2D and 3D numerical modelling of the flow and sediment transport in shallow reservoirs: application to a real case

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***Abstract*— A hydro-sedimentary numerical study is performed on a real shallow reservoir to evaluate the ability of both Telemac-2D/Sisyphe and Telemac-3D/Sedi3D to reproduce the flow structure and sediment transfer in these infrastructures. Both 2D and 3D models are able to capture correctly the global behaviour of the hydrodynamic and sediment transport processes at the reservoir scale. However, models exhibit some difficulties to predict accurately the local evolution of sediment dynamic. Overall, results of the 2 models present few discrepancies. The 3D modelling improves slightly the results due to the structure mainly bi-dimensional of hydro-sedimentary mechanisms generated in this shallow reservoir with the boundary conditions simulated here.**

I. Introduction

Shallow reservoirs are common hydraulic structures usually used as water storage reservoirs, as sedimentation tanks as well as in aquaculture [1]. Complex flow develops in these structures involving large-scale horizontal coherent structures responsible for momentum transfers. Interactions between reservoir dimensions, hydraulic boundary conditions [2] and sediment load [3] control the flow structure which exhibit different patterns (Figure 1). Therefore, flow fields can present large recirculation zones organized either in symmetric configurations (S0 and S1) or in asymmetric patterns with one (A1 and A2) or multiples reattachment points (A3) [2, 4, 5]. In other configurations, flows can also show a channel-like pattern (CH-L) [4, 5] or a meandering jet (M) [6]. These flow characteristics influence significantly the transport, deposition and erosion of contaminants and sediments inside reservoirs through complex processes [3, 7, 8]. In turn, sediment deposition and bed evolution can modify flow structure by retroaction [9].

Due to these complex mechanisms, modelling of flow and sediment transport in shallow reservoirs remains a great challenge and an important task to provide operational tools sufficiently accurate for improving design and management of these infrastructures [10]. For these purpose, a hydro-sedimentary numerical study is performed on a real shallow reservoir. The objective is to evaluate the ability of Telemac-2D/Sisyphe and Telemac-3D/Sedi3D to reproduce the flow structure and sediment transfer in a real basin.

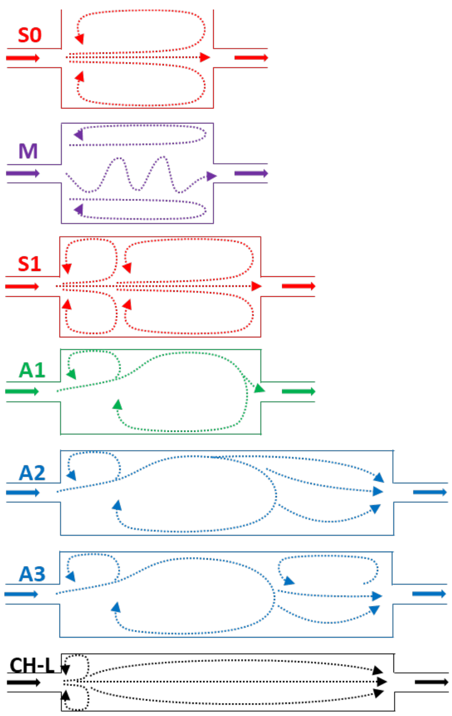

Figure 1: Flow patterns observed in shallow reservoirs.

II. Materials and Methods

A. Study site

The studied shallow reservoir is located in the French Alps and belongs to Arc-Isère hydropower structures (Figure 2). The basin is 1,400 m long and 450 m wide (Figure 3). Water depth ranges between [0-14] m. Bed topography presents a sinuous channels that delimit 3 large deposits and connect the basin inlet to the outlet (Figure 3). Transported particles have a mean grain size of 20 µm and are considered as cohesive.

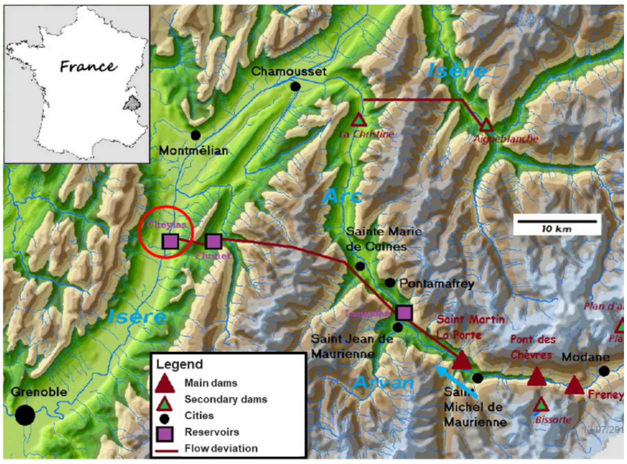

Figure 2: Location of the study site

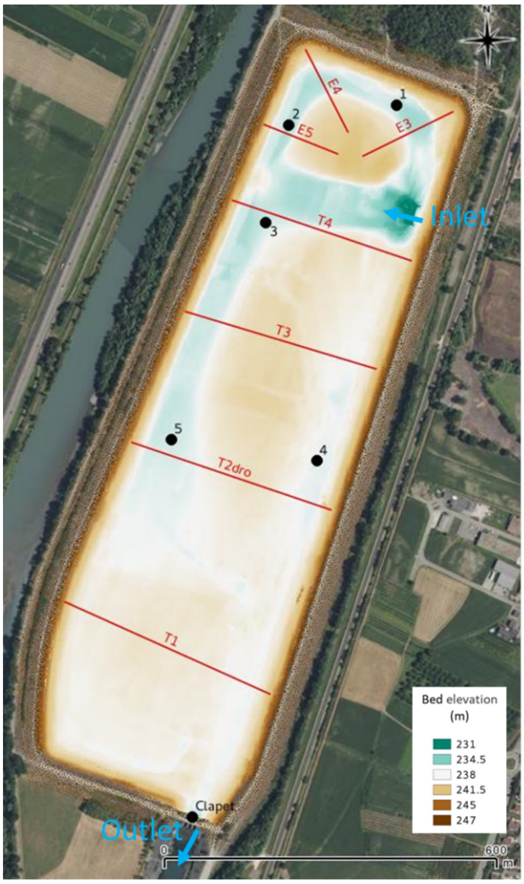

Figure 3: Location of ADCP cross-sections (red lines) and sediment concentration measurements (black points).

B. Field measurements

A large field campaign involving ADCP (Acoustic Doppler Current Profiler) measurements on 7 cross-sections and sediment concentration gauging on 6 locations was performed during 2 weeks in June 2018 in order to characterize the 3D flow structure as well as the spatial and temporal distribution of sediments in the basin. Devices for sediment concentration gauging are located roughly at 1 m deep. Flow discharges (Q) and water levels monitored during the field campaign are presented on Figure 4. ADCP data were acquired during the 1st week at flow discharges approximatively equals to 98 m^3/s (see black points on Figure 4). Sediment concentrations were recorded continuously during the 2nd week.

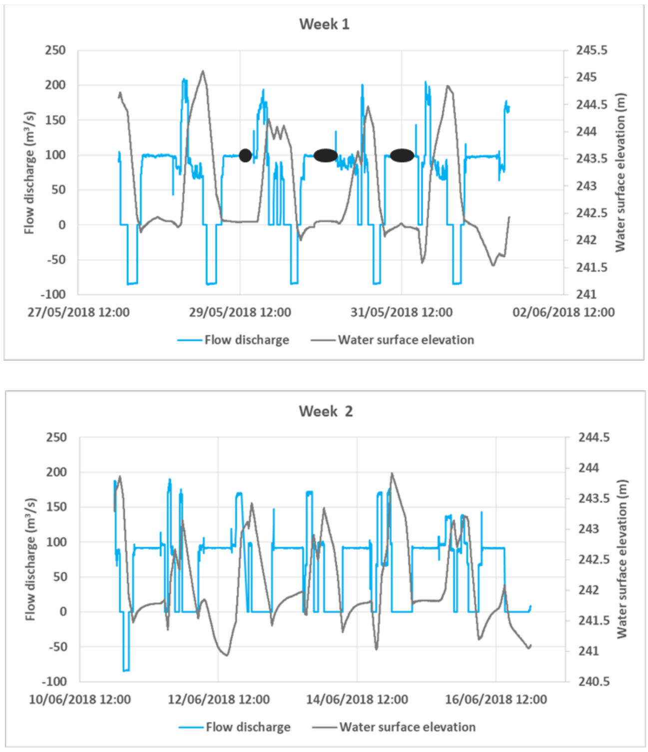

Figure 4: Hydraulic boundary conditions during field measurements.

C. Models set-up

Coupling of Telemac-2D/Sisyphe and Telemac-3D/Sedi3D are used for the bi and tri-dimensional modelling, respectively. The 2 models are based on unstructured meshes of approximately 160,000 nodes leading to an element mean size of 2 m. The 3D model is composed of 5 layers uniformly distributed on the vertical. Flow discharge and water surface elevation are imposed on the upstream (basin inlet) and downstream (outlet) boundary conditions, respectively. The end of the tunnel from which water enters in the basin is represented as an island. Numerical schemes ERIA and LIPS are used in the 2D and 3D model, respectively [11, 12].

Calibrated bed roughness is equal to a Manning –Strickler coefficient of 55 m$^{1/3}$/s in the 2D model and to a Nikuradse coefficient of 3x10^{-5} m in the 3D model. Turbulence is modelled with a constant eddy viscosity both in the 2D model (1x10^{-4} m^2/s) and in the 3D model for the horizontal plan (1x10^{-5} m^2/s). Turbulence on the vertical plan is computed in the 3D case with a mixing length model (constant base eddy viscosity = 1x10^{-4} m^2/s).

Dynamic of cohesive sediments is modelled in both models from calibrated laws for settling velocities. According to these laws, settling velocity varies with sediment concentration (Figure 5). Critical shear stress for deposition and erosion as well as Partheniades coefficient have constant values equals to 2.5 N/m², 5 N/m² and 0.01 kg/m²/s, respectively, in the 2 models.

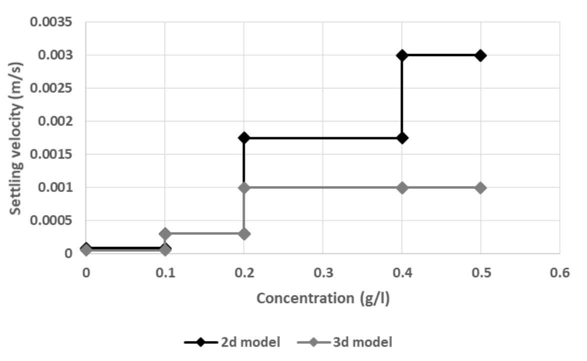

Figure 5: Evolution of settling velocity as a function of sediment concentration in the 2D and 3D models.

III. Results

A. Horizontal flow structure

Velocities observed at Q ~ 98 m³/s from ADCP measurements (Figure 6) indicate that the flow structure in the studied shallow reservoir presents an asymmetric pattern with 2 large recirculation zones similar to pattern A2 illustrated on Figure 1. Recirculation cells are located in the north and middle parts of the reservoir. A main current flows along the west bank in the middle part of the basin and crosses the downstream deposition to join the reservoir outlet.

Results of hydrodynamic simulations performed with the 2 models show a flow field with the same spatial layout (Figure 7). Both models are able to reproduce correctly and qualitatively the flow structure observed in the shallow reservoir.

B. Flow velocity

Comparison of observations and simulation results along ADCP cross-sections confirms that spatial distribution of flow velocities is effectively well modelled (Figure 8 and Figure 9). Indeed, computed velocities are generally included in the uncertainty range of measurements (equal to standard deviation of observations along cross-section). Therefore, the hydraulic models reproduce quantitatively the reservoir hydrodynamic. Results of the 2 models are equivalent even though the 2D model tends to more underestimate velocity magnitudes than the 3D model.

Vertical distribution of velocities only shows a small flow stratification (Figure 9) which explains the weak differences between the 2 models.

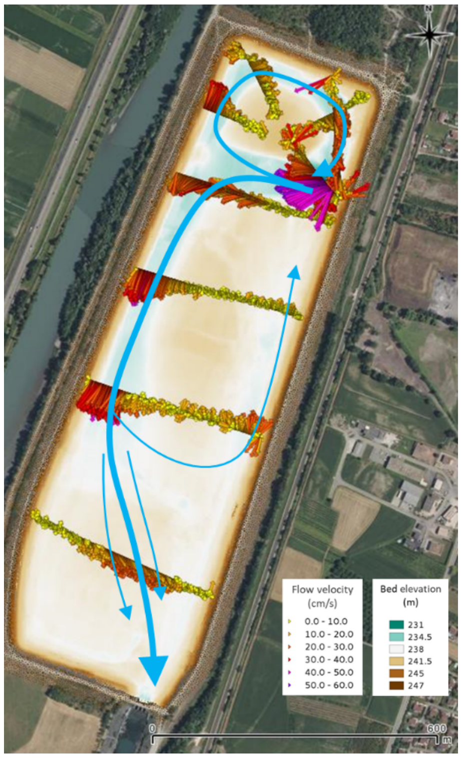

Figure 6: Flow structure observed from ADCP measurements.

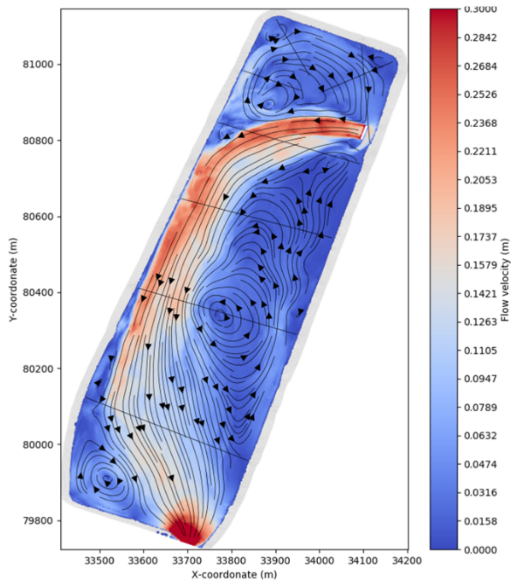

Figure 7: Example of flow structure obtain with the 3D model at Q = 98.24 m/s.

C. Sediment concentration

Observations of backscatter signals from ADCP (which constitute a proxy of sediment concentrations) and concentrations computed from the 3D model indicates that the sediment distribution along the water column is slightly less uniform than for velocities (**Erreur ! Source du renvoi introuvable.**).

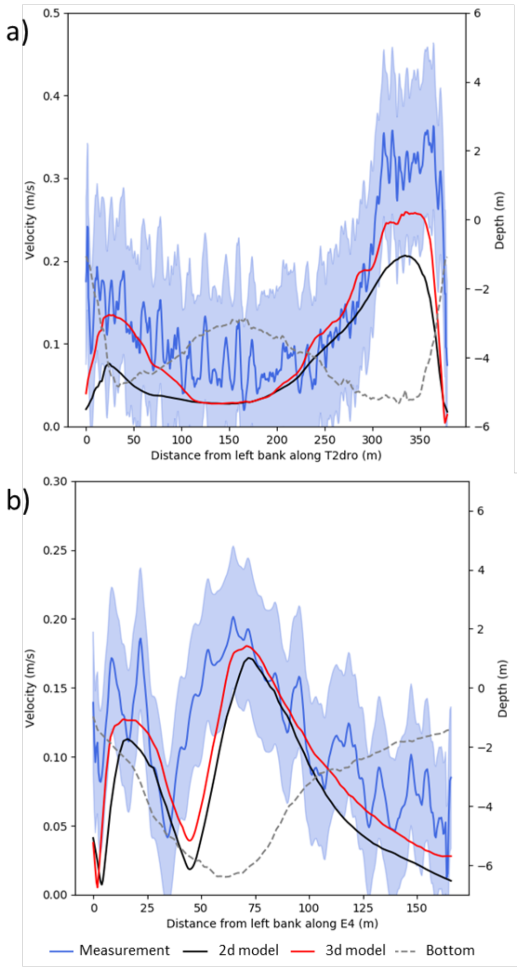

Figure 8: Comparison of depth-averaged flow velocities measured and simulated at cross-sections a) T2dro and b) E4 (see Figure 3 for cross-section locations). Measurement uncertainty is delimited by blue areas and corresponds to standard deviation of observations along cross-section.

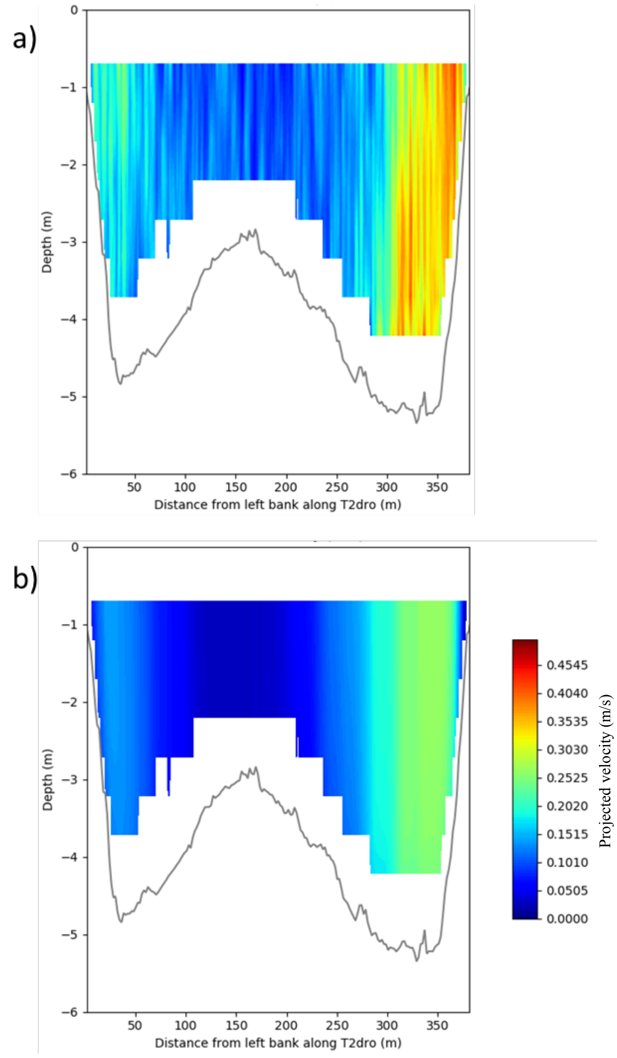

Figure 9: Comparison of flow velocities a) measured and b) simulated at cross-sections T2dro (see Figure 3 for cross-section locations).

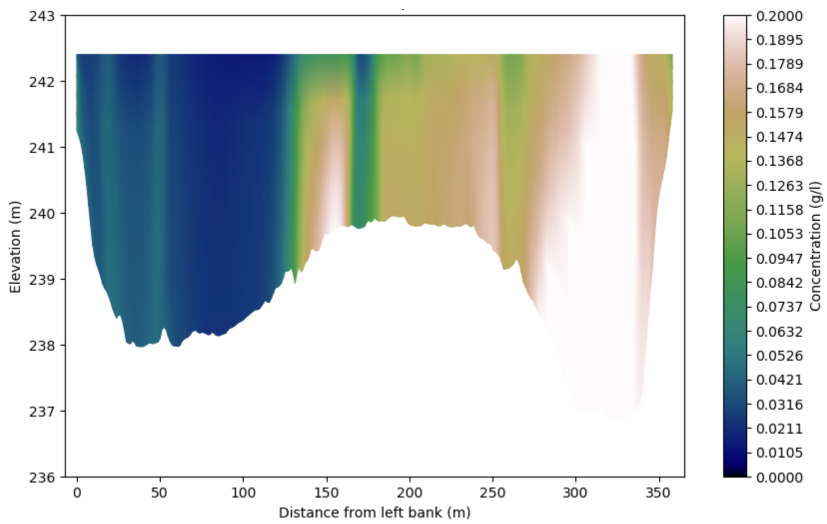

Figure 10: Sediment concentration at cross-section T3 (see Figure 3 for cross-section location).

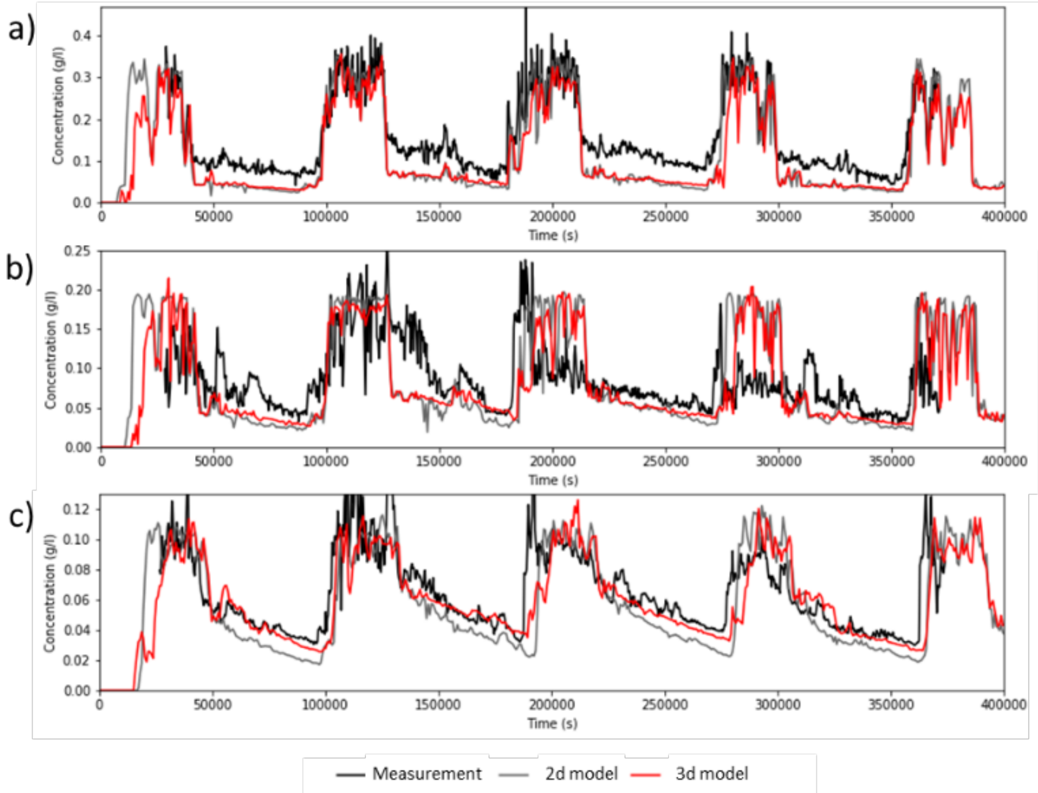

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Figure 11: Comparison of temporal sediment concentration at locations a) P3, b) P5 and c) outlet (see Figure 3 for measurement locations).

Figure 11 presents temporal evolution of sediment concentration recorded along the main current. Sediment fluxes show large variations associated to hydraulic condition fluctuations (Figure 4). Concentrations decrease from upstream (location P3, see Figure 3Figure 3) to downstream (outlet, see Figure 3) which indicates that particle transport and deposition constitute the main sedimentary processes.

Sediment suspension load is relatively well predicted by the 2 models in the upstream part of the main current (location P3, see Figure 3 and Figure 11a) during high concentration periods. At the opposite, computations give underestimation of the suspension load in this area at low concentrations. Downstream, at location P5 in the middle part of the main current (Figure 3), concentrations are correctly modelled until 130,000s (Figure 11b). Then, fluxes are first underestimated and finally significantly overestimated during the high concentration periods encountered throughout the last 200,000s of the simulation. At the basin outlet, temporal evolution of sediment concentrations is well reproduced even if the 2D model tends to underestimate fluxes during low concentration periods (Figure 11c).

Analysis of sediment concentrations indicates that the global behaviour of the sediment dynamic (transport and deposition) is correctly captured at the reservoir scale. However, both models show some difficulties to predict accurately the local evolution of sediment transport.

IV. Conclusions

A hydro-sedimentary numerical study is performed on a real shallow reservoir to evaluate the ability of Telemac-2D/Sisyphe and Telemac-3D/Sedi3D to reproduce the flow structure and sediment transfer in these infrastructures.

The studied shallow reservoir is located in the French Alps and belongs to Arc-Isère hydropower structures. The basin is 1,400 m long and 450 m wide. Water depth ranges between [0-14] m. A large field campaign involving ADCP measurements and sediment concentration gauging was performed in order to characterise the 3D flow structure as well as the spatial and temporal distribution of sediments in the basin. Transported particles have a mean grain size of 20 µm and are considered as cohesive.

Comparison between measurements and simulation results shows that the 2D and 3D models are able to reproduce quite well the flow structure and velocity magnitude observed in the shallow reservoir. The 2 models capture correctly the global behaviour of the sedimentary processes (mainly characterized by transport and deposition of particles) at the reservoir scale but exhibit some difficulties to predict accurately the local evolution of sediment transport.

Overall, results of the 2 models present few discrepancies and 3D modelling only brings a slight improvement in this study case. This result is explained by the bi-dimensional behaviour of hydraulic and sediment transport mechanisms in a shallow reservoir such as the studied reservoir and with the boundary conditions encountered during measurements.

V. References

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