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St Egrève Reservoir – Multi-Dimensional Modelling of Flushing and Evolution of the Channel Bed

St Egrève reservoir – Multi-dimensional modelling of flushing and evolution of the channel bed

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***Abstract*—Sediment transport and deposition in reservoirs are natural processes. 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 account for the influence of sediment transport when operating dams, as they need to evaluate the consequences of dam operations on the reservoir morphology.**

The Saint Egrève dam is located downstream of the city of Grenoble, on the Isere river in France. Over time, the reservoir has silted up. Frequent flushing operations allow the maintenance of a channel in the reservoir, but siltation bank formation on either side of the channel is irreversible. Due to the urban location of the reservoir, maintaining the freeboard of the upstream dike of the reservoir during the design flood is a major issue. Nowadays, the evolution of the filling is such that the channel erosion during the flood must be taken into account to estimate a realistic freeboard.

During a first part of the study, 1D morphodynamics simulations were performed by using the MASCARET/COURLIS module. The model was calibrated and validated with measured sediment fluxes corresponding to two flood scenarii and then applied to a project design situation. A second part of the study consisted on performing 2D and 3D numerical simulations using TELEMAC-2D and TELEMAC-3D coupled to SISYPHE, respectively, and comparing results with the 1D model.

I. INTRODUCTION

Sediment transport and deposition in reservoirs are natural processes. Recently, it has been estimated that the worldwide sedimentation in reservoirs corresponds to about one per cent of the whole capacity per year [5]. In specific areas, sedimentation rates can be significantly higher; it may reach more than 70% of reservoir initial capacity [1]. The filling of reservoirs depends on the production of sediment from the watersheds, the hydrology of the watershed, geometry and hydraulics of the reservoir and management of reservoir capacity [4]. The reservoir sedimentation impacts the river reach upstream the dam as much as the downstream reach: storage loss, delta deposition, blocking or clogging of intakes or bottom gates, downstream erosion, ecology, etc. Consequently, one has to take into account sediments when operating dams; therefore we need means to predict the consequences of dam operations on sediment transport and reservoir morphology.

Flushing operations aim at eroding sediments from reservoirs to maintain or to 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 and should be controlled [2]. There are different ways of predicting the downstream impacts of such operations, often relying on the experience. Nevertheless, numerical modelling can be used as a tool for planification and operation activities. In this work, the flushing of Saint Egrève reservoir is simulated with different modules of the TELEMAC-MASCARET System and comparisons with experimental data are presented and discussed.

II. SITE DESCRIPTION

The St-Egrève reservoir (France) is located in the Grenoble urban area, as shown on Fig. 1, downstream the confluence of the Isère and Drac rivers (9270 km² catchment area). The St-Egrève dam is a run-of-river power station, with a maximum turbine discharge of 540 m^3/s. The dam comprises 5 identical openings with overflow flaps, and a 25-meter wide tainted gate with 6 meters of lifting height and a weir at elevation 196.50 m NGF. The normal reservoir level (FSL) during operation is 205.50 m NGF. The capacity of the reservoir in 1992 was 3.86 hm^3. For safety reasons, a security distance of 1 meter with respect to the crest of the reservoir embankment must be guaranteed for a flood of 3000 m^3/s.

Figure 1. Location of the St-Egrève reservoir

The Isère River is highly loaded with fine sediment, and in the St-Egrève reservoir this sediment is deposited. The St-Egrève reservoir shows a sediment accumulation on the left bank that continues to silt up (see Fig. 2). In 2010 its elevation was 204.5 m NGF on average, i.e. one meter below the FSL. If this bar continues to silt up, bank volume will reach 1.45 hm^3. The remaining channel has a variable topography in its cross sections: its minimum area in the absence of flushing can be estimated at 250 m², i.e. a volume of about 0.6 hm^3 along 2500 meters. The channel is deepened during floods, and the maximum volume that it can reach is estimated at 2.41 hm^3, as shown on Fig. 3.

Figure 2. St Egrève reservoir during a flushing event.

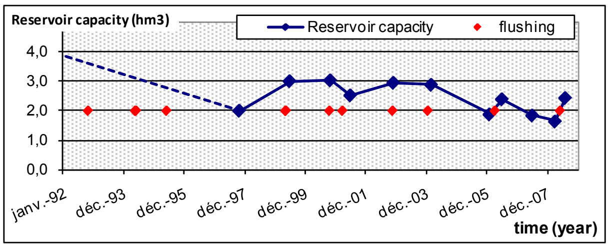


Figure 3. Evolution of the reservoir capacity

III. 1D MORPHODYNAMICS SIMULATIONS

A. *Aim of the study*

The COURLIS software (internally coupled to the 1D hydrodynamics model MASCARET) was used to determine the bottom evolution kinetics during floods. COURLIS computes the bottom evolutions in a channel section as a function of the bed shear distribution in the cross-wise direction of the flow [3]. The objective was to verify that when starting with a high degree of siltation, the erosion at the start of flushing is sufficient to guarantee the preservation of the 1-meter freeboard with respect to the crests of the dikes. In this work, only the calibration and validation of the model are presented.

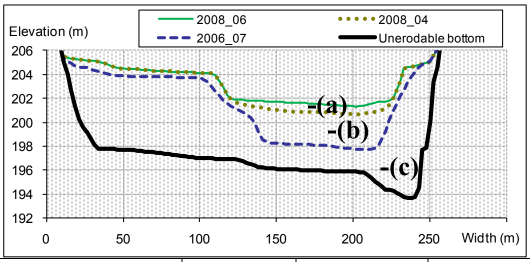
B. *Available measurements*

Two events were used to calibrate and validate the numerical model: flushing operations performed in May 2008 and May-June 2010. Bathymetries of the reservoir were surveyed before and after each of these events. Turbidity meters placed upstream and downstream of the reservoir enable monitoring of the sediment concentration evolution during a flood and determination of the silt volumes having passed through between the bathymetric measurements and the flushing operations. In addition, sediment samples were taken from the reservoir in September 2010.

C. *Model calibration*

The calibration data corresponds to the May 2008 flushing operation. This flushing operation was preceded and followed by two bathymetric measurements, one in April and one in August 2008. The grid was based on cross-section profiles 100 meters apart derived from the bathymetric data. These profiles were pre-processed to achieve a calculation profile every 50 meters. The chosen Strickler coefficient is taken equal to 45 $m^{1/3}\ s^{-1}$.

Model calibration revealed the necessity to model three distinct sediment layers, as shown in Fig. 4. The top layer represents the slightly consolidated sediment (easily remobilised), the second layer the recently deposited sediment (few years), and the third sediment layer the most consolidated. Sediment layers were constructed from the bathymetric data: (i) In 2008, the previous flushing operation dated from April 2006. The layer of old sediment was comprised between the non-erodable bottom measured in the topographic surveys prior to the impounding of the dam and the bathymetry of July 2006; (ii) The layer of recent sediment was represented by the sediment deposited between the bathymetries of July 2006 and April 2008; and (iii) The layer of slightly consolidated sediment was considered equal to the estimated volume of sediment deposited between the date of the bathymetry and the flushing episode, i.e. 150,000 tons. Assuming a dry matter concentration of 1000 g/l, this layer represents a deposit of roughly 70 cm at the bottom of the channel with respect to the April 2008 profile. Besides, the slope stability angle is considered constant and equal to 15°.



Sediment layers	C (kg/m^3)	τ_{ce} (Pa)	M ($kg/s/m^2$)
(a) Slightly consolidated	1000	1	0.005
(b) Recent	1100	6	0.06
(c) Old	1100	8	0.02

Figure 4. Sedimentary layer creation

The flushing parameters and the results are summarized on Fig. 5.

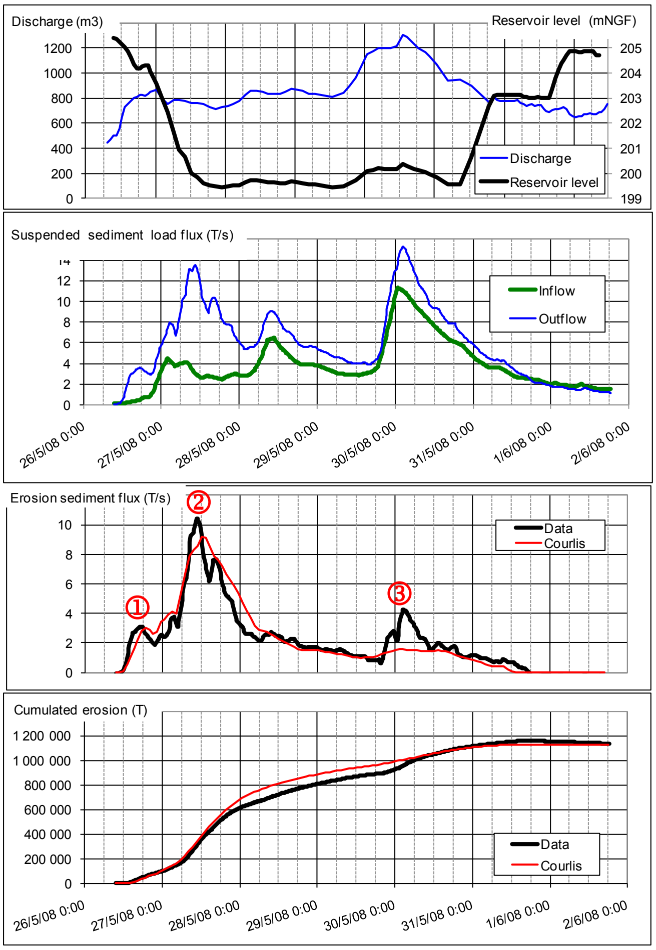


Figure 5. Simulation results of the calibration.

The following phases can be observed:

- During the lowering of the water level (phase 1), we observe an erosion peak due to the slightly consolidated silt①,
- The main erosion peak ② corresponds to the end of the phase 1, when the water level has reached its minimum level. It is well represented by the 1D model although the maximum peak value is slightly underestimated, The increased erosion ③ is due to the passage of the flood peak (phase 3). This third peak is also underestimated. ③

The calculated mass of eroded sediment (1.13 Mt) is in good agreement with the measured mass (1.14 Mt. The evolution of the eroded mass over time can also be well adapted. At the time of the flood peak on May 30 at 1 pm, over a million tons of sediment had already been eroded. A comparison of the profiles measured during August 2008 with the computed profiles yields to satisfactory results, Fig. 6. However, the COURLIS simulation results in the channel are deeper than those measured in bathymetry. This can be attributed to a considerable accumulation of sediment in the reservoir during the period between the end of flushing (end of COURLIS simulation) and the bathymetry date. Indeed, the high flow episode of June 2008 lasted after the flushing, causing solid matter inflows and significant settling in the reservoir of an order of magnitude of 300,000 tons (i.e. 1 meter of sediment deposited on average in the channel over three months).

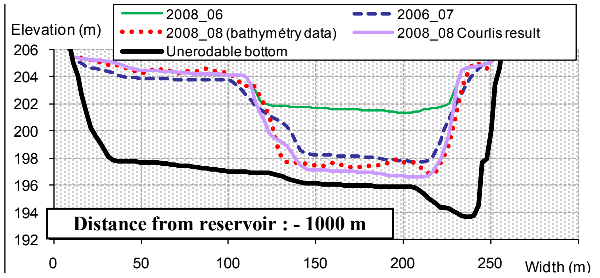


Figure 6. Evolution of the cross-section profiles

D. *Model validation*

The model was validated with data from the flushing operation of May-June 2010. Two bathymetric surveys preceded and followed this flushing, in April and August 2010, respectively.

The layer construction is based on the calibration values and results, Fig. 7:

- (c) An old sediment layer is comprised between the non-erodable bottom and the result of the 2008 COURLIS calculation.
- (b) A recent sediment layer is comprised between the bottoms produced by the 2008 COURLIS calculation and the bathymetric profiles of April 2010 translated by -30 cm.
- (a) A layer of slightly consolidated material is constructed from the bathymetric profiles of April 2010 and the same one translated by -30 cm in the channel.

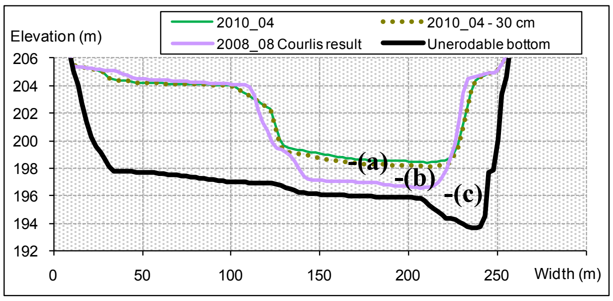


Figure 7. Sediment layer characteristics (see Fig. 4 for values)

The flushing parameters and the results are summarized in Fig. 8. The following points should be highlighted:

- During the phase of the lowering of the water level, we clearly see the erosion peak due to the slightly consolidated sediment.

- The main erosion peak, corresponding here to the passage of the flood peak during the lowering phase, is well represented.
- The flux at the end of the episode is underestimated in comparison with measurements.

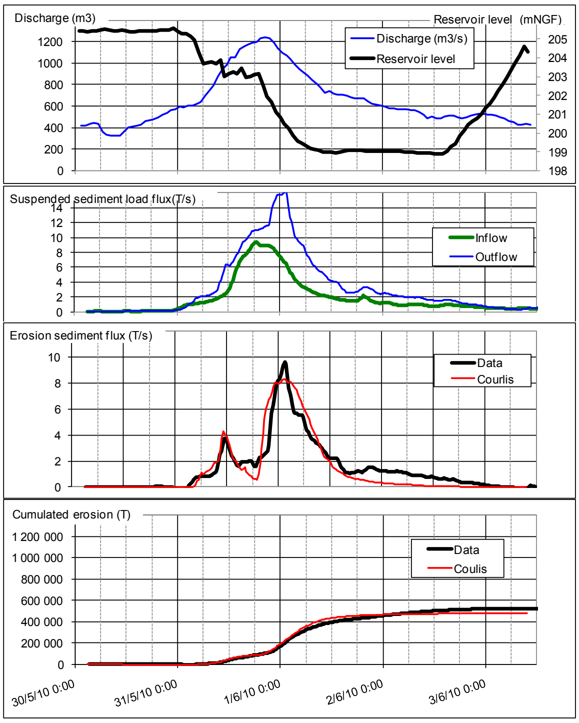


Figure 8. Validation calculation results

The correlation between the calculated mass of eroded sediment (0.48 Mt) and the measured one (0.52 Mt) is satisfactory. The evolution of the eroded mass over time is also well represented (the scale used on this graph during the calibration was maintained). The Analysis of cross-section profiles yields results similar to those presented for the calibration, Fig. 9. The deeper erosion depth obtained by COURLIS can be attributed to a considerable accumulation of sediment in the reservoir during the period between the end of flushing and the bathymetry date (non-simulated period). Indeed, the high flow episode of June 2010 lasted after the flushing, causing solid matter inflows and significant settling in the reservoir of an order of magnitude of 400,000 tons (i.e. 1 to 1.5 meter of sediment deposited on average in the channel over three months).

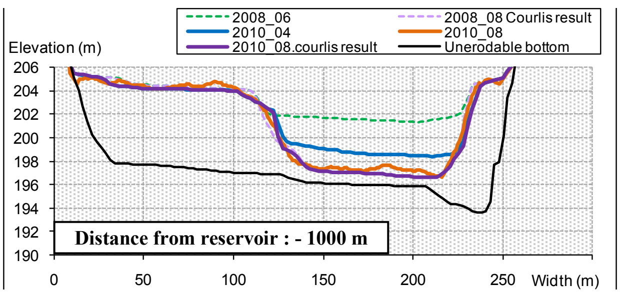


Figure 9. Evolution of the cross-section profiles

E. *Influence of parameters: number of layers*

The erosion stress, the surface erosion rate and the number of layers are the main parameters of the erosion module and have a strong influence on the results. An illustration of the influence of the number of layers is given in Fig. 10 and Fig. 11. Assuming only one single layer it is impossible to determine correctly the evolution of the erosion for the considered floods. The use of a single stress of 9 Pa, given acceptable results for the flood 2008, leads to an excessively low value for the 2010 flood.

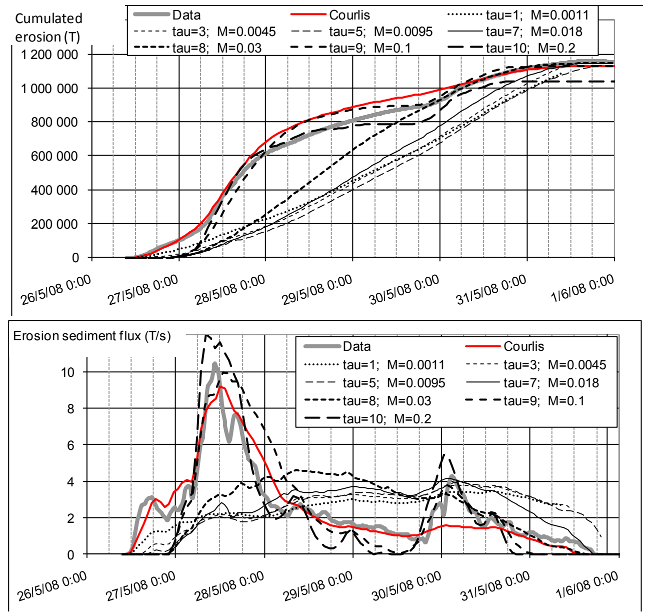


Figure 10. Calibration with a single constant layer of sediment

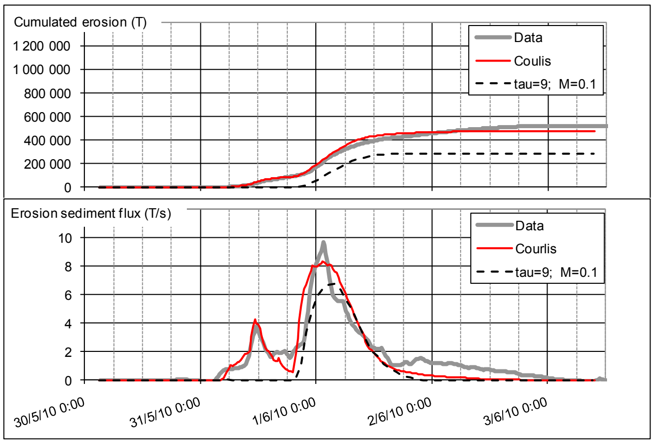


Figure 11. Results for the validation case

IV. 2D/3D MORPHODYNAMICS SIMULATIONS

In complement to 1D simulations, 2D and 3D numerical computations were also performed using (*i*) the 2D hydrodynamic module TELEMAC-2D, internally coupled to the two-dimensional sediment transport module SISYPHE, and (*ii*) the 3D hydrodynamics module TELEMAC-3D, internally coupled to SISYPHE.

Our objective was to compare the different modules of the TELEMAC-MASCARET System in this simple elongated geometrical configuration which is perfectly adapted for 1D simulation, even if the 2D and 3D simulations would give more insight in the detailed structure. In this section, the accuracy of the various models, their adaptability, and required CPU time are studied.

A. Multi-layer model development

In the 1D model (COURLIS), the sediment bed layers have been defined based on historical bathymetries.

In SISYPHE, for 2D and 3D simulations, the bed layers and properties are supposed to be uniform and determined according to the 1D model hypothesis, allowing for some slight variations: the different layers, their initial thicknesses and concentrations, are assumed to be uniformly distributed through the whole domain at the start of the flushing event. The erosion parameter M is also supposed to be constant, while the critical erosion shear stress increases as a function of bed density. SISYPHE model parameters are summarized in Table 1.

TABLE I. SEDIMENTARY LAYER SETUP

Sediment layers	**C (kg/m^3)**	**τ_{ce} (Pa)**	**M (kg/s/m^2)**	**Thickness (m)**
Slightly consolidated	600	2	0.03	0.3 (channel) 0 (bank)
Recent	1000	5	0.03	2.5 (channel) 0.5 (bank)
Old	1100	10	0.03	2->10 (2008) 3->10 (2010)

B. Comparison of model results for the 2008 flood

Both 2D and 3D hydrodynamic models use the same value of the Strickler friction coefficient (52 $m^{1/3}s^{-1}$). Both 2D and 3D models are therefore equivalent and give similar results regarding the main hydrodynamics parameter for sediment transport applications (the bed shear stress): The only difference comes from the directions: in 2D, the bed shear stress is supposed to be aligned with the mean flow direction, whereas in 3D, the bed shear stress is aligned with the near bed flow. Fig. 12 shows the comparison between all model results and the data for the net eroded sediment fluxes. All models give globally similar results and successfully reproduce the two first peaks (1, 2), but underestimate the third one corresponding to the flood peak.

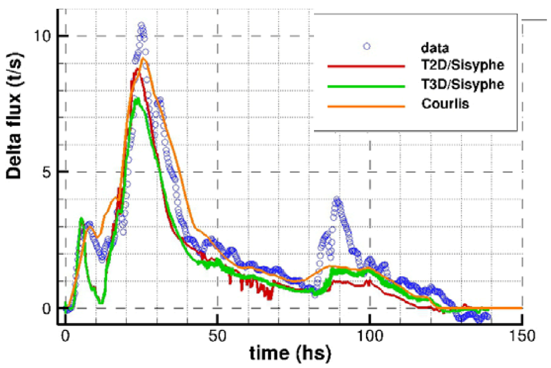


Figure 12. Total sediment flux (2008)

Fig. 13 shows a plan view of the bed elevation, at the end of the flushing event, in 2D (13.b) and 3D (13.c) which are compared with the differential bathymetry (Fig. 13.a). As can be observed, the bed erosion should be overestimated in both 2D and 3D simulations. Similar results were also obtained in the 1D model. However, this discrepancy could be attributed to an accumulation of sediment in the reservoir during the period between the end of flushing and the date of the bathymetry (non-simulated period): 1 meter of sediment deposited on average in the channel in 2008, 1 to 1.5 meter in 2010.

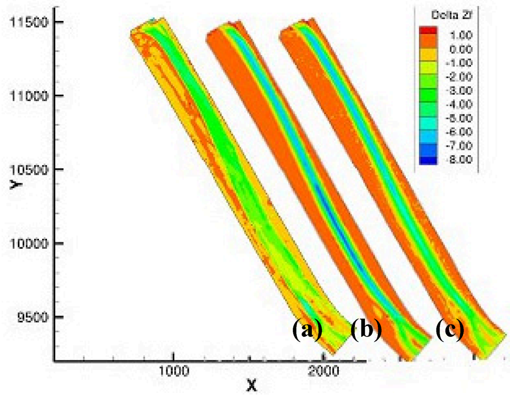


Figure 13. (a) Measurements – Δz 04/2008 – 08-2008; (b) 2D results; (c) 3D results

C. Comparison of model results for 2010

After the calibration step model parameters (bed friction, as well as the number of layers and their characteristics) are fixed for the validation step. All models are able to reproduce the observed net sediment fluxes, as shown in Fig. 14. Fig. 15 shows the bathymetric evolution, obtained by the 2D (Fig. 15b) and 3D models (Fig. 15c) in comparison with the data (left hand side). Despite the good agreement when comparing with observations, all models tend to overestimate the bed evolution (Cf. § III D).

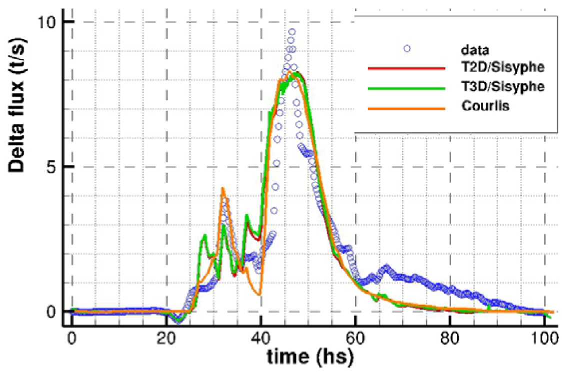


Figure 14. Total sediment flux (2010)

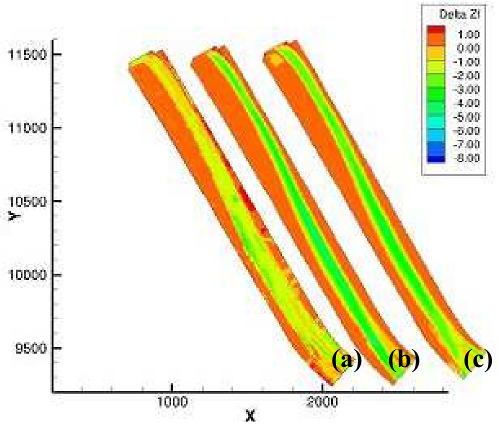


Figure 15. (a) Measurements – Δz 06/2010 – 08-2010; (b) 2D results; (c) 3D results

V. Comparison of 1D, 2D and 3D model results

A. Discussion

After proper calibration to define the bed structure (number of bed layers and sediment characteristics), model results for the 2008 event as well as for the 2010 flushing event, show that all three modules (1D, 2D and 3D) were able to predict accurately the amount of sediment which is flushed out during a typical flushing event. All the modules may be used conveniently as operational tools to monitor the efficiency of flushing events.

This simple geometrical configuration does not necessitate the use of a complex 2D or 3D models, and the 1D model assumption is perfectly adapted to represent this type of event. In addition the 2D and 3D model give more insight in the flow structure and access to a detailed plan view of the model results (bed evolution, bed shear stress distribution…). On the other hand, the 1D tool can be viewed as a handier tool for the initialization of the bed layers based on historical bathymetry.

B. Comparison of CPU time

To compare CPU time, the number of processors, as well as compiler type, need to be specified. All 1D, 2D and 3D simulations have been run on Linux station Z600 (compiler intel 64b). Both 2D and 3D models were run in parallel using 8 processors. The use of parallel computing allows performing 2D simulations for a computational time comparable with the time required to run the 1D model, whereas the 3D model (5 vertical planes) showed to be more expensive.

TABLE II. Comparison of CPU Time

	1D (1 Proc)	2D (8 Proc)	3D (8 Proc)
Number of mesh Dx Dt	300 Variable	2-10 m 10s	5 layers 0.5 s
2008 Flushing 6 days 9 h	10 mn	12 mn	3 h 44 mn
2010 flushing 4 days 6 h	6 mn	7 mn	1.5 h

VI. Conclusion

Three hydrodynamic and sediment transport models of the TELEMAC-MASCARET System, namely COURLIS/ MASCARET (1D) and SISYPHE coupled to TELEMAC-2D and -3D, have been applied to simulate the effect of a flushing event. After proper calibration of the various sediment parameters and bed structure, all models could successfully reproduce the amount of sediment eroded and therefore could be used as operational tools to predict the efficiency of flushing event.

The computational domain presented an elongated, unidirectional geometrical configuration, which is particularly well adapted for a 1D application and, therefore, allowed a fair comparison with the 2D and 3D models. We emphasize that the choice of the spatial dimension to which apply the different models depends mainly on the scale of the problem (time and space) and the degree of detail of application. For more complex configurations than the one presented here, 1D models can be used to simulate the entire reach, providing then the boundary conditions for more detailed 2D or 3D analysis in important subreaches.

Future work will include the implementation, verification and validation of the fully 3D cohesive sediment transport processes within TELEMAC-3D.

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