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Modelling the sediment dynamics in the Chambon Reservoir with Telemac 3D

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Abstract—**The Chambon Reservoir on the Romanche River has a high rate of sedimentation. In order to help identifying a sustainable sediment management strategy, a modelling of sediment dynamics in this reservoir was built. Numerical simulations were performed according to a comprehensive understanding of sediment transport in this lake based on a large set of in situ data. Suspended sediment concentration monitoring upstream the dam leads to the identification of the main contributing hydrological events. Downstream monitoring demonstrates that specific operating conditions (reservoir level, discharge) allow sediment routing throughout the reservoir. In order to elaborate a clear comprehension of sediment processes, field surveys have also been performed in the reservoir. Bathymetry, Velocity field, sediment concentration were monitored. An innovative device has been built in order to identify sediment and flow dynamics inside the reservoir. Calculations using TELEMAC3D allow to well reproduce the three dimensional patterns of suspended sediment transport in this large reservoir. Turbidity currents due to upstream erosion of sediments are observed in the reservoir and are reproduced with the model. Calculations are compared to in situ measurements, the global sediment dynamics is well reproduced, but there are some differences in the quantitative values.**

I. INTRODUTION

As it has been observed in many countries [9], sedimentation in reservoirs is unavoidable and may have several consequences: (i) loss of capacity, (ii) siltation near bottom gates, (iii) large sediment releases during reservoir emptying...

In order to define long-term management of reservoir sedimentation, deposition in existing reservoirs needs to be mitigated by using appropriate measures for sediment release. The management of sedimentation in large reservoirs is a major issue. Indeed, large amount of fine sediments and gravels could deposit. In the case of large dams, flushing operations (opening of dam gates) could only venture turbidity current or erode a limited part of the sediment bed near the gates. It could require research works to define the appropriate way of dealing with sediments in large reservoirs.

For example, [2] studied turbidity current in Luzzone lake comparing 3D numerical calculations with in situ measurements ; using laboratory experiments and numerical simulation [11] suggests to use geo-textile or underwater obstacle to deal with turbidity current, some numerical calculation were performed using Grimsel reservoir geometry, or [10] analyze the flow patterns and suspended sediment movement in pumped-storage facilities.

Before defining sediment operation, the main processes involved in sediment transport should be identified owing to measurements (bathymetric surveys, concentration monitoring, velocity measurements...). They may help to identify the locations of deposition and the propagating ways (turbidity currents or homogeneous suspension).

EDF stock of facilities accounts for approximately 200 large dams and more than 600 water intakes linked to run off river schemes. In several cases, sedimentation must be dealt with to avoid loss of storage or siltation near the bottom gates.

We focus on the Chambon Reservoir, located in the Alps Mountains. In order to understand the dynamics of sediment, the sediment propagation through this large reservoir has been analyzed, first measuring sediment output and input, then we analyze the internal dynamics using in situ monitoring [15]. Some preliminary numerical simulation of sediment dynamics in the reservoir using TELEMAC2D and SISYPHE have been presented [15], they give a good simulation of the global pattern of sediment dynamics. A 3D model is essential to reproduce the vertical stratification in the lake. Therefore the present paper details the 3D calculations. First the Chambon Reservoir and the sediment monitoring are described. Then the 3D model is introduced and the numerical results are analyzed.

II. SEDIMENTATION IN THE CHAMBON RESERVOIR

A. *Description of dam and reservoir*

The Chambon dam is located on the Romanche River in the French Alps, Figure 1. The watershed area at the dam is 254 km^2 and the elevation of the area is around 990 m. The Romanche River and a small water derivation flow into the reservoir, the Ferrand derivation. This derivation enters the reservoir as a water fall, Figure 2 (b).

The hydropower facility, St Guillerme II, has been in activity since 1935, the head is 293 m and the electric power 110 MW.

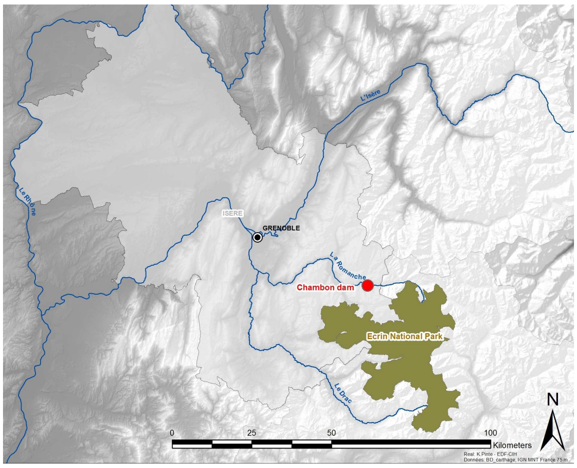


Figure 1. Location of the Chambon Dam.

(a)

(b)

Figure 2. (a) aeriel picture of the Chambon Reservoir (Geoportail). (b) Water fall of the Ferrand derivation.

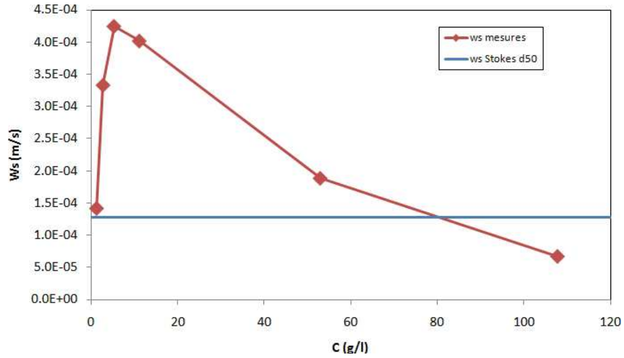


Figure 3. Settling velocity measurement of Chambon sediments.

The volume of water in the reservoir is estimated to be 47.5 10^6 m^3 and the reservoir is 3.5 km long at the highest water level. The water elevation varies depending on seasons, the water level fluctuations could be up to 60 m. Since the beginning of its use, the reservoir has undergone a high rate of sedimentation, it is due to the watershed geology, made of different areas of crystalline rocks but also metamorphic schist. The fine sediment deposition rate in the reservoir is around 100 000 m^3/year. In 2005, in order to protect the bottom gate of the dam, a dredging of 25 000 m^3 of sediments was performed. The sedimentation in the reservoir is studied to find the best sustainable way to manage sediments.

B. Bathymetric and sediment monitoring

A large set of data is available to understand the sediment dynamic in the lake. A comprehensive description of the measurements and their analysis is given in [15].

From the bathymetric data, we could conclude that the reservoir bed evolution is strongly impacted by the water level in the reservoir and its geometry: sediment are eroded in the upstream part of the reservoir where the water flows with high velocities and low water depths; sediment are deposited in the downstream part of the reservoir where the water is still and where the water depth could be high.

Sediment were sampled from the bed in 2004, d50 is around 50 µm, and the concentration of the bed varies from 900 to 1200 g/l. The content of organic matter is low (around 2 %). Due to their small grain size, these sediments are cohesive. Sediment fall velocity measurements have been performed in the laboratory on a representative sample of suspended sediments (d10 =3.7µm, d50 =10.9 µm, d90 =37.9 µm). Settling velocity have been measured owing to an Andreasen pipette, a sediment weight device [8] and a SCAF device [14]. The data from three devices indicate the same trend, figure 3: the settling velocity is the highest, 0.4 mm/s, for a concentration of 10g/l, this value is much higher than the one that could be calculated owing to Stokes formula, 0.12 mm/s. For concentrations higher than 10 g/l a hindered regime is measured [3].

The monitoring of sediment input and output shows that the output of sediment from the reservoir is strongly correlated to the water level in the reservoir, figure 3 shows that: (i) above 985 m, sediment deposit in the upstream part of the reservoir; (ii) below 985 m, sediment are eroded and they could be transported to the water intake.

In order to have a better insight to the internal sediment dynamics, an innovative device has been designed. Its goal is to give continuous measurement of sediment concentration and flow velocities in the lake at a specific location and for two depths, near the surface and near the bottom of the lake. The data are used in the 3D calculations.

III. DESCRIPTION OF THE 3D NUMERICAL MODEL

Numerical modeling could be a relevant tool in order to test sediment management strategies. In the specific case of large reservoirs, 1D models have been used to predict the sediment concentration during lowering operations [6]. But due to the complex geometry of the large reservoirs, and stratification processes, 2D or 3D model could be required. 3D numerical modeling is now used to study reservoir sedimentation [10, 11]. First the results of some preliminary 2D calculations were studied [15] and in the following we show the 3D results.

TELEMAC 3D from the open source Telemac system (www.opentelemac.org) is used.

A. *Description of the model*

The geometry of the model is based on the last bathymetry (2011, 1 point/m), the area of the model is the area under water for a water level of 1018 m (maximal operating level during the last years).

The horizontal mesh is made of triangular elements with a size of 5m everywhere but in the talweg where there have a size of 2m and near the bottom gate and the water intake. In order to focus on the sediment processes near the dam, only the area located 1km upstream the dam is included in the model, Figure 4. HYPACK [5] and BLUEKENUE [1] softwares were used to build the horizontal mesh. Two vertical meshes were tested, a z-layer with 22 planes at constant elevations and a σ-layer with 10 planes, Figure 5.

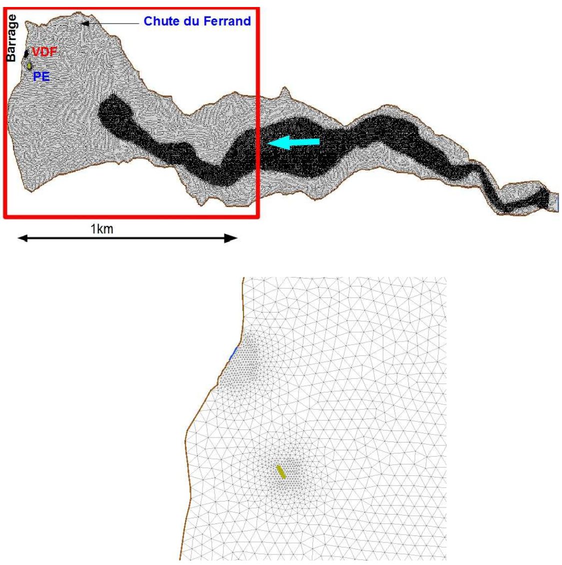
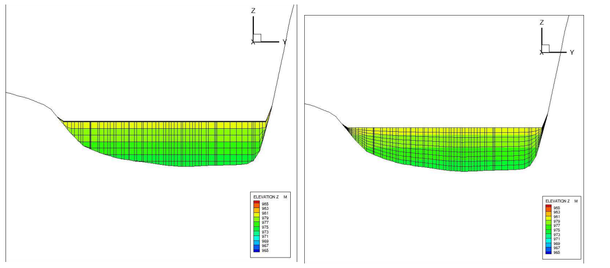


Figure 4. Horizontal mesh.



(a) (b)

Figure 5. View of the vertical mesh. (a) z-layer with 22 planes at constant elevations (b) σ-layer with 10 planes.

The upstream hydraulic condition is a varying discharge and the downstream condition could be an imposed water level or an output discharge. The concentration of sediment is chosen on the upstream boundary and it is a free condition on the downstream boundary. The water intake which is not at the boundary line, is represented by a sink.

No data is available to calibrate the friction coefficient, therefore the Strickler coefficient is chosen equal to $52m^{1/3}s^{-1}$. The turbulence chosen model is a constant viscosity ($D = 10^{-3}m^2s^{-1}$). In these first calculations, a simple configuration is designed according to the measurements, the sediment bed is made of 2m of uniform cohesive sediments, concentration of the bed is fixed to 900 g/l, fall velocity is 0.4 mm/s. Due to a lack of measurements, other parameters are chosen by analogy with other similar studies [13], that is to say : lateral and longitudinal diffusivity ; critical shear stress for erosion $\tau_{CE} = 1$ Pa ; Partheniades coefficient $M = 10^{-2}$ $kgm^{-2}s^{-1}$; and critical shear velocity for deposition $v_{CD} = 0.01$ m/s, equivalent to a critical shear stress of 0.1 Pa.

IV. NUMERICAL RESULTS

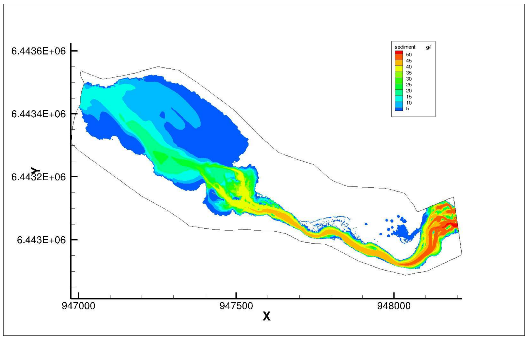
A. *Sensitivity tests*

Several sensitivity tests have enabled to choose the numerical parameters and the unknown physical parameters.

Calculations were performed for a time step from 0.1 to 1s. Results are compared for a calculation with constant water elevation at the dam, constant input discharge and concentration. The results show that above 0.2s significant discrepancies are observed. Therefore all the calculations are performed with a 0.2s time step. The calculation time is twice the simulated duration with 192 cores.

The σ-layer vertical mesh is chosen because it shows a longer propagation of sediment in the reservoir.

Four turbulence models were tested (2 values of constant viscosity, kε, and Nezu Nagakawa mixing length model). Figures 6 and 7 show respectively the concentration in the lake and the bathymetric evolution after 22400s (constant elevation 980m, constant input discharge and concentration $20m^3/s$ and 50g/l) for the kε model and (b) horizontal 10^{-3} m^2/s constant viscosity and vertical Nezu Nagakawa mixing length model. There are some significant differences between both calculations, the pattern of sediment propagation in the lake for the kε model indicates that the sediments reach the dam and its gates whereas for the other model the sediment are directed towards the right bank. As the measurements at this water elevation and discharge show an output of sediment. All the calculations are performed with the kε model.



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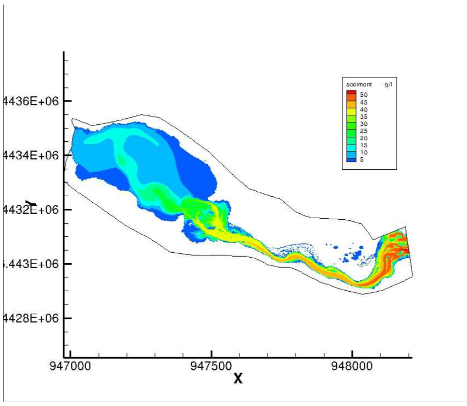
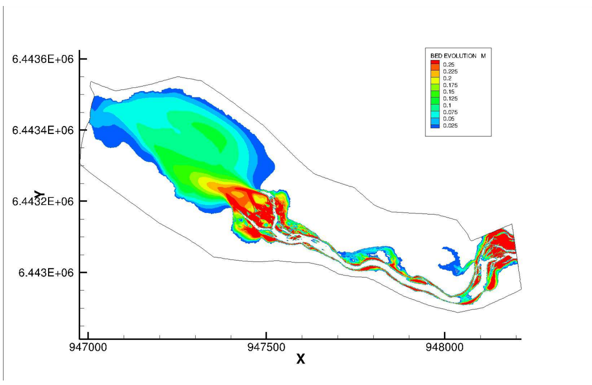


(b)

Figure 6. Concentration in the lake after 22400s (constant elevation 980m, constant input discharge and concentration 20m./s and 50g/l). (a) kε model and (b) horizontal 10^{-3} m^2/s constant viscosity and vertical Nezu Nagakawa mixing length model.



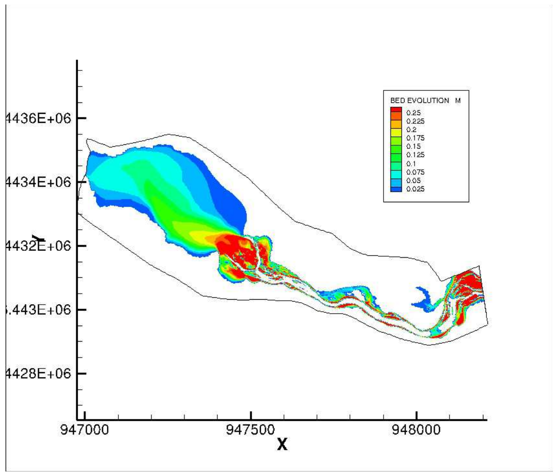
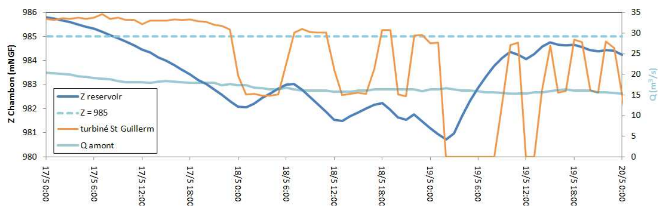


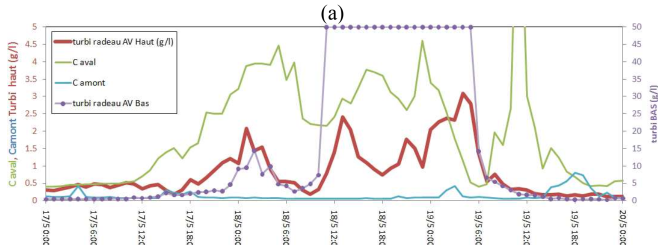
Figure 7. Bathymetric evloution in the lake after 22400s (constant elevation 980m, constant input discharge and concentration $20m^3$/s and 50g/l). (a) kε model and (b) horizontal 10^{-3} m^2/s constant viscosity and vertical Nezu Nagakawa mixing length model.

B. Calculation of sediment dynamics for a real event

In order to test the model on a real event, we simulate the period from May 17^{th} to the 20^{th}. The upstream discharge is nearly constant around $17m^3$/s, the upstream concentration is lower than 0.5g/l, and there is a lowering of the water level in the reservoir which induced erosion in the reservoir. Consequently the data show that the downstream concentration increases, Figure 8. The concentration measured by the upstream platform in the lake is chosen as the upstream boundary condition.



(a)



(b)

Figure 8. Hydraulic and sediment conditions around May 17^{th} 2013. (a) Water elevation at the dam, input and output discharge; (b) input and output concentrations.

Figure 9 shows the concentration in the lake during the event. A plunging effect of the current can be observed, and the sediments reach the dam. Figure 10 shows a comparison between the concentrations measured downstream the dam and the concentrations calculated at the dam outlet. The order of magnitude and the dynamic is well reproduced but a temporal lag exists between measured and calculated values. This could be due to several reasons:

- A downstream lag between the dam and the measurement point ;
- An upstream lag between the measurement station (discharge and concentration) and the upstream boundary of the model;
- A simplified description of the sediment bed;
- The fact that the hydrodynamics has not been calibrated (friction and turbulence);
- Etc…

Further measurements would help to better reproduce the sediment dynamics in the lake.

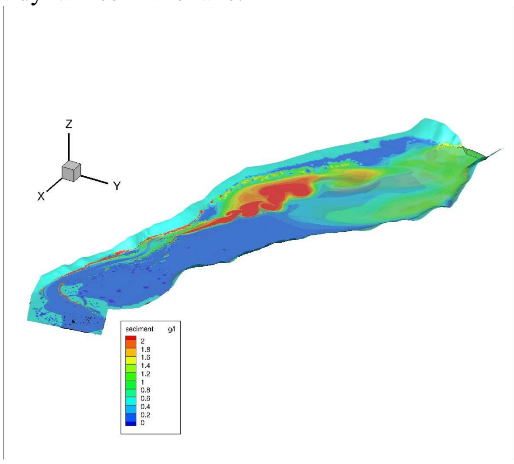


Figure 9. Concentration in the lake for the real event after 50 000s.

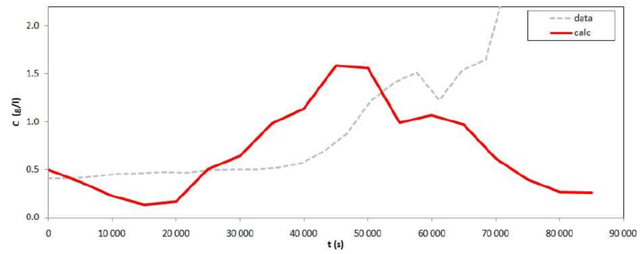


Figure 10. Measured and calculated concentration near the dam outlet for the real event of May 17th 2013.

C. *Effect of the water fall*

The previous monitoring indicates that the water fall near the dam, on the right bank, has an effect on the water velocities in the lake. Some simple tests are performed to try to simulate this effect. The water fall is reproduced with a discharge source on a node.

Figures 11 and 12 show the differences without and with the water fall. The water fall has an effect on the sediment propagation in the lake. The vertical stratification is changed near the dam.

Further measurement would be necessary to calibrate and to analyse the effect of the water fall more deeply.

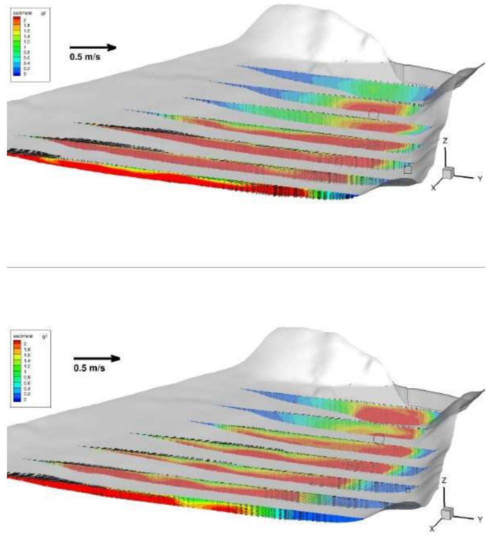


Figure 11. Tests to simulate the effect of the water fall. Top : concentarion in the lake without the water fall and Bottom : concentration in the lake with water fall. The water fall is represented by a "o" on the bottom picture.

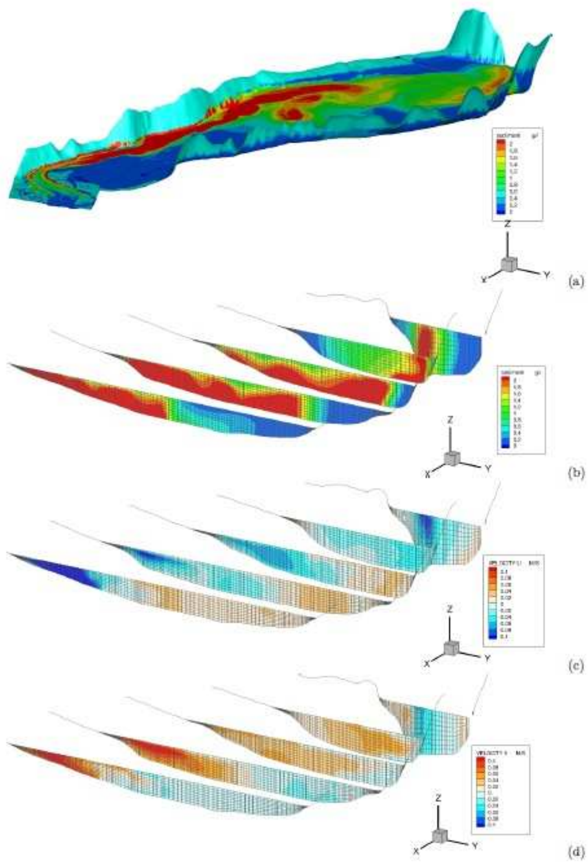


Figure 12. Calculation with the water fall, (a) surface concentration (b) ceoncentration in the lake (c) and (d) vx and vy components of the velocity vector.

V. Conclusion and Prespectives

3D calculation of sediment propagation in the Chambon reservoir were performed with Telemac 3D. Sensitivity tests enabled to choose the numerical parameters and the unknown physical parameters.

The calculations allow to reproduce the main trend of the sediment dynamics in the lake but some differences between the measurements and the numerical results are observed.

Identifying the source of the discrepancies is not easy but additional data could be a way to improve the calculations. The code could also be tested on experiment data in order to determine the best parameterization to simulate turbidity currents. Besides, the modelling of the turbidity currents in reservoirs will help to find ways to manage the sedimentation.

Acknowledgement

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