

Solver for Hydrologic Unstructured Domain (SHUD)

User Guide

Lele Shu (lele.shu@gmail.com)

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Contents

1 Overview

This file is a user guide or technical documentation of the SHUD modeling system. PDF version of the User Guide is available via :SHUD User Guide

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).

SHUDtoolbox is an open-source GIS and hydrological analysis toolbox designed for the SHUD modeling system. The SHUDtoolbox 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 SHUDtoolbox 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 shoulders of giants

As a descendant of PIHM, SHUD inherits the fundamental idea of solving hydrological variables in CVODE. The code has been completely rewritten in a new programming language, with a new discretization and corresponding improvements to the underlying algorithms, adapting new mathematical schemes and a new user-friendly input/output data format. Although SHUD is forked from PIHM’s track, SHUD still inherits the use of CVODE for solving the ODEs but modernizes and extends PIHM’s technical and scientific capabilities. The SHUD is incompatible 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 represent our strategy for the synthesis of *multi-state*, *multi-scale* 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 a 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 cells 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, pollutants, 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 (?) 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

1.2 Brief History of PIHM system

Dr. Gopal Bhartt (?) 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 SHUD

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:

- (?)
- (?)
- (?)
- (?)
- (?)
- (?)
- (?)
- (?)
- (?)
- (?)
- (?)
- (?)

2 Install SHUD and SHUDtoolbox

2.1 SUNDIALS/CVODE

The SHUD model requires the support of the 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*.

```
mkdir builddir
cd builddir/
```

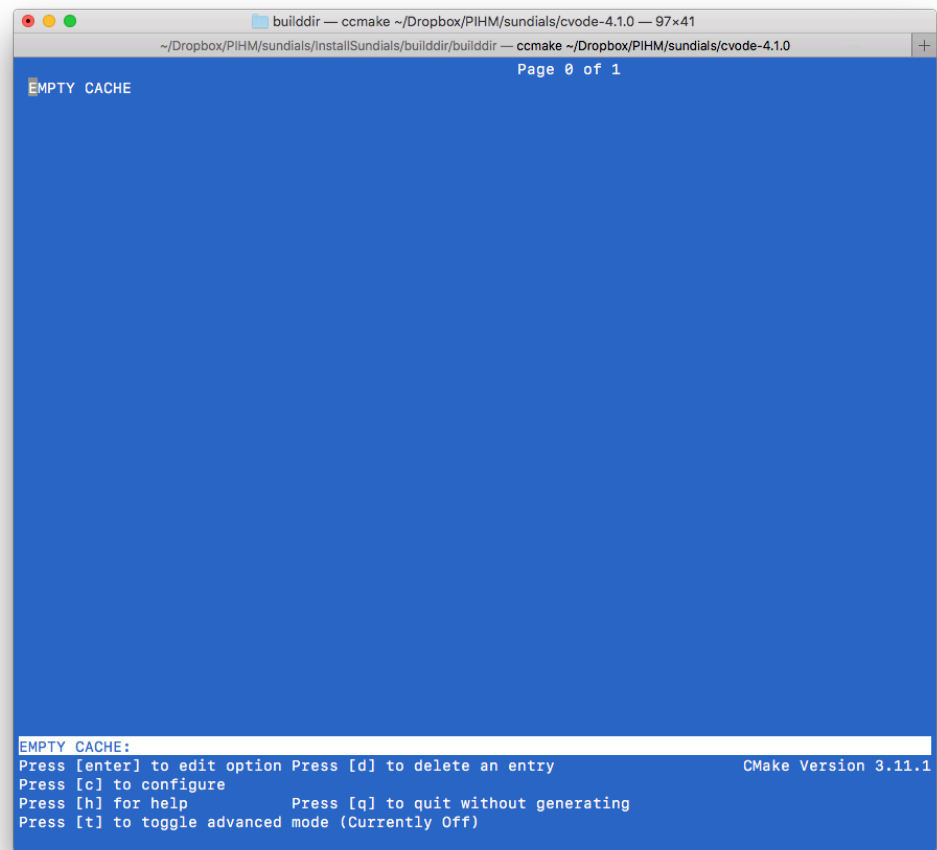
3. Try cmake. Install **cmake** if you don't have one.

```
ccmake
```

4. Run cmake to configure your compile environment.

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

2 Install SHUD and SHUDtoolbox



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

```

Page 1 of 2
BUILD_ARKODE OFF
BUILD_CVODE ON
BUILD_CVODES OFF
BUILD_IDA OFF
BUILD_IDAS OFF
BUILD_KINSOL OFF
BUILD_SHARED_LIBS ON
BUILD_STATIC_LIBS ON
BUILD_TESTING ON
CMAKE_BUILD_TYPE
CMAKE_C_COMPILER /Applications/Xcode.app/Contents/Develop
CMAKE_C_FLAGS
CMAKE_INSTALL_LIBDIR lib
CMAKE_INSTALL_PREFIX /Users/leleshu/sundials
CMAKE_OSX_ARCHITECTURES
CMAKE_OSX_DEPLOYMENT_TARGET
CMAKE_OSX_SYSROOT
CUDA_ENABLE OFF
EXAMPLES_ENABLE_C ON
EXAMPLES_ENABLE_CXX OFF
EXAMPLES_INSTALL ON
EXAMPLES_INSTALL_PATH /Users/leleshu/sundials/example
F2003_INTERFACE_ENABLE OFF
F77_INTERFACE_ENABLE OFF
HYPRE_ENABLE OFF
KLU_ENABLE OFF
LAPACK_ENABLE OFF
MPI_ENABLE OFF
OPENMP_DEVICE_ENABLE OFF
OPENMP_ENABLE OFF
PETSC_ENABLE OFF
PTHREAD_ENABLE OFF
RAJA_ENABLE OFF
SUNDIALS_INDEX_SIZE 64
SUNDIALS_PRECISION double

BUILD_ARKODE: Build the ARKODE library
Press [enter] to edit option Press [d] to delete an entry CMake Version 3.11.1
Press [c] to configure
Press [h] for help Press [q] to quit without generating
Press [t] to toggle advanced mode (Currently Off)

```

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

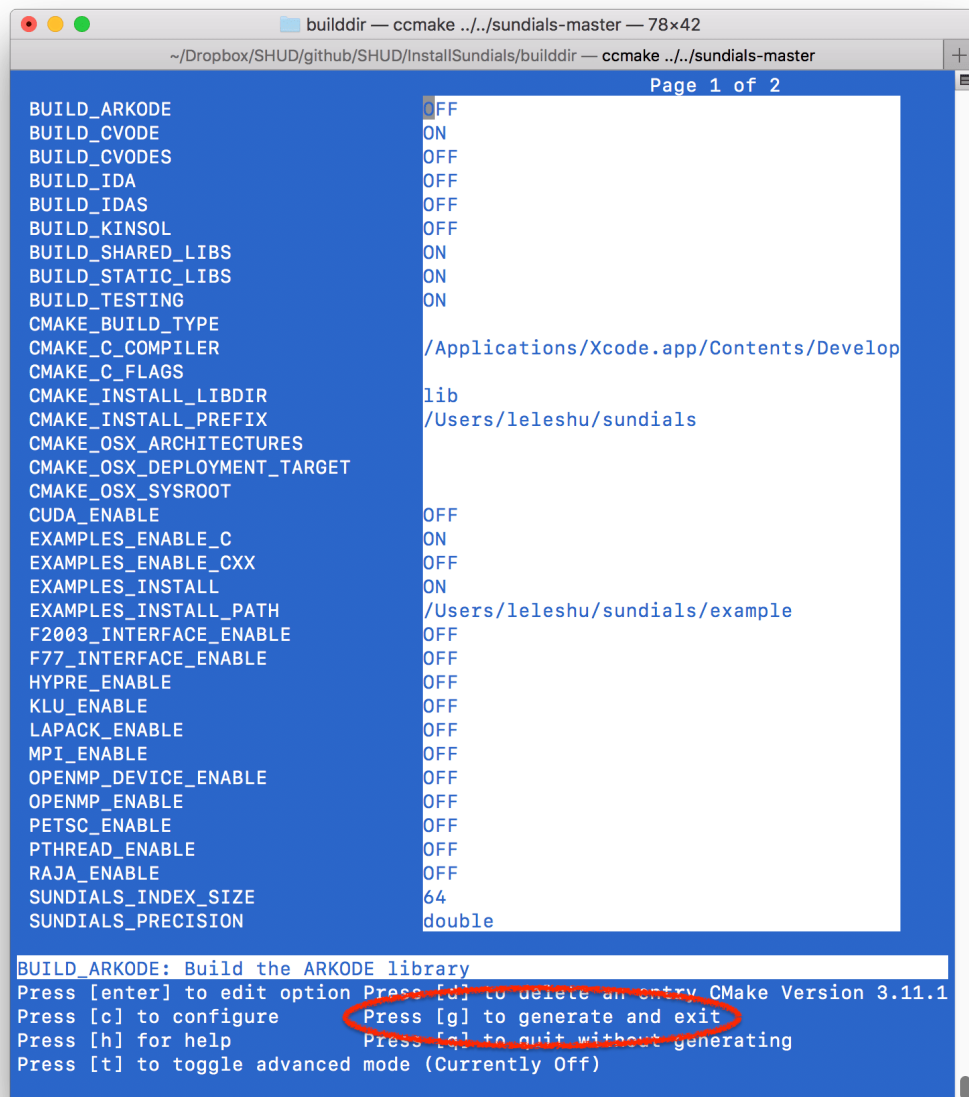
```

BUILD_CVODE = ON
CMAKE_INSTALL_PREFIX = ~/sundials
EXAMPLES_INSTALL_PATH = ~/sundials/examples

```

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

2 Install SHUD and SHUDtoolbox



```
builddir — cmake ../../sundials-master — 78x42
~/Dropbox/SHUD/github/SHUD/InstallSundials/builddir — cmake ../../sundials-master
Page 1 of 2

BUILD_ARKODE      OFF
BUILD_CCODE      ON
BUILD_CCODES     OFF
BUILD_IDA        OFF
BUILD_IDAS       OFF
BUILD_KINSOL     OFF
BUILD_SHARED_LIBS ON
BUILD_STATIC_LIBS ON
BUILD_TESTING    ON
CMAKE_BUILD_TYPE
CMAKE_C_COMPILER  /Applications/Xcode.app/Contents/Develop
CMAKE_C_FLAGS
CMAKE_INSTALL_LIBDIR lib
CMAKE_INSTALL_PREFIX /Users/leleshu/sundials
CMAKE_OSX_ARCHITECTURES
CMAKE_OSX_DEPLOYMENT_TARGET
CMAKE_OSX_SYSROOT
CUDA_ENABLE      OFF
EXAMPLES_ENABLE_C ON
EXAMPLES_ENABLE_CXX OFF
EXAMPLES_INSTALL ON
EXAMPLES_INSTALL_PATH /Users/leleshu/sundials/example
F2003_INTERFACE_ENABLE OFF
F77_INTERFACE_ENABLE OFF
HYPRE_ENABLE     OFF
KLU_ENABLE       OFF
LAPACK_ENABLE     OFF
MPI_ENABLE       OFF
OPENMP_DEVICE_ENABLE OFF
OPENMP_ENABLE    OFF
PETSC_ENABLE     OFF
PTHREAD_ENABLE   OFF
RAJA_ENABLE      OFF
SUNDIALS_INDEX_SIZE 64
SUNDIALS_PRECISION double

BUILD_ARKODE: Build the ARKODE library
Press [enter] to edit option Press [d] to delete an entry CMake Version 3.11.1
Press [c] to configure      Press [g] to generate and exit
Press [h] for help          Press [q] to quit without generating
Press [t] to toggle advanced mode (Currently Off)
```

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
```

2.2 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 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
```

2.2.2 Run SHUD executables.

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

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


2 Install SHUD and SHUDtoolbox

The prerequisite packages for SHUDtoolbox are:

- Rcpp
- reshape2
- ggplot2
- gridExtra
- grid
- fields
- xts
- hydroGOF
- zoo
- raster ($\geq 2.1.0$)
- sp
- rgeos
- RTriangle
- rgdal ($\geq 1.1.0$)
- proj4
- abind
- utils
- lubridate
- geometry
- methods
- ncdf4
- GGally
- doParallel

One of the required packages, RTriangle, must be installed via GitHub instead of CRAN, using command:

```
install_github('shulele/RTriangle/pkg')
```


3 Input files

List of input files:

	File	Category	Comments	Header	# of column		
.mesh	sp		Domain cell (triangular mesh)			Yes	
.att	sp		Attribute table of triangular cells			Yes	
.riv	sp		Rivers			Yes	
.rivseg	sp		Topologic relation b/w River and cell			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.

3 Input files

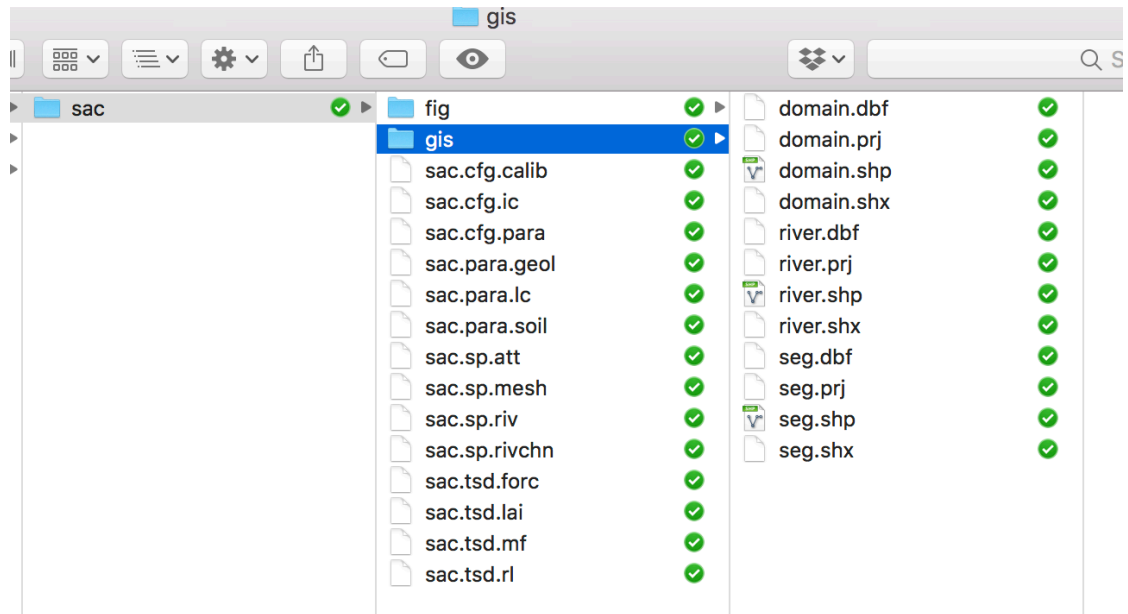


Figure 3.1: The screenshot of input files for SHUD

3.1 Spatial data

3.1.1 .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 cells and the other is a table of nodes of cells.

- Block 1 (cell information)
- Pre-table

3 Input files

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

- Table

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

3.1.2 .sp.att file

- Pre-table

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

- Table

3.1 Spatial data

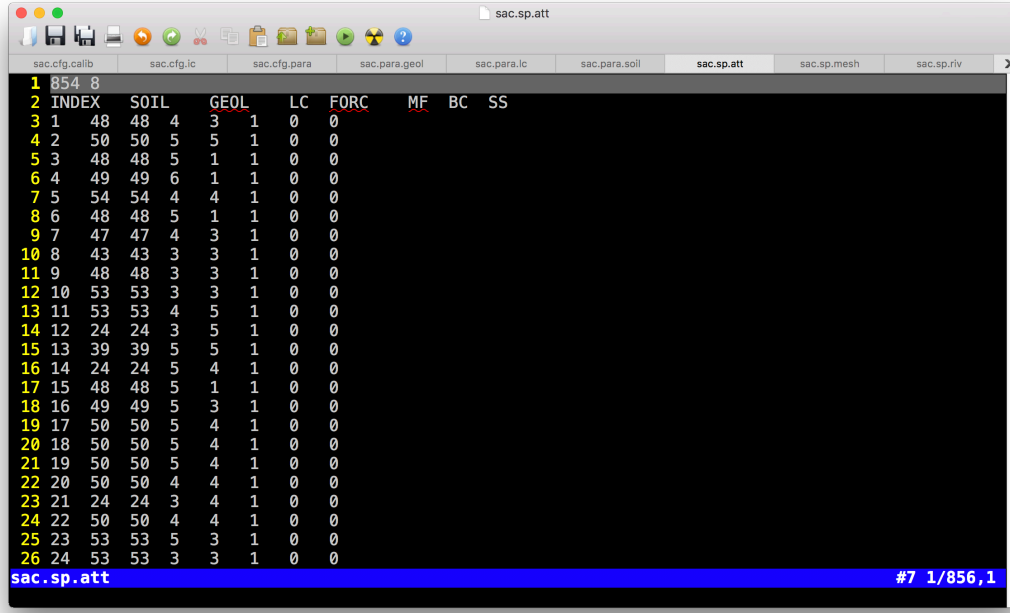


Figure 3.2: Example of .sp.att file

Colname	Meaning	Range	Unit	Comments
ID	Index of cell i	$1 \sim N_{cell}$	-	-
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	$1 \sim N_{bc}$	-	-
SS	Index of Source/Sink condition	$1 \sim N_{bc}$	-	-

3.1.3 .sp.riv file

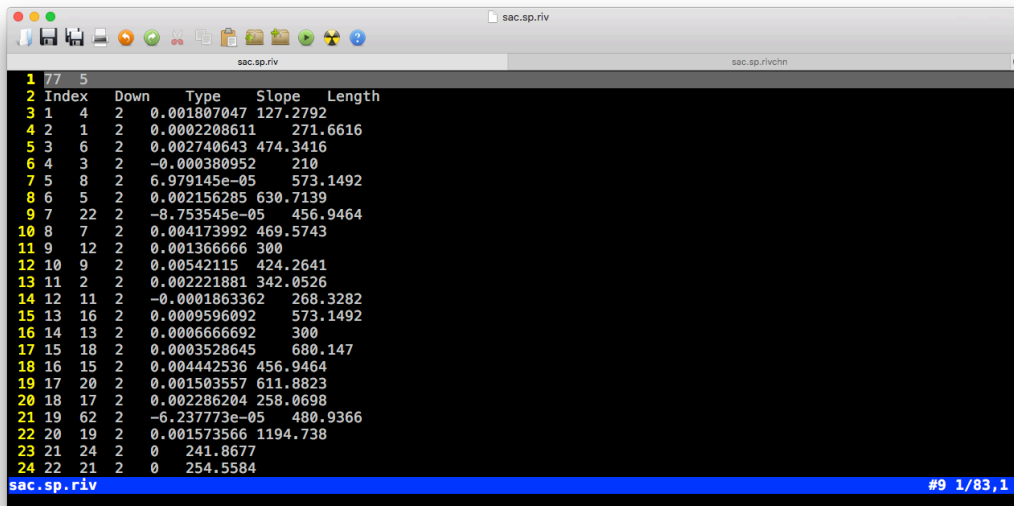


Figure 3.3: Example of .sp.riv file

3 Input files

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	$-10 \sim 10$	m/m	Height/Length
Length	Length of the river i	$0 \sim \text{inf}$	m	

3.1.4 .sp.rivseg file

```

1 197 4
2 Index iRiv iEle Length
3 1 1 527 63.75981
4 2 1 792 63.51941
5 3 2 527 247.3515
6 4 2 850 24.31004
7 5 3 737 222.1544
8 6 3 779 109.8271
9 7 3 792 56.38609
10 8 3 794 85.97407
11 9 4 792 210
12 10 5 534 229.0608
13 11 5 540 237.3175
14 12 5 766 63.25649
15 13 5 768 43.51438
16 14 6 692 144.5274
17 15 6 737 157.9207
18 16 6 739 116.1062
19 17 6 741 160.278
20 18 6 766 51.88162
21 19 7 537 22.45777
22 20 7 750 285.8696
23 21 7 782 148.619
24 22 8 541 198.1699
sac.sp.rivchn

```

Figure 3.4: Example of .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	$1 \sim N_{segment}$	-	

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

3.2 Model configuration files

3.2.1 .cfg.para file

- Table

Colname	Meaning	Range	Unit	Default value
VERBOSE	Verbose mode	-	-	0
INIT_MODE	Initial condition mode	0~3	-	3 (0=Relief conditon, 1=Dry condition, 2=Default guess, 3=Warm start)
ASCII_OUTPUT	ASCII ouput	1/0	-	0
Binary_OUTPUT	Binary output	1/0	-	1
SPINUPDAY	Days for spinup	$0 \sim \text{inf}$	<i>day</i>	0
SCR_INTV	Number of threads for OpenMP	$0 \sim N_{threads}$	<i>min</i>	1440
ABSTOL	Abosolute tolerance for CVMODE solver	$1\text{e-}6 \sim 0.1$	-	0.0001
RELTOL	Relative tolerance for CVMODE solver	$1\text{e-}6 \sim 0.1$	-	0.0001
INIT_SOLVER_STEP	Time step for CVMODE solver	-	<i>min</i>	1
MAX_SOLVER_STEP	Maximum time step for CVMODE solver	1~60	<i>min</i>	10
ET_STEP	Time step of Evapotranspiration	1~360	<i>min</i>	60
START	Start Time	$0 \sim \text{inf}$	<i>day</i>	0
END	End Time	-	<i>day</i>	-
dt_ye_snow	Time step of output snow storage	$0 \sim \text{inf}$	<i>min</i>	1440
dt_ye_surf	Time step of output surface storage	$0 \sim \text{inf}$	<i>min</i>	1440
dt_ye_unsat	Time step of output unsaturated storage	$0 \sim \text{inf}$	<i>min</i>	1440

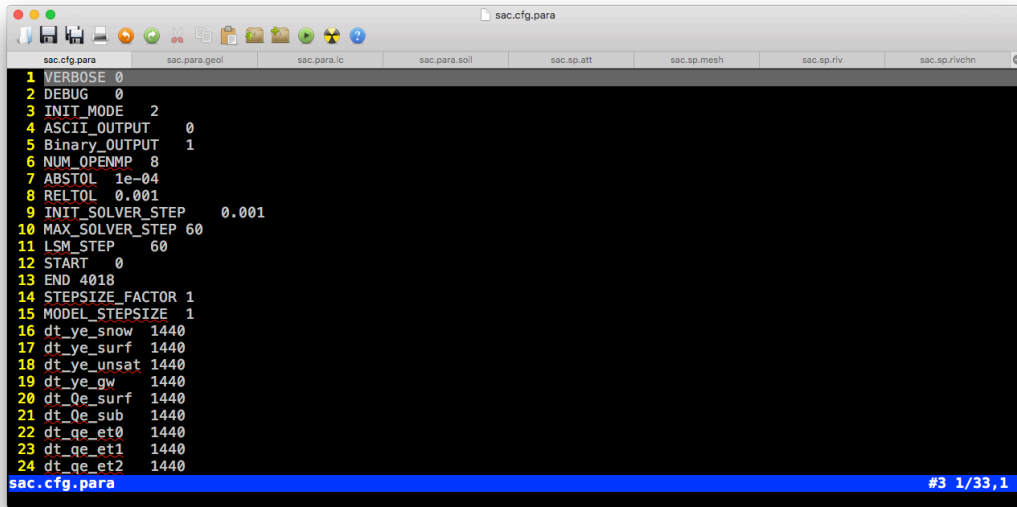
3 Input files

Colname	Meaning	Range	Unit	Default value
dt_Qe_surf	Time step of output surface cell flux	0 ~ inf	<i>min</i>	1440
dt_Qe_sub	Time step of output subsurface cell flux	0 ~ inf	<i>min</i>	1440
dt_qe_et0	Time step of output cell flux, interception	0 ~ inf	<i>min</i>	1440
dt_qe_et1	Time step of output cell flux, transpiration	0 ~ inf	<i>min</i>	1440
dt_qe_et2	Time step of output cell flux, evaporation	0 ~ inf	<i>min</i>	1440
dt_qe_etp	Time step of output cell flux, potential ET	0 ~ inf	<i>min</i>	1440
dt_qe_prcp	Time step of output cell flux, interception	0 ~ inf	<i>min</i>	1440
dt_qe_infil	Time step of output cell flux, interception	0 ~ inf	<i>min</i>	1440
dt_qe_rech	Time step of output cell flux, interception	0 ~ inf	<i>min</i>	1440
dt_yr_stage	Time step of output river stage	0 ~ inf	<i>min</i>	1440
dt_Qr_down	Time step of output river flux, downstream	0 ~ inf	<i>min</i>	1440
dt_Qr_surf	Time step of output river flux, surface flow	0 ~ inf	<i>min</i>	1440
dt_Qr_sub	Time step of output river flux, base flow	0 ~ inf	<i>min</i>	1440
dt_Qr_up	Time step of output river flux, upstream	0 ~ inf	<i>min</i>	1440

3.2.2 .cfg.calib file

- Table

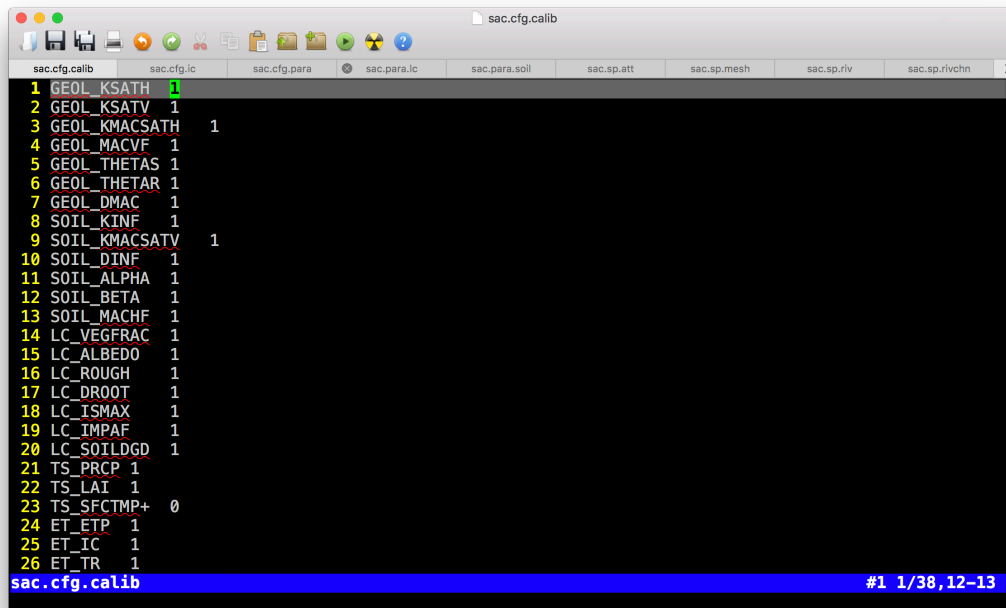
3.2 Model configuration files



The screenshot shows a text editor window titled 'sac.cfg.para'. The editor contains a list of 24 numbered configuration parameters. The parameters are: 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. 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
sac.cfg.para #3 1/33,1
```

Figure 3.5: Example of .cfg.para file



The screenshot shows a text editor window titled 'sac.cfg.calib'. The editor contains a list of 26 numbered configuration parameters. The parameters are: 1. GEOL_KSATH 1, 2. GEOL_KSATV 1, 3. GEOL_KMACSATH 1, 4. GEOL_MACVF 1, 5. GEOL_THETAS 1, 6. GEOL_THETAR 1, 7. GEOL_DMAC 1, 8. SOIL_KINF 1, 9. SOIL_KMACSATV 1, 10. SOIL_DINF 1, 11. SOIL_ALPHA 1, 12. SOIL_BETA 1, 13. SOIL_MACHF 1, 14. LC_VEGFRAC 1, 15. LC_ALBEDO 1, 16. LC_ROUGH 1, 17. LC_DROOT 1, 18. LC_ISMAX 1, 19. LC_IMPAF 1, 20. LC_SOILDGD 1, 21. TS_PRCIP 1, 22. TS_LAI 1, 23. TS_SFCTMP+ 0, 24. ET_ETP 1, 25. ET_IC 1, 26. ET_TR 1. The status bar at the bottom indicates 'sac.cfg.calib' and '#1 1/38,12-13'.

```
1 GEOL_KSATH 1
2 GEOL_KSATV 1
3 GEOL_KMACSATH 1
4 GEOL_MACVF 1
5 GEOL_THETAS 1
6 GEOL_THETAR 1
7 GEOL_DMAC 1
8 SOIL_KINF 1
9 SOIL_KMACSATV 1
10 SOIL_DINF 1
11 SOIL_ALPHA 1
12 SOIL_BETA 1
13 SOIL_MACHF 1
14 LC_VEGFRAC 1
15 LC_ALBEDO 1
16 LC_ROUGH 1
17 LC_DROOT 1
18 LC_ISMAX 1
19 LC_IMPAF 1
20 LC_SOILDGD 1
21 TS_PRCIP 1
22 TS_LAI 1
23 TS_SFCTMP+ 0
24 ET_ETP 1
25 ET_IC 1
26 ET_TR 1
sac.cfg.calib #1 1/38,12-13
```

Figure 3.6: Example of .cfg.calib file

3 Input files

	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 cell surface			-
	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

3.2.3 .cfg.ic file

- Block 1 (cell initial condition)
- Pre-table

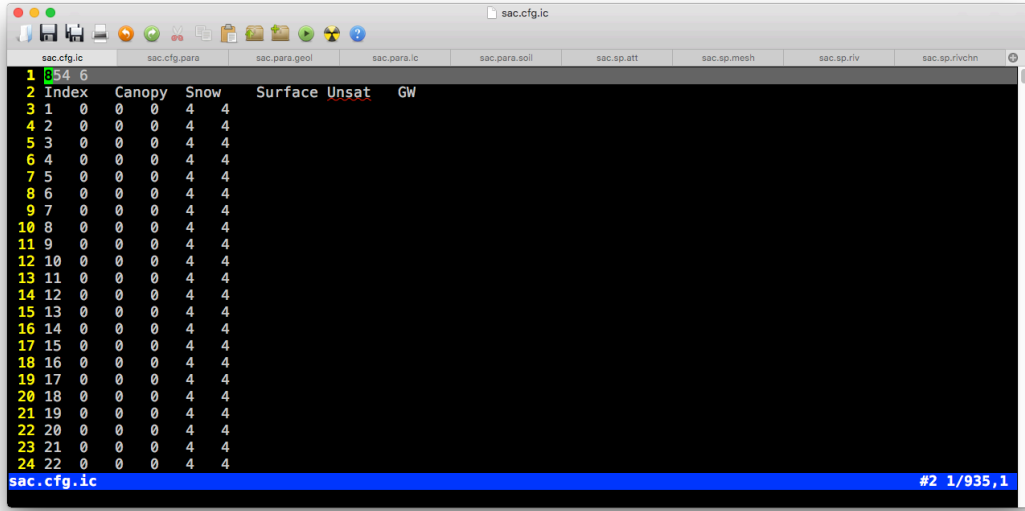


Figure 3.7: Example of .cfg.ic file

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

- Table

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

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

3.3 Time-series data

3.3.1 .tsd.forc file

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

3 Input files

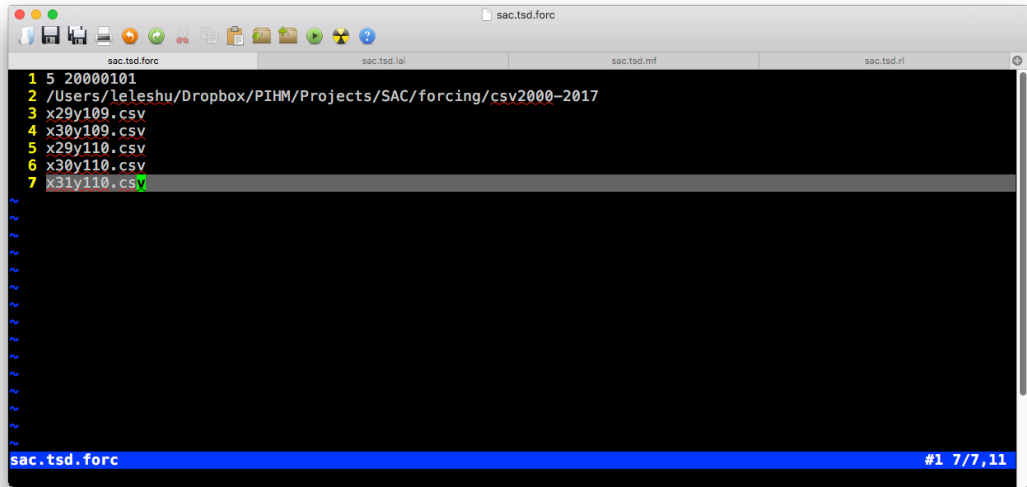


Figure 3.8: Example of .tsd.forc file

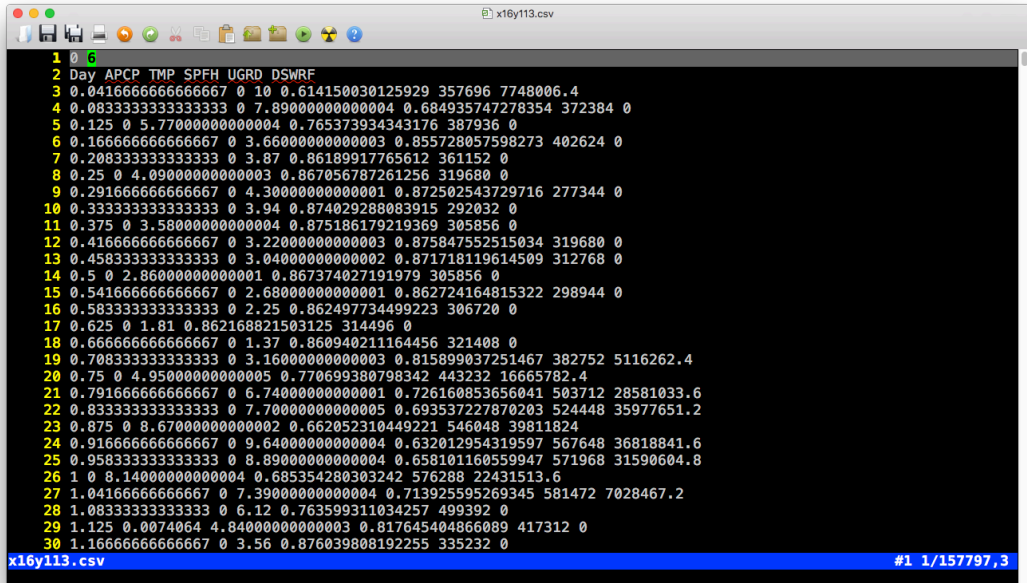


Figure 3.9: Example of .csv forcing file

- Table

	Colname	Meaning	Range	Unit	Comments
Day		Time	$0 \sim N_{day}$		<i>day</i>
PRCP		Precipitation	$0 \sim 1$		<i>m/day</i>
TEMP		Temperature	$-100 \sim 70$		<i>C</i>
RH		Relative Humidity	$0 \sim 1$		—
wind		Wind Speed	$0 \sim \text{inf}$		<i>m/day</i>
Rn	Solar (shortwave) radiation		?		<i>J/day/m²</i>

3.3.2 .tsd.lai file

```

1 133 17 20000101
2 Time_Day X11 X12 X21 X22 X23 X24 X31 X41 X42 X43 X52 X71 X81 X82 X90 X95
3 0 0.5276088 0.5276088 0.8829429 0.95865 1.110064 1.236243 0.03291743 0.6248 3.383 3.0968
4 0.661133 0.7039 0.782 0.7039 0.348333 0.6256
5 31 0.5528588 0.5528588 0.9933199 1.06856 1.21904 1.34444 0.03327174 0.6692 3.4274 3.2612 0.73460
6 39 0.8038 0.893 0.8038 0.3774039 0.7144
7 60 0.6006132 0.6006132 1.11334 1.195344 1.359354 1.496028 0.02602606 0.9218 3.4718 3.6098
8 0.7787348 0.9037 1.004 0.9037 0.3771348 0.8032
9 91 0.6442597 0.6442597 1.247345 1.345854 1.542872 1.707054 0.01878356 1.7106 3.5166 4.1
10 064 0.8235276 1.0045 1.116 1.0045 0.3771276 0.8928
11 121 0.7244881 0.7244881 1.929405 2.039958 2.261065 2.445321 0.02090943 3.417 3.783 5.1
12 729 1.264353 1.6039 1.782 1.6039 0.551553 1.4256
13 152 0.8363947 0.8363947 3.764154 3.834019 3.973749 4.090191 0.0273254 5.5322 4.5386 6.7
14 283 2.529527 3.304 3.671 3.304 1.061127 2.9368
15 182 0.8540044 0.8540044 4.829846 4.86573 4.937499 4.997306 0.03551171 6.2166 4.983 7.2126
16 3.443218 4.3039 4.782 4.3039 1.530418 3.8256
17 213 0.8126544 0.8126544 4.297516 4.350403 4.456177 4.544322 0.06491387 5.595 4.761 6.7
18 11 3.222959 3.8044 4.227 3.8044 1.532158 3.3816
19 244 0.7253301 0.7253301 2.172887 2.299553 2.552883 2.763992 0.09427062 3.8256 3.8718 5.3
20 415 1.838785 1.8037 2.004 1.8037 1.037185 1.6032
21 12 274 0.6329191 0.6329191 1.358725 1.457518 1.655105 1.819761 0.06473787 1.7946 3.561 4.0
22 908 1.073039 1.1044 1.227 1.1044 0.5822385 0.9816
sac.tsd.lai #2 1/135,1

```

Figure 3.10: Example of .tsd.lai 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	$0 \sim N_{time}$		<i>day</i>
Column 2	LAI of land cover 1		$0 \sim \text{inf}$		<i>m²/m²</i>

3 Input files

	Colname	Meaning	Range	Unit	Comments
Column 1	LAI of land cover 1		0 ~ inf	m^2/m^2	
...	

3.3.3 .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 ~ N_{time}	<i>day</i>
Column 2	Roughness length of land cover 1		0 ~ inf		<i>m</i>
Column i	Roughness length of land cover $i - 1$		0 ~ inf		<i>m</i>
...

3.3.4 .tsd.mf file

- Pre-table:

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

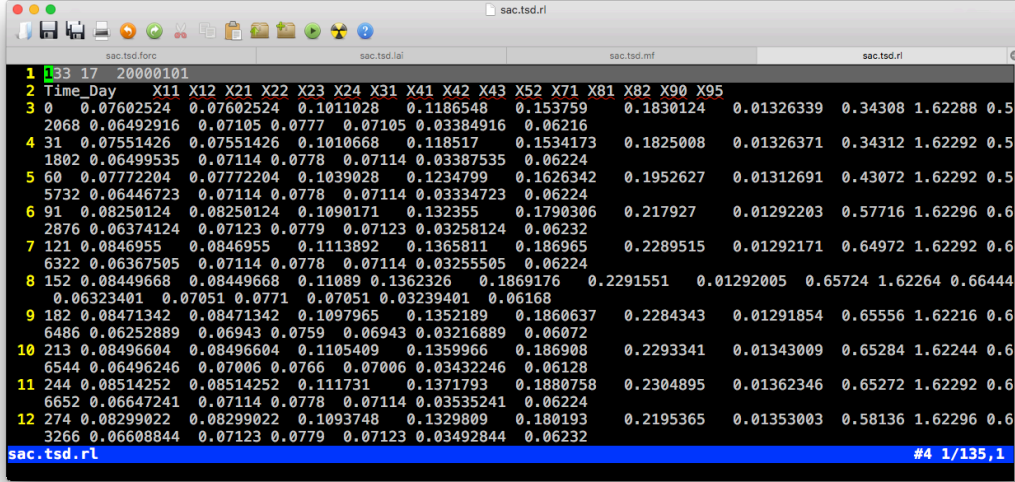
- Table

	Colname	Meaning	Range	Unit	Comments
TIME		Time		0 ~ N_{time}	<i>day</i>
Column 2	Melt factor 1		0 ~ inf		-
Column i	Melt factor $i - 1$		0 ~ inf		-
...

3.3.5 .tsd.obs file

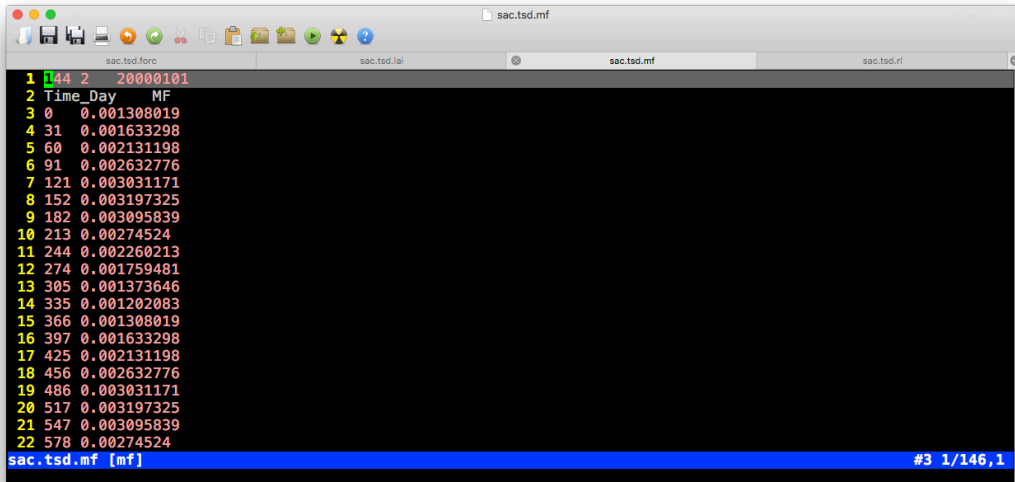
- Pre-table:

3.3 Time-series data



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										

Figure 3.11: Example of .tsd.rl file



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 3.12: Example of .tsd.mf file

3 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

```

Figure 3.13: Example of .tsd.obs file

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

- 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 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	
.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	$\frac{m^3}{m^2d}$	
.elegsurf.	ele	q	surf		Overland flow	m^3/d	
.elegsub.	ele	q	sub		Subsurface flow	m^3/d	
.rivystage.	riv	y	stage		River Stage	m	

4 Output files

	Identifier	Mod unit	Type	Var Name	Meaning	Unit
<i>.rivqup.</i>	riv	q	up		Flux to upstream	m^3/d
<i>.rivqdown.</i>	riv	q	down		Flux to downstream	m^3/d
<i>.rivqsurf.</i>	riv	q	surf		Flux to landsurface	m^3/d
<i>.rivqsub.</i>	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	$v_{1.1}$	$v_{1.2}$	...	$v_{1.N}$	
T_2	$v_{2.1}$	$v_{2.2}$	...	$v_{2.N}$	
T_3	$v_{3.1}$	$v_{3.2}$	...	$v_{3.N}$	
...	
T_m	$v_{m.1}$	$v_{m.2}$	...	$v_{m.N}$	

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	$v_{1.1}$	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

4.3 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

