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1D sediment transport modeling for a sustainable sediment management: Two Case Studies of Reservoir Flushing

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***Abstract*—COURLIS [1] is a one dimensional sediment transport numerical code developed by EDF-R&D-LNHE in association with CETMEF. COURLIS is based on a coupling between the hydraulic open-source software MASCARET [2] (part of TELEMAC-MASCARET system) and a sediment module which handles sediment processes for sand and silt. This numerical tool is used to predict the effects of dam operations as emptying or flushing. In this work, the capability of the code is illustrated with two examples of reservoir flushing, which concern the Saint-Martin-La-Porte Reservoir in the Alps and the Plan d'Arem Reservoir in the Pyrenees.**

I. COURLIS NUMERICAL CODE

Among the different options for modeling flow and sediment transport in reservoir, one dimensional modeling is well adapted if one is not trying to explain and reproduce patterns in deep areas, or around confluences and bifurcations. One dimensional modeling is well suited if long term simulations are expected, and if cross section average values are looked for. Besides, in longitudinal configurations, one dimensional modeling performs as well as 2D modeling as shown by the example of St-Egrève Reservoir modeling [3].

COURLIS numerical code allows the calculation of the sediment transport of mud and sand in open channels under unsteady flow conditions. The outputs of the model are the sediment concentrations throughout the waterway and the changes in the river bed bathymetry due to sediment transport, erosion and deposition.

COURLIS numerical code has already been used to define efficient sediment management for various French reservoirs: the Genissiat Reservoir [1], the Grangent Reservoir [4], the flushing of Saint-Egreve Reservoir in the Alps [5], and the empying of Tolla Reservoir in Corsica [6]. When data were available [4] and [5], the comparison between calculations and measurement showed very good agreement.

A. Cross section view

Despite a one dimensional computation for the flow, the sediment bed is described by a bi-dimensional approach, that is to say sediment layers are defined transversally to the flow axis and bed elevation is computed in 2D, see Fig. 1.

Each sediment layer is characterized by its thickness, its concentration (C_{layer}), its percentages of sand and silt, sand grain size and cohesive sediment characteristics.

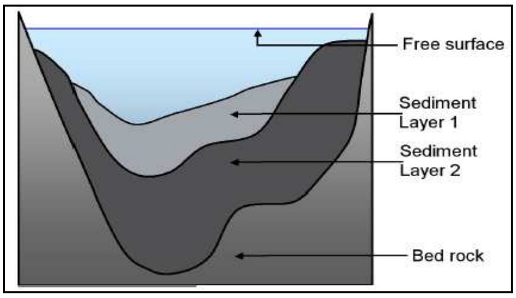


Figure 1. Sedimentary layers for modeling

B. Equations

COURLIS is based on an internal-coupling between the component MASCARET [2], part of the TELEMAC-MASCARET system, which solves the 1D shallow water equations and the sediment module 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 sediment transport and the bed evolution are calculated.

For both type of sediments, sand and silt, an advection-dispersion is solved:

$$\frac{\partial AC}{\partial t} + \frac{\partial QC}{\partial x} = \frac{\partial}{\partial x}\left(kA\frac{\partial C}{\partial x}\right) + E - D \qquad (1)$$

where A is the cross sectional flow area, C the suspended concentration, Q the flow rate, k the dispersion coefficient, E and D are respectively the Erosion and Deposition linear rates.

Erosion and deposition for sand and cohesive sediment are dealt separately:

- For cohesive sediments, Partheniades [7] and Krone [8] empirical formulae are used:

$$E = M\left(\frac{\tau}{\tau_{CE}} - 1\right) \tag{2}$$

$$D = w_s C\left(1 - \frac{\tau}{\tau_{CD}}\right) \tag{3}$$

where M is the erosion rate coefficient, w_s is the settling velocity, τ_{CD} and τ_{CE} are respectively the deposition and the erosion critical shear stresses.

The local shear stress is written:

$$\tau = \frac{\rho g h u^2}{K_s^2 R_h^{4/3}} \tag{4}$$

where g is the gravity, h the local water depth (variable in the section), u the mean velocity, K_s the Strickler coefficient, R_h the hydraulic radius, and ρ the fluid density.

- For sand, the transport capacity is calculated with the Engelund and Hansen [9] formula:

$$q_s = 0.05\sqrt{\frac{\delta d^3}{g}}\frac{K^2 R_h^{1/3}}{(\rho_s - \rho)gd}\tau_{eff} \quad \text{where } \tau_{eff} = \tau\left(\frac{K}{K_p}\right)^{3/2} \tag{5}$$

where K_p is the grain friction coefficient, ρ the fluid density and ρ_s the sediment density, d the particle median diameter, and $\delta = \frac{\rho_s - \rho}{\rho}$.

The equilibrium concentration, C_{eq}, is written:

$$C_{eq} = \frac{\rho_s q_s}{Q} \tag{6}$$

The erosion and deposition rates are calculated depending on:

$$\begin{cases} \text{if } C_{sand} \geq C_{eq} \text{ deposition} & D = w_s\left(C_{sand} - C_{eq}\right) \\ \text{if } C_{sand} \leq C_{eq} \text{ erosion} & E = w_s\left(C_{eq} - C_{sand}\right) \end{cases} \tag{7}$$

For both cohesive sediments and sand, the bed evolution is then expressed depending on the erosion and deposition rates:

$$\frac{\partial Zb}{\partial t} = \frac{D}{C_{deposition}} - \frac{E}{C_{layer}} \tag{8}$$

The bank failure 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 and is spread along the section. A more complex model based on soil mechanics is also implemented [4].

II. ST-MARTIN-LA-PORTE

A. *Introduction*

The Saint-Martin-la-Porte Reservoir, on the Arc River, with a storage capacity of 68 000 m^3, is one of the many reservoirs on the river. Besides, it limits the suspended particles entering the downstream Longefan, Flumet and Cheylas Reservoirs, all managed by EDF.

A long term study for a more sustainable management of the reservoir is on-going to optimize the flushing scenarios and frequency and to assess the optimal geometry of the reservoir for an adequate decantation rate.

A 1D model of the Saint-Martin-la Porte Reservoir was built to optimize the sediment management.

B. *Modeling reservoir flushing*

The structure of the 1D model is described by three sedimentary layers, which are depicted in Fig. 2.

The model was calibrated on the last flushing event of June 2012, with a lot of site measurements: bathymetries (before and after flushing event), sediment concentration (inflow and outflow) measured during the event, and a large scale scanner surveying of the water level during the event.

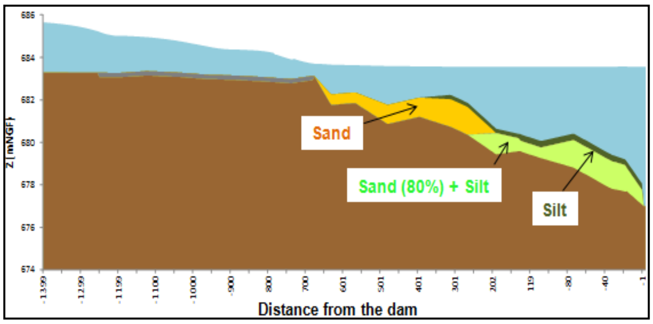
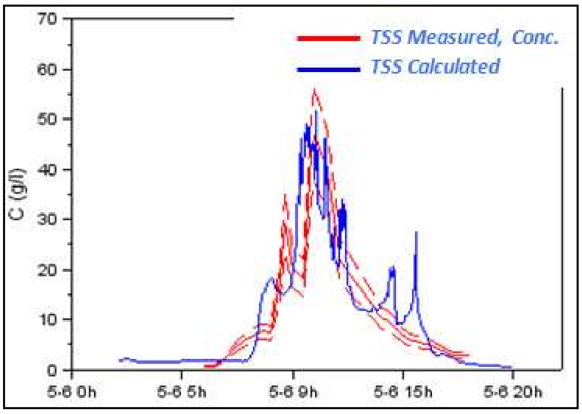
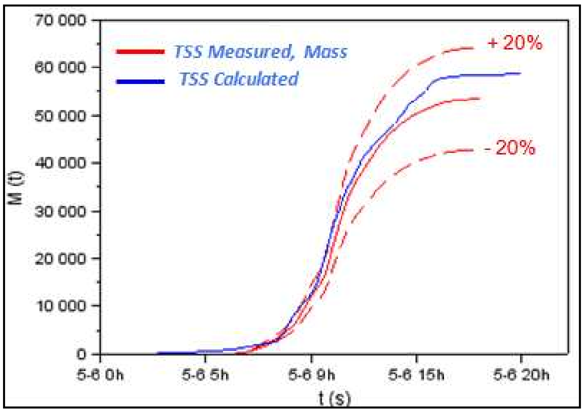


Figure 2. Sedimentary layers for modeling Saint-Martin-la-Porte Reservoir

Despite the few direct measurements of the sediment characteristics, and the torrential flow observed during the flushing event (high speed flow leading to high constraint on sand layer, which in turn results on fast changes of the bathymetry), the comparison of the model results with the measurements shows that the model reproduces well the erosive behaviours of the reservoir during flushing events. Indeed the suspended sediment concentrations calculated by the model downstream of the dam are closed to the measured concentrations, see Fig. 3.



(a)



(b)

Figure 3. (a) concentrations, (b) cumulated mass transferred

Further work will include testing different flushing scenarii (intensity and duration) and studying the decantation processes.

III. PLAN D'AREM

A. *Introduction*

The Plan d'Arem Reservoir was completed in 1970 with a total storage capacity of 500 000 m^3. It is the first upstream dam located past the Spanish/French border on the Garonne River and managed by EDF. The Plan d'Arem Reservoir has high sedimentation rates which lead to continued capacity reduction.

A dredging project is planned for 2014. It would be followed by annual hydraulic flushing events to maintain the reservoir at the best operating capacity. Flushing operations have to be controlled to limit environmental impact, i.e. the release of sediments to the downstream reach.

The Plan d'Arem 1D model shows how numerical modeling can be used to assess the sediment release and to define an optimal flushing scenario.

B. *Modeling reservoir flushing*

The Plan d'Arem Reservoir is characterized by a sedimentation of both sand and mud. In the 1D model, based on field data, two sedimentary layers are therefore distinguished: one layer of sand in the upstream area, and one layer of silt in the downstream area, see Fig. 4.

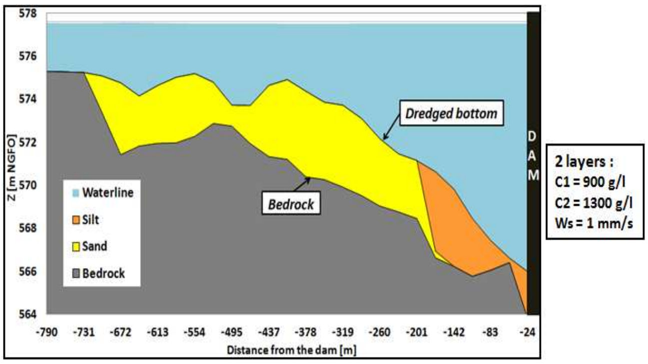


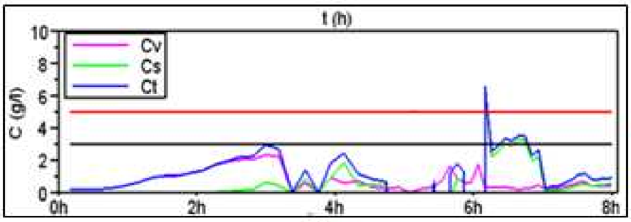
Figure 4. Sedimentary layers for modeling

C. *Flushing scenario*

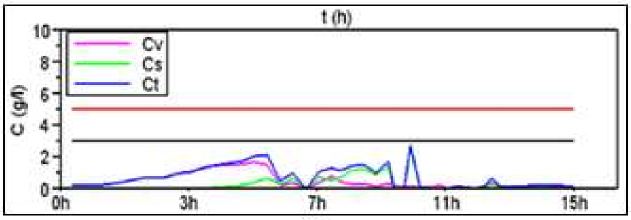
Hydraulic flushing events have two goals: to maintain the dredged state, and to limit environmental impact.

Downstream impact is mainly about water quality degradation, and in our specific area, the impact on troutlet mortality, starting to be observed when the sediment concentration reaches 10 g/l, after 24 hours of exposure.

A reference scenario was defined by the dam operator during the establishment of the dredging project. We compare it to another scenario with a level lowering rate in the reservoir two times slower. The downstream maximum reached sediment concentration is then reduced from 6.6 g/l to 2.8 g/l, see Fig. 5.



(a)



(b)

Figure 5. Output concentrations: (a) reference scenario, (b) with halving speed of level lowering.
Cv: silt concentration, Cs: sand concentration, Ct: total concentration

Future work will imply an inter-comparison between the 1D and 2D models of Plan d'Arem and the development of the bank erosion module to consolidate the results.

IV. CONCLUSION

Both cases show how COURLIS is a useful tool for reservoir management, as it reproduces well the erosive processes observed during a flushing event and is able to assess the sediment release to the downstream reach. COURLIS can therefore be used to define an optimal flushing scenario and to predict scenarios (by means of calibration) as illustrated in the second case.

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