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Introducing GAIA, the brand new sediment transport module of the TELEMAC-MASCARET system

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Contributors to Gaia *in alphabetical order:* Yoann Audouin[4], Thomas Benson[5], Matthieu Delinares[1], Jacques Fontaine[4], Boris Glander[2], Nicolas Huybrechts[3], Rebekka Kopmann[2], Agnès Leroy[4,6], Sara Pavan[4], Chi-Tuân Pham[4], Florent Taccone[4], Pablo Tassi[4,6,*] & Regis Walther[1]

[1]Artelia; [2]BAW; [3]CEREMA; [4]EDF R&D; [5]HR-Wallingford; [6]Laboratoire d'Hydraulique Saint-Venant

[*] *Corresponding author:* pablo.tassi@edf.fr

***Abstract*—GAIA is the brand new open-source, sediment transport and bed evolution module of the TELEMAC-MASCARET 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.**

I. Introduction

Over the last few decades, the access to more precise measurement data from both field and laboratory, the enormous increases in computer speed and power, and the requirement for more accurate predictions of sediment transport and bed evolution of river, coastal and estuarine zones, have motivated the scientific community to develop more rigorous and elaborate predictive tools for morphodynamics applications.

In light of this, the historical module Sisyphe of the Telemac-Mascaret modelling system (TMS) has been developed for more than 25 years [9], originally based on the same finite element structure as the two-dimensional code solving the shallow water equations*.

Despite its robustness, flexibility and capability of dealing with a large number of river [4, 6, 11], coastal [3, 14, 20], and estuarine [15, 16, 7] sediment transport and morphodynamics problems [22], 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 [5], 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.

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. Gaia can also be coupled with the modules for sediment dredging Nestor, wave propagation Tomawac and water quality Waqtel.

II. 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., $\leq$ 0.5 mm). Within this new sediment transport framework, the solution of the ADE, com-

*Interestingly, this shallow water code later evolved into a module that was baptized Telemac-2d.

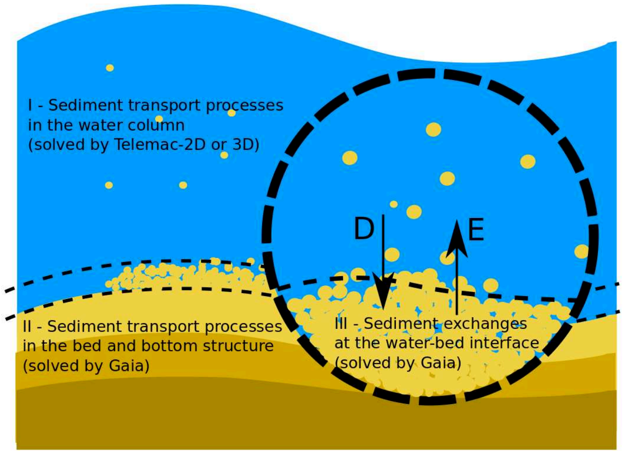


Fig. 1: Sketch summarizing the way in which the sediment transport mechanisms are dealt in GAIA. Above, D and E stand for deposition and entrainment fluxes.

pleted with appropriate boundary and initial conditions, is computed by TELEMAC-2D or TELEMAC-3D for 2D and 3D cases respectively. The solution procedure remains invisible to the user since the physical parameters are provided by the GAIA steering file. 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).

III. SEDIMENT TRANSPORT PROCESSES IN THE BED AND STRATIGRAPHY

A. 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: $\mathbf{Q}_{mb} = \rho\mathbf{Q}_b$ in (kg/ms), with $\mathbf{Q}_b$ the vector of volumetric transport rate per unit width without pores (m^2/s), with components (Q_{bx}, Q_{by}) along the x and y directions, respectively, and ρ the sediment density. Numerical computation of sediment fluxes in dry mass minimizes roundoff error, particularly for the mass transfer algorithms used for the bed layer model.

B. Bottom stratigraphy

For sand graded distributions, an algorithm based on the classical active layer formulation of Hirano is used [2]. 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, 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 mass of sediment 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.

C. Mixed sediments

The bed model algorithm introduced above 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 [21]. 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.

D. Consolidation processes

For the current version of Gaia, consolidation processes are based on the semi-empirical formulation originally developed by Villaret and Walther [23], which uses the isopycnal 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.

In the case of mixed sediment, the presence of non-cohesive sediment in the stratigraphy of the mixture is considered to not alter the cohesive sediment consolidation.

IV. 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 [25] and [13, 8], respectively.

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 "simultaneous" paradigm allowing erosion and deposition to occur at the same time has been adopted [24]. This paradigm implies that sediment deposition takes place at all times regardless of the value of the bottom shear stress.

A. Erosion of mixed sediments

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 [10]:

- 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.

B. Deposition processes

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.

V. Influence of waves on sediment transport processes

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 [19] and [17], 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) [18] 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.

VI. 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 §III-A), where bedload, suspension or both sediment transport modes can be considered simultaneously. In its simplest form (only bedload, one sediment class) this equation reads: $(1-\lambda)\partial_t(\rho\, z_b)+\nabla\cdot\mathbf{Q}_{mb} = 0$, with λ the sediment porosity 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.

Key physically-based processes that are retained in GAIA from SISYPHE include the influence of secondary currents to precisely capture the complex flow field induced by channel curvature in 2D simulations, the effect of bed slope associated with the influence of gravity, bed roughness predictors, the collapse of bed slope over a critical slope or angle of repose, and non-erodible bed areas.

VII. EXAMPLES

Similarly to SISYPHE, the coupling between the hydrodynamics and sediment transport module is done by the keyword `COUPLING WITH = 'GAIA'` and the companion keyword `GAIA STEERING FILE`.

A. Racetrack shape domain in 2D and 3D

A racetrack shape configuration has been adopted during the earlier developments of GAIA to assess its conservativeness properties, to test its ability at reproducing bed and layer thicknesses evolutions and to optimize the code implementation within the new module structure. To further simplify the involved physical processes, wind is considered as the only driving force of the flow and no liquid boundaries are included in the numerical simulations. The bump and the lateral banks in the initial bathymetry (see Figure 2) favor the bed evolution on both longitudinal and lateral slopes. Lateral banks allow the formation of dry areas in the computational domain. During the development process, the new implementations were tested using this model for a large number of cohesive and/or non-cohesive sediment combinations by coupling GAIA with either TELEMAC-2D or TELEMAC-3D. As an example, two of these configurations are presented below. This test is available in the example database of GAIA as it shows users how to set the model for different combinations of sediment classes. It can also be useful to advanced users who want to test their own developments on a simple configuration.

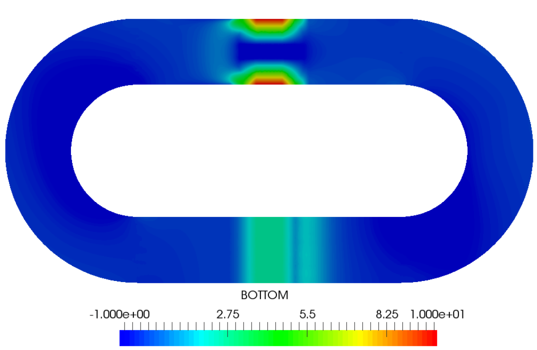


Fig. 2: Bathymetry for the racetrack shape case.

1) Case 1: The bottom structure consists of one layer with an initial thickness equal to 1 m. The sediment diameter $D = 10\ \mu$m, the settling velocity $w_s = 0.001$ m/s, mud concentration 50 kg/m^3, Partheniades constant $M = 1 \times 10^{-4}$ and critical shear stress for erosion $\tau_{ce} = 0.1$ N/m^2. The same steering file for GAIA has been used for both 2D and 3D cases.

As one sediment class of cohesive sediment is used, the corresponding keyword is `CLASSES TYPE OF SEDIMENT = CO`, where `CO` stands for cohesive sediments, see Appendix A. If consolidation is not considered in the numerical simulation, then `BED MODEL = 1`. For this test, the following keyword is required `SUSPENSION FOR ALL SANDS = YES`. If consolidation processes are accounted in the numerical simulation, the following keywords are provided, assuming a bottom discretization consisting of 4 layers:

```
BED MODEL = 2
/
NUMBER OF LAYERS FOR INITIAL STRATIFICATION = 4
LAYERS INITIAL THICKNESS = 0.25;0.25;0.25;0.25
CLASSES INITIAL FRACTION = 1.D0
/
LAYERS MUD CONCENTRATION = 50.D0;100.D0;200.D0;
300.D0
LAYERS CRITICAL EROSION SHEAR STRESS OF THE MUD =
0.1;0.2;0.3;0.4
LAYERS PARTHENIADES CONSTANT = 1.E-4; 1.E-4;
1.E-4; 1.E-4
LAYERS MASS TRANSFER = 0.01;0.005;0.001;0.0D0
```

2) Case 2: A mixed sediment bed material is considered, with 4 classes of non-cohesive sediments and 4 classes of cohesive sediments. For this case, the settling velocity values are provided for the cohesive sediments and computed by GAIA for the non-cohesive sediments. Assuming the bed model discretized with 4 layers and that accounts for consolidation processes, a sketch of the GAIA steering file is provided below:

```
CLASSES TYPE OF SEDIMENT =
NCO;NCO;NCO;NCO;CO;CO;CO;CO
CLASSES SEDIMENT DIAMETERS  =
0.0002;0.0002;0.0002;0.0002;0.00001;
0.00001;0.00001;0.00001
CLASSES SETTLING VELOCITIES =
-9.;-9.;-9.;-9.;0.001;0.001;0.001;0.001
/---------------------------------------------
BED LOAD FOR ALL SANDS                   = YES
BED-LOAD TRANSPORT FORMULA FOR ALL SANDS = 5
/
SUSPENSION FOR ALL SANDS                 = YES
SUSPENSION TRANSPORT FORMULA FOR ALL SANDS = 1
/---------------------------------------------
BED MODEL = 2
/
NUMBER OF LAYERS FOR INITIAL STRATIFICATION = 4
LAYERS INITIAL THICKNESS =
0.25;0.25;0.25;0.25
CLASSES INITIAL FRACTION =
0.15D0;0.15D0;0.15D0;0.15D0;0.1D0;0.1D0;
0.1D0;0.1D0
/
LAYERS MUD CONCENTRATION =
50.D0;100.D0;200.D0;300.D0
LAYERS CRITICAL EROSION SHEAR STRESS OF THE MUD =
```

```
0.1;0.2;0.3;0.4
LAYERS PARTHENIADES CONSTANT =
1.E-4; 1.E-4; 1.E-4; 1.E-4
LAYERS NON COHESIVE BED POROSITY=
0.4D0;0.4D0;0.4D0;0.4D0
LAYERS MASS TRANSFER =
0.01D0;0.005D0;0.001D0;0.0D0
```

These examples can be found in the folders `examples/gaia/hippodrome-t2d` and `examples/gaia/hippodrome-t3d` of the TMS.

B. Morphological evolution in a channel bend

The purpose of this test is to assess the ability of GAIA to reproduce the bed evolution in a channel bend under unsteady flow conditions. This test is based on the experimental setup (RUN 5) proposed by Yen and Lee [26]. In this case, the bed evolution of a 180° channel bed with an initial flat bottom is computed for a triangular-shaped inflow hydrograph. Numerical results are validated against measured contours of bed evolution at the end of the experiment and against measured bottom elevations at two different cross sections (90° and 180°). This case assumes non-cohesive graded sediment distribution with 5 sediment classes with diameters D=0.31, 0.64, 1.03, 1.69 and 3.36 mm and initial distribution fraction = 20% for each class, being transported by bedload. In the GAIA steering file this is specified as follows:

```
BED LOAD FOR ALL SANDS = YES
SUSPENSION FOR ALL SANDS = NO
CLASSES TYPE OF SEDIMENT = NCO;NCO;NCO;NCO;NCO
CLASSES SEDIMENT DIAMETERS =
0.00031;0.00064;0.00103;0.00169;0.00336
CLASSES INITIAL FRACTION =
0.2;0.2;0.2;0.2;0.2
```

As an example, when the Meyer-Peter and Müller formula is used to calculate the solid discharge, the corresponding keyword is set up as follows:

```
BED-LOAD TRANSPORT FORMULA FOR ALL SANDS = 1
```

For all sediment classes, the sediment density is equal to ρ = 2650 kg/m^3, the Shields parameter = 0.047 and the bed porosity λ = 0.375:

```
CLASSES SEDIMENT DENSITY =
2650.;2650.;2650.;2650.;2650.
CLASSES SHIELDS PARAMETERS =
0.047;0.047;0.047;0.047;0.047
LAYERS NON COHESIVE BED POROSITY = 0.37500
```

Two sediment layers with a total thickness equal to 20 cm are assumed. The bed structure is provided by the user's FORTRAN file `user_bedload_qb.f`.

The normalized bed evolution shown in Figure 3 evidences the asymmetrical section formed in the 180° bend under unsteady flow conditions, with the presence of a steady, forced bar located approximately between sections 30° and 90°. The model is therefore able to reproduce the expected sediment processes, with erosion along the outer bank and deposition along the inner bank. Figure 4 shows the comparison between laboratory observations and numerical results at the sections 90° and 180° of the channel bend using different bedload sediment transport

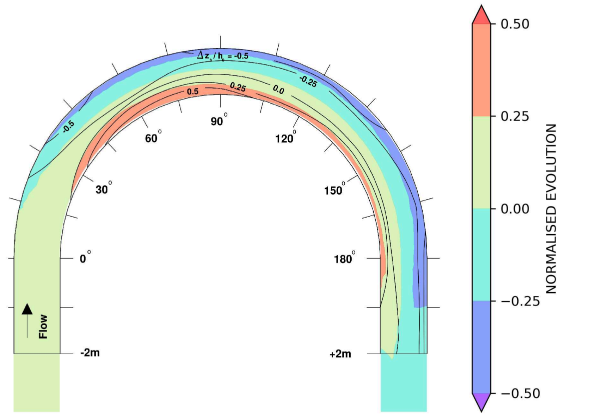
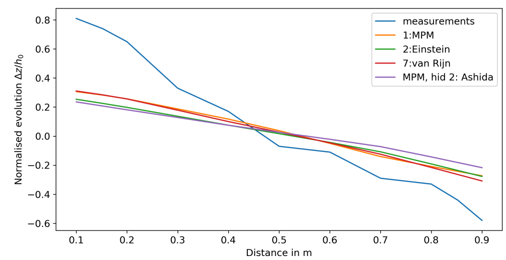
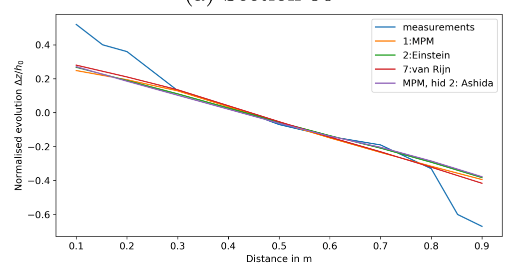


Fig. 3: Normalized bed evolution for the Yen & Lee's [26] channel bend.



(a) Section 90°



(b) Section 180°

Fig. 4: Comparison of observed vs. numerical normalized evolution.

formulae (Einstein, van Rijn, and Meyer-Peter and Müller with and without activating the Ashida's hiding factor). For this test case, numerical results were obtained without any calibration procedure. This example can be found in the folder `examples/gaia/yen-t2d` of the TMS.

C. Rhine river application

An 11 km long stretch of the lower Rhine River near Düsseldorf (Germany) is used for comparison between the modules GAIA and SISYPHE. The morphodynamic calibration was adapted from an existing, longer reach model [1]. Figure 5 shows the model domain, boundaries and bathymetric information. For this river reach, the hydrodynamics is strongly influenced by the presence of large-amplitude bends. In the study area, field surveys

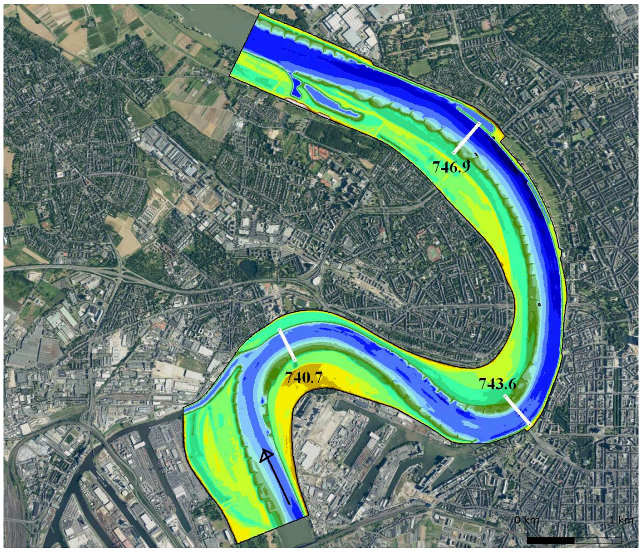


Fig. 5: Lower Rhine river topography and numerical model boundaries nearby Düsseldorf (Germany) (© Bundesamt für Kartographie und Geodäsie (2018)).

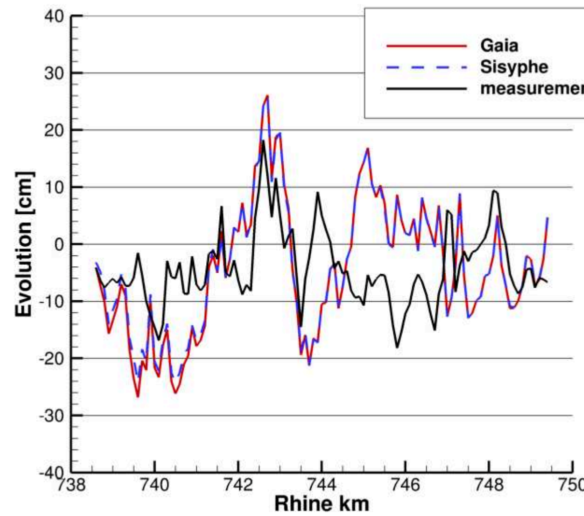


Fig. 6: Comparison of the mean bottom evolution after 6.5 years computed by GAIA and SISYPHE to measurements.

Mass balance	SISYPHE	GAIA
Mass lost (t)	493	655
Initial mass (Mt)	669	669
Relative error to initial mass	0.7×10^{-4}	1×10^{-4}

TABLE I: Comparison of final mass balance between SISYPHE and GAIA.

showed a tendency for the long term erosion, with periodic sediment management operations including artificial bed load supply as well as dredging and disposal activities. These operations were not accounted in the current version of the model. A total simulation time of 6.5 years of the natural hydrograph for the period January 1st 2000 to June 22nd 2006 was chosen. The model consists of 56,825 nodes and has a fine grid resolution in the range [5-50] m, that is able to capture the existing groyne geometries. The morphodynamic parameters for GAIA and SISYPHE were equivalent and are listed below:

- Hydrodynamic time step: 4 s, morphological factor 4.
- Nikuradse friction law, four different friction zones.
- Elder turbulence model.
- Multi-grain (10 sediment classes), Hirano-Ribberink multi-layer model (3 layers, constant active layer thickness: 0.1 m), bed load only.
- Meyer-Peter and Müller transport formula; Karim, Holly, Yang hiding exposure formulation.
- Soulsby and Talmon slope effect formulation.
- Secondary currents approach for morphodynamics, with the radius of curvature provided in an additional file.

For the total simulation time, the CPU time using GAIA ($\approx$ 42 h) was approximately 6% smaller compared with the CPU time using SISYPHE ($\approx$ 45 h) using 160 cores at a cluster (CPU Intel(R) Xeon(R) Gold 6138, 2×20 cores per node) available at BAW. Table I presents mass balance results after the 6.5 year simulation time and summed-up for the 10 sediment classes for both SISYPHE and GAIA. The mass balance of both modules are satisfying and of a similar order of magnitude. Note that SISYPHE needed hardcoded checks and limitations in the `layer.f` subroutine to ensure stability and mass balance, while GAIA worked straight out of the box.

One of the most important results of a morphodynamic simulation is the comparison of a simulated versus observed mean bed evolution over flow length. For this case, the mean bed evolution is computed each 100 m of the flow length in the area between the groynes. Figure 6 shows the comparison between simulated and measured mean bottom evolution for both modules SISYPHE and GAIA. Numerical simulations performed with GAIA and SISYPHE reasonably good fit the measurements and show similar results. In Figure 7 the difference between the bed evolution computed by GAIA and SISYPHE is presented. Most of the differences occur at the transition zone from rigid to movable bed. This effect is stronger near the model inlet which points to a different behaviour at the inlet boundary. Further investigations are necessary to clarify the causes. The bottom evolution and mean diameter distribution for the total simulation time are shown in Figures 8 and 9 for both GAIA and SISYPHE modules. In Figure 10, comparisons between SISYPHE and GAIA at cross sections Rhine-km 740.7, 743.6 and 746.9 (see Figure 5), show that the model is able to reproduce bed evolution levels at the meandering reach.

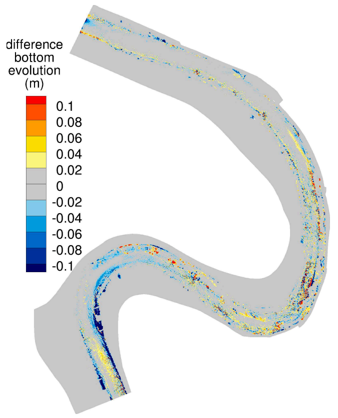
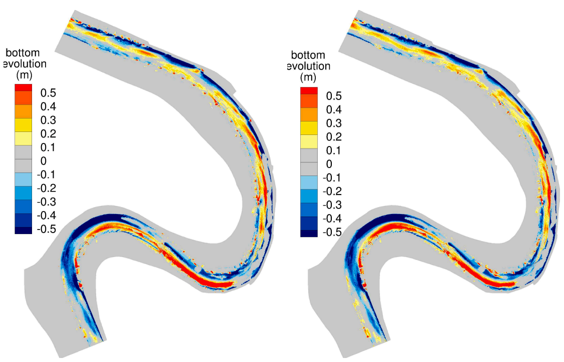


Fig. 7: Differences of the bottom evolution between Gaia and Sisyphe after 6.5 years.



(a) Gaia (b) Sisyphe

Fig. 8: Bottom evolution after 6.5 years

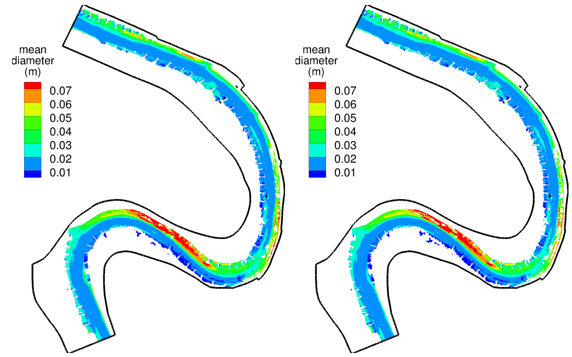
VIII. Outlook

Within this new code structure available in the TMS, a large number of complex physical processes commonly found in river, coastal and estuarine modelling applications benefit of an optimized framework.

Gaia can easily be expanded and customized to particular requirements by modifying user-friendly, easy-to-read, and well-documented `FORTRAN` files. Last but not least, theoretical aspects and validation test cases are documented and continually updated so that the quality of the source code remains assured.

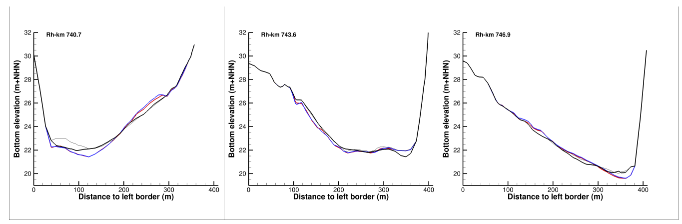
For the current release of the TMS, the adaptation of the Continuous Vertical grain Sorting Model (CVSM) methodology [12] within the Gaia framework is underway.

Verification and validation cases presented in this work and being performed by the TMS's development team show that Gaia is on its way towards operational readiness.



(a) Gaia (b) Sisyphe

Fig. 9: Mean diameter distribution after 6.5 years



(a) sec. 740.7 (b) sec. 743.6 (c) sec. 746.9

Fig. 10: Bottom elevation at different sections of the river reach, see Figure 5 for locations. Above, red line: Gaia, blue line: Sisyphe, black thick line: measured 2006 and black thin line: measured 2000.

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Appendix

A summary of new keyworks and printout variables is given below (variable values are provided as an example).

A. New keywords

1) General:

- `CLASSES TYPE OF SEDIMENT = NCO;NCO;NCO;NCO;NCO`, with `NCO` and `CO` for non-cohesive and cohesive sediments, respectively.
- `LAYERS NON COHESIVE BED POROSITY = 0.37500` one value for each initial stratification layer (see below: A5 *Bed model*)
- `CLASSES SEDIMENT DENSITY = 2650.;2650.;2650.;2650.;2650.`
- `CLASSES SHIELDS PARAMETERS = 0.047;0.047;0.047;0.047;0.047`
- `CLASSES SEDIMENT DIAMETERS = 0.00031;0.00064;0.00103;0.00169;0.00336`
- `CLASSES INITIAL FRACTION = 0.2;0.2;0.2;0.2;0.2`

2) Bedload:

- `BED LOAD FOR ALL SANDS = YES`
- `BED-LOAD TRANSPORT FORMULA FOR ALL SANDS = 1`. Use `= 0` if the bed transport formula is provided by the user with the FORTRAN file `user_bedload_qb.f`.
- `CLASSES HIDING FACTOR = 1.;1.;1.;1.` default if `HIDING FACTOR FORMULA = 0`
- `MORPHOLOGICAL FACTOR ON TIME SCALE = 1`

3) Suspended load:

- `SUSPENSION FOR ALL SANDS = NO`
- `CLASSES SETTLING VELOCITIES = -9;-9;-9;-9;-9`. Use `= -9` if the settling velocity is computed by Gaia.
- `SUSPENSION TRANSPORT FORMULA FOR ALL SANDS = 1`
- `MORPHOLOGICAL FACTOR ON BED EVOLUTION = 1`

4) Cohesive sediment:

- `LAYERS MUD CONCENTRATION = 50.`
- `LAYERS CRITICAL EROSION SHEAR STRESS OF THE MUD = 0.1`
- `LAYERS PARTHENIADES CONSTANT = 1.E-4`

5) Bed model:

- `BED MODEL = 1`, options: `= 1` multilayer case, Gaia sets automatically the active layer if several classes; `= 2` multilayer with consolidation; and `= 3` consolidation model based on Gibson's theory.
- `NUMBER OF LAYERS FOR INITIAL STRATIFICATION = 1`
- `LAYERS INITIAL THICKNESS = 1`

The subroutine `user_bed_init.f` allows the user to define the bed structure by a given (constant) number of layers.

6) Consolidation:

- `NUMBER OF LAYERS OF THE CONSOLIDATION MODEL = 1`
- `LAYERS MASS TRANSFER : 0.`

7) Numerics:

- `ADVECTION-DIFFUSION SCHEME WITH SETTLING VELOCITY = 1`

8) Waves:

- `TYPE OF WAVES = 2`, the option by default is `= 2` (irregular waves). Use `= 1` for regular (monochromatic) waves.

B. New printout variables

- `kRi="fraction of cohesive sediment of class i, in k layer"`
- `kXKV="porosity of 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"`

Above, `k` stands for the layer number (i.e. `1` is the first layer, `2` is the second layer, etc.).

C. *Converter* SISYPHE *to* GAIA

The python script `converter.py` converts the steering files from Sisyphe to Gaia (to be used with caution): `converter.py sis2gaia sis_cas gaia_cas`, with `sis_cas` and `gaia_cas` the steering files for Sisyphe and Gaia, respectively.