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Experimental and numerical study of long term sedimentation in a secondary channel: example of the Beurre island on the Rhône River, France

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ABSTRACT: Two numerical models (1D and 3D) have been used to reproduce significant deposits that have been observed in two secondary channels located next to the Beurre island on the Rhône River, France. Both models yield relatively good results compared to the measurements but are sensitive to the upstream boundary condition for the concentration, which is poorly understood. Several issues also arose thanks to this modelling. Computation of discharge repartition in the two secondary channels appeared to have a strong impact on long-term estimation of fine sediment deposits, and is an interesting challenge for 1D modelling. Discharges in the Rhône River above the one year return period flood yield approximately 50% of the fine sediment mass transiting in the secondary channels, which represents approximately 1% of the total SSM fluxes. And 1 to 10% of these fine sediments appeared to settle down. Also, erosion and deposition laws that are implemented in 1D and 3D models induce different strategies for calibration and validation.

1 INTRODUCTION

Flood risk is a major economical issue in many countries. When the flow is out of bank, i.e., typically during a flood, there is a significant increase in the complexity of flow behaviour, even for relatively straight reaches. This complexity results in an even larger complexity for the dynamics of fine sediments in a compound channel. While many studies exist on river overflowing to the flood plain since the work of Sellin (1964), only few studies exist on the fine sediment dynamics (James, 1985; Frassellet al., 2010; Hu et al., 2010). However, consequent damages of a flood are often aggravated by fine sediment deposits, especially in urban areas. Moreover, this fine sediment deposits may be a source of pollutants such as PCBs or heavy metals

This study deals with the estimation of long-term deposits in active secondary channels that are connected to the main channel for relatively low discharges. The Beurre island is a protected area located on the Rhône River. Since significant deposition of fine sediments with potential pollution and clogging effects was observed (Pb, PCBs), this site is surveyed since 2002 with regular bathymetric measurements as well as deposited sediment characterizations. Two numerical models solving the advection-dispersion equations were applied and compared to this system: a 3D model (Telemac3D) and a 1D river network model (Mage-AdisTS).

2 PRESENTATION OF THE STUDY SITE

2.1 Location

The Beurre and Chèvre islands are located on the Rhône River, France, approximately 40 km south of the city of Lyon (Fig. 1). It consist in two secondary channels: the Chèvre channel (or “Grande lône”), which is 2700 long, and the Beurre channel (or “Petite lône”), which is 350 m long. The Rhône River is in average 200 m wide along this reach.

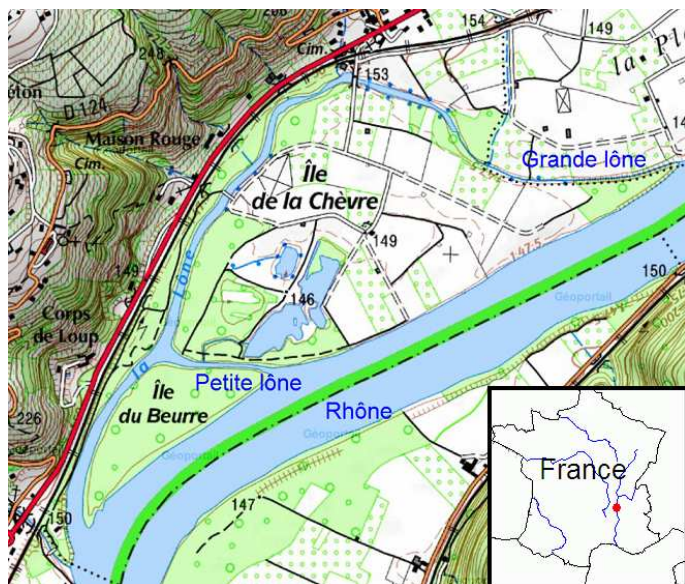


Figure 1. Location and plane geometry of the Beurre island.

2.2 Experimental data

The Nature Observation Centre of the Beurre island achieved several bathymetric and sedimentologic surveys since 2002. Measurements were carried out yearly on the Beurre channel, and in 2002, 2004, 2005, and in 2009 on the Chèvre channel. They consisted in a description of the two secondary channels thanks to 30 cross-sections more or less regularly distributed along the channels (Fig. 2). The spatial position uncertainty is estimated to 30 cm approximately and the vertical uncertainty of these measurements equal to 5 cm. The bathymetric and topographic description of the site was completed thanks to cross-sections of the Rhône River and scattered elevation points taken from the Rhône data base provided by IGN (Institut Géographique National). Two additional campaigns (2009 and 2011) were achieved to collect samples and characterize sediment grain sizes at different locations.

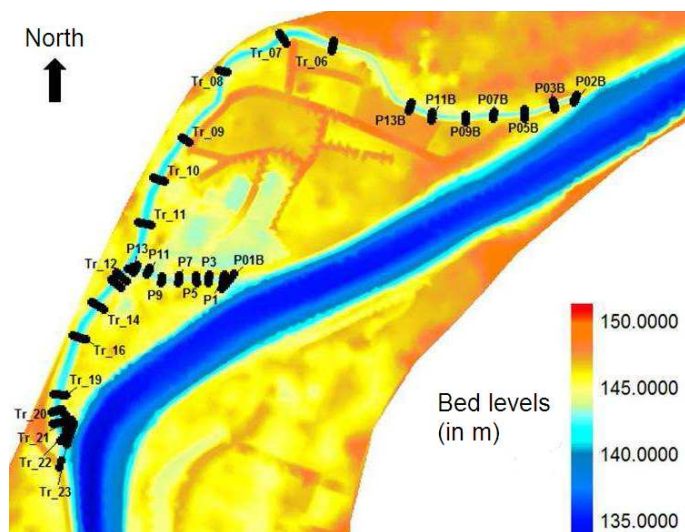


Figure 2. Topography of the Beurre island and position of the measured cross-sections.

2.3 Morphodynamics of the Beurre Island

In Fig. 3 are represented the measured bed evolution of the two secondary channels. To obtain these results, an active channel was defined for all cross-sections excluding margins and only bed evolution within this active channel was compared. The middle part of the Chèvre channel is not studied because of the lack of temporal data. It can be observed that significant deposition occurred these last 10 years on both entrances of the secondary channel (Fig. 3a and b) with a total deposit thickness up to 0.5 and 1 m locally for the Chèvre and Beurre channels, respectively. On the Beurre island, it appears that the deposition rate tends to decrease with time. On the downstream part of the Chèvre channel (after the confluence with the Beurre channel), even if deposition is prevailing, the morphodynamic behaviour of this sub-reach is not as clear. The later deposition (between 2005 and 2008) may be attributed to a downstream transfer of sediments. Between 2008

and 2009, a large erosion occurred, which may be due to the effects with the downstream connection to the Rhône River in the lower part of this secondary channel.

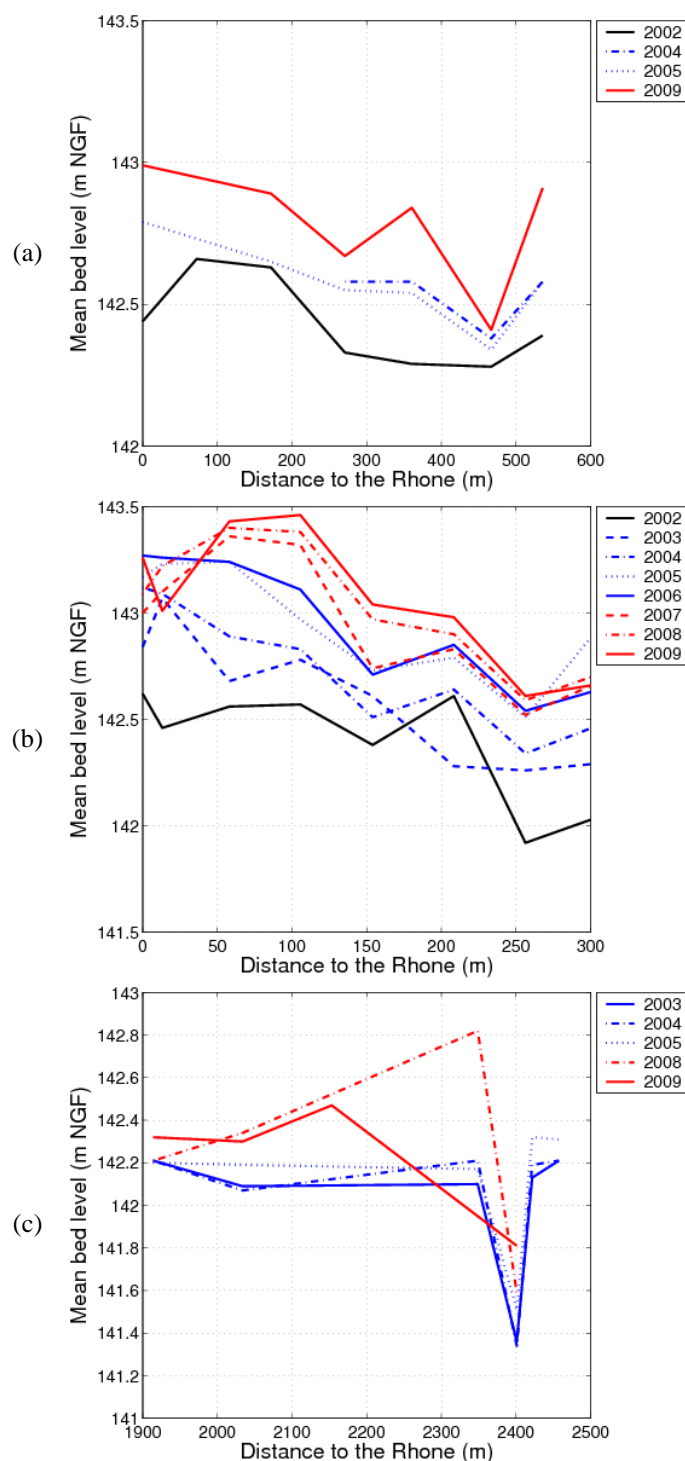


Figure 3. Bed evolution of the upstream part (a) and downstream part (c) of the Chèvre channel (Grande île), and (b) the Beurre channel (Petite île).

Grain size characterization indicates a clear downstream fining with the two secondary channels. The upstream part of the Chèvre and Beurre channels are mainly composed of medium (0.2 – 0.5 mm) and fines sands (50 – 200 μm). In the middle part of these channels, medium sands are replaced by coarse silts (20 – 50 μm). And finally, at the downstream

part of the Chèvre channel, coarse and fine (2 – 20 μm) silts (clay) are prevailing.

2.4 Hydrology

Discharge time series were obtained from a hydro-metric station located at Ternay, approximately 20 km upstream to the Beurre island. The characteristic discharges are the following:

- low flow: $Q = 280 \text{ m}^3/\text{s}$;
- 1 year return period flood: $Q = 2500 \text{ m}^3/\text{s}$;
- 2 year return period flood: $Q = 3200 \text{ m}^3/\text{s}$;
- 10 year return period flood: $Q = 4200 \text{ m}^3/\text{s}$.

The discharge time series are presented Fig. 4. It can be observed that two decennial flood occurred during the first part of the studied period (March 2001, and November 2002). Then, four biannual flood occurred from 2004 to 2008. And eventually, discharges never exceed $Q = 2500 \text{ m}^3/\text{s}$ from 2008 to 2010. Deposit dynamics in the Beurre channel appears to be well correlated to this hydrology.

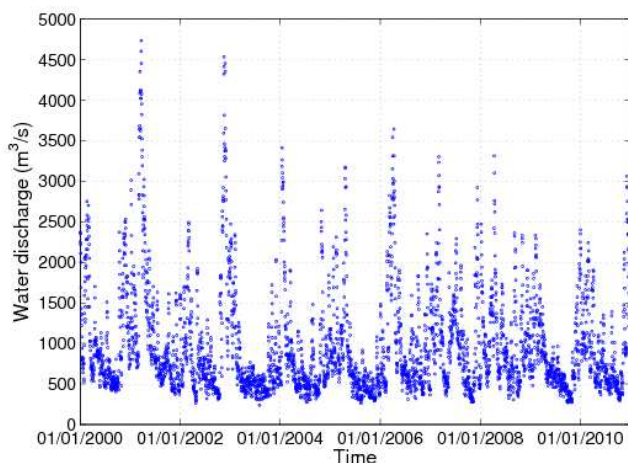


Figure 4. Daily stream discharges measured upstream to the study site.

2.5 Fine sediment suspension

Suspended Sediment Matter (SSM) measurements are lacking close to the study site. However, in order to understand the dynamics of the sediment deposits, it is fundamental to have an idea of the SSM time series at the upstream boundary. Some scattered measurements were made at Chasse-sur-Saône (*CsR*, close to Ternay) but the quality of these samples is poor since the SSM concentrations were observed very heterogeneous throughout the cross-section. Other measurements were collected at St Vallier (*StV*), which is located nearly 100 km downstream. As observed on Fig. 5, there is a very poor correlation between the SSM concentrations measured at these two positions and the flow discharge. The only possibility to build long time series is to provide a direct relationship between the concentration C and the discharge Q following a power law such as:

$$C = aQ^b \quad (1)$$

Much better documented and complete data sets exist upstream on the Saône River and on the Rhône River next to Lyon; and no significant SSM input can be assumed between these two stations and the study site. Hence, an estimation of the SSM concentration at Ternay was possible by applying calibrated equations (based on Eq. (1)) for the Saône and Rhône river for different set of discharges, and so estimating the resulting concentration for the sum of the two discharges. The obtained results yield an additional series of potential data points in Fig. 5 (grey zone). It was then possible to fit an Eq.(1)-type equation with $a = 8 \times 10^{-7}$ and $b = 1.5$ (fit 1 on Fig. 5). A lower value for a ($a = 5 \times 10^{-7}$, fit 2) was tested to estimate the sensitivity on the concentration. Finally, in order to take into account possible increase of SSM concentration during flood of the upper Rhône, a third fit was used (fit 3 in Fig. 5). Based on the discharge data series, a estimation of the averaged annual SSM flux is then possible, which is in the order of one million of tons:

- fit 1: $\Phi_{SSM} = 1.64 \text{ Mt}$;
- fit 2: $\Phi_{SSM} = 1.02 \text{ Mt}$;
- fit 3: $\Phi_{SSM} = 2.17 \text{ Mt}$.

If the highest occurrence for the discharge is $Q = 400 \text{ m}^3/\text{s}$, the discharge that induces the largest amount of SSM flux is $Q = 2000 \text{ m}^3/\text{s}$.

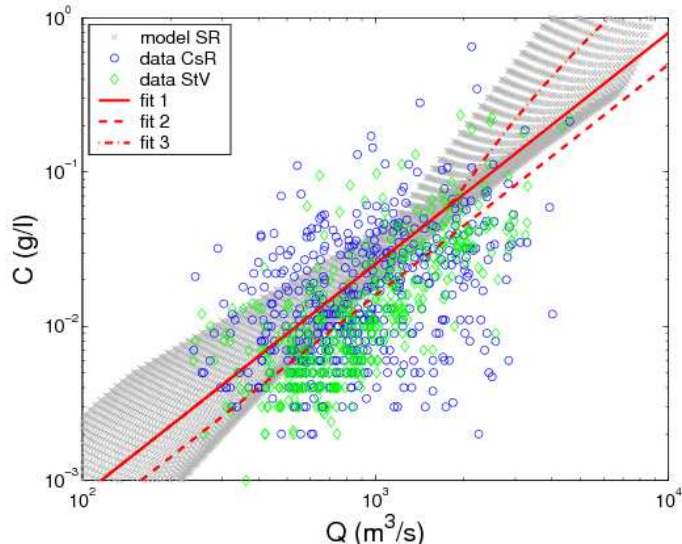


Figure 5. Relationships between daily discharges et average SSM concentrations.

There are very few data on the grain size analyse of the SSM in the Rhône River. Based on Sogréah (2000) and data provided by CNR, it appears that 90% of the particles are silt and clay and d_{50} is approximately equal to 10 μm . In the following study (for the 1D modelling), we will assumed three classes of sediments to describe the SSM in the Rhône River:

- class 1: $d = 8 \mu\text{m}$, 65% in mass;
- class 2: $d = 20 \mu\text{m}$, 25% in mass;
- class 3: $d = 50 \mu\text{m}$, 10% in mass.

3 DESCRIPTION OF THE MODELLING

3.1 1D modelling: Mage-Adis-TS

The 1D models used for this study are Mage and Adis-TS (Faure, 2009, 2012). Adis-TS solves the 1D advection-dispersion equation. Both models were developed for long river networks and long-term modelling (implicit schemes, parallelization...). For this reason, both models are fully uncoupled and bed elevation is assumed constant. The mass of fine sediments available on the bed as a source term is thus fictional but allows a mass conservation with the sediments deposited D or eroded E (Andries et al., 2011). The source terms are estimated for both main channel and flood plains using a decomposition of the flow discharge (Nicollet and Uan, 1979). For both main channel and flood plain, they are computed using Eq. 2, which is based on the equations of Partheniades (1965) for the erosion and Krone (1962) for the deposition:

$$(E - D)W = a_{PD} e_{disp,k} (C_{eq,k} - C) \frac{W_s}{H_k} W_k \quad (2)$$

where W is the width of the river, a_{PD} is a calibration coefficient, e_{disp} a coefficient indicating the sediment availability on the sub-channel k (k yields for main channel or flood plain), $e_{disp} = 0$ if there is erosion and no sediment available on the bed ; $e_{disp} = 1$ otherwise, C_{eq} the equilibrium concentration, W_s the settling velocity (computed for each class of sediments using Camenen, 2007), H the averaged depth. It is assumed here that the concentration C is homogeneous in the section. Basically, for each sub-channel, there is erosion if the equilibrium concentration C_{eq} is larger than the average concentration computed thanks to the model C . The equilibrium concentration may be estimated for each sub-channel as a function of the effective bed shear stress τ made dimensionless with its critical value for inception of movement, such as,

$$C_{eq} = a_C \left(\frac{\tau}{\tau_{cr}} - 1 \right)^{b_C} \quad (3)$$

where a_C and b_C are calibration parameters ($b_C = 1$ as a first approximation). $\tau_{cr} = 0.24 \text{ N/m}^2$ is used as a typical value for silt sediments (Ternat et al., 2008).

The 1D model is 36 km long, from Ternay hydro-metric station to the Saint-Pierre-de-Boeuf dam (15 km downstream). It should be noted that the Vaugris dam is located approximately 3 km upstream to the Beurre island. For the long-term simulation, this induces some additional uncertainties as the precise dam management is unknown. The Beurre and Chèvre channels were introduced in the 1D model as independent secondary channels within the river network instead of being included in the floodplain to better describe their dynamics.

3.2 3D modelling: Telemac3D

Telemac3D (<http://www.opentelemac.org/>) was used for the detailed modelling of the site. It solves the 3D advection-dispersion equations where the source terms $D-E$ correspond to the exchange of sediments between the water column and the bed. For the erosion, a Partheniades (1965)-type law is used:

$$E = M \left(\frac{\tau}{\tau_{cr}} - 1 \right) \quad (4)$$

with $M = 2.4 \times 10^{-4} \text{ kg/m}^2/\text{s}$ a erosion coefficient. For the deposit term, it is estimated using the settling velocity of the sediments (given by the user, $W_s = 3.6 \times 10^{-4} \text{ m/s}$ for the present study) and the bottom concentration C_b :

$$D = W_s C_b \quad (5)$$

Fig. 6 presents the final plane mesh used for the 3D calculations. The total length of the model is 6 km long. The size of the mesh varies from 10 to 30 m in the secondary channels to 300 m in the flood plain and on the Rhône River. In total, the 2D mesh is composed of 8254 nodes, which means 82540 nodes for the 3D mesh since 10 layers were used.

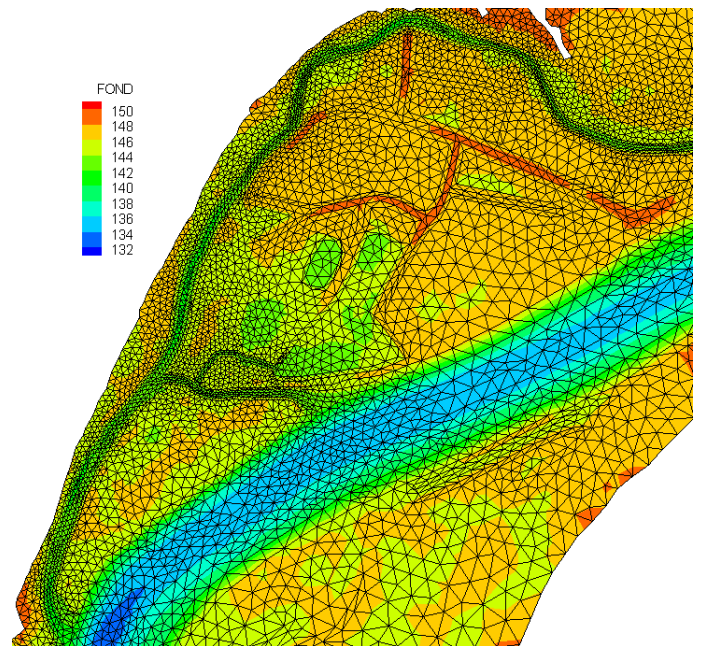


Figure 6. Unstructured mesh for Telemac3D.

3.3 Calibration of the models

The downstream boundary condition for the model is based on a simplified stage discharge relationship for the Saint-Pierre-de-Boeuf dam (see Fig. 10b). The model calibration has been achieved by adjusting Strickler coefficients on the main channel (low discharge) and flood plain (i.e. margins, islands ...) in order to simulate similar water level as observed. As observed in Fig. 7, obtained results are satisfactory for large discharges. It seems that some uncertainties may be observed for lower discharge as the down-

stream dam influence may be not very well reproduced.

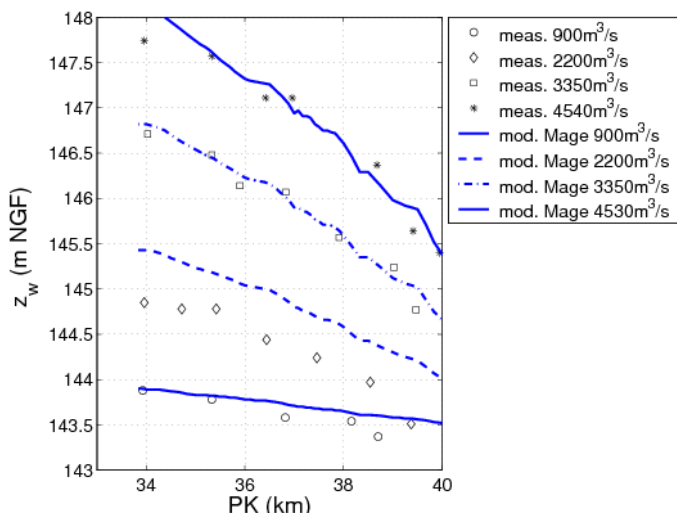


Figure 7. Calibration of the 1D model using measured water levels at different discharges.

A important challenge for the 1D but also 3D models when the description of the bathymetry is not precise enough is to properly describe diffluences. Flow repartition at diffluences is very sensitive to the flow direction and amplitude before and after the diffluence, and so very sensitive to the bathymetry and roughness repartition. Results from 1D et 3D modelling are presented in Fig. 8.

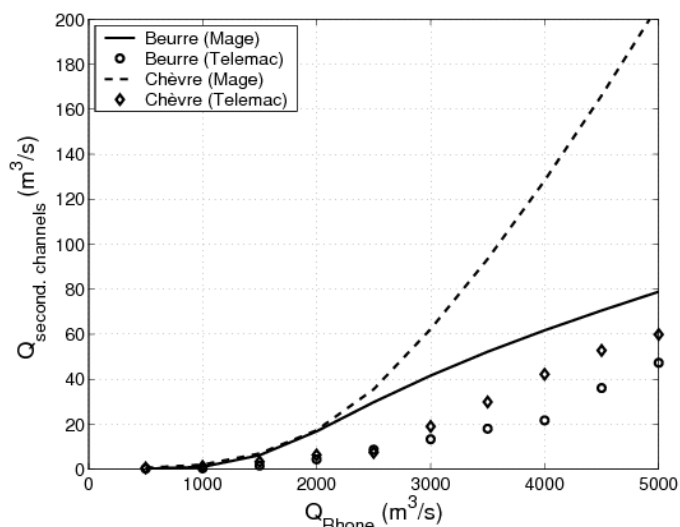


Figure 8. Comparison between 1D and 3D modelling for the water discharge repartition in secondary channels.

If both models yield similar critical discharges for overflowing in the secondary channels ($Q \approx 1000 \text{ m}^3/\text{s}$), for larger discharges of the Rhône River, the 1D model yields discharges in the secondary channels two to three times larger than the 3D model. Even if one may expect more accurate results from the 3D model, since there is no discharge measurement to validate one or another model, it is difficult to conclude on this point. It should be noted that the significant sediment deposits that occurred

in the Beurre channel may also influence this flow repartition.

Both 1D and 3D numerical model do not compute bedload transport. However, for sediments smaller than 0.1 mm, it can be assumed that suspended load largely prevails.

4 ANALYSES OF THE BEURRE ISLAND MORPHODYNAMICS

4.1 Estimation of the SSM fluxes in the system

Although, there are significant uncertainties on the flow discharges in the two secondary channels depending on the discharge in the main channel, it is possible to estimate the amount of fine sediments transiting into these channels. Using fit 3 for Eq. 1 and the 1D model, a first estimation of the total amount of fine sediment transiting yearly in the two secondary channels is 18,000 and 30,000 tons for the Beurre and Chèvre channels, respectively. It represents only 2% of the total yearly SSM flux in the Rhône River (22×10^6 tons). In Fig. 9, one can observe that how significant is the input of major floods. Thus, most of the SSM input in the occurred in 2001 and 2002, during the two decennial floods.

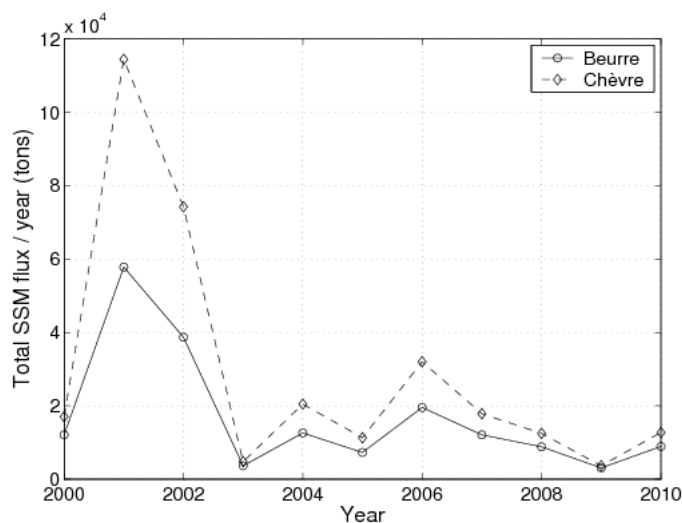


Figure 9. Estimation of the annual SSM fluxes entering the two secondary channels

A comparison can be made between this first estimate of SSM transiting in the two secondary channels and the volume of sediment deposited ($M = \rho_s(1-p)V$ where $\rho_s = 2650 \text{ kg/m}^3$ is the sediment density and $p = 0.4$ the porosity of the deposits). It appears that around 10% of the SSM transiting in the Beurre channel deposited within the reach. However, a more detailed study of Fig. 3b indicates that the amount of deposits within the Beurre channel is not much larger during the year 2002. This may suggest that larger bed shear stress occurring in the Beurre channel during large flood limit the amount of fine sediment deposits.

4.2 Bed shear stress calculations

To better understand the impact of bed shear stress on the fine sediment deposits, they were computed for different values of the Rhône River discharge using the following equation:

$$\tau = \frac{\rho g}{K^2 H^{1/3}} U^2 \quad (6)$$

where $\rho=1000 \text{ kg/m}^3$ is the water density, g the acceleration of gravity, K is the Strickler coefficient, and H the section-averaged water depth.

It appears that bed shear stress is proportional to the Rhône River discharge in the Chèvre channel. For the Beurre channel, a maximum of bed shear stress is observed for $Q = 2000 \text{ m}^3/\text{s}$. For a larger discharge, the water level after the confluence with the Chèvre channel seems to limit flow velocities and so bed shear stress. However, a comparison of the 1D and 3D models indicates that for the same discharge in the secondary channels, the 1D model tends to overestimate bed shear stresses especially in the downstream part of the Chèvre channel.

4.3 Common test scenario for the 1D and 3D modelling

A common scenario has been tested to compare the two models based on the 2009 bathymetry. The upstream hydrograph (Fig. 10a) has been built based on a discharge frequency analysis and using a flood-shape hydrograph (flood rise and fall), which lasts 7 days. In order to get the yearly averaged bed evolution, the final bed evolution from this test scenario have been multiplied by a factor 50.

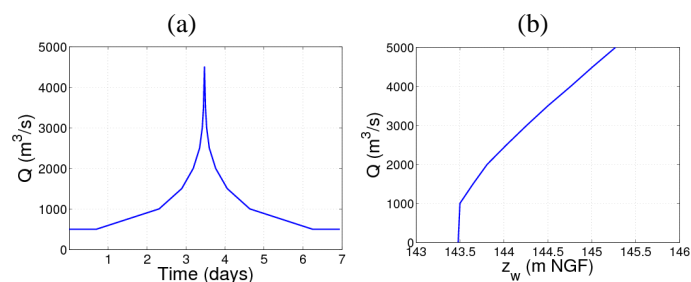


Figure 10. Upstream (a) and downstream (b) boundary conditions for the test case.

Results obtained for the 3D model are in agreement with measurements (10 cm of deposits in the Beurre channel and 5 cm in the Chèvre channel) although some underestimation is generally observed, especially in the downstream part of the Chèvre channel (Fig. 11). It also showed that most of the deposition occurs for discharges between 1000 and 3000 m^3/s . For larger discharges, one can observe locally some erosion, especially in the upstream part of the Chèvre channel. Significant erosion occurred during the flood rise but is often compensated by a larger deposition during the flood fall.

In tab. 1, a sensitivity analyses is presented on the effect of the choice of a_{PD} and a_C (with $a_{PD} \times a_C = 1 \times 10^{-4}$) on total amount of sediments deposited in the different sub-reaches reaches for 1D computations. It appears that a_{PD} directly influences the amount of sediment deposited or eroded whereas the choice of a_C impacts the net tendency for erosion or deposition. In general, Adis-TS tends to predict deposits 5 to 10 times larger than Telemac3D for this test case. It also tends to overestimates deposits in the Chèvre channel compared to the Beurre channel since data show an opposite behaviour (see Tab. 2). The 3D model appears more accurate for the repartition of the deposits. As observed in Fig. 11, these deposits would be located mainly on the main channel margins and close to the entrance of the Beurre secondary channel.

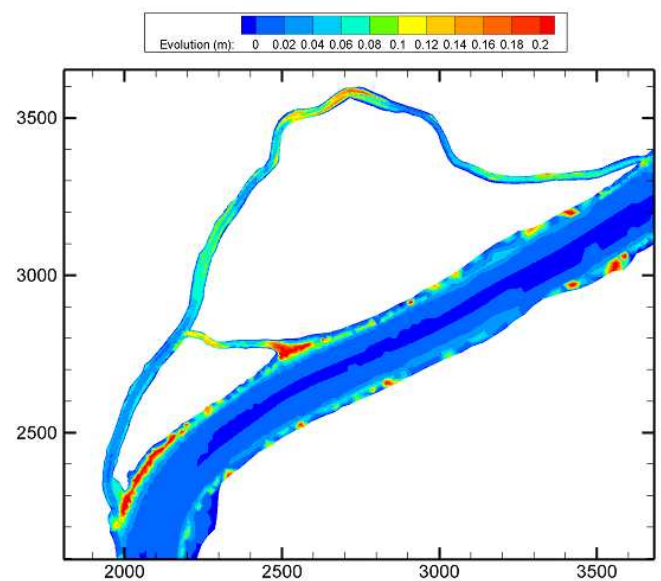


Figure 11. Bed evolution obtained using Telemac3D

Table 1. Estimation of the deposits (in tons) in different sub-reaches for the test case (7 days); sensitivity on the coefficients a_{PD} and a_C for the 1D model.

Adis-TS		Chèvre up	Chèvre-mid	Beurre up	Beurre mid	Beurre down
a_{PD}	a_C					
0.1	1×10^{-3}	7.6	14.9	1.4	1.7	2.6
0.2	5×10^{-4}	17.9	26.6	6.7	7.9	5.6
1.0	1×10^{-4}	55.7	58.2	28.4	28.8	13.3
Telemac3D		0.4	1.3	0.2	0.2	0.6

An interest of the 1D model is to present the results for different class of sediments. In Fig. 12, one can observe that the coarser class (class 3 with $d = 50 \mu\text{m}$) represents 30% of the total deposits whereas consists in only 10% of the SSM total mass. On the other hand, the finest class (class 1: $d = 8 \mu\text{m}$) represents only 30% of the total deposits whereas consists in 65% of the SSM total mass. These results are in good agreement with experimental data and give an indication of the sensitivity of the settling velocity (which is basically a function of the grain size) on the amount of sediment deposited.

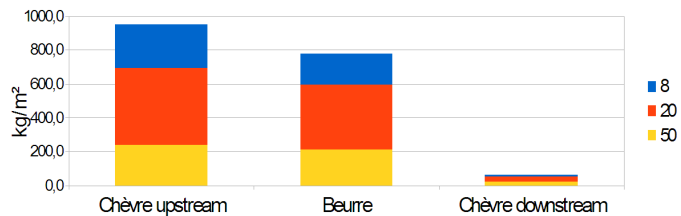


Figure 12. Distribution of the deposits in the three main parts of the secondary channels using Adis-TS as a function of the size of the particles ($a_{PD} = 0.2$ and $a_C = 5 \times 10^{-4}$ g/l).

4.4 Long-term simulation using the 1D model

Using Adis-TS model, it was also possible to directly simulated the amount of sediments deposited in the two secondary channel using the real discharge time-series from 2002 to 2010 with an geometry based on the 2002 topography. For this simulation, the following coefficients have been used: $a_{PD} = 0.2$ and $a_C = 5 \times 10^{-4}$ g/l. In order to compare directly numerical results to experimental results, experimental volumes of sediments deposited or eroded were calculated using the following equation:

$$V = \frac{1}{(T_j - T_{j-1})} \sum (z_{m,i,j} - z_{m,i,j-1}) L_i \Delta x_i \quad (7)$$

where T_j is the year of measurements, $z_{m,i,j}$ is the mean bed level of the active channel for the cross-section i and year j (see Fig. 3), L_i the width of the active channel, and $\Delta x_i = (x_{i+1} - x_{i-1})/2$ the characteristic streamwise length for the cross-section i .

Results from this simulation are presented in Fig. 13 for the three main part of the secondary channels. Results are very encouraging for the upstream part of the Chèvre channel and Beurre channel. A similar order of magnitude may be observed for the yearly bed evolution. However, the model seems to be not sensitive enough to the input from large flood. Also, as there is no update of the bathymetry, no feedback from the deposits on the dynamics can be observed on the contrary to what the experimental results suggest. Indeed, after the large deposits that occurred from 2002 to 2004, the deposition rate dropped significantly. On the other hand, Adis-TS did not reproduce correctly the deposition in the downstream part of the Chèvre channel. This may be due to an underestimation of the water stage on the Rhône River next to the downstream connexion, which has led to an overestimation of the velocities and bed shear stress, and so, an underestimation of the deposits. The impact of the St-Pierre-de-Boeuf dam regulation on the water level does reach the Beurre island despite of the distance

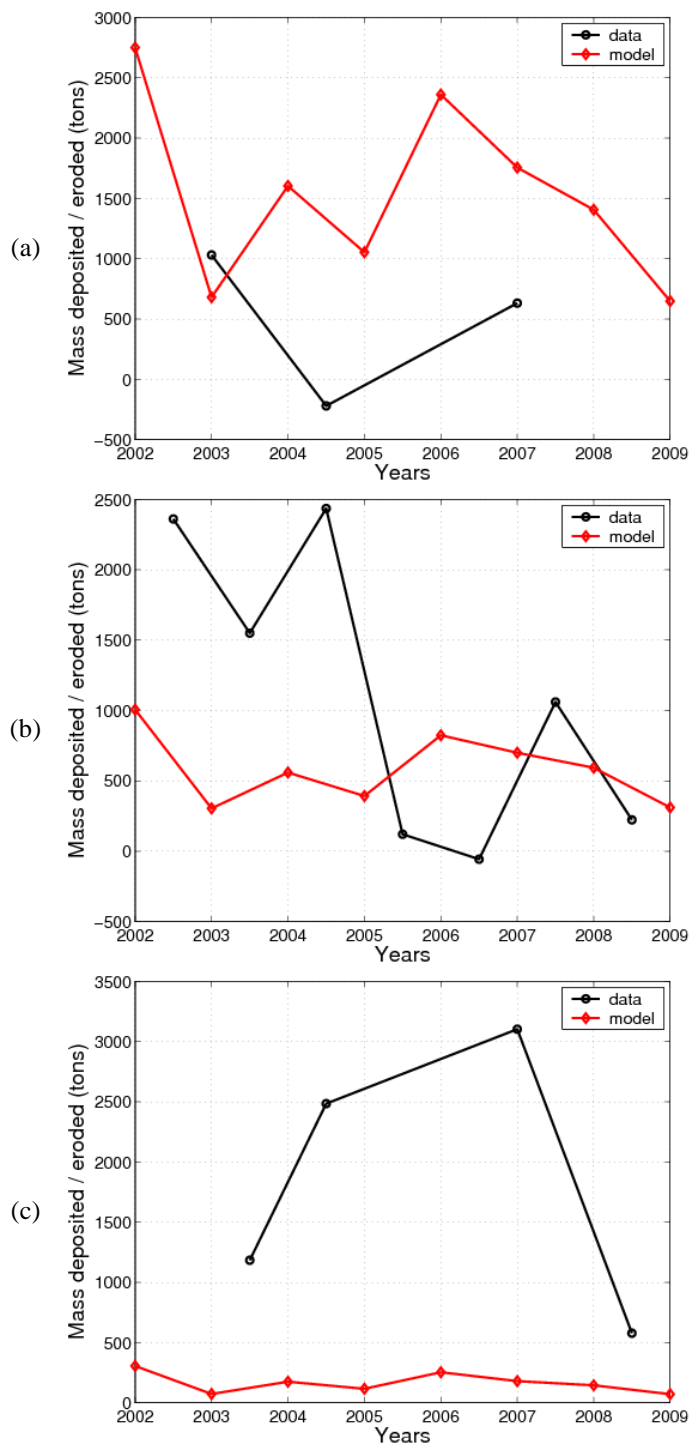


Figure 13. Yearly bed evolution of the upstream part (a) and downstream part (c) of the Chèvre channel (Grande îlone), and (b) the Beurre channel (Petite îlone).

Global results for each sub-reach using Adis-TS are presented in Tab. 2. It appears that the calculation based on reference test case tends to overestimated deposition compared to the calculation based on the discharge time series although the geometry (based on 2010 bathymetry) would lead to opposite results (all other parameter are identical). Compared to the experimental data, as observed previously, it appears that deposition is overestimated in the upstream part of the Chèvre channel and underestimated in the downstream part.

Table 2. Estimation of the deposits (in tons) in different sub-reaches from 2002 to 2010.

Calculation	Chèvre upstream	Beurre	Chèvre downstream
Based on the reference test case	18700	6150	2350
Based on the discharge time series	12250	4700	1300
Measurements	1400	7700	7350

5 CONCLUSION

Two numerical models (1D and 3D) have been used to better understand the dynamics of the deposits that have been observed in two secondary channels located next to the Beurre island on the Rhône River, France. Several issues linked with the lack of data arose thanks to this study:

- deposit characteristics (total volume and grain size diameter) are extremely sensitive to the imposed upstream SSM concentrations and quality. However, there is a serious lack of data to characterise this parameter especially during large floods;
- discharge distribution at diffuence may be correctly simulated if detailed bathymetry and discharge measurements were available, which is not the case. Large difference were observed between the two models. The 3D model should be more accurate but still needs data for validation;
- downstream water stage may also have a significant influence on the deposition rate in the downstream part of the secondary channel.

Despite these difficulties, both models were able to reproduce qualitatively (and even quantitatively for the upstream part of the Beurre channel using the 1D model) the long-term dynamics of these secondary channels. Most of the deposits occurred for discharge of the Rhône River between 1000 and 3000m³/s. For larger discharge, erosion during the flood rise limits significantly the total deposition. It also seems that sediments propagates within the secondary channels for intermediate discharges. Discharges in the Rhône River above the one year return period flood yield approximately 50% of the fine sediment mass transiting in the secondary channels, which represents approximately 1% of the total SSM fluxes. And 1 to 10% of these fine sediments appeared to settle down.

Some additional data (discharge measurements in the secondary channels, SSM characterisation at Ternay) will be carried out to improve the actual results. The calibration of the source term in the Adis-TS model may also be improved using a more extensive sensitivity analysis.

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