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CONCEPTUAL MODELLING OF THE SEDIMENT FLUX DURING A FLUSHING EVENT (ARC EN MAURIENNE, FRANCE)

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ABSTRACT

Dam flushing events have a significant impact on the morphology and ecology of the downstream part of the river. A conceptual model is proposed to estimate the evolution of the suspended sediment concentration (SSC) along the Arc River (France) during a flushing event completed regularly (almost every year). The main assumption of the model is the balance between deposition and erosion rates. Only three parameters need to be calibrated: the celerity of the sediment distribution peak, the mean diffusion rate along the river, and the initial SSC distribution (represented by a simple function based on the maximum concentration and the width of the SSC distribution). This model yields encouraging results for the prediction of the concentrations along the river. It has been calibrated on the 2006 flushing event and validated against data from the 2005 and 2007 events for the celerity and diffusion parameters. Some discrepancy appeared between the model and data for the maximum concentration as the erosion and deposition rates are not always and everywhere equal. However, a comparison allows to locate zones where deposition and erosion potentially occurred.

Keywords: dam flushing event, suspended sediment concentration (SSC), conceptual model

1. INTRODUCTION: THE ARC RIVER

The Maurienne valley is characterised by a high density of infrastructures (railway Lyon-Torino, national road RN6 and motorway A43) in a narrow valley. The Arc River bed is thus strongly constrained laterally with mean slope varying from 1% to 0.2% (Hydratec & Cemagref, 1999). Because of the water intakes and tailraces used for the hydropower generation, compensation water flows in long reaches of the river (80% of the Arc River). This valley is also marked by an intense input of sediments from the catchment area, and especially an input of fine sediments (schist mainly) from the Arves Mountains. The lower part of the valley that is studied in this paper is significantly impacted by the EdF dam flushings performed yearly.
The superficies of the catchment area is 1957 km^2 (grey area in Fig. 1) with a nival hydrologic regime and a mean water flux from 6-8m^3/s in winter to 15-20m^3/s in summer (La Chambre, study site A0 in Fig. 1). Main floods usually occur in the beginning of summer and in autumn. If the dams may even out small floods, because of their small capacity, they are usually open during larger floods and have no impact on the downstream part of the valley (Marnézy, 1999). As often observed in dam reservoirs, sediment transport is strongly affected. Fine and especially coarse sediments are stocked in the reservoir. And because of the compensation water, water flux is often not strong enough to wash out sediments deposited in the river bed

by small tributary torrents. This induces formations of small fans.
After their construction, the three dams (Freney, Pont des Chèvres and Saint Martin la Porte) rapidly needed flushing procedures in order to keep their storage capacity (EDF, 2002). Many studies on dam reservoir desiltation showed that these techniques may be efficient for small reservoirs only (Brandt, 2000). In the same way, most of the previous studies on the flushing effects on the downstream part of the river focused on the morphology evolution due to the flow (Wilcock et al., 1996), i.e. on the coarse sediments. A better understanding of the impact of a dam flushing on the deposition of fine sediment in the downstream part of the river is of great importance. Indeed, it strongly affects biodiversity and vegetation. During the flushing event in the Arc River, concentrations over 10g/l propagate along the stream over more than 100km (Jodeau, 2007). The purpose of this paper is to provide a simple model that allows to follow the flux of suspended particles matter (SPM) or suspended sediment concentration (SSC). After a quick description of the measurements performed during these events, a presentation of the model is provided followed by its calibration and validation. We conclude by a discussion on the interests and limitations of such a simple model.

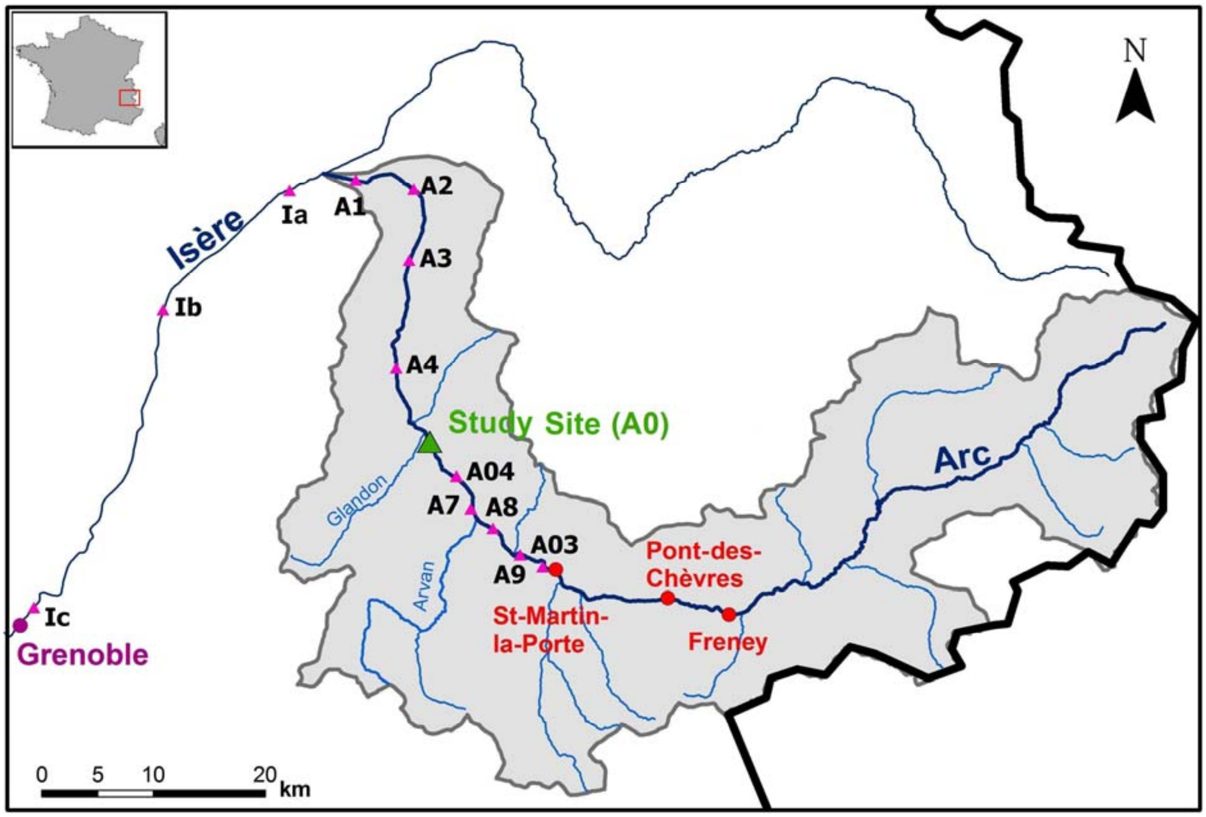

Figure 1 – Location map of the Arc River (France) and positions of the SSC sampling points, dams, study site, and the city of Grenoble.

2. DAM FLUSHING IN THE ARC RIVER

Measurements have been done during the flushing event of the three dams (see locations on the map in Fig. 1) in June 2005, 2006, and 2007. They consisted in water level and flux estimations and SSC sampling on different locations (see Fig. 1) from the last dam (St Martin la Porte) to the city of Grenoble, as well as topographic and grain-size measurements on a limited part of the river bed (study site A0) before and after the flushing event.

2.1. Experimental set-up and results

Pressure gauges (autonomous pressure gauges DIVER typed -2005 and 2007- and bubbler system -2006 and 2007-). have been used to measure water level at several locations. At the study site A0, additional discharge measurements (using a classical current meter or LSPIV image analysis technique, Jodeau et al., 2008) were used to establish a relationship between water level and water discharge.

SSC have been estimated from samples taken at the water surface (bucket samples from a bridge) or by the side of the river (automatic sampler ISCO 4230). A comparison both methods at location A3 showed a good correlation with a deviation lower than 10%. Samples have been filtered and weighted following the ISO 11923 norm. Samples showed that concentrations from tributaries were negligible during the event. Therefore, the only effect of the tributaries was a dilution of the matter.

At the “Isère-campus” station located upstream to city of Grenoble, aDcp measurements were completed to improve the rating curve. Water discharge estimation and SSC measurements (turbidimeter + automatic sampler) gave a good representation of the time evolution of the SSC flux (Mano et al., 2007) during the event. This study also confirmed the hypothesis of homogeneity in fine sediment concentrations throughout the river section.

During these flushing events, water flux at A0 site varies from 10 to 150m^3/s and back to 10m^3/s over 12 hours. And concentrations can easily exceed 10g/l. In Fig. 2, results for the temporal and spatial evolution of the water flux and SSC are presented for the 2006 event. A balance between the erosion and deposition rates seems to be obtained quickly since mass is approximately conserved. Then, the maximum concentration appears to be mainly function of the dilution due to the tributaries.

(a) (b)

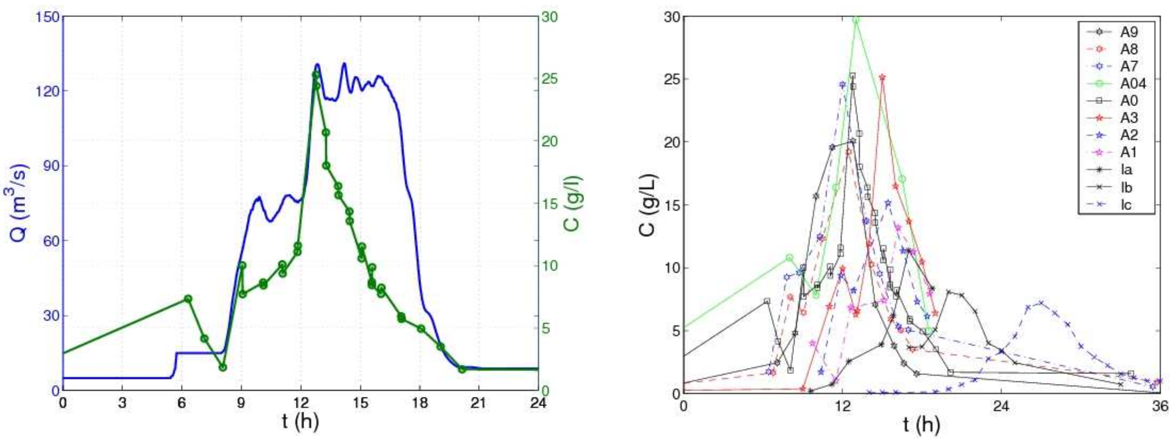

Figure 2 – Temporal evolution of the water flux and SSC at the point A0 (a) and temporal evolution of the SSC along the Arc and Isère Rivers (b) during the 2006 dam flushing (time 0 corresponds to June 27th, 0:00 am).

2.2. Temporal and spatial evolution of the SSC signal

Temporal evolution of the SSC signal appeared to be directly correlated to the different phases of the hydrograph.

1. The warning wave was followed by a small peak of concentration. As the water was spilled over the gates and thus has low SSC, these sediments were expected to be eroded from the river bed.
2. A second peak of SSC (10g/l) happened when the flow became supercritical in the reservoir. Sediments should have come from the erosion of the reservoir.
3. During the following relatively constant water flux, a constant erosion / upstream input of sediment may be observed.
4. The maximum peak of concentration (25g/l) appeared simultaneously with the last increase of water flux related to the input of water from the most upstream dams. This phase appeared to be the most efficient for eroding fine sediments. As observed by Le Coz et al. (2007) in the Saône River, erosion may be also a function of the acceleration (increase of bed shear stress).
5. Even if the water flux remained constant at its maximum value ($150m^3/s$), SSC decreased regularly. The water flux decrease did not seem to affect the concentration afterwards.
6. When the level was back to the compensation water, SSC reached a relatively low value (< 5g/l) and remained stable.

The SSC evolution is presented in Fig. 2b. The main characteristics of the SSC signal appeared to be preserved along the propagation. Only diffusion effects tend to smooth the signal and erase narrow peaks.

3. A CONCEPTUAL MODEL FOR THE SSC FLUX

3.1. Main assumption of the model

From the above observations, it appears that mass conservation was roughly conserved. And so, the erosion and deposition rates were approximately balanced. Following this idea, all the concentration profile were made dimensionless by dividing every concentration by the local maximum C_{max}, centring the SSC distribution on the time t_{max} where this maximum occurred, and dividing the width of the signal by the width Δt estimated at $C=2/3C_{max}$.

In Fig. 3, all the dimensionless concentration profiles have been plotted together. It appears that a simple Gaussian function (Eq. 1) may fit correctly all these profiles. If this simplified display appears approximate in the upstream part of the river (where secondary peaks may be observed, due to the warning wave for example), it is quite realistic in the downstream part (Isère River) where the signal has been smoothed due to diffusion. One each point of the river, the time dependent concentration distribution may be written as follows,

$$f(x,t) = C_{\max} \exp\left[-2 \frac{(t - t_{\max})^2}{\Delta t^2} \right] \quad (1)$$

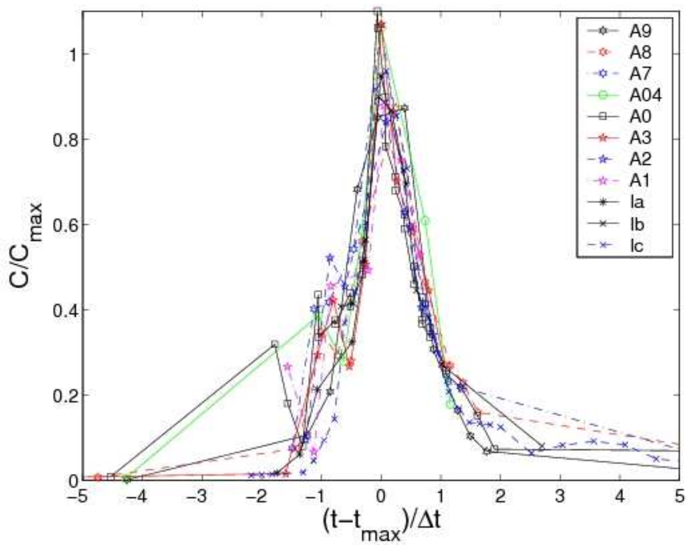

Figure 3 – Dimensionless profiles for the SSC along the Arc and Isère Rivers during the dam flushing of 2006.

3.2. Presentation of the model

Based on experimental observations, a conceptual model is suggested by describing the SSC distribution with a simple function $f(x,t)$, which is varying according to two main phenomena:

- **dilution** due to an introduction of clear water (cf. Fig. 4a); the SSC decreases locally by a factor A_{dil}. Assuming a tributary with a water flux Q_{tr} and a concentration negligible, the solid and liquid mass conservation equations lead to:

$$Q_{up} = Q_{dn} + Q_{tr}$$
$$C_{dn} = \frac{Q_{up}}{Q_{dn}} C_{up} = A_{dil} C_{up} \qquad (2)$$

where Q_{dn} and Q_{up} correspond to the downstream and upstream water flux, and C_{up} and C_{dn} to the downstream and upstream concentrations, respectively.

- **diffusion** along the river (cf. Fig. 4b), taken through a coefficient $A_{dif}(x)$ defined as the variation of $\Delta t(x)$, temporal width of the SSC distribution observed for C=2/3C_{max}, over a distance dx:

$$A_{dif}(x) = \frac{d\Delta t(x)}{dx} > 0 \qquad (3)$$

The coefficient $A_{dif}(x)$ was chosen with a dimension (h/km) to calibrate the model easily (cf. Figs. 3 and 4b). It could be make dimensionless by the celerity of the SSC peak (dx/dt_{max}). Between two observation points x_1 and x_2, $A_{dif}(x)$ is assumed to be constant. The widening of the SSC distribution is related with a decrease of the peak concentration which is directly function of $A_{dif}(x)$.

Using the mass conservation equation, Eq. 1 for $f(x,t)$ yields a decrease of the concentration maximum due to the diffusion between two points x_1 and x_2 ($x_2 > x_1$) equal to $\Delta t(x_1) / \Delta t(x_2) = 1 - A_{dif}(x_1)(x_2 - x_1) / \Delta t(x_2) < 1$, and so $C_{max}(x_2) = C_{max}(x_1)[1 - A_{dif}(x_1)(x_2 - x_1) / \Delta t(x_2)]$.

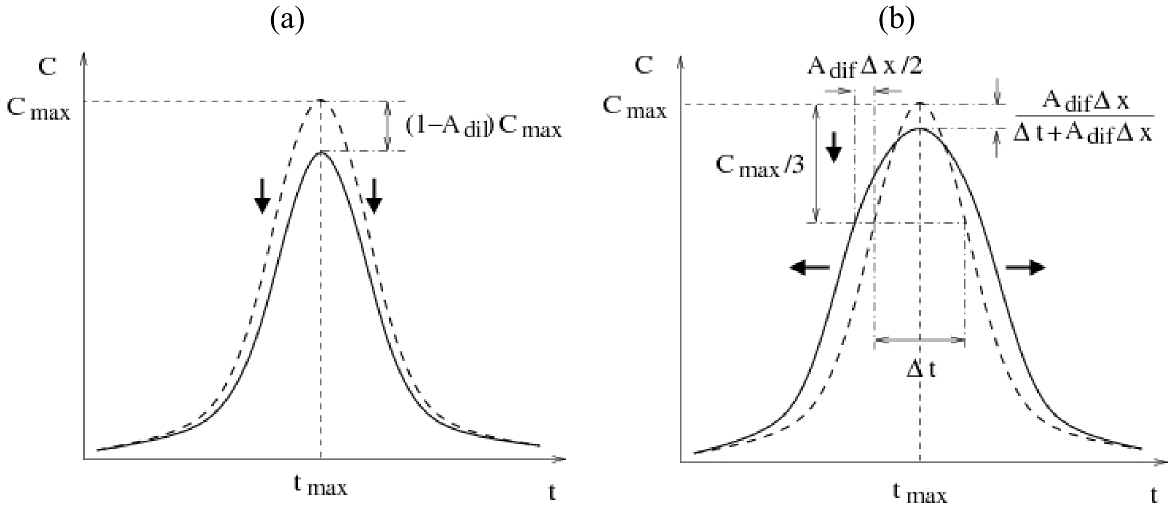

Figure 4 – Scheme of the dilution effects (a) and diffusion effects on a distance Δx (b) for a SSC distribution described by the function $f(x,t)$ with a maximum C_{max} and centred on t_{max}.

If both conservative hypothesis are verified, the evolution of the SSC flux may be estimated from the initial SSC concentration profile and only three parameters, which are function of the distance x to the origin only:

- the concentration maximum $C_{max}(x)$ (function of $A_{dif}(x)$ and $A_{dil}(x)$ only) ;
- the time position of the concentration peak $t_{max}(x)$;
- the temporal width of the SSC distribution $\Delta t(x)$ (function of $A_{dif}(x)$ only).

3.3. Model settings

$A_{dil}(x)$ was estimated first by assuming two dilution points: at the EDF tailrace at Randens (A2, $A_{dil}(x)$= 0,65 based on Eq. 2) and at the confluence with the Isère River ($A_{dil}(x)$= 0,75). $A_{dif}(x)$ and $\Delta t(x)$ were estimated using dimensionless concentration profiles (cf. Fig. 3). In the same way, the celerity of the SSC peak dx/dt_{max} is computed using experimental data. Results obtained from the calibration with data of the 2006 flushing event are presented in Fig. 5a where $A_{dif}(x)$, $\Delta t(x)$, and t_{max} are estimated using simple linear functions.

As the model cannot include effects of the erosion or deposit of sediments, it cannot reproduce variations as observed in 2006 between points A9 to A7 where C_{max} was slightly increasing (cf. Fig. 5a). The propagation speed of the SSC distribution (dx/dt_{max}) appeared to be quasi constant (10km/h approximately) with a slight decrease on the Isère River (dx/dt_{max} = 7km/h; cf. Fig. 5a). This may be due to the significant widening of the river. Similarly, the diffusion term appeared to be constant on both reaches (Arc and Isère Rivers): $A_{dif} \approx 0.010$ h/km for the Arc River and $A_{dif} \approx 0.025$ h/km for the Isère River. The third term for the model calibration is actually an initial condition as it is the maximum concentration of the SSC distribution after the last dam (St Martin la Porte). $C_{max}(x=0)$ has been estimated such as a realistic value was obtained at the point A4. Indeed, the first part of the reach appeared to be more dynamic with some sections with erosion and others with deposition. The model yields a constant decrease of the maximum concentration because of the diffusion term. Nevertheless, the model presents very encouraging results despite a rough calibration (cf. Fig. 5b). The slight underestimation of the propagation speed of the SSC peak in the downstream part of the Isère River may be improved easily.

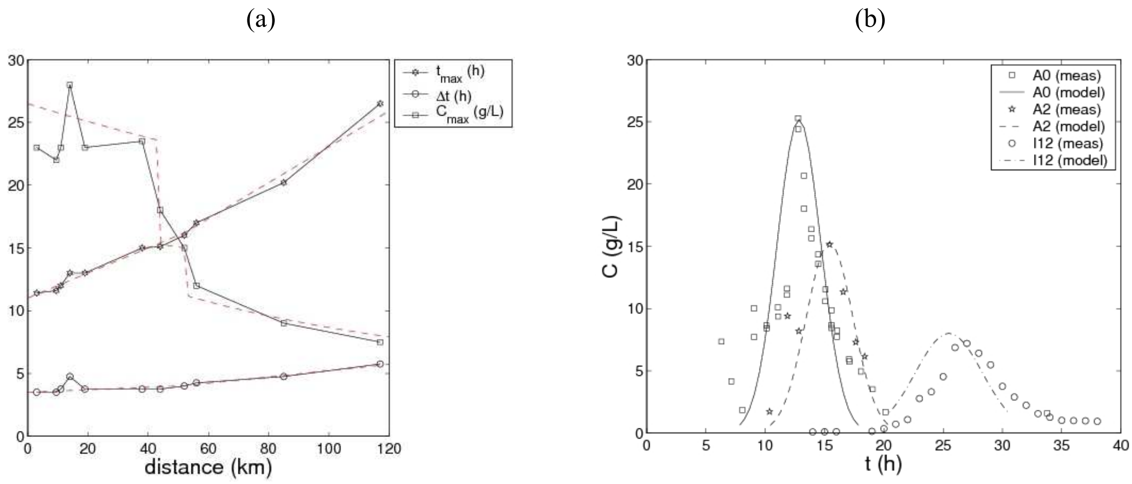

Figure 5 – Fit of the three parameters of the model (symbols : data points obtained from the dimensionless profiles ; dashed line : model) (a) and test of the model compared to the experimental results from the dam flushing of 2006 (b).

The limits of the model may be observed as soon as erosion and deposition rates are not balanced. It is however possible to locate specific sections where erosion (or sedimentation) rates is larger than the sedimentation (or erosion) rate. In the case of erosion, the slope dC_{max}/dx given by the model is smaller compared to the experimental observations; in case of sedimentation, the slope given by the model is larger. For example in Fig. 5a, some erosion occurred between A9 and A7; and some deposition occurred between A7 and A6. The Longefan reservoir, located between A7 and A8 may be one explanation of this phenomena. It is used as outlet for the turbinate water (Q_t) from St Martin la Porte dam. Water is also pumped (Q_p) from the reservoir to Flumet reservoir and the hydraulic power plant of Cheylas (STEP system, energy transfer with pump house). When $Q_p<Q_t$, there is a discharge of clear water from the reservoir that could erode fine sediments and thus increase the deposition capacity of the river bed. This would enable larger deposition during flushing events.

In Fig. 6, results have been plotted for the three studied dam flushing events in 2005, 2006, and 2007. In order to compare the results, all the curves have been made dimensionless using their initial values $(t_{max}-t_{max,0})/T$ (where T=15hours corresponds to the time for the SSC peak to travel from the last dam to the city of Grenoble), $\Delta t/\Delta t_0$, $C_{max}/C_{max,0}$. For both propagation speed of the SSC peak and diffusion term, the model with the calibrations based on the 2006 flushing event reproduced correctly the evolution of the SSC distribution for the 2005 and 2006 dam flushings. It indicates that for a specific flushing procedure at the dams, the speed and diffusion of the SSC distribution are easily reproducible. For the concentration maximum, there were some uncertainties, especially in the first part of the reach (Arc River) where some erosion (and deposition in a weaker manner) was often observed. It is however possible to say that erosion and deposition rates were globally balanced downstream of x=30km. This hypothesis is thus relevant.

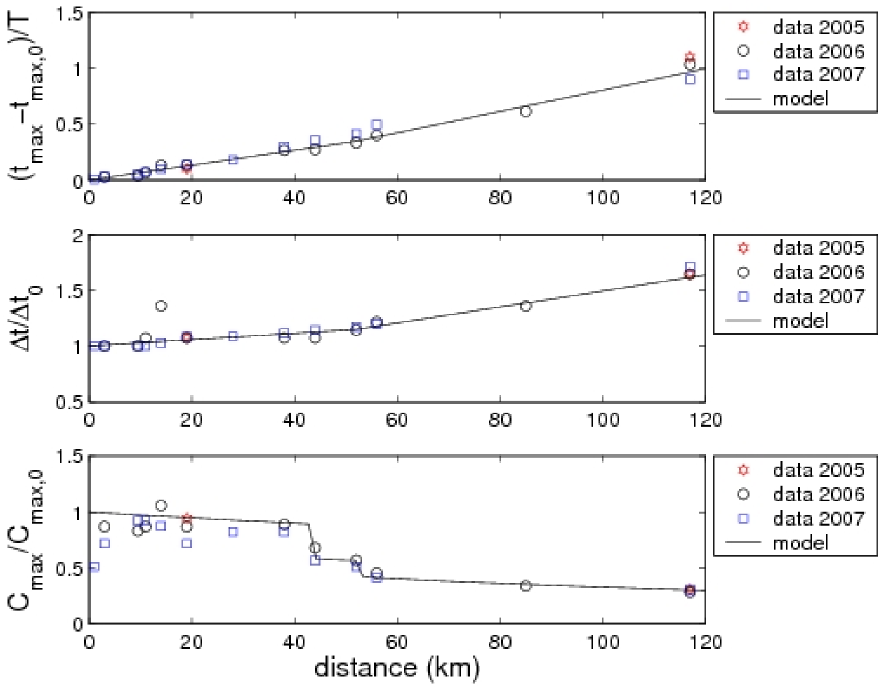

Figure 6 – Model parameters made dimensionless by the time *T* to reach the city of Grenoble from the last dam, and their initial values, respectively, compared to the data points obtained from the dimensionless profiles from the dam flushing events of 2005, 2006, and 2007.

4. CONCLUSIONS AND PERSPECTIVES

A conceptual model was implemented to estimate the propagation of a SSC distribution along the Arc and Isère Rivers during the yearly flushing events of the upstream dams. This model has for main assumption that erosion rate balances deposition rate (conservative flux). It has been calibrated using three parameters only. They are the peak concentration of the SSC distribution, the propagation speed of the SSC peak, and the width of the SSC distribution. These parameters are mainly function of the diffusion and dilution in the river. A test on the measurements in 2005, 2006, and 2007 showed that this model is repeatable for the flushing events. A more complex initial concentration profile (with several maxima) could be simulated by adding several functions $f_i(x)$ such as $f(x)=\sum f_i(x)$.

It would be interesting to see if this model could be applied to a natural flood (with some correction for the concentration peak speed and diffusion as they are function of the water level and flux). A permanent station (pressure gauge, turbidimeter and automatic sampler) will be installed during the year 2008 and will allow us to answer this question. In 2006, a natural flood occurred, of similar amplitude to the flushing event but on a much longer time scale (40 hours instead of 12 hours; Jodeau, 2007). Fine sediment input from the tributaries (Valoirette, Arvan, and Glandon) was not negligible and large deposition has been observed on the studied site. A comparison between effects of three dam flushings in 2006 and 2007 on a gravel bar showed that the bar was globally eroded during both events but with many differences in term of fine sediment depositions. It appeared from this study that the history of the river (flood, flushing event) is of major importance for the initial conditions for the next event, *i.e.* erosion capacity in the reservoir, presence or not of fine sediment in the river bed. In 2007, weaker concentrations observed during the flushing event could be explained because of a small flood that occurred a few days before.

The main limitation of the model remains the balance between erosion and deposition.

However, the methodology suggested in this paper (concentration profiles made dimensionless) compared to the model results allows to locate places where erosion or sedimentation may have occurred. It would be interesting to see if there is a variability in these locations or if some reaches are favourable for erosion or sedimentation. This simple model may be useful for engineers to quickly predict the position of the SSC distribution. It would be also useful for the development of more complete 1D model of the Arc and Isère Rivers (advection diffusion model including erosion and deposition terms). In particular, the diffusion term could be incorporate easily in a model such as ADIS developed by the Cemagref.

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