Brandenburgische Technische Universität Cottbus - Senftenberg

Director of EuroAquae Master Program
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SISYPHE

Morphodynamic Modelling

EUROAQUAE+

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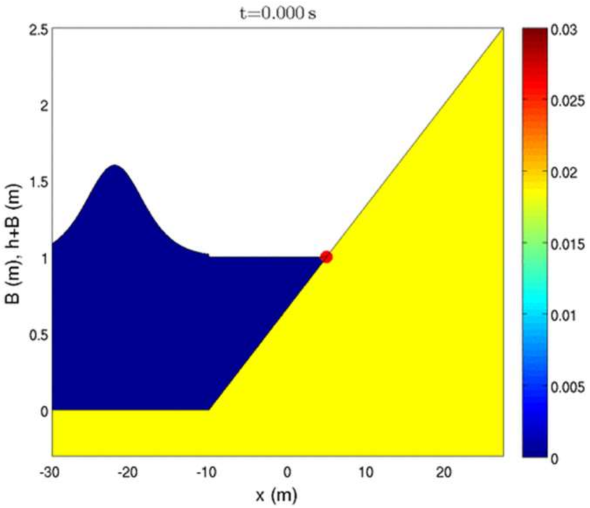
Morphodynamic Modelling

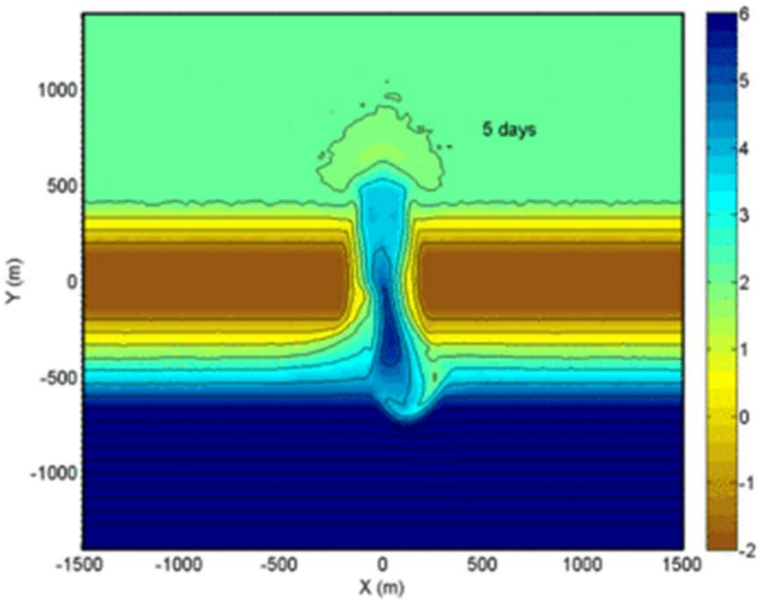
- Definition: prediction of topographic changes in sediment discharges within a computational domain on a specific time window.
- Morphological changes are applied within the following constraints

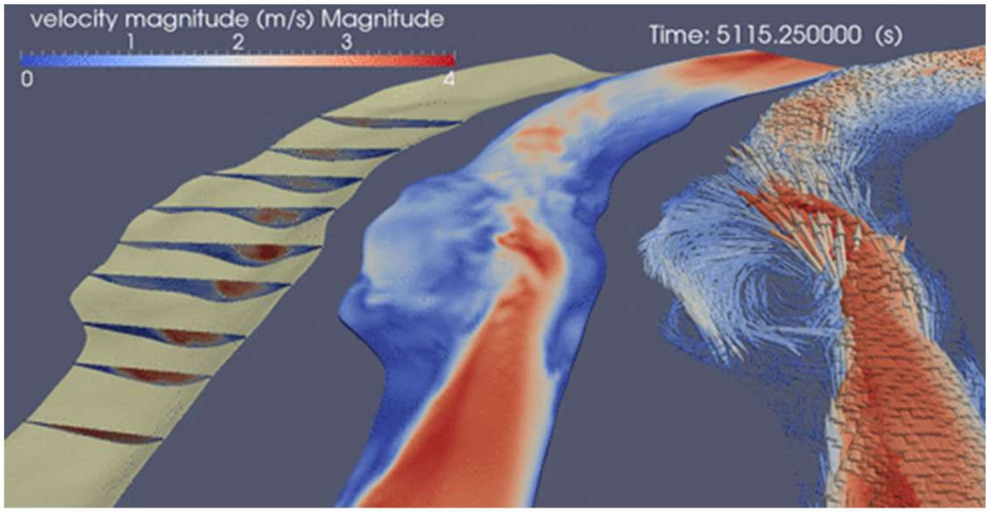
1. Hydrodynamics: conservation of laws of mass and momentum.
2. Sediment transport: predictors for sediment transport capacity.
3. Bed evolution: conservation law for sediment mass.



Mechanisms for transport of sediments

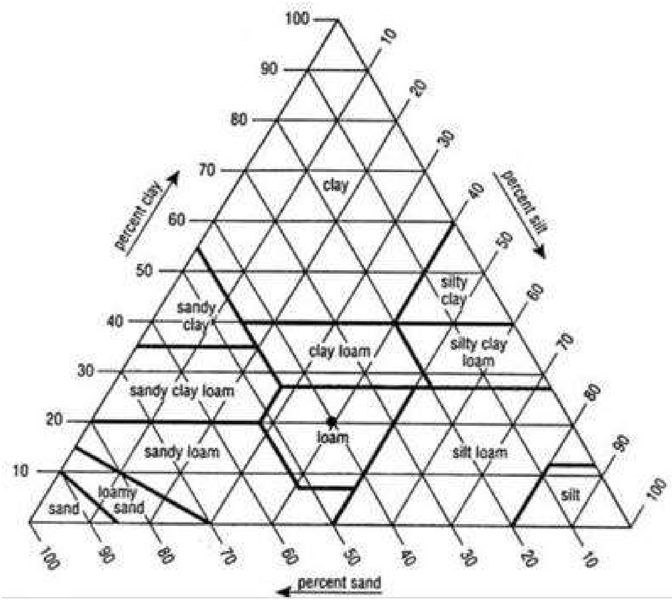
- Bedload: particles in a flowing fluid that are transported along the bed, moved by rolling, sliding or saltating.
- Suspended load: portion of the sediment that is carried by a fluid flow which settles slowly enough so that it almost never touches the bed.
- Bed evolution: combination of deposition phenomena of initial conditions, suspended load and bedload.

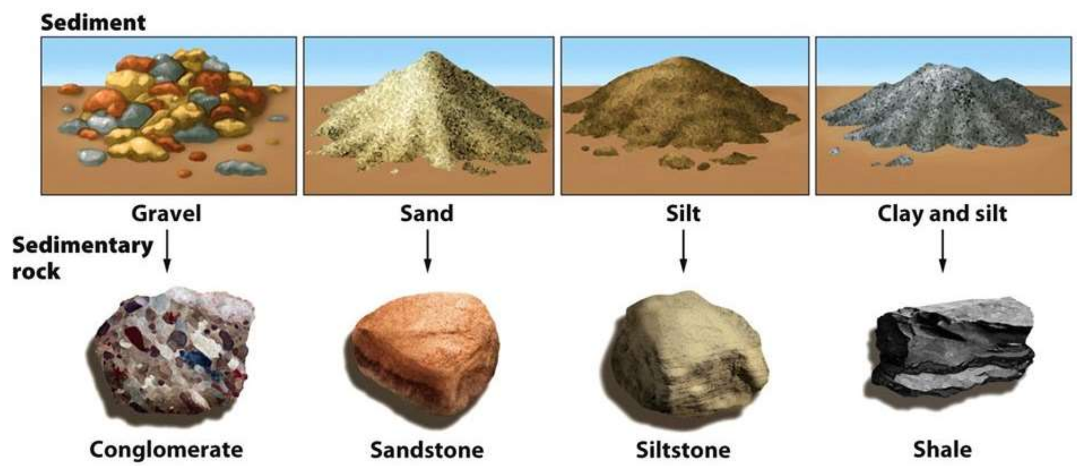




Types of sediments

- Non-cohesive: following equilibrium formulas.
- Cohesive: erosion and deposition laws, consolidation models.
- Mixed-size sediments: moderately/poorly sorted sediment distribution, sand-gravel and sand-mud mixtures.





- Tries to solve the conservative law equation for sediment mass

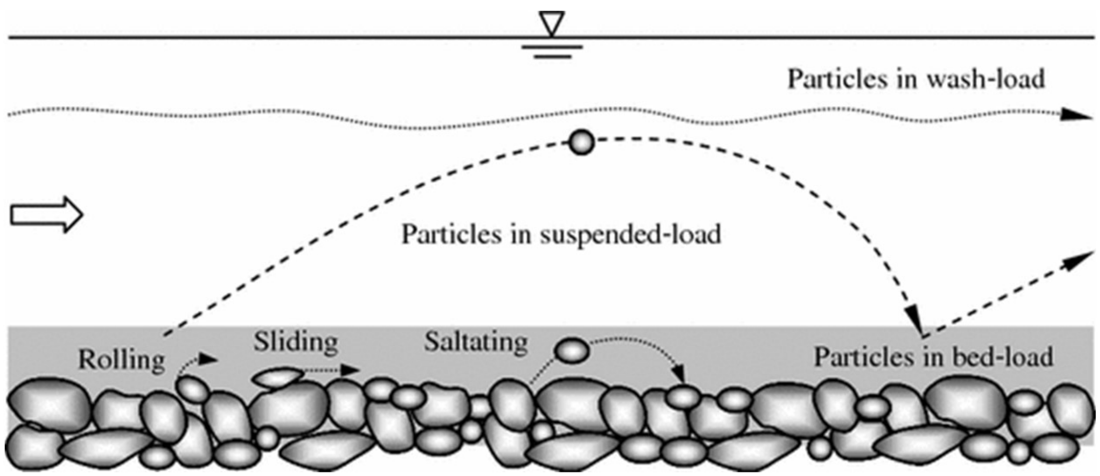
$$(1-\lambda)\frac{\partial z_b}{\partial t} + \nabla * Q_b = 0$$

λ: bed porosity

Q_b: vector of volumetric transport per unit width without pores (m2/s)

z_b: bed evolution respective to time (m)

- Considers grain sizes between 0.4-29



- The dimensionless current-induced sediment transport rate

$$\Phi_b = \frac{Q_b}{\sqrt{g(s-1)d^3}}$$

- Bedload formulas are generally computed as function of the Shields number θ:

$$\theta = \frac{\mu\tau_b}{(\rho_s - \rho)gd}$$

- The different bedload transport formulas will depend on the type of sediment that is available.
- Usual classical approach is Meyer-Peter and Mueller formula for Φ_b, considering critical shields parameter equal to 0.047.

Q_b:bedload transport rate per unit width
g: gravity
ρ: water density
ρ_s: sediment density
d: sand grain diameter (= d_{50} for uniform sediment distribution)
μ: correction factor for skin friction
τ_b: bottom shear stress

$$\Phi_b = \begin{cases} 0, if\theta < \theta_{cr} \\ \alpha_{mpm}(\theta - \theta_{cr})^{\frac{3}{2}}\ otherwise \end{cases}$$

Suspended sediments

- Two-dimensional advection-diffusion equation

$$\frac{\partial hC}{\partial t} + \frac{\partial hUC}{\partial x} + \frac{\partial hVC}{\partial y} = \frac{\partial}{\partial x}\left(h\varepsilon_s \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(h\varepsilon_s \frac{\partial C}{\partial y}\right) + E - D$$

$C(x, y, t)$: depth-averaged concentration expressed in % volume.

ε_s: turbulent diffusivity of the sediment.

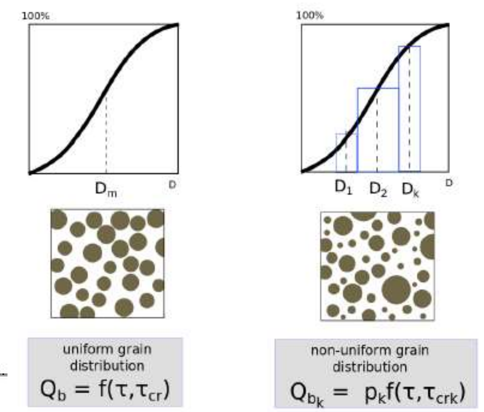
D: non-cohesive deposition rate

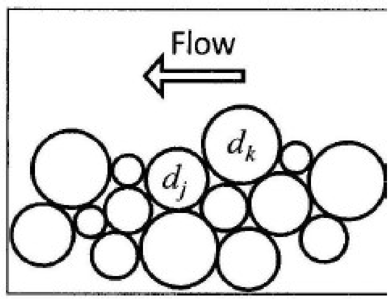
E: non-cohesive erosion rate

- 4 different equilibrium equations are available for solving near-bed concentration are available, depending on the Shields parameter and the diameter of the sediment.

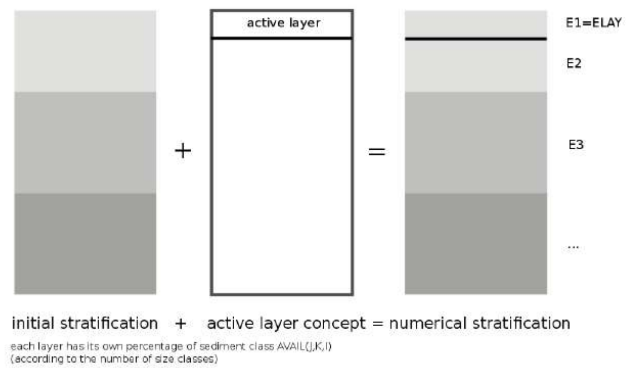
Non-Uniform sediment transport

- In non-uniform bedload sediment transport, moving sediment particles collide and interact.
- Each sediment can be transported by suspended-load or bedload.
- Suspended load mass is exchanged vertically between the water column and the uppermost bed layer.
- Bedload mass is exchanged horizontally between top layer of the bed.





$$
\frac{\partial}{\partial t}(hC_k) + \frac{\partial}{\partial x}(hUC_k) + \frac{\partial}{\partial y}(hVC_k)
= \frac{\partial}{\partial x}\left(h\varepsilon_s \frac{\partial C_k}{\partial x}\right) + \frac{\partial}{\partial y}\left(h\varepsilon_s \frac{\partial C_k}{\partial y}\right)
+ \omega_{sk}\left(C_{eq_k} - C_{Z_{refk}}\right)
$$



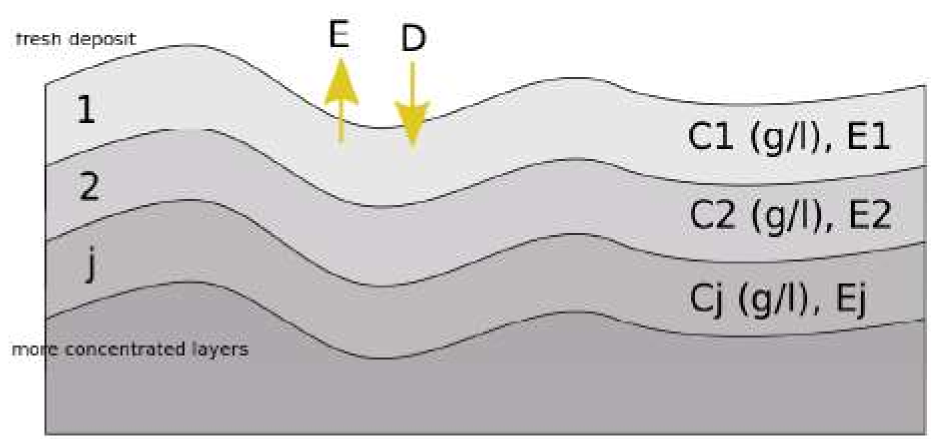
Cohesive sediment transport

- Cohesive particles: fine particles like silts and clay that have a diameter less than a limiting value of about 60μm.
- In cohesive sediment are mainly transported in suspension and transport processes strongly depend on flocculation, consolidation and other physic-chemical processes.
- Similar to before, the transport can be modelled using advection-diffusion equation.

$$\frac{\partial hC}{\partial t} + \frac{\partial hUC}{\partial x} + \frac{\partial hVC}{\partial y} = \frac{\partial}{\partial x}\left(h\varepsilon_s \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(h\varepsilon_s \frac{\partial C}{\partial y}\right) + E - D$$

$$E = \begin{cases} M\left[\left(\dfrac{\tau_b}{\tau_{ce}}\right) - 1\right], if \tau_b > \tau_{ce} \\ 0 \end{cases}$$

$$D = w_s C\left[1 - \left(\frac{\sqrt{\dfrac{\tau_b}{\rho}}}{u_{mud}^{cr}}\right)^2\right]$$



Cj the mud concentration of layer j [g/l]

Mixed sediment transport

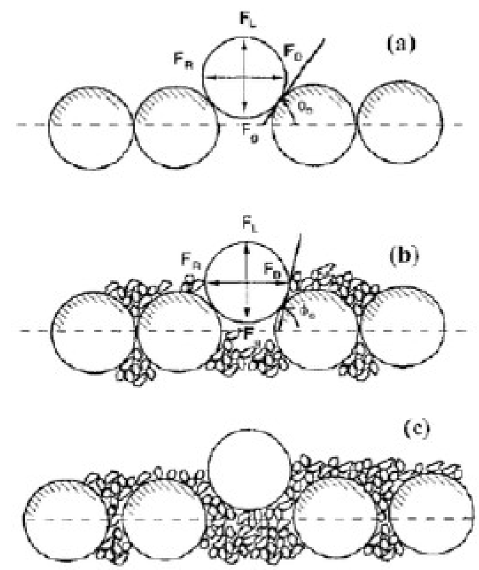
- Two different sediment classes are considered to solve sediment mixtures

1. Non-cohesive sediment: represented by grain diameter D_1, settling velocity w_{s1}
2. Cohesive sediment: represented by grain diameter D_2 that is less than 60μm. The setting velocity is a function of the flocs properties which differs from cohesive particles.

$$\frac{\partial hC_k}{\partial t} + \frac{\partial hUC_k}{\partial x} + \frac{\partial hVC_k}{\partial y} = \frac{\partial}{\partial x}\left(h\varepsilon_s \frac{\partial C_k}{\partial x}\right) + \frac{\partial}{\partial y}\left(h\varepsilon_s \frac{\partial C_k}{\partial y}\right) + E^k - D^k$$

$$E_j = \begin{cases} M\left[\left(\dfrac{\tau_b}{\tau_{ce}}\right) - 1\right], if \tau_b > \tau_{ce} \\ 0 \end{cases}$$

$$D_j = w_s C\left[1 - \left(\frac{\sqrt{\dfrac{\tau_b}{\rho}}}{u_{mud}^{cr}}\right)^2\right]$$



Sisyphe: Couplying hydrodynamics with morphodynamics

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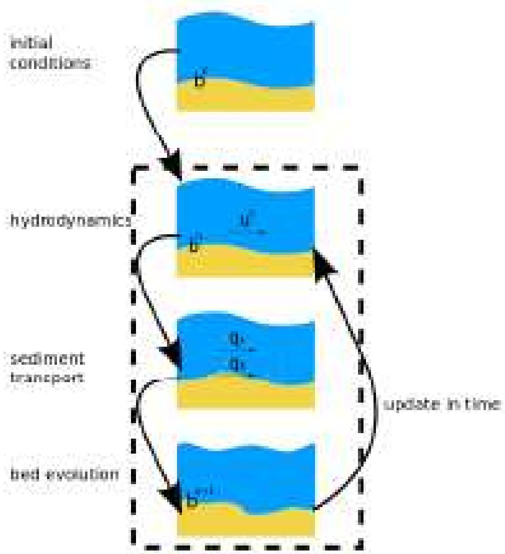
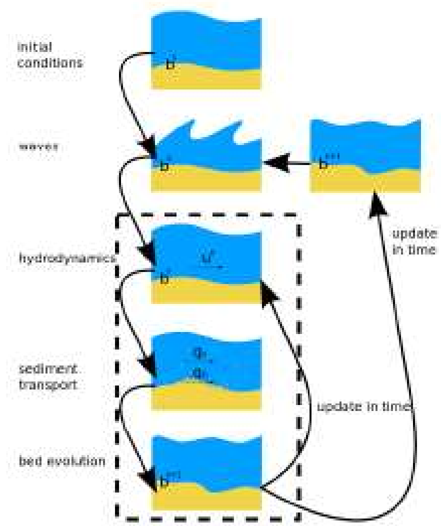
- Morphological models can be run fully coupled and decoupled.
- Fully coupled: sediment transport and flow occur simultaneously, thus they should be solved at the same time. Examples: debris flow, sediment-laden floods.
- Decoupled: time scale for river or seabed is much longer tan typical time scale for water flow.



(a) currents only



(b) currents + waves

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- Minimum set of files for running a morphodynamic simulation:

1. Steering file(s) (text/ascii file *.cas)
2. Geometry file (format selafin/binary *.slf)
3. Boundary conditions file (text/ascii file *.cli)
4. Additional or optional input files as the fortran file (text/ascii file *.f), reference file (format selafin/binary *.slf)

* All files should be contained within the same folder.

Sisyphe steering file

- Following with a correct outline for morphodynamic simulation, sisyphe's steering file specifies the following:

1. Input and output files
2. Physical parameters such as sand diameter, settling velocity, etc.
3. Main sediment transport processes such as transport mechanisms, closure relationships, etc.
4. Additional sediment transport processes like secondary currents, slope effect, etc.
5. Numerical options and parameters like numerical schemes, solvers, etc.

Examples of physical parameters

```
/---------------------------------------------------------------------/
/ SISYPHE bedload                                                     /
/---------------------------------------------------------------------/
/
/---------------------------------------------------------------------/
/  FILES                                                              /
/---------------------------------------------------------------------/
/
/ --- GEOMETRY ---
GEOMETRY FILE                          = '../geo_bifurcation.slf'
BOUNDARY CONDITIONS FILE               = '../bc_bifurcation_tel.cli'
/
/ --- RESULTS ---
RESULTS FILE                           = 'res_bifurcation_sis.slf'
/
...
/-----------------------------------------------
/  PHYSICAL PARAMETERS
/-----------------------------------------------
/
BED LOAD                                  = YES
BED-LOAD TRANSPORT FORMULA                = 1
SEDIMENT DIAMETERS                        = 0.000120
/
...
/---------------------------------------------------------------------/
/  NUMERICAL PARAMETERS                                               /
/---------------------------------------------------------------------/
/
MASS-BALANCE                             = YES
SOLVER ACCURACY                          = 1.E-12
MASS-LUMPING                             = YES
...
```

- Sediment diameters
- Sediment density
- Sediment parameter (Shields Parameter)
- Settling velocity
- Bed porosity

FORTRAN files

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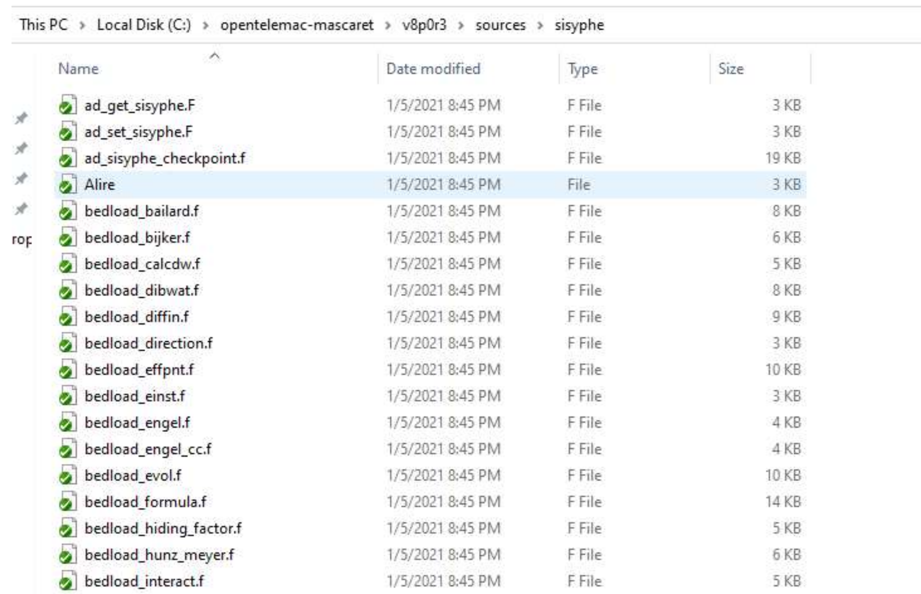
- Just as with telemac2d, FORTRAN subroutines can be specified for the simulation of special conditions using SISYPHE. Examples of these are

1. Definition of rigid areas
2. New sediment transport formula
3. Read data from result files

- Many available subroutines can be found in the folder /sources/sisyphe/ of the TELEMAC-MASCARET SYSTEM.



This PC › Local Disk (C:) › opentelemac-mascaret › v8p0r3 › sources › sisyphe

Name	Date modified	Type	Size
ad_get_sisyphe.F	1/5/2021 8:45 PM	F File	3 KB
ad_set_sisyphe.F	1/5/2021 8:45 PM	F File	3 KB
ad_sisyphe_checkpoint.f	1/5/2021 8:45 PM	F File	19 KB
Alire	1/5/2021 8:45 PM	File	3 KB
bedload_bailard.f	1/5/2021 8:45 PM	F File	8 KB
bedload_bijker.f	1/5/2021 8:45 PM	F File	6 KB
bedload_calcdw.f	1/5/2021 8:45 PM	F File	5 KB
bedload_dibwat.f	1/5/2021 8:45 PM	F File	8 KB
bedload_diffin.f	1/5/2021 8:45 PM	F File	9 KB
bedload_direction.f	1/5/2021 8:45 PM	F File	3 KB
bedload_effpnt.f	1/5/2021 8:45 PM	F File	10 KB
bedload_einst.f	1/5/2021 8:45 PM	F File	3 KB
bedload_engel.f	1/5/2021 8:45 PM	F File	4 KB
bedload_engel_cc.f	1/5/2021 8:45 PM	F File	4 KB
bedload_evol.f	1/5/2021 8:45 PM	F File	10 KB
bedload_formula.f	1/5/2021 8:45 PM	F File	14 KB
bedload_hiding_factor.f	1/5/2021 8:45 PM	F File	5 KB
bedload_hunz_meyer.f	1/5/2021 8:45 PM	F File	6 KB
bedload_interact.f	1/5/2021 8:45 PM	F File	5 KB

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Boundary Condition file

- The boundary condition file would include a number of 13 variables at each node.
- The same variables as for telemac2d apply, with some additional ones
- The flags can be:

1. =2: closed boundary (wall)
2. =4: free boundary (Nuemann's type)
3. =5,6: imposed value(Dirichlet's type).

TELEMAC-2D

```
LIHBOR LIUBOR LIVBOR HBOR UBOR VBOR AUBOR LITBOR TBOR ATBOR BTBOR N K
```

SISYPHE

```
LIHBOR LIQBOR LIVBOR Q2BOR UBOR VBOR AUBOR LIEBOR/LICBOR EBOR/CBOR ATBOR BTBOR N K
```

- ✓ LIHBOR: set for water depth
- ✓ LIUBOR: set for discharge or velocity in x direction
- ✓ LIVBOR: set for discharge or velocity in y direction
- ✓ LITBOR: set to tracer
- ✓ LIEBOR: set to bottom elevation
- ✓ LICBOR: set to equilibrium or imposed concentration
- ✓ LIQBOR: set to imposed bedload discharge
- ✓ HBOR: prescribed water depth
- ✓ UBOR: prescribed discharge or velocity in x direction
- ✓ VBOR: prescribed discharge or velocity in y direction
- ✓ AUBOR: friction coefficient on lateral walls
- ✓ EBOR: prescribed bed evolution
- ✓ CBOR: prescribed concentration
- ✓ Q2BOR: prescribed bedload discharge

Results/graphical printouts

- The variables for graphic output will depend merely on the type of problem that is required to be ran.
- There are specific variables that can be used for each of the problems that can be solved using SISYPHE.

```
U="velocity along x axis (m/s)";
V="velocity along y axis (m/s)";
C="wave celerity (m/s)";
H="water depth (m)";
S="free surface elevation (m)";
B="bottom elevation (m)";
F="Froude number";
Q="scalar flowrate of fluid (m2/s)";
I="flowrate along x axis (m2/s)";
J="flowrate along y axis (m2/s)";
M="bed-load discharge (m2/s)";
N="bed-load discharge along x axis (m2/s)";
P="bed-load discharge along y axis (m2/s)";
E="bottom evolution (m)";
R="non erodable bottom";
KS="total bed roughness (m)";
TOB="Bed Shear stress (Totalfriction) (N/m2)";
MU = "Skin friction correction factor";
D50 = "Mean grain diameter";
THETAW="wave angle with axis Oy (deg)";
QSSUSP="suspended load transport rate (m2/s)";
QSBL="bed load transport rate (m2/s)";
W="wave height";
X="wave period";
UWB="wave orbital velocity (m/s)";
1Ai="fraction of sediment of class i in the first layer";
2Ai="fraction of sediment of class i in the second layer";
kAi="fraction of sediment of class i in the k layer";
kES="thickness of the k layer";
kCONC="concentration of bed layer k";
QSi="bed load transport rate of sediment of class i";
CSi="concentration volumic or mass concentration for class i";
CSAT="saturated concentration (kg/m3)";
A="supplementary variable A";
G="supplementary variable G";
L="supplementary variable L";
O="supplementary variable O"
```

Coupling process

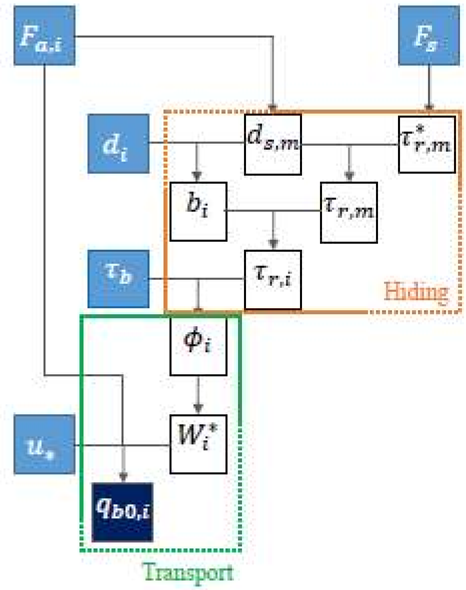
- SISYPHE can be coupled with both Shallow Water Equations (TELEMAC2D) or Reynolds Averaged Navier Stokes Equations (TELEMAC3D).
- The main function caller is dealt by the steering of either of the latter.
- Hotstart file can be added for a fully developed hydrodynamic model.

```
...
INITIAL TIME SET TO ZERO                     = YES
TIME STEP                                    = 20.0
NUMBER OF TIME STEPS                         = 100000
...
/------------------------------------------------------------------------/
/   COUPLING WITH SISYPHE                                                /
/------------------------------------------------------------------------/
/
COUPLING WITH                                 = 'SISYPHE'
SISYPHE STEERING FILE                         = 'run_bifurcation_sis.cas'
COUPLING PERIOD FOR SISYPHE                   = 1
/
/----------------------------------------------------------------------
/ INITIAL CONDITIONS
/----------------------------------------------------------------------
/
COMPUTATION CONTINUED                 = YES
PREVIOUS COMPUTATION FILE             = 'res_bifurcation_hotstart_tel.slf'
...
```

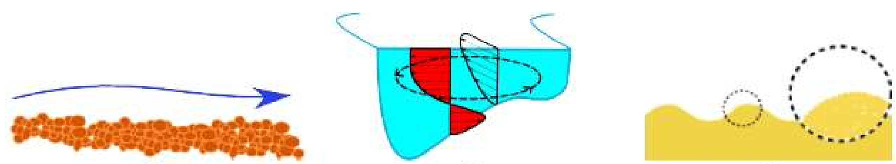
Bed Load transport

- If including bed load transport, then the keyword BED LOAD = YES must be included on the steering file.
- Need to select BED-LOAD TRANSPORT FORMULA, which will solve the Shields number depending on the grain size and movement.
- The modification of the bed must consider the following aspects:

1. Effect of local bed slope
2. Secondary flow effects on direction to bed shear stress
3. The bed shear stress partitioning affected by skin friction.




```
1 : MEYER-PETER and MUELLER
2 : EINSTEIN-BROWN
3 : ENGELUND-HANSEN + CHOLLET ET CUNGE (total sediment transport)
30: ENGELUND-HANSEN (total sediment transport)
7 : VAN RIJN
```



(a) (b) (c)

Bed Load transport

Numerical treatments available

- Rigid beds: non erodible beds are treated numerical by limiting bed erosion and letting incoming sediment pass over. This can be modified using the subroutine noerod.f
- Tidal flats: areas where the water depth can become zero during the simulation. Use subroutine positive_depths.f. If selected, can give numerical parameter MINIMUM DEPTH FOR BEDLOAD = 1E-2.
- Morphological factor: increases the bottom change rates with a constant factor N. The keyword MORPHOLOGICAL FACTOR has to be given.
- Sediment slide: preventing bed slope to become greater than the maximum friction angle which is between 32 to 40 degrees. Use subroutine maxslope.f to maintain stability during slides. If option SEDIMENT SLIDE = YES, add friction angle to it.

Useful variables for printout

```
TOB="Bed shear stress(N/m2)";
MU ="Skin friction coefficient";
M="bed-load discharge (m2/s)";
N="bed-load discharge along x axis (m2/s)";
P="bed-load discharge along y axis (m2/s)";
E="bottom evolution (m)";
QSBL="bed load transport rate (m2/s)";
```

Suspended sediments transport

- If including suspended sediment transport, the keyword SUSPENSION = YES must be specified.
- Many concentration formulas are available for near-bed processes, given by keyword REFERENCE CONCENTRATION FORMULA: [1-4]

```
1: Zyserman and Fredsoe
2: Bijker
3: Van Rijn
4: Soulsby & van Rijn
```

Diffusion and dispersion for depth-averaged suspended concentration is taken into account with keyword DIFFUSION =YES and OPTION FOR DISPERSION following options

1. DISPERSION ALONG THE FLOW, DISPERSION ALONG ACROSS THE FLOW
2. Elder model

```
TOB="Bed shear stress (N/m2)";
MU="Skin friction coefficient";
M="Solid discharge";
N="Solid discharge along axis x";
P="Solid discharge along axis y";
E="bottom evolution (m)";
QSSUSP="suspended load transport rate (m2/s)";
CSi="concentration volumic or mass
concentration for class i";
```

Non-Uniform Sediments

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- If working with sediments that have different sizes, set up the keywords BED LOAD = YES and SUSPENSION = YES.
- Non uniform sediments can be set with keyword NUMBER OF SIZE-CLASSES OF BED MATERIAL from 1 to 20.
- The granulomtric distribution id discretized in the number of classes as a list:

1. SEDIMENT DIAMETERS = 0.01
2. INITIAL FRACTION FOR PARTICULAR SIZE CLASS = 1, 0,0… (percentage that must be equal to 1)

- Constant active layers are given with keyword CONSTANT ACTIVE LAYER THICKNESS = number
- For each class, shields critical parameter can be either specified in the cas field or computed by sisyphe using subroutine init_sediment.f

```
E="bottom evolution (m)";
M="bed-load discharge (m2/s)";
1Ai="fraction of sediment of class i
in the first layer";
2Ai="fraction of sediment of class i
in the second layer";
kAi="fraction of sediment of class i
in the k layer";
kES="thickness of the k layer";
QSi="bed load transport rate of sediment
of class i"
```

```
QSSUSP="suspended load transport rate (m2/s)";
CSi="concentration volumic or mass concentration
for class i"
kCONC="concentration of bed layer k"
```

Cohesive sediment transport

- If working with cohesive sediments, with diameters less than 60μm, specify keyword COHESIVE SEDIMENTS = YES, which sets automatically the following keywords depending on the selected type of sediment: SUSPENSION =YES and BED LOAD = NO
- The number of cohesive layers can be represented as fixed number of layers less than 20 with keyword NUMBER OF LAYERS OF THE CONSOLIDATION MODEL
- Each layer is characterized by its concentration and resistance to erosion. For concentration, use keyword MUD CONCENTRATION PER LAYER =20.; 60.; 100.;… in kg/m3.
- The resistance o each layer can be specified with keyword CRITICAL EROSION SHEAR STRESS OF THE MUD = 0.01.; 0.02.;… in N/m2
- The initialization can also be done with subroutine init_compo_coh.f

```
kES="thickness of the k layer";
kCONC="concentration of bed layer k";
CSi="concentration volumic or mass concentration
for class i";
```

Mixed sediment transport

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- So far it is only supposed suspended load, implying models that solve mixtures of fine sad grains and mud.

Current limitations of TELEMAC2D/3D

1. Only one sediment size is allowed for the sand, with constant density for all layers: the volume percentage can vary for different layers.
2. Only one sediment size is allowed for the mud: the mass concentration and volume percentage can vary for different layers.
3. A simple consolidation of the sand/mud mixture is proposed.

MIXED SEDIMENT = YES

- BED LOAD = NON
- SUSPENSION = YES
- COHESIVE SEDIMENTS = NON

NUMBER OF SIZE-CLASSES OF BED MATERIAL = 2

SEDIMENT DIAMETERS = D1, D2

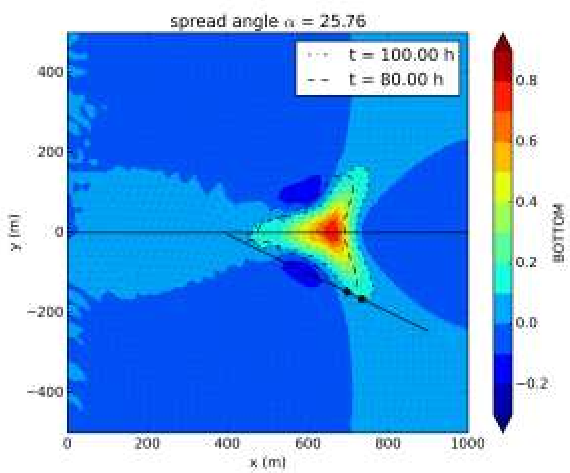
INITIAL FRACTION FOR PARTICULAR SIZE CLASS = f1, f2

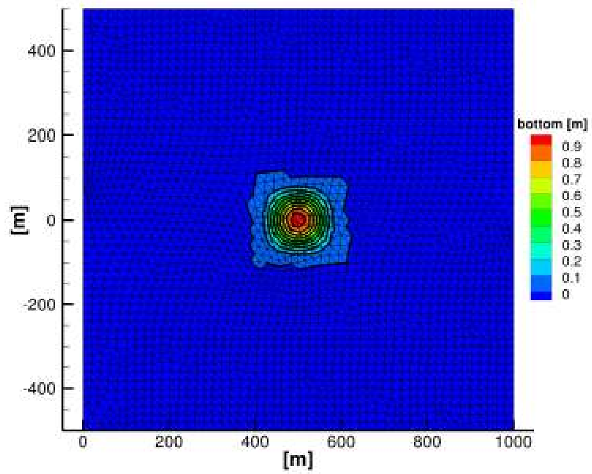
SETTLING VELOCITIES = ws1, ws2

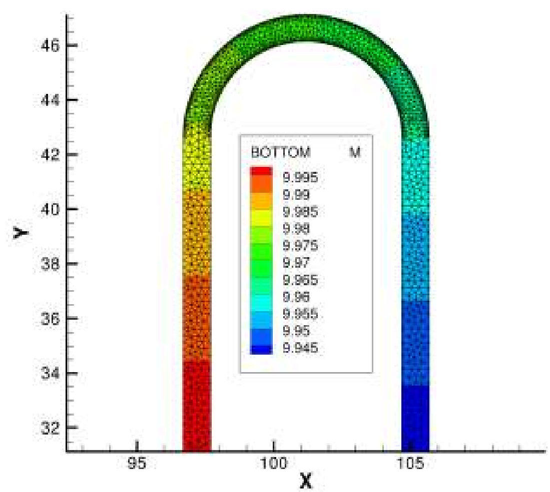
CRITICAL EROSION SHEAR STRESS OF THE MUD= 0.01; 0.02; …

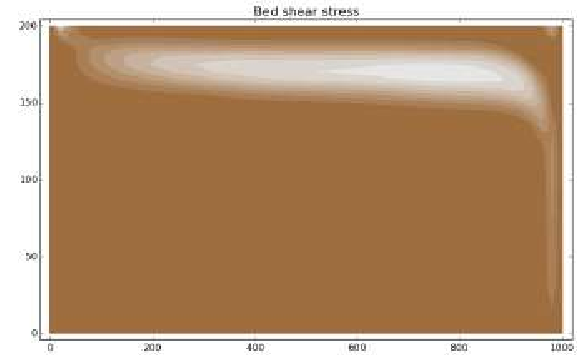
Initial layer distribution: init_compo_coh.f

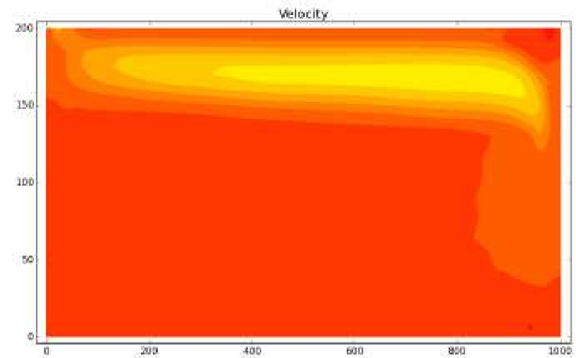
Results

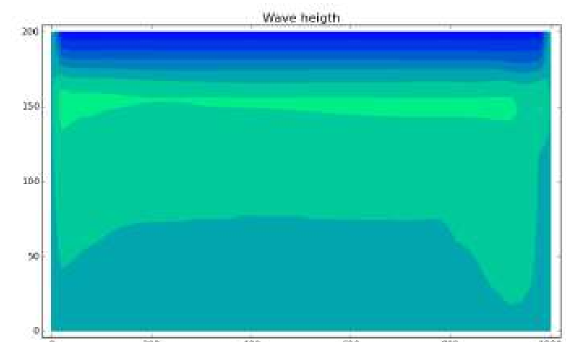

spread angle α = 25.76
t = 100.00 h
t = 80.00 h
BOTTOM
x (m)
y (m)


bottom [m]
[m]
[m]


BOTTOM M
X
Y


Bed shear stress


Velocity


Wave heigth