Conference Paper, Published Version

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COURLIS: a new sedimentology 1D module for MASCARET

COURLIS: a new sedimentology 1D module for MASCARET

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***Abstract*— COURLIS is a 1D sedimentology module coupled with MASCARET. The code has been developed by EDF R&D for many years. Recently, CIH identified the need to have a 1D bedload code to model the long term evolution of rivers and reservoirs (several decades).**

After a benchmark of existing and available 1D codes, we chose to develop an efficient version of COURLIS which calculates bedload transport. New numerical schemes were implemented, some improvements were done in the geometry evolution algorithms. In terms of performance and robustness, the best scheme implemented is a finite volume upwind/downwind scheme.

This new version of COURLIS was validated successfully on several test-cases (Soni, Newton ...). A real case of a river with a reservoir has been simulated during an 11 year period. These 11 years were reduced to 2 years after cutting flowrates lower than the sediment incipient flowrate. The calculation time on this real case is very similar to those obtained with codes tested in the benchmark and the results are in a good agreement with measurements and other code results.

The next step for COURLIS will be its integration into the TELEMAC-MASCARET system.

I. INTRODUCTION

Sediment management, sediment deficit or deposit in rivers and reservoirs are major issues:

- Environmental issue: Sediment continuity is required for the sustainable management and achievement of a good ecological state of the water resources mentioned by the Water Law (2006), French translation of the European Water Framework Directive (2000).
- Safety issue: Sediment deficit may lead to the alteration of the anthropic structures (bridge, dam ...) by scouring, and it may cause disturbance of drinking groundwater supply facility. Conversely, the presence of alluvial banks (mainly vegetated) can lead to an increase of flood risk and erosion of embankments due to the reduction of section caused by fixed bars.
- Tourism and economic issues: navigation can be affected by an increase in bed level and the visual impact (banks).

In addition, the hydraulic energy producer EDF also encounters production problems, for example, the reduction of the storage capacity of a reservoir. Fig. 1 illustrates the simplified issues that EDF is regularly confronted with: by reducing the flow velocities, the reservoir leads to the deposition of sediment (solid backwater due to the deposit of coarse sediment upstream and siltation close to barrage). Deposition leads to several problems: increased risk of flooding, reduced capacity of the reservoir, sealing of the bottom gate. In addition, the dam limits sedimentary continuity by limiting the solid supply downstream, causing a gradual erosion of the bed downstream of the reservoir.

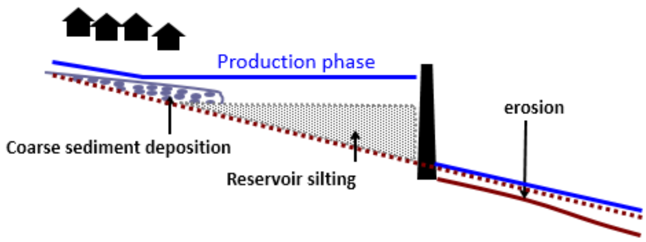

Figure 1. *Morphological evolution due to the dam*

To address these issues, EDF seeks to define optimized sediment management methods. This work should be done at the scale of its hydraulic valleys because in many rivers several reservoirs are managed together.

Numerical tools can be used to evaluate the consequences of several scenarios of sediment management (dredging, flooding, sluicing...). Among all available codes, 1D hydro-morphodynamic models allow the calculation of orders of magnitude concerning:

- total volumes transported and deposited,
- average bed level evolution.

Such results could be calculated for a period from some hours (floods) to several decades without large computation times.

In order to be able to lead sediment studies, CIH was looking for a 1D sediment transport code which would be stable with low computation times. First a review of existing tools has been performed then specific developments have been done in MASCARET-COURLIS.

II. Inventory of 1D numerical tools available in 2015

A. COURLIS

COURLIS is a one-dimensional numerical code originally developed at EDF (R&D) under the TELEMAC-MASCARET suite. A morphodynamic module is coupled with the MASCARET hydraulic code and allows to model the transport of the sediments and the bed evolution.

The first version of COURLIS modelled the transport of cohesive sediments in one-dimensional flows. The main applications were the optimization of flooding, emptying of reservoirs, and the study of settling basin [1], [2], [3], [4], [5].

The second version included the transport of sand by suspension.

And a third version of the software was developed to integrate the bedload transport (sands and gravels). Laboratory validation tests case had been successfully performed, but the code was unstable when used on real cases geometry. Moreover, the CPU time was too important for real applications.

B. 1D sediment transport software

Several 1D sediment transport software exist outside TELEMAC-MASCARET suite. After an initial selection, EDF CIH has selected two software to realize a benchmark (HEC-RAS, MIKE) in 2015.

Additional tests were performed by Artelia with their in-house developed software (CAVALCADE).

1)HEC-RAS:

It is a freeware but it presents too many problems which limit the calibration possibilities: many test cases failed due to the appearance of a non-physical diameter (3.048×10^{-8}m in the active layer).The transport formulas are limited and non-representative of the ones used in France.

The code is not open-source. Attempts to use the forum or contact a developer by mail have not been successful.

2)MIKE :

This software gave correct results for the chosen test cases. The customer service is good. However, the required formation time is significant.

The file formats between MASCARET and MIKE are not compatible and the integration of non-georeferenced geometries is problematic with a text file. As the CIH hydraulic studies are performed using MASCARET, the hydarulic and sediment files should be compatible.

Interpretation of results is sometimes difficult due to the limited number of available output data. The 'average bed level' result is not available whereas it is the data used for the calibration of the model. Otherwise the code is not open-source.

3) Conclusion

Following this benchmark, and taken into its needs, the CIH decided to continue the developments of the EDF-R&D software COURLIS. The new developments aim at adding a robust bedload module.

III. Model

COURLIS bedload is a sediment module and is coupled with MASCARET (same way as TELEMAC – SISYPHE):

$$\partial_t A_z(t,x) + \partial_x Q_s(t,x) = 0 \quad (1)$$

with A_z (m^2) sediment volume in a cross-section and Q_s (m^3/s) volumetric sediment flux integrated along the transversal direction. The flow mean velocity is calculated by MASCARET and used by COURLIS to calculate the mean shear stress on the bed. The bottom evolution is calculated with the Exner equation (1) and a relation between A_z and Z the bottom elevation. This new bottom elevation is sent to MASCARET, and so on.

To close the Exner – shallow water equation system a bedload formula is required. Four different bedload formulas are coded:

- Meyer-Peter and Müller (1948);
- Engelund and Hansen (1967);
- Recking (2011);
- Lefort (2015).

To solve the Exner equation, a 1D finite volume discretization is adopted:

$$(A_z)_i^{n+1} = (A_z)_i^n - \frac{\Delta t}{\Delta x}\left((F^{Q_s})_{i+1/2}^n - (F^{Q_s})_{i-1/2}^n\right) \quad (2)$$

with $(F^{Q_s})_{i+1/2}^n$ numerical flux evaluated at $x_{i+1/2}$ interface, Δt a timestep and Δx a space step ($X_i^n = X(n\Delta t, i\Delta x)$). Three different schemes were tested to solve numerical fluxes:

- a Roe scheme [6] (abandoned),
- a staggered scheme [7], [8] (named stag scheme in the following),
- an uncentered scheme, upwind or downwind according to the flow regime before and after the cells interface (critical and/or subcritical) [9], [10].

The third scheme was identified during the development as the most stable and robust.

In addition to the implementation of bedload formulas and numerical schemes to solve the Exner equation, a new method has been developed to optimize the update of the bottom elevation. Initially, the MASCARET subroutines calculating 1D geometric quantities from real geometry (1D profiles) were used to update the bottom from COURLIS calculations ("to planimeter" refers to these calculations in the following). However, these routines slowed dramatically the simulations.

First, a threshold condition has been defined. The bottom is modified only when sediment erosion or sediment deposition were higher than a percentage of the water depth defined in the code. Before this modification, the "planimeter criterion" was a fixed value equal to 10^{-5} m.

Secondly, a new method to calculate deposition was implemented. Initially, deposition was done according to water depth. This definition is coming from COURLIS suspension, it allows to take into account a constant deposition on each node of the cross-section under the water level (named "delta constant planimeter method" in the following). It is not adapted to bedload sediment transport and so, constant elevation deposition was implemented (named "level constant planimeter method"). This method is *a priori* more suitable for bedload sediment transport and it is also more efficient. It allows to calculate the bed evolution easily and the1D quantities required by MASCARET like wetted areas.

Tests were also performed using either supercritical or subcritical kernels for the hydraulic solver.

IV. Validation Test Cases

A set of three experiments was selected to test the new developments.

A. Dam Break Experiment

The experiment of B. Spinewine and Y. Zech [11] reproduces a series of small-scale laboratory experiments of dam-break waves propagating over loose granular beds, established in a dedicated flume equipped with a fast downward-moving gate.

The sediment bed saturated with water is made of PVC, the grains are lighter than gravel or sand, in order to accentuate the geomorphological action of the dam break on the laboratory scale. To reproduce a dam, a 6 mm thick gate is placed in the center of the flume and retains a volume of water with a depth of 35 cm. When the gate is suddenly removed, a dam-break wave is formed and causes a strong sediment transport.

This test case allows us to verify the robustness of the numerical schemes. Therefore, the aim is not to reproduce the erosion rate because the bedload formula underestimates erosion (maybe because a part of sediment is transported by suspension). Furthermore, the evolution of the bed is very quick: the reference time for comparing the results to the observations is 1.4 second.

Table 1. Dam Break experimental parameters

Length **width** **slope**	Lo=6 m L=0.25 m S=0
Upstream flowrate **Level upstream the dam** **Level downstream the dam**	Q=0 $m^3.s^{-1}$ h=0.35 m h=0 m
Sediment layer concentration **Mean diameter** **Sediment density**	C=1650 $kg.m^{-3}$ D_{50}=0.32 mm s=1.58 $g.cm^{-3}$

The result shows that the uncentered scheme is stable on this case while the stag scheme is not stable (see Fig. 2). This instability eliminated the stag scheme, and so the results for this scheme are not presented in the following test cases.

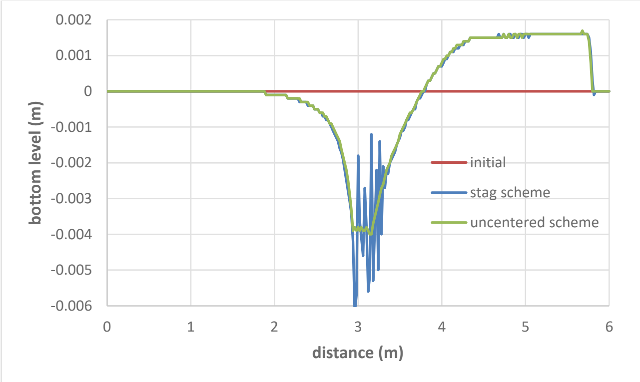

Figure 2. *Bottom evolution due to the dam break after 1.4s*

B. Soni Experiment

The aim of this experiment, carried out by J.P. Soni in 1980, is to study aggradation of sediment. The sediment supply is increased above the equilibrium sediment transport capacity of the flume [12], [13]. The evolution of the deposit is monitored during the experiment at 30, 60 and 90 min.

Table 2. Soni experimental parameters

Length **width** **slope**	Lo=30 m L=0.2 m S=0.0051
Flow rate **water level** **velocity**	Q=0.0071 $m^3.s^{-1}$ h=0.072 m V=0.49 $m.s^{-1}$
Mean diameter **Grain size range** **Sediment density** **Upstream concentration**	D_{50}=0.32 mm σ=1.30 s=2.65 $g.cm^{-3}$ C_s=4.88 $kg.m^{-3}$

Results are presented in Fig. 3 for the uncentered scheme and the Meyer-Peter and Müller formula. The comparison shows a fairly good agreement with the 3 measurements (30, 60 and 90 min).

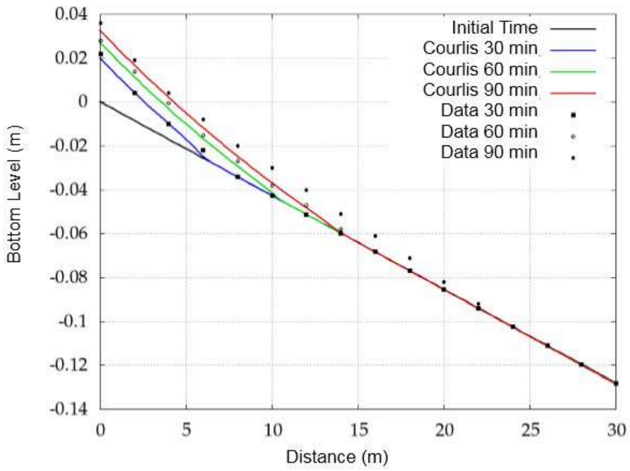

Figure 3. *Bottom evolution of the Soni experiment: measurement and calculations*

Tab. 3 summarize the calculation times. The uncentered scheme drastically reduces the calculation time. The subcritical kernel and the planimeter criterion reduce also this time. The new planimeter method does not increase performance in this case.

TABLE 3. SONI EXPERIMENT EXECUTION TIME

Scheme	*old vers.*	*ROE*	*Stag*	*Uncentred*			
Planim. Crit.	*10^{-5} m*				*5% of water level*		
Numérical scheme	*supercritical*						*subcritical*
Planim. method	*delta const.*					*level const.*	
Execution time	1h 43min	31min 22s	11s	39s	11	11s	1.4s

C. Newton Experiment

A degradation is often observed downstream of dams due to the interruption of sediment flow from upstream. The aim of the experiment, carried out by T. Newton in 1951 [14], is to study the erosion process in a flume in order to better understand this phenomenon. The evolution of the bottom of the flume following the interruption of the sediment supply is observed during 24 hours.

TABLE 4. NEWTON EXPERIMENTAL PARAMETERS

Length **width** **slope**	Lo=9.14 m L=0.3048 m S=0.00416
Flow rate **water level** **velocity**	Q=0.00566 m3.s-1 h=0.041 m V=0.45 m.s-1
Mean diameter **Sediment density** **specific weight of sediment**	D50=0.68 mm s=2.65 g.cm-3 C=1610 kg.m-3

Results are given on Fig. 3 for the uncentered scheme and the Meyer-Peter and Müller formula. The comparison show a fairly good agreement with the 3 measurements (1, 4 and 24h).

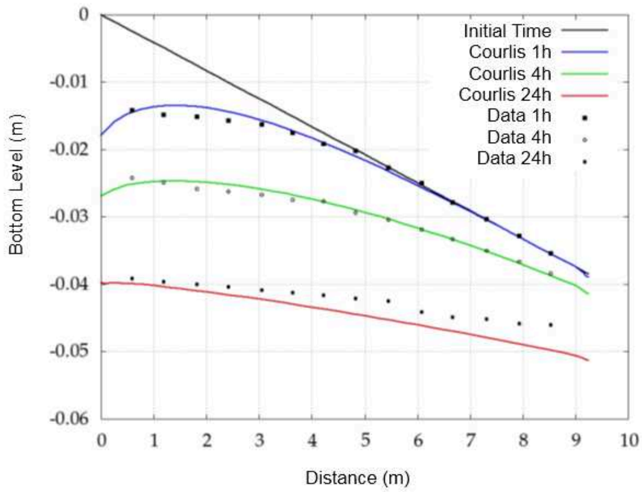

Figure 4. *Bottom evolution during the Newton experiment: measurement and calculations*

Tab. 5 gives calculation times. The conclusion are the same as for the Soni case except for the planimeter criterion that does not increase performance here.

TABLE 5: NEWTON EXECUTION TIME

Scheme	*old vers.*	*ROE*	*Stag*	*Uncentred*			
Planim. Crit.	*10^{-5} m*				*5% of water level*		
Numérical scheme	*supercritical*						*subcritical*
Planim. method	*delta const.*					*level const.*	
Execution time	1h 20min	1h 28min	4min 30s	4min 47s	4min 35s	4min 19s	30s

V. REAL RESERVOIR TEST CASE

This test case is based on an EDF reservoir. The study area is 3.9 km long (1.8 km of reservoir and 2.1 km upstream the reservoir). The objective is to simulate the bed evolution from the end of the year 2002 to the beginning of 2014. This period includes flushing events. Consequently, in different zones of the model, the bed alternates between periods of deposition and erosion of sediments generated by high flows (for this first step of calibration, flowrates below 20m^3/s are excluded). The river bed presents strong discontinuities (significant increase of the slope, variation of width). These discontinuities are a real challenge and the main difficulty of this test case in terms of modelling.

It is a well-documented reservoir with many campaigns of topographic and bathymetric surveys. The first step of the study addresses the robustness and the calculation time. This first step is presented hereafter. The second step, calibration and comparison with the measurement results will be carried out in the future.

Two meshes are used (fine and coarse), the geometric and physical parameters of the model are presented in Tab. 6.

TABLE 6. REAL TEST CASE PARAMETERS

Length **Width** **Slope**	Lo=3900 m around 150 m S=0.00416
Flow rate	$0.8 < Q < 754\ m^3.s^{-1}$
Sediment diameter **Sediment density** **Sediment layer concentration**	D50=2.5 10^{-2} m s=2.65 $g.cm^{-3}$ C=2000 kg.m-3
Number of cross-sections	196 (fine mesh) 48 (large mesh)

Results are presented in Fig. 5 (the lowest point of the cross-section is plot). There are few differences between the two meshes (less than 10 cm).

The difference between the two planimeter methods is normal. The level constant method tends to suppress the trenches in the cross-section.

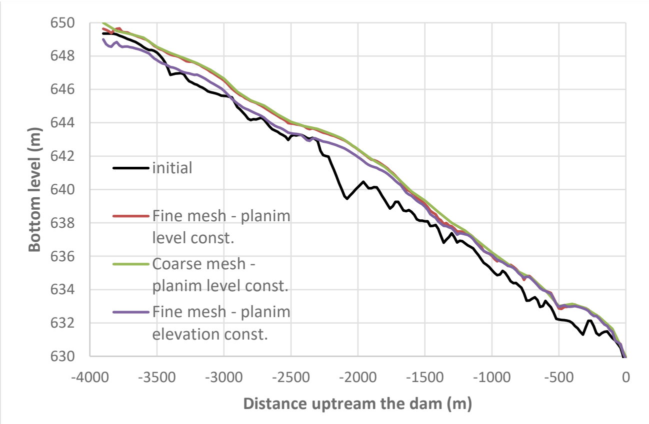

Figure 5. *Bottom evolution of the Real test case calculation*

Calculation times are given in the Tab. 7. The planimeter method does not decrease the calculation time. Important parameters are the mesh and the planimeter criterion. Improvement are still possible with the use of the subcritical scheme (unstable here with the old version of MASCARET currently being used in COURLIS).

TABLE 7. REAL TEST CASE EXECUTION TIME

Mesh	***Fine***			***Large***
Scheme	***Uncentred***			
Planim. Crit.	***10^{-5} m***	***5% of water level***		
Numérical scheme	***supercritical***			
Planim. method	***delta const.***	***delta const.***	***level const.***	***level const***
Execution time	> 100 day	17h 41min 54s	17h 15min 15s	2h 28 min 27s

The calculation times obtained with HEC-RAS and MIKE are respectively 30 min and 3h 15min (simulation of the whole duration with the flow rate under $20m^3/s$). The calculation time obtained with CAVALCADE (Artelia software) is 1h 30 min (simulation with the hydrograph excluding flow under $20m^3/s$).

VI. PERSPECTIVE

A. *Real test case calibration*

A calibration of the real test case reservoir will be carried out in 2018. COURLIS bedload version will be tested also on other test cases.

B. *Developments*

A post-doctoral work will start in 2018. The main objectives of this post-doctoral work will be to further develop the software by integrating new physical processes such as.

- Integration of several transport formulas,
- Integration of an extended granulometry model,
- Management of the transition from a rocky bottom to an alluvial bottom (adaptation of the friction law)

C. *TELEMAC-MASCARET trunk integration*

COURLIS should be integrated in the trunk in 2018 (possibly, with the suspension version). Some adaptations of the code have to be done because a lot of developments are still “hardcoded”.

Besides, MASCARET version currently used is an old one. Integration with the trunk version of MASCARET will allow us to have the last version of MASCARET coupled with COURLIS. Better stability and efficiency are expected with this update.

VII. CONCLUSION

Laboratory test cases (dam-break, Soni and Newton experiments) show that COURLIS (in its new bedload version) is giving results in a fairly good agreement with measurements. Moreover, several numerical schemes have been tested and the uncentered scheme showed good properties (stability, robustness, efficiency, etc.). Some developments have been done to reduce calculation times.

A real test case shows that developments carried out on the bedload version of COURLIS allow the software to simulate long term evolution of gravel bed rivers. This work will continue in 2018 to integrate COURLIS in the TELEMAC MASCARET open source system.

REFERENCES

[1] Bertier, C., Bouchard, J.-P. & Dumond, L. (2002) - One dimensional model for reservoir sedimentation management. Proc. River Flow 2002

[2] Valette E., Jodeau M., How to predict the sedimentological impacts of reservoir operations? Proc. ISCE-6 2012 unspublished

[3] Valette E., Villaret C., Tassi P., Jodeau M., Villaret C., St Egrève reservoir – Multi-dimensional modelling of flushing and evolution of the channel bed. Proc User Club TELEMAC-MASCARET 2013 unpublished

[4] Antoine G., Besnier A.-L., Jodeau M., Camenen B., Esteves M., Numerical modeling of suspended sediment transport during dam flushing : From reservoir dynamic to downstream propagation. Proc. River Flow 2014, published in Reservoir Sedimentation (crc Press) p175-184

[5] Valette E., Tassi P., Jodeau M., Villaret C., St-Egrève reservoir – Modelling of flushing and evolution of the channel bed. Proc. River Flow 2014, published in Reservoir Sedimentation (crc Press) p185-184

[6] C. Juez, J. Murillo, and P. Garcia-Navarro. A 2D weakly-coupled and efficient numerical model for transient shallow flow and movable bed. Adv. Water Resour., 71 :93–109, 2014

[7] P. H. Gunawan, R. Eymard, and S. R. Pudjaprasetya. Staggered scheme for the exner–shallow water equations. Computat. Geosci., 19(6) :1197–1206, 2015

[8] E. Audusse, S. Boyaval, N. Goutal, M. Jodeau, and P. Ung. Numerical simulation of the dynamics of sedimentaryriver beds with a stochastic exner equation. ESAIM : Proc., 48 :321–340, 2015

[9] S. Cordier, M. H. Le, and T. Morales de Luna. Bedload transport in shallow water models: Why splitting (may) fail, how hyperbolicity (can) help. Adv. Water Resour., 34 :980–989, 2011.

[10] P. Ung. Simulation numérique du transport sédimentaire : aspects déterministes et stochastiques. PhD thesis, Unversité d'Orléans, 2016

[11] B. Spinewine and Y. Zech. Small-scale laboratory dam-break waves on movable beds. Journal of Hydraulic Research, 45, 2007. pp. 73-86

[12] Soni J. P, (1981). Laboratory study of aggradation in alluvial channels. Journal of Hydrology, 49(1), 87-106.

[13] Soni J. P, (1981). Unsteady sediment transport law and prediction of aggradation parameters. Water Resources Research, 17(1), 33-40.

[14] Newton C.T, (1951). An experimental investigation of bed degradation in an open channel. Technical report, Boston Society of Civil Engineers, pp 28-60.