A Guide to the Glacial Retreat Module in CAESAR-Lisflood

This guide provides an introduction to the CAESAR-Lisflood landscape evolution model and the enhancements to simulate the geomorphic impacts of glacial retreat. These enhancements were developed as part of the NERC PEGASUS project to investigate the role proglacial lakes have in moderating downstream water and sediment supply.

Proglacial lake at the toe of the Chumpe Glacier, Peru. Taken by Josh Wolstenholme, 2019.

Sections:

1. A brief introduction to CAESAR-Lisflood
2. The glacial retreat module
3. Setting up you CAESAR-Lisflood model simulation

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Features material from the CAESAR-Lisflood Wiki created by Professor Tom Coulthard.

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1. A brief introduction to CAESAR-Lisflood

CAESAR-Lisflood (Coulthard et al., 2013) is a second-generation Landscape Evolution Model (LEM). LEMs are a class of models designed to simulate long-term (hundreds to millions of years) changes in landscapes, with the purpose of understanding how large-scale processes (e.g., climate and tectonics) influence landscape developments. To achieve this, modellers needed to simplify and aggregate many of the morphodynamic processes to create models efficient enough to be useful - such models are often referred to as 'reduced complexity'. One common simplification is to represent hydrology as steady-state flow, limiting the temporal detail that can be represented.

The key development of CAESAR-Lisflood over the original CAESAR was the replacement of the steady-state hydrology with the Lisflood-FP hydraulic code. This development meant that the hydrological and hydraulic processes could be simulated at timesteps as small as 1s. To maintain efficiency, CAESAR-Lisflood usually uses a variable timestep, modelling in finer resolution when flows are likely to be morphodynamically significant yet aggregating during periods when little change is likely to occur. Using these development, CAESAR-Lisflood is able simulate event scale changes within scenarios lasting thousands of years without the need for a supercomputer. Figure 1 provides a simplified overview of the processes that occur during each timestep of CAESAR-Lisflood.

The 'Geomorphic Multiplier' and model uncertainty

(Coulthard et al., 2012) described the 'geomorphic multiplier', a physical effect where increases in discharges can result in much larger increases in sediment transport. This is because most of the sediment transport laws, based on limited observations of river systems or experiments in physical flumes, include a cubic relationship between the two. Unfortunately for modellers, this relationship also acts as a prism within the uncertainty cascade in the modelling, where even small input uncertainties, for example within rainfall observations, translate to small, linear differences in discharges but large and diverging differences in sediment yields and landscape changes (Skinner et al., 2020).

There is no definitive sediment transport law that governs the relationship between river flows and sediment processes. There are several laws in use, each based on only a limited set of observations of natural systems, physical experiments, or a combination of two. Consequently, each law is said to be better suited to the range of sediment sizes included in the observations. CAESAR-Lisflood currently includes the choice of three different laws. Often the choice of law is arbitrary yet is the largest source of uncertainty in the modelling, with different laws sometimes producing an order of magnitude difference in outputs (Skinner et al., 2017).

The consequence of the above is that the uncertainties inherent in LEMs, like CAESAR-Lisflood, are far greater than for models that simulate hydrological or hydraulic processes in isolation to morphodynamic processes. An added issue is that there is yet to be developed metrics with which to assess the performance of LEMs - observed records of landscape change have nowhere near the temporal extent to cover the timescales involved in landscape development, nor do they have the spatial and temporal resolution to capture event scale changes. Catchment outlet metrics, often used to assess hydrological models, provide limited information about changes within the catchment and are subject to equifinality (Skinner et al., 2017). This means that CAESAR-Lisflood has not undergone the same level of scrutiny, in terms of calibrations, validations, and verifications, as other forms of modelling used operationally.

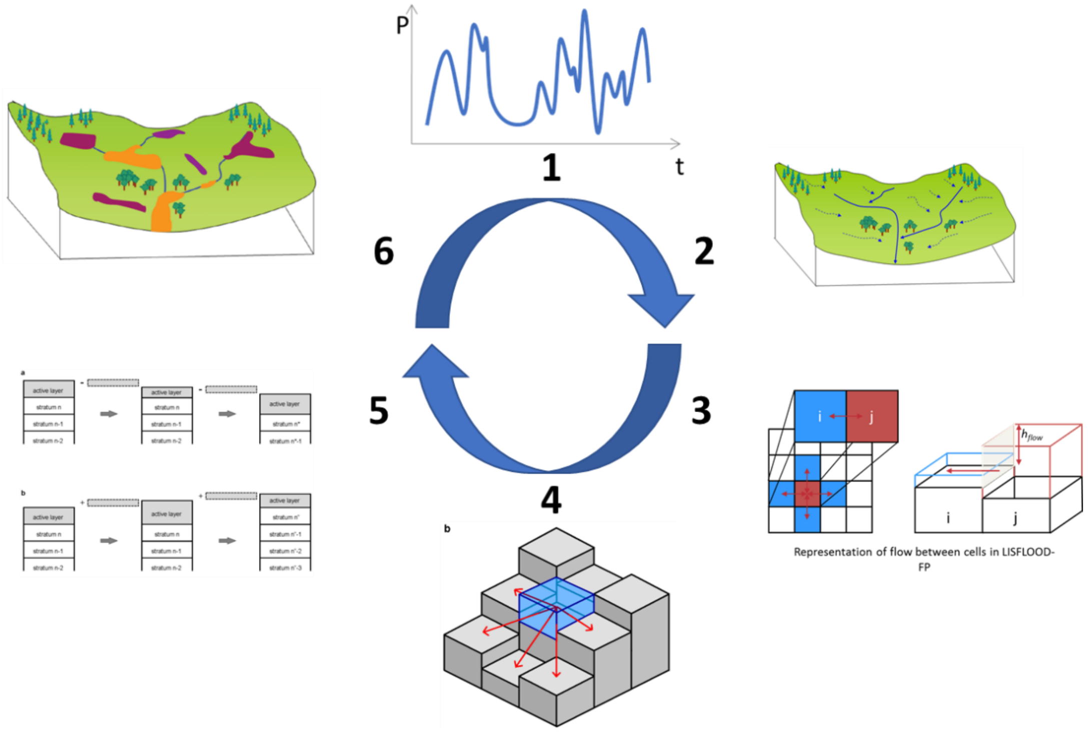


Figure 1 - A reductionist view of the processes that occur in each timestep within CAESAR-Lisflood. 1 = an hydrological input is applied, either as rainfall, discharge, or a water level applied to a set area (for tidal flows). 2 = In the case of rainfall, this input (as rate) is converted to a water volume using TOPMODEL and the volume distributed around the catchment area. 3 = The Lisflood-FP hydraulic code moves water between cells in four directions. 4 = If the sediment process modules are applied, the CAESAR code will convert the Lisflood-FP flow velocities to shear stresses based on channel and water slopes. 5 = The calculated shear stresses are used to erode the bed according to the selected sediment transport law. It can do this across a distribution of up to nine grainsize classifications. Eroded material is distributed between cells downstream. CAESAR-Lisflood uses an active layer system, so once the surface layer exceeds this depth it closes that layer and starts a new one - this can be used to produce a proxy of stratigraphy. 6 = Patterns of erosion and deposition develop across the landscape. (Figure adapted from materials produced by Prof Tom Coulthard)

Appropriate Application

The reduced complexity and highly uncertain nature of CAESAR-Lisflood means it needs to be applied appropriately. The model simulates processes at temporal scales as fine as 1s allowing it to model event scale changes to the landscape - that does not mean that the model *should* be used to do this.

"All models are wrong but some are useful." - George Box

The use of CAESAR-Lisflood should not deviate too far from the original purpose of LEMs. The most useful information it can provide it to see how systems respond, broadly, to shocks and changes. It will produce numbers for sediment yields and changes in elevations, but these are uncertain and not as useful as information on the direction and relative scales of changes of those things.

2. The glacial retreat module

The NERC PEGASUS project aims to better understand the role proglacial lakes have on moderating the supply of water and sediments downstream in the Peruvian Andes. The modelling work forms part of Work Package 2 and is using CAESAR-Lisflood to simulate landscape changes in areas of glacial retreat, with and without proglacial lakes. The latest version of the model (v1.9j) does not have the functionality to do this and therefore has been modified.

New ice melt mode.

CAESAR-Lisflood currently allows you to select from three different input types: rainfall (catchment mode); discharge (reach mode); and, water levels (stage/tidal mode). The model can operate with combinations of all three but must include at least one. Here, a fourth mode has been included - ice melt mode.

To operate in ice melt mode a few input files are required - an ice-free DEM, a layer of ice thicknesses (at the same resolution and extent as DEM), a timeseries of freeze level heights, and a time series of melt rates ($m.h^{-1}$).

Upon initialisation, the model will merge the ice-free DEM with the ice thickness file as the initial elevation. All cells with an ice thickness > 0 are assigned as containing ice and becomes unerdoable (this is done by setting the bedrock for these cells as equivalent of the elevation).

In each timestep, the following process take place in addition to those shown in Figure 1:

1. Each cell is checked in sequence. If a cell is shown to both contain ice and is below the freezing level height (FLH) for this timestep the model will proceed to 2., else the model moves to the next cell in the sequence.

2. The melting rate for this timestep is applied to the cell, lowering the ice thickness by the appropriate amount and updating the elevation and bedrock layers accordingly.

3. If the ice thickness for a cell is set to zero or below the cell will be reassigned as not containing ice, reverting to the elevation of ice free DEM and the initial bedrock.

4. The volume of melted ice is converted into a water volume by multiplying it by 0.8 (based on assumption of Drenkhan *et al.* (2018) that remaining ice will be less dense firn type). This volume is applied directly to the cell. If suspended sediment is being used, the water will be given a hard-coded concentration of suspended sediment (currently $1g.l^{-1}$).

5. The model then continues from step 3 of the processes in Figure 1.

A negative side-effect of the ice-melt mode is that to maintain computational efficiency it is necessary to hard-code a fixed timestep (currently 30mins).

The rest of this guide will describe how you can get set up with running your own simulations using the ice melt functions, plus a more detailed look at the parameters required for the model.

3. Setting up your CAESAR-Lisflood model simulation

This section will take you through the steps you need to take to set up and run your own CAESAR-Lisflood model simulation. Before you start you will need (at least) the following things in the same folder:

1. The CAESAR-Lisflood ice melt executable
2. A text file of ice-free elevations for your domain
3. A text file of ice thicknesses for your domain
4. A text file of bedrock elevations for your domain
5. A configuration file with all the parameter values and filenames saved within

Any spatial data used by the model need have the same extent and use the same resolution (aka pixel/cell size). They also need the same headers. If you choose to use spatially variable rainfall or Manning's n, these also need to use the same format, extent, and resolution. These are in the same format as files exported using the Raster-to-ASCII tool in ArcMap.

You will also need to know the values for parameters specific to your domain, for example, grain size distributions or Manning's n values. This may require a field visit if not available already.

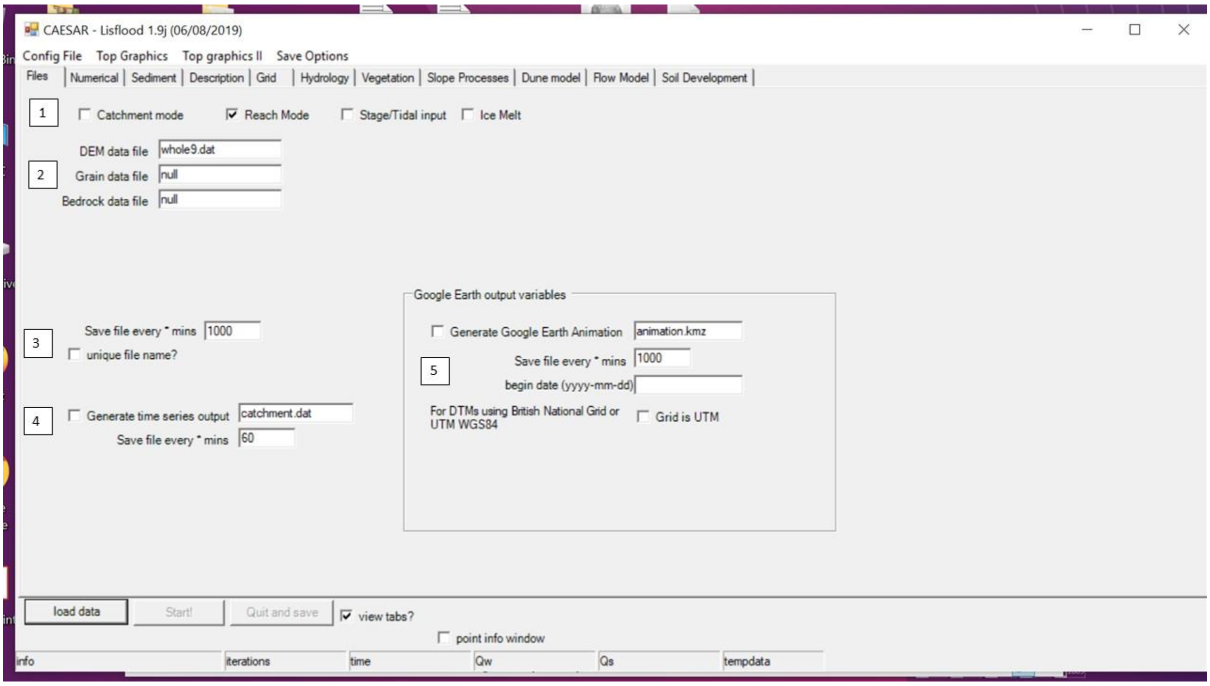
The Graphical User Interface (GUI) for CAESAR-Lisflood does not allow you set file pathways to bring in data or to save data, therefore all the date to be used by the model needs to be in the same folder as the executable file you use. Likewise, any data saved will go to the same location. Some simulations and settings can end up creating a lot of information, so make sure you have ample storage there before you start. The model will crash if it runs out of storage space for outputs.

Use the following steps to get your model up and running:

1. Double click the executable file to open the programme. The model should open with the view of the File Tab with default values, as shown in Figure 2.
2. If you have a saved configuration (henceforth config) file, you can open this by clicking "Config File" in the top menu, then "Open", and selecting your saved config file (Note: this will default open the last folder you saved a config file too, NOT the folder you are working in. Check you are in the right folder!).
3. Whether using the default or a previously saved file, you should now modify the parameters in the GUI. Go through the Tabs as described in this document and enter the relevant values.
4. Save your config file by clicking "Config File" and then "Save as", giving your file a recognisable name and save. (Note: Again, make sure you are in the right folder here).
5. Click "Load Data" in the bottom-left to initiate the model. Read and dismiss any warnings that come up - act on them if required, for example it may be that one or more of your files is not formatted correctly.
6. Click "Top Graphics" in the top menu and tick the "DEM" option on. Your domain should now show.
7. Click "Start" in the bottom-left. The model will now start to resolve. Time to make a cup of tea and wait for it to finish.

The sections below will now take you through each of the relevant Tabs in turn and describe the parameters and values required for each. Use these when performing Step 3 in the list above.

Tab 1 - The File tab



☐ Catchment mode ☑ Reach Mode ☐ Stage/Tidal input ☐ Ice Melt

DEM data file: whole9.dat
Grain data file: null
Bedrock data file: null

Save file every * mins: 1000
☐ unique file name?

☐ Generate time series output: catchment.dat
Save file every * mins: 60

☐ Generate Google Earth Animation: animation.kmz
Save file every * mins: 1000
begin date (yyyy-mm-dd):
For DTMs using British National Grid or UTM WGS84 ☐ Grid is UTM

☑ view tabs?
☐ point info window

Figure 2 - Screen shot of the default File tab in CAESAR-Lisflood

1 - Select modes to run the model in

CAESAR-Lisflood can run in different modes and combinations of these modes. These are -

Catchment Mode - for using a rainfall input
Reach Mode - for using a river discharge input
Stage/Tidal Mode - for using a water level input
Ice Melt Mode - for modelling glacier retreat

For modelling glacier retreat you will be using the Ice Melt Mode always, so make sure this is ticked. If using rainfall too, also tick Catchment Mode. We can ignore the other two modes for now, make sure those are not ticked. We will learn more about setting the inputs for these when we look at the Hydrology tab.

2 - Enter files for Elevation, Grain data, and Bedrock

Here are three boxes to enter file names for different inputs. These inputs describe the initial conditions for elevations, grain size distributions, and bedrock across the model domain. In each box, either enter the name of the file (as either .dat or .txt) - that file must be in the same folder as the model's executable file - or "null" if a file is not being used.

DEM data file - This is the Digital Elevation Model, DEM, and needs to be a text file containing a regular grid of cells, each cell containing an elevation in metres. The format of the file is the same as ASCII, so if you use the Raster-to-ASCII tool in ArcMAP, for example, the exported file will be the correct format. The model cannot operate without a DEM so this box cannot be "null".

Grain data file - You can most likely leave this box as "null". When null, each cell will be assigned a global distribution of grainsizes as described in the Sediment tab. You may want to enter a file in here, for example after performing a 'spin-up' of the model to initially distribute sediments before performing experiments. In this case, set the model to save grainsizes and the final grain.dat file produced will be the correct format.

Bedrock data file - The bedrock data file needs to be in exactly the same format at the DEM, with the same extent and resolution, but instead of elevations of the land surface it includes elevations of a bedrock layer that the model cannot erode below. This can be used to limit excessive scouring in the model (e.g. by setting all bedrock elevations as DEM -10m), or if data is available on bedrock it can be used to improve model representation. If "null" there will be no limit to erosion in the model.

3 - Saving data

These settings allow you to tell the model to save different data at the specified timestep (enter the value in the box, the units are minutes of simulated time). If you tick the box, the model will save all selected options from "Save Options" at the specified timestep.

4 - Catchment outlet output

Ticking the box labelled "Generate time series output" will make the model create a timeseries recording fluvial and sediment outputs from the model - this is anything that exits the model domain, from any edge, during that timestep.

The model will create a text file (either .dat or .txt) with the filename entered into the box. The file will show in the same folder as the model's executable file. Note - if you do not give the file a unique name it will append data to the existing file, not overwrite it.

The exported file will have new line for each time step and several columns. Left-to-right these columns are -

1. Timestep number
2. Mean discharge of water exiting the domain ($m^3.s^{-1}$)
3. Calculated discharge for the timestep from internal TOPMODEL hydrological model ($m^3.s^{-1}$)
4. Blank column
5. Total sediment yield (m^3)
6. Sediment yield for grainsize 1 (m^3)
7. Sediment yield for grainsize 2 (m^3)
8. Sediment yield for grainsize 3 (m^3)
9. Sediment yield for grainsize 4 (m^3)
10. Sediment yield for grainsize 5 (m^3)
11. Sediment yield for grainsize 6 (m^3)
12. Sediment yield for grainsize 7 (m^3)
13. Sediment yield for grainsize 8 (m^3)
14. Sediment yield for grainsize 9 (m^3)

Note - this output can be used as an input for the model's Reach Mode. We will look at this in more detail under the Hydrology tab.

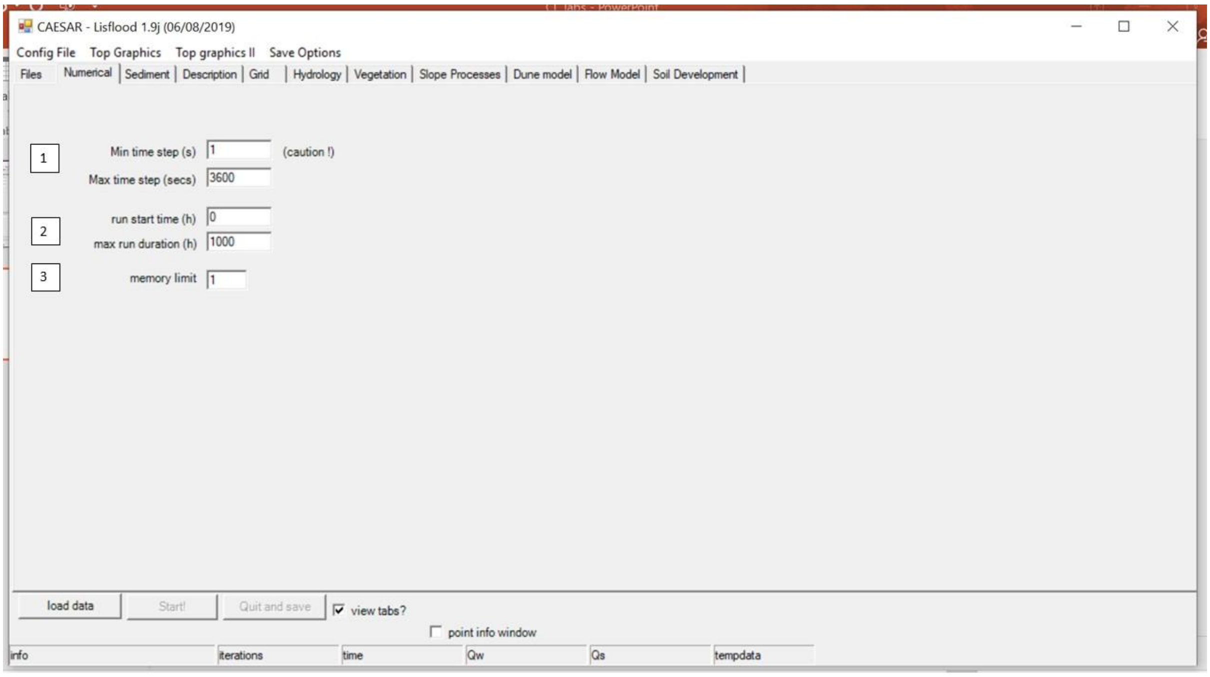
5 - Make an animation

Here you can set the model up to export an image at specified timesteps. Using additional software (e.g., VirtuaDub) these can be stitched together to make animations. This will also create a .kmz to export this data to Google Earth but this is a legacy function and may not work properly.

To create images make sure the box labelled "Generate Google Earth Animation" is ticked. You can rename the .kmz file in the text box next to it. Below this specify the timestep between saved images, the units are minutes. You need to enter a start date in the format specified - this does not need to be a meaningful date but cannot be left blank. Finally, specify the co-ordinate system used - the options are limited but will only have an impact if you are trying to export to Google Earth.

The model will create a folder called Animation in you model folder and save images in there. If an Animation folder already exists it will delete any previously saved images.

Tab 2 - Numerical Tab



Min time step (s) 1 (caution !)
Max time step (secs) 3600
run start time (h) 0
max run duration (h) 1000
memory limit 1
☑ view tabs?
☐ point info window

Figure 3 - Screenshot of the default Numerical tab

1 - Timestep controls

In an unmodified version of CAESAR-Lisflood, the model will adopt a variable timestep in order to manage computational efficiency. This prioritises periods with larger inputs and flows using finer scale timesteps. Here, you can set the bounds of the smallest and largest timesteps the model will use, the units are seconds.

For the ice melt function these have been over-ridden for a hard-coded fixed timestep of 30 minutes, so these can be ignored.

2 - Run start time and duration

Here you can set how long you want your simulation to run for by entering a value in the max run duration box, units are in simulated hours. The model will stop running once it has simulated this duration period.

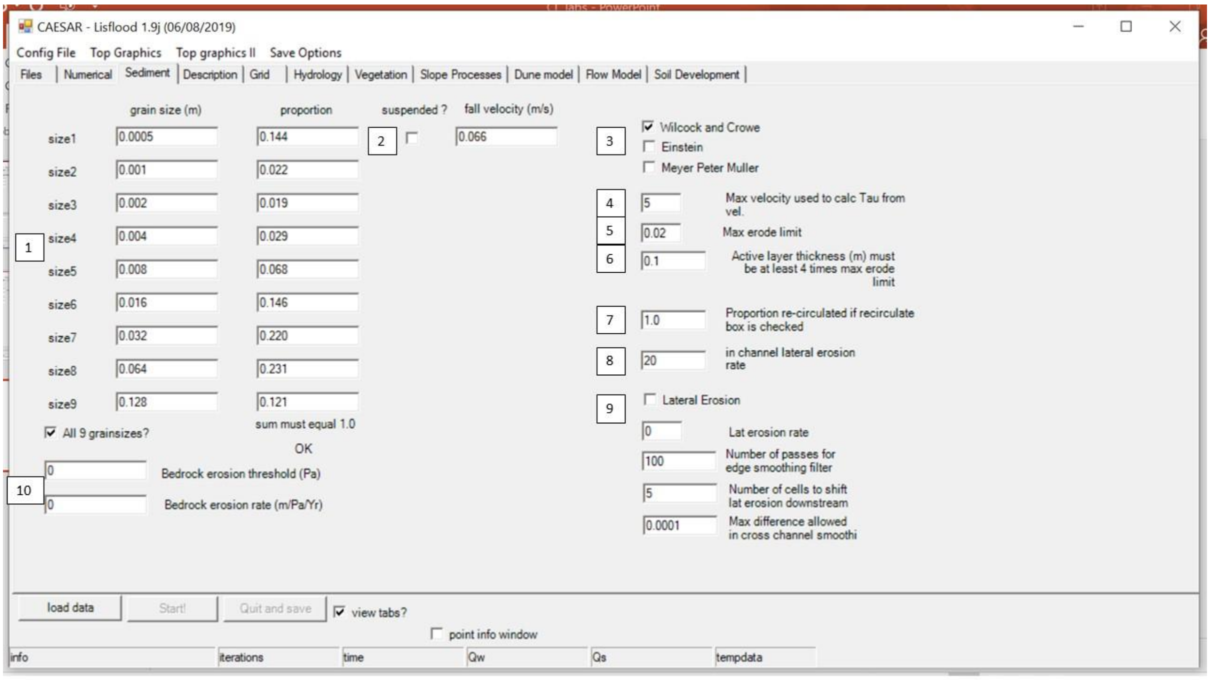
If you have a timeseries file for your input but want to start part way through then use the run start time box to specify where you want it to start. If you want to run the whole timeseries, use 0. Units are in simulated hours.

3 - Memory Limit

The number of data points that CAESAR-Lisflood needs to store can get very large. For example, for grainsizes the model needs to store 10 numbers for each cell for each active layer in use. If, for example, you model has 10 active layers in each cell, and 100,000 grid cells, the model needs to store 10,000,000 data points in single array. For larger domains it may not be possible to store all the required data points in single arrays and by setting a larger memory limit it allows the model to split them between arrays.

You do not need to worry about this parameter unless the model throws up a warning on initialisation. If this is the case, keep increasing this value until it works.

Tab 3 - Sediment Tab



	grain size (m)	proportion
size1	0.0005	0.144
size2	0.001	0.022
size3	0.002	0.019
size4	0.004	0.029
size5	0.008	0.068
size6	0.016	0.146
size7	0.032	0.220
size8	0.064	0.231
size9	0.128	0.121

☑ All 9 grainsizes?
sum must equal 1.0
OK

suspended ? ☐
fall velocity (m/s) 0.066

0 Bedrock erosion threshold (Pa)
0 Bedrock erosion rate (m/Pa/Yr)

☑ Wilcock and Crowe
☐ Einstein
☐ Meyer Peter Muller

5 Max velocity used to calc Tau from vel.
0.02 Max erode limit
0.1 Active layer thickness (m) must be at least 4 times max erode limit
1.0 Proportion re-circulated if recirculate box is checked
20 in channel lateral erosion rate

☐ Lateral Erosion
0 Lat erosion rate
100 Number of passes for edge smoothing filter
5 Number of cells to shift lat erosion downstream
0.0001 Max difference allowed in cross channel smoothi

☑ view tabs?
☐ point info window

Figure 4 - Screenshot of the default Sediment tab

1 - Sediment Grain Sizes

CAESAR-Lisflood allows you to enter a distribution of grain sizes with up to nine different classifications that it will apply globally - these will be over-ridden if you have entered a grain data file in the File tab. The default classifications are based on common sieve diameters so it is recommended that you do not change these. You enter the width in the left-hand column, units are metres, and the proportion of the total in the right-hand column. The proportions must add up to exactly 1 and the model will warn you when they do not.

2 - Suspended Sediment

Suspended sediment is optionally in CAESAR-Lisflood and can be activated by ticking the 'suspended?' box here. Suspended sediment uses the grain size entered into the size1 grain size. You can change the minimum velocity threshold below which the suspended sediment deposits by entering a new value in the text box, units in $m.s^{-1}$.

3 - Sediment Transport Law

CAESAR-Lisflood allows you to select from a choice of three different sediment transport laws. Each has been determined based on limited observations of natural systems and physical experiments so are best applied to appropriate ranges of grain sizes. The different laws can produce quite different outputs so it is worth investing a bit of time to research the best choice and/or running separate tests using each and viewing outputs as an ensemble.

4 - Max velocity used to calculate Tau

This parameter helps manage excessive erosion on very steep slopes by setting a maximum velocity used in the sediment transport calculations. Maintaining the default value of 5 is appropriate in the majority of cases. Units in $m.s^{-1}$.

5 - Max Erode Limit

If too much material is moved from one cell to another in a single timestep it can create a numerical instability where the model tries to return some of the material back in the next timestep. This parameter limits the depth of material, units are metres, that can be eroded in a single cell each timestep and thus controls the timestep the model chooses. This should be set at 0.01 for DEMs of resolution 10m or finer, but can be slightly higher for coarser DEMs - for TanDEM-X data at ~12m resolution, use 0.01.

With the ice melt mode fixing the timestep, changing this value will likely alter the amount of erosion that occurs.

6 - Active Layer Thickness

CAESAR-Lisflood uses a series of active layers in each cell to represent the bedload, surface layer, and sub-surface layers. The parameter determines the thickness, units are metres, the active layer can become before becoming in active (thus creating a new active layer). Normal values to use are 0.1 or 0.2. The value must be at least four times the value for the maximum erosion limit (see 5 above). This will likely have little impact on the results of your tests.

7 - Proportion Re-circulated if recirculate box is checked

You can ignore this box. It only applies when running in reach mode and helps to stop the channel being stripped of sediment. If the recirculate sediment box on the model tab is ticked it will use output sediment yields as an input for the next timestep, the value in this box is the proportion, so the default of 1.0 means 100% is returned.

8 - In-channel lateral erosion rate

Lateral erosion occurs when erosion from part of channel results in movement or sliding from neighbouring areas, reducing a feedback effect where erosion and deepening leads to enhanced flows. The value of this parameter should reflect how cohesive the sediment is in the area. Loose and non-cohesive sediments are more easily eroded leading to shallow and wide channels (use values closer to 20). Where sediment is more cohesive it becomes harder to erode and transport, leading to narrower and deeper channels (use values closer to 10). Values used should be between 10 and 20 in most cases.

Here is a useful explanation of the in-channel lateral erosion rate from Prof Tom Coulthard: http://www.showme.com/sh/?i=24567

9 - Lateral Erosion Settings

The lateral erosion settings, when checked, turn on an additional meander evolution module in CAESAR-Lisflood. This simulates processes of bank erosion not covered by the in-channel lateral erosion above. Using this module will impact computational efficiency and likely not required in most cases.

If checked, you need to provide four further parameter values:

Lateral Erosion Rate

The rate of lateral erosion is calculated by the radius of curvature using the edge counting method described in Coulthard and Van de Wiel, (2007). The value you enter here needs to calibrated to your field site but values of 0.01-0.001 can be applied to braided rivers and values of 0.0001 suitable for meandering channels. The rate is independent of grid cell resolution.

Number of passes for edge smoothing filter

This value determines the smoothness of the curvature of meander bends in the model. This too requires calibrating to your field site and should be the typical number of grid cells between two meanders. This must be an integer.

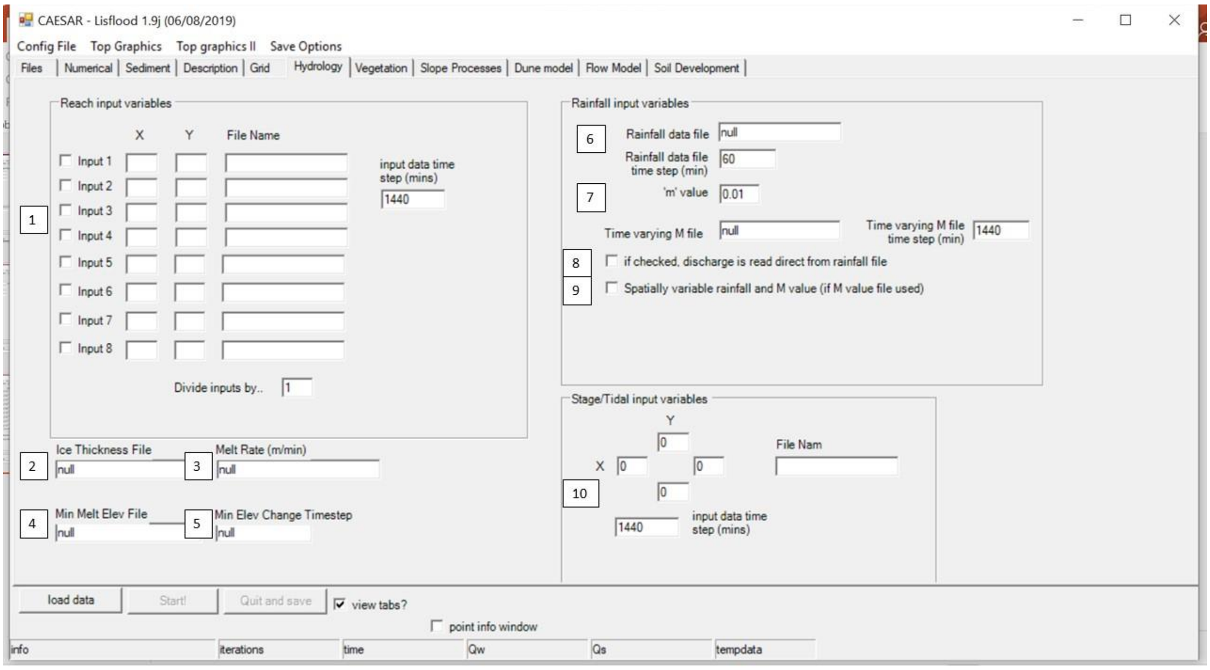
Number of cells to shift lat erosion downstream

In reality, meanders tend to migrate downstream and this parameter determines how the model simulates this by shifting the lateral erosion downstream. It is suggested that a value around 10% of the smoothing filter above is used. This must be an integer.

Max difference allowed in cross channel smoothing of edge values

The above parameters are used by CAESAR-Lisflood to determine the radius of the curvature of the outside edge of meander bends. This parameter is used to determine the lateral gradient across the channel through smoothing values so ratios between cells are less than the threshold specified here. A smaller number creates a smoother channel but impacts greatly on computational efficiency. Too large a number and deposition can occur in the middle of the channel. The default value is 0.0001 and is suitable in most cases, yet for channels wider than 10 cells it will need to be lowered to 0.00001.

Tab 4 - The Hydrology Tab



☐ Input 1
☐ Input 2
☐ Input 3
☐ Input 4
☐ Input 5
☐ Input 6
☐ Input 7
☐ Input 8
input data time step (mins): 1440
Divide inputs by..: 1
Ice Thickness File: null
Melt Rate (m/min): null
Min Melt Elev File: null
Min Elev Change Timestep: null
Rainfall data file: null
Rainfall data file time step (min): 60
'm' value: 0.01
Time varying M file: null
Time varying M file time step (min): 1440
☐ if checked, discharge is read direct from rainfall file
☐ Spatially variable rainfall and M value (if M value file used)
Y: 0
X: 0
0
0
File Nam:
input data time step (mins): 1440
☑ view tabs?
☐ point info window

Figure 5 - Screenshot of the default Hydrology tab

Reach Mode Parameters

1 - Reach input box

If you are using Reach mode (see Tab 1 - The File Tab) you can enter up to eight different inputs for the model. Inputs can be .txt or .dat files and must contain all the information that is saved in the discharge output file, i.e., 14 columns containing the following:

1. Timestep number
2. Mean discharge of water exiting the domain ($m^3.s^{-1}$)

3. Calculated discharge for the timestep from internal TOPMODEL hydrological model ($m^3.s^{-1}$)
4. Blank column
5. Total sediment yield (m^3)
6. Sediment yield for grainsize 1 (m^3)
7. Sediment yield for grainsize 2 (m^3)
8. Sediment yield for grainsize 3 (m^3)
9. Sediment yield for grainsize 4 (m^3)
10. Sediment yield for grainsize 5 (m^3)
11. Sediment yield for grainsize 6 (m^3)
12. Sediment yield for grainsize 7 (m^3)
13. Sediment yield for grainsize 8 (m^3)
14. Sediment yield for grainsize 9 (m^3)

If you are not using sediment as part of your input you must enter 0 into these columns.

To apply an input, make sure the correct input box is checked and enter the file name into the corresponding box. The location is where that input will begin but note X is the number of cells from left to right and Y the number of cells from top to bottom of the grid.

If using more than one input they all must be the same timestep. Enter this in the timestep box, the units are minutes.

The Divide inputs by box at the bottom is used if you have a single input file but you want to divide it across multiple points, e.g., your channel is several cells wide and you want to reduce boundary conditions by distributing the flow. Use the same file in each box but divide the input by the number of points you are distributing it between.

Ice Melt Mode Parameters

2 - Ice Thickness File

When running the model in Ice Melt mode you must provide an initial ice thickness file. This needs to be the same extent and resolution as the DEM file with a file of ice thickness for each cell. The units are in metres and should be measure from the land surface. Cells with no ice should contain the value 0.

3 - Melt Rate

The model is currently set to apply a constant melting rate to any cell containing ice. Enter this value in here, units are in metres per minute. This is planned to be replaced with a timestep file later to allow variation.

4 - Min Melt Elev File

The minimum melt elevation file should actually be called the maximum melt elevation file! It lays out the freezing level height (FLH) for each timestep and all ice containing cells below that elevation will experience melt at the melt rate above. This should be a .txt or .dat file with a single column with the values for each timestep on separate lines.

5 - Min Elev Change Timestep

The value in this box is the timestep for the minimum melt elevation file. Units are in minutes.

Catchment Mode Parameters

6 - Rain data file and timestep box

If using Catchment Mode you need to provide the model some information about rainfall. First is the rainfall data itself and this needs to be a .txt or .dat file with a single column and each timestep value on a separate line. Units are rainfall rates in millimetre per hour.

The timestep for the file is set in the box below. Units are in minutes.

7 - m value

CAESAR-Lisflood does not directly apply the rainfall rate to the grid instead it first applies through a TOPMODEL hydrological model. This converts the rainfall to a hydrological input, accounting for losses and lags due to various hydrological processes. ‘m’ here is a parameter in TOPMODEL and determines how the model simulates the system’s response to rainfall. Typical values should vary between 0.005 and 0.02, where lower values simulate flashier, faster response systems and higher values slower responses and longer hydrographs. If calibrating modelled discharges to observed data, this is the dominant parameter to change.

Instead of a global value, you can instead vary this through timesteps by entering a file name here and specifying the timestep value in minutes.

8 - Read directly from discharge

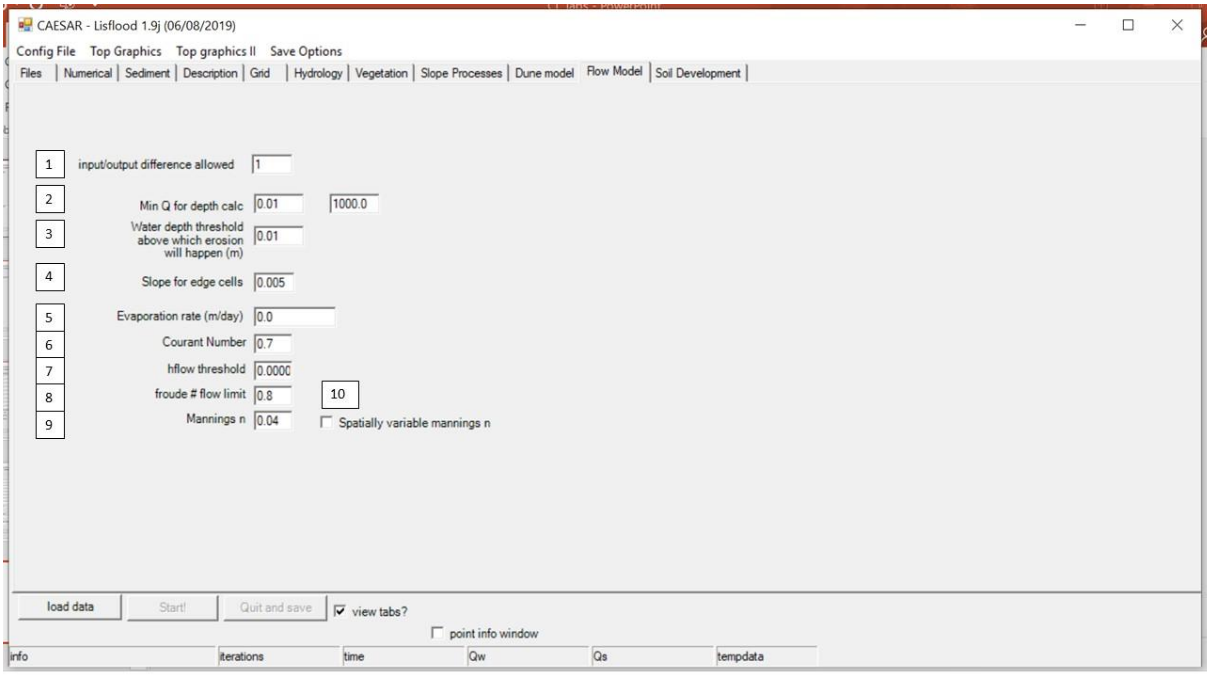
If this box is checked, the model will not apply rainfall via the TOPMODEL. Instead it will read the rain data file (6. above) as a hydrograph and run the TOPMODEL in reverse to create the water input to produce that discharge in an idealised system. Consequently, if using this option the units of your rain data files should be in $m^3.s^{-1}$ instead. Note: the output discharge will be different to the input you provide as the water input will be modified by the topography of the DEM not accounted for by TOPMODEL.

9 - Spatially varied rainfall options

It is possible to provide the model with spatially distributed rainfall. If this box is ticked, the model will require a text file input to instruct it how to distribute the rainfall. This file should be in the same format and extent as the elevation file, with the same headings, but instead of elevations each cell should be given a single integer number.

These numbers are used to tell the model where to read the rainfall from. This refers back to the rain data file (see 6), which, instead of a single column, for spatially varied rainfall ought to be multiple columns. Cells with a value of 1 will use the rainfall from column 1 in this file, cells with a value of 2 will use rainfall from column 2, and so on. The intention is to make use of contiguous areas from gridded rainfall data sets. It has not been tested on non-contiguous areas.

Tab 5 - Flow Model Tab



input/output difference allowed: 1

Min Q for depth calc: 0.01 | 1000.0

Water depth threshold above which erosion will happen (m): 0.01

Slope for edge cells: 0.005

Evaporation rate (m/day): 0.0

Courant Number: 0.7

hflow threshold: 0.0000

froude # flow limit: 0.8

Mannings n: 0.04

☐ Spatially variable mannings n

☑ view tabs?

☐ point info window

Figure 6 - Screenshot of the default Flow Model tab

1 - input/output difference allowed

This parameter is normally used to control the timestep used by the model, allowing it to skip over periods of low flows where it is assumed there is no significant geomorphic activity ongoing. It uses the output values determined by the model's TOPMODEL calculations - whilst they are below the threshold specified by this parameter the model will run in steady-state, yet when it goes above the model will significantly shorten the timestep and operate more dynamically. The value corresponds to a discharge in cumecs and the mean annual flow for a catchment is typically used.

For the ice melt version here, the timestep has been hard fixed within the code so this parameter is not used. Set it to 0.

2. Min Q for depth calc & Max

These two parameters determine how any rainfall input is distributed around the catchment area. CAESAR-Lisflood does not use direct-to-grid rainfall and it is not distributed uniformly across the area. Instead it distributes in a way driven by the TOPMODEL, with inputs from surface flows distributed further away from the channel and groundwater sources closer. The values here are a threshold above which the model will start calculating flow depths.

The value is scale dependent so set the min value to 1/100 of the resolution in m. So, for a 12m grid resolution, this value should be 0.12.

The unlabelled box to the right is the Max Q value, so the maximum depth the model will calculate to for inputs. Hence, the model will start adding water to the model when it reaches above the min Q and stop when it reaches max Q - lowering it sufficiently will force the model to add more water in the headlands rather than progressively down the catchment. It is recommended you leave this as the default value.

3 - Water depth threshold above which erosion will happen (m)

This parameter is used to improve efficiency and assumes that flows below this threshold are not significant geomorphically, so it will not apply the erosion/deposition module below the threshold.

This parameter also affects the graphical output of the model and flows below this threshold will not be visualised even though the model is processing them.

Typically, this value is left at 0.1m and this will be suitable for most applications where grid sizes are in the range of 5-50m.

4 - Slope for edge cells

When water exits the model from the edge of the domain it still needs to calculate a velocity and sheer stress for the cells at the edge. This value is the slope angle it will use for flows between the edge pixels and the hypothetical adjacent pixel outside of the domain. This is an important value as it strongly controls erosion/deposition in this area - too shallow and excessive sediment will build up, too steep and the channel will scour headwards.

The best way to set this is to find the mean slope angle for the channel close to the outlet, for example for 100m/10 pixels.

5 - Evaporation rate

The evaporation rate in the model is taken separately to the rainfall input for the model and instead removes water from the land surface. The value is in m/day.

6 - Courant Number

This parameter relates to the Lisflood element of the model and helps to ensure numerical stability by controlling the speed of operation of the flow model. Values should be within the range on 0.3 and 0.7 - larger values allow for larger timesteps, meaning the model runs more efficiently, but creates a greater risk of numerical stability as more water is moved with each timestep. Lowering the value means the model will use smaller timesteps so water is moved more incrementally, reducing the risk of instability. For simulations where there are deep lakes, it is likely that the lowest values of 0.3 or 0.4 will be required. It is unlikely to impact model simulations using the ice melt module due to the fixed timestep.

7 - hflow threshold

This another parameter that is used to maintain numerical stability in the Lisflood element of the model. It represent a threshold difference in elevation (in m) between adjacent cells, below which the model will not attempt to move water between them. It is recommended that this is kept at the default of 0.000001.

8 - Froude # flow limit

A further parameter that is used to maintain numerical stability in the Lisflood element. This one works together with the Courant number (in 6) by limiting the amount of water that can be moved in each timestep, limiting this so flows cannot exceed the Froude number specified in this box. Where the Courant number only influences the timestep and efficiency of the model, this parameter influences the speed at which the flood wave passes through the catchment - lower numbers result in slower, deeper flows and this will impact the erosion/deposition modules in the model.

As you will likely to simulating deep lakes you may need to use values of 0.8 or even lower.

9 - Manning’s n

This parameter is global value for the Manning’s n roughness coefficient used by the model. You will need to establish an appropriate value for your study site. This guide provides some indicative values.

10 - Spatially variable Manning’s n

By ticking this box you can override the global value of Manning’s n. Instead, you will need to supply the model with a text file in the same format, extent, and resolution as the elevation file, with the same headers. Instead of elevations, each cell will be provided with an individual value of Manning’s n. This can be useful for representing spatially varied land covers.

Bibliography

Coulthard, T., Neal, J., Bates, P., Ramirez, J., de Almeida, G. and Hancock, G.: Integrating the LISFLOOD-FP 2D hydrodynamic model with the CAESAR model: implications for modelling landscape evolution, Earth Surf. …, 38(15), 1897–1906, doi:10.1002/esp.3478, 2013.

Coulthard, T. J., Ramirez, J., Fowler, H. J. and Glenis, V.: Using the UKCP09 probabilistic scenarios to model the amplified impact of climate change on drainage basin sediment yield, Hydrol. Earth Syst. Sci., 16(11), 4401–4416, doi:10.5194/hess-16-4401-2012, 2012.

Drenkhan, F., Guardamino, L., Huggel, C. and Frey, H.: Current and future glacier and lake assessment in the deglaciating Vilcanota-Urubamba basin, Peruvian Andes, Glob. Planet. Change, 169, 105–118, doi:10.1016/j.gloplacha.2018.07.005, 2018.

Skinner, C. J., Coulthard, T. J., Schwanghart, W., Van De Wiel, M. J. and Hancock, G.: Global Sensitivity Analysis of Parameter Uncertainty in Landscape Evolution Models, Geosci. Model Dev. Discuss., (October), 1–35, doi:10.5194/gmd-2017-236, 2017.

Skinner, C. J., Peleg, N., Quinn, N., Coulthard, T. J., Molnar, P. and Freer, J.: The impact of different rainfall products on landscape modelling simulations, Earth Surf. Process. Landforms, esp.4894, doi:10.1002/esp.4894, 2020.