Innovative in-situ measurements, analysis and modeling of sediment dynamics in Chambon reservoir

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Innovative in-situ measurements, analysis and modeling of sediment dynamics in Chambon reservoir, France

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ABSTRACT: This paper focuses on siltation processes in an Alpine reservoir, the Chambon Reservoir on the Romanche River. 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. Some preliminary numerical simulation of sediment dynamics in the reservoir using TELEMAC2D and SISYPHE show encouraging results. Actually modeling could be a useful tool to evaluate sediment management strategy. The main processes involved in suspended sediment transport were identified and their understanding will help to define strategies to reduce sedimentation in Chambon reservoir.

Keywords: Reservoir sedimentation; suspended sediment transport; in situ monitoring

1 INTRODUCTION

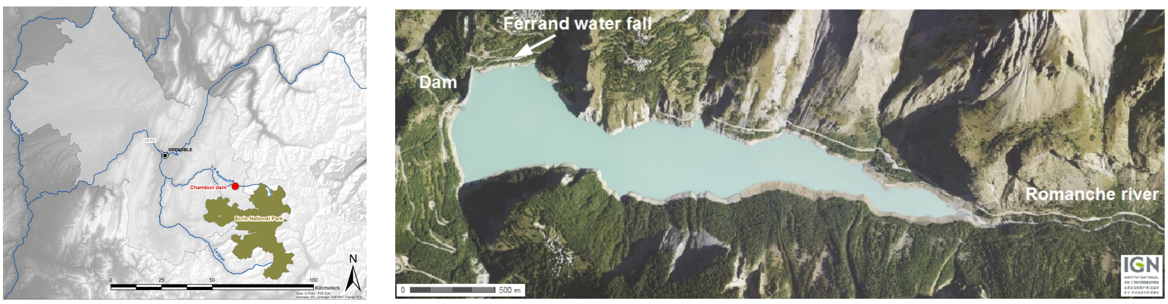
As it has been observed in many countries [9], sedimentation in reservoirs is unavoidable and may have several consequences: (i) loss of capacity, (ii) siltation near bottom gates, (iii) large sediment releases during reservoir emptying...
In order to define long-term management of reservoir sedimentation, 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 ans 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 manages more than 400 dams. In several cases, sedimentation must be dealt with to avoid loss of storage or siltation near the bottom gates.
In this paper, we focus on the Chambon Reservoir, located in the Alps Mountains. We try to analyze the dynamics of sediment in the reservoir in order to be able to implement relevant sedimentation operations. In order to understand the dynamics of sediment, we analyze how sediment propagate trough this large reservoir, first measuring sediment output and input, then we analyze the internal dynamics using in situ monitoring. The last part of this paper shows some preliminary numerical simulation of sediment dynamics in the reservoir using TELEMAC2D and SISYPHE. Actually modeling could be a useful tool to evaluate the sustainability of sediment management strategies.

2 SEDIMENTATION IN CHAMBON RESERVOIR

2.1 *Description of dam and reservoir*

The Chambon dam is located on the Romanche River in the French Alps. The watershed area at the dam is 254 km^2 and the elevation of the area is around 990 m. The Romanche river and two small water derivations flow into the reservoir, The Ferrand and Mizoen derivations, figure 1. The hydropower facility, St Guillerme II, has been in activity since 1935, the head is 293 m and the electric power 110 MW.
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 it 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.

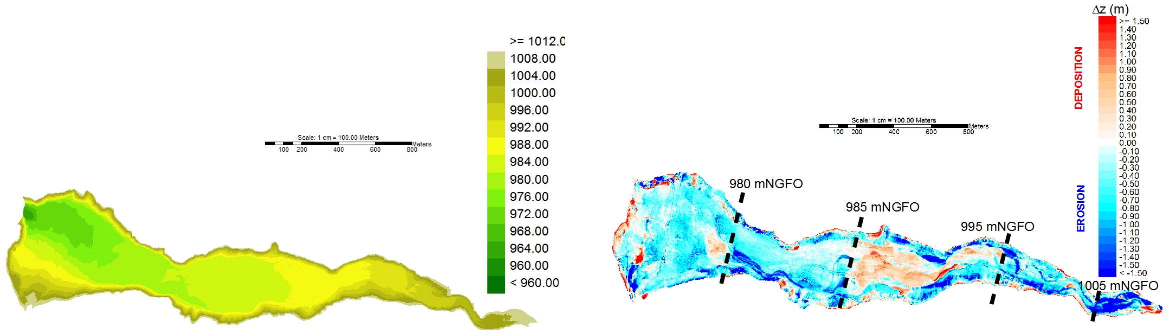


(a) (b)

Figure 1. (a) Location of hydropower facility Chambon-St Guillerme II. (b) Aerial picture of the reservoir, the water fall created by the Ferrand derivation (intake's outlet) is on the right bank.

2.2 *Bathymetric analysis : impact of water level regulation*

Several bathymetries have been performed since the construction of the dam (six bathymetries from 1993 to 2011), they show that (i) from 1993 to 2006, a siltation rate of 100 000 to 200 000 m^3/year is measured ; (ii) from 2006 to 2009, erosion of sediment is observed, it is due to the dredging near the bottom gate and to the low water level of the reservoir that induced an erosion of the upstream part of the reservoir. The difference between the last bathymetries (2009 and 2011, figure 2] highlights the significant role of specific water elevation due to particular reservoir operations:



(a) (b)

Figure 2. (a) Bed elevation, data from 2011 bathymetric survey. (b) Measurement of bed evolution in the reservoir : difference between 2009 and 2011 bathymetries.

- erosion is observed in the upstream part of the reservoir, in the areas higher than 1005 m. During this period (2009-2011) water level was always lower than 1005 m ;
- deposition is measured between 985 and 995 m, where the reservoir is the largest ;
- then erosion is showed between 985 and 980 m, 980 is the minimal turbinable water level, and 985 m is a water level that is not often reach;
- a deposited delta of sediment is observed below 980 m.

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 ; the enlargement impacts the deposition/erosion processes.

2.3 *Sediment characterization*

Sediment were sampled from the bed in 2004, d_{50} 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 (d_{10} =3.7 μm , d_{50} =10.9 μm , d_{90} =37.9 μm). Settling velocity have been measured owing to a Andreasen pipette, a sediment weight device [8] and a SCAF device [14]. The data from three devices indicate the same trend : 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].

2.4 *ANALYSIS OF SEDIMENT INPUT AND OUTPUT*

Continuous measurement of sediment concentration has been performed at several locations in order to characterize sediment input and output. Turbidimeters are located : (i) 4 km upstream the dam in the Romanche River ; (ii) in the Ferrand derivation ; (iii) downstream the reservoir in the Clapier Bassin. Turbidimeters (Hachlange SC100) are calibrated using samples, the calibration relation could be difficult to establish, therefore concentration measurements should be considered precociously.
The incoming sediment flux in the reservoir is calculated as the sum of the main Romanche input, both derivation inputs, and input from the reservoir subwatershed (between the upstream measurement site and the dam, the ratio of drainage area is 256/220).
They indicate that the annual mean input in the reservoir is around 120 000 t, 78 000 t come from the upstream river, 8 100 t from the intermediate watershed and that the rest comes from the Ferrand derivation. From this quantity of sediment, 25 % are transported downstream and 90 000 t deposit in the reservoir. These measurements also indicate the time variation of the sediment input: 50 % of the sediment from the Ferrand derivation flow during 3 % of the year and it corresponds to 4 % of the global volume of water.
Furthermore, The input of sediment in the reservoir is controlled by daily snow-melt cycles, figure

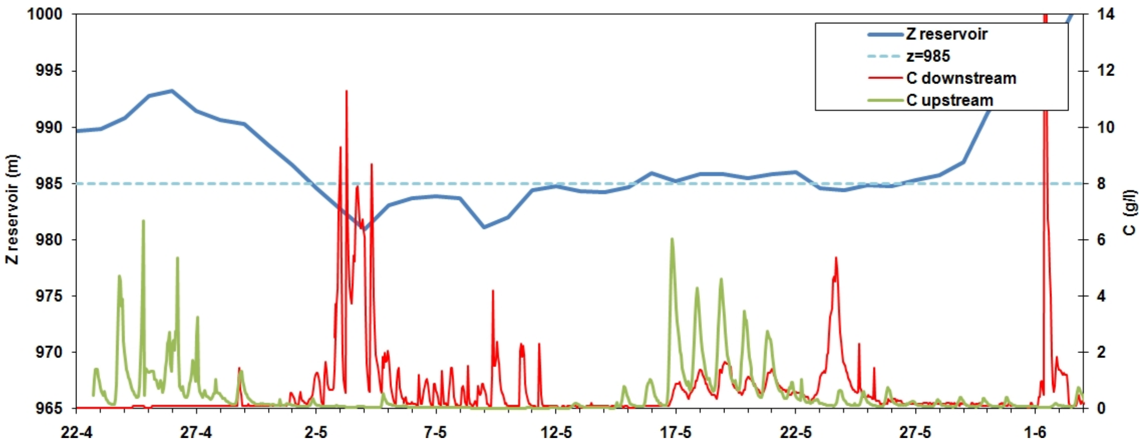


Figure 3. Measurement of sediment concentration upstream and downstream the dam, example of 2004

3, as it has been described by 7. 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.

These bathymetric and concentration observations clearly show the part of the reservoir geometry in the sediment dynamics: the narrowing and the enlargement of the reservoir geometry impacts the deposition and erosion processes at the reservoir scale ; water level in the reservoir is significant in the sediment dynamics.
Observation at low level of sediment transfer in the still area of water show that the transfer time is around 3 hours whereas the stay time is around 20 hours. This high difference could have two explanations : (i) sediment could be transported at high velocity near the bottom owing to turbidity currents ; (ii) the Ferrand derivation and its water fall homogenize quickly the suspended sediments in the downstream part of the reservoir.

3 ANALYSIS OF INTERNAL SEDIMENT DYNAMICS

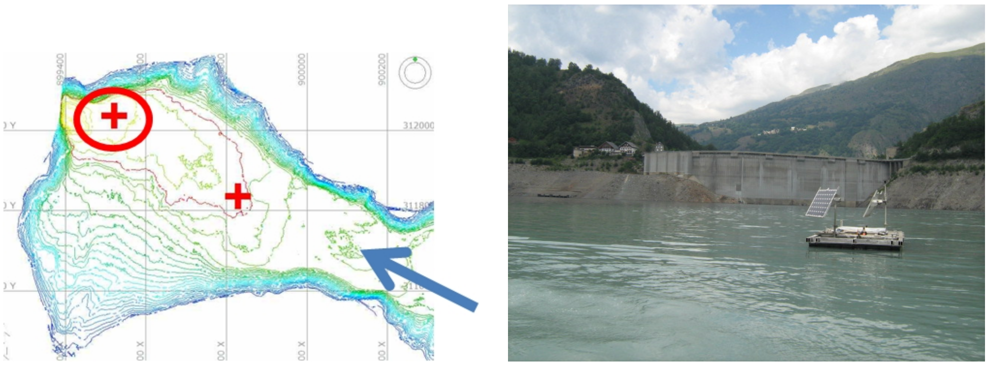
In order to have a better insight to the internal sediment dynamics, an innovative device has been designed. Its goal is to give continuous measurement of sediment concentration and flow velocities in the lake at a specific location. We wanted to have measurement in very different flow conditions. As the lake is very difficult to navigate in winter at low level, an autonomous device was chosen.

3.1 *Measurement of concentration and flow velocity in the reservoir*

The device was designed around a floating platform, two dead weights and a pulley system maintain the platform at the same location despite significant water elevation fluctuations. One turbidimeter (Hach Lange, solitax) was fixed near the bed (1 m) and another one near the water surface. A velocity measurement device (Nivus Doppler device) is fixed near the bed (1 m). The device has solar cells in order to be autonomous and data are uploaded owing to a GSM system.
Two platforms were put in the reservoir in order to compare sediment concentrations at two locations, figure 4. The upstream one had some problems. When the water level had been very low, the platform touched down the sediment bed and when the water level rose again, around mid March, the platform stayed on the bottom under water, therefore it became out of service.

3.2 *Analysis of measurements from the platforms*

We presented the data for the first six months of 2013. Data should be analyzed regarding the incoming discharges and concentrations and the reservoir water level, figure 5. In the beginning of 2013, the water level in the reservoir is very low due to work improvements on the dam. At several time the water level is lower than 985 m. Incoming discharges vary from 2 to 3 m^3/s from



(a) (b)

Figure 4. Autonomous platform to measure sediment flux in reservoir : (a) location of both platform in Chambon reservoir; (b) Photograph of the downstream platform.

January to the beginning of April, then they become larger due to the snow smelt, till 32 m^3/s. The incoming sediment concentrations are correlated to the incoming discharges, the higher measured value is 9g/l the 11^{th} May.

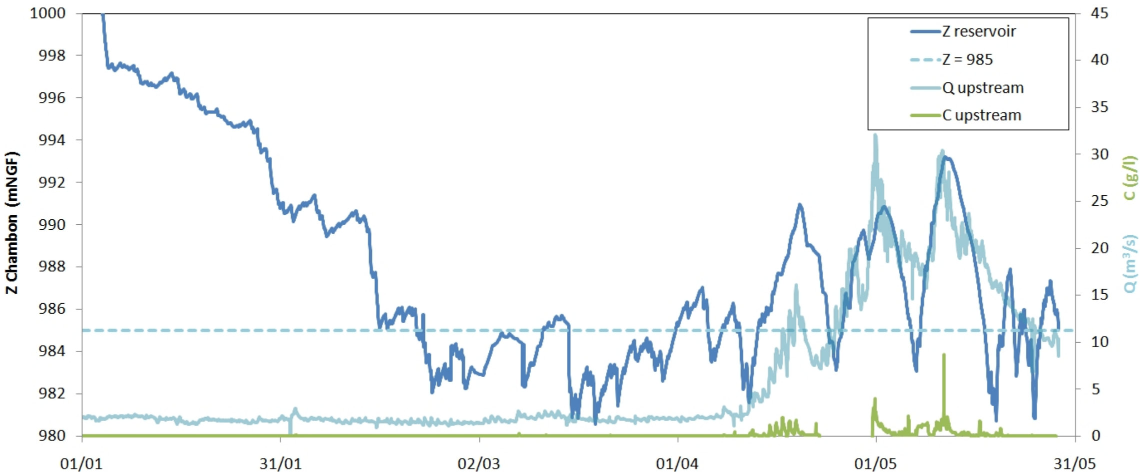
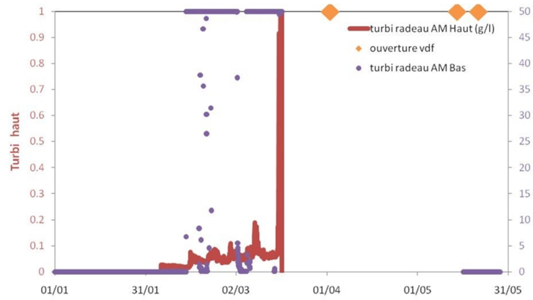


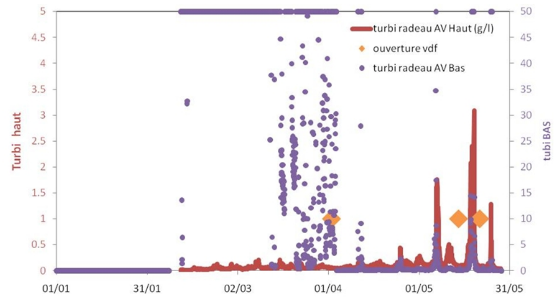
Figure 5. 2013 reservoir operating conditions : water elevation, incoming discharge and upstream sediment concentration.

The measurements from the platforms present some lacks due to dysfunctions, figure 6. Nevertheless they give information about sediment dynamics :

- the data from the top turbidimeter of the upstream platform could be analyzed till mid-March : value stay lower than 0.3g/l but rises in concentration are observed when the water level is lower than 985 m ;
- at the downstream platform : measured velocities (near the bed) show a first increase to 40 cm/s when the water level became lower than 990 m. Concerning the concentrations : the data from the bottom turbidimeter could not be used from 2-02 to 10-03. From the beginning of April, data show strong correlation between the top and the bottom turbidimeters but with a difference of an order of magnitude (concentration around 3.5g/l near the surface and around 15g/l near the bottom. Two rises in concentration of May (6 and 9th) are not correlated with a increase of incoming discharge but with a lowering of the water level below 985 m.



(a)



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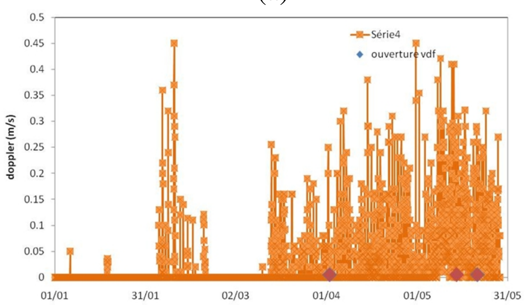


(c)

Figure 6. Platform measurements for the six first months of 2013 : (a) concentration measurements at the upstream platform ; (b) concentration measurements at the downstream platform; (c) velocity measurement near the bottom at downstream platform .

4 NUMERICAL MODELING OF SEDIMENT DYNAMICS IN CHAMBON RESERVOIR

Numerical modeling could be a relevant tool in order to test sediment management strategies. In the specific case of large reservoir, 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 [2, 13]. We plan to build a 3D model of Chambon reservoir, first we analyze in this paper the results of some preliminary 2D calculations. Therefore, in this paper, we don't focus on 3D stratification in the downstream part of the reservoir.

4.1 *Brief presentation of numerical tools and description of the model*

Tools from the open source Telemac system (www.opentelemac.org) are used : TELEMAC 2D [4] for the hydrodynamic part of the calculation and SISYPHE [12] for the modeling of the sediment transport processes, that is to say in this case transport by suspension, erosion and deposition of cohesive materials. TELEMAC 2D solves the shallow water equations using either a finite element or finite volume schemes. Sisyphe solves a dispersion-advection equation with Krone and Partheniades formulas for respectively deposition and erosion flux (source terms).

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). We built an 50 m upstream prolongation of the model in order to avoid problems with the upstream boundary condition.

The 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. This mesh has 99 479 nodes and 197500 elements. HYPACK [5] and BLUEKENUE [1]softwares were used to build the mesh.

The upstream hydraulic condition is a varying discharge and the downstream condition could be a imposed water level or a 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 52 $m^{1/3}s^{-1}$. 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 $M = 10^{-2}$ kg $m^{-2}s^{-1}$; and critical shear velocity for deposition $v_{CD} = 0.01$ m/s, equivalent to a critical shear stress of 0.1 Pa.

4.2 *Hydrodynamic results*

Calculations of hydrodynamics, using TELEMAC2D , have been performed first in order to identify the major areas in the reservoir and their possible role in the sediment transport dynamics. Figure 7 shows permanent results for an incoming discharge of 20 m^3/s and a downstream water level of 980 m (minimal turbinable water level), water depth (a), scalar velocity (b), friction velocity (c) and Froude number are plotted.
Everywhere but in the still downstream part, the water depths are small, often less than 1m. In the upstream part, the water flows in a narrow channel (30-50 m wide) where flow velocities are high, till 3 m/s. The downstream boundary of this narrow channel is located at the elevation of 999.35 m. According to Shields law about the shear stress for the beginning of motion, in these hydraulic conditions 3 cm gravels move. Downstream, in the enlargement, the talweg gets larger and the flow is braided and velocities decrease. The downstream boundary of this braided and large area is located at the elevation 985 m. Then, downstream the enlargement, there is another narrow channel where flow velocities are higher than 1 m/s. A typical pattern of sediment delta could be seen at the downstream boundary of this narrow channel. Near the dam, large water depths, low velocities are observed. In both narrow channels, the flow is super critical.
These calculations could explain the observations, reported paragraph 2.4, which highlight the key role of the enlargement : (i) above 985 m, sediment deposit in the upstream part of the reservoir (ii) around 985 m, sediment deposit in this area and (iii) below 985 m, sediment are eroded and they could be transported to the water intake.

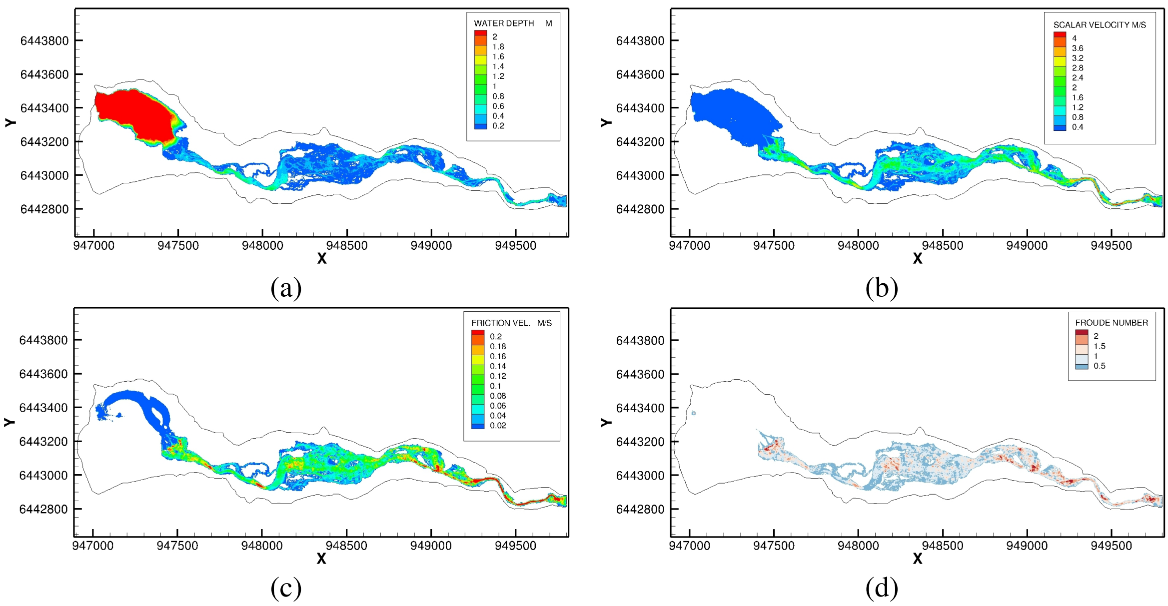
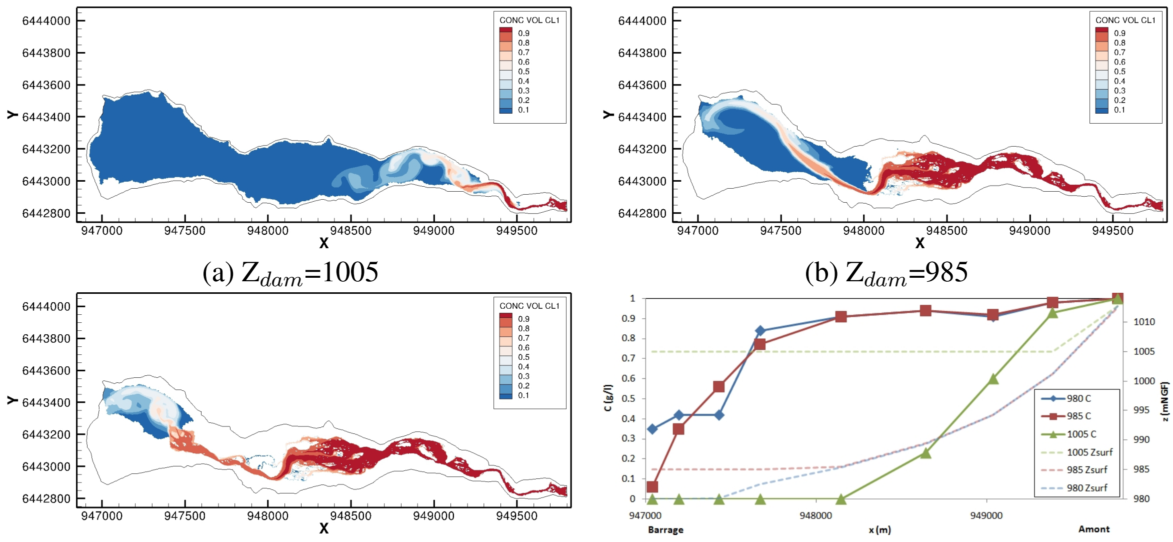


Figure 7. Numerical results with TELEMAC2D for $Q_{upstream} = 20$ m^3/s et $Z_{downstream} = 980$ m :(a)water depths ; (b) depth average velocities ; (c) shear velocities; (d) Froude number.

4.3 *Sediment transport numerical results*

Calculations using SISYPHE are first performed to compare sediment settling for several water level in the reservoir (z=1005,985 and 980 m). The incoming discharge is set to 20 m^3/s which



(a) Z_{dam}=1005 (b) Z_{dam}=985 (c) Z_{dam}=980 (d)

Figure 8. (a) (b) (c) Numerical results of settling calculations : $Q_{upstream}$=20 m^3/s et Z_{dam}=1005-985-980 m : sediment concentration. (d) sediment concentration (plain lines) and water elevation (dot lines), x is the distance from the dam

is typical of a snow melt discharge of the upstream Romanche River (figure 5), the upstream sediment concentration is set equal to 1g/l. No bed evolution is taken into account, that is to say no erosion of the bed and deposition does not modify the bed elevation. We compare results for a computation that allows the permanent state to be reached, around 40 000 s.

Figures 8 (a,b,c) show the concentration in the reservoir in the case of 1005, 985 and 980 m water levels at the dam. Figure 8 (d) gives the concentration along the talweg in function of the distance to the dam. These figures show that

- whatever the downstream water level is, the sediment are convected in the narrow upstream channel with a concentration near the one imposed at the upstream boundary ;
- for the lowest water level (985 and 980 m), we see some deposition in the secondary channels of the braided enlargement ;
- as it could have been foreseen, deposition mainly occurs in the still downstream zone ;
- the lower the downstream water level is, the higher the concentration at the dam is : the calculations give 0, 0.05 and 0.35 g/l at the dam for the respective water level of 1005, 985 and 980 m.

These values are coherent with the concentrations measured by the platform.

5 CONCLUSION AND PERSPECTIVES

This paper focuses on the understanding of the sedimentation in the Chambon Reservoir. Analysis of input and output flux indicates that the deposition rate strongly depends on the water level in the reservoir. About the sediment dynamic in the reservoir, measurement data highlight the specific role of the geometry of the reservoir : the enlargement induced deposition and downstream an erosion zone could be observed. The mixing of water induced by the water fall of the Ferrand derivation is also a key process that forced sediment in suspension in the whole water depth in the downstream part of the reservoir. An innovative platform has been designed to allow a better insight in sediment concentration and flow velocity in the reservoir all over the 2013 year. More data will help to clearly identify the part of Ferrand water fall on the hydrodynamics in the lake. Measurements data are compared with numerical calculations using TELEMAC2D and SISYPHE. Even if these calculation are very improvable they show a good agreement between numerical results and measurement. This 2D model could not be yet used to test sediment management

strategies but it encourages further developments, for example 3D tests or more detailed description of the sediment bed. Real events of sediment transfer will be simulated and compared to in situ data. Then a 3D hydrodynamic and sediment model will be built using TELEMAC3D. A 2D model is satisfying in the upstream part of the reservoir where the velocities are high, the water depths low and the concentration homogeneous. In the downstream area, using a 3D model is the only way to reproduce stratification.
Furthermore, improvement of sedimentation management will be implemented using observation and modeling, it could be based on water level strategy.

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