Sediment transport in cold region catchments: the MESH-SED model

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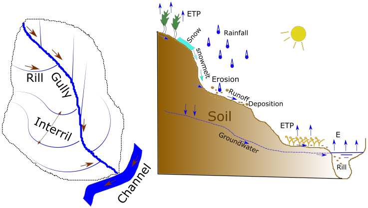
Introduction

- Solutes are transported across the catchment via surface runoff and groundwater flow.
- Nitrogen (N) and phosphorus are abundant nutrient especially in agricultural areas.
- Nutrients can cause eutrophication and water quality deterioration. Pollutants can also deteriorate the water quality.
- Sediments can be considered as proxies of solutes.

Sediment transport processes

- Overland and in-stream erosion and deposition.
- Soil leaching of sediments.
- Atmospheric deposition
- In cold region:
  - Soil freeze-thaw cycles enhance rock weathering and soil leaching
  - Frozen soil-enhance runoff and erosion in surface layer

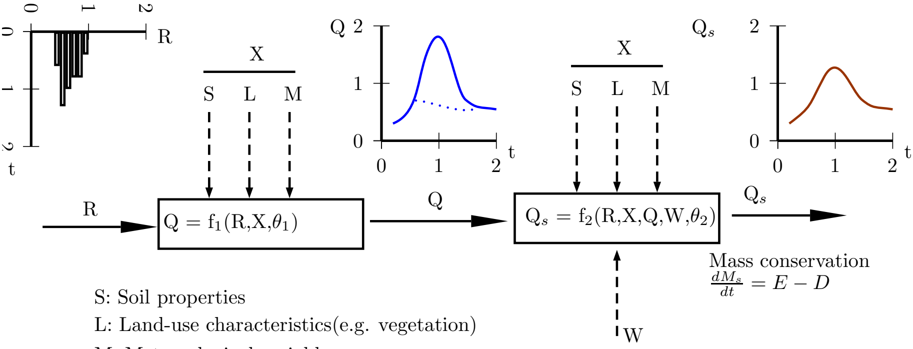


Controls in overland and groundwater transport.

- Slope, land type, soil type (diameter, resistance, specific weight, etc)
- Rainfall, air temperature, soil water content, soil conductivity

Controls in in-stream transport:

- Channel slope and section geometry
- Bank and bottom material properties (diameter, resistance, specific weight), discharge, shear stress (function of slope and discharge) and



S: Soil properties

L: Land-use characteristics(e.g. vegetation)

M: Meteorological variables

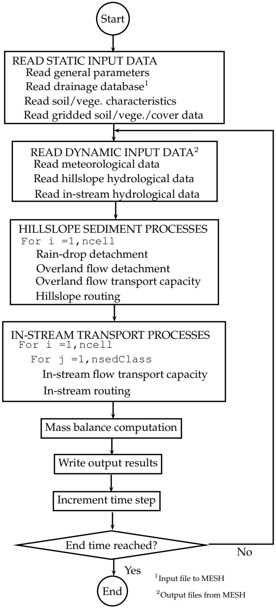
W: Cold region processes (e.g. freeze-thaw cycle)

E: Erosion

D: Deposition

Some **MESH-SED** features:

- loosely coupled with MESH [1].
- physically-based watershed sediment transport model.
- developed based on SHETRAN [2] and SHESED [3].
- semi-distributed model that work on a orthogonal grid (MESH grid).
- suitable for large-scale catchment to run on a continuous basis.
- include different sediment classes.



MESH-SED input/output structure

abc Output from MESH

abc Input to MESH

Notes: In the output files:

`ts`: indicate time series

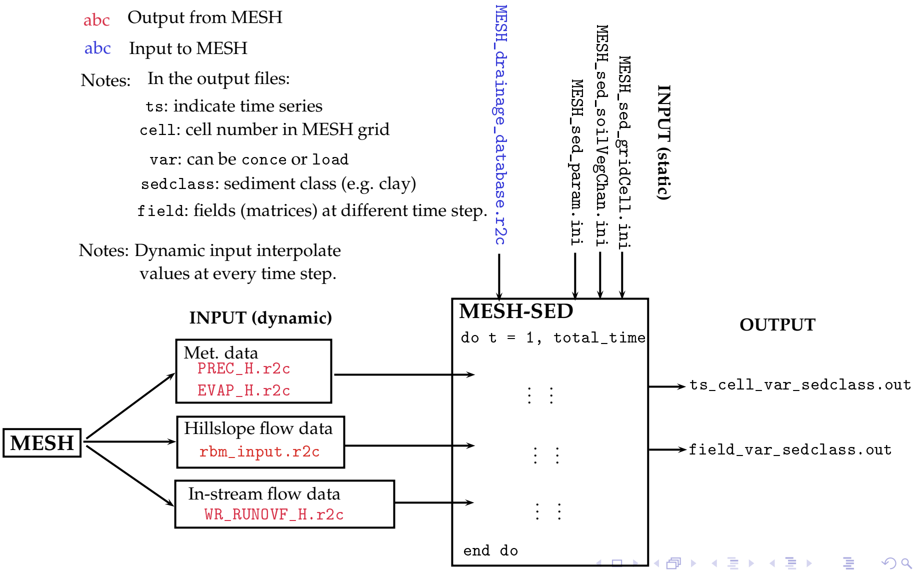
`cell`: cell number in MESH grid

`var`: can be `conce` or `load`

`sedclass`: sediment class (e.g. clay)

`field`: fields (matrices) at different time step.

Notes: Dynamic input interpolate values at every time step.



MESH drainage database data

The information regarding catchment topology, cells connectivity, and model 'skeleton' is contained in `MESH_drainage_database.r2c`. This file is an input file for MESH and it is usually produced by Green Kenue.
In **MESH-SED** , `MESH_drainage_database.r2c` is read at the beginning of the model.

Sediment transport model data

The following input files are read at the beginning of the program.

- `MESH_sed_param.ini`: Contains general information require to run de model.
- `MESH_sed_soilVegChan.ini`: Contains the soil and vegetation type characteristics.
- `MESH_sed_gridCell.ini`: Soil, vegetation and cover information for every cell of the grid.

MESH_sed_param.ini

Line 1	Comment
Line 2	MESH study case directory path
Line 3	Comment
Line 4	MESH study case directory path that contain output fields
Line 5	Comment
Line 6	Hillslope_time_weighting_factor in-stream_time_weighting_factor in-stream_space_weighting_factor
Line 7	Comment
Line 8	Hillslope transport capacity method: 1[Yalin, 1963][4] 2[Engelund-Hansen, 1967][5]
Line 9	Comment
Line 10	In-stream transport capacity method: 1[Engelund-Hansen, 1967][5], 2[Ackers and White, 1973][6], 3[Day, 1980][]
Line 11	Comment
Line 12	Simulation time step (sec). It must be a multiple or factor of 60 sec
Line 13	Comment
Line 14	Comment
Line 15	Start time: year julian_day hour minutes seconds
Line 16	End time: year julian_day hour minutes seconds
Line 17	Comment
Line 18	Upper limit of volumetric suspended sediment concentration
Line 19	Comment
Line 20	Output directory
Line 21	Comment
Line 22	Number of output grid points (ngr)
Line 23	Comment
Line 24	Comment
Line 25	

$$
\begin{array}{lll}
\text{cell\_number}_1 & \text{variable}_1 & \text{particle\_class}_1 \\
\vdots & \vdots & \vdots \\
\text{cell\_number}_{ngr} & \text{variable}_{ngr} & \text{particle\_class}_{ngr}
\end{array}
$$

where *cell_number* is equal to *rank* in `MESH_drainage_database.r2c`, *variable* can be *conce* (concentration) or *load* and *particle$_c$lass* is listed in Table 1.

Table: Sediment/soil particles classes and diameters [7]

	particle_class		ϕ range (mm)
Mud	1	clay	$0.00006 \leq \phi > 0.0039$
Silt	2	veryFineSilt	$0.0039 \leq \phi > 0.0078$
	3	fineSilt	$0.0078 \leq \phi > 0.0156$
	4	mediumSilt	$0.0156 \leq \phi > 0.0313$
	5	coarseSilt	$0.0313 \leq \phi > 0.0625$
Sand	6	veryFineSand	$0.0625 \leq \phi > 0.125$
	7	fineSand	$0.125 \leq \phi > 0.25$
	8	mediumSand	$0.25 \leq \phi > 0.5$
	9	coarseSand	$0.5 \leq \phi > 1.0$
	10	veryCoarseSand	$1.0 \leq \phi > 2.0$
Gravel	11	granule	$2.0 \leq \phi > 4.0$
	12	pebble	$4.0 \leq \phi > 64.0$
	13	cobble	$64.0 \leq \phi > 256.0$
	14	boulder	$256.0 \leq \phi > 4096.0$

Example

```
! MESH study case directory path
'/media/giws_research/Luis/MESH/Graham_River_WFDEI_Luis/07FA005_Graham_Riv/'
! MESH study case directory name that contain output fields
'Out_Fields_R2C'
! Hillslope time weigh. factor        in-stream time weigh. factor        in-stream space weigh. factor
0.65        0.50        0.50
! Flag for overland sediment transport capacity
2       ! Choose transport capacity method: 1[Yalin, 1963] 2[Engelund-Hansen, 1967]
! Flag for instream sediment transport capacity
3       ! Choose transport capacity method: 1[Engelund-Hansen, 1967], 2[Ackers and White, 1973], 3[Day, 1980]
! Simulation time step sec
60
! Simulation Run Times
---#---#---#---#---#
2002 365  23   0   0                                    ! Start year, jday, hour, minutes, seconds
2003   1   1   0   0                                    ! Stop year, jday, hour, minutes, seconds
! Upper limit of volumetric suspended sediment concentration
0.9
! Output Directory
'/media/giws_research/Luis/MESH/MESH_SED/test/output_ts/'
! Number of output grid points
5
! Grid numbersranks        variable_name        sed_class_name
123456789012345678901234567890123456789012345678901234567890
1         load          clay
2         conce         veryCoarseSand
4         conce         cobble
10        conce         boulder
15        load          clay
! Others parameters?????
! Printing selection
```

MESH_sed_soilVegChan.ini

Line 1 Comment
Line 2 Number of soil types (ns)
Line 3 For each soil type i

$$
\begin{array}{lllll}
\mathrm{frac}_1^1 & \dots & \mathrm{frac}_j^1 & \dots & \mathrm{frac}_{14}^1 \\
\rho_s^1 & \lambda^1 & k_R^1 & k_F^1 & k_b^1 \\
\vdots & \vdots & \vdots & & \\
\mathrm{frac}_1^i & \dots & \mathrm{frac}_j^i & \dots & \mathrm{frac}_{14}^i \\
\rho_s^i & \lambda^i & k_R^i & k_F^i & k_b^i \\
\vdots & \vdots & \vdots & & \\
\mathrm{frac}_1^{ns} & \dots & \mathrm{frac}_j^{ns} & \dots & \mathrm{frac}_{14}^{ns} \\
\rho_s^{ns} & \lambda^{ns} & k_R^{ns} & k_F^{ns} & k_b^{ns}
\end{array}
$$

Line 4 Comment
Line 5 Number of vegetation classes (nv)
Line 6 For each vegetation type j

$$
\begin{array}{ccccc}
\mathrm{vege}_1 & \dots & \mathrm{vege}_j & \dots & \mathrm{vege}_{nv} \\
X_1 & \dots & X_j & \dots & X_{nv} \\
d_1 & \dots & d_j & \dots & d_{nv} \\
\mathrm{DRIP}_1 & \dots & \mathrm{DRIP}_j & \dots & \mathrm{DRIP}_{nv}
\end{array}
$$

Line 7 Comment
Line 8 β δ_{max} α

frac = Fraction occupied for each particle class.

ρ_s = Soil density (kg m^{-3}).

λ = Soil surface porosity ($0. \leq \lambda \leq 1.$).

k_R = Soil detachability (J^{-1}).

k_F = Overland flow detachment (mg m^{-2} s^{-1}).

k_b = Channel bank flow detachment (mg m^{-2} s^{-1}).

vege = Vegetation class.

X = Fall height (m).

d = Leaf drip diameter (mm).

DRIP = % drainage as leaf drip.

Example

```
! Soil type characterization
5
0.          .05         .10         .30         .30         .25         0.          0.          0.          0.          0.
2650.          0.2         25.         2.          2.
0.          .05         .20         .25         .30         .20         0.          0.          0.          0.          0.
2650.          0.2         25.         2.          2.
0.          0.          .10         .35         .25         .30         0.          0.          0.          0.          0.
2650.          0.2         25.         2.          2.
0.05        0.05        0.05        0.20        0.30        0.15        0.10        0.10        0.          0.
2650        0.2         25.         2.          2.
0.05        0.05        0.05        0.20        0.30        0.15        0.10        0.10        0.          0.
2650.          0.2         25.         2.          2.
! Canopy vegetation parameters
8                                                                                     ! # of vegetation type
maize    bsprout  subeet  potato    tforest     soybean     spruce      sycamore      ! Vegetation type
0.5      1.1      0.5     1.1       6.          0.87        18.         20.           ! Fall height m
4.5      6.3      4.6     5.9       6.          5.          7.          3.            ! Drip diameter mm
35       23       18      2         3           4           10          5             ! % drainage as leaf drip
! In-stream sediment transport parameters
5.0                 0.01        0.4



! 3
! 0.0          0.50        0.40        0.10        0.0         0.0         0.0         0.0         0.0         0.0
! 2650.          0.3
! 0.30          0.40        0.30        0.0         0.0         0.0         0.0         0.0         0.0         0.0
! 2650.          0.3
! 0.05          0.10        0.40        0.30        0.15        0.0         0.0         0.0         0.0         0.0
! 2650.          0.3
```

MESH_sed_gridCell.ini

Line 1 Comment
Line 2 Initial depth of loose soil

$$\begin{matrix} \delta_{11} & \delta_{12} & \cdots & \delta_{1n} \\ \delta_{21} & \delta_{22} & \cdots & \delta_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \delta_{m1} & \delta_{m2} & \cdots & \delta_{mn} \end{matrix}$$

Line 3 Comment
Line 4 Ground cover

$$\begin{matrix} G_{11} & G_{12} & \cdots & G_{1n} \\ G_{21} & G_{22} & \cdots & G_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ G_{m1} & G_{m2} & \cdots & G_{mn} \end{matrix}$$

Line 5 Comment
Line 6 Hillslope soil type

$$\begin{matrix} hst_{11} & hst_{12} & \cdots & hst_{1n} \\ hst_{21} & hst_{22} & \cdots & hst_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ hst_{m1} & hst_{m2} & \cdots & hst_{mn} \end{matrix}$$

Line 7 Comment
Line 8 Steady-state sediment flux boundary conditions

$$\begin{matrix} bc_{11} & bc_{12} & \cdots & bc_{1n} \\ st_{21} & bc_{22} & \cdots & bc_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ bc_{m1} & bc_{m2} & \cdots & bc_{mn} \end{matrix}$$

Line 9 Comment

m = Number of rows (latitutes coordinates) of the MESH grid.

n = Number of columns (longitudes coordinates) of the MESH grid.

δ = Initial depth of hillslope loose soil (m) at each cell.

G = Proportion $[0 \leq G \leq 1]$ of impervious area in the cell.

hst = Index ($hst = 1 \ldots ns$) of the predominant hillslope soil type at each cell.

Steady-state sediment flux boundary conditions at each cell .

Note: **MESH-SED** can be modified to introduce dynamically time-dependant G and bc fields.

MESH_sed_gridCell.ini

Line 10 Predominant vegetation type

$$\begin{matrix} vt_{11} & vt_{12} & \cdots & vt_{1n} \\ vt_{21} & bc_{22} & \cdots & vt_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ vt_{m1} & vt_{m2} & \cdots & vt_{mn} \end{matrix}$$

Line 11 Comment

Line 12 Canopy cover

$$\begin{matrix} C_{11} & C_{12} & \cdots & C_{1n} \\ C_{21} & C_{22} & \cdots & C_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ C_{m1} & C_{m2} & \cdots & C_{mn} \end{matrix}$$

Line 13 Comment

Line 14 Channel soil type

$$\begin{matrix} cst_{11} & cst_{12} & \cdots & cst_{1n} \\ cst_{21} & cst_{22} & \cdots & cst_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ cst_{m1} & cst_{m2} & \cdots & cst_{mn} \end{matrix}$$

Line 15 Comment

vt = Predominant vegetation class at each cell (see *vege*)

C = Proportion $[0 \leq G \leq 1]$ of the cell area covered by vegetation (canopy) at each cell.

cst = Index ($hst = 1...ns$) of the predominant channel bed soil type at each cell.

Note: **MESH-SED** can be modified to introduce dynamically time-dependent vt and C fields

MESH_sed_gridCell.ini

Line 16 Channel bank soil type

$$\begin{matrix} cbst_{11} & cbst_{12} & \cdots & cbst_{1n} \\ cbst_{21} & cbst_{22} & \cdots & cbst_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ cbst_{m1} & cbst_{m2} & \cdots & cbst_{mn} \end{matrix}$$

Line 17 Comment

Line 18 Initial thickness of channel bed material

$$\begin{matrix} \delta c_{11} & \delta c_{12} & \cdots & \delta c_{1n} \\ \delta c_{21} & \delta c_{22} & \cdots & \delta c_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \delta c_{m1} & \delta c_{m2} & \cdots & \delta c_{mn} \end{matrix}$$

- $cbst$ = Index ($hst = 1...ns$) of the predominant channel-bank soil type at each cell.
- δc = Initial thickness of channel bed material (m). Usually $0.5m \leq \delta c \leq 5m$ for small to medium size streams, $\delta c \geq 5m$ for large rivers.

Example

```
! Initial depth of loose soil m
1.0E-03      1.0E-03      1.0E-03      1.0E-03      1.0E-03      1.0E-03      1.0E-03      1.0E-0
1.0E-03      1.0E-03      1.0E-03      1.0E-03      1.0E-03      1.0E-03      1.0E-03      1.0E-0
1.0E-03      1.0E-03      1.0E-03      1.0E-03      1.0E-03      1.0E-03      1.0E-03      1.0E-0
1.0E-03      1.0E-03      1.0E-03      1.0E-03      1.0E-03      1.0E-03      1.0E-03      1.0E-0
! Ground cover: %[0. -> 1.] of cell area covered by snowe.g. glaciers, rock or impervious
0.1 0. 0.2 0.6 0.3 0.5 0.9 0.8 0.1 0.2 0.8 0.9 0.1
0.1 0. 0.2 0.6 0.3 0.5 0.9 0.8 0.1 0.2 0.8 0.9 0.1
0.1 0. 0.2 0.6 0.3 0.5 0.9 0.8 0.1 0.2 0.8 0.9 0.1
0.1 0. 0.2 0.6 0.3 0.5 0.9 0.8 0.1 0.2 0.8 0.9 0.1
! Soil type
1        2        3        4        5        1        2        3        4        5        1        2        3
1        2        3        4        5        1        2        3        4        5        1        2        3
1        2        3        4        5        1        2        3        4        5        1        2        3
1        2        3        4        5        1        2        3        4        5        1        2        3
! Sediment flux boundary conditions
0.0        0.0        0.0        0.0        0.0        0.0        0.0        0.0        0.0        0.0        0
0.0        0.0        0.0        0.0        0.0        0.0        0.0        0.0        0.0        0.0        0
0.0        0.0        0.0        0.0        0.0        0.0        0.0        0.0        0.0        0.0        0
0.0        0.0        0.0        0.0        0.0        0.0        0.0        0.0        0.0        0.0        0
! Predominant vegetation type in each cell
maize    bsprout subeet potato    tforest     soybean     spruce      sycamore      maize    spruce   tforest sub
maize    bsprout subeet potato    tforest     soybean     spruce      sycamore      maize    spruce   tforest sub
maize    bsprout subeet potato    tforest     soybean     spruce      sycamore      maize    spruce   tforest sub
maize    bsprout subeet potato    tforest     soybean     spruce      sycamore      maize    spruce   tforest sub
! Canopy cover: %[0. -> 1.] of cell area covered by canopy see the canopy types above
0.9        1.0        0.8        0.4        0.7        0.5        0.1        0.2        0.9        0.8        0
0.9        1.0        0.8        0.4        0.7        0.5        0.1        0.2        0.9        0.8        0
0.9        1.0        0.8        0.4        0.7        0.5        0.1        0.2        0.9        0.8        0
0.9        1.0        0.8        0.4        0.7        0.5        0.1        0.2        0.9        0.8        0
! Channel-bed soil type
1        2        3        1        2        3        1        2        3        1        2        3        1
1        2        3        1        2        3        1        2        3        1        2        3        1
1        2        3        1        2        3        1        2        3        1        2        3        1
1        2        3        1        2        3        1        2        3        1        2        3        1
```

Meteorological data

Hourly precipitation (*PREC*) data and evapotranspiration (*EVAP*) data are interpolated at every time step from the following MESH output files:

`PREC_H.r2c`

`EVAP_H.r2c`

[-2.7em]

$$
\begin{array}{cccc}
HEADER & & & \\
time\_1 & & & \\
PREC_{11} & PREC_{12} & \cdots & PREC_{1n} \\
PREC_{21} & PREC_{22} & \cdots & PREC_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
PREC_{m1} & PREC_{m2} & \cdots & PREC_{mn} \\
\vdots & \vdots & & \vdots \\
\vdots & \vdots & & \vdots \\
time\_n & & & \\
PREC_{11} & PREC_{12} & \cdots & PREC_{1n} \\
PREC_{21} & PREC_{22} & \cdots & PREC_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
PREC_{m1} & PREC_{m2} & \cdots & PREC_{mn}
\end{array}
$$

$$
\begin{array}{cccc}
HEADER & & & \\
time\_1 & & & \\
EVAP_{11} & EVAP_{12} & \cdots & EVAP_{1n} \\
EVAP_{21} & EVAP_{22} & \cdots & EVAP_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
EVAP_{m1} & EVAP_{m2} & \cdots & EVAP_{mn} \\
\vdots & \vdots & & \vdots \\
\vdots & \vdots & & \vdots \\
time\_n & & & \\
EVAP_{11} & EVAP_{12} & \cdots & EVAP_{1n} \\
EVAP_{21} & EVAP_{22} & \cdots & EVAP_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
EVAP_{m1} & EVAP_{m2} & \cdots & EVAP_{mn}
\end{array}
$$

Hillslope flow data

Hourly overland flow ($RUNOFF$) data are interpolated at every time step from `WR_RUNOVF.r2c`

$$\begin{array}{cccc}
\textit{HEADER} & & & \\
\textit{time_1} & & & \\
RUNOFF_{11} & RUNOFF_{12} & \cdots & RUNOFF_{1n} \\
RUNOFF_{21} & RUNOFF_{22} & \cdots & RUNOFF_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
RUNOFF_{m1} & RUNOFF_{m2} & \cdots & RUNOFF_{mn} \\
\vdots & \vdots & & \vdots \\
\vdots & \vdots & & \vdots \\
\textit{time_n} & & & \\
RUNOFF_{11} & RUNOFF_{12} & \cdots & RUNOFF_{1n} \\
RUNOFF_{21} & RUNOFF_{22} & \cdots & RUNOFF_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
RUNOFF_{m1} & RUNOFF_{m2} & \cdots & RUNOFF_{mn}
\end{array}$$

Other overland flow variables are calculated as:

- water depth (m) $h = 0.34Q^{0.341}$ according to [8]
- velocity (m/s) $V = Q/A$, assuming a rectangular channel cross section, $A = h * width$.

In-stream flow data

From `rbm_input.r2c` MESH output file the following hourly variables are interpolated at every time step:

- $DISC$ = In-stream discharge (m^3/s)
- $DEPT$ = Channel water depth (m)
- $WIDT$ = Channel width (m)
- $VELO$ = Channel flow velocity (m/s)

$$
\begin{array}{cccc}
HEADER & & & \\
time\_1 & & & \\
DISC_{11} & DISC_{12} & \cdots & DISC_{1n} \\
DISC_{21} & DISC_{22} & \cdots & DISC_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
DISC_{m1} & DISC_{m2} & \cdots & DISC_{mn} \\
DEPT_{11} & DEPT_{12} & \cdots & DEPT_{1n} \\
DEPT_{21} & DEPT_{22} & \cdots & DEPT_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
DEPT_{m1} & DEPT_{m2} & \cdots & DEPT_{mn} \\
WIDT_{11} & WIDT_{12} & \cdots & WIDT_{1n} \\
WIDT_{21} & WIDT_{22} & \cdots & WIDT_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
WIDT_{m1} & WIDT_{m2} & \cdots & WIDT_{mn} \\
VELO_{11} & VELO_{12} & \cdots & VELO_{1n} \\
VELO_{21} & VELO_{22} & \cdots & VELO_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
VELO_{m1} & VELO_{m2} & \cdots & VELO_{mn} \\
\vdots & \vdots & & \vdots \\
\vdots & \vdots & & \vdots
\end{array}
$$

Output data

MESH-SED estimates sediment concentration and loads at every cell of the computational grid and for every sediment class at every time step. **MESH-SED** also estimates changes of the land surface due to accumulation or erosion of sediments. The format of the output information is specified in `MESH_sed_param.ini`. The typical output files are:

`ts_cell_var_sedclass.out`
(e.g. `ts_10_load_veryFineSand.out`)

$$\begin{array}{cc} time_1 & var_1 \\ time_2 & var_2 \\ \vdots & \vdots \\ time_n & var_n \end{array}$$

- `ts`: indicate time series.
- `cell`: cell number in MESH grid (`rank`).
- `var`: it can be `conce` or `load`.
- `sedclass`: sediment class (see Table 1)
- `field`: field (matrices) at different time steps.

`field_var_sedclass.out`
(e.g. `field_conce_coarseSilt.out`)

$$\begin{array}{cccc} time\_1 & & & \\ var_{11} & var_{12} & \cdots & var_{1n} \\ var_{21} & var_{22} & \cdots & var_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ var_{m1} & var_{m2} & \cdots & var_{mn} \\ \vdots & \vdots & & \vdots \\ \vdots & \vdots & & \vdots \\ time\_n & & & \\ var_{11} & var_{12} & \cdots & var_{1n} \\ var_{21} & var_{22} & \cdots & var_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ var_{m1} & var_{m2} & \cdots & var_{mn} \end{array}$$

References I

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