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

Version 1.0

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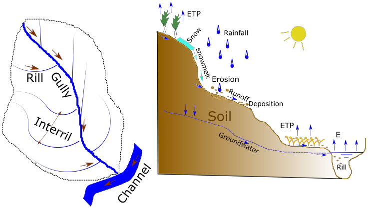
Introduction

- 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

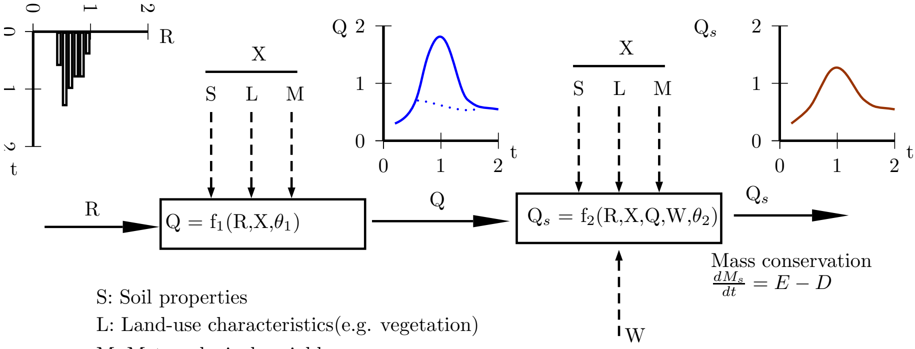


Controls in overland and groundwater transport.

- 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

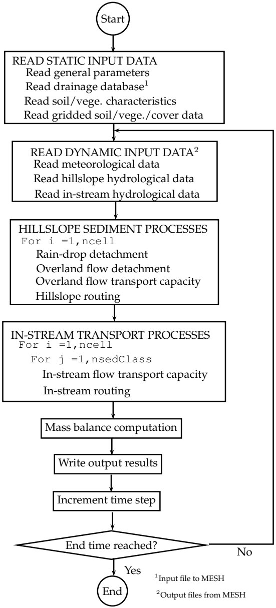
W: Cold region processes (e.g. freeze-thaw cycle)

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.
- future work: sedimentation in reservoirs, code parallelization.



MESH-SED input/output structure

abc Output from MESH

abc Input to MESH

Notes: In the output files:

`ts`: indicate time series

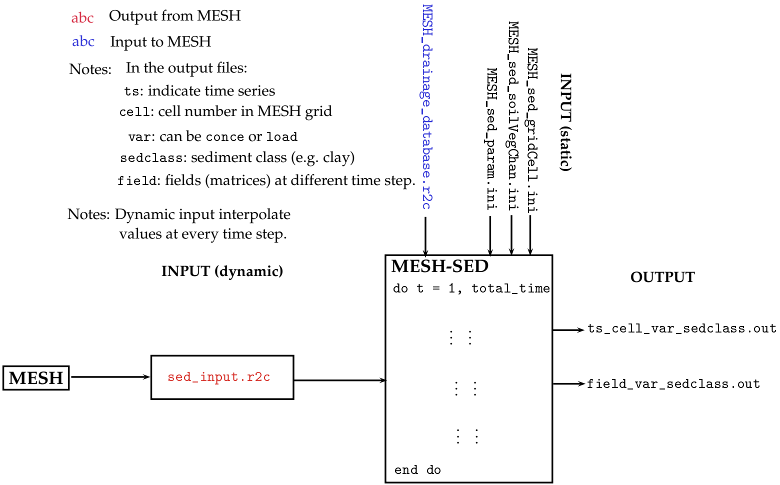
`cell`: cell number in MESH grid

`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	Hillslope_time_weighting_factor in-stream_time_weighting_factor in-stream_space_weighting_factor
Line 5	Comment
Line 6	Hillslope transport capacity method: 1[Yalin, 1963][4] 2[Engelund-Hansen, 1967][5]
Line 7	Comment
Line 8	In-stream transport capacity method: 1[Engelund-Hansen, 1967][5], 2[Ackers and White, 1973][6], 3[Day, 1980][]
Line 9	Comment
Line 10	Simulation time step (sec). It must be a multiple or factor of 60s but $\leq 3600s = 1h$.
Line 11	Comment
Line 12	Comment
Line 13	Start time: year julian_day hour minutes seconds
Line 14	End time: year julian_day hour minutes seconds
Line 15	Comment
Line 16	Upper limit of volumetric suspended sediment concentration
Line 17	Comment
Line 18	Output directory
Line 19	Comment
Line 20	Number of output grid points (ngr)
Line 21	Comment
Line 22	Comment
Line 23	

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

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.

MESH_sed_param.ini

Line 24	Comment
Line 25	Number of output fields (gridded data)
Line 26	Comment
Line 27	Comment
	variable_1 particle_class_1
	$\vdots$ $\vdots$
	variable_{ngr} $\text{particle\_class}_{ngr}$

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/'
! 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
! TS 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
1234567890123456789012345678901234567890123456789012345678901234567890
1         load           clay
2         conce          veryCoarseSand
4         conce          cobble
10        conce          boulder
15        load           clay
! Field output Directory
'/media/giws_research/Luis/MESH/MESH_SED/test/output_field/'
! Number of output fields gridded
0
! variable_name        sed_class_name
1234567890123456789012345678901234567890123456789012345678901234567890
load            clay
conce           fineSand
```

MESH_sed_soilVegChan.ini

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

$$
\begin{array}{lllll}
frac_1^1 & \ldots & frac_j^1 & \ldots & frac_{14}^1 \\
\rho_s^1 & \lambda^1 & k_R^1 & k_F^1 & k_b^1 \\
\vdots & \vdots & \vdots & & \\
frac_1^i & \ldots & frac_j^i & \ldots & frac_{14}^i \\
\rho_s^i & \lambda^i & k_R^i & k_F^i & k_b^i \\
\vdots & \vdots & \vdots & & \\
frac_1^{ns} & \ldots & frac_j^{ns} & \ldots & frac_{14}^{ns} \\
\rho_s^{ns} & \lambda^{ns} & k_R^{ns} & k_F^{ns} & k_b^{ns}
\end{array}
$$

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

$$
\begin{array}{ccccc}
vege_1 & \ldots & vege_j & \ldots & vege_{nv} \\
X_1 & \ldots & X_j & \ldots & X_{nv} \\
d_1 & \ldots & d_j & \ldots & d_{nv} \\
DRIP_1 & \ldots & DRIP_j & \ldots & DRIP_{nv}
\end{array}
$$

Line 7 Comment
Line 8 $\beta \quad \delta_{max} \quad \alpha$

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.

β = Threshold sediment concentration in channels for infiltration and overbank sediment flow.

δ_{max} = Maximun thickness (m) of top (active) bed sediment layer in channel. δ_{max} = 1 or 2 $D_9 9$ for gravel-bed channels and δ_{max} = 10 mm for sand-bed channels.

α = Ratio of critical shear stresses for deposition and initiation of motion ($\alpha < 1$). Likely range 0.25-0.75.

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
```

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 (latitudes 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

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

Line 11 Comment

Line 12 Canopy cover

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

Line 13 Comment

Line 14 Channel soil type

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

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

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

Line 17 Comment

Line 18 Initial thickness of channel bed material

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

- $cbst$ = Index ($hst = 1 \ldots ns$) 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
```

sed_input.r2c

All the dynamic input data required by **MESH-SED** is saved into sed_input.r2c file. This file is produced by MESH and contains gridded information in r2c format at 1h time step. Variables are written into the file in the following order:

1. Average flow (discharge) (m^3 s^{-1}). Note: Averaged over the time-step.
2. Channel depth (m).
3. Channel width (m).
4. Channel length (m).
5. Channel slope (m m^{-1}). slope = sqrt(SLOPE_CHNL)
6. Stream velocity (m s^{-1}). Take stream speed to be average flow (m^3 s-1) divided by channel x-sec area (m^2) (from rte_sub.f).
7. Precipitation (mm h^{-1}). Note: Accumulated over the time-step.
8. Evapotranspiration (mm h^{-1}). Note: Of evapotranspiration accumulated over the time-step.
9. Overland water depth (mm). Note: Accumulated over the time-step.
10. Surface slope (m m^{-1}). SLOPE_INT isn't used in CLASS, so average slope from tiles in cell?
11. Cell width (m).

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`)

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

Download, compile and execute

Download

MESH-SED can be download from Github Repository or from command line as: `git clone https://github.com/lmoralesma/MESH-SED.git`

Compile

Compile **MESH-SED** by typing `make`; produce `sa_mesh_sed`. Use `make clean` for removing `*.o` and `*.mod` files.

execute

To run **MESH-SED** , `./sa_mesh_sed projname` (e.g. `./sa_mesh_sed test`).

References I

A. Pietroniro, V. Fortin, N. Kouwen, C. Neal, R. Turcotte, B. Davison, D. Verseghy, E. Soulis, R. Caldwell, N. Evora, *et al.*, "Using the mesh modelling system for hydrological ensemble forecasting of the laurentian great lakes at the regional scale," *Hydrology and Earth System Sciences Discussions*, vol. 3, no. 4, pp. 2473–2521, 2006.

J. Ewen, G. Parkin, and P. E. O'Connell, "Shetran: distributed river basin flow and transport modeling system," *Journal of hydrologic engineering*, vol. 5, no. 3, pp. 250–258, 2000.

J. Wicks and J. Bathurst, "Shesed: a physically based, distributed erosion and sediment yield component for the she hydrological modelling system," *Journal of Hydrology*, vol. 175, no. 1-4, pp. 213–238, 1996.

References II

- M. S. Yalin, "An expression for bed-load transportation," *Journal of the Hydraulics Division*, vol. 89, no. 3, pp. 221–250, 1963.
- F. Engelund and E. Hansen, "A monograph on sediment transport in alluvial streams," *Technical University of Denmark 0stervoldgade 10, Copenhagen K.*, 1967.
- P. Ackers and W. R. White, "Sediment transport: new approach and analysis," *Journal of the Hydraulics Division*, vol. 99, no. hy11, 1973.
- C. K. Wentworth, "A scale of grade and class terms for clastic sediments," *The Journal of Geology*, vol. 30, no. 5, pp. 377–392, 1922.
- P. M. Allen, J. C. Arnold, and B. W. Byars, "Downstream channel geometry for use in planning-level models," *JAWRA Journal of the American Water Resources Association*, vol. 30, no. 4, pp. 663–671, 1994.