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1D sediment transport modeling of reservoir operations

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Test cases and application

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***Abstract*— COURLIS numerical code has been developed in order to calculate sediment transport, erosion and deposition. This numerical tool is used to simulate the effects of reservoir operations as emptying or flushing. COURLIS is based on a coupling between MASCARET (hydrodynamic) and a sediment component which allows calculation for sand and silt. Calculations with COURLIS on test cases are compared with experimental data. Eventually the capability of the code is illustrated with an example of reservoir emptying.**

I. INTRODUTION

Sediment transport and deposition in reservoirs is a worldwide subject of interest [1]. There may be impacts downstream and upstream of dams. In the French valleys, the filling of reservoirs depends on the production of sediment from the watersheds; it can be large and may be composed of gravel and/or silts. Hydroelectricity operators as EDF, have to take into account sediments when operating dams, therefore they need ways to predict the consequences of dam operations on sediment transport and reservoir morphology.

During emptying operations, one should avoid sediment erosion and downstream sediment output in order to mitigate water quality degradation. Reversely, flushing operations aim at eroding sediments from reservoirs to maintain or increase their storage capacity and/or prevent flooding upstream the dam. In such operations, the release of sediments to the downstream reach may be significant [1] and should be controlled [7]. There are different ways of predicting the downstream impacts of such operations, it often relies on experience, nevertheless numerical modeling could be used with relevant results.

This paper describes the use of a one dimensional sediment transport numerical model, COURLIS, to simulate reservoir operation or sediment transport in rivers. COURLIS is a one dimensional code for fine sediment transport modeling, it has been developed at EDF for more than 20 years, it is a component of the open-source TELEMAC-MASCARET system (www.opentelemac.org).

First, the basic principles of COURLIS are described. Then calculations with COURLIS on test cases are compared with experimental data. Eventually the capability of the code is illustrated with an example of reservoir emptying. The emptying of Tolla reservoir shows how numerical modeling can be used to assess the sediment release and to define an optimal emptying scenario.

II. COURLIS NUMERICAL CODE

A. Overview of COURLIS

COURLIS numerical code allows the computation of one dimensional flow and the sediment transport of mud and sand. COURLIS is based on a coupling between the hydraulic open-source component MASCARET which solves the 1D shallow water equations [3] and the sediment component which handles sediment processes. Both hydraulic and sediment components could be coupled at each time step, i.e. the hydraulic variables are calculated for a fixed bed then the bed evolution is calculated. If the hydrodynamic varies slowly, the user could define a less frequent coupling, for example coupling every ten or more hydraulic time steps. Details about the implemented equations can be found in previous papers [1] or [5], the following paragraphs give the main principles of the code.

B. Sediment transport, erosion and deposition modeling

Sand and cohesive sediment are dealt separately. For both type of sediments a one dimensional advection-dispersion equation is solved:

$$\frac{\partial A.C}{\partial t}+\frac{\partial Q.C}{\partial x}=\frac{\partial}{\partial x}\left(k.A.\frac{\partial C}{\partial x}\right)+Q_{erosion}-Q_{deposition}+Q_{bank}+S.q$$

Where : k dispersion coefficient (m^2/s)
q volumic sources ($kg/m^3/s$)
$Q_{erosion}$, … source terms for erosion, deposition and bank stability (kg/m/s)

For cohesive sediments, Partheniades (1961) and Krone (1962) empirical formulae are used to calculate erosion and deposition fluxes respectively:

Deposition $\quad q_{deposition}=C.W_s.\left(1-\frac{\tau}{\tau_{cd}}\right) \quad$ if $\tau < \tau_{cd}$

Erosion $q_{erosion} = M.\left(\frac{\tau}{\tau_{ce}} - 1\right)$ if $\tau > \tau_{ce}$

Where τ_{ce} and τ_{cd} are respectively critical shear stresses for erosion and deposition.

For sand, i.e. non cohesive sediments, the transport capacity, q_s, is calculated with the Engelund Hansen formula (1967). An equilibrium concentration, C_{eq}, is obtained:

$$q_s = 0.05\sqrt{\frac{\delta d^3}{g}}\frac{K^2 R_h^{1/3}}{(\rho_s-\rho)gd}\tau_{eff} \qquad C_{eq} = \frac{\rho_s q_s}{Q}$$

Deposition and erosion fluxes depend on the difference between concentration in the flow, C_{sand}, and equilibrium concentration:

$$\begin{cases} \text{if } C_{sand} \geq C_{eq} \text{ deposition} & D = w_s\left(C_{sand} - C_{eq}\right) \\ \text{if } C_{sand} \leq C_{eq} \text{ erosion} & E = w_s\left(C_{eq} - C_{sand}\right) \end{cases}$$

$$\frac{\partial Zb}{\partial t} = \frac{D}{C_{deposition}} - \frac{E}{C_{layer}}$$

Besides, the bank deformation is taken into account using a simple model, the bank slope is compared to a stability slope (submerged or emerged). If the critical slope is exceeded, sediment deposit is supposed to collapse immediately.

COURLIS numerical code has already been used to define efficient sediment management for various French reservoirs: the flushing of Genissiat and Saint Egrève reservoirs, [1] and [8], the emptying of Grangent and Tolla reservoirs, [5] and [4].

III. TEST CASES: COMPARISON WITH EXPERIMENTAL DATA

The following comparisons between numerical calculations and laboratory experiments show the capability of COURLIS to well calculate sand transport.

A. Erosion : Newton experiment

The Newton laboratory experiment [7] gives data to test erosion process. A flume is fed with sediment at equilibrium concentration. Measurements were performed in the flume after the stop of the upstream sediment input. Bed erosion is observed. The experiment parameters are given in TABLE I.

TABLE I. NEWTON EXPERIMENT, PARAMETERS

Flume length	L	9.14	(m)
Flume width	w	0.3048	(m)
Slope	S	0.00416	
discharge		0.00566	(m3/s)
Downstream water depth	Hd	0.041	(m)
Upstream concentration	Cu	0.88	(g/l)
Median grain size	d50	0.68	(mm)

In order to model this experiment, COURLIS is tested. The mesh size is 25cm, Strickler coefficient value is $67m^{1/3}s^{-1}$ and dispersion coefficient is $1.0\ m^2s^{-1}$. The calculation gives very good results, Figure 1 . For the three measurement times, calculated values of bed evolution are very near from the measurements. The Meyer Peter Formula is also tested and gives even better results, in particular in the upstream part of the flume, Figure 2.

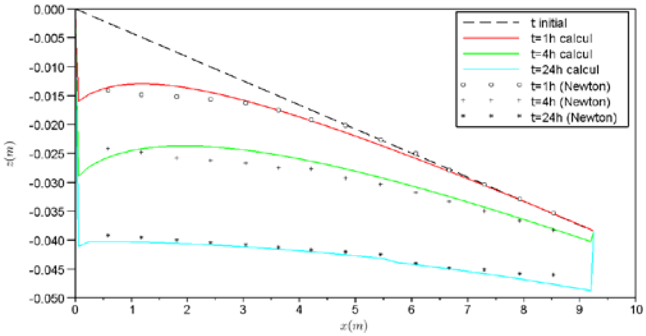


Figure 1. Newton experiment, calculation with Engelund Hansen formula.

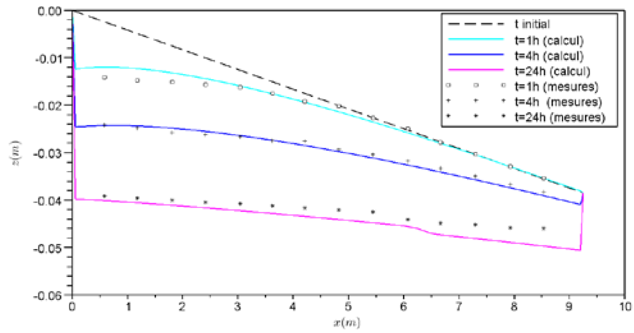


Figure 2. Newton experiment, calculation with Meyer Peter and Muller formula.

B. Deposition : Soni experiment

The Soni experiment [9] provides experimental data to test deposition process. A flume was fed with sediment at equilibrium concentration. Measurements were performed in the flume after an increase of the upstream sediment input. Bed deposition is measured. The experiment parameters are given in TABLE II.

TABLE II. SONI EXPERIMENT, PARAMETERS

Flume length	L	30	(m)
Flume width	w	0.2	(m)
Slope	S	0.00427	
discharge		0.0071	(m3/s)
Downstream water depth	Hd	0.072	(m)
Upstream concentration	Cu	4.88	(g/l)
Median grain size	d50	0.32	(mm)

In this calculation the mesh size is 25cm, Strickler coefficient is $45m^{1/3}s^{-1}$ and dispersion coefficient is

0.025m^{2}s^{-1} . A non equilibrium coefficient [3] is used in the deposition law in order to better represent the dynamic of deposition. The value of this coefficient is set to 0.54.

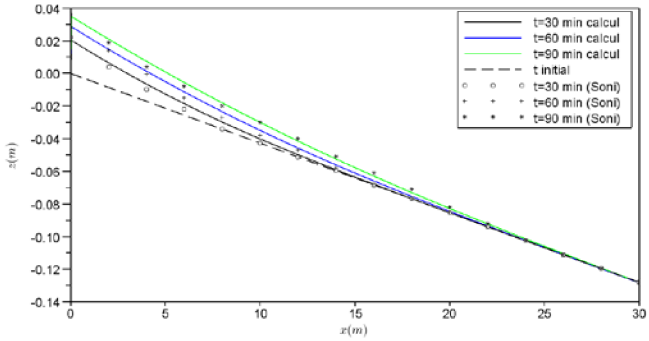


Figure 3. Soni experiment, calculation with COURLIS.

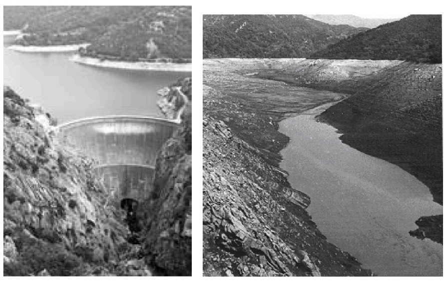
Results of deposition calculations well reproduce the experiment, Figure 3. There is a small over estimation of deposition in the upstream part of the flume.

IV. MODELLING RESERVOIR EMPTYING

COURLIS has been developed in order to model reservoir operations. It allows calculation of flushing flows but also simulation of reservoir emptying.

A. Tolla Reservoir

Tolla reservoir is located in South Corsica (France), the upstream watershed (132 km^2) is made of granite and covered by dense vegetation. Therefore sediment inputs are sand and organic matter. The dam, 90m height, was put in operation in 1965, Figure 1. The reservoir has a volume of 35 10^6 m^3 and a surface of 1.18 km^2. An emptying of the reservoir has to be done in the next years. One way to achieve mitigation of water quality degradation during operations is to control sediment output through the reservoir. Numerical modelling is performed to compare drawdown scenarios and to identify the less downstream impacting scenario. One dimensional modelling is well suited because of the large size of the reservoir (5km long), but also because we focus on the output concentration and we don't need details on three dimensional patterns in the reservoir.



(a) (b)

Figure 4. (a) Tolla dam; (b) Picture of the reservoir during the 1981 emptying;

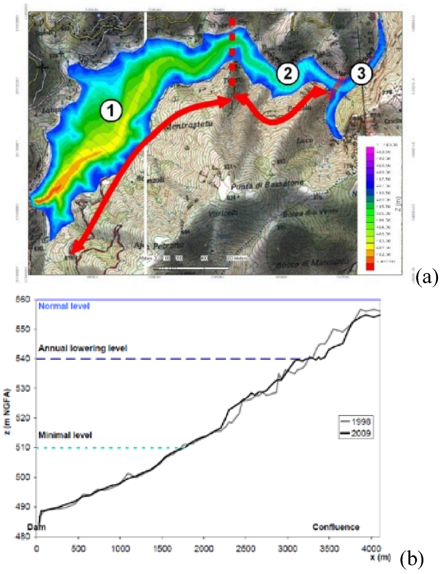


Figure 5. (a) reservoir bathymetry, definition of the three sediment specific area of the reservoir; (b) longitudinal profile.

In order to quantify sedimentation in the reservoir and estimate sediment properties, measurements were performed. Two bathymetries, 1998 and 2009, indicate that the reservoir shows three specific areas, Figure 5. . In addition, 15 sediment cores have been sampled using an Uwitech sampler to characterise the reservoir bed. Cores were located along the thalweg from the dam to the upstream part. The composition of the bed differs in the three areas: **(i) the downstream area**, from the dam to 2.1km upstream, is a deposition area where the sediment bed rises of 4.5cm per year. Low concentrated cohesive sediments are sampled; 1m layer of mud is implemented in the model. Some layers of tree leaves are squeezed in the sediments; **(ii) the middle area**, from 2.1km to 3.2km, is a delta deposit due to annual level lowering. The bed is made of a surface layer of silt (30cm) and a sub layer of sand (1m), leaves layers are also observed; **(iii) the upstream area**, from 3.2km, is an erosion area. Boulders, gravels, and layers of tree leaves fill the bed. Due to a lack of previous monitored emptying, there is not any calibration data to validate the model. Therefore the model is built upon the available measured data, analogy with sediment from other reservoirs is performed [7][6][1].A parametric analysis is used in order (i) to assess the weight of each parameter and (ii) to model the emptying with the most pessimistic (but still realistic) set of parameters.

B. Hydraulic and sediment boundary conditions

The emptying of the reservoir is controlled by the opening of the bottom gate and by the upstream discharge. Therefore (i) the upstream boundary condition is the assessed upstream discharge; in a first step, calculations were based on monthly averaged discharges and (ii) the downstream boundary condition is a water level calculated from the opening of the dam gates. Based on input discharge and gate opening, a reference emptying scenario is established from September to mid-February. In the beginning of the period, the level lowering is slow (1.4cm/h from level 558 to 520mNGF and 2.36cm/h, from 520 to 490mNGF), then, due to the smaller amount of water, the lowering is greatly increased to 20cm/h for the last 5m.Upstream sediment concentration is assumed to be almost zero, and downstream boundary condition is a free output (i.e.$\frac{\partial C}{\partial x} = 0$).

C. Numerical parameters

The numerical parameters (vertical and longitudinal meshes, numerical schemes, coupling time step) are chosen in order to obtain reliable results with the shortest calculation times. An explicit scheme is used for the resolution of the hydraulic equation, thus the Courant-Friedrich-Lewy stability condition sets $\left(u + \sqrt{gh}\right)\frac{dt}{dx} < 1$. During the emptying, the low discharge and the high slope in the upstream part lead to supercritical flows and high Froude numbers in the backwater limit zone. Thus a fine mesh must be chosen there. Downstream the backwater limit, water-depth increases to reach 60m at the dam. Thereby, fine meshes lead to small time steps, smaller than 1s. The duration of the emptying is long; it takes 3 months to reach the lowest level, i.e. 1.4 10^7s. The best way to deal with this issue would have been to use a mesh adaptation, that is to say a fine mesh upstream the backwater limit and a large mesh downstream.

The coupling between the hydraulic and the sediment components is time consuming, so we tested different coupling frequencies and chose the one that leads to the smaller calculation time and gives results with small difference to the 1/1 coupling calculation. The coupling frequency has to be fitted to the characteristic time of hydrodynamic variations, i.e. to the speed of the level lowering. In the case of a slow level lowering (2.36cm/h), it highlights the relevant results of some low frequency couplings, below 1000 the results are similar to the 1/1 coupling. Calculation time for a 1000/1000 is 100 times faster than a 1/1 coupling meanwhile results are near from 1/1 results. The same comparisons are performed for a faster lowering (20cm/h), results indicate that a 100/100 coupling should be used.

The size of the vertical mesh (number of points to describe a cross section) is also investigated. The same issue as longitudinal mesh arises. Due to low discharges during the emptying (~4m^3/s), the modifications of the bed are located in the lowest parts of the section, which therefore require a fine discretization where there is erosion. For large meshes (50 points per a 150m large section), erosion is not well represented. We tested different meshes and we eventually selected the one given identical results as a very fine discretization (400 points per section) while leading to the smallest calculation time. In the following, lateral mesh is 200 points per section, i.e. Δx= 0.75m.

D. Parametric Analysis

The lack of calibration data to model reservoir emptying often occurs if there has not been any previous monitored operation. Therefore, the user of a numerical model may follow different means to estimate sediment output. Sensitivity analysis is a way to assess the weight of calculation parameters. Due to large calculation times, the Tolla model does not allow to perform a sensitivity analysis using Monte Carlo simulations. Notwithstanding, we perform sample runs to identify the impact of each parameter on the results. In this emptying calculation, the goal of the calculation is to give an assessment of the masses of sediment eroded from the reservoir (M_{silt} and M_{sand}) and assess the downstream maximal reached concentrations ($C_{max\ silt}$ and $C_{max\ sand}$). Therefore both criteria on mass and maximal concentration were used to identify the set of physical parameters which, in a relevant range, leads to the maximal value, i.e. the worst for the downstream hydro system. We start with common values previously used on this type of reservoir and explore limited ranges below and above these reference parameters. These parameters will be called *default parameters* in the following.

Some parameter variation effects are predictable. But the consequences on maximal output concentrations of sand or silt are not straightforward and effects of some parameters are not easy to foresee. Consequently, each parameter is tested while the others remain constant and equal to their default values. Table 1 shows the whole results. It highlights the small effect of some of the parameters (for example silt Dispersion coefficient) and the weight of others on the results (Parteniades coefficient, for example). In some cases, there is no obvious trend tendency in the effect of an increase of the coefficient on the results, one is able to identify maximising value (for example, Strickler coefficient Ks=30$m^{1/3}s^{-1}$). Parameters of sediment erosion and deposition laws lead to foreseeable results: (i) an increase of Parteniades coefficient, M, or a decrease of the erosion critical shear stress, τ_{ce}, give an increase of silt erosion and consequently of concentration; (ii) an increase of deposition critical shear stress, τ_{cd}, or a decrease of settling velocity lead to a decrease of silt deposition and therefore an increase of output masses. This analysis allows us to identify the set of realistic parameters that provide maximal output concentrations and masses.

E. Emptying scenario

The model is used to compare the reference scenario to different kind of emptying. The velocity of level lowering is increased to 10cm/h and 20cm/h instead of 2.5cm/h in the beginning of the emptying, and 20cm/h is kept in the end of the operation. It would be a way to reduce the duration of the operation. Results on Figure 6. show that the increase of the lowering speed in the first part of the emptying does not affect the value of the maximal output concentration, around 10g/l, as well as the total output mass which is around 6000t. But the duration of concentration exceeding 1g/l varies from 58 to 111h depending on the lowering speed. A longest duration may affect more the downstream fishes. In the case of a large increase of the lowering speed during the end of the emptying, the maximal concentration is strongly affected; it reaches the high value of 25g/l.

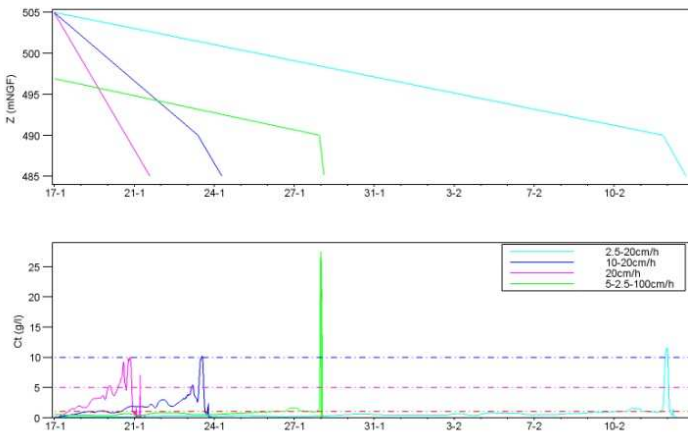


Figure 6. Emptying scenario: (scenarii A, B, C : 2.36, 10 and 20cm/h in the beginning and then 20cm/h of the lowering ; scenario D : first 10cm/h and then 50cm/h), (a) level variations and (b) output concentrations.

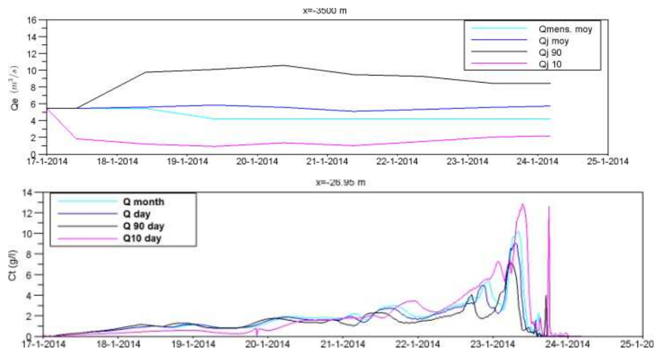


Figure 7. Emptying calculations (10cm/h) for different upstream discharges.

As the upstream discharge remains a source of uncertainty (there is no way of controlling it during the operation), we investigated the effect of the upstream discharge. Calculations were performed with mean monthly and daily discharges, and quartiles 10 and 90 of daily discharges, Q_{10} and Q_{90}, Figure 7. The value of the upstream discharge clearly affects the results: the lower the discharge, the lower the total eroded mass and the higher the maximal output concentration. The calculation with Q_{10} induces a maximal output concentration of 13g/l and an output total mass of 2600t whereas the calculation with Q_{90} leads to a maximal concentration of 7.2g/l and an output mass of 9000t. Even if a higher discharge increases the quantity of eroded sediments, the dilution effect induces a smaller output concentration.

V. CONCLUSION AND PERSPECTIVES

The cases presented in this paper illustrate how numerical modeling of sediment transport with COURLIS is used as a reliable tool to predict the effects of dam operations on sediment transport. Besides, these cases highlight the need of good quality field data sets to perform numerical modeling. Measurements made during dam operation and comparisons with calculated values would have improved the reliability of the numerical results. Unfortunately, no data are available so the numerical results must be analysed with cautiousness. They only allow a qualitative comparison of the scenarios.

REFERENCES

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

[2] S.A. Brandt, "Reservoir desiltation by means of hydraulic flushing: sedimentological and geomorphological effects in reservoir and downstream reaches as illustrated by the Cachi Reservoir and the Reventazon river, Costa Rica" PhD Thesis Institute of geography, University of Copenhagen 1999

[3] D. Chen,; K. Acharya, & M. Stone, "Sensitivity analysis of nonequilibrium adaptation parameters for modeling mining-pit migration" *Journal of Hydraulic Engineering,* 806-811, 2010

[4] N. Goutal & F. Maurel, " A finite volume solver for 1D shallow-water equations applied to an actual river". Int. J. Numer. Meth. Fluids, 38: 1-19, 2002

[5] M. Jodeau & S. Menu, ,"Sediment transport modelling of a reservoir drawdown, example of Tolla reservoir" *River Flow Conference,* 2012

[6] D. Marot, J.-P. Bouchard & A. Alexis, "Reservoir bank deformation modeling: application to Grangent reservoir". Journal of Hydraulic Engineering, 586-595, 2005

[7] G. L. Morris & J. Fan, "Reservoir sedimentation handbook McGraw-Hill", 1997.

[8] C. Newton, "An experimental investigation of bed degradation in an open channel"*Trans., Boston Society of Civil Engineers*, 28-60 , 1951

[9] H. Shen, "Flushing sediment through reservoirs". *Journal of Hydraulic Research*, 37-6, p.743-757, 1999

[10] J. Soni, "Laboratory study of aggradation in alluvial channels" *Journal of Hydrology, 49*, 87-106 , 1981

[11] E. Valette, & M. Jodeau, "How to predict the sedimentological impacts of reservoir operations?" International Conference on scour and erosion, 2012