Benchmark of hydro-sedimentary 1D codes: HEC-RAS, COURLIS and ADIS-TS

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Abstract — The objective of this work is to discussed the performance of three different 1-D hydro-sedimentary numerical codes: (i) HEC-RAS (Corps of Engineers of the US Army), (ii) TELEMAC-MASCARET/COURLIS (EDF) and (iii) MAGE/ADIS-TS (Irstea). These numerical codes are commonly used in France in engineering or research projects. Their hydrodynamic module is based on similar equations (1D Shallow Water Equations). However, the sedimentary modules often differ in the description and modelling of parameters such as bed shear stress representation, grain size distribution, or bed evolution and involve different input data. The three numerical codes were used to simulate the 2016 dam flushing operation on the French Upper Rhône River, which is characterised by three different phases: (i) sediment deposition, (ii) erosion and (iii) propagation. The calibration of the hydro-sedimentary models was performed using Suspended Particle Matter (SPM) loads (from calibrated turbidity records), particle-size measurements and bathymetric data. Sensitivity analysis was performed for the most relevant parameters of each software (critical bed shear stress, median grain size, etc.). The main criterions of the benchmark are the user experience, the ability to reproduce observations and the time calculation.

I. INTRODUCTION

Suspended Particulate Matter (SPM) transport through engineered rivers is of primary concern for security and operational purposes. Indeed, sediment deposition in dam reservoirs can increase the water level and endanger surrounding inhabited areas, and it affects the hydro-electric production by reducing the reservoir capacity. Several desiltation technics exist to reduce deposition in a long-term perspective but they need to be carefully managed in order to limit downstream ecological impacts [10]. To develop efficient sediment management and control strategies, river managers need relevant field data and practical numerical tools.

Combined with field and laboratory measurements, numerical modelling of transport, deposition and erosion of SPM is commonly used in engineering studies. Nowadays, different numerical codes (1D, 2D and 3D) exist to represent those phenomena; however, the choice of the model dimension is conditioned by the objective of the study, the user's need and the available resources. This is represented by the temporal and spatial scales and the degree of simplification.

Each kind of model has its strengths and weaknesses: (i) 1D hydro-sedimentary numerical codes are relevant to simulate long-term events on a long river network with small time steps [8]. They help to improve the understanding of hydro-sedimentary processes in the river and they can be used in some cases to predict long-term bed evolution [12]. (ii) 2D hydro-sedimentary numerical models are mainly used to simulate both short and medium terms events on a specific river reach in order to evaluate the sediment behaviour in vertical and horizontal axis and the local bed evolution [16]. (iii) 3D hydro-sedimentary numerical models are appropriate to represent the local and/or punctual (small scale) morphological phenomenon like sediment effects around hydulics structures such as intakes, controls structures, transitions, bridge piles, etc.

The present study arises from the need of the Compagnie Nationale du Rhône (CNR) to find a numerical modelling tool able to represent the dynamics of suspended sediments and bed evolution during a dam flushing operation event on the French Upper Rhône River. In accordance with the industrial needs of the company, this tool must be reliable, robust and user-friendly, for both internal and external projects. Due to the complex phenomenon involved, its numerical simulation requires an important amount of field data, before, during and after the event; nevertheless, the acquisition of the data is expensive, especially bathymetric profiles and measurements of the bed sediment grain size distribution. The length of the studied reach (about 30 km) and the lack of data (cross-section every 200 m in average) are the main reasons leading to the choice of a 1D modelling.
The aim of this paper is (i) to present a short description of the case used for the benchmark, which is a dam flushing event in the Upper Rhône River in 2016, (ii) to present the numerical codes used for the project, (iii) to describe the construction of the models and finally, (iv) to illustrate and discuss the obtained results with each numerical code and the performance of the code.

II. THE 2016 UPPER RHÔNE DAM FLUSHING EVENT

Every 3 years, between end of May and beginning of June, to prevent flood hazards, regulatory sediment flushing are carried out to reduce the volume of sediments in the Verbois reservoir. These sediment flushing involve the sediment flushing of downstream dam reservoirs, including Genissiat and Seyssel (see Figure 1a).

Figure 1: (a) Schematic overview of the upper Rhone River situation and (b) Modelized reach from Pyrimont station to Seyssel hydro-electric power scheme (Source: Géoportail, 2018).

This kind of events is controlled on the Upper French Rhône River. For example, the suspended sediment concentrations released from the Génissiat reservoir (upstream Pyrimont station, Figure 1b) have not to exceed 5 g/l on average over the entire operation, 10 g/l on average over any 6 hour period, and 15 g/l over any 30 minutes period. Based on the above, the numerical simulation becomes relevant in order to “predict” the evolution of SPM concentration during the flushing event.

The modelled area is a reach of the French Upper Rhône river from Pyrimont monitoring station (downstream Génissiat dam) onto Seyssel hydro-electric power scheme, whose length is about 6.8 Km (Figure 1b). This reach is characterized by 1D flow; there are not naturals or anthropic (structures) singularities.

The flushing event selected for this benchmark, which took place between May 20th, 2016 and May 30th, 2016, presents at Seyssel, three characteristic phases: (i) deposition, (ii) erosion and (iii) propagation (Figure 2b). Several measurements (discharge, water level and SPM concentration) were undertaken during the event both upstream (Pyrimont) and downstream (Seyssel) (Figure 2).

Figure 2: field measurements at Pyrimont and Seyssel stations during the flushing event of 2016. (a): Water Discharge at Pyrimont and water level at Seyssel station; (b) SPM concentrations.

III. SELECTION OF THE NUMERICAL CODES

Several hydro-sedimentary numerical codes are available. Among them, some are commercial or shareware and others are freeware. According to the industrial needs, the CNR decided to evaluate the capabilities of three different 1-D hydro-sedimentary numerical codes, commonly used in France in engineering or research projects, in order to know
the advantage and disadvantage of each one: (i) HEC-RAS (Corps of Engineers of the US Army) a software used worldwide, (ii) TELEMAC-MASCARET/OURLIS (EDF) and (iii) MAGE/ADISTS (Irstea); both EDF and Irstea are French institutions working together with CNR to develop this project.

For the three numerical codes, the hydrodynamic module is based on similar equations (1D Barré de Saint-Venant equations). However, the sedimentary modules often differ in the description and modelling of parameters such as bed evolution, bed shear stress representation or grain size distribution and involve different input data.

A. HEC-RAS V5.0.3

HEC-RAS (Version 5.0.3, Hydrologic Engineering Centers - River Analysis System) allows to perform the 1D and 2D hydraulic simulations and its integrated sedimentary module makes it possible to perform simulations of both bed load and suspended sediment transport and represent the bed evolution (quasi-unsteady flow and unsteady flow). [14][15]

HEC-RAS has several functions and parameters included in sedimentary module. The user, based on its expertise, has to choose the appropriate functions and values in order to obtain physical and coherent results. The most relevant parameters are:

- Thickness of the bed sedimentary layer: Only one sedimentary layer with different depths along the reach can be modelled.
- Critical shear threshold: as HEC-RAS uses the equations of Krone (1962) [6] and Partheniades (1965) [9] to represent deposition and erosion for cohesive sediments, it is necessary to define a value for the critical shear stress (in Pa), which is used for erosion and deposition for particle erosion. There is also a second shear stress thresholds \( \tau_m (\tau_m > \tau_c) \) implemented in HEC-RAS for mass wasting erosion. The slopes of the erosion rate curve for each type of erosion (in N/m²/hr) must be defined [15].
- Bed grain size distribution (GSD): HEC-RAS allows defining the particle size-distribution (in mm).
- Inlet SPM concentration: as for bed gradation, HEC-RAS allows defining the particle size-distribution and also the concentration, in tons per day.
- Settling velocity method \( (w_s) \): the user has to choose between Van Rijn, Ruby, Toffaleti, Report 12 and Dietrich.
- Sorting method: 3 options are available, Thomas (Ex5), Active Layer and Copeland (Ex7).
- Transport function: there is a set of several semi-empirical sediment transport formulas. The user has to select one of them (Ackers & White, Engelund & Hansen, Laursen (Copeland), Meyer Peter & Muller, Toffaleti, MPM-Toffaleti, Yang, and Wilcock & Crowe) according to the characteristic of the case to model.
- The user must select between quasi-unsteady flow and unsteady flow to carry out a sediment transport simulation.

B. COURLIS - MASCARET

COURLIS is a one-dimensional hydro-sedimentary code, developed by EDF (Electricité de France). In its suspension module, by solving advection-diffusion equation (Eq. 1), it can model transport, deposition and erosion of fine sediments (sands and silts), as well as the bed evolution. It can be used to model flows in rivers or in reservoirs when the flows can be considered as 1D. The code is weakly coupling with the hydraulic module MASCARET, also developed by EDF.

\[
\frac{\partial A.C}{\partial t} + \frac{\partial Q.C}{\partial x} = \frac{\partial}{\partial x}(k.A.\frac{\partial C}{\partial x}) + E - D
\]  

(1)

The most relevant parameters to perform sediment’s transport simulation are:

- Number of sedimentary layers: COURLIS can use up to 5 layers with different thickness.
- Critical constraints for erosion and deposition: as COURLIS uses the equations Krone (1962) [6] and Partheniades (1965) [9] to represent the deposition (Eq. 2) and the erosion (Eq. 3), of cohesive sediments, respectively, it is necessary to provide a critical threshold for both erosion and deposition (in Pa) and the Partheniades coefficient (in kg/m²/s).

\[
D = w_1 C \left( 1 - \frac{\tau}{\tau_{cd}} \right)
\]  

(2)

where, \( \tau \) is the local shear stress (Pa), \( \tau_{cd} \) is the deposition critical shear stress (Pa), and \( w_1 \) is the settling velocity (m/s).

\[
E = M \left( \frac{\tau}{\tau_{ce}} - 1 \right)
\]  

(3)

where, \( \tau \) is the local shear stress (Pa), \( \tau_{ce} \) is the erosion critical shear stress (Pa) (or slope of the erosion rate curve), and M is the erosion rate coefficient (kg.m².s⁻¹).
- The settling velocity value \( (w_s) \) in (m/s); this parameter is adapted according to the sediment grain size (correlation between the settling velocity and the particle diameter).
- The value of the estimated skin Strickler roughness coefficient \( (K_d) \): one value for each sedimentary layer (m¹³/s).
- Inlet SPM concentration: COURLIS uses only one sediment class and the concentration should be defined in g/l for each time step.
- The boundary sections of the reach: the first and the last section of the simulation domain are “fixed profiles” and do not evolve along the simulation; for that reason, it is important to define the study area in between those profiles.
C. ADISTS - MAGE

ADISTS is a sedimentary module weakly coupled with the hydraulic module Mage, both codes developed by Irstea. ADISTS has been first developed to simulate the transport of pollutants in a hydrographic network; it was then adapted to simulate the transport of suspended sediments [2][3][4][5]. ADISTS solves the advection-dispersion equation (Eq. 1) using a simplified version of the source terms:

\[(E - D) = a_{pd} \cdot (C_{eq} - C)w_g\]  \hspace{1cm} (4)

where \(a_{pd}\) is a calibration coefficient, \(C\) the concentration (kg/m³ or g/L) and \(C_{eq}\) the equilibrium concentration:

\[C_{eq} = C_o \left( \frac{\tau}{\tau_{cr}} - 1 \right)\]  \hspace{1cm} (5)

where, \(C_o\) (g/l) is a calibration coefficient, \(\tau\) effective bed shear stress (Pa), \(\tau_{cr}\) critical bed shear stress (Pa).

The most relevant parameters to compute sediment’s transport simulation are:

- Thickness of the sedimentary layer: there may be one layer per sediment type and its thickness may vary along the reach but must be constant for each cross section.
- Number of sediment types: ADISTS can work with several classes of sediments.
- Characteristics of each class of sediments: defined by several parameters such as average diameter \(d_{50}\) (in m), porosity of the deposit, density, and the calibration parameters to solve the advection-dispersion equation [3].
- Inlet sediments load: the concentration of upstream sediments (in g/l) should be defined for each type of sediment.

IV. CONSTRUCTION OF THE MODELS

Three models (one per numerical code) were built to reproduce the flushing event of 2016. Due to some differences between the input parameters of each software, the models were carefully built in order to be homogeneous and consistent.

The bathymetry of the reach was represented by 73 cross-sections with a regular interval of 100 m. The downstream cross-sections, near Seyssel dam, are closer.

The time steps for the simulations were selected for each numerical code as follow: (i) 10 s for HEC-RAS, (ii) 1 s for COURLIS and (iii) 60 s for ADIS-TS.

The simulations were initially performed with only one sediment class with a \(d_{50} = 20 \mu\)m. This diameter corresponds to the most often observed sediment in the French Upper Rhone River [13][7][2]. This sediment diameter was used for the inlet SPM concentration as well as for the characteristics of the bed. The sediment’s characteristics were defined according to the parameters of each software and adapted in order to find more accurate results.

Based on estimation of the stocked volume of sediments, three different bed configurations (distribution of sediment’s deposit along the reach) were defined: (i) 0 m³ stocked along the reach, (ii) 3 sectors of thickness, 0 m – 1 m – 3 m, and (iii) 2 sectors of thickness, 0 m – 3 m (Figure 3). They are useful to identify the influence of the stocked sediments before the flushing event, on the SPM concentration signal registered during the event.

V. RESULTS

A. Hydraulic

The three hydrodynamic models were calibrated and validated along the whole river reach using water elevation longitudinal profiles and discharge measurements.

In general, the hydraulic performance is the same for the three software. However, a little deviation exists in the first section of the reach (between Pyrimont (Pk 158.575) and section Pk 158.00) where the flow regime is supercritical (Figure 4).
B. Hydro-sedimentary calibration and sensitivity analysis

Calibration of the hydro-sedimentary models was performed using SPM loads from calibrated turbidity records, particle-size measurements and bathymetric data.

Sensitivity analysis was performed for the most relevant parameters (critical bed shear stress, \(d_{50}\) of particles and volume of sediments stocked before the event) keeping up the same hydraulics characteristics and inlet SPM concentration.

The results clearly show the numerical codes’ sensitivity to parameter calibration, which have a strong influence on deposition and erosion phenomena. Among many results, the figures below were selected to show the impact of the parameters mentioned above on the sedimentary results during the 3 phases of the simulated event (deposition, erosion and propagation).

Figure 5 shows the influence of the stored volume of sediment in the river bed on the concentration signal during the erosion phase (between May 21st and May 22nd, 2016). The bigger the amount of stored sediments, the longest is the erosion phase.

Figure 6 shows the influence of the sediment GSD on the deposition phase (between May 20th and May 21st, 2016); the settling velocity is linked to the diameter and in consequence the behaviour of the models during the deposition period is affected. The bigger the diameter, the fastest the sediments settled.

Figure 7 shows that the critical bed shear thresholds have strong influence on the motion to start the erosion phase and therefore on the peak representation.

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Figure 4: Water elevation longitudinal profile at the end of simulation

![Water elevation longitudinal profile at the end of simulation](image)

Figure 5: Sensitivity analysis of stored sediments volume.

![Sensitivity analysis of stored sediments volume](image)

(a) COURLIS \((\tau_e = 0.6; \tau_d = 0.1; w_s = 0.00035 \text{ m/s})\)

(b) HEC-RAS \((\tau_e = 0.16; M = 50; d_{50} \in [0.032 – 0.0625 \text{ mm}])\)

(c) ADIS-TS \((d_{50} = 50 \mu\text{m}; \phi_{pd} = 0.1; \phi_c = 1)\)
Figure 6: Sensitivity analysis of sediments size

(a) COURLIS (Thickness: 0m – 1m – 3m; $\tau_e = 0.6$; $w_s = 0.00035$ m/s)
(b) HEC-RAS (Thickness: 0m; $\tau_e = 0.16$; $M = 3.7$; $d_{50} = [0.016 – 0.032$ mm$])
(c) ADIS-TS (Thickness: 0m – 1m – 3m; $a_{pd} = 0.1$)

Figure 7: Sensitivity analysis of shear thresholds

(a) COURLIS (Thickness: 0m – 1m – 3m; $\tau_e = 1.2$, $\tau_d = 1$)
(b) HEC-RAS (Thickness: 0m; $\tau_e = 1$)
(c) ADIS-TS (Thickness: 0m – 1m – 3m; $d_{50} = 20$ $\mu m$)
C. Discussion

Once the sensitivity analysis and the calibration were done, the most accurate results of each software were compared.

The results show that the three numerical codes have the same hydraulic performance. For sedimentary simulations, it is possible to well represent the phenomena of deposition, erosion and propagation with the 3 of them (Figure 8).

However, it was necessary to adjust the values of the different parameters to properly calibrate the results at Seyssel (Table 1 shows the different parameters according to the software). It should be noted that equations are not exactly the same for each code, which explains why best results are not obtained for the same parameter calibration depending on the code used.

<table>
<thead>
<tr>
<th><strong>HEC-RAS</strong></th>
<th><strong>COURLIS</strong></th>
<th><strong>ADIS-TS</strong></th>
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<tbody>
<tr>
<td>- Critical shear stress ($\tau_c$) = 0.16 Pa</td>
<td>- Critical erosion shear stress ($\tau_{ce}$) = 1.2 Pa</td>
<td>- APD = 0.1</td>
</tr>
<tr>
<td>- Erosion rate ($M$) = 50 N/m² hr</td>
<td>- Critical deposition shear stress ($\tau_{cd}$) = 1 Pa</td>
<td>- Diameter ($d_{50}$) = 50 µm</td>
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<tr>
<td>- Diameter ($d_{50}$) = 32 µm – 62.5 µm</td>
<td>- Settling velocity ($w_s$) $d_{50}$ = 7x10⁻⁴ m/s [27 µm]</td>
<td>- Bottom configuration = 0m et 3m.</td>
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<td>- Bottom configuration = 0m et 3m.</td>
<td>- Bottom configuration = 0m et 3m.</td>
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Figure 8 clearly demonstrates that the overall performance of the three numerical codes is good; as soon as they are properly calibrated following recommendations prescribed for each code. Nevertheless, some differences have been noticed between the models. First; although the deposit is well presented, the concentrations are slightly different, probably due to the critical shear parameters. Second, even though the erosion phase has been represented with the three codes, the general shape and the width of the peak are not the same. Those differences could stem from the critical bed shear stress thresholds. Finally, the fluctuations along the propagation phase are well represented and the dissimilarities with the measured signal are mostly the same at the same time step.
VI. Conclusion

A. Benchmark conclusions and recommendations

The three numerical codes used in this study (HEC-RAS, ADISTS and COURLIS) are able to accurately reproduce water discharge and level measurements during a dam flushing event on the Upper-Rhône River. The modelled suspended sediment transport time series agree acceptably well with field measurements. However, in the deposition and erosion phases, some differences have been noticed between the models. Those differences are potentially due to the selected bed shear stress threshold. The three codes are sensitive to calibration parameters. Indeed, if the modelling of a single hydro-sedimentary event in a river reach can be accurately performed with any of these numerical codes, the simulation of another event (even in the same river reach) using identical calibration parameters may lead to significant errors. There is a strong need to provide recommendations (based on field, lab, and simulation experience to know the possible order of magnitude of each value) to better characterize these physical-based parameters.

The aim of this study was to identify a numerical tool able to well reproduce a flushing event; despite the lacks and difficulties identifying to perform this type of simulations, the objective has been achieved. Although, it is necessary to provide parameter recommendations in order to better replicate a past event, and for further studies, to make predictions of sediments behaviour during a flushing event knowing the initial variables as stored by the lab. These predictions will be very useful for operational actors.

B. Conclusions for COURLIS

In terms of computational time, Courlis was the longest among the three numerical codes tested. The average simulation time on this case were: 60 s for HEC-RAS, 1050 s for COURLIS and 180 s for ADISTS. It is mainly due to the chosen time steps (10s for HEC-RAS, 1s for COURLIS and 60s for ADISTS). This small time step for COURLIS was forced by the imperativeness with the version used during this benchmark to run the calculation with the supercritical kernel of MASCARET (with an explicit time numerical scheme).

With the implementation of COURLIS in the TELEMAC-MASCARET trunk, the MASCARET version will be the last and should allow more flexibility for the kernel. It will be also possible to use the unsteady subcritical kernel (named “REZO”) and even, the Steady kernel (named “SARAP”). These abilities should improve a lot the computational time.

Otherwise, comparison with ADISTS and HEC-RAS was interesting about their approach on shear stress thresholds. Unlike COURLIS, these codes forced user to have only one thresholds for deposition and erosion. HEC-RAS allows also another mode of erosion, with mass wasting erosion.

Finally, this benchmark highlighted some limitations of COURLIS suspension like the ability of model GSD, the lack of classical settling velocities laws proposed to users or, the impossibility to have multiple reaches (only punctual tributaries on the main reach for now).

VII. References
