GAIA

User Manual

Version v8p3

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Contents

This manual was possible thanks to the contribution of Yoann Audouin, Tom Benson, Florian Cordier, Jacques Fontaine, Nicolas Huybrechts, Rebekka Kopmann, Agnès Leroy, Matthieu de Linares, Sara Pavan, Chi-Tuân Pham, Florent Taccone, Pablo Tassi & Régis Walther.

1. Introduction

1.1 Preliminaries

GAIA is the brand new open-source, sediment transport and bed evolution module of the TELEMAC-MASCARET SYSTEM modelling system. GAIA is based on the historical sediment transport module SISYPHE, where a large number of improvements, corrections and optimizations have been implemented. Thanks to its unified framework, GAIA efficiently manages different sediment classes, sand-mud mixtures, etc. for both 2D and 3D spatial dimensions.

The module SISYPHE of the TELEMAC-MASCARET SYSTEM modelling system (TMS) has been developed for more than 25 years [29], originally based on the same finite element structure as the two-dimensional code solving the shallow water equations. This shallow water code later evolved into a module that was baptized TELEMAC-2D.

Despite its robustness, flexibility and capability of dealing with a large number of river [10, 15], coastal [7, 41, 47], and estuarine [20, 42, 43] sediment transport and morphodynamics problems [52], as well as the tremendous effort to deliver a module able to be used in both industrial and scientific contexts, a number of issues arose regarding the improvement of the treatment of graded and mixed (cohesive and non-cohesive) sediments, as well as the full compatibility between 2D and 3D processes.

From early discussions starting *circa* 2014 following the developments on mixed sediment implemented *ad hoc* by a consortium member for an estuarine model [12], going through strategic meetings, animated coffee debates and *hackathons* involving several members of the TELEMAC-MASCARET consortium, and more recently the participation of final users and an increasing number of threads with suggestions and recommendations posted in the TMS's webpage forum, the brand new sediment transport and bed evolution module GAIA of the TMS is introduced.

GAIA, building upon the SISYPHE module, is able to model complex sediment and morphodynamic processes in coastal areas, rivers, lakes and estuaries, accounting for spatial and temporal variability of sediment size classes (uniform, graded or mixed), properties (cohesive and non-cohesive) and transport modes (suspended, bedload and both simultaneously). **The generalized framework used for bed layering enables any combination of multiple size classes for both non-cohesive and cohesive sediment to be modelled simultaneously.** Compatibility is ensured between an active layer model (an approach traditionally adopted for non-cohesive sediment) and the presence of different classes of fine sediment and consolidation. **In contrast to SISYPHE, the quantity of each sediment class in the bed is evaluated using dry mass instead of volume, which minimizes roundoff errors.**

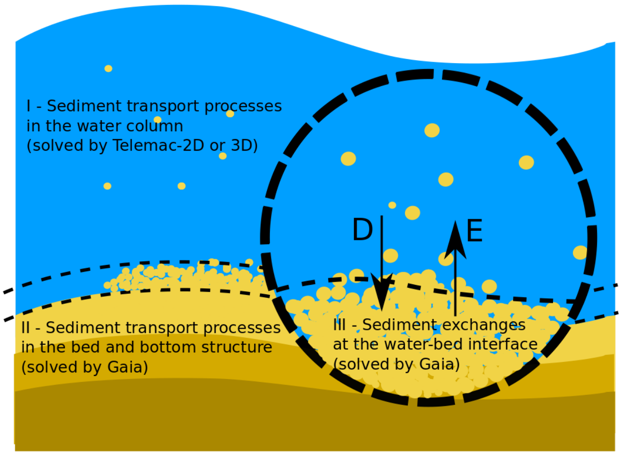


Figure 1.1: Sketch summarizing the way in which the sediment transport mechanisms are dealt in GAIA. Above, D and E stand for deposition and entrainment fluxes.

Although invisible to the end user, suspended sediment transport processes are dealt with by the hydrodynamic modules (TELEMAC-2D or TELEMAC-3D), while near-bed, bedload and processes in the bottom layer are handled by GAIA. This allows a clearer treatment of sedimentary processes that happen in the water column, in the bed structure and at the water-bed interface, see Figure 1.1. GAIA can also be coupled with the modules for sediment dredging NESTOR, wave propagation TOMAWAC and water quality WAQTEL.
GAIA can easily be expanded and customized to particular requirements by modifying friendly, easy to read Fortran files. An overview of different applications of GAIA can be consulted in the yearly-published Telemac-Mascaret User Conference proceedings, freely available at the website `www.opentelemac.org`.

1.1.1 Sediment transport and morphodynamic modelling

The prediction of topography changes and sediment discharges can be performed by integrating several modules. It is a **multi–scale problem**, with different physical mechanisms acting according to their space and time response. In summary, the relevant mechanisms that drives morphological changes are:

- **hydrodynamics:** with conservative laws of mass and momentum,
- **sediment transport:** with predictors for sediment transport capacity,
- **bed evolution:** with conservative law for sediment mass.

Such a modelling system is often referred to as a *morphodynamic model* and is the one adopted in the TELEMAC-MASCARET SYSTEM.
From the literature, the main mechanisms of sediment transport are classified as:

- **bedload:** with a variety of closure relationships for sediment transport capacity,
- **suspended load:** with the solution of the advection-diffusion equation (ADE) plus closures for erosion and deposition fluxes, equilibrium concentration,
- **bed evolution:** with the solution of the sediment mass conservation equation or *Exner equation*.

Different types of sediment can be classified as:

- **non-cohesive:** with equilibrium formulas
- **cohesive:** erosion and deposition laws, consolidation models
- **mixed-size sediments:** accounting for moderately or poorly sorted sediment distribution, sand-gravel and sand-mud mixtures.

1.1.2 Choice of hydrodynamic models for sediment transport applications

The choice of appropriate model equations for flow and sediment transport will depend upon the scales of interest.

At the scale of ripples, the mechanics of sediment transport could be coupled with the Reynolds–averaged Navier Stokes equations (NS) to describe the phenomenon. At large scales, however, the shallow water equations (SWE) are known to capture quite accurately the salient features –in an average sense– of water bodies. The SWE are derived by simplifying the hydrodynamics in the vertical direction instead of using the full three–dimensional NS or Euler equations.

As such, the SWE are obtained by assuming a hydrostatic pressure distribution and a uniform velocity profile across the water layer, resulting in a two–dimensional problem where the primary variables are the vertical averages of the horizontal flow velocities and water depth.

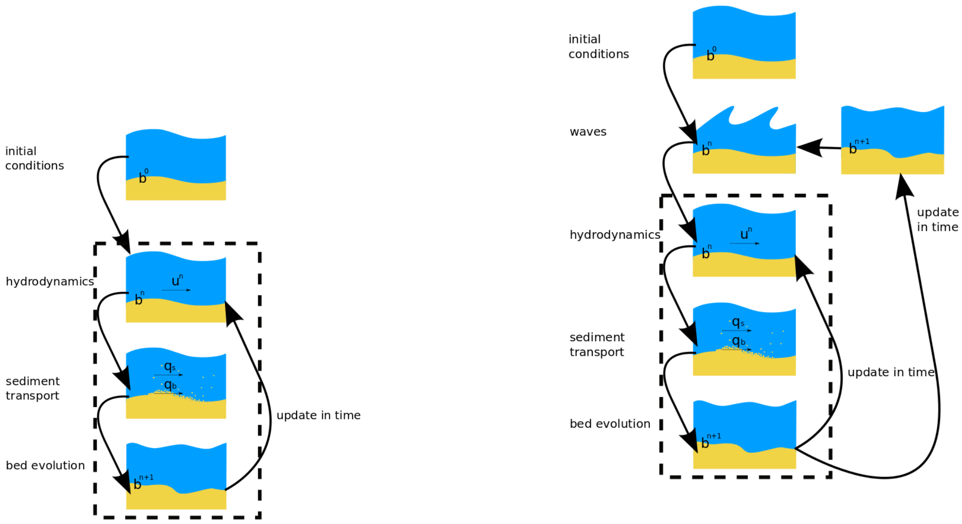
This simplification enhances the speed of computations and facilitates further analytical approaches. In brief, the SWE are often used to model advection–dominated open channel flows, river and lake hydrodynamics, floodplain flows, estuarine and coastal circulation as well as long wave run-up and hydraulic bores, among other problems of interest within the engineering community [8].

1.1.3 Coupling hydrodynamics to morphodynamics

Morphological models can be run fully coupled [56] and decoupled [13]. In a fully coupled model, sediment transport and flow occur simultaneously, and thus, their respective equations are coupled and should be solved simultaneously. Rapid morphological evolution processes due to hyper-concentrated sediment–laden floods, and debris flow are typical examples were the fully coupled approach must be employed [18].

In contrast, decoupled models are applicable when the typical time scale for river or sea bed adjustment is much longer than the typical time scale for water flow. The approach used by GAIA follows the decoupled treatment, i.e., to alternate between the simulation of flow and bed evolution. This procedure, also known as *asynchronous* solution, considers that the bottom is fixed when the flow variables are computed by the hydrodynamics module.

Hydrodynamic solution is therefore to solve the hydrodynamic continuity and momentum equations on a short time scale. During this hydrodynamic step the bottom is frozen and the discretized sediment equation is subsequently solved separately. For the current version of GAIA, the decoupled approach is implemented.



(a) currents only

(b) currents + waves

Figure 1.2: Schematic coupling strategies for GAIA: (a) coupling morphodynamic and hydrodynamic, current only, (b) coupling morphodynamic and hydrodynamic including the effect of waves.

1.2 GAIA's structure

1.2.1 Coupling hydrodynamics and morphodynamics

GAIA can be internally coupled with the hydrodynamic models TELEMAC-2D or TELEMAC-3D. In the TELEMAC-2D or TELEMAC-3D steering files, the following keywords need to be specified:

- `COUPLING WITH = 'GAIA'`
- `GAIA STEERING FILE = '<name of the gaia steering file>'`

For a *hotstart* from a fully developed hydrodynamic, the following information must be included in the TELEMAC-2D or TELEMAC-3D steering files:

- `COMPUTATION CONTINUED` (logical type, set to = `NO` by default)

The file name is provided with the keyword `PREVIOUS COMPUTATION FILE`. Optionally, `INITIAL TIME SET TO ZERO` (logical type, set to = `NO` by default).
The time step used for morphodynamic computation is the same used for hydrodynamics. It is specified in the TELEMAC-2D or TELEMAC-3D steering file. For suspended load, the advection-diffusion equation obeys the same Courant number criteria on the time step as the hydrodynamics, and therefore needs to be solved at each time-step. Typically the morphodynamic scale induced by bed load is much smaller, than the hydrodynamic scale. This leads to very small bed level changes in a hydrodynamic time step. The use of a coupling period > 1 is very useful in this case. It allows the bed load transport rates and resulting bed evolution not to be re-calculated at every time step.

1.2.2 Equivalence between GAIA and SISYPHE

Mandatory keywords to be included in GAIA's steering files are:

- `TYPE OF SEDIMENT`
- `BED LOAD FOR ALL SANDS`
- `SUSPENSION FOR ALL SANDS`
- `BED-LOAD TRANSPORT FORMULA FOR ALL SANDS`

Note:
Documenting a module such as GAIA is a time-consuming, never-ending activity that we will try to improve for each new release. Nevertheless, the avid reader is referred to the examples folders located at `examples/gaia` and/or the "dico" file, found at `sources/gaia/gaia.dico`, for a glimpse of new developments and improvements.

2. Sediment Transport Processes in the Water Column

Suspended sediment particles being transported by the flow at a given time and maintained in temporary suspension above the bottom by the action of upward-moving turbulent eddies are commonly called *suspended load*. The equation describing mass conservation of suspended sediment is the advection-diffusion equation (ADE), that is valid only for dilute suspensions of particles that are not too coarse (i.e., ≤ 0.5 mm).

Within this new sediment transport framework, the solution of the ADE, completed with appropriate boundary and initial conditions, is computed by TELEMAC-2D or TELEMAC-3D for 2D and 3D cases respectively, assuming the suspended sediment as a tracer. The solution procedure remains almost invisible to the user since the physical parameters are provided by the GAIA steering file. Even though, we suggest to readers to refer to the tracer transport chapters of TELEMAC-2D and TELEMAC-3D user guides for a complete overview of advection-diffusion problems. Two advantages of this procedure are evident: (*i*) to stay up-to-date with the numerical schemes and algorithm developments in the hydrodynamics modules for the solution of the advection terms and (*ii*) for a clearer distinction between sediment transport processes happening in the water column, in the near-bed, and in the bed structure (for example in cases where exchanges with the bottom are not required such as suspended sediment transport over a rigid bed).

The chapter is organized in two main parts according to the type of sediment class (non cohesive or cohesive). For each part, the user guides are described without distinguishing between 2D or 3D where possible. When differences arise between the 2D and the 3D sediment treatment, a clear distinction is done.

2.1 Non-cohesive suspended sediment transport

In 2D cases, the suspended sediment transport is accounted by solving the two-dimensional advection-diffusion equation, expressed by:

$$\frac{\partial hC}{\partial t}+\frac{\partial hUC}{\partial x}+\frac{\partial hVC}{\partial y}=\frac{\partial}{\partial x}\left(h\varepsilon_s\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(h\varepsilon_s\frac{\partial C}{\partial y}\right)+E-D \tag{2.1}$$

where $C=C(x,y,t)$ is the depth-averaged concentration **expressed in g/l**, (U,V) are the depth-averaged components of the velocity in the x and y directions, respectively, ε_s is the turbulent diffusivity of the sediment, often related to the eddy viscosity $\varepsilon_s=\nu_t/\sigma_c$, with σ_c the Schmidt number. In our case, $\sigma_c=1.0$.

In 3D cases, the suspended sediment transport is accounted by solving the three-dimensional advection-diffusion equation, expressed by:

$$\frac{\partial C}{\partial t}+\frac{\partial uC}{\partial x}+\frac{\partial vC}{\partial y}+\frac{\partial wC}{\partial z}-\frac{\partial w_s C}{\partial z}=\frac{\partial}{\partial x}\left(\varepsilon_s\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_s\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial y}\left(\varepsilon_s\frac{\partial C}{\partial z}\right) \tag{2.2}$$

where $C=C(x,y,z,t)$ is the concentration **expressed in g/l**, (u,v,w) are the components of the velocity in the x, y and z directions, respectively. w_s is the sediment settling velocity. ε_s is the turbulent diffusivity of the sediment, often related to the eddy viscosity $\varepsilon_s=\nu_t/\sigma_c$, with σ_c the Schmidt number. In our case $\sigma_c=1.0$.

2.1.1 Initial conditions for suspended sediment transport

The initial condition value of the concentration can be specified through the keyword `INITIAL SUSPENDED SEDIMENTS CONCENTRATION VALUES` (real type list, = `0.0` by default), following the order given in `CLASSES TYPE OF SEDIMENT`. These values must be **expressed in g/l**. In 2D, this keyword is not considered on boundary nodes if `EQUILIBRIUM INFLOW CONCENTRATION = YES`.

```
INITIAL SUSPENDED SEDIMENTS CONCENTRATION VALUES :0.D0;1.D0;...
```

2.1.2 Boundary conditions for suspended sediment transport

The specification of boundary conditions is done in a boundary condition file, usually named with extension `*.cli`. The reader is referred to §6.1.2 for the definition of the different flags used in the boundary condition file.

Wall boundary conditions

At banks and islands, the no-flux boundary condition is imposed: the suspended load concentration gradients are set to zero.

$$\varepsilon_s\frac{\partial C}{\partial n}=\varepsilon_s \mathbf{Grad}C\cdot\boldsymbol{n}=0 \tag{2.3}$$

For this case, the flag `LIEBOR` is set = `2` as shown in the example below:

```
2 2 2 0.0 0.0 0.0 0.0 2 0.0 0.0 0.0 565 1
```

Inflow boundary conditions

Several ways to impose the concentration at inflow boundary conditions are proposed in GAIA. For this case, the flag `LICBOR` is set = `5`, with the following options for the concentration values:

- Specified in the column `CBOR`. In the example below, a concentration value = `1.0` g/l is provided:

```
4 5 5 0.0 0.0 0.0 0.0 5 1.0 0.0 0.0 565 1
```

- Specified by the concentration values at the boundary through the keyword `PRESCRIBED SUSPENDED SEDIMENTS CONCENTRATION VALUES` (real type list of size equal to the number of boundaries × the number of sediment classes), expressed in g/l:

```
4 5 5 0.0 0.0 0.0 0.0 5 0.0 0.0 0.0 565 1
```

```
PRESCRIBED SUSPENDED SEDIMENTS CONCENTRATION VALUES =
0.0; 0.0; 1.0; ...
```

The order is the following: boundary 1 (class 1, class2, etc.), then boundary 2, etc.

- Computed by GAIA in 2D cases through the keyword `EQUILIBRIUM INFLOW CONCENTRATION` (logical type variable, `= NO` by default) and according to the choice of the formula of equilibrium near-bed concentration (`SUSPENSION TRANSPORT FORMULA FOR ALL SANDS = 1` by default)

```
4 5 5 0.0 0.0 0.0 0.0 5 0.0 0.0 0.0 565 1
```

```
EQUILIBRIUM INFLOW CONCENTRATION = YES
SUSPENSION TRANSPORT FORMULA FOR ALL SANDS = 1
```

- Time-varying concentration values (in g/l) must be provided in an external `ASCII` file. In this case the keyword `LIQUID BOUNDARIES FILE` has to be used in the hydrodynamic steering file of TELEMAC-2D or TELEMAC-3D according to the case. Suspended sediment concentrations are treated like tracers, the reader is thus referred to the user manual of modules TELEMAC-2D or TELEMAC-3D. If tracers and sediments are declared at the same time, sediments will be allocated after tracers. For example if we have 3 tracers and 2 suspended sediments, the first sediments will be the fourth tracer.

```
4 5 5 0.0 0.0 0.0 0.0 5 0.0 0.0 0.0 565 1
```

```
LIQUID BOUNDARIES FILE = '<file name>'
```

- Vertical profile provided in 3D cases through the keyword `VERTICAL PROFILES OF SUSPENDED SEDIMENTS`, which can be equal to:
  - 0 if the profile is programmed by users,
  - 1 if constant profile,
  - 2 if Rouse profile,
  - 3 if normalised Rouse profile and assigned concentration,
  - 4 if modified Rouse profile with molecular viscosity.

According to the hydrodynamic forcing, the use of the keyword `EQUILIBRIUM INFLOW CONCENTRATION` can be used to prevent the excessive erosion and deposition on the inflow boundary (for 2D cases).

2.1.3 Outflow boundary conditions

At the outflow boundary, the suspended load concentration gradient in the flow direction is set to zero. For this case, the flag `LICBOR` is set `= 4` as shown in the example below:

```
5 4 4 0.0 0.0 0.0 0.0 4 0.0 0.0 0.0 565 1
```

Stability issues at inflow boundaries can be solved by activating the keyword `TREATMENT OF FLUXES AT THE BOUNDARIES` (integer type variable, `= 2`, default option) in the steering file of TELEMAC-2D or TELEMAC-3D. The choice `= 1` can be activated when prescribed values are provided. The choice `= 2` is used when fluxes are imposed.

2.1.4 Numerical treatment of the diffusion terms

The keyword `OPTION FOR THE DIFFUSION OF TRACER` (integer type, set = `1` by default) allows to choose the treatment of the diffusion terms in the advection-diffusion equation 2.1 for the depth-averaged suspended concentration:

- = `1`: the diffusion term is solved in the form $\nabla \cdot (\varepsilon_s \nabla T)$
- = `2`: the diffusion term is solved in the form $\frac{1}{h} \nabla \cdot (h \varepsilon_s \nabla T)$

This keyword must be activated in the steering file of TELEMAC-2D; user can refer to the corresponding user manual for further details.

2.1.5 Numerical treatment of the advection terms

The choice for the scheme for the treatment of the advection terms can be done with the keyword `SCHEME FOR ADVECTION OF SUSPENDED SEDIMENTS` (integer type, set = `5` by default):

```
1="CHARACTERISTICS"
2="SUPG"
3="CONSERVATIVE N–SCHEME"
4="CONSERVATIVE N–SCHEME"
5="CONSERVATIVE PSI–SCHEME"
13="EDGE–BASED N–SCHEME"
14="EDGE–BASED N–SCHEME"
15="ERIA SCHEME"
```

The keyword `SCHEME OPTION FOR ADVECTION OF SUSPENDED SEDIMENTS` can be used to choose futher options for advection schemes. In particular, if characteristics are used, the following options are possible :

- `1`: strong form;
- `2`: weak form.

If advection is solved by the N or PSI scheme, options are:

- `1`: explicit scheme;
- `2`: first order predictor-corrector scheme;
- `3`: second order predictor-corrector scheme;
- `4`: local semi-implicit scheme.

To have more details about these keywords, readers can refer to the TELEMAC-2D or TELEMAC-3D user guide (cf. chapters about tracer advection). In fact, the advection scheme used by sediments is exactly the same used by tracers, implemented in hydrodynamics modules. Keywords `SCHEME FOR ADVECTION OF SUSPENDED SEDIMENTS` and `SCHEME OPTION FOR ADVECTION OF SUSPENDED SEDIMENTS` have been added from V8P2 in GAIA in order to have proper steering files.

> **Note:**
> It is recommended to use the schemes `4` or `14` for a good compromise between accuracy and computational time (specially if tidal flats are present). It is also suggested to activate the keyword `CONTINUITY CORRECTION = YES`.

A brief description of the numerical schemes implemented in GAIA is given below:

- **Method of characteristics** (`1`)
  - Unconditionally stable and monotonous
  - Diffusive for small time steps, Not conservative
- **Method Streamline Upwind Petrov Galerkin SUPG** (`2`)
  - Based on the Courant number criteria
  - Less diffusive for small time steps, Not conservative
- **Conservative N-scheme (similar to finite volumes)** (`3, 4`)
  - Solves the continuity equation under its conservative form
  - Recommended for correction on convection velocity
  - Courant number limitation (sub-iterations to reduce time step)
- **Edge-based N-scheme NERD** (`13, 14`)
  - Same as `3` and `4` but adapted to tidal flats
  - Based on positive-depth algorithm
- **Distributive schemes PSI** (`5`)
  - fluxes corrected according to the tracer value: relaxation of Courant number criteria, less diffusive than schemes `4, 14` but larger CPU time
  - Should not be applied for tidal flats
- **Eria scheme** (`15`)
  - Works for tidal flats

For further information about these schemes, refer to TELEMAC-2D user manual.

2.1.6 Correction of the convection velocity

As most of the sediment transport processes occur near the bed, it often exhibits an overestimation of suspended sand transport. A correction method accounting for the vertical velocity and concentration profiles is therefore proposed. A straightforward treatment of the advection terms would imply the definition of an advection velocity and replacement of the depth-averaged velocity U along the $x-$axis in Eq. (2.1) by:

$$U_{conv} = \overline{UC}/C.$$

A correction factor is introduced in GAIA, defined by:

$$F_{conv} = \frac{U_{conv}}{U}.$$

A similar treatment is done for the depth-averaged velocity V along the $y-$axis. For further details, see [34]. The convection velocity should be smaller than the mean flow velocity ($F_{conv} \leq 1$) since sediment concentrations are mostly transported in the lower part of the water column where velocities are smaller. We further assume an exponential concentration profile which is a reasonable approximation of the Rouse profile, and a logarithmic velocity profile, in order to establish the following analytical expression for F_{conv}:

$$F_{conv} = -\frac{I_2 - \ln\left(\frac{B}{30}\right) I_1}{I_1 \ln\left(\frac{eB}{30}\right)},$$

with $B = k_s/h = Z_{ref}/h$ and

$$I_1 = \int_B^1 \left(\frac{(1-u)}{u}\right)^R du, \quad I_2 = \int_B^1 \ln u \left(\frac{(1-u)}{u}\right)^R du.$$

The keyword `CORRECTION ON CONVECTION VELOCITY = YES` (logical type, set = `NO` by default) modifies the depth-averaged convection velocity to account for the vertical gradients of velocities and concentration.

2.1.7 Settling lag correction

Sediment transport exhibits temporal lags with flow due to flow and sediment velocity difference and bed development [21, 55]. A scaling factor that accounts for both the settling velocity and the lag time is therefore required for the saturation concentration profile to adjust to changes in the flow. The keyword `SETTLING LAG` (logical type, set to `NON` by default) allows to compute the bed exchange factor beta based on Miles [21]. This keyword must be used with the Nikuradse friction law, prescribed in the TELEMAC-2D steering file as `LAW OF BOTTOM FRICTION = 5`.

2.2 Cohesive sediment transport

Cohesive properties appear for fine particles (silts and clay), with diameter less than a limiting value of about 60 μm, depending on the physico-chemical properties of the fluid and salinity. The separation value at 60μm to discriminate non-cohesive from cohesive sediment is conventional. This value is different depending on the country (e.g. 63μm in The Netherlands, 75μm in USA as pointed by Winterwerp and Van Kesteren [26]). Moreover, aggregation of flocs can lead to the formation of macro-flocs larger than 100μm.

Fine cohesive sediments are mainly transported in suspension and transport processes strongly depend on the state of flocculation of the suspension and consolidation of the bed. The erosion rate mainly depends on the degree of consolidation of the sediment bed, while the settling velocity depends on the state of flocculation and aggregates properties.

In GAIA, cohesive sediments are accounted by solving the 2D advection-diffusion equation:

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

$C = C(x,y,t)$ is the depth-averaged concentration **expressed in g/l**, (U,V) are the depth-averaged components of the velocity in the x and y directions, respectively, ε_s is the turbulent diffusivity of the sediment. Variables E and D are respectively the erosion and deposition fluxes.

3. Sediment Transport Processes in the Bed and Stratigraphy

3.1 Bedload Transport

Sediment particles which are transported in direct contact with the bottom or next to the bed without being affected by the fluid turbulence are commonly called *bedload*. **In contrast to SISYPHE, in GAIA bedload fluxes are computed in terms of (dry) mass transport rate per unit width, without pores.** The numerical computation of sediment fluxes in terms of dry mass minimizes roundoff error, particularly for the mass transfer algorithms used for the bed layer model.

3.1.1 Preliminaries

The classical form of the conservative law equation for sediment mass (or Exner equation) accounts for the vector of volumetric transport rate per unit width without pores $\mathbf{Q}_b$, expressed in $(\mathrm{m}^2/\mathrm{s})$, with components Q_{b_x}, Q_{b_y} in the x and y direction respectively. The bedload transport vector can be decomposed into $x-$ and $y-$direction components as:

$$\mathbf{Q}_b = (Q_{b_x}, Q_{b_y}) = (Q_b \cos\alpha, Q_b \sin\alpha). \tag{3.1}$$

Above, Q_b is the bedload transport rate per unit width, computed as a function of the equilibrium sediment load closure (or sediment transport capacity) and α is the angle between the sediment transport vector and the downstream direction ($x-$axis). The deviation of the bed load direction from the flow direction is mainly influenced by the bed slope and the presence of secondary flows [3], see Section 3.1.3.

As presented and discussed in § 3.4, GAIA solves the Exner equation as a function of the mass transport flux rate and not in terms of volumetric transport rate, as follows:

$$\mathbf{Q}_{mb} = \rho \mathbf{Q}_b, \tag{3.2}$$

where $\mathbf{Q}_{mb}$ is the vector of mass transport rate per unit width without pores (kg/(m s)), with ρ the density.

3.1.2 Steering file setup for bedload transport

For non-cohesive sediments, the bedload sediment transport can be set with the keyword `BED LOAD FOR ALL SANDS = YES` (logical type variable, set to `= NO` by default). This keyword explicitly stated that all non-cohesive sediments considered in the computation will be transported by the bedload sediment transport mechanism.

The dimensionless current-induced sediment transport rate Φ_b is expressed by:

$$\Phi_b = \frac{Q_b}{\sqrt{g(s-1)d^3}}, \tag{3.3}$$

with $s = \rho_s/\rho$ the relative density $(-)$; ρ_s the sediment density $(\mathrm{kg/m^3})$, with corresponding keyword `CLASSES SEDIMENT DENSITY` and default value equal to 2650 $\mathrm{kg/m^3}$; ρ the water density $(\mathrm{kg/m^3})$; d the sand grain diameter ($= d_{50}$ for uniform sediment distribution (m)) and g the gravity acceleration constant $(\mathrm{m/s^2})$. The keyword `CLASSES SEDIMENT DIAMETERS` allows the user to introduce the mean sand grain diameter per class.

Different choices of Φ_b can be selected with the keyword `BED-LOAD TRANSPORT FORMULA FOR ALL SANDS` (integer type variable, set to `= 1` by default corresponding to the Meyer-Peter and Müller formula). This keyword explicitly stated that all non-cohesive sediments considered in the computation (see also §sec:nonuniform) will account for the same sediment transport capacity formula.

Bedload transport formulas

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

$$\theta = \frac{\mu \tau_b}{(\rho_s - \rho) g d}, \tag{3.4}$$

with τ_b the bottom shear stress [Pa] and μ the correction factor for skin friction (discussed later in Section 3.1.8).

Keyword `BED-LOAD TRANSPORT FORMULA FOR ALL SANDS` (integer type variable, set to = `1` by default) can be used to set a bedload transport formula. Available formulas in GAIA for bedload transport are:

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

For example, the keyword `BED-LOAD TRANSPORT FORMULA FOR ALL SANDS = 7` sets the van Rijn formula. Please note that bedload transport formulas `3` and `30` account for the total sediment transport.

Available bedload transport formulas

Meyer-Peter and Müller

- `BED-LOAD TRANSPORT FORMULA FOR ALL SANDS = 1`
- Classical, wide application range $d = d_{50} = [0.4 - 29]$mm, based on grain mouvement threshold concept. The dimensionless current-induced sediment transport rate is given by:

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

  with α_{mpm} a coefficient and θ_{cr} the critical Shields parameter (keyword `CLASSES SHIELDS PARAMETERS`)

> **Note:** To be consistent with the classical Meyer-Peter and Müller formula, the value of the critical Shields parameter θ_{cr} must be explicitly set equal to 0.047 in the steering file (`CLASSES SHIELDS PARAMETERS = 0.047`).

- For calibration purposes, the coefficient α_{mpm} can be modified in the steering file by the keyword `MPM COEFFICIENT` (real type variable, = `8` by default).

> **Note:** A value of `MPM COEFFICIENT = 8` was proposed for the original MPM formula [19] with $\theta_{cr} = 0.0470$, while `MPM COEFFICIENT = 3.97` is equivalent to the modified Meyer-Peter and Müller formula proposed by Wong and Parker [54], with $\theta_{cr} = 0.0495$.

- Fortran subroutine `bedload_meyer_gaia.f`.

Einstein-Brown

- `BED-LOAD TRANSPORT FORMULA FOR ALL SANDS = 2`
- Based on the energy concept (no threshold), valid for gravel and large shear stresses (application range $d = d_{50} = [0.25-32]$mm). The dimensionless current-induced sediment transport rate is given by:

$$\Phi_b = F(D_*)f(\theta),$$

with

$$F(D_*) = \left(\frac{2}{3}+\frac{36}{D_*}\right)^{0.5} - \left(\frac{36}{D_*}\right)^{0.5},$$

and

$$f(\theta) = \begin{cases} 2.15\exp(-0.391/\theta) & \text{if } \theta \leq 0.2 \\ 40\,\theta^3 & \text{otherwise} \end{cases}$$

where the non-dimensional diameter $D_* = d[(\rho_s/\rho-1)g/\nu^2]^{1/3}$, with ν the water viscosity (keyword `WATER VISCOSITY`, equal to 10^{-6} m/s^2 by default).

- Fortran subroutine `bedload_einst_gaia.f`.

Engelund-Hansen modified by Chollet & Cunge

- `BED-LOAD TRANSPORT FORMULA FOR ALL SANDS = 3`
- The dimensionless current-induced sediment transport rate is given by:

$$\Phi_b = 0.05\frac{\theta_*^{\frac{5}{2}}}{c_f}$$

with c_f the adimensional friction coefficient and θ_* depending on the transport regime:

$$\theta_* = \begin{cases} 0 & \text{if } \theta \leq 0.06 & \text{no transport} \\ [2.5\,(\theta-0.06)]^{0.5} & \text{if } 0.06 < \theta < 0.384 & \text{dune regime} \\ 1.066\theta^{0.176} & \text{if } 0.384 < \theta < 1.08 & \text{transition regime} \\ \theta & \text{if } 1.08 < \theta & \text{sheet flow regime} \end{cases}$$

with θ the Shields parameters including the skin ratio coefficient, defined in (3.4).

- Fortran subroutine `bedload_engel_cc_gaia.f`.

van Rijn's

- `BED-LOAD TRANSPORT FORMULA FOR ALL SANDS = 7`
- Valid for finer material in the range $d = d_{50} = [0.2-2]mm$. The dimensionless current-induced sediment transport rate is given by:

$$\Phi_b = 0.053D_*^{-0.3}\left(\frac{\theta-\theta_{cr}}{\theta_{cr}}\right)^{2.1}.$$

- Fortran subroutine `bedload_vanrijn_gaia.f`.

Wilcock and Crowe

- `BED-LOAD TRANSPORT FORMULA = 10`

  The Wilcock and Crowe model [53]:

  i) it is based on surface investigations and is particularly adapted for the prediction of transient conditions of bed armoring and scenarios of bed aggradation/degradation,

  ii) it considers the full size distribution of the bed surface (from finest sands to coarsest gravels),

  iii) it was calibrated using a total of 49 flume experiments with small-to-high water discharges and five different sediment mixtures and later modified and validated with 6239 values of solid discharge, and

  iv) the hiding function has been designed to resolve discrepancies observed from previous experiments [35, 38] including the hiding-exposure effect of sand content on gravel transport for weak to high values of sand content in the bulk.

- Fortran subroutine `bedload_wilcock_crowe_gaia.f`.

For each i^{th} size fraction, the magnitude of the fractional transport rate without gravitational effects $q_{b0,i} = |\boldsymbol{q}_{b0,i}|$ [m^2/s] is estimated using the bedload capacity formula of Wilcock and Crowe (WC-2003) [53]:

$$W_i^* = f(\tau_b/\tau_{r,i}) = \frac{\Delta_s g q_{b0,i}}{F_{a,i} u_*^3} \quad , \tag{3.5}$$

where W_i^* [-] corresponds to the dimensionless transport rate for the i^{th} size fraction of sediment, $\Delta_s = \frac{\rho_s}{\rho} - 1$ [-] is the relative submerged sediment density, with ρ [kg/m^3] the water density and ρ_s the sediment density [kg/m^3], τ_b [Pa] is the bed shear stress, $\tau_{r,i}$ [Pa] the reference shear stress of the i^{th} size fraction and $u_* = \sqrt{\tau_b/\rho}$ [m/s] the shear velocity (also called friction velocity). The transport function of WC-2003 is defined as follows:

$$W_i^* = \begin{cases} 0.002\Phi_i^{7.5} & \text{for } \Phi_i < 1.35 \\ 14\left(1 - \frac{0.894}{\Phi_i^{0.5}}\right)^{4.5} & \text{for } \Phi_i \geq 1.35 \end{cases} \quad , \tag{3.6}$$

where the ratio $\Phi_i = \tau_b/\tau_{r,i}$ is incorrectly referred to as Φ in the literature [40, 53].
The hiding-exposure function is defined so that the sediment transport rates are lowered for finer fractions (i.e. increase of $\tau_{r,i}$) and increased for coarser material (i.e. decrease of $\tau_{r,i}$), and is accounted in the model as follows:

$$\frac{\tau_{r,i}}{\tau_{r,m}} = \left(\frac{d_i}{d_{s,m}}\right)^{b_i} \quad \text{with} \quad b_i = \frac{0.67}{1 + \exp\left(1.5 - \frac{d_i}{d_{s,m}}\right)} \quad , \tag{3.7}$$

where d_i [m] corresponds to the sediment diameter of the i^{th} size fraction, $d_{s,m}$ [m] is the mean sediment diameter of surface, $\tau_{r,m}$ [Pa] is the reference shear stress of the mean sediment diameter of surface and b_i is the power-coefficient of the hiding-exposure function which is incorrectly referred to as b in the literature. $\tau_{r,m}$ is computed as a function of the dimensionless median reference shear stress of bed surface $\tau^*{}_{r,m}$ such that $\tau^*{}_{r,m} = \frac{\tau_{r,m}}{\Delta_s \rho g d_{s,m}}$ where $\tau^*{}_{r,m} = 0.021 + 0.015\exp[-20F_s]$. The dimensionless median reference shear stress of bed surface was shown to decrease exponentially as a function of the sand fraction at the bed surface denoted F_s (wrongly mentionned as the percentage of sand in the original article of [53]).
By using independent sediment transport measurements, several authors [e.g. 4, 40] have shown that the performance of the formula of WC-2003 could be improved by modifying one or several

parameters. For instance, [40] modified the intercepting value of Φ_i and the power exponent of the equation to compute $W_i{}^*$, enhancing the performance of the formula. The authors showed that reducing the power exponent increased the transport rate for a given bed shear stress and compensated for under-prediction within the range considered. Alternatively, [4] proposed to use a dimensionless calibration parameter to modify the value of the median reference shear stress $\tau_{r,m}$.

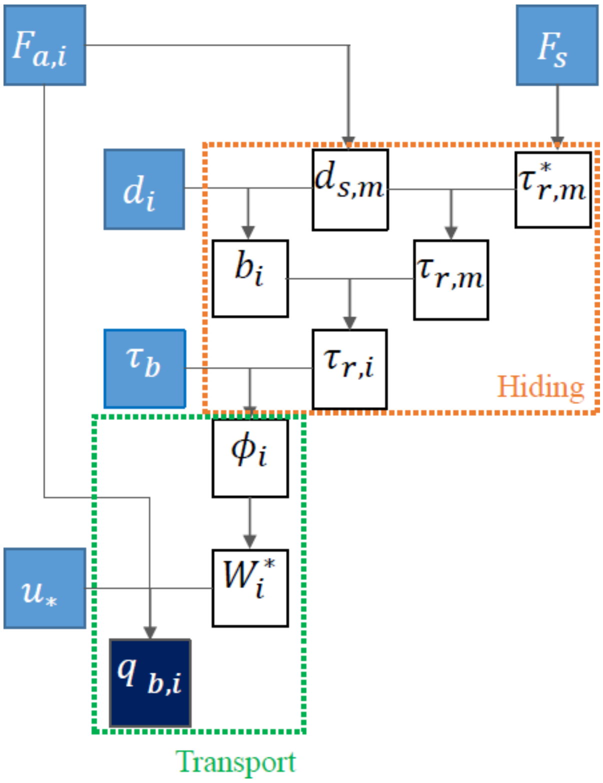


Figure 3.1: Scheme of application of the graded sediment transport model of WC-2003. Parameters in blue boxes are input parameters, those in white boxes are intermediary variables computed to estimate the transport rate of size fraction i in the black box.

Further details on the WC-2003 formula and applications can be found in [9, 11].

Engelund-Hansen

- `BED-LOAD TRANSPORT FORMULA FOR ALL SANDS = 30`
- The dimensionless current-induced sediment transport rate is given by:

$$\Phi_b = 0.05\frac{\theta^{\frac{5}{2}}}{c_f}$$

with c_f the adimensional friction coefficient and θ the Shields number without the correction factor for skin friction ($\theta = \frac{\tau_b}{(\rho_s-\rho)gd}$).

- Fortran subroutine `bedload_engel_gaia.f`.

An exhaustive revision of some common bedload transport formulas and associated information presented in chronological order of development can be found in Table D-2 of [19].

3.1.3 Modification of the magnitude and direction of bedload

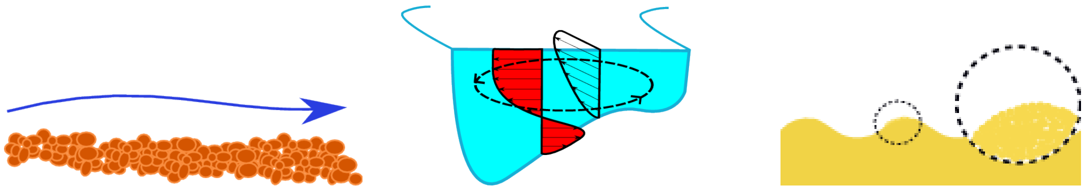
Three key aspects must be considered for computing the magnitude and direction of the bed load [2]:

(a) The effect of the local bed slope

(b) Secondary flow effects on the direction of the bed shear stress, also refered as to helical flows in the literature

(c) The bed shear stress partitioning into components affected by skin friction and drag force from bedforms

GAIA includes methods for evaluating these three aspects.



(a) (b) (c)

3.1.4 Correction of the direction of the sediment transport

The angle α is the angle between the sediment transport direction and the $x-$axis direction will deviate from that of the shear stress by combined action of a transverse slope and secondary currents. In a Cartesian coordinate system, the relation of van Bendegon is:

$$\tan\alpha = \frac{\sin\delta - \frac{1}{f(\theta)}\frac{\partial z_b}{\partial y}}{\cos\delta - \frac{1}{f(\theta)}\frac{\partial z_b}{\partial x}}. \tag{3.8}$$

Above, the terms $\partial z_b/\partial x$ and $\partial z_b/\partial y$ represent respectively the transverse and longitudinal slopes, z_b the bottom position and δ the angle between the sediment transport vector and the flow direction, modified by spiral flow. The sediment shape function $f(\theta)$ is a function weighting the influence of the transverse bed slope, expressed as a function of the non-dimensional shear stress or Shields parameter θ. It can be computed according to:

- Koch and Flokstra [17]:

$$f(\theta) = \frac{3}{2\theta}$$

- Talmon *et al.* [3]:

$$f(\theta) = \beta_2\sqrt{\theta}$$

where β_2 is an empirical coefficient. The default value is $\beta_2 = 0.85$, but an optimal value of $\beta_2 = 1.6$ was found for the calibration of numerical experiments of dunes and bars in a laboratory channel [1].

3.1.5 Correction by secondary flow effects on the direction of the bed shear stress

In curved channels, the direction of the sediment transport will no longer coincides with the direction of the bed shear stress, due to the effect of the secondary flows:

$$\delta = \tan^{-1}\left(\frac{v}{u}\right) - \tan^{-1}\left(\frac{A}{r_s}h\right) = \delta^* - \Delta\delta, \tag{3.9}$$

with h the water depth, (u,v) the components of the depth-averaged velocity field, r_s the local radius of curvature and A the spiral flow coefficient. Above, the term highlighted in red accounts for the effect of the spiral motion on the sediment flux. The angles δ^* and $\Delta\delta$ indicate respectively the direction of the bed shear stress (which coincides with the direction of the depth-averaged velocity) and the direction due to the effect of secondary currents.
In GAIA $A = 7^*$ (Engelund's value). Nevertheless, an optimal value of $A = 12$ was found for the calibration of numerical experiments of dunes and bars in a laboratory channel [1].

3.1.6 Correction of the magnitude of the sediment transport

The correction of the magnitude of the sediment transport proposed by Koch and Flokstra [17] is based on the modification of the bed load transport rate by a factor that acts as a diffusion term in the bed evolution equation:

$$\begin{aligned} Q_b^* &= Q_b\left(1+\beta\frac{\partial z_b}{\partial s}\right) \\ &= Q_b\left[1+\beta\left(\frac{\partial z_b}{\partial x}\cos\alpha+\frac{\partial z_b}{\partial y}\sin\alpha\right)\right], \end{aligned} \tag{3.10}$$

where s is the flow direction and β is an empirical factor accounting for the streamwise bed slope effect ($= 1.3$ by default).
The correction proposed by Soulsby [39] is based on the modification of the critical Shields parameter and is therefore only valid for threshold bedload formulas:

$$\frac{\theta_{\beta cr}}{\theta_{cr}} = \frac{\cos\psi\sin\chi + \sqrt{\cos^2\chi\tan^2\phi - \sin^2\psi\sin^2\chi}}{\tan\phi}$$

where $\theta_{\beta cr}$ is the corrected critical Shields number for a sloping bed, θ_{cr} is the critical Shields number for a flat, horizontal bed, ϕ is the angle of repose of the sediment, χ is the bed slope angle with the horizontal, and ψ is the angle between the flow and the bed slope directions.

3.1.7 Keywords for the modification of the intensity and direction of bed load

The keyword `SLOPE EFFECT` (logical type variable, set to = `YES` by default) activates the bed slope effects. If `SLOPE EFFECT = NO`, the keywords `FORMULA FOR DEVIATION` and `FORMULA FOR SLOPE EFFECT` are not taken into account.

Correction of the direction of bedload transport

The correction of the direction of bedload transport can be done by either the Koch and Flokstra formulation `FORMULA FOR DEVIATION = 1` (integer type variable, set to = `1` by default) or the Talmon et al. formulation `FORMULA FOR DEVIATION = 2`. For the latter, an associated keyword is available `PARAMETER FOR DEVIATION` (real type variable named `BETA2`, set to = `0.85` by default).

Correction of the intensity of bedload transport rate

The correction of the intensity of bedload transport rate can be done by either:

- the Koch and Flokstra formulation `FORMULA FOR SLOPE EFFECT` (integer type variable, set to = `1` by default). This keyword has the associated keyword `BETA` (real type variable, set to = `1.30` by default)
- the Soulsby formulation `FORMULA FOR SLOPE EFFECT = 2`. This keyword has the associated keyword `FRICTION ANGLE OF THE SEDIMENT` (real type variable, set to = `40.` by default).

The keyword `SECONDARY CURRENTS` (logical type variable, set to = `NO` by default) accounts for the secondary flow correction. This keyword has the associated keyword `SECONDARY CURRENTS ALPHA COEFFICIENT` (real type variable, set to = `1.` by default) that allows the modification of the coefficient A in Equation 3.9. This value can be chosen as: $\rightarrow 0.75$ (rough bottom) $\leq \alpha_{SC} \leq 1.0$ (smooth bottom). For example, if $\alpha_{SC} = 1$ then $A = 7$.

3.1.8 Influence of the roughness on sediment transport processes

Skin friction correction

The total bed shear stress is due to skin friction and bed form drag but **only the component due to skin friction acts on bedload**. The shear stress due to skin friction is expressed as:

$$\tau' = \mu \tau_b, \tag{3.11}$$

where $\tau_b = 0.5\rho C_f (U^2 + V^2)$ is the total bed shear stress and μ is the friction factor:

$$\mu = \frac{C'_f}{C_f} \tag{3.12}$$

where C_f is the friction coefficient due to form drag plus skin friction (specified in the hydrodynamics module), and C'_f is the friction coefficient due only to skin friction, which is computed as:

$$C'_f = 2\left(\frac{\kappa}{\log(12h/k'_s)}\right)^2, \tag{3.13}$$

where κ is the von Kármán coefficient $(= 0.40)$, the roughness height $k'_s = \alpha_{k_s} d_{50}$, the coefficient α_{k_s} is a calibration parameter.

Keywords for skin friction correction

The keyword `SKIN FRICTION CORRECTION` (integer type variable, = `1` by default) activates the correction of the bed shear stress due to skin friction:

- If `SKIN FRICTION CORRECTION = 0`, then $\mu = 1$ and the total bed shear stress issued from the hydrodynamics computation is used
- If `SKIN FRICTION CORRECTION = 1`, μ is computed according to Equation 3.12. In this case, the friction coefficient C_f is provided by the hydrodynamics steering file and C'_f is computed by Equation 3.13. To compute $k'_s = \alpha_{k_s} d_{50}$, the coefficient α_{k_s} can be modified with the keyword `RATIO BETWEEN SKIN FRICTION AND MEAN DIAMETER` (real type variable, = `3.` by default). In the numerical experiments of Mendoza *et al.* [1], $\alpha_{k_s} = 37$ for dunes and $\alpha_{k_s} = 3.6$ for bars.

> **Note:**
> By default, the keyword `SKIN FRICTION CORRECTION = 1`. In the presence of very shallow waters, this correction can present stability issues. For this case, we suggest the user to set the keyword `SKIN FRICTION CORRECTION = 0`.

- If `SKIN FRICTION CORRECTION = 2`, the presence of ripples is taken into account to compute μ (see subroutine `tob_gaia.f`). For this option, a bedform predictor is used to calculate the bedform roughness k_r in order to account for the effect of ripples. Both k_r and k'_s should influence the transport rates. It is assumed that:

$$\mu = \frac{C_f'^{0.75} C_r^{0.25}}{C_f}, \tag{3.14}$$

where the quadratic friction C_r due to bedforms is calculated as a function of k_r (see § 3.1.9).

3.1.9 Bed roughness predictor

A natural sediment bed is generally covered with bedforms, with length λ_d (m) and height η_d (m). The presence of bed forms greatly modifies the boundary layer flow structure, with the formation of recirculation cells and depressions in the lee of bedforms.

Depending on the flow and sediment transport rates, the size of bed forms ranges from a few centimeters for ripples to a few tens of meter for mega-ripples. The dimension of dunes scales with the water depth h, such that $\eta_d \approx 0.4h$ and $\lambda_d \approx [6-10]h$.

In most cases, large scale models do not resolve the small to medium scale bedforms (such as ripples or mega-ripples) which need therefore to be parameterized by increasing the friction coefficient. To determine bed roughness, there are two options available in GAIA:

- By imposing the friction coefficient based on friction laws: in this case the values of the friction coefficients are provided by TELEMAC-2D or TELEMAC-3D.

- By predicting the value of the bed roughness as a function of flow and sediment parameters using a bed roughness predictor. This option is discussed below.

Different options are programmed in GAIA to predict the total bed roughness through the associated keywords `COMPUTE BED ROUGHNESS AT SEDIMENT SCALE` (logical type variable, set to `= NO` by default) and `BED ROUGHNESS PREDICTOR OPTION`. It is recalled that the bed friction option of GAIA is not used in the case of internal coupling with TELEMAC-2D or TELEMAC-3D.

- For `BED ROUGHNESS PREDICTOR OPTION = 1`: the bed is assumed to be flat $k_s = k'_s = \alpha_{k_s} d_{50}$, with α_{k_s} a constant (assumed to be equal to 3.), modified by the keyword `RATIO BETWEEN SKIN FRICTION AND MEAN DIAMETER`.

- `BED ROUGHNESS PREDICTOR OPTION = 2`: the bed is assumed to be covered by ripples.

  - For currents only, the ripple bed roughness is function of the mobility number, see [50]:

$$k_r = \begin{cases} d_{50}(85 - 65\tanh(0.015(\Psi - 150))) & \text{for } \Psi < 250 \\ 20 d_{50} & \text{otherwise} \end{cases}$$

    with $\Psi = U^2/(s-1)gd_{50}$.

– For waves and combined waves and currents, bedform dimensions are calculated as a function of wave parameters following the method of Wiberg and Harris [37]. The wave-induced bedform bed roughness k_r is calculated as a function of the wave-induced bedform height η_r:

$$k_r = \max(k_s', \eta_r). \tag{3.15}$$

Then $k_s = k_s' + k_r$.

- `BED ROUGHNESS PREDICTOR OPTION = 3`: for currents only, the van Rijn's total bed roughness predictor [34, 50] has been implemented. The total bed roughness can be decomposed into a grain roughness k_s', a small-scale ripple roughness k_r, a mega-ripple component k_{mr}, and a dune roughness k_d:

$$k_s = k_s' + \sqrt{k_r^2 + k_{mr}^2 + k_d^2}. \tag{3.16}$$

Both small scale ripples and grain roughness have an influence on the sediment transport laws, while the mega-ripples and dune roughness only contribute to the hydrodynamic model (total friction). In Equation 3.16, the general expression for megaripples roughness k_{mr} is given by:

$$k_{mr} = 0.00002\, f_{ts}\, h\, (1 - \exp^{-0.05\Psi})\, (550 - \Psi), \tag{3.17}$$

with

$$f_{ts} = \begin{cases} d_{50}/(1.5 d_{sand}) & \text{for } d_{50} \leq 1.5 d_{sand} \\ 1.0 & \text{otherwise} \end{cases}$$

and the general expression for dune roughness $k_d = 0.00008\, f_{ts}\, h\, (1 - \exp^{-0.02\Psi})\, (600 - \Psi)$.

3.1.10 Boundary conditions for bedload

The specification of boundary conditions is done in a boundary condition file, usually named with extension `*.cli`. The reader is referred to §6.1.2 for the definition of the different flags used in the boundary condition file.

Wall boundary conditions

At banks and islands, the bedload transport rate is set to zero. For this case, the flag `LIEBOR` is set = `2` as shown in the example below:

```
2 2 2 0.0 0.0 0.0 0.0 2 0.0 0.0 0.0 565 1
```

3.1.11 Inflow boundary conditions

In a depth-averaged 2D sediment transport model, the sediment discharge must be given at each point of the inflow boundary. The different cases can be present:

Equilibrium sediment discharge

For this case, the flag `LIEBOR` is set = `5` and the flag `EBOR` is set = `0.0` (no bottom change at the inflow boundary) as shown in the example below:

```
4 5 5 0.0 0.0 0.0 0.0 5 0.0 0.0 0.0 565 1
```

Constant sediment discharge

For this case, boundary condition files are needed for both TELEMAC-2D and GAIA. In the GAIA's boundary condition file, the flag `LIQBOR = 5` and `LIEBOR = 4`. The imposed solid discharge can be specified as follows:

- A value of the unit solid discharge [kg/(m s)] in the column `Q2BOR` of the GAIA's boundary condition file, as shown in the example below for an imposed unit discharge `Q2BOR`=1.0 kg/(m s):

```
4 5 5 1.0 0.0 0.0 0.0 4 0.0 0.0 0.0 565 1
```

  Particular cases of `Q2BOR` can be programmed in the subroutine `conlit_gaia.f`.

- A value of the total solid discharge (without pores) [kg/s] given through the keyword `PRESCRIBED SOLID DISCHARGES` (sequence of real values separated by semi-colons, one value per liquid boundary, no default value) in the steering file, as shown in the example below for an imposed total discharge equal to 1.0 kg/s:

```
4 5 5 0.0 0.0 0.0 0.0 4 0.0 0.0 0.0 565 1
```

```
PRESCRIBED SOLID DISCHARGES : 1.0
```

Time-series of sediment discharge

Time-series values of sediment discharge are specified in a file through the keyword `LIQUID BOUNDARIES FILE` (character type), declared in the hydrodynamic steering file. The GAIA's boundary condition file must contain the flags as shown below:

```
4 5 5 0.0 0.0 0.0 0.0 4 0.0 0.0 0.0 565 1
```

The keyword `PRESCRIBED SOLID DISCHARGES` must be also included in the steering file, with an arbitrary value.

3.1.12 Outflow boundary conditions

At the outflow boundary, bedload does not require any particular boundary condition. For this case, the flag `LIEBOR` is set = `4` as shown in the example below:

```
5 4 4 0.0 0.0 0.0 0.0 4 0.0 0.0 0.0 565 1
```

Note:
When the keyword `PRESCRIBED SOLID DISCHARGES` is used, the mass balance provided in the listing printouts information accounts for the pores = $Q_b/(1-\lambda)$, with λ the porosity.

3.1.13 Useful graphical printouts for bedload

Through the keyword `VARIABLES FOR GRAPHIC PRINTOUTS`, some useful printouts for bedload sediment transport are listed below:

```
TOB="Bed shear stress(N/m2)";
MU ="Skin friction coefficient";
M="bed-load discharge (kg/(m*s)";
```

```
N="bed-load discharge along x axis (kg/(m*s))";
P="bed-load discharge along y axis (kg/(m*s))";
E="bottom evolution (m)";
QSBL="bed load transport rate (kg/(m*s))";
```

> Note:
> The sediment discharge is the mass of sedimentary material, both particulate and dissolved, that passes across a given flow-transverse cross section of a given flow in unit time. The flag `M` accounts for the total solid discharge (bedload plus suspended load), while `QSBL` accounts for the bed load solid discharge. If suspended load is not taken into account in the simulation, the output values of `M` and `QSBL` are equivalent.

3.1.14 Useful graphical printouts for continuing a computation

As for the module TELEMAC-2D, in GAIA it is possible to continue a computation, taking a time step of a previous computation, on the same mesh as initial state. As well as for the hydrodynamic part, it is necessary to declare two keywords in the steering file:

1. `COMPUTATION CONTINUED`, which must be set equal to YES

2. `PREVIOUS SEDIMENTOLOGICAL COMPUTATION FILE`, to give the name of the file that will supply the initial state.

When continuing a computation it is important that the previous sedimentological computation file contains the appropriate variables in order to properly continue the computation. Below some advices are introduced:

> Note:
>
> - the bottom (B) and the layer thickness (*ES) are mandatory
> - the non erodable bottom (R) is optional since when missing, it is computed using the layer thickness
> - the masses are mandatory to continue the computation, so:
>   - if the variables *S* (or *M*) are saved in the previous file, they will be directly taken for continuing computation
>   - if the previous file does not contain masses, they will be reconstructed using the ratios (*A*,*R*) and the porosity, as well as the thickness.

3.2 Bottom stratigraphy

For sand graded distributions, an algorithm based on the classical active layer formulation of Hirano is used [6]. The active layer supplies material that can be eroded or deposited as bedload or suspended load. Its thickness can be specified by the user or set by default to the value $3 \times d_{50}$, with d_{50} the median diameter of sediment material contained in the active layer.

The bed model can be discretized by a constant number of layers along the vertical direction. Since layers are allowed to be emptied, the utilized number of layers at each mesh node can vary during a numerical simulation. When more than one sediment class is specified in the steering file, the following cases arise: (*i*) for a given initial bed stratification (i.e. through a given number of layers N_{lay}), an active layer is added inside this stratification at the beginning of the simulation. In this case the total number of layers is $= N_{lay} + 1$; (*ii*) if the initial bed stratification is not provided, the sediment bed is thus subdivided in two layers: the active layer and a substrate layer located directly below. In this case, the total number of layers is $= 2$.

To maintain a constant active layer thickness throughout the numerical simulation, at each time step the following procedures are performed:

- In the case of erosion, the sediment mass is taken from the active layer, therefore the sediment flux is transferred from the substratum (first non-empty layer below the active layer) to the active layer. Note that the rigid bed algorithm is applied to the active layer, i.e. only the sediment mass in the active layer is available at the given time step. This is important as bedload transport rate and/or the rate of entrainment for suspension are computed using the sediment composition available in the active layer.

- If the erosion during the time step exceeds the sediment mass available in the top layer, this layer is fully eroded and a new erosion rate is computed using the composition of the layer underneath, that is now the surface layer.

- In the case of deposition, the increased thickness generates a sediment flux from the active layer to the first substratum layer.

The bed model algorithm introduced before has been modified to account for the presence of mud or sand-mud mixtures. Mixed sediment consists of a mixture of $N_{nco} \geq 1$ classes of non-cohesive sediment (sand and/or gravel) with $N_{co} \geq 1$ classes of fine, cohesive sediment. Non-cohesive sediments are assumed to be transported by bedload and/or suspension, while cohesive sediment is transported only by suspension.

In the algorithm for mixed sediments, the layer thickness results from the mass ratio of cohesive and non-cohesive sediment contained in each layer. If the cohesive sediment volume is $\leq 40\%$ of the non-cohesive sediment volume, the layer thickness only depends on the mass of non-cohesive sediment volume. Conversely, if the cohesive sediment volume is $\geq 40\%$ of the non-cohesive sediment volume, the layer thickness is computed from the non-cohesive sediment volume plus the cohesive sediment volume minus the interstitial volume between non-cohesive sediment classes.

The presence of high concentrations of cohesive sediment in the bed are known to prevent bedload transport from occurring [48]. Therefore, in GAIA, bedload transport is only computed if the mass fraction of cohesive sediment in the active layer is $\leq 30\%$. In this case, the non-cohesive sediment can still be transported in suspension. In addition, erosion of non-cohesive sediment by bedload transport causes cohesive sediment present in the mixture to be entrained into suspension.

3.2.1 Active layer model

The active layer is the surface layer, which supplies material that can be transported as bedload or suspended load and receives the deposited sediment material. Therefore the composition of the active layer is used to compute the rate of bedload transport and the rate of erosion in suspension for each sediment class, where decomposition of bedload transport and suspension transport in size-classes is presented. This composition is variable in space and time as it depends on the composition of the sediment deposited and/or eroded from this layer, as well as the exchange of mass with the substratum.
The active layer thickness depends on the flow and sediment characteristics. In GAIA, the active layer thickness is constant, with a target value set by the user. The active layer thickness can be internally modified during the simulation.
At the beginning of the computation, if there is more than one sediment class set in the steering file, the active layer is created automatically at the surface of the sediment bed.

- In the case where the user does not set any initial bed stratification (i.e. the initial bed material composition is set constant over the vertical direction), the sediment bed is subdivided in two layers: an "active" or "mixing" layer in contact with the water column, and a substrate layer located immediately below.
- In the case where the user does set an initial bed stratification (i.e. layers of different bed compositions, see chapter 6), then:
  - An active layer will be added inside this stratification at the beginning of the computation. Therefore, the actual number of layers will be equal to the number of layers for the initial stratification plus one.
  - If the first (surface) layer of the initial stratification is larger than the target active layer thickness, this surface layer is split in two sub-layers: the active layer plus a layer immediately below with a thickness equal to the first stratification layer thickness minus the active layer thickness. For this case, the initial composition of the active layer is assumed to be the same as the composition of the first layer.
  - If the first (surface) layer of the initial stratification is smaller than the target active layer thickness, the active layer is "merged" by the first layer, and also take from the stratification layer(s) underneath the remaining amount of sediment necessary to reach its target thickness. The initial composition of the active layer will thus be a mix of the sediment from the first and (partially) the second stratification layers.

If during a simulation, the thickness of sediment available in the bed is smaller than the target active layer thickness, the actual active layer thickness for this node will be equal to the sediment thickness. All sediment in the bed will thus be mixed in the active layer. The target active layer thickness is thus only respected if there is enough available sediment. This enables smooth implementation of the rigid bed algorithm also for the case of the active layer model. This point is also important as it enables the user to "force" a full mixing of sediment composition over the whole sediment thickness by imposing a very large target active layer thickness (see chapter 6). At each time-step, the substratum exchanges material with the active layer in order to keep the active layer at a target thickness:

- In the case of erosion, mass is taken from the active layer to be sent in suspension, or to the active layer of neighbouring nodes (through bedload). Therefore, to keep active layer thickness at a target value, the sediment mass has to be transferred from the substratum (first non-empty layer below the active layer plus layers underneath if necessary) and incorporated into the active layer. The mass transferred has the composition of the substratum: this correction flux does not change the composition of the substratum but might change the composition of the active layer. Note that the rigid bed algorithm is applied to the active layer, i.e. only the mass of sediment in the active layer is available for erosion during a given time-step. Therefore the amount of erosion during a time-step should not exceed the amount of mass in the active-layer (this is important for physical coherence as the bedload transport rate as well as the rate of erosion in suspension are computed using the composition of the active layer).

- In the case of deposition, mass is added to the active layer. Therefore a flux of sediment mass has to be taken from the active layer and added to the substratum (first non-empty layer below the active layer). The mass transferred has the composition of the active layer: this correction flux does not change the composition of the active layer but might change the composition of the substratum. No bookkeeping of the composition of deposits, that is the creation of new layers of substratum to discretize the deposits, has been implemented for the current version of GAIA.

The active layer model is automatically selected when there are at least two size-classes of sediment (set by the dimension of keyword `CLASSES TYPE OF SEDIMENT`). By default, the composition of the sediment mixture is constant over the computational domain and set by keyword `CLASSES INITIAL FRACTION`. The target active layer thickness is set by the keyword `ACTIVE LAYER THICKNESS`.
The user might wish not to use the active layer model, and thus to mix the sediment composition on the sediment bed, resulting in one sediment layer. For this case, the user can set a target active layer thickness value larger than the maximum sediment layer thickness. Note that this is the default case, since the default value for keyword `ACTIVE LAYER THICKNESS` is equal to 10,000 m, while the default value for sediment thickness is equal to 100 m (as hard-coded in `lecdon_gaia`). This value can be modified with the keyword `LAYERS INITIAL THICKNESS`).
To set a variable bed composition along the vertical direction, the keyword `NUMBER OF LAYERS FOR INITIAL STRATIFICATION` can be used.
Layers thicknesses and compositions must be set using the variables `ESTRATUM(ISTRAT,IPOIN)` and `RATIO_INIT(ICLA,ISTRAT,IPOIN)`. The same user subroutine must be used to set spatially-dependent bed compositions.

Mixed sediment

Mixed sediment is defined as the mixture of `Nnco` classes ($Nnco \geq 1$) of non-cohesive sediment (e.g. sand and/or gravel) and `Nco` classes ($Nnco \geq 1$) of fine, cohesive sediment (e.g. mud). The non-cohesive sediment is transported by bedload and/or suspension, and the cohesive sediment is transported only by suspension. The bed model is a generalization of the active-layer bed model implemented for non-cohesive sediment, as follows:

1. The composition of the surface layer (the active layer) of the bed sediment mixture is considered for computing the critical shear stress for erosion, the bedload transport rate, and the erosion rate in suspension.

2. Each layer's thickness, and thus the resulting bed elevation at the end of each time step, is computed from the mass of non-cohesive sediment and cohesive sediment using the following hypothesis:

    - If the cohesive sediment volume is smaller than 40% of the non-cohesive sediment volume, the layer thickness is only function of non-cohesive sediment mass.

- If the cohesive sediment volume is larger than 40% of the non-cohesive sediment volume, the layer thickness is computed from non-cohesive sediment volume plus cohesive sediment volume minus interstitial volume between non-cohesive sediment grain sizes.

3. For several cohesive sediment classes in the mixture, it is assumed that each sediment class has its own settling velocity value.

Following [30], the critical shear stress for a mass cohesive sediment fraction of the mixture is computed as follows.

If the mass cohesive sediment fraction of the mixture is:

- $> 50\%$, its value is equal to the critical shear stress of the cohesive sediment fraction (that depends on cohesive sediment concentration)
- $< 30\%$, its value is equal to the critical shear stress of the non-cohesive sediment fraction, with a correction that increases the critical shear stress to account for the cohesive sediment fraction
- in the range $[30-50]\%$, its value is computed by linear interpolation of values computed from the two previous cases.

If the erosion rate for a mass cohesive sediment fraction of the mixture is:

- $> 50\%$, its value is equal to the erosion rate for cohesive sediment fraction
- $< 30\%$, its value is equal to the erosion rate computed for the non-cohesive sediment fraction
- in the range $[30-50]\%$, its value is computed by linear interpolation of values computed from the two previous cases.

Bedload

Bedload transport is computed only if mass cohesive sediment fraction in the active layer is lower than 30%. Otherwise, non-cohesive sediment can still be transported in suspension. Erosion of non-cohesive sediment through bedload causes cohesive sediment present in the mixture to be entrained in suspension. As for deposit from suspension, deposit of non-cohesive sediment caused by bedload is added to the third layer of the consolidation bed model (corresponding to a sediment concentration equal to 100 g/l).

3.3 Consolidation processes

For the current version of GAIA, consolidation processes are based on the semi-empirical formulation originally developed by Villaret and Walther [51], which uses the iso-pycnal and first-order kinetics formulations. Consolidation of mud deposits is modeled using a layer discretization, where the first layer corresponds to the freshest deposit, while the lower layer is the most consolidated layer. Sediment deposition from the water column is added directly to the first layer. A rate (or *flux*) of consolidation is computed for each layer and for each class of cohesive sediment separately. The values of the computed fluxes depend on the availability of each class in the layer considered.

Consolidation can be activated using the keyword `BED MODEL = 2` (integer type variable, set to `= 1` by default).

3.3.1 Associated keywords for consolidation models

- Multilayer model (`BED MODEL = 2`)

  - `LAYER MASS TRANSFER` (real list, set to `= 5.D-05;4.5D-05;...` by default) provides the mass transfert coefficients of the multilayer consolidation model (in s^{-1})

Further information about both models can be found in [5].

The parameters per layer of the consolidation (cohesive sediment concentration, critical erosion shear stress, and rate of mass transfer to the layer underneath) model are set using the following keywords respectively: `LAYERS MUD CONCENTRATION`, `LAYERS CRITICAL EROSION SHEAR STRESS OF THE MUD`, `LAYERS PARTHENIADES CONSTANT` and `LAYERS MASS TRANSFER`.

Consolidation fluxes

The transfer of mass of sediment from one layer (`ILAYER`) to the more consolidated layer (`ILAYER+1`) below is computed according to the following law:

$$\frac{dM(ILAYER)}{dt} = TRANS\_MASS(ILAYER) \times M(ILAYER) \tag{3.18}$$

With M mass of sediment in the layer (kg/m^2) and $TRANS\_MASS$ the rate of mass transfer (s^{-1}). This proposed law to model consolidation could of course be adapted or changed by the user inside subroutine `bed1_consolidation_layer.f`

3.4 Bed evolution

In GAIA, the bed evolution is computed by solving the mass conservation equation for sediment or *Exner equation*, expressed in terms of mass (see 3.1), where bedload, suspension or both sediment transport modes can be considered simultaneously. In its simplest form (only bedload, one sediment class) this equation reads:

$$(1-\lambda)\frac{\partial(\rho\, z_b)}{\partial t} + \nabla\cdot\mathbf{Q}_{mb} = 0 \tag{3.19}$$

with $\mathbf{Q}_{mb}$ is the vector of mass transport rate per unit width without pores (kg/(m s)), λ is the sediment porosity (keyword `LAYERS NON COHESIVE BED POROSITY` with default value equal to 0.4 per layer, and z_b the bed elevation above datum. In GAIA, two different morphological accelerators are proposed: (*i*) a morphological factor on the hydrodynamics, which distorts the evolution of the hydrodynamics with respect to the morphodynamics; and (*ii*) a morphological factor on the bed, which distorts the evolution of the morphodynamics with respect to the hydrodynamics. The first option is suitable for river applications accounting for bedload transport whereas the second option is suitable for coastal and estuarine applications as it is compatible with suspended sediment transport processes.
The solution of the conservative law equation for sediment mass (or Exner equation) can be written with respect to the bottom elevation, as follows:

$$(1-\lambda)\frac{\partial z_b}{\partial t} + \nabla\cdot\mathbf{Q}_b = 0 \tag{3.20}$$

with $\mathbf{Q}_b$ the vector of volumetric transport rate per unit width without pores (m^2/s), with components Q_{b_x}, Q_{b_y} in the x and y direction respectively, z_b is the bottom elevation (m) and λ the bed porosity. The bedload transport vector can be decomposed into $x-$ and $y-$direction components as:

$$\mathbf{Q}_b = (Q_{b_x}, Q_{b_y}) = (Q_b\cos\alpha, Q_b\sin\alpha). \tag{3.21}$$

Above, Q_b is the bedload transport rate per unit width, computed as a function of the equilibrium sediment load closure (or sediment transport capacity) and α is the angle between the sediment transport vector and the downstream direction ($x-$axis). The deviation of the bed load direction from the flow direction is mainly influenced by the bed slope and the presence of secondary flows [3], see Section 3.1.3.
GAIA does not solve equation (3.20) but solves the Exner equation which has mass as main variable. The equation is obtained writing the conservative law equation for sediment and integrating along the vertical, keeping density in the equation:

$$(1-\lambda)\frac{\partial\,(\rho z_b)}{\partial t} + \nabla\cdot(\mathbf{Q}_{mb} z_b) = 0 \tag{3.22}$$

where $\mathbf{Q}_{mb} = \rho\mathbf{Q}_b$ is the vector of mass transport rate per unit width without pores (kg/(m s)).

3.4.1 Numerical treatments for the Exner equation

The Exner equation can be solved in GAIA using a finite element or a finite volume scheme. A property which needs to be satisfied is the layer thickness positivity or the rigid bed condition.
When using the finite element scheme (default option), the equation is solved using the subroutine `positive_depths` and in particular the `NERD` algorithm (`positive_depths_nerd`).
This is also one of the scheme used to preserve the water depth positivity when solving the shallow water equations.

To use finite volumes, the following keyword must be activated in the GAIA's steering file: `FINITE VOLUMES = YES`. Then the scheme will be by default a centred one but an upwind scheme can be chosen setting `UPWINDING FOR BEDLOAD = 1`.

4. Sediment Exchanges at the Water-Bed Interface

The unified framework proposed for sediment transport processes in 2D and 3D eliminates unnecessary code duplication. Within this new code structure, the dimensionless entrainment rate of bed sediment into suspension per unit bed area per unit time E is computed by the same subroutine for both 2D and 3D dimensions. As in SISYPHE, for non-cohesive and cohesive sediments the dimensionless entrainment and deposition rates are computed for each sediment class following the formulae of [55] and [28, 36], respectively.

4.1 Non-cohesive sediment

The non-cohesive deposition rate is $D = w_s C_{z_{ref}}$, where w_s is the settling velocity and $C_{z_{ref}}$ is the near-bed concentration, evaluated at the interface between the bed load and the suspended load, $z = z_{ref}$.

In 2D cases, the near-bed concentration is computed assuming a Rouse profile for the vertical concentration distribution, which is theoretically valid in uniform steady flow conditions:

$$C(z) = C_{z_{ref}} \left(\frac{z-h}{z} \frac{a}{a-h} \right)^R, \tag{4.1}$$

where R is the Rouse number defined by

$$R = \frac{w_s}{\kappa u_*}, \tag{4.2}$$

with κ the von Karman constant ($\kappa = 0.4$), u_* the friction velocity corresponding to the total bed shear stress, and a the reference elevation above the bed elevation. The distance a, defined variously by various authors, is taken to be very close to the bed.
By depth-integration of the Rouse profile (4.3), the following relation can be established between the depth-averaged concentration and the reference concentration (near-bed concentration):

$$C_{z_{ref}} = FC,$$

where:

$$F^{-1} = \left(\frac{z_{ref}}{h} \right)^R \int_{z_{ref}/h}^{1} \left(\frac{1-u}{u} \right)^R du. \tag{4.3}$$

In GAIA, the following expression is used to compute F:

$$F^{-1} = \begin{cases} \frac{1}{(1-Z)} B^R \left(1 - B^{(1-R)}\right) & \text{if} R \neq 1 \\ -B \log B & \text{if} R = 1 \end{cases}$$

with $B = z_{ref}/h$.
The non-cohesive erosion rate is $E = w_s C_{eq}$, where C_{eq} is the equilibrium near-bed concentration determined by using an empirical formula.
For non-cohesive sediments, the net sediment flux $E - D$ is therefore determined based on the concept of equilibrium concentration, see [23]:

$$(E - D)_{z_{ref}} = w_s \left(C_{eq} - C_{z_{ref}}\right). \tag{4.4}$$

4.1.1 Available equilibrium near-bed concentration formulas

Zyserman-Fredsoe

- The Zyserman-Fredsoe formula [25] `SUSPENSION TRANSPORT FORMULA FOR ALL SANDS = 1`
$$C_{eq} = \frac{0.331(\theta' - \theta_{cr})^{1.75}}{1 + 0.72(\theta' - \theta_{cr})^{1.75}},$$
where θ_{cr} is the critical Shields parameter and $\theta' = \mu\theta$ the shear stress due to skin friction (see §3.1.8).

- The reference elevation $z_{ref} = \alpha_{k_s} \times d_{50}$ ($= 3.0 \times d_{50}$ by default, α_{k_s} can be modified with the keyword `RATIO BETWEEN SKIN FRICTION AND MEAN DIAMETER`)

- Fortran subroutine `suspension_fredsoe_gaia.f`.

Bijker

- Bijker formula `SUSPENSION TRANSPORT FORMULA = 2`

- This formula is related to the bedload sediment transport Q_b, therefore this option cannot be used without activating the bedload transport mechanism `BED LOAD FOR ALL SANDS = YES`
$$C_{eq} = \frac{Q_b}{b\, z_{ref}\, u_*}$$
with b a constant ($= 6.34$) and u_* the shear velocity

- The reference elevation $z_{ref} = k_{sr}$, with k_{sr} the rippled bed roughness

- Fortran subroutine `suspension_bijker_gaia.f`.

van Rijn

- van Rijn formula [49] `SUSPENSION TRANSPORT FORMULA = 3`
$$C_{eq} = 0.015\, d_{50} \frac{(\theta'/\theta_{cr} - 1)^{3/2}}{z_{ref} D_*^{0.3}}$$
with θ_{cr} the critical Shields parameter and and $\theta' = \mu\theta$ the shear stress due to skin friction.

- The reference elevation $z_{ref} = 0.5 \times k_s$, with k_s the total roughness (from the hydrodynamics steering file)

- Fortran subroutine `suspension_vanrijn_gaia.f`.

Soulsby & van Rijn

- Soulsby and van Rijn formula [39] `SUSPENSION TRANSPORT FORMULA = 4`

$$C_{eq} = \begin{cases} A_{ss}\left(\sqrt{U_c^2 + \frac{0.018}{C_D}U_w^2} - U_{cr}\right)^{2.4} & \text{if} \geq U_{cr} \\ 0.0 & \text{otherwise} \end{cases}$$

with U_c the norm of the depth-averaged current velocity and U_w the wave orbital velocity (see Chapter 5.1). The threshold current velocity U_{cr} is computed as:

$$U_{cr} = \begin{cases} 0.19(d_{50}^{0.1})\log_{10}\left(\frac{4.0h}{d_{90}}\right) & \text{if}\, d_{50} < 0.0005 \text{ m} \\ 8.5(d_{50}^{0.6})\log_{10}\left(\frac{4.0h}{d_{90}}\right) & \text{otherwise} \end{cases}$$

with d_{90} the particle diameter representing the 90% cummulative percentile value (90% of the particles in the sediment sample are finer than the d_{90} grain size), in meters.

If wave effects are considered, the quadratic drag coefficient C_D is computed as follows:

$$C_D = \left(\frac{0.4}{\log(\max(h, z_0)/z_0 - 1)}\right)^2,$$

with $z_0 = 0.006$ m the bed roughness.

The empirical suspended transport factor A_{ss} is computed by:

$$A_{ss} = \frac{0.012hd_{50}\left(\left(\frac{g(s-1)}{\nu^2}\right)^{1/3} d_{50}\right)^{-0.6}}{((s-1)gd_{50})^{1.2}}$$

- Fortran subroutine `suspension_sandflow_gaia.f`.

4.2 Cohesive and mixed sediment

If different classes of cohesive sediment are present, deposition fluxes are computed for each sediment class according to its settling velocity. Conversely, as cohesive sediments have the same mechanical behaviour when they are in the bed, the same value of critical shear stress is used for all classes. Nevertheless, since the computation of erosion sediment fluxes accounts for the availability of each class, the computed values of erosion fluxes can be different for each sediment class.

In GAIA, the default value of the critical shear stress for deposition is set to 1000 N/m^2. It implies that sediment deposition takes place at all times regardless of the value of the bottom shear stress.

The erosion flux is computed with the Partheniades formula:

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

with M the Krone-Partheniades erosion law constant [kg/m^2/s] and τ_{ce} the critical bed shear stress.

The deposition flux for mud is computed by the expression:

$$D = w_s C\left[1 - \left(\frac{\sqrt{\tau_b/\rho}}{u_{*mud}^{cr}}\right)^2\right], \tag{4.5}$$

where u_{*mud}^{cr} is the critical shear velocity for mud deposition.

Erosion flux

The erosion flux is computed with the Partheniades formula. For uniform beds, the erosion flux is related to the excess of applied bed shear stress to the bed shear strength at the bed surface:

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

where M the Krone-Partheniades erosion law constant [kg/m^2/s] is provided by the keyword `LAYERS PARTHENIADES CONSTANT` (real type, set to `= 1.E-03` by default).
The value of τ_{ce} can be provided for the different layers with the keyword `LAYERS CRITICAL EROSION SHEAR STRESS OF THE MUD` (real list, set to `= 0.01;0.02;0.03;...` by default), expressed in N/m^2.
The composition of the sediment mixture in the surface (active) layer is taken into consideration when computing the critical shear stress for erosion and the erosion rate. This is achieved by combining the critical shear stresses for erosion for all the sediment classes (cohesive and non-cohesive), according to [30]:

- If the mass of cohesive sediment as a fraction of the mixture is $\geq 50\%$, then the erosion rate and critical shear stress for cohesive sediment alone is used.
- If the mass of cohesive sediment as a fraction of the mixture is $\leq 30\%$, then the erosion rate for non-cohesive sediment is used and the critical shear stress for non-cohesive sediment is used with a correction.
- If the mass of cohesive sediment as fraction of the mixture is $\geq 30\%$ and $\leq 50\%$, then the values are interpolated between the previous values.

The total erosion rate is then distributed among the non-cohesive and cohesive sediment according to their respective fractions in the mixture.

Deposition flux

The deposition flux for mud is computed by the expression:

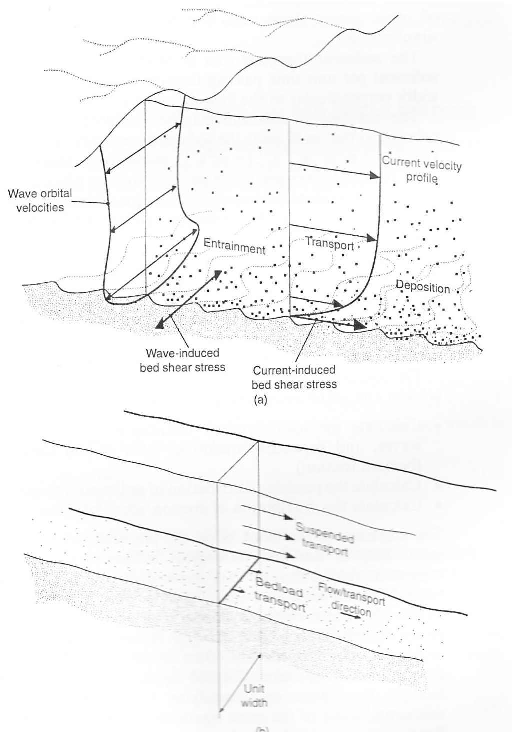
$$D = w_s C \left[1 - \left(\frac{\sqrt{\tau_b/\rho}}{u^{cr}_{*mud}}\right)^2\right], \tag{4.6}$$

where u^{cr}_{*mud} is the critical shear velocity for mud deposition, expressed in [m/s] and computed as $\sqrt{\tau_{d,mud}/\rho}$ with $\tau_{d,mud}$ provided by the keyword `CLASSES CRITICAL SHEAR STRESS FOR MUD DEPOSITION` (real type, set to `= 1000.` N/m^2 by default).
For the evaluation of the settling velocity w_s, if the keyword `CLASSES SETTLING VELOCITIES` is not included in the steering file, GAIA computes the settling velocity for each sediment class by the Stokes, Zanke or van Rijn formulae depending on the grain size. The same result is found by providing the keyword and its corresponding value as `CLASSES SETTLING VELOCITIES = -9`. Further details can be found in the subroutine `settling_vel.f`.
By default, the flux of non-cohesive sediment deposits from the water column is added to the first layer of the consolidation bed model. It can alternatively be considered to immediately settle through the fresh cohesive sediment and thus be added to a given layer (of a given concentration) chosen by the user.

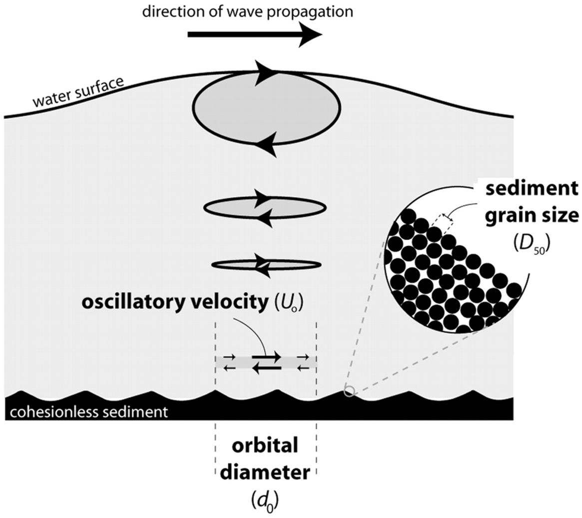
5. Additional Physical Processes

5.1 Influence of waves on sediment transport processes

In coastal zones, the effect of waves superimposed to a mean current (wave-induced or tidal) can have an impact on the behaviour of the seabed. Due to the reduced thickness of the bed boundary layer, the bottom shear stress increases largely and the resulting sand transport rate could be in many cases of one order of magnitude than in the case of currents alone.



Underneath the wave surface, there is a fluid motion associated with the motion of the water surface, where the fluid particles describe an orbital path.



As in SISYPHE, the bottom shear stress due to the effect of waves and by the combined action of currents and waves are computed according to [46] and [44], respectively.
In GAIA, the computation of the maximum wave orbital velocity U_w can be performed according to the waves characteristics: (*i*) regular (monochromatic) or (*ii*) irregular (JONSWAP spectrum) [45] cases. The latter method calculates the r.m.s. orbital velocity U_{rms} and then converts it to a monochromatic orbital velocity $U_w = \sqrt{2}U_{rms}$, as required by many sediment transport formulae.

5.1.1 Procedure for internal coupling waves-currents and sediment transport

The internal coupling between waves-currents and sediment transport is implemented in the TELEMAC-MASCARET SYSTEM, requiring the set of input files (steering file, geometry file, etc.) for the modules TELEMAC-2D, TOMAWAC and GAIA:

- TELEMAC-2D steering file:
  - The keyword `COUPLING WITH = 'TOMAWAC, GAIA'` activates the internal coupling with modules TOMAWAC and GAIA
  - The keyword `WAVE DRIVEN CURRENTS = YES` (real type, set to = `NO` by default) allows to incorporate the influence of *radiation stresses* in the mean flow (wave-induced currents), computed by the subroutine `radiat.f` (TOMAWAC).
- GAIA steering file:
  - The keyword `EFFECT OF WAVES` (logical type, set to = `NO` by default) is used to consider the effect of the waves on the solid transport formula
  - The keyword `BED-LOAD TRANSPORT FORMULA FOR ALL SANDS` (integer type variable, = `1` by default) allows to choose among the transport formulas that consider the combined effect of currents and waves:

```
4 : BIJKER
5 : SOULSBY - VAN RIJN
8 : BAILARD
9 : DIBAJNIA ET WATANABE
```

5.1.2 Time steps and coupling period considerations

We call $\Delta t_{T2D}, \Delta t_{GAI}, \Delta t_{TOM}$ respectively the time steps for hydrodynamics (computed by TELEMAC-2D), sediment transport (computed by GAIA) and waves (computed by TOMAWAC). We define $CP_{T2D-GAI}$ the coupling period for TELEMAC-2D and GAIA and $CP_{T2D-TOM}$ the coupling period for TELEMAC-2D and TOMAWAC. The morphological time step is $\rightarrow \Delta t_{T2D} \times CP_{T2D-GAI}$.

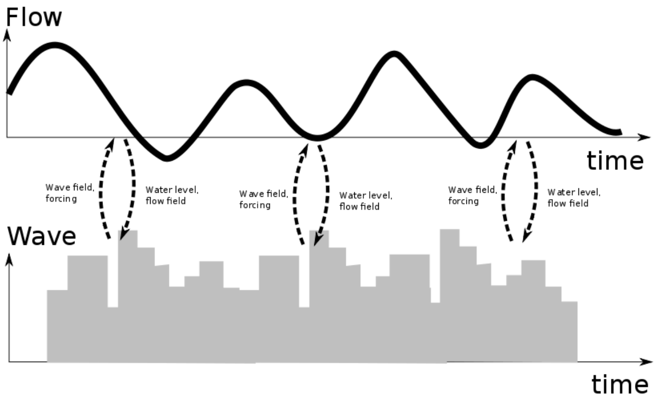
In the subroutine `wac.F` of TOMAWAC, the following restrictions are verified:

(1) Check for multiplicity between Δt_{TOM} and Δt_{T2D}:

$$\left| \| \frac{\Delta t^{\max}}{\Delta t^{\min}} \| - \frac{\Delta t^{\max}}{\Delta t^{\min}} \right| > \varepsilon$$

$\Delta t^{\max} = \max\left(\Delta t_{TOM}, \Delta t_{T2D} \times CP_{T2D-TOM}\right)$, $\Delta t^{\min} = \min\left(\Delta t_{TOM}, \Delta t_{T2D} \times CP_{T2D-TOM}\right)$, $\| \cdot \|$=`NINT(A)` rounds its argument to the nearest whole number

(2) Check $\Delta t_{TOM} \leq \Delta t_{T2D} \times CP_{T2D-TOM}$



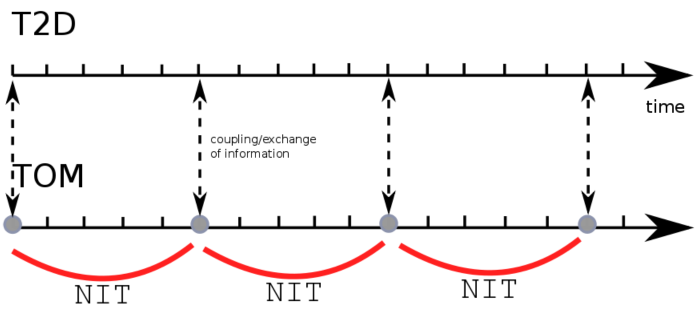


Figure 5.1: Example for $\Delta t_{T2D} = 1$ s, $\Delta t_{TOM} = 1$ s, $CP_{T2D-TOM} = 5$ ($NIT = \Delta t_{T2D} \times CP_{T2D-TOM}/\Delta t_{TOM}$)

5.1.3 Wave orbital velocity

The wave orbital velocity U_w is computed assuming the validity of the linear theory:

$$U_w = \frac{H_s \omega}{2\sinh(kh)},$$

where h is the water depth, $\omega = 2\pi/T_p$ is the intrinsic angular frequency, $k = 2\pi/L$ is the wave number, with L the wave length. The wave number is calculated from the dispersion relation:

$$\omega^2 = gk\tanh(kh).$$

This variable (`UWBM`) is computed by TOMAWAC in the subroutine `vitfon.f`.

5.1.4 Wave-induced bottom friction

The maximum stress due to waves is calculated at each time step as a function of the wave-orbital velocity U_w by use of a quadratic friction coefficient f_w due to waves:

$$\tau_w = \frac{1}{2}\rho f_w U_w^2.$$

The wave friction factor f_w is calculated as a function of relative density:

$$f_w = f_w\left(A_0/k_s\right),$$

where $A_0 = U_w/\omega$ is the semi-orbital excursion and k_s the bed roughness. In GAIA, the expression proposed by Swart [14] is implemented (`tobw_gaia.f`):

$$f_w = \begin{cases} \exp\left(-6.0 + 5.2\left(\frac{A_0}{k_s}\right)^{-0.19}\right), & \text{if } \frac{A_0}{k_s} > 1.59 \\ 0.30, & \text{otherwise} \end{cases}$$

5.1.5 Wave-current interactions

For combined waves and currents, the wave-induced bottom stresses are, in many cases, of an order of magnitude larger than in the case of currents alone. Different models can be found in the literature to calculate the wave and current bottom stresses τ_{cw}, as a function of the bottom shear stress due to currents only τ_c and the maximum shear stress due to waves only τ_w. Following Bijker [16]:

$$\tau_{cw} = \tau_c + \frac{1}{2}\tau_w. \tag{5.1}$$

See e.g. the soubroutine `bedload_bijker_gaia.f`.

5.1.6 Wave-induced sediment transport formulas

The choice of the transport formula is done with the keyword `BED-LOAD TRANSPORT FORMULA FOR ALL SANDS` (integer type variable, set to = `1` by default). Available formulas in GAIA accounting for the effect of waves superimposed to currents:

```
4 : BIJKER
5 : SOULSBY - VAN RIJN
8 : BAILARD
9 : DIBAJNIA ET WATANABE
```

Soulsby-van Rijn's formula

- `BED-LOAD TRANSPORT FORMULA FOR ALL SANDS` = `5`, the total transport rate due to the combined action of waves and current is computed by [39]:

$$Q_{b,s} = A_{b,s} U_c \left[\left(U_c^2 + \frac{0.018}{C_D} U_w^2 \right)^{0.5} - U_{cr} \right]^{2.4}.$$

  This formula can be applied to estimate both components of the total sand transport rate (bedload Q_b and suspension Q_s), and it is suitable for rippled beds (bed roughness = 6mm)

- The bedload and suspended load coefficients, $A_{b,s}$ are computed:

$$A_b = \frac{0.005h\,(d_{50}/h)^{1.2}}{((s-1)gd_{50})^{1.2}}, \quad A_s = \frac{0.012 d_{50} D_*^{-0.6}}{((s-1)gd_{50})^{1.2}},$$

  where U_c is the norm of the depth-averaged current velocity, U_w is the orbital velocity of waves, and C_D is the quadratic drag coefficient due to current alone.

- The critical entrainment velocity U_{cr} is given by:

$$U_{cr} = \begin{cases} 0.19 d_{50}^{0.1} \log_{10}\left(\dfrac{4h}{d_{90}}\right), & \text{if } d_{50} < 0.0005 \text{ m} \\ 8.5 d_{50}^{0.6} \log_{10}\left(\dfrac{4h}{d_{90}}\right), & \text{otherwise.} \end{cases}$$

- The diameter d_{90}, characteristic of the coarser grains, can be specified with the keyword `D90` (real list type, if the keyword is not in the steering file, the default value is the value of the mean diameter of the sediment)

- Fortran file `bedload_soulsby_gaia.f`

Bijker's formula

- `BED-LOAD TRANSPORT FORMULA FOR ALL SANDS = 4`, the Bijker's formula can be used for determining the total transport rate [16]. The bedload transport rate is:

$$Q_b = b\,d_{50}\sqrt{\tau_c/\rho}\exp\left(-0.27\frac{(\rho_s-\rho)gd_{50}}{\mu\tau_{cw}}\right),$$

  where τ_c is the shear stress due to currents alone, τ_{cw} the shear stress due to wave-current interaction, and μ is a correction factor which accounts for the effect of ripples. The shear stress under combined wave and current is calculated by Equation (5.1).

- By default, in GAIA $b = 2$ but this value can be modified with the keyword `B VALUE FOR THE BIJKER FORMULA` (real type, set to `= 2.0` by default)

- The ripple factor correction μ is calculated in the same way as for currents only

- For the suspended load transport, the concentration profile is assumed to be in equilibrium.

- After depth-integration and by assuming a Rouse profile for the concentration and a logarithmic velocity profile for the mean velocity profile, the suspended load can be written as:

$$Q_s = Q_b I,$$

  where

$$I = 1.83\times 0.216\frac{B^{A-1}}{(1-B)^A}\int_B^1\left(\frac{1-y}{y}\right)^A \ln\left(\frac{33y}{B}\right)dy,$$

  with

$$A = \frac{w_s}{\kappa u_*},\quad u_* = \sqrt{\frac{\tau_{cw}}{\rho}},\quad B = k_s/h.$$

- Fortran file `bedload_bijker_gaia.f`

Details of Bailard and Dibajnia and Watanabe wave-induced sediment transport formulas can be found in [24] and [32], respectively.

5.1.7 Steering file setup for sediment transport including waves effects

In GAIA, the effect of waves can be incorporated into the numerical simulation when the keyword `EFFECT OF WAVES` (logical type, set to `= NO` by default) is activated.
To compute sediment transport rates due to the action of waves, the spectral significant wave height ($H_s =$, variable `HM0`), the wave peak period ($T_p =$, variable `TPR5`) and the mean wave direction ($\theta_w =$, variable `DMOY`, relative to the $x-$axis) need to be specified.

- Spectral significant wave height ($H_s =$ `HM0`): $H_s = 4\sqrt{m_0}$, with m_0 the momentum of order 0 of the wave spectrum (variance of the sea state) [m]

- Wave peak period ($T_p =$ `TPR5`): peak period computed by the Read's method of order 5 [s]

- Mean wave direction ($\theta_w =$ `DMOY`, relative to the $x-$axis) [deg.]

This information can be provided from a Fortran file (subroutine `user_forcing_gaia.f`) which reads a file containing those variables previously computed by the wave module (e.g. TOMAWAC), or by internal coupling with the wave module.

5.1.8 Procedure for external coupling waves-currents and sediment transport

- A TELEMAC-2D + TOMAWAC simulation (same mesh) is launched and the spectral significant wave height (H_s = HM0), the wave period (T_p = TPR5) and the mean wave direction (θ_w = DMOY) are recorded in the TOMAWAC's result file (format selafin). The mean wave direction can be recorded following the nautical or the trigonometrical convention (with respect to the $x-$axis), according to the keyword TRIGONOMETRICAL CONVENTION set in the TOMAWAC steering file (see the TOMAWAC user manual for more details).

- In TELEMAC-2D steering file, the keyword WAVE DRIVEN CURRENTS (logical type, set to = NO by default) allows to incorporate the influence of radiation stresses in the mean flow (wave-induced currents)

- The external coupling between waves-currents and sediment transport requires the set of input files (steering, geometry, etc.) for the modules TELEMAC-2D and GAIA and a results file TOMAWAC

- TELEMAC-2D steering file:

  - The keyword COUPLING WITH = 'GAIA' activates the internal coupling with module GAIA
  - The keyword BINARY DATA FILE 1 is used to open the TOMAWAC results file
  - A Fortran file containing the subroutine prosou.f allows to read non-stationary wave data from a binary result file produced on the same mesh by TOMAWAC

- GAIA steering file:

  - The keyword EFFECT OF WAVES (logical type, set to = NO by default) is used to consider the effect of the waves on the solid transport formula
  - The keyword BED-LOAD TRANSPORT FORMULA FOR ALL SANDS (integer type variable, = 1 by default) allows to choose among the transport formulas that consider the combined effect of currents and waves
  - The keyword TRIGONOMETRICAL CONVENTION IN WAVE FILE (logical type variable, = NO by default) allows to consider the convention (nautical or trigonometrical) used in TOMAWAC's result file for wave direction. This keyword is necessary when there is no internal coupling between GAIA and TOMAWAC (i.e. the TOMAWAC's result file is generated separately by a TELEMAC-2D + TOMAWAC simulation).

- In TELEMAC-2D, the keyword NAMES OF CLANDESTINE VARIABLES names the variables that belong to the other code and are given back in the results file:

```
NAMES OF CLANDESTINE VARIABLES=
'WAVE HEIGHT HM0 M                  ';
'PEAK PERIOD TPR5S                  ';
'MEAN DIRECTION   DEG               '
```

5.1.9 Useful graphical printouts

Keyword `VARIABLES FOR GRAPHIC PRINTOUTS`:

```
THETAW="wave angle with axis Oy (deg)";
W="wave height";
X="wave period";
UWB="wave orbital velocity (m/s)";
TOB="bed shear stress(N/m2)";
MU ="skin friction coefficient";
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)";
```

6. How-To?

6.1 Running a morphodynamics simulation: first steps

The minimum set of files to run a morphodynamics simulation includes:

- the steering file(s) (text/ASCII file `*.cas`)
- the geometry file (format selafin/binary `*.slf`)
- the boundary conditions file (text/ASCII file `*.cli`)
- additional or optional input files as the Fortran file (text/ASCII file `*.f`), the reference file (format selafin/binary `*.slf`), etc.

Typically, these files are contained in a folder, for example in the folder simulation:

```
simulation\bc_bifurcation_tel.cli
simulation\geo_bifurcation.slf
simulation\res_bifurcation_hotstart_tel.slf
simulation\run_bifurcation_sis.cas
simulation\run_bifurcation_tel.cas
```

Running a simulation from a Linux terminal:

```
telemac2d.py run_bifurcation_tel.cas
```

6.1.1 GAIA's steering file (`*.cas`)

This file contains the necessary information for running a simulation, it also must include the values of parameters that are different from the default values (as specified in the dictionary file `gaia.dico`):

- Input and output files
- Physical parameters (sand diameter, settling velocity, etc.)
- Main sediment transport processes (transport mechanisms, closure relationships, etc.)
- Additional sediment transport processes (secondary currents, slope effect, etc.)
- Numerical options and parameters (numerical scheme, solvers, etc.)

Sketch of the gaia's steering file (`*.cas`)

```
/---------------------------------------------------------------------/
/ gaia bedload                                                     /
/---------------------------------------------------------------------/
/
/---------------------------------------------------------------------/
/  FILES                                                              /
/---------------------------------------------------------------------/
/
/ --- GEOMETRY ---
GEOMETRY FILE                          = '../geo_bifurcation.slf'
BOUNDARY CONDITIONS FILE               = '../bc_bifurcation_tel.cli'
/
/ --- RESULTS ---
RESULTS FILE                           = 'res_bifurcation_gai.slf'
/
...
/----------------------------------------------
/  PHYSICAL PARAMETERS
/----------------------------------------------
/
BED LOAD FOR ALL SANDS                    = YES
BED-LOAD TRANSPORT FORMULA FOR ALL SANDS  = 1
CLASSES SEDIMENT DIAMETERS                = 0.000120
/
...
/---------------------------------------------------------------------/
/  NUMERICAL PARAMETERS                                               /
/---------------------------------------------------------------------/
/
MASS-BALANCE                            = YES
...
```

Examples of physical parameters in the GAIA's steering file

- Sediment diameters, defined by the keyword `CLASSES SEDIMENT DIAMETERS` (real list, = `0.01` m by default)

- Sediment density, defined by the keyword `CLASSES SEDIMENT DENSITY` (real type, = `2650.0` kg/m^3 by default)

- Shields parameter τ_c [N m^{-2}], defined by the keyword `CLASSES SHIELDS PARAMETERS` (real list, = -9 by default). If it is not known, it is necessary to give a negative value to let GAIA compute it as a function of the non-dimensional grain diameter $D_* = d_{50}[(\rho_s/\rho - 1)g/\nu^2]^{1/3}$ in the subroutine `shields.f`:

$$\frac{\tau_c}{g(\rho_s-\rho)d_{50}} = \begin{cases} 0.24 D_*^{-1}, & D_* \le 4 \\ 0.14 D_*^{-0.64}, & 4 < D_* \le 10 \\ 0.04 D_*^{-0.10}, & 10 < D_* \le 20 \\ 0.013 D_*^{0.29}, & 20 < D_* \le 150 \\ 0.045, & 150 \le D_* \end{cases}$$

  with d_{50} the median sand grain diameter (m), ρ the water density $= 1000$ kg/m^3 by default, ρ_s the sediment density $= 2650$kg/m^3 by default, and ν the kinematic viscosity $= 1.0 \times 10^{-6}$m^{2}s^{-1} by default.

- Settling velocity, it can be specified by the user or calculated by the model as a function of grain diameter, keyword `SETTLING VELOCITIES` (real list, =-9 by default). If a negative value is given, GAIA will compute it as function of grain diameter:

$$w_s = \begin{cases} \dfrac{(s-1)gd_{50}^2}{18\nu}, & \text{if } d_{50} \leq 10^{-4} \\ \dfrac{10\nu}{d_{50}}\left(\sqrt{1+0.01\dfrac{(s-1)gd_{50}^3}{\nu^2}}-1\right), & \text{if } 10^{-4} \leq d_{50} \leq 10^{-3} \\ 1.1\sqrt{(s-1)gd_{50}}, & \text{otherwise} \end{cases}$$

with $s = \rho_s/\rho_0$ is the relative density and g is the acceleration of the gravity.

- Bed porosity, keyword `LAYERS NON COHESIVE BED POROSITY` (real type, = `0.40` by default)

6.1.2 Boundary conditions file

Thirteen variables for each boundary nodes are specified in the boundary condition file (usually named with extension `*.cli`). An example is given below:

```
5 4 4 0.0 0.0 0.0 0.0 4 0.0 0.0 0.0 565 1
5 4 4 0.0 0.0 0.0 0.0 4 0.0 0.0 0.0 564 2
5 4 4 0.0 0.0 0.0 0.0 4 0.0 0.0 0.0 563 3
5 4 4 0.0 0.0 0.0 0.0 4 0.0 0.0 0.0 562 4
5 4 4 0.0 0.0 0.0 0.0 4 0.0 0.0 0.0 561 5
5 4 4 0.0 0.0 0.0 0.0 4 0.0 0.0 0.0 560 6
```

Each column is named after a flag, as follows:

TELEMAC-2D

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

GAIA

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

where `N, K` are respectively the global and local boundary node numeration. Flags `ATBOR`, `BTBOR` are discussed in the TELEMAC-2D user manual. For both modules TELEMAC-2D and GAIA, flags can be specified as follows:

- `=2:` closed boundary (wall)
- `=4:` free boundary (Neumann's type)
- `=5,6:` imposed value (Dirichlet's type)

The different types of boundaries are (integer variables):

TELEMAC-2D

- `LIHBOR:` flag to set the water depth (=`5`)
- `LIUBOR:` flag to set the discharge (=`5`) or the velocity (=`6`) in the $x-$direction
- `LIVBOR:` flag to set the discharge (=`5`) or the velocity (=`6`) in the $y-$direction
- `LITBOR:` flag to set the tracer

For further details see the TELEMAC-2D's or TELEMAC-3D user manual.

GAIA

- LIEBOR: flag to set the bottom elevation
- LICBOR: flag to set the equilibrium or imposed concentration
- LIQBOR: flag to set the imposed bedload discharge

Values (real variables) can be specified as follows:

TELEMAC-2D

- HBOR: prescribed water depth
- UBOR: prescribed discharge or velocity in the $x-$direction
- VBOR: prescribed discharge or velocity in the $y-$direction
- AUBOR: friction coefficient on lateral walls

GAIA

- EBOR: prescribed bed evolution
- CBOR: prescribed concentration
- Q2BOR: prescribed bedload discharge, expressed in m^2/s excluding voids.

For the particular case where a bedload solid discharge is imposed, an extra boundary condition file needs to be defined for GAIA. The treatment of boundary conditions for bedload and suspended sediment transport is given in §3.1 and §2, respectively.

Coupling hydrodynamics and morphodynamics: sketch of the Telemac-2d's steering file with the required keywords

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

6.1.3 Fortran files (*.f)

Programming can be necessary for particular applications. A Fortran file (keyword FORTRAN FILE) can be specified in the TELEMAC-2D or TELEMAC-3D or GAIA steering file with the required subroutine(s). All subroutines (GAIA subroutines also) can be incorporated in the TELEMAC- Fortran file. Is is also possible to have a TELEMAC-A nd a GAIA Fortran file. Be aware, if there is no TELEMAC-2D or TELEMAC-3D Fortran file, the GAIA Fortran file will not taken into account. Some common applications are given below:

- **Definition of rigid areas:** `user_bed_init.f` is used for specifying the rigid areas. The thickness of the erodable area (array `ESTRATUM`) is imposed in this subroutine

- **New sediment transport formula**: `user_bedload_qb.f` can be used to program a sediment transport formula that is different from those already implemented in GAIA

- **Replace data from a result file**: `user_forcing_gaia.f` can be used for replacing data from a results file computed from a simulation performed for example from the waves module TOMAWAC

GAIA's main subroutines are found in the folder `$HOMTEL/sources/gaia/` of the TELEMAC-MASCARET SYSTEM. Please note that if there is no Fortran file specified in TELEMAC-2D or TELEMAC-3D, then GAIA's Fortran file must be specified in the TELEMAC-2D or TELEMAC-3D steering file.

Graphical printouts

The keyword VARIABLES FOR GRAPHIC PRINTOUTS can include a variety of output variables to be printed in the results file (character list, set to = U,V,H,S,B,R,E by default). The graphic and listing printout periods are the same as in the TELEMAC-2D or TELEMAC-3D computation. The list of variables that can be printed in the GAIA's results file can be found in the dictionary and is:

```
U="velocity along x axis (m/s)";
V="velocity along y axis (m/s)";
H="water depth (m)";
S="free surface elevation (m)";
B="bottom elevation (m)";
Q="scalar flowrate of fluid (m2/s)";
I="flowrate along x axis (m2/s)";
J="flowrate along y axis (m2/s)";
R="non erodable bottom";
TOB="Bed Shear stress (Totalfriction) (N/m2)";
W="wave height";
X="wave period";
THETAW="wave angle with axis Oy (deg)";
M="bed-load discharge (kg/(m*s))";
N="bed-load discharge along x axis (kg/(m*s))";
P="bed-load discharge along y axis (kg/(m*s))";
E="bottom evolution (m)";
KS="total bed roughness (m)";
MU="Skin friction correction factor";
D50="Mean grain diameter";
UWB="wave orbital velocity (m/s)";
kAi="fraction of non cohesive sediment of class i, in k layer";
QSi="solid transport load of class i";
CSi="mass concentration of class i";
C2DSi="mass concentration of class i for 2D graphic printouts";
SVXi="sediment viscosity along x axis (m2/s) - only 3D";
SVYi="sediment viscosity along y axis (m2/s) - only 3D";
SVZi="sediment viscosity along z axis (m2/s) - only 3D";
QSBL="bed load transport rate (kg/(m*s))";
QSBLX="bed load transport rate x axis";
QSBLY="bed load transport rate y axis";
QSBLi="bedload transport rate of class i";
kES="thickness of the k layer";
kCONC="concentration of bed layer k";
QSi="bed load transport rate of sediment of class i";
A="supplementary variable A";
G="supplementary variable G";
L="supplementary variable L";
O="supplementary variable O";
kRi="fraction of cohesive sediment of class i, in k layer";
kSi="mass of non cohesive sediment of class i, in k layer";
kMi="mass of cohesive sediment of class i, in k layer";
ZRL="reference level for Nestor"'
```

It is worth to notice that the following variables will be printed in the hydrodynamic results file (of TELEMAC-2D or TELEMAC-3D) even if asked in the GAIA steering file: CSi,C2DSi,SVXi,SVYi,SVZi. The graphical printout period is controlled in the TELEMAC-2D steering file through the keyword GRAPHIC PRINTOUT PERIOD (integer type, = 1 by default). Similarly, the keyword LISTING PRINTOUT PERIOD (integer type, = 1 by default) controls the printout period on the screen.

6.2 Compute sediment fluxes through a given section(s)

Use the keywords FLUXLINE (logical type, set to NO by default) and FLUXLINE INPUT FILE (character type).

The format of the FLUXLINE INPUT FILE includes (see Figure 6.1):

- The number of fluxlines (integer)
- The definition of the fluxlines, given by:
  - The specification of two points of the fluxline (`fluxline_x1, fluxline_y1, fluxline_x2, fluxline_y2`), followed by
  - the definition of the bounding box (`box_x1, box_y1, box_x2, box_y2`)
  - An integer (value not used)

An example of the `FLUXLINE INPUT FILE` is given below:

```
5
94.0   31.2  99.0  31.2 95.0  31.0  98.0  31.6 1
94.0   42.5  99.0  42.5 96.0  42.0  98.0  43.0 1
101.0  42.5  107.0 42.5 104.0 42.0  106.0 43.0 1
101.0  31.2  107.0 31.2 104.0 31.0  106.0 31.6 1
100.0  45.0  102.0 48.0 100.0 46.0  102.0 47.5 1
```

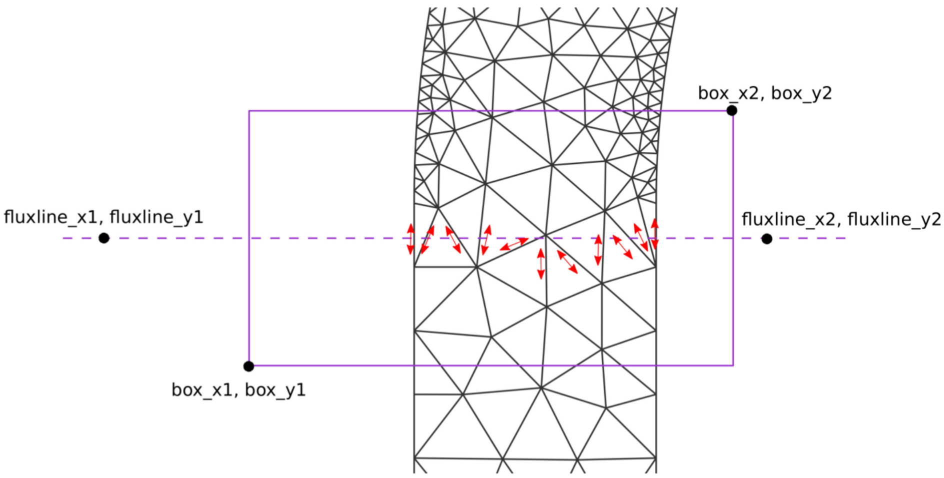


Figure 6.1: Description of a single fluxline and edge fluxes (red).

Further details can be found in Stadler L. (2015) *Calculating correct water and sediment fluxes in TELEMAC2D and SISYPHE*. Proceedings of the 22nd Telemac & Mascaret User Club, STFC Daresbury Laboratory, UK, 13-16 October.

6.3 Implement a new bedload transport formula

To implement a new bedload transport formula, the keyword `BED-LOAD TRANSPORT FORMULA FOR ALL SANDS` must be set to `= 0`. The Fortran subroutine must be added into the Fortran file of TELEMAC-2D or TELEMAC-3D, keyword `FORTRAN FILE`.
The template subroutine is called `user_bedload_qb.f` and can be found in the folder `$HOMETEL/sources/gaia`

```
!                 **************************
                  SUBROUTINE USER_BEDLOAD_QB
!                 **************************
     & (HN, U2D, V2D, THETAC, HOULE, HW, TW, THETAW,
     &  TOB,TOBW,TOBCW_MEAN,TOBCW_MAX, DCLA, DENS, GRAV, DSTAR, AC,
```

```
     &  XMVE, XMVS, TETAP, MU, NPOIN, QSC, QSS, CSTAEQ)
!
!***********************************************************************
! GAIA
!***********************************************************************
!
!>@brief Allows the user to code their own bedload transport
!!       formulation, best suited to their application.
!
!>@warning User subroutine; sand transport formula must be coded by the user
!>@todo Missing description of arguments
!
!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
!>@param[in]     HN
!>@param[in]     U2D
!>@param[in]     V2D
!>@param[in]     THETAC
!>@param[in]     HOULE
!>@param[in]     HW
!>@param[in]     TW
!>@param[in]     THETAW
!>@param[in,out] TOB
!>@param[in,out] TOBW
!>@param[in,out] TOBCW_MEAN
!>@param[in,out] TOBCW_MAX
!>@param[in]     DM
!>@param[in]     DENS
!>@param[in]     GRAV
!>@param[in]     DSTAR
!>@param[in]     AC
!>@param[in]     XMVE
!>@param[in]     XMVS
!>@param[in]     TETAP
!>@param[in]     MU
!>@param[in]     NPOIN
!>@param[in,out] QSC
!>@param[in,out] QSS
!>@param[in,out] CSTAEQ
!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
!
      USE INTERFACE_GAIA, EX_USER_BEDLOAD_QB => USER_BEDLOAD_QB
      USE BIEF
      USE DECLARATIONS_SPECIAL
      IMPLICIT NONE
!
!!-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
!
      TYPE(BIEF_OBJ),   INTENT(IN)    :: HN,U2D,V2D,THETAC
      TYPE(BIEF_OBJ),   INTENT(IN)    :: HW, TW, THETAW
      TYPE(BIEF_OBJ),   INTENT(IN)    :: TOB,TOBW,TOBCW_MEAN,TOBCW_MAX
      DOUBLE PRECISION, INTENT(IN)    :: DCLA, DENS, GRAV, DSTAR, AC
      DOUBLE PRECISION, INTENT(IN)    :: XMVE, XMVS
      TYPE(BIEF_OBJ),   INTENT(IN)    :: TETAP, MU
      TYPE(BIEF_OBJ),   INTENT(IN)    :: CSTAEQ
      INTEGER,          INTENT(IN)    :: NPOIN
      LOGICAL,          INTENT(IN)    :: HOULE
      TYPE(BIEF_OBJ),   INTENT(INOUT) :: QSC, QSS
!
!!-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
!
      INTEGER           :: I
!     DOUBLE PRECISION :: C1, C2, T
!
!=======================================================================!
!=======================================================================!
!                               PROGRAM                                 !
!=======================================================================!
!=======================================================================!
!
!     EXAMPLE BY VAN RIJN
```

```
!
!     C1 = DENS * GRAV * DCLA
!     C2 = 0.053D0 * SQRT(DCLA**3*DENS*GRAV) * DSTAR**(-0.3D0)
!
      DO I = 1, NPOIN
!
!       TRANSPORT STAGE PARAMETER
!
!       IF(TETAP%R(I) .LE. AC) THEN
!         T = 0.D0
!       ELSE
!         T = (TETAP%R(I)-AC)/MAX(AC,1.D-06)
!       ENDIF
!
!       BEDLOAD TRANSPORT RATE
!
        QSC%R(I) = 0.D0 ! C2 * T**2.1D0
        QSS%R(I) = 0.D0
!
      ENDDO
!
!  FOLLOWING LINES NEED TO BE COMMENTED OUT
!
      WRITE(LU,53)

53    FORMAT(/,1X,'GAIA IS STOPPED : ',/
     &   ,1X,' SAND TRANSPORT MUST BE CALCULATED IN USER_BEDLOAD_QB')
      CALL PLANTE(1)
      STOP
!
!-----------------------------------------------------------------------
!
      RETURN
      END
```

6.4 Print a new output variable in the selafin file

- Declare the PRIVE variable, for example as:

  USE DECLARATIONS_GAIA, ONLY : PRIVE

- Use the following expression to include the variable you want to visualize:

  PRIVE%ADR(N)%P%R(K) = [Here the variable you want to visualize], where N is the number of variables that you want to visualize and K is the number of nodes.

- In the GAIA's steering file you can use the flags 'A', 'G', 'L' or 'O' to visualize the PRIVE variable, for example as:

  VARIABLES FOR GRAPHIC PRINTOUTS='U,V,S,H,B,Q,M,E,QSBL,TOB,MU,A'

The default name PRIVE 1 (for N=1) can be modified in the subroutine nomvar_gaia.f.

```
DO K=1, NPOIN
  PRIVE%ADR(1)%P%R(K) = [variable to visualize]
ENDDO
```

6.5 Introduce a new keyword

- In declarations_gaia.f declare the variable to be called from a keyword e.g. HMIN_BEDLOAD

- In lecdon_gaia.f declare .... HMIN_BEDLOAD=MOTREA(ADRESS(2,52))
- Declaration in the modified subroutine through USE DECLARATIONS_GAIA, ONLY : HMIN_BEDLOAD

6.6 Define the soil stratigraphy (user_bed_init)

In case of several layers with different sediment ratios, the subroutine user_bed_init must be used.
Here different layer thickness (ESTRATUM) and different mass ratios (RATIO_INIT) for each sediment can be set. For example for 2 layers and 4 sediments:

```
DO IPOIN=1,NPOIN
  ESTRATUM(1,IPOIN) = 0.12D0
  RATIO_INIT(1,1,IPOIN) = 0.5D0
  RATIO_INIT(2,1,IPOIN) = 0.5D0
  RATIO_INIT(3,1,IPOIN) = 0.D0
  RATIO_INIT(4,1,IPOIN) = 0.D0
  ESTRATUM(2,IPOIN) = 2.D0
  RATIO_INIT(1,2,IPOIN) = 0.D0
  RATIO_INIT(2,2,IPOIN) = 0.D0
  RATIO_INIT(3,2,IPOIN) = 0.5D0
  RATIO_INIT(4,2,IPOIN) = 0.5D0
ENDDO
```

6.7 Using a non-declared variable in a GAIA's subroutine

If you want to use, for example, parameter NPTFR and the table NBOR(NPTFR) in a subroutine, declare:
USE DECLARATIONS_GAIA, ONLY : NPTFR, MESH
INTEGER, POINTER :: NBOR(:)
Then the following alias can be declared:
NBOR=>MESH%NBOR%I

6.8 Prevent erosion when water depth is smaller than a threshold value

At for example intertidal wetlands with flooding and drying or tidal areas, the bottom friction could be very high when the water depth is very small, even for small velocities, leading to high and unphysical erosion rates. To prevent that, the keyword MINIMAL VALUE OF THE WATER HEIGHT can be used (the value by default is 1.0×10^{-3}m). This keyword is activated when TIDAL FLATS = YES.

6.9 Set a non-erodible bottom

The non-erodible bottom (or rigid bed) can be set using the keyword LAYERS INITIAL THICKNESS which is equal to 100 m by default, in case of a single layer.
For more complex set-up (e.g. rigid bed variable in space), the subroutine user_bed_init can be used. Here the variable ESTRATUM which states the thickness of the erodible bed, needs to be modify.

6.10 Modify the bottom from the subroutine corfon

For example, you want to set the bottom at node 325 equal to 2.1 m

- Sequential: ZF%R(325)=2.1D0

- Parallel: `ZF%R(GLOBAL_TO_LOCAL_POINT(325,MESH))=2.1D0`

If there are several nodes to be modified, use a loop.
Thanks to JMH (post #9747)

6.11 Dredge and dump activities

When using the module NESTOR (keyword: `NESTOR = YES`) to carry out dredge or dump activities, these files are used to specify the action, location, geometry and the last status. The keywords identifying these files are:

1. `NESTOR ACTION FILE`
2. `NESTOR POLYGON FILE`
3. `NESTOR SURFACE REFERENCE FILE`
4. `NESTOR RESTART FILE`

These files are described in detail in the NESTOR User Manual.

7. API

Information on the GAIA API can be found in the telapy user documentation. The GAIA API does not exist in stand alone you must use the TELEMAC-2D or TELEMAC-3D API.

8. Appendices

8.1 Keyword equivalence between GAIA and SISYPHE

SISYPHE	GAIA
NUMBER OF BED MODEL LAYERS	NUMBER OF LAYERS FOR INITIAL STRATIFICATION
SOLVER FOR SUSPENSION	SOLVER FOR DIFFUSION OF SUSPENSION
SOLVER OPTION FOR SUSPENSION	SOLVER OPTION FOR DIFFUSION OF SUSPENSION
PRECONDITIONING FOR SUSPENSION	PRECONDITIONING FOR DIFFUSION OF SUSPENSION
SOLVER ACCURACY FOR SUSPENSION	ACCURACY FOR DIFFUSION OF SUSPENSION
SUSPENSION	SUSPENSION FOR ALL SANDS*
REFERENCE CONCENTRATION FORMULA	SUSPENSION TRANSPORT FORMULA FOR ALL SANDS*
TETA SUSPENSION	THETA IMPLICITATION FOR SUSPENSION
CRITICAL SHEAR VELOCITY FOR MUD DEPOSITION	CRITICAL SHEAR STRESS FOR MUD DEPOSITION
BED LOAD	BED LOAD FOR ALL SANDS*
BED-LOAD TRANSPORT FORMULA	BED-LOAD TRANSPORT FORMULA FOR ALL SANDS*

*For non-uniform sediment distribution, it must be applied to all sand classes.

9. A non-exhaustive list of documents using GAIA and SISYPHE

9.1 Journal papers

- Mendoza A., Abad J.D., Langendoen E., Wang D., Tassi P., and El Kadi Abderrezzak K. Effect of sediment transport boundary conditions on the numerical modeling of bed morphodynamics. *J. of Hydr. Eng.*, 2016
- El Kadi Abderrezzak K., Die Moran A., Tassi P., Ata R., and Hervouet J.M. Modelling river bank erosion using a 2d depth-averaged numerical model of flow and non-cohesive, non-uniform sediment transport. *Advances in Water Resources*, 93, Part A: 75 – 88, 2016. URL `http://www.sciencedirect.com/science/article/pii/S0309170815002638`

9.2 Proceedings

- Huybrechts N., Villaret C., and Hervouet J-.M. Comparison between 2D and 3D modelling of sediment transport: application to the dune evolution. In *Proceedings of the Riverflow 2010 conference*, 2010
- Knaapen M.A.F. and Joustra R. Morphological acceleration factor: usability, accuracy and r un time reductions 2d and 3d modelling of sediment transport – application to the dune evolution. In *Proceedings of XIXth TELEMAC -MASCARET User Conference*, Oxford, UK, 18-19 October 2012
- Razafindrakoto E. Hervouet J.M. and Villaret C. Dealing with dry zones in free surface flows, a new class of advection scheme. In *Proceedings of the 34th IAHR World Congress*, Brisbane, Australia, July 2011

9.3 PhD thesis

- Lan A.V.D. *Numerical modelling of sand-mud mixtures settling and transport processes : application to morphodynamic of the Gironde estuary (France)*. PhD thesis, Université Paris-Est, Paris, France, 2012
- Matthieu De Linares. *Modélisation numérique bidimensionnelle du transport solide et de la dynamique fluviale. Validation sur deux sites en Loire et sur l'Arc*. PhD thesis, Université Joseph-Fourier - Grenoble I, 2007. In French

9.4 Master thesis

9.5 Miscellaneaous

[1] Mendoza A., Abad J.D., Langendoen E., Wang D., Tassi P., and El Kadi Abderrezzak K. Effect of sediment transport boundary conditions on the numerical modeling of bed morphodynamics. *J. of Hydr. Eng.*, 2016.

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