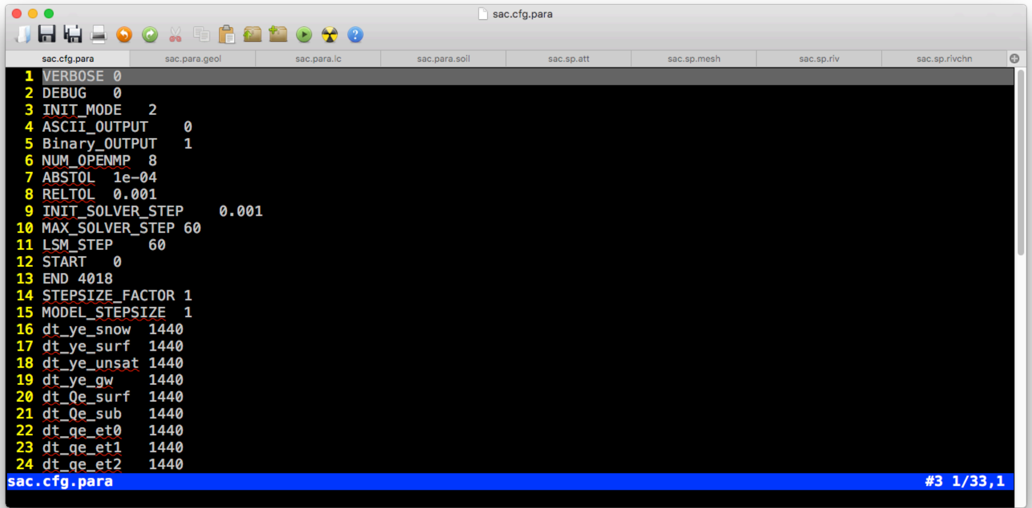
Colname	Meaning	Range	Unit	Comments
ID	Index of element i	$1 \sim N_{element}$	-	
Canopy	Canopy storage of element i	0 ~ inf	m	
Snow	Snow storage of element i	0 ~ inf	m	
Surface	Surface storage of element i	0 ~ inf	m	
Unsat	Unsaturated storage of element i	0 ~ inf	m	
GW	Groundwater head of element i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

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



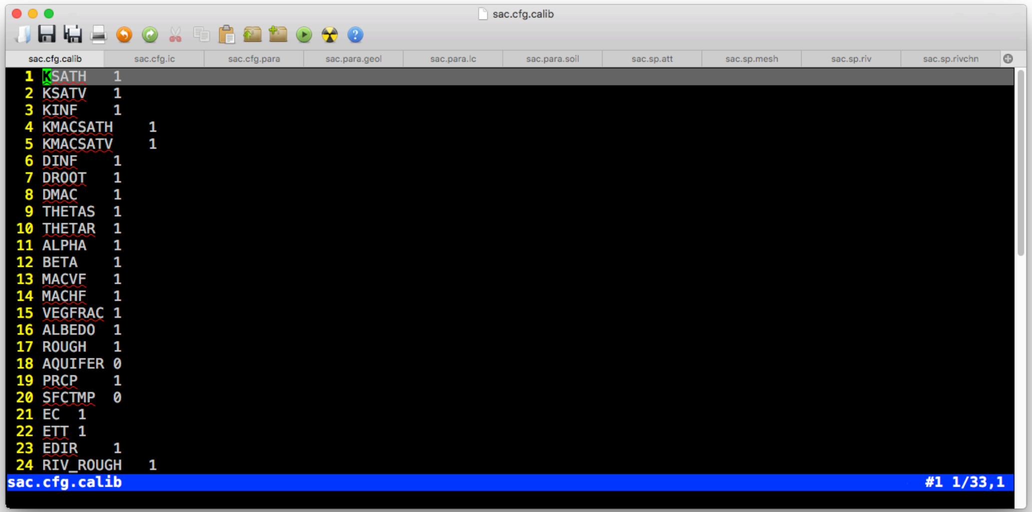

```
197 4
Index   iRiv    iEle    Length
1   1   527 63.75981
2   1   792 63.51941
3   2   527 247.3515
4   2   850 24.31004
5   3   737 222.1544
6   3   779 109.8271
7   3   792 56.38609
8   3   794 85.97407
9   4   792 210
10  5   534 229.0608
11  5   540 237.3175
12  5   766 63.25649
13  5   768 43.51438
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
```


Figure 3.4: Example of .sp.rivseg file



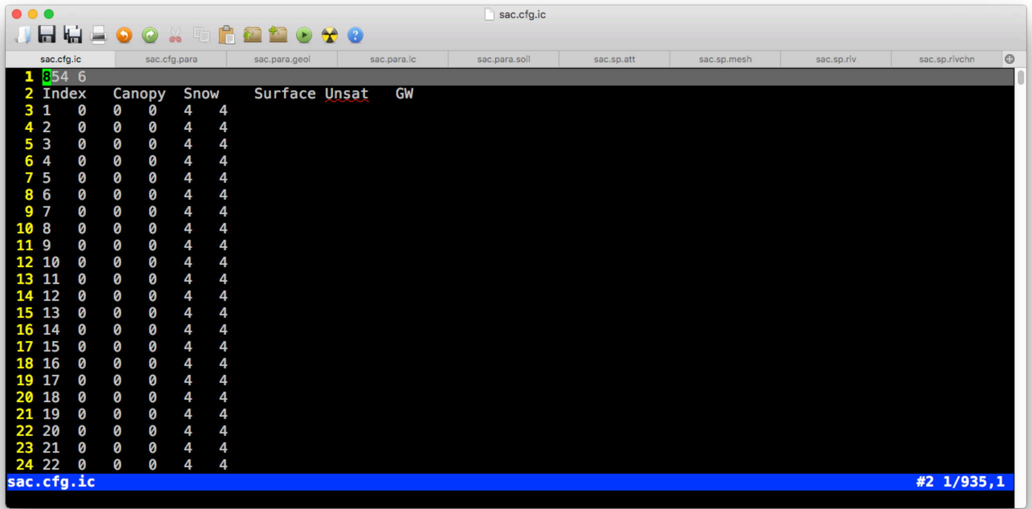

```
VERBOSE 0
DEBUG   0
INIT_MODE   2
ASCII_OUTPUT    0
Binary_OUTPUT   1
NUM_OPENMP  8
ABSTOL  1e-04
RELTOL  0.001
INIT_SOLVER_STEP    0.001
MAX_SOLVER_STEP 60
LSM_STEP    60
START   0
END 4018
STEPSIZE_FACTOR 1
MODEL_STEPSIZE  1
dt_ye_snow  1440
dt_ye_surf  1440
dt_ye_unsat 1440
dt_ye_gw    1440
dt_Qe_surf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


Figure 3.5: Example of .cfg.para file



```
KSATH   1
KSATV   1
KINF    1
KMACSATH    1
KMACSATV    1
DINF    1
DROOT   1
DMAC    1
THETAS  1
THETAR  1
ALPHA   1
BETA    1
MACVF   1
MACHF   1
VEGFRAC 1
ALBEDO  1
ROUGH   1
AQUIFER 0
PRCP    1
SFCTMP  0
EC  1
ETT 1
EDIR    1
RIV_ROUGH   1
sac.cfg.calib                                          #1 1/33,1
```

Figure 3.6: Example of .cfg.calib file



```
854 6
Index   Canopy  Snow    Surface Unsat   GW
1   0   0   0   4   4
2   0   0   0   4   4
3   0   0   0   4   4
4   0   0   0   4   4
5   0   0   0   4   4
6   0   0   0   4   4
7   0   0   0   4   4
8   0   0   0   4   4
9   0   0   0   4   4
10  0   0   0   4   4
11  0   0   0   4   4
12  0   0   0   4   4
13  0   0   0   4   4
14  0   0   0   4   4
15  0   0   0   4   4
16  0   0   0   4   4
17  0   0   0   4   4
18  0   0   0   4   4
19  0   0   0   4   4
20  0   0   0   4   4
21  0   0   0   4   4
22  0   0   0   4   4
sac.cfg.ic                                             #2 1/935,1
```

Figure 3.7: Example of .cfg.ic file

- 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	$0 \sim \inf$	m	

3.3 Time-series data

3.3.1 .tsd.forc file

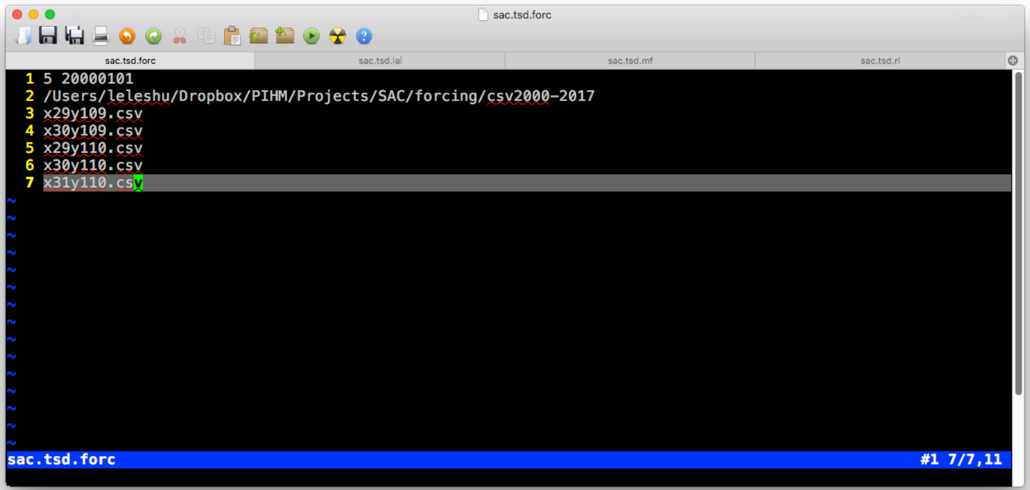
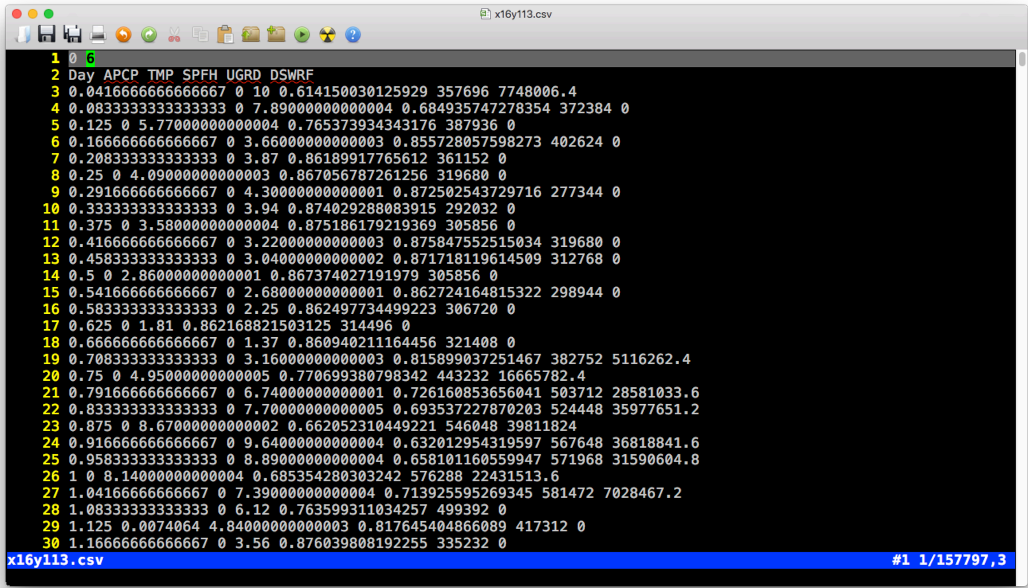


Figure 3.8: Example of .tsd.forc file

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

- Pre-table:



```
0 6
Day APCP TMP SPFH UGRD DSWRF
0.0416666666666667 0 10 0.614150030125929 357696 7748006.4
0.0833333333333333 0 7.89000000000004 0.684935747278354 372384 0
0.125 0 5.77000000000004 0.765373934343176 387936 0
0.166666666666667 0 3.66000000000003 0.855728057598273 402624 0
0.208333333333333 0 3.87 0.86189917765612 361152 0
0.25 0 4.09000000000003 0.867056787261256 319680 0
0.291666666666667 0 4.30000000000001 0.872502543729716 277344 0
0.333333333333333 0 3.94 0.874029288083915 292032 0
0.375 0 3.58000000000004 0.875186179219369 305856 0
0.416666666666667 0 3.22000000000003 0.875847552515034 319680 0
0.458333333333333 0 3.04000000000002 0.871718119614509 312768 0
0.5 0 2.86000000000001 0.867374027191979 305856 0
0.541666666666667 0 2.68000000000001 0.862724164815322 298944 0
0.583333333333333 0 2.25 0.862497734499223 306720 0
0.625 0 1.81 0.862168821503125 314496 0
0.666666666666667 0 1.37 0.860940211164456 321408 0
0.708333333333333 0 3.16000000000003 0.815899037251467 382752 5116262.4
0.75 0 4.95000000000005 0.770699380798342 443232 16665782.4
0.791666666666667 0 6.74000000000001 0.726160853656041 503712 28581033.6
0.833333333333333 0 7.70000000000005 0.693537227870203 524448 35977651.2
0.875 0 8.67000000000002 0.662052310449221 546048 39811824
0.916666666666667 0 9.64000000000004 0.632012954319597 567648 36818841.6
0.958333333333333 0 8.89000000000004 0.658101160559947 571968 31590604.8
1 0 8.14000000000004 0.685354280303242 576288 22431513.6
1.04166666666667 0 7.39000000000004 0.713925595269345 581472 7028467.2
1.08333333333333 0 6.12 0.763599311034257 499392 0
1.125 0.0074064 4.84000000000003 0.817645404866089 417312 0
1.16666666666667 0 3.56 0.876039808192255 335232 0
x16y113.csv                                              #1 1/157797,3
```

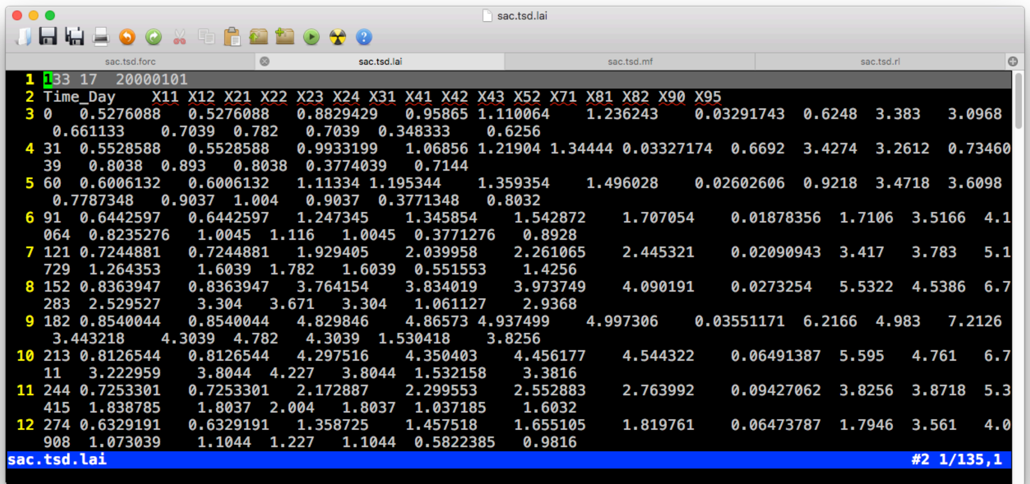
Figure 3.9: Example of .csv forcing file

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 ~ 70	C	
RH	Relative Humidity	$0 \sim 1$	–	
wind	Wind Speed	0 ~ inf	m/day	
Rn	Solar (shortwave) radiation	?	$J/day/m^2$	

3.3.2 .tsd.lai file



```
sac.tsd.forc    sac.tsd.lai    sac.tsd.mf    sac.tsd.rl
133 17  20000101
Time_Day    X11 X12 X21 X22 X23 X24 X31 X41 X42 X43 X52 X71 X81 X82 X90 X95
0   0.5276088   0.5276088   0.8829429   0.95865 1.110064    1.236243    0.03291743  0.6248  3.383   3.0968
 0.661133   0.7039  0.782   0.7039  0.348333    0.6256
31  0.5528588   0.5528588   0.9933199   1.06856 1.21904 1.34444 0.03327174  0.6692  3.4274  3.2612  0.73460
39  0.8038  0.893   0.8038  0.3774039   0.7144
60  0.6006132   0.6006132   1.11334 1.195344    1.359354    1.496028    0.02602606  0.9218  3.4718  3.6098
 0.7787348  0.9037  1.004   0.9037  0.3771348   0.8032
91  0.6442597   0.6442597   1.247345    1.345854    1.542872    1.707054    0.01878356  1.7106  3.5166  4.1
064 0.8235276   1.0045  1.116   1.0045  0.3771276   0.8928
121 0.7244881   0.7244881   1.929405    2.039958    2.261065    2.445321    0.02090943  3.417   3.783   5.1
729 1.264353    1.6039  1.782   1.6039  0.551553    1.4256
152 0.8363947   0.8363947   3.764154    3.834019    3.973749    4.090191    0.0273254   5.5322  4.5386  6.7
283 2.529527    3.304   3.671   3.304   1.061127    2.9368
182 0.8540044   0.8540044   4.829846    4.86573 4.937499    4.997306    0.03551171  6.2166  4.983   7.2126
 3.443218   4.3039  4.782   4.3039  1.530418    3.8256
213 0.8126544   0.8126544   4.297516    4.350403    4.456177    4.544322    0.06491387  5.595   4.761   6.7
11  3.222959    3.8044  4.227   3.8044  1.532158    3.3816
244 0.7253301   0.7253301   2.172887    2.299553    2.552883    2.763992    0.09427062  3.8256  3.8718  5.3
415 1.838785    1.8037  2.004   1.8037  1.037185    1.6032
274 0.6329191   0.6329191   1.358725    1.457518    1.655105    1.819761    0.06473787  1.7946  3.561   4.0
908 1.073039    1.1044  1.227   1.1044  0.5822385   0.9816
sac.tsd.lai                                              #2 1/135,1
```

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	
...	...	...	...	

3.3.3 .tsd.rl file

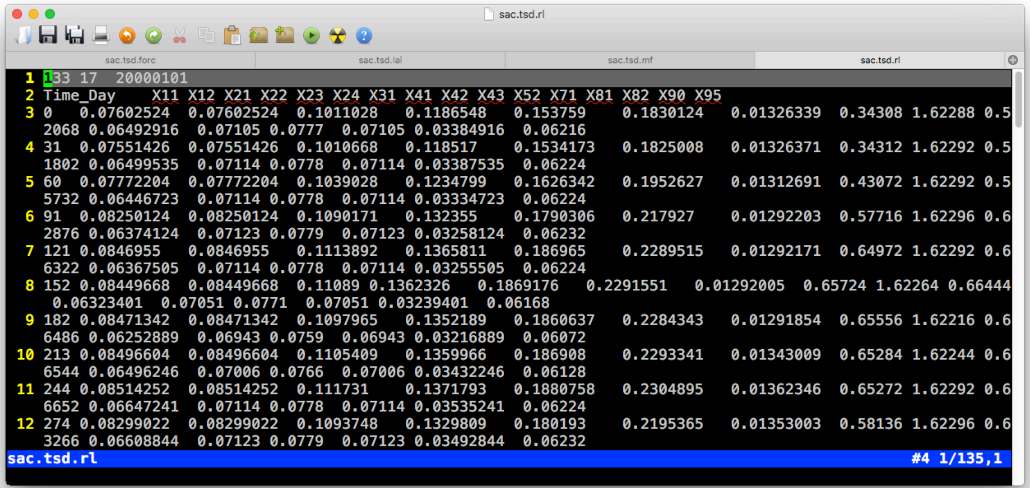

```
133 17  20000101
Time_Day    X11 X12 X21 X22 X23 X24 X31 X41 X42 X43 X52 X71 X81 X82 X90 X95
0   0.07602524  0.07602524  0.1011028   0.1186548   0.153759    0.1830124   0.01326339  0.34308 1.62288 0.5
2068 0.06492916  0.07105 0.0777  0.07105 0.03384916  0.06216
31  0.07551426  0.07551426  0.1010668   0.118517    0.1534173   0.1825008   0.01326371  0.34312 1.62292 0.5
1802 0.06499535  0.07114 0.0778  0.07114 0.03387535  0.06224
60  0.07772204  0.07772204  0.1039028   0.1234799   0.1626342   0.1952627   0.01312691  0.43072 1.62292 0.5
5732 0.06446723  0.07114 0.0778  0.07114 0.03334723  0.06224
91  0.08250124  0.08250124  0.1090171   0.132355    0.1790306   0.217927    0.01292203  0.57716 1.62296 0.6
2876 0.06374124  0.07123 0.0779  0.07123 0.03258124  0.06232
121 0.0846955   0.0846955   0.1113892   0.1365811   0.186965    0.2289515   0.01292171  0.64972 1.62292 0.6
6322 0.06367505  0.07114 0.0778  0.07114 0.03255505  0.06224
152 0.08449668  0.08449668  0.11089 0.1362326   0.1869176   0.2291551   0.01292005  0.65724 1.62264 0.66444
 0.06323401  0.07051 0.0771  0.07051 0.03239401  0.06168
182 0.08471342  0.08471342  0.1097965   0.1352189   0.1860637   0.2284343   0.01291854  0.65556 1.62216 0.6
6486 0.06252889  0.06943 0.0759  0.06943 0.03216889  0.06072
213 0.08496604  0.08496604  0.1105409   0.1359966   0.186908    0.2293341   0.01343009  0.65284 1.62244 0.6
6544 0.06496246  0.07006 0.0766  0.07006 0.03432246  0.06128
244 0.08514252  0.08514252  0.111731    0.1371793   0.1880758   0.2304895   0.01362346  0.65272 1.62292 0.6
6652 0.06647241  0.07114 0.0778  0.07114 0.03535241  0.06224
274 0.08299022  0.08299022  0.1093748   0.1329809   0.180193    0.2195365   0.01353003  0.58136 1.62296 0.6
3266 0.06608844  0.07123 0.0779  0.07123 0.03492844  0.06232
sac.tsd.rl                                                                                    #4 1/135,1
```

Figure 3.11: 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	$0 \sim$ inf	m	
Column i	Roughness length of land cover $i-1$	$0 \sim$ inf	m	
...	...	...	...	

3.3.4 .tsd.mf file

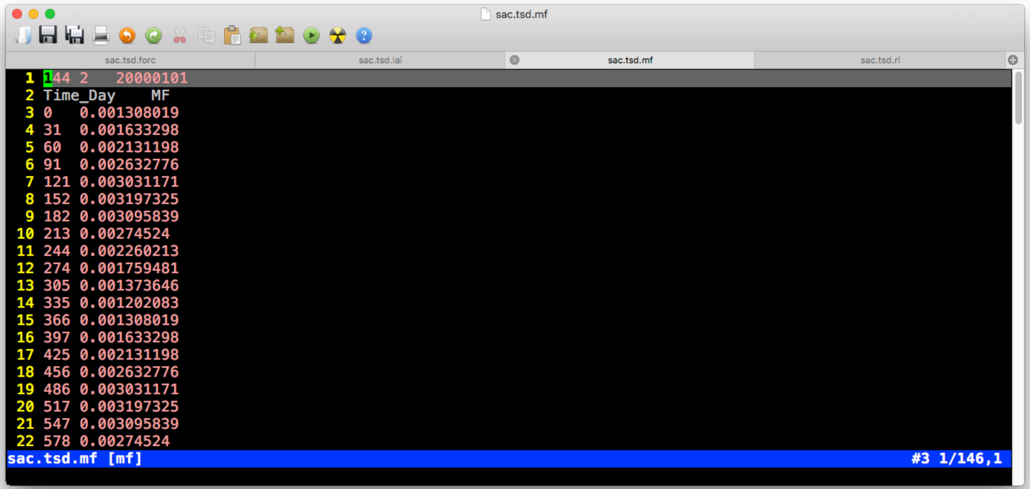


Figure 3.12: Example of .tsd.mf file

- 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	$0 \sim$ inf	-	
Column i	Melt factor $i-1$	$0 \sim$ inf	-	
...	...	...	...	

3.3.5 .tsd.obs file

- Pre-table:

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

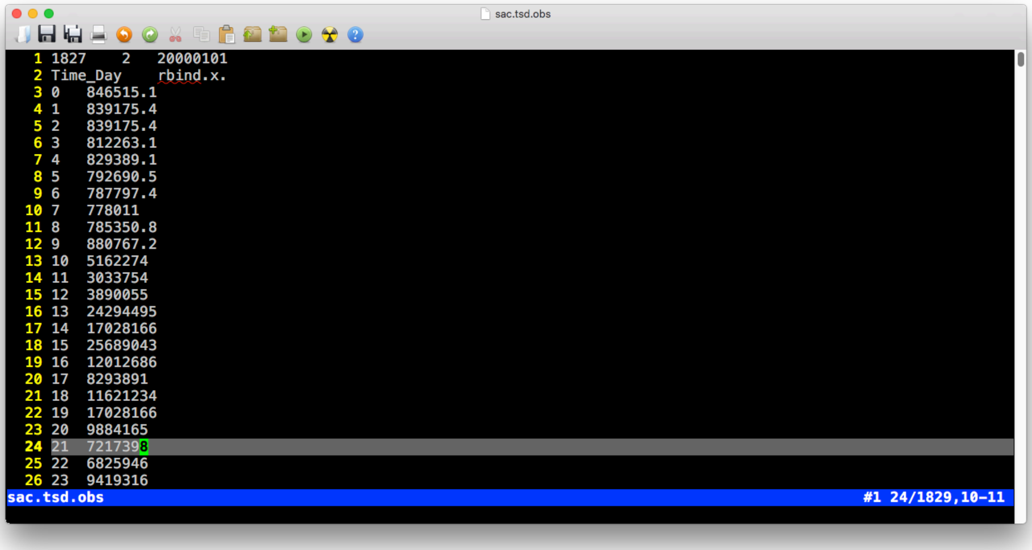


Figure 3.13: Example of .tsd.obs file

- Table

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

4 Output files

4.1 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 bindary 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* (elemtns), *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	
.eleyic.	ele	y	ic	Storage of Interception	m	
.eleysnow.	ele	y	snow	Storage of snow equivalence	m	
.eleysurf.	ele	y	surf	Storage of surface	m	
.eleyunsat.	ele	y	unsat	Storage of vados zone	m	
.eleygw.	ele	y	gw	Groundwater head	m	.GW
.elevetp.	ele	v	etp	Potential ET	$\frac{m^3}{m^2d}$	
.eleveta.	ele	v	eta	Actual ET	$\frac{m^3}{m^2d}$	
.elevetic.	ele	v	etic	Evap of interception	$\frac{m^3}{m^2d}$	
.elevettr.	ele	v	ettr	Transpiration	$\frac{m^3}{m^2d}$	
.elevetev.	ele	v	etev	Soil Evaporation	$\frac{m^3}{m^2d}$	
.elevprcp.	ele	v	prcp	Precipitation	$\frac{m^3}{m^2d}$	
.elevnetprcp.	ele	v	netprcp	Net Precipitation	$\frac{m^3}{m^2d}$	
.elevinfil.	ele	v	infil	Infiltration Rate	$\frac{m^3}{m^2d}$	
.elevexfil.	ele	v	infil	Exfiltration Rate	$\frac{m^3}{m^2d}$	
.elevrech.	ele	v	rech	Recharge Rate	$\frac{m^3}{m^2d}$	
.eleqsurf.	ele	q	surf	Overland flow	m^3/d	
.eleqsub.	ele	q	sub	Subsurface flow	m^3/d	
.rivystage.	riv	y	stage	River Stage	m	

Identifier	Mod unit	Type	Var Name	Meaning	Unit
.rivqup.	riv	q	up	Flux to upstream	m^3/d
.rivqdown.	riv	q	down	Flux to downstream	m^3/d
.rivqsurf.	riv	q	surf	Flux to landsurface	m^3/d
.rivqsub.	riv	q	sub	Flux to subsurface	m^3/d

4.2 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	$v_{1\cdot 1}$	$v_{1\cdot 2}$	...	$v_{1\cdot N}$
T_2	$v_{2\cdot 1}$	$v_{2\cdot 2}$	...	$v_{2\cdot N}$
T_3	$v_{3\cdot 1}$	$v_{3\cdot 2}$	...	$v_{3\cdot N}$
...	...	...	...	...
T_m	$v_{m\cdot 1}$	$v_{m\cdot 2}$	...	$v_{m\cdot N}$

4.3 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	$v_{1\cdot 1}$	double	8
5	2	$v_{1\cdot 2}$	double	8
...	...	...	double	8
$(N+1)*(T-1)+i+3$	N	$v_{1\cdot N}$	double	8
$(N+1)*(T-1)+i+3$	0	T_2	double	8
$(N+1)*(T-1)+i+3$	1	$v_{2\cdot 1}$	double	8
$(N+1)*(T-1)+i+3$	2	$v_{2\cdot 2}$	double	8
$(N+1)*(T-1)+i+3$	...	...	double	8
$(N+1)*(T-1)+i+3$	N	$v_{2\cdot N}$	double	8
$(N+1)*(T-1)+i+3$	0	T_3	double	8
$(N+1)*(T-1)+i+3$	1	$v_{3\cdot 1}$	double	8
$(N+1)*(T-1)+i+3$	2	$v_{3\cdot 2}$	double	8

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

5 Applications

Some *significant* applications are demonstrated in this chapter.

5.1 Best practice suggestions

1. Derive and QC all inputs (time mean, accumulation, screen fo anormalies …)
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 expection
5. If all above works, then hook all modules and run with your forcing data.

This chapter is imcomplete

5.2 Example 1: Vauclin Experiment

5.3 Example 2: Shall Hill CZO

5.4 Example 3: Conestoga Watershed, Pennsylvanis

6 Calibration

This chapter is imcomplete

File	Comments	Header	# of column
.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 *best* 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 logrithm | 0 | 0/1 | - | | min | Minimun value | - | - | - | | max | Maximun value | - | - | - |

7 Quick, Reproducible and Automatic hydrological modeling

Automatic deployment of SHUD System

8 Source code and program design

The source code of SHUD and SHUD-tool are avaliable via Github: https://github.com/SHUD-System/SHUD and https://github.com/SHUD-System/SHUD-tools.

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