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Toward an operational approach for the characterization and modelling of fine sediments dynamics in reservoirs

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Abstract. Achieving a sustainable management of sediment fluxes in existing or proposed reservoirs is a challenging but essential requirement for dam operators. Such objective is of utmost importance to avoid sedimentation-related consequences. Numerical modelling is of great interest to understand the flow and sediment dynamics in a reservoir, to simulate the long-term evolution of sediment deposits and to evaluate the efficiency of various management strategies. This paper presents recent case studies, which validate the feasibility and relevancy of such technical option. The progresses obtained on essential stages of the numerical modelling of sediments dynamics in reservoirs are particularly emphasized. Concerning the distribution of deposits, a promising field method based on an optimum combination of direct samplings with acoustic measurements and video auscultations is detailed. Feedbacks are then provided concerning an innovative device deployed in the field for a direct measurement of the settling velocity. Issues about the assessment of calibration parameters are also addressed in this communication. Lab experiments performed on deposits sampled in several reservoirs provide practical guidance to evaluate the erosion parameters of sediments. Finally, several examples of sediment dynamics modelling in reservoirs including both cohesive and non-cohesive sediment are presented.

1. Introduction

1.1. Sedimentation issue in reservoirs

By storing and regulating water for the human consumption, irrigation, energy production, navigation and flood control, dam reservoirs provide essential services for the development, health and welfare of human civilizations. Sedimentation processes affecting reservoirs worldwide cause however significant losses to the storage volume each year. Water intakes and bottom outlets clogging, damages to turbines and sediment starvation below dams are

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among other adverse and costly consequences induced by the sediment continuity disruption due to particles trapping into reservoirs. Annually, those costs may represent between 10 and 15 billion USD [1]. Consequently, the implementation of efficient sediment management facilities and strategies is essential and should be seen as an investment that contribute (1) to ensure as long as possible the sustainability of existing and proposed reservoirs, (2) to optimize the economic profitability of those projects and (3) to facilitate their social acceptability in the future.

1.2. Tools to define sustainable reservoir sediment management

To achieve those objectives, simulations of hydraulic flows and sedimentation processes in reservoirs are needed right from the conception of the project. The aim of those simulations is to predict the trapping efficiency of the reservoir and test alternative mitigation measures likely to prevent as much as possible sediment-related hazards.

The choice of the most appropriate model depends on the goal of modelling activities. For instance, one-dimensional (1D) models are very convenient to provide global insights on long and narrow reservoirs, to simulate long-term trends or to perform a preliminary screening of managing scenarios among a large set of feasible alternatives. To perform detailed surveys about local processes or complex structures interacting with water and sediment flows, small-scale physical models are more appropriate, especially when the dynamics of coarse sediments is simulated. However, in the case of fine sediments, a relevant representation of processes with a scale model is at best very tricky to obtain and at worst impossible because of parasite phenomenon due to cohesive forces. For sites characterized by complex geometric features and fine or mixed sediments inflows, two-dimensional (2D) and three-dimensional (3D) numerical models are suitable alternatives to scale models. Two-dimensional models are indeed relevant tools to simulate morphological processes in shallow run-of-river reservoirs and are particularly efficient for long-term simulations. Three-dimensional models allow detailed simulations of sediment transport in all types of water bodies including deep storage reservoirs. Obviously, the precision of the results obtained with such models will never exceed the precision of the data used for their construction and calibration. The more precise and extensive is the available calibration dataset, the less is the model uncertainty. For reservoir sedimentation surveys, needs regarding field data are significant and must focus on the river geometry, flow hydraulics but also on sediment features. A frequent issue in projects is that sediment sample collection and lab experiments are often challenging, costly and time consuming. Another issue is that the characterization of transported and deposited sediments concerns several parameters for which standardized methods may not exist yet.

Rather than providing a detailed view of one specific project, this paper presents several illustrating cases that demonstrate the robustness and replicability of a generic approach dedicated to reservoir sedimentation management. In particular, in and ex-situ experimentations implemented to provide sediment calibration data are described, as well as essential validation stages required for numerical modelling surveys.

2. Numerical modelling of reservoir with TELEMAC

TELEMAC-MASCARET is an open-source system of numerical codes developed by a consortium of organizations (http://www.opentelemac.org). The integrated suite of solvers covers free surface flows and associated processes such as sediment transport and biogeochemical processes. One dimensional to three dimensional hydrodynamics solvers are available. Suspension as well as bed-load can be simulated. In this paper the description of the numerical tools focuses on fine sediment transport by suspension.

2.1. One-dimensional modelling: COURLIS

COURLIS is the one dimensional sediment solver. It is coupled with MASCARET [2] which solves the 1D shallow-water equations and uses a finite volume scheme. MASCARET has been used to simulate dam breaks and allows the calculation of unsteady supercritical flows. For the transport of fine sediment by suspension a 1D advection-dispersion equation is solved using finite volume schemes. Details about the implemented equations can be found in previous papers [3], the following paragraphs give the main principles of sediment equations. For cohesive sediments, erosion and deposition fluxes are computed using a Partheniades and a Krone laws. For non-cohesive sediments, such as sand, deposition and erosion fluxes depend on the difference between solid concentration in the flow and the equilibrium concentration estimated with the sediment transport capacity calculated with the Engelund Hansen formula. The main parameter describing the sediment in this approach is the sediment grain size.

2.2. Two and three-dimensional modelling: TELEMAC-2D & 3D - SISYPHE

SISYPHE is the sediment module coupled with TELEMAC-2D and TELEMAC-3D which solve the 2D shallow water equations or Navier Stokes equations respectively. Finite elements or finite volume numerical schemes can be used. Similarly to the 1D code, a 2D or 3D advection-dispersion equation deals with the suspended sediments. For cohesive sediments Krone and Partheniades are also used to treat the source terms of this equation. For non-cohesive sediment, the net sediment flux is determined by comparing a reference suspended concentration estimated near the bed to an equilibrium near-bed concentration (Zyserman-Fredsoe, van Rijn or Bijker Formulae). The main parameters describing sediments in TELEMAC-MASCARET models are concentrations and grain sizes in the bed, settling velocities, critical shear stress for erosion and deposition and Partheniades coefficient for erosion.

3. In situ measurements: characterizing reservoir deposits & suspended sediment

3.1. Solid fluxes measurements

One way of achieving a sustainable sediment management in reservoirs is to bring sediment inflow and discharge into balance while maximizing usable storage capacity. Usually, solid fluxes are represented as the summation of the bed-load (cobble, gravel and sand), graded suspension (fine sand) and washload (silt and clay). As each play different roles in the river-system and as their susceptibility to being trapped by reservoirs is radically different, determining the relative importance of those different processes is an essential but challenging prerequisite in hydraulic projects. Ideally, the length of the time series required should cover at minimum one to several complete hydrological cycles to explore the seasonal distribution of sediment flows. Solid fluxes measurement should be also concomitant with bathymetric monitoring in order to facilitate the morphological changes understanding and to obtain a robust calibration of numerical model.

For bed-load and graded suspension, fluxes can be an evaluated experimentally through direct measurements with specific samplers (Helley-Smith, Delft bottle…) or surrogate techniques based on instantaneous (hydrophone, ADCP…) or time-averaged (sediment traps, scour chains…) recordings. Although promising developments are emerging, such measurements are still challenging, costly and time consuming. In cases for which it is relevant to assume an equilibrium state between the sediment supply to the river and the transport capacity of the flow, the bed-load and graded suspension fluxes can also be evaluated from semi empirical formulae taking into account local hydraulic conditions. An important interest of rating curves using such physically-based model is that one can compute yearly sediment fluxes and long term sediment budgets based on statistical discharges and/or discharge time series [4]. Comparatively, the part of solid fluxes corresponding to washload appears relatively easier to measure in the field because the concentration in fine sediments across the flow section is rather uniform. This means practically that a measurement at bank may provide a relevant estimate of the concentration in the whole section. In many streams, this situation has pushed forward the deployment of continuous monitoring stations for fine suspended sediment using surrogate technologies (such as turbidity, laser diffraction or acoustic backscatter) associated with an automatic sampling system for calibration. To take advantage of existing infrastructure and to facilitate computations of sediment loads, those stations are generally co-located with existing stream gages. Contrary to bed material fluxes, physically-based formulas are not a possible alternative to field measurements because the amount of fines depends mainly on upstream sediment sources.

3.2. Settling velocity measurements

For non-cohesive sediments, settling velocity is calculated using the diameter of particles and formulae such as Camenen [5]. For cohesive sediment, due to flocculation, settling velocity does not depend on the diameter and may vary from 10^{-5} to 10^{-1}m/s [6]. Depending on the concentration, settling regime can be free for low values, flocculated for intermediate concentrations and hindered for high values of concentrations. Only direct measurements of settling velocities give realistic values of this parameter. In order to characterize sedimentation in reservoirs and to anticipate downstream impacts of sedimentation operations, EDF has been measuring settling velocity of sediments from 19 reservoirs. The innovative SCAF device [7] allows quick measurement in the lab but also in situ. A comprehensive description of the measurements is given in [8]. Settling velocity values depending on the concentration were obtained, covering a large range of values from 0.02mm/s to 13.1mm/s. As no relationship with other parameters (diameters, organic content) was found, it therefore highlights the relevance of direct measurements.

3.3. Bed characterization

Information regarding the bed characteristics is required to represent adequately the friction losses due to the bed roughness as well as the possible sediment exchanges between the flow and the reservoir bottom. In the model, the variables accounting for the bed description includes in particular the median grain size of the bed material, the thickness of the different uniform layers accumulated, the bulk density, and the erosion parameters of deposits in the case of cohesive sediments. Those requirements need to address several challenges: (1) to describe accurately the spatial distribution of deposits, (2) to choose representative sites for sample collection and (3) to collect undisturbed samples for further lab analysis. To satisfy these objectives, acoustic techniques inspired from oceanography were recently deployed in the case of Champagneux dam (Rhône River, France) and led to promising results [9]. First, a prior scan of the survey area is performed with a side-scan sonar and a sub-bottom profiler to provide an overall mapping of units showing a similar pattern. Then the different clusters identified are qualified thanks to direct investigations with underwater video. Finally, this overall mapping guides the choice of sampling sites to guarantee their good representativeness.

3.4. Erodability measurements

There is still no standardized method to characterize the erodibility of reservoir deposits. This situation leads to apply erosion protocols derived from other uses such as the Jet Erosion Test (JET) or the erodimeter test. Those tests provide an assessment of the critical shear stress for erosion, as well as an empirical relation between the erosion rate and the bottom shear stress.

The JET was designed to test the resistance of soils in earthen spillways. It consists of a high velocity, submerged jet of water impinging perpendicularly on the sample surface [10]. The erodimeter test has been originally proposed for evaluating the scour rate of natural ground of rivers at bridge crossing or in estuarine environments. It consists in inserting a sample into the bottom of a rectangular flume in which the water flows and the induced shear stress causes the sample erosion [11]. Specific versions of the erodimeter, such as the "IFREMER" type, allow the measurement of the shear stress using pressure probes as well as a continuous monitoring of turbidity to estimate the erosion fluxes.

Both tests have been applied and compared in the frame of the Champagneux dam (Rhône River, France) and Longefan reservoir (Arc River, France) projects. The samples tested were composed of silt, sand or a mixture of silt and sand. Feedbacks obtained demonstrate that the erodimeter test has a better sensitivity and is more appropriate for deposits characterized by a low proportion of fines. The calibration of 3D numerical models based on the erosion parameters derived from flume experimentations (or erodimeter test) leads to very consistent simulation results compared to observations. Comparatively, simulations based on the erosion parameters derived from JET appear less reliable. Even if it is still an ongoing research, this may indicate that the use of erodimeter tests is probably more adapted than JET for that kind of applications.

4. Examples of reservoir modelling with TELEMAC

4.1. St Egrève reservoir (France)

The Saint-Egrève dam is located downstream of the city of Grenoble (Isere River, 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 for the design flood is a major issue, and sedimentation must be taken into account to estimate a realistic freeboard. 1D, 2D and 3D morphodynamics simulations were performed using the whole TELEMAC system to investigate flushing scenarios, in particular for the design flood [12]. The models were calibrated and validated with sediment fluxes measurements carried out during two flushing operations performed in May 2008 and May-June 2010. Bathymetries of the reservoir were also surveyed before and after each of these events. Two turbidity probes were placed upstream and downstream of the reservoir. These sensors enable a continuous monitoring of the sediment concentration evolution during flood and the determination of the silt volumes, which passed through between the bathymetric measurements and the flushing operations. In addition, sediment samples were taken from the reservoir bottom in September 2010. The model calibration revealed the necessity to account for three distinct sediment layers. The top layer represents the slightly consolidated sediment (easily remobilized), the intermediate layer corresponds to the recently deposited sediment (few years), and the deeper layer is the most consolidated one. Sediment layers were constructed from the bathymetric data. The good agreement between observations and simulation results demonstrates that numerical models of sediment dynamics can be used as a reliable tool to predict the effects of dam operations (Figure 1). During the lowering of the water level, the erosion peak (1) due to slightly consolidated silts is well represented by numerical models. The main erosion peak (2) occurs when the water level is at its minimum value. The sediment dynamics is well represented by models although the maximum peak value is slightly underestimated. The last peak (3) is due to an increase of the flood discharge and appears underestimated. Besides, this case highlights the need for suitable field data to perform relevant numerical modelling.

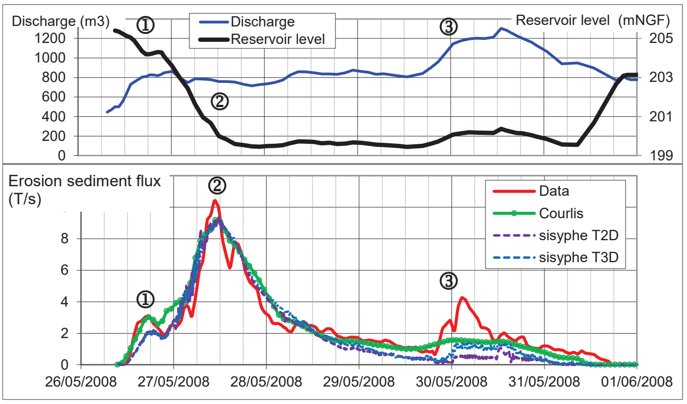

Fig. 1. Total solid flux downstream Saint Egrève dam observed and simulated by different models for the 2008 flushing operation.

4.2. Kapichira reservoir (Malawi)

Kapichira reservoir, on the Shire River in Malawi, has experienced significant deposition since its completion in 2001. Field data have been collected at site, including bathymetry survey data, suspended sediment samples and bed sediment samples. The grain-size analysis of bed materials shows that the deposits consist in both sand and fine sediment. This field dataset has enabled the set up and calibration of a numerical model (Telemac-3D) which is able to reproduce the sediment deposits in the reservoir since the building of the dam. The model takes into account at the same time the transport of fine cohesive sediment (in suspension, with Partheniades erosion law) and non-cohesive sediment (using a total load transport formula). The result of this calibration is presented in Figure 2.

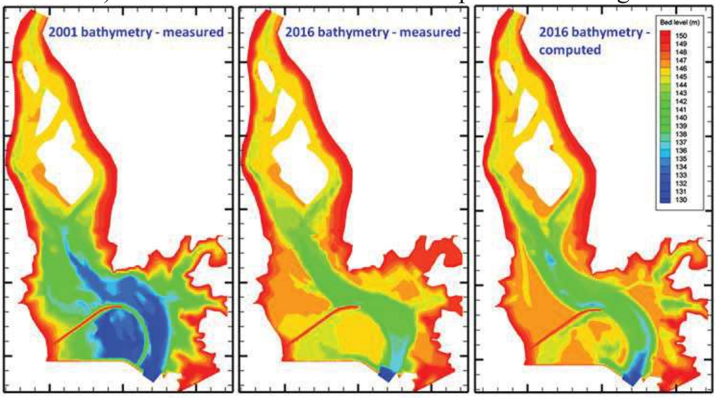

Fig. 2. Comparison of computed and measured bed evolution at Kapichira reservoir.

4.3. Longefan reservoir (France)

The Longefan reservoir is a silt trap for the hydro-electric facilities diverting the Arc River (French Alps). The large sediment deposits in the reservoir were suspected to reduce the siltation capacity of the reservoir. A TELEMAC-3D model has been set up and calibrated based on bathymetric, hydrodynamic and sedimentary (in particular with tests for erodibility characterization) surveys in the reservoir. It has then be used to help preparing flushings, and to study the impact of the deposits in the reservoir on the siltation capacity of the reservoir.

On-site Jet Erosion Tests (JET) estimated critical erosion stresses at 2-4 Pa and erosion coefficients at about 0.3kg/s/m². The critical erosion stress values are consistent with the expected values for cohesive sediments, but the estimated erosion coefficients are very high and would indicate a very erodible material.

Laboratory tests on cores taken from the basin were also carried out at the University of Caen with an erodimeter flume ("IFREMER" type erodimeter). These tests and their results are described in more detail in [13]. The results of these lab erosion tests confirmed that the classical Partheniades law was adapted to simulate the erosion flow. The estimated critical erosion stress was 0.5 Pa and the erosion coefficients were in the order of 0.002kg/s/m². These results are thus very different from those of JET.

The parameters of the erosion law in the final version of the numerical model are those determined by the erodimeter test. This model shows a much better agreement with the observed behaviour of the reservoir than with the parameterization from the JET measurements. In particular, the correct order of magnitude and locations of long-term sedimentary deposits in an initially empty reservoir during a representative unsteady hydrological scenario are simulated (figure 3). The model results indicate that deposition occurs in the whole basin during periods where water level in the basin is high (it that case there is a single clockwise vortex in the whole basin), and erosion of the channel between the entrance and the outlet occurs when the water level is low, and during flushings. The numerical model with this same parameterization also makes it possible to reproduce the order of magnitude (with a slight overestimation) of the volume of sediment eroded during flushings. This may indicate that the use of erodimeter tests rather than JET is probably more adapted for that kind of applications.

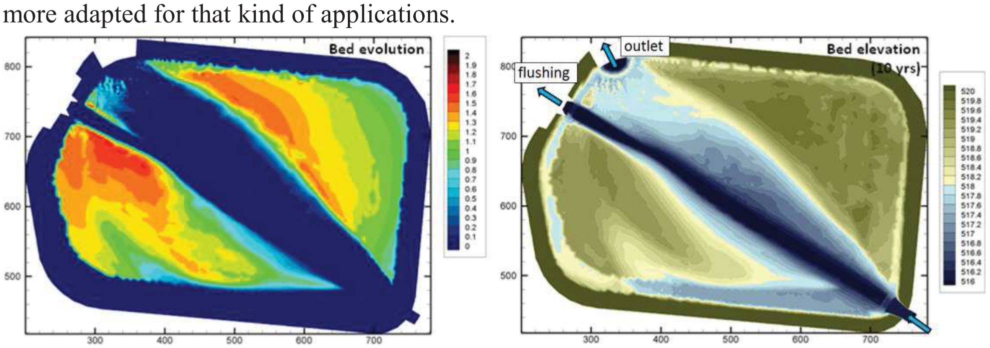

Fig. 3. Computed bed evolution (left) and final bathymetry after 10 years of operation (right).

5. Conclusion and perspectives

The different examples presented in this paper show that 1D, 2D or 3D numerical modelling can simulate accurately sediment transport (and in particular the evolution of sediment deposits) in reservoirs, for a wide range of processes and configurations. This paper described three examples of continuous moderate concentrations, recent works also show that Telemac3D simulate turbidity currents correctly [14]. It is therefore a powerful tool in order to devise and evaluate strategies for the management of the different issues associated with sediment transport in reservoirs.

A proper sedimentary data set is in any case a prerequisite for such work, in order to set-up and calibrate adequately the different parameters of the model that concern sediment transport.

Field and/or laboratory work is thus necessary to (1) quantify and characterize (settling velocity) the sediment load to the reservoir, and (2) map the composition of existing sediment deposits in the reservoir, and characterize their erodibility.

The paper describes examples of the application of state-of-the-art methodologies for these different surveys. Some of the techniques used are relatively new (at least in the context of reservoir sedimentation) and there is a pressing need to standardize these methods so that industrial subcontractors can use them.

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