The global hydrodynamic model

CaMa-Flood (version 3.6.2)

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NOTE:

Please contact to the developer (Dai Yamazaki) for the acquisition of the CaMa-Flood package. Do not re-distribute the package to someone else without a notice to the developer. This is because the developer wants to keep the list of users for making a notice of the updates and bugs of the CaMa-Flood package.

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1. Introduction

1.1 Model Overview

This document is the user's manual for the global river model, CaMa-Flood (Catchment-based Macro-scale Floodplain model).

The CaMa-Flood model is designed to simulate the hydrodynamics in continental-scale rivers. The entire river networks of the world are discretized to the hydrological units named unit-catchments for achieving efficient flow computation at the global scale. The water level and flooded area are diagnosed from the water storage at each unit-catchment using the sub-grid topographic parameters of the river channel and floodplains. By adapting "gird-vector hybrid river network map" which corresponds one irregular-shaped unit-catchment to one grid-box, both realistic parameterization of sub-grid topography and easy analysis of simulation results are achieved. The river discharge and flow velocity are calculated with the local inertial equation [Bates et al., 2010] along the river network map which prescribes the upstream-downstream relationship of unit-catchments. The time evolution of the water storage, the only one prognostic variable, is solved by the water balance equation which considers inflow from the upstream cells, outflow to the downstream cell and input from runoff forcing at each unit-catchment. Bifurcation of river channels can be also represented by analyzing high-resolution topography. The detailed description of the CaMa-Flood model is found in the description papers [Yamazaki et al., 2011; 2013; 2014a]

The major advantage of the CaMa-Flood simulations is the explicit representation of flood stage (water level and flooded area) in addition to river discharge. In addition to traditional model validation with gauged river discharge, it is possible to make a direct comparison between model simulations and satellite observations. Observations of water surface elevation by satellite altimeters and/or flooded area by SAR and microwave imagers are very useful to enhance the calibration/validation of the global river model [e.g. Yamazaki et al., 2012a; Biancamaria et al., 2013]. Explicit representation of flooded area is helpful for flood damage assessment by overlaying it with socio-economic datasets [e.g. Hirabayashi et al., 2013]. The assimilation of observed flood stage into the CaMa-Flood simulation is a potential research topic, for optimizing model parameters and extending the forecast skill for near future flooding.

Another advantage of the CaMa-Flood model is its high computational efficiency of the global river simulations. The complexity of the floodplain inundation processes is reasonably approximated to a diagnostic scheme at the scale of a unit-catchment by introducing the sub-grid topographic parameters. The cost of the prognostic computation of river discharge and water storage is optimized by implementing the local inertial equation [Bates et al., 2010] and the adaptive time step scheme [Hunter et al., 2005]. The high computational efficiency of the CaMa-Flood model is beneficial for computational demanding experiments such as ensemble/long-term experiments [Pappenberger et al., 2012; Hirabayashi et al., 2013] and dynamic coupling between river routine and other hydrological schemes [Cohen et al., 2013].

1.2 Recent Change History

- ***Bug fix*** [v3.6.2]. OUTFLW output (changed from snapshot to daily ave.), netCDF restart (2D to 1D conversion), storage only restart (RIVDPH_PRE initialization), netCDF runoff input (SAVE statement).

- ***River network maps are updated*** [v3.6.1]. Seamless connection of HydroSHEDS (below 60N) and GDBD (above 60N). Flow direction modification to keep consistency to GWD-LR [Yamazaki et al., 2014b].

- Simplified ***restart option only using river and floodplain storages*** [v3.6.1].

- ***Channel bifurcation scheme*** is included [v3.6.1]

- ***Satellite-based river width (GWD-LR)*** is included [v3.6.1]

- A code for ***floodplain depth downscaling*** is included [v3.4.4].

- ***High resolution regional simulation*** [v3.4.4].

- ***Change in the source code structure.*** Diagnosed variables are moved to the module “mod_diag”. The names of some subroutine at “Control Level” are changed. [v3.4.3]

- ***A bug in DEM (25-30E, 10-15N)*** was fixed. [v3.4.2].

- ***Floodplain flow along river network is introduced.*** It is represented by the subroutine “calc_fldout”. [v3.4.0]. [bug fixed in v3.4.3].

- ***Stabilized version of the local inertial equation*** is introduced. The previous hybrid routine is replaced with the new local inertial equation. [v3.3.1].

- ***The adaptive time step scheme*** to calculate the maximum acceptable time step length to avoid the numerical instability is implemented. [v3.0].

- The grid-vector-hybrid river network map (the river network maps in previous versions) is updated in order to optimize the computational efficiency of simulations using the local inertial equation. The simulation speed with the new grid-vector-hybrid map is about 150% faster than the simulation using the previous maps.

- ~~***The vector-based river network map*** is introduced. The simulation speed using the vector-based map is about 90% faster than that of the grid-vector-hybrid map.~~ [not supported in v3.6 and later]

- The simulation using ***the fully-grid-based river network map*** is stabilized. The fully-grid-based map uses the rectangular grid boxes as unit-catchment area, which makes the coupling of the CaMa-Flood model and another model (e.g. a land surface model) easier.

- ***The runoff interpolation considering mass conservation*** is realized by introducing the input matrix. It is more realistic compared to the nearest point interpolation used in the previous versions.

2. CaMa-Flood Package & Instruction

2.1 Contents of the Package

The package of the CaMa-Flood model contains the main programs of global river simulations, some sets of river network map and its sub-grid topography parameters, a sample dataset of input runoff forcing, and some tools used for analysis.

Please extend the **CaMa-Flood_$(version)_$(date).tar.gz** package on your computer. The you will find the following directories under the main directory **$(CaMa-Flood)/** .

Table 2.1: List of directories in the CaMa-Flood package

Directories	Purpose
$(CaMa-Flood)/	
adm/	Administration Directory, contains Mkinclude
gosh/	Shell Scripts Directory, for executing simulations
src/	Main Source Code Directory
lib/	Library Code Directory
mod/	Module Code directory
map/	Map Directory, contains river netwrok maps
inp/	Input Directory, contains a sample inut data
out/	Output Directory, contains some programs for data processing
etc/	Various programs for analysis, visualization, etc

2.2 Quick Instruction for global simulation

The quick instruction to execute a test run with the CaMa-Flood model is described in this section. The test run is global hydrodynamic simulation at the 15 minute resolution (**map/global_15min/**) for the period from 1990 to 1991 with the sample input runoff forcing (**inp/ELSE_GPCC/Roff/**). The local inertial equation is used for the calculation of river discharge and flow velocity, and the adaptive time step scheme is activated in order to optimize the time step. Bifurcation channels are not considered.

(1) Please edit the Mkinclude file, **$(CaMa-Flood)/adm/Mkinclude** , according to the computer environment. If you do not use the MPI or netCDF, comment out the lines **#DMPI=-DUseMPI** and **#DCDF=-DUseCDF**, respectively. (NOTE: MPI is not fully supported

in v3.6 and later). If endian conversion of input map or input runoff is needed, please activate **DEND=-DConvEnd**.

(2) The shell script to automatically compile all the source codes is prepared. Go to **$(CaMa-Flood)/gosh/** directory, and execute the command:

```
% compile.sh (yes)
```

Then, the source codes **mod/** **lib/** **src/** **map/** **out/** directories are compiled with the command **% make all**. When you put the argument "**yes**", the command **% make clean** is executed before compiling.

(3) Go to the map directory (**map/global_15min/**), then execute the following commands to calculate river discharge climatology and channel cross-section parameters (**rivwth.bin** and **rivhgt.bin**)

```
% ../s01-channel_params.sh
```

Note that all the dataset in the CaMa-Flood archive is prepared in "little endian" byte order. If the default byte order of your computer environment is "big endian", you have to convert the endian of the sample dataset. The endian conversion program for 4 byte data format, **endian4.f90**, is prepared in the library directory (**lib/**).

(4) Go to the shell script directory (**gosh/**), and edit the executable script **global_15min.sh** if needed. You can modify, for example, the experiment name, the number of OpenMP nodes, the usage of the adaptive time step scheme, the interpolation with the input matrix, and the list of output files.

After editing the executable shell script, type the command to run the simulation.

```
% ./global_15min.sh
```

(5) The simulation results are outputted to the running directory specified in the script, **$(CaMa-Flood)/out/global_15min/** in the default setting. The progress of the simulation is written to the log file, **run_YYYY.log**.

(6) The output file is in the “plain binary” format, which consists of the sequence (nx*ny) of 4 byte real data without any header. The data array is from 180W to 180E (1440 grid cells) and from 90N to 90S (720 grid cells).

2.3 Runoff forcing setting

CaMa-Flood requires daily runoff forcing in plain binary format or netCDF format.

Runoff forcing data should be prepared in “plain binary format” (or Fortran direct access, GrADS binary, ArcGIS EHdr), and should be named as **$(PREFIX)yyyymmdd$(SUFFIX)**. The sample runoff data prepared in **inp/ELSE_GPCC/Roff/** directory. The runoff file is named Roff____yyyymmdd.one by setting **PREFIX=”Roff____”** and **SUFFIX=”.one”**. Default runoff data is prepared in the unit [mm/day], and converted in CaMa-Flood to [m3/s] by setting the seconds in runoff time step **DTIN=86400** (daily) and unit conversion ratio **DROFUNIT=1.D-3** (from [mm] to [m]).

NetCDF runoff input can be used by setting **LINPCDF=.TRUE.**, NetCDF runoff directory **CROFDIR**, NetCDF runoff file **CROFCDF**, NetCDF runoff variable name **CROFVAR**, NetCDF data start date **SYEARIN**, **SMONIN**, **SDAYIN** shoule be specified.

If prepared runoff forcing is different from the default grid coordinate system (i.e. global domain in Cartesian grid coordinate at 1 degree spatial resolution), a new input matrix should be generated. Please go to **$(map)/** directory, and edit **s03-generate_inpmat.sh** if the runoff forcing is at linear Cartesian grid coordinate. By executing **../s03-generate_inpmat.sh** in map/grid_15min/ directory, a new dimension file “**diminfo.txt**’ and a new input matrix “**inpmat.bin**” are generated. Please specify these files in executable shell scripts.

If runoff forcing is prepared at other grid coordinate, Please edit **generate_inpmat.F**. There is a part which relates the (lon,lat) of each sub-grid high-resolution pixel to the (ixin, iyin) of input runoff forcing. Please edit these lines according to the grid coordination of your runoff forcing.

2.4 Global Width Database for Large Rivers (GWD-LR)

Instead of river width parameter estimated by empirical equation (**rivwth.bin**), satellite-based river width (GWD-LR) can be used. Please go to **map/global_15min** directory, and execute **../s01-channel_params.sh** (this step is automatically done when channel parameter is calculated). The river width parameter based on GWD-LR (**rivwth_gwdlr.bin**) is generated. Please Specify the map file **rivwth_gwdlr.bin** in the shell script **gosh/${go_script}**.

Note that the GWD-LR has large error in river width above 60N, due to the baseline data (MODIS water mask at 250m resolution, GDBD flow direction at 1km resolution). Also, simulation is not stable when large lakes exists in target domain. Please do not use GWD-LR river width in such a case.

2.5 Channel Bifurcation Scheme

Chanel bifurcation scheme is activated by setting **LPTHOUT=.TRUE.** in the go script. Bifurcation channel can be automatically delineated by analysing the high-resolution topography.

In order to delineate bifurcation channel, you have to get the original high-resolution database (HydroSHEDS + GWD-LR + SRTM3 DEM) used to generate river network maps by FLOW algorithm. The original high-resolution database is not included in the CaMa-Flood package because of its data size (30GB). Please download the database (**sheds_0.005_140807**) separately and locate the high-resolution database to **map/** directory. Go to **map/global_15min/** directory and make a link **% ln –s ../sheds_0.005_140807 sheds** .

Then, go to **map/global_15min** and execute **../s02-set_bifurcation.sh**. The list of bifurcation channels (**fldpth.txt**) and channel depth map with modification associated with bifurcation channel (**rivwth_pth.bin**) are generated. Please specify **fldpth.txt** and **rivhgt_pth.bin** in the go script.

2.6 Downscaling

Simulated floodplain depth can be downscaled onto the original high-resolution DEM. The sample code for downscaling is prepared in **etc/downscale_flddph/** directory. The sample file **downscale_flddph.f90** is used to downscale simulated floodplain depth onto the original high-resolution DEM. In the sample file, constant flood depth of 5 m is assumed.

Please specify the map directory and output directory in **s00-set_directory.sh** . And then execute **s01-downscale.sh** . You have to modify the script s01-downscale.sh to specify the simulated flood depth file and target time. The downscaling is performed separately for each hi-res domain domain because of the RAM limitation. The sample monthly flood depth file is prepared (**sample/flddph1990.mon**).

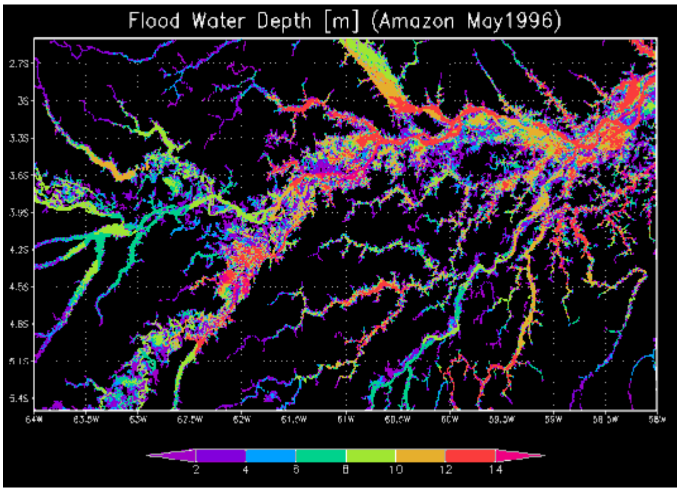

Figure 2.1 Example of downscaled floodplain depth.

2.7 Regionalization

For regional simulations, tools to extract regional maps from the global maps are prepared. Please go to the sample regional map directory "**map/region_15min/**". Go to "**map/region_15min/src**" directory, and edit the file to specify the domain of regional maps "**region_info.txt**". (sample is prepared for the Amazon River)

Execute **s01-regional_map.sh** which includes **cut_domain.f90** (extract regional maps), **combine_hires.f90** (extract sub-grid high-resolution info), **set_map.f90** (calculate associate info from river network maps), and **generate_inpmat-1deg.f90** (generate input matrix for regional simulations for 1deg input file). Then, execute **s02-wrte_ctl.sh** and **s03-hires_ctl.sh** to generate CTL file for GrADS.

In case of delineating bifurcation channels (or high-resolution original database is needed), execute **s04-set_sheds.sh** and **s05-sheds_ctl.sh** in order to regionalize original high-resolution database.

Another procedures (e.g. generate channel cross-section parameters, use GWD-LR river width, set bifurcation channels) are same as the global river network map.

Regional simulations can be executed by just changing map descriptions in the executable shell scripts. Sample shell scripts (**region_15min**) is prepared in **gosh/** directory.

2.8 River network map at different resolutions

The river network map at different resolutions (6min, 30min) is prepared. The higher resolution map is mainly developed for regional simulations. Note that the quality of the river network map above 60N is not ensured because of the uncertainty in baseline topography data. The lower resolution map is prepared for faster simulations, but the accuracy may be lower compared to the simulation with 15min map. Please ask the developer for the access to the higher and lower resolution river network map, which is not included in the package.

River network maps at other spatial resolutions or other grid coordination are not available at current stage. The developer is currently preparing the package for automatically generating river network maps at any grid coordination.

2.7 Visualization with sub-grid information

The river network maps and simulation results be visualized as raster-grid data, but it can also be visualized as vector-shape data using sub-grid information of the river network map. A sample GMT (Generic Mapping Tool) script combined with Fortran90 codes is prepared in **$CaMa-Flood/etc/visualization/** directory. Please go to **visualization/bin/** directory, and compile Fortran90 programs by **% make all**. Then you can execute GMT script **s01-draw-rivmap.sh**. The river network map is visualized in psfile **rivmap.ps**.

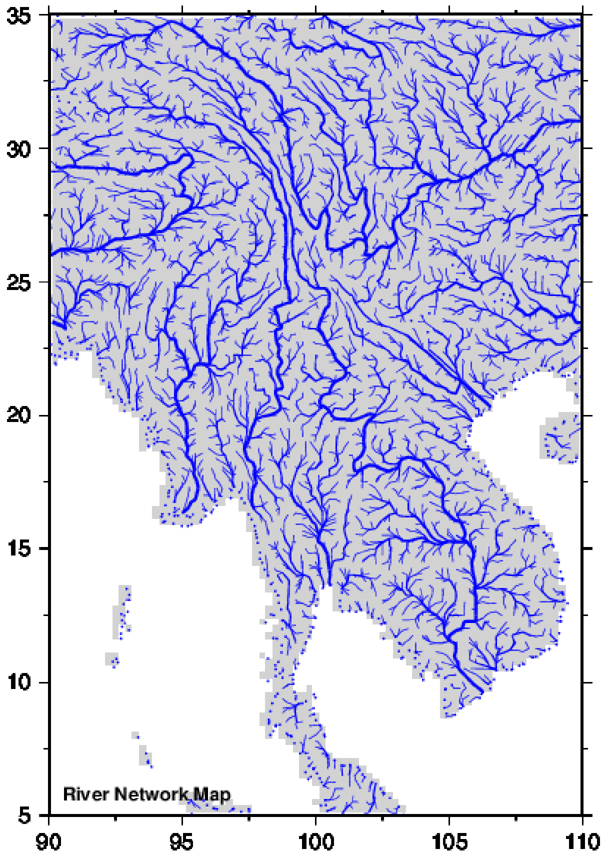

Figure 2.2 Visualization of river network map with sub-grid information using GMT.

2.9 ArcGIS format

The plain binary file (Fortran direct access format) is same as the ArcGIS .bsq format (for integer variable) and .flw format (for real/float variable). These files can be open in ArcGIS by changing the suffix to .bsq/.flw and by making .hdr file. Information on the domain grid coordination can be found in GrADS .ctl files prepared in the map directories.

3. Main Program Source Codes

The programs of the CaMa-Flood global river model are written in Fortran90. The programming structure follows the basic coding guidelines of Fortran90 as much as possible (this was achieved under the collaboration with Dr. Emanuel Dutra in ECMWF). The program includes the parallelization by OpenMP and MPI. Note that the parallelization by MPI is only effective in global simulations, and OpenMP must be used for regional simulation. The netCDF input/output is also supported. The MPI and netCDF schemes sometimes cause trouble when compiling the codes, so these schemes can be excluded from the program by preprocessing of the codes.

The program building is supported by the “make” function, and compiling rules are written in the “**Makefile**” in the **mod/** **lib/** **src/** directories. The original files with the suffix (*.F) are firstly converted to Fortran90 source codes with suffix (*.f90) by preprocessing, and then the main executable program (**MAIN_DAY**) is built from *f90 source codes using Fortran90 compiler. The lines related to the MPI and netCDF schemes are excluded in the preprocessed *.f90 files if the options for using MPI and netCDF are commented out in **Mkinclude** of **$(CaMa-Flood)/adm/** directory.

3.1 Code Tree

The code trees of the CaMa-Flood program are shown in Table 3.1, Table 3.2 and Table 3.3. The programs are divided into: (1) main program (**src/**), (2) modules to save variables in (**mod/**), and (3) libraries of common and small programs (**lib/**).

The main program consists of the main executable (**MAIN_DAY.F**), job control program (**CONTROL0.F**), initialization programs (**INIT_*.F**) and programs within the time step loop (called by **CONTROLSTEP.F**). The main hydrodynamic calculations are written in the source code **CALC_*.F**, which are called by the control program for physics schemes (**CONTROLPHY.F**).

Table 3.1: The code tree of main programs (src/ directory)

src/	Main program source codes
MAIN_DAY	Main executable program
CONTROL0	Controls the job at level 0
INIT_INPUTNAM	Read namelist
INIT_MAP	Read a river netwrok map
INIT_TOPO	Read topography parameters
INIT_COND	Set initial condition
INIT_TIME	Set simulation time period
CONTROLTSTEP	lontrols time step integration
CREATE_OUTBIN	Create output bunary file
CREATE_OUTCDF	Create output netCDF file
CONTROL_INP	Controls input forcing
CONTROL_PHY	Controls physics, main calculation
CALC_FLDSTG	Calculate flood stage from water storage
CALC_RIVOUT	Calculate river discharge
CALC_FLDOUT	Calculate floodplain flow
CALC_PTHOUT	Calculate bifurcation channel flow
CALC_STONXT	Calculate storage change
CALC_WATBAL	Calculate global water balance error
CONTROL_OUT	Controls output data
CONTROL_REST	Controls restart files

Table 3.2: The code tree of modules (mod/ directory)

mod/	Modules to save shared variables
PARKIND1	Variable type setting to avoid machine dependancy
MOD_INPPUT	for input namelist
MOD_TIME	for date and time steps
MOD_MAP	for river netwrok map and sub-grid topography
MOD_PROG	for prognostic variables
MOD_DIAG	for diagnostic variables
MOD_PARAM	for parameters
MOD_OUTPUT	for output files

Table 3.3: The code tree of libraries (lib/ directory)

lib/	Libraries
LIB_DATES	Library to manage time
IGETDAY	function to calculate days in (year month)
LEN_TRIM	function to count the lenggth of a string
ENDIAN4	subroutine to convert the endian of 4byte data
LIB_NETCDF_UTIL	Library to use netCDF

3.2 Codes for hydrodynamic calculations

The main scheme of hydrodynamic calculation is controlled by **CONTROLPHY.F**. The flow of the hydrodynamic calculation is as follows:

(1) Diagnose flood stage (CALC_FLDSTG.F).

In **CALC_FLDSTG.F**, the flood stage is diagnosed from the water storage at each grid cell. River channel water storage, S_r, floodplain water storage, S_f, river water depth, D_r, floodplain water depth, D_f, and flooded area, A_f, are diagnosed from the total water storage of a grid point, S, by solving either of simultaneous equations (3.1) or (3.2). Either of the simultaneous equations (3.1) or (3.2) is chosen by comparing the total water storage, S, and the flood initiation storage, S_{ini}. The flood initiation storage is given as, S_{ini}=BWL, where B is channel depth, W is channel width, and L is channel length. For the case that the total water storage, S, is less or equal to the flood initiation storage, S_{ini}, the simultaneous equations (3.1) are applied:

$$\begin{aligned} Sr &= S \\ Dr &= \frac{Sr}{WL} \\ Sf &= 0 \\ Df &= 0 \\ Af &= 0 \end{aligned} \qquad (3.1)$$

For the case that the total water storage, S, is greater than the flood initiation storage, S_{ini}, the simultaneous equations (3.2) are applied:

$$
\begin{aligned}
&Sr = S - Sf \\
&Dr = \frac{Sr}{WL} \\
&Sf = \int_0^{Af} (Df - D(A))dA \\
&Df = Dr - B \\
&Af = D^{-1}(Df)
\end{aligned}
\tag{3.2}
$$

The equation $D_f = D_r - B$ in (3.2) means that the water surface elevations of the river channel and the floodplain are same. This equation is based on the assumption that water mass is instantaneously exchanged between the channel and the floodplain to balance the water surface elevations of the two reservoirs. The function $D^{-1}(D_f)$, which is the inverse function of the floodplain elevation profile $D(A_f)$, describes flooded area, A_f, as a function of floodplain water depth, D_f (see Figure 4.2c).

(2) Calculate river discharge (`CALC_RIVOUT.F`)

In **`CALC_RIVOUT.F`**, the river discharge from each cell toward its downstream cell indicated by the river network map is calculated. The river discharge is calculated with the local inertial equation [Bates et al., 2010].

The local inertial equation is derived by neglecting the second term of the St. Venant momentum equation (3.3):

$$
\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left[\frac{Q^2}{A}\right] + \frac{gA\partial(h+z)}{\partial x} + \frac{gn^2Q^2}{R^{4/3}A} = 0 \tag{3.3}
$$

where Q is the river discharge (m^3s^{-1}), A is the flow cross section area (m^2), h is the flow depth (m), z is the bed elevation (m), R is the hydraulic radius (m), g is acceleration due to gravity (ms^{-2}], n is the Manning's friction coefficient ($m^{-1/3}s^{-1}$). The x and t are the flow distance and time, respectively. The first, second, third, and fourth terms represent the local acceleration, advection, water slope, and friction slope, respectively. The explicit form of the he local inertial equation (3.4) is used in the CaMa-Flood model:

$$Q^{t+\Delta} = \frac{Q^t - \Delta t\, gAS}{\left(1 + \dfrac{\Delta t\, gn^2 \left|Q^t\right|}{R^{4/3} A}\right)}. \tag{3.4}$$

where S is the water surface slope, Q^t is the discharge at the previous time step, and $Q^{t+\Delta t}$ is the river discharge between the time t and t+Δt. The hydraulic radius R is approximated by flow depth h_{flw}. The Manning's coefficient is set to n=0.03.

The negative river discharge, which may occur in the calculation by the local inertial equation and the diffusive wave equation, represents the backward water flow from the downstream grid cell towards the current grid cell.

The flow limiter is introduced in **CALC_RIVOUT.F** in order to prevent the situation that the total outflow from a grid exceeds the total water storage of the grid. The amount of the water leaving each grid cell is calculated, and the modification rate is applied on the river discharge calculated by the local inertial equation when the total outflow is larger than the total storage of the grid.

(3) Calculate floodplain flow (CALC_FLDOUT.F) *optional, recommended

Floodplain discharge (i.e. high water channel flow) is calculated when floodplain flow scheme is activated in the shell script (**LFLDOUT=.TRUE.**). Floodplain discharge is also calculated by the local inertial equation (Eq. 3.4). The flow area A is calculated by dividing floodplain storage by channel length. The flow depth h is given by the floodplain depth. The manning's coefficient for floodplain flow is set to n=0.10.

(4) Calculate bifurcation channel flow (CALC_PTHOUT.F) *optional

Bifurcation channel discharge is calculated when bifurcation flow scheme is activated in the shell script (**LPTHOUT=.TRUE.**). Bifurcation channel discharge is also calculated by the local inertial equation (Eq. 3.4). The flow area A and flow depth h is calculated for aggregated bifurcation channels with same bifurcation channel elevations. The manning's coefficient for floodplain flow is set to n=0.03 for river bifurcation and n=0.10 for overland bifurcation.

Discharge in each bifurcation channel is saved as **pthflwYYYY.pth** (dimension, npthout*npthlev), while net bifurcation flow at each grid is saved as **pthoutYYYY.bin** (dimension: nx*ny)

(5) Calculate storage change (CALC_STONXT.F)

The storage change at each grid cell from the time t to t+Δt is calculated by the mass conservation equation (3.5):

$$S_i^{t+\Delta t} = S_i^t + \sum_k^{Upstream} Q_k^t \Delta t - Q_i^t \Delta t + Ac_i R_i^t \Delta t \qquad (3.5),$$

where S_i^t and $S_i^{t+\Delta t}$ represent the water storage of grid i at the time t and t+Δt, Q_i^t and represents the river (+ floodplain + bifurcation channel) discharge outflow from grid i at time t, Q_k^t represents the river (+ floodplain + bifurcation channel) discharge inflow from the upstream grid k, Ac_i is the unit-catchment area of grid i, R_i^t represents the input runoff to the grid i.

4. River Network Map

The river network map and its associated sub-grid topographic parameters required for the CaMa-Flood simulations are stored in the **$(CaMa-Flood)/map/** directory. These maps are generated from the fine-resolution global flow direction maps (HydroSHEDS [Lehner et al., 2008]; GDBD [Masutomi et al., 2009]) and Digital Elevation Models (SRTM3 and SRTM30 [Farr et al., 2007]) by the upscaling algorithm (the FLOW method [Yamazaki et al., 2009]). The errors in the baseline fine-resolution data were removed as much as possible before applying the FLOW method [e.g. Yamazaki et al., 2012b; Yamazaki et al/. 2014b].

The dataset in the **map/** directory is prepared in the “plain binary” format, which consists of the sequence (nx*ny) of 4 byte real data without any header. The data array is from 180W to 180E and from 90N to 90S in case of global gridded maps. The byte order of the data is “little endian”. For the conversion of the endian, the subroutine **endian4.f90** is prepared in the **library/** directory. The description files (***.ctl**) to visualize the data on GrADS are included along with the map datasets.

4.1 Global 15 minute river network map (global_15min/)

The three sets of a river network map and topographic parameters are prepared in the CaMa-Flood v3.2 package. The **global_15min/** directory contains the grid-vector-hybrid river network map at the 15’ resolution. The river network map is upscaled from the 3” HydroSHEDS (between 60N and 60S) and the 1km GDBD (above 60N). Each 15’ grid box corresponds to one unit-catchment (Figure 4.1a), so that the grid-vector-hybrid river network map is easy to handle in the analysis and visualization procedure, though the computational efficiency is about half of the vector-based river network map.

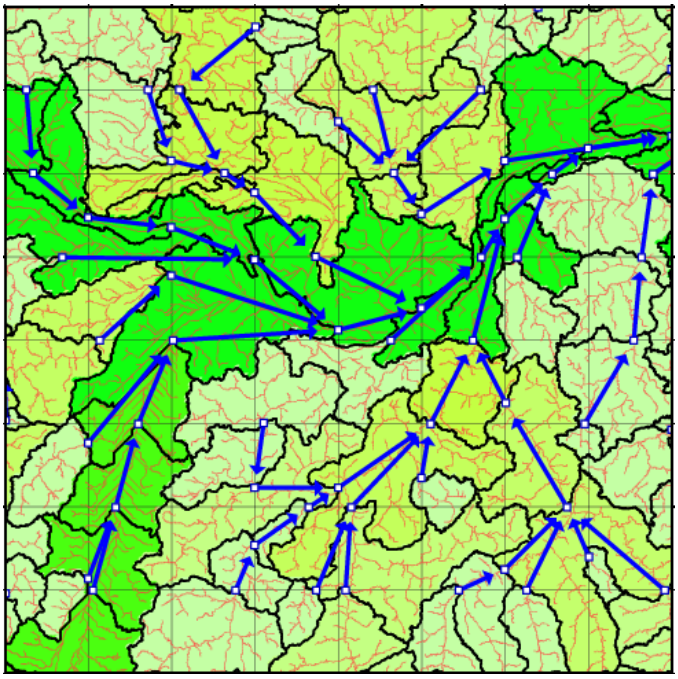

Figure 4.1: Discretization of unit-catchments in the river network map. The outlet pixel of each unit-catchment is marked with a blue circle.

The information of the dimension of the river network map is written in the **params.txt**. The west and north domain boundary (**west**, **north**), the size of the river network map (east-west grid number, **nx**; north-south grid number, **ny**), size of the grid box (**gsize**), the number of floodplain layers (**nfpl**) are listed, as well as the number of the hires database area (**narea**) and the resolution of the hires database (**csize**).

The river network map (**nextxy.bin**) prescribes the downstream cell of each grid cell. The records 1 and 2 denote the downstream grid point ix (**nextx**) and iy (**nexty**), respectively. A set of topographic parameters (Figure 4.2a) consists of the unit-catchment area A_c [m^2] (**grarea**), base elevation Z [m] (**elevtn**), channel length L [m] (**rivlen**), channel depth B [m] (**rivhgt**), channel width W [m] (**rivwth**), downstream distance X [m] (**nxtdst**), and floodplain elevation profile D_f=D(A_f) [m] (**fldhgt**). The floodplain elevation profile is the CDF function (Figure 4.2b) of the height above the nearest river channel within each unit-catchment (Figure 4.2c), which is used to calculate the flooded area A_f [m^2] from the flood depth D_f [m]. 10 values from each 10th percentile of the CDF function are stored in **fldhgt.bin**. For example, the record 3 of the **fldhgt.bin** represents the flood depth [m] of the unit-catchment when 30% of its area is flooded.

Channel width and depth parameters (**rivwth.bin**, **rivhgt.bin**) are calculated using empirical equations (see **map/s01-channel_params.sh**). The satellite-based river width from GWD-LR [Yamazaki et al., 2014b] is also prepared (**width.bin**).

The input matrix (lookup table) for interpolating gridded runoff forcing to irregular unit-catchments is also prepared (**inpmat-1deg.bin** and **inpmat-1deg.txt**). Each unit-catchment receives input water mass from the input grid boxes which overlap the unit-catchment. The input water mass into the grid cell i is calculated by Equation (4.1):

$$F_i = \sum_N A_{i,j} R_j \tag{4.1}$$

where F_i is the input water mass into the grid cell i [m^3s^{-1}], $A_{i,j}$ is the overlapped area between the unit-catchment of the grid cell i and the runoff grid box j [m^2], R_j is the runoff forcing of the runoff grid box j [ms^{-1}]. N is the maximum number of the overlapped runoff grid boxes for one unit-catchment (**inpnum**) which determines the size of the input matrix (**nxin*nyin*inpnum**), and it is written in the dimension file (**diminfo.txt**). Records 1 and 2 of the input matrix represents the (**ixin, iyin**) location of the corresponding runoff grid box, and the record 3 represents the overlapped area $A_{i,j}$ [m^2] (**inpa**).

A file to specify dimensions of simulation (domain, resolution, number of CaMa-Flood grids and input grids, input matrix filename) is prepared (e.g. **diminfo_1deg.txt**, for simulation wit 1 degree runoff input).

Table 4.1: The river network map and topographic parameters

File	Variable	Symbol	Description		Unit	Format
params.txt	–	–	Map Parameters			text
nextxy.bin	nextx	jx	Downstream X	(rec=1)		integer
	nexty	jy	Downstream Y	(rec=2)		
grarea.bin	grarea	Ac	Unit-catchment Area		[m2]	real
elevtn.bin	elevtn	Z	Base Elevation		[m]	real
rivlen.bin	rivlen	L	Channel Length		[m]	real
rivhgt.bin	rivhgt	B	Channel Depth		[m]	real
rivwth.bin	rivwth	W	Channel Width		[m]	real
width.bin	width		GWD-LR width		[m]	real
nxtdst.bin	nxtdst	X	Downstream Distance		[m]	real
fldhgt.bin	fldhgt	X	Floodplain Elevation Profile	(rec=1~10)	[m]	real
inpmat-1deg.bin	inpx	–	Corresponding Input Grid X	(rec=1)	–	integer
	inpy	–	Corresponding Input Grid Y	(rec=2)	–	integer
	inpa	Aij	Area of input grid XY	(rec=3)	[m2]	real
diminfo_1deg.txt	–	–	Dimention Info (1deg input)			text

Table 4.2: The river network map and topographic parameters

File	Variable	Symbol	Description		Unit	Format
lsmask.bin	–	–	Land ID of corresponding hires area		–	integer
basin.bin	–	–	Bain ID		–	integer
bsncol.bin	–	–	Basin Color Patern for Visualization		–	integer
lonlat.bin	lon	–	Longitude, catchment outlet	(rec=1)	deg	real
	lat	–	Latitude, catchment outlet	(rec=2)	deg	real
uparea.bin	uparea	–	Upstream Drainage Area		[m2]	real
upgrid.bin	upgrid	–	Upstream Grid Number		–	integer
grdc_loc.txt			GRDC gauge location			txt
envisat_loc.txt			LEGOS Envisat station location			txt

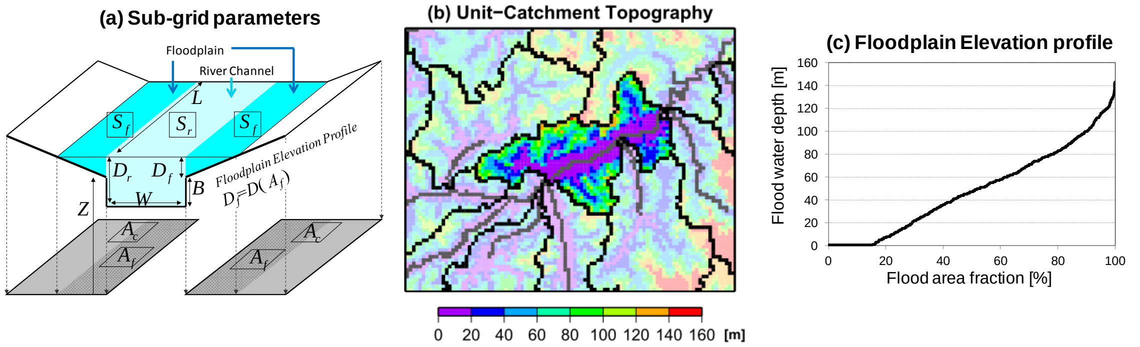

Figure 4.2: (a) Schematic illustration of the sub-grid parameters for the river channel and floodplains. (b) Unit-catchment topography. The height above the nearest river channel is shown by the background color. (c) Floodplain elevation profile.

Some additional datasets associated with the river network map are also prepared in the same directory, and they are listed in Table 4.2. These associated datasets are mainly used in the analysis and visualization of the simulation results. The locations of the GRDC gauges are listed in the **grdc_loc.txt**, whose data indicates (from left to right):

GRDC-ID, River, Station, Downstream Info, Longitude, Latitude, Grid (X, Y), Drainage Area.

The downstream info “a” indicates the gauge is allocated most downstream within the river basin, while “b” indicates there is another gauge in the downstream. The locations of the Envisat virtual stations (LEGOS: http://www.legos.obs-mip.fr/soa/hydrologie/hydroweb/Page_2.html) are listed in **envisat_loc.txt**, which represents (from left to right):

ID, Virtual Station Name, Longitude, Latitude, Grid (X, Y), Drainage Area.

Some high-resolution data required for generating input matrix and floodplain depth downscaling are prepared in **map/global_15min/hires/** directory. The high-resolution data is divided into 13 continental regions as in "**location.txt**" file. The regions below 60N (except na2, eu3, and as4) are based on HydroSHEDS and SRTM3. These hires data is prepared at Cartesian grid coordination system at the resolution of 0.005 degree. The regions above 60N (na2, eu3, and as4) are based on GDBD and GTOPO30, and prepared in Lambert equal area projection at 1km resolution (following Hydro1k). The parameters of Lambert equal area projection can be found in the code **add_lonlat.f90**.

The data named **$(area).catmxy** describes the CaMa-Flood grid (iXX,iYY) of each hires pixel (ix,iy). The data named **$(area).flddif** describes the height above the ground elevation of each pixel [m].

4.2 Fully-grid-based Map (within global_15min/)

Instead of using irregular unit-catchments, the CaMa-Flood model can stably execute hydrodynamic simulations with traditional rectangular grid boxes as its computational elements (fully-grid-based approach). In the fully-grid-based approach, the irregular unit-catchment area is replaced with the area of the rectangular grid box of the 15' resolution Cartesian coordinate system, while the river network map of the grid-vector-hybrid approach is diverted. The channel length and downstream distance are also replaced with the distance between the centers of the grid box and its downstream grid box. The topographic parameters for the fully-grid-based approach are prepared in the same directory of the grid-vector-hybrid approach.

Table 4.3: The files required in the fully-grid-based approach

File	Grid-vector Hybrid	Grid-based
Dimention Information	diminfo_1deg.bin	diminfo_1deg_grid.bin
Unit-catchment Area	grarea.bin	grarea_grid.bin
Channel Length	rivlen.bin	rivlen_grid.bin
Downstream Distance	nxtdst.bin	nxtdst_grid.bin
Input Matrix	inpmat-1deg.bin	inpmat-1deg_grid.bin

4.4 Channel Cross-section Parameters

The channel cross-section parameters (channel length and channel depth) are estimated by an empirical function of river discharge climatology, while the other topographic parameters are explicitly derived from the fine-resolution flow direction map and DEM.

Firstly, the climatology of daily river discharge is calculated by the **calc_rivout.F** program in **$(CaMa-Flood)/map/** directory. The climatology of daily river discharge is written to the output file **rivout.bin**. The record 1 is the annual maximum of 30-day moving average of upstream runoff (m^3/s), R_{up}, while the record 2 represents the annual averaged river discharge (m^3/s). Here, the annual maximum of 30-day moving average of upstream runoff, R_{up}, is introduced because it is assumed that the size of a channel cross-section is determined by flood peak discharge rather than the annual average discharge.

Second, the channel cross-section parameters (channel width (m), W; Channel depth (m), B) are calculated by the program **calc_rivwth.F** in the **$(CaMa-Flood)/map/** directory. The channel width **rivwth.bin** and channel depth **rivhgt.bin** are generated. These two parameters were derived by the following empirical equations:

$$W = \max[\,0.70 \times R_{up}^{0.75}, 10.0] \qquad (4.2),$$

$$B = \max[\,0.14 \times R_{up}^{0.40}, 2.00] \qquad (4.3),$$

where W is the channel width (m), B is the channel depth (m), and R_{up} is the annual maximum of 30-day moving average of upstream runoff [m^3s^{-1}].

Note that the uncertainty in these cross-section parameters is still very high, so extensive calibration is recommended when you set up a new simulation. The coefficients of Equation (4.2) and (4.3) can be changed in the shell script ***s01-channel_params.sh***.

For generating cross-section parameters, go to the map file directory (e.g. **map/global_15min/**) and execute **% ../s01-channel_params.sh** .

5. Input Runoff Forcing

A set of sample input runoff forcing is prepared at **$(CaMa-Flood)/inp/ELSE_GPCC/Roff/** directory. The sample input data is prepared for the years 1990 and 1991, from the output of Ensemble Land State Estimator (ELSE) [Kim et al., 2010]. The sample runoff is calculated using the land surface model MATSIRO forced by the climate forcing from the JRA-25 reanalysis with precipitation correction using GPCC. The sample runoff data is at 1 degree resolution, and prepared in the “plain binary” format. The data array is from 180W to 180E and from 90N to 90S. Note that the byte order of the sample data is “little endian”, so that endian conversion may be required according to the computer environment.

The naming convention of the input runoff forcing is **$(prefix)YYYYMMDD$(suffix)**. In case of the sample data, the prefix is “**Roff____**” and the suffix is “**.one**”. This setting can be changed in a shell script in **$(CaMa-Flood)/gosh/** directory.

The default unit of runoff input is [mm/day] and it’s converted to [m^3/s] in simulation. another unit [water mass / unit area / unit time] can be used by changing the following parameters in gosh script. **DTIN**: seconds in one runoff time step (default set to 86400 for daily runoff), **DROFUNIT**: runoff unit conversion ratio (set to 1.D-3 in default for conversion from [mm] to [m])

If you want the runoff input forcing for the full period other than the sample data period (1990 and 1991), please contact to the CaMa-Flood developer. You can also replace the sample input data with another runoff dataset. Runoff input files in netCDF format can also be used. Sample netCDF runoff at 0.5 degree is prepared in **inp/ELSE_GPCC/runoff_nc/** directory.

In case the grid coordinate system of the runoff forcing is different from the sample dataset, you have to re-calculate the input matrix **inpmat-$(resolution).bin** for the runoff interpolation scheme. The input matrix can be generated by editing and executing the shell script **map/s03-generate_inpmat.sh**. The default value in **map/s03-generate_inpmat.sh** can be used to generate the input matrix for the sample 0.5 deg netCDF runoff.

6. Output Files

The CaMa-Flood has, in a default setting, the 11 output variables listed in Table 7.1. These output files are in plain binary format at the same grid coordinate system as the river network map. The output is daily in a default setting. Undefined value (for ocean grids) is set to 1.e20.

Table 6.1 List of output variables

File	Variable	Symbol	Description	Unit	Format
rivoutYYYY.bin	rivout	Qr	River Discharge	[m3/s]	real
rivstoYYYY.bin	rivsto	Sr	River Wter Storage	[m3]	real
rivdphYYYY.bin	rivdph	Dr	River Water Depth	[m]	real
rivvelYYYY.bin	rivvel	V	River Flow Velocity	[m/s]	real
fldoutYYYY.bin	flddph	Qf	Floodplain Flow	[m3/s]	real
fldstoYYYY.bin	fldsto	Sf	Floodplain Water Storage	[m3]	real
flddphYYYY.bin	flddph	Df	Floodplain Water Deoth	[m]	real
fldareYYYY.bin	fldare	Af	Flood Area	[m2]	real
fldfrcYYYY.bin	fldfrc	Ff	Flood Fraction	[m2/m2]	real
sfcelvYYYY.bin	sfcelv	WSE	Water Surface Elevation	[m]	real
outflwYYYY.bin	outflw	Qall	Total Discharge (Qr + Qf)	[m3/s]	real
storgeYYYY.bin	storge	Sall	Total Storage (Sr + Sf)	[m3]	real
pthoutYYYY.bin	pthout	Qp	Net bifurcation flow from grid (ix,iy)	[m3/s]	real
pthflwYYYY.pth	pthflw	-	Flow of bifurcation channel (ipth, ilev)	[m3/s]	real

Flood fraction represents the fraction of the flooded area to the unit-catchment area of each grid cell. The water surface elevation is calculated as WSE=Z-B+Dr, where Z is base elevation, B is channel depth. Flood Fraction is the fraction of flooded area to the unit-catchment area of each grid cell. Note that flooded area and flood fraction is calculated based on the irregular shaped unit-catchment, so that they are not suitable for a rigorous comparison against gridded dataset. The river discharge and flow velocity are outputted as daily average, while the other variables are outputted as the instantaneous value at GMT 00:00 of each day.

In the sample executable shell script, the output files are written in the running directory **$(CaMa-Flood)/gosh/tmp/$(ExerimentName)/** . After the calculation, it is recommended to move the running directory to the output directory **$(CaMa-Flood)/out/** where some analysis tools are prepared (such as conv_day2mon.sh, monthly average calculation)

7. Shell Script to execute simulations

Executable shell scripts to run a CaMa-Flood simulation are prepared in the shell script directory **$(CaMa-Flood)/gosh/**. The sample executable shell script is **global_15min.sh**. In the executable shell script, the simulation settings are written in the input namelist "**input_flood.nam**", and then the simulation is executed in the running directory specified in the shell script.

The setting of the sample executable shell script (**global_15min.sh**) is as follows.

- BASE Directory: **BASE="$(CaMa-Flood)/"** or **BASE=`pwd`/../**

- Experiment name: **EXP="global_15min"**

- The simulation is executed in the running directory **RDIR="${BASE}/out/$EXP"**. The OpenMP parallelization with 4 CPUs.

- Floodplain flow is activated (**LFLDOUT=.TRUE.**), bifurcation channel scheme is deactivated (**LPTHOUT=.FALSE.**). Storage only restart is deactivated (**LSTOONLY=.FALSE.**)

- River discharge is calculated by the local inertial equation (the local inertial equation for small slope areas; the diffusive wave equation for steep areas). Adaptive time step is activated (**LADPSTP=.TRUE.**).

- Simulation time is set from 1990 to 1991 **(YSTART, YEND**). The simulation starts from the zero storage condition (**SPINUP=2**) and spin-up period is set to 1 years (**NSP=1**).

- The river network map and topography parameters in the map directory **FMAP="$(CaMa-Flood)/map/global_15min/"** are used. Channel width parameter is from GWD-LR (**CRIVWTH=${FMAP}/rivwth_glwlr.bin**), channel depth parameter is from empirical equation (**CRIVHGT=${FMAP}/rivhgt.bin**).

- Input runoff forcing is interpolated by using the input matrix (LINTERP=.TRUE. ; **CINPMAT=${FMAP}/inpmat-1deg.bin**). Runoff input forcing in the runoff directory **CRUNOFFDIR="${BASE}/inp/ELSE_GPCC/Roff/"** is used.

- The output is written in the running directory **COUTDIR="./"** . Total river discharge (outflw), river water depth (rivdph) and flooded area (fldare), flooded fraction (fldfrc), water surface elevation (sfcelv), total water storage (storge) are outputted, while the other variables are not written (variables which do not have to be output are set to “**NONE**”). The bifurcation channel flow output is automatically set to NONE in the simulation when bifurcation channel scheme is deactivated.

8. Simulation Settings

The simulation options available in the CaMa-Flood model are explained in this section. The switches (or variables) to control the simulation setting are stored in “**mod_input.F**”, and they can be changed by editing the input namelist “**input_flood.nam**”.

8.1 Restart Mode

The CaMa-Flood can be run from the zero-storage condition or from the initial condition given by a restart file. For the simulation from the zero-storage condition, set **IRESTART=2** (default). Spin-up period can be specified by setting **NSP=$(spin-up years)**.

For the simulation from the restart file, set **IRSTRT=1**, and specify the restart file directory (**CRESTDIR**) and the restart file name (**CRESTSTO**). The restart files are outputted at the end of each year as defaults (**RESTFREQ=0**), but daily restart file can be acquired by setting **RESTFREQ=1**.

For discharge calculation by local inertial equation, discharge and flood stage of the previous time step is required for a strict restart. When restart only from water storage is preferred, please change the setting in gosh script to **LSTOONLY=.TRUE.**

8.2 Simulation Time

Simulation time can be specified at specific dates by editing **ISYEAR, ISMON, ISDAY** (for the start date, 00:00am) and **IEYEAR, IEMON, IEDAY** (for end date, 00:00am).

8.3 Fully-grid-based map

Instead of using irregular-shaped unit-catchment, the CaMa-Flood simulation can be executed with the fully-grid-based river network map with rectangular grid-boxes (for details, see [Yamazaki et al, 2013]). For this purpose, please replace the topographic parameters in a map directory from the one with the irregular unit-catchments (**diminfo.txt, grarea.bin, nxtdst.bin, rivlen.bin, impmat-1deg.bin**) to the ones with the rectangular grid-boxes (**diminfo_grid.txt, grarea_grid.bin, nxtdst_grid.bin, rivlen_grid.bin, impmat-1deg_grid.bin**). The sample shell script to execute a simulation with the fully-grid-based map is prepared in **gosh/** directory (**test_fullgrid.ksh**).

8.4 Runoff Interpolation

Runoff forcing can be inputted to unit-catchment by the “nearest point interpolation” or the “runoff interpolation scheme with mass conservation”. The nearest point interpolation is activated by setting **LINTERP=.FALSE.** . The nearest point interpolation is valid only when either of the grid-vector-hybrid map or the fully-grid-based map is used. The runoff interpolation scheme with mass conservation is activated by setting **LINTERP=.TRUE.** and by specifying the input matrix name (**CINPMAT**).

8.5 Compressed Vector Output

In order to reduce the size of the output files, the compressed vector format which only writes the values on land grid cells can be activated by setting **LOUTVEC=.TRUE.** . The compressed vector output can be converted to the normal 2D map by using the script **conv_vec2map.sh** in the **out/** directory.

8.6 Routing Scheme

Floodplain flow routing can be activated by setting **LFLDOUT=.TRUE.** .

Bifurcation channel scheme can be activated by setting **LPTHOUT.TRUE.** . Bifurcation channel parameters must be generated in the map directory by **map/s02-set_bifurcation.sh** .

The kinematic wave routing can be used by setting **LKINE=.TRUE.** .

The floodplain inundation scheme can be deactivated by setting **LFLD=.FALSE.** . Note that the run without floodplain inundation is not stable with the diffusive wave equation, so the no floodplain option must be used with the kinematic wave equation (**LDIFF=.FALSE.**).

8.7 Adaptive and Constant Time Step Schemes

The adaptive time step scheme is activated by setting **LADPSTP=.TRUE**. and set the time step **DT=86400** (1 day). Then the adaptive time step routine automatically selects the maximum acceptable time step at the initiation of the daily calculation loop in **contrplphy.F**. Note that the adaptive time step scheme is valid only when the local inertial equation is used (**LDIFF=.TRUE.**).

In order to use the constant time step scheme, deactivate the adaptive time step (**LADPSTP=.FALSE.**) and manually set the time step **DT=$(timestep_in_sec)**.

8.8 Usage of netCDF

The netCDF I/O commands are supported in the CaMa-Flood model. Please activate the flag **DCDF=-DUseCDF** in **$(CaMa-Flood)/adm/Mkinclude**. The netCDF I/O is activated by the following flags in the namelist: for river network maps (**LMAPCDF**); for restart data (**LRESTCDF**), and output data (**LOUTCDF**). Note that netCDF river network map is mainly used in ECMWF, and not included in the sample package.

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Version History

CaMa-Flood Ver 1

The first version developed in U-Tokyo as a part of the master thesis of the developer. This version was used for the simulations in [Yamazaki et al., 2011, WRR].

CaMa-Flood Ver 2

The program was improved under the collaboration with ECMWF. Many schemes for improving the computational efficiency have been implemented to the model, including the 2D-map to 1D-vector conversion and parallelization using OpenMP and MPI. This version was used for the simulations in [Yamazaki et al., 2012a, WRR].

CaMa-Flood Ver 3

The routing scheme was finally stabilized in this version by implementing the local inertial equation developed in U-Bristol.

- Ver 3.0: Implementation of “the local inertial equation” and “the adaptive time step scheme”
- Ver 3.1: New river network maps in which the elevations of river mouth are corrected to 0 m.
- Ver 3.2: Implementation of “the vector-based river network map”, and “the runoff interpolation considering mass conservation”. Many additional changes are included along with these new schemes.
- Ver 3.3.0: ~~The hybrid routing which uses both of the local inertial equation and the diffusive wave equation. The error of discharge calculation in high slope areas was fixed.~~ (problem solved in v3.3.1)
- Ver 3.3.1: The stabilized local inertial equation (instead of the hybrid routing). This version is used for the simulation in [Yamazaki et al , 2013]

- Ver 3.4.0: Floodplain flow is implemented. Minor changes in model structure (e.g. diagnostic variable, subroutine names at the control level.)
- Ver 3.4.4: Regionalization, Downscaling, Input matrix generation.
- Ver 3.4.5: Bug fix in elevation map.
- Ver 3.5: Test Version for Bifurcation Flow (not distributed)
- Ver 3.6.0: Test Version for Global Bifurcation and GDW-LR
- Ver 3.6.1 Distributed Version: Global Bifurcation Flow, GWD-LR, etc.
- Ver 3.6.2 Bug fix.