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SUSPENDED-LOAD DYNAMICS DURING FLOODS IN THE RIVER SAÔNE, FRANCE

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Abstract
With a 30,060 km^2 catchment area and a mean annual discharge of 442 m^3/s near the confluence in Lyon, the River Saône is the main tributary of the upper French Rhône. The 165 km-long lower reach shows very low gradients (about 0.06 m/km) and wide floodplains. As for most French streams, the River Saône suspended sediment concentration (SSC) is not continuously monitored. In order to get a first insight of the SSC behaviour during the 2006 spring floods, quasi daily measurements by surface water sampling and filtration were performed at the CNR “St-Georges” gauging station in Lyon. Water level, velocity and discharge time series were continuously recorded by a side-looking acoustic Doppler profiling system (H-aDcp). Besides, for contrasted discharge and SSC values, 8 water sampling surveys at different points of the cross-section showed that the SSC is quite homogeneous in the section. The SSC time series suggests that concentration peaks in Lyon stem from the resuspension of fine material stored in upstream reaches: pronounced SSC peaks were observed during each rising limb and the maximum levels of successive SSC peaks decreased with time order. Actually SSC peaks occur during phases of bottom shear stress increase, as expected for resuspension. An examination of upstream catchment hydrometric data helps understand the formation and propagation of the successive flood waves. However SSC and water velocity measurements at upstream gauging stations are lacking in order to assess precisely the mechanisms of sediment routing in the river Saône.

Keywords: Saône river, flood wave, suspended-load, bottom shear-stress, H-aDcp

INTRODUCTION

The understanding of suspended-load processes is important from both ecological and engineering points of view. Suspended solid concentrations (SSC) and fluxes influence water quality and govern sedimentation rates in reservoirs, for instance.

At the event-scale, the correlation between SSC and water discharge is usually poor and often show hysteresis phenomena. Suspended-load rates remain difficult to assess and predict due to the complexity of hydrological controls on erosion rates from heterogeneous watersheds and river channels upstream.

The present paper reports some observations of suspended-load at the very outlet of the Saône river catchment, at the Saint-Georges gauging station, in Lyon, France, during the 2006 spring floods. Through the analysis of available hydrometric data from the station and also from upstream stations, some assumptions on the sediment processes at work can be derived.

THE SAÔNE RIVER CATCHMENT

With a 30,060 km^2 catchment area and a mean annual discharge of 442 m^3/s (Astrade 1998) near the confluence in Lyon, the River Saône is the main tributary of the upper French Rhône. Fig. 1 gives an overview of the river catchment and of the hydrometric network.

The Ognon river and the Doubs river are the main tributaries of the upstream Saône river. In this upstream part, the mean river gradients are 0.2 m/km for the “Petite” Saône (km 165 to km 280) and 1 m/km for the “Haute” Saône (km 280 to the source) (Balland and Cottereau 1991).

By contrast, the 165 km-long lower reach shows very low gradients (about 0.06 m/km) and wide floodplains. Tributaries are smaller but can supply a significant suspended-load during floods. In the last 35 km before the junction with the Rhône in Lyon, the stream power increases dramatically, due to an increase of the river gradient (Astrade 1998).

Winter and spring floods are frequent and may last for several weeks. Main floods usually form in the upper parts of the basin and propagate slowly towards the Rhône river.

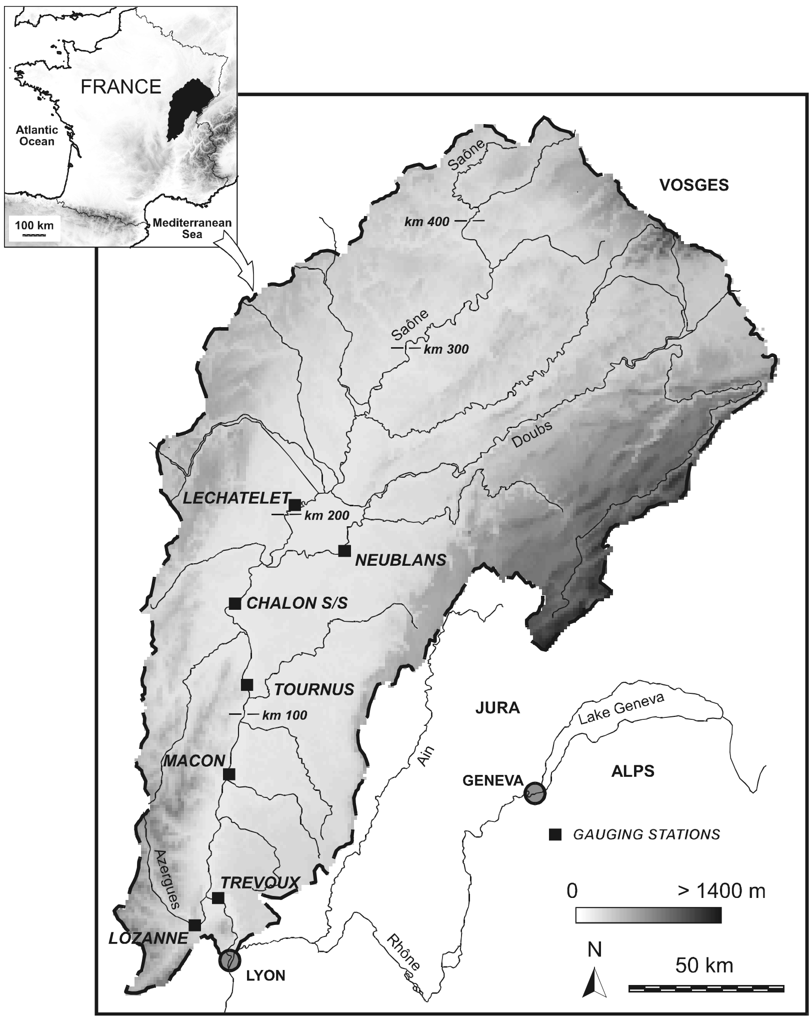


Figure 1. The Saône river catchment

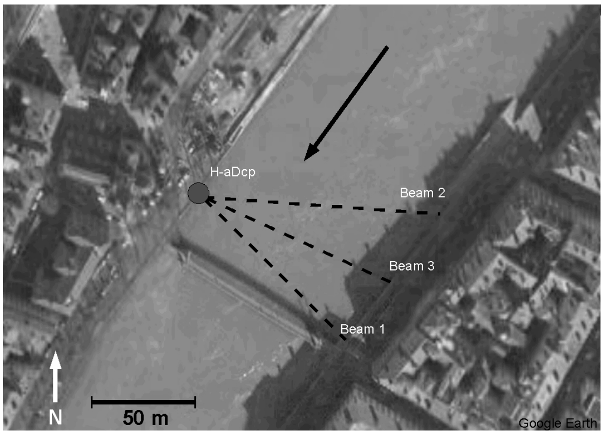


Figure 2. St-Georges gauging station (H-aDcp).

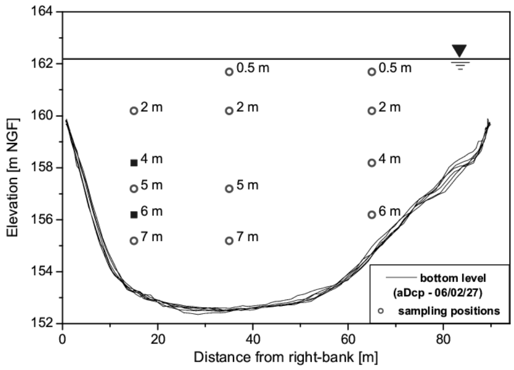


Figure 3. Sampling points in the cross-section.

THE SAINT-GEORGES GAUGING STATION IN LYON

To investigate the suspended-load dynamics during spring floods, it was planned to collect water samples at the Saint-Georges gauging station, situated in Lyon, at the outlet of the river catchment.

At the beginning of February 2006, the Compagnie Nationale du Rhône (CNR) equipped this gauging station with a 300 kHz TRDI horizontal acoustic Doppler current profiler (H-aDcp). This device was installed on the right-side embankment, 1.90 m below the usual free-surface level, i.e. at elevation 160.00 m NGF (Pierrefeu, 2006). Ultrasonic signals are emitted along 3 acoustic beams across the river (Fig. 2). Beam 1 and beam 2 are separated from beam 3 by 20°. A narrow-beam H-aDcp (beam width 0.7°) was chosen in order to avoid bed and free-surface reflection. The water level is measured by an independent pressure gauge.

Every minute, the measuring system records the water level, the water temperature, the acoustic backscatter intensity and the horizontal water velocities in 4 m-wide bins across the river. The total discharge is computed by fitting theoretical vertical profiles against measured velocities, using the VISEA-H commercial software (AquaVision, NL). These discharge estimates were validated by comparison with 18 discharge measurements by classical aDcp from 100 m^3/s to 1800 m^3/s: differences were always less than 5% of the reference discharge.

WATER SAMPLING PROCEDURES

Water sampling was performed manually by using a 2-liter horizontal Niskin bottle. According to usual procedures (ISO 11923, NF EN 872), the water samples were filtered through 0.45 µm glass-fiber filters in the laboratory. Then the filters were dried and weighed to compute the suspended solid concentration.

Water sampling campaigns were carried out according to two different procedures. During 8 vessel-mounted aDcp campaigns, water samples were taken from the powered boat at several depths and at 15 m, 35 m and 65 m from the right bank (Fig. 3). The aDcp bottom-tracking data were used to position the boat, which was kept at the same distance from the right bank during water sampling. Beyond 7 m deep, the operation was difficult to carry out due to high velocities up to 3 m/s in the central part of the channel.

In order to monitor the suspended-load concentration throughout the successive flood events, a simplified water sampling procedure was followed. On a daily basis, as far as possible, 3 successive water samples were taken just below the free-surface, in the middle of the channel, from the pedestrian bridge that can be seen on Fig. 2. Differences between the 3 resulting concentration values were typically lower than 5%. Then the average concentration was recorded.

Concentrations [mg/l] obtained across the section using the first procedure are reported in Table 1. For each campaign, concentrations are strikingly homogeneous on all sampling points: differences do not seem significant and the standard-deviation values are only a few % of the mean concentration across the section. As a matter of fact, the concentration variability on all sampling points is at least one order of magnitude lower than the typical daily fluctuations of the mean concentration. So we can assume that surface concentrations acquired according to the second procedure are representative of the mean concentration in the whole section.

This last consideration must be moderated by the fact that we were not able to investigate the sediment transport occurring very close to the bed. Indeed one can expect that a high-concentrated flow layer is active near the bottom, inducing higher solid transport rates. In the absence of data, this study focuses on the quite homogeneous suspended-load in the water column.

Table 1. Concentration data across the section.

depths	06/02/17	06/02/20	06/02/21	06/02/27	06/03/10	06/03/13	06/03/15	06/03/17
15 m from right bank								
2 m	19	146	93	30	42	66	44	35
5 m *(4 m)*	20	133	97	29	***43***	***66***	***52***	***34***
7 m *(6 m)*	19	143	87	31	***55***	***63***	***47***	***36***
35 m from right bank								
0.5 m	-	135	91	29	42	60	47	35
2 m	15	134	97	27	44	69	45	35
5 m	24	131	96	30	40	62	48	32
7 m	24	133	92	29	45	60	44	35
65 m from right bank								
0.5 m	-	134	92	-	-	-	-	-
2 m	15	130	89	26	39	59	46	34
4 m	18	136	87	27	45	58	46	36
6 m	20	130	91	26	42	58	48	35
mean	**19**	**135**	**92**	**28**	**44**	**62**	**47**	**35**
st-deviation	3	5	4	2	5	4	2	1

OBSERVATIONS IN LYON

From the beginning of February 2006 to the end of April 2006, a series of 5 flood events occurred after a long period with very scarce floods – no flood in summer and autumn, 3 small floods in winter (600, 1000 and 800 m^3/s). The (hourly-averaged) discharge time series from the H-aDcp and the concentration time series from water sampling are presented in Fig. 4. The gap in discharge data from 29th March to 3rd April is due to a breakdown in the H-aDcp power supply. One can also notice that some missing concentration data would have been useful to follow some abrupt changes in suspended-load rate. But this first manual monitoring of SSC is detailed enough to allow some interesting observations.

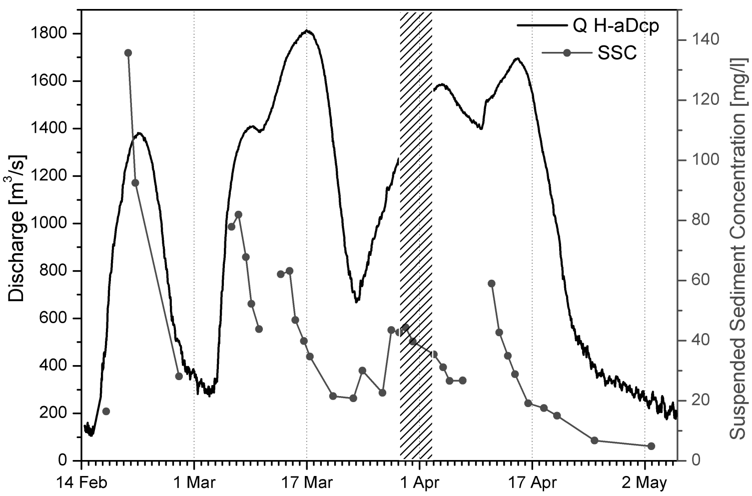


Figure 4. Water discharge (from hourly-averaged H-aDcp data) and suspended-solid concentration (samples).

First, it is clear that, as usually expected for large rivers, each of the 5 flood rising limbs is associated with a SSC peak. The SSC begins to decrease before the flood peak, so that at the event-scale, the correlation between discharge and concentration is not bijective. Instead, hysteresis loops can be derived (not shown here).

Second, for the series of 5 flood events considered, the intensity of the peak concentrations is not correlated to the peak discharge values. For instance, whereas the first two 1400 m^3/s floods are quite equivalent in shape, the second concentration peak is at least twice lower than the first one, besides difficult to assess precisely. Quite independently from the flood intensities, the successive SSC events decrease quite regularly in intensity. As an exception to the rule, the last SSC event shows an abrupt rise, not fully monitored due to a lack of samples.

RESUSPENSION OF SEDIMENT STOCKS

The observations made above lead to several assumptions on the suspended-load mechanisms at work. The continuous decrease in SSC peaks along the flood series suggests that the suspended-load observed at the outlet must come from a limited sediment stock distributed upstream in the river catchment. After a flood peak, this sediment stock does not seem to be as readily available as before, since the following SSC peak is weaker, even for similar flood conditions. This means that the stock needs some time to be regenerated: so it is highly probable that the suspended-load observed in Lyon comes from fine deposits accumulated during low-flow periods in upstream reaches. Of course, one cannot discard the possibility of direct wash-load supply from the nearest tributary catchments during specific storm events for instance.

If the observed suspended-load comes from the resuspension of stocks stored upstream ("indirect phase"), one can expect that the SSC be correlated (in time and magnitude) with the mean bottom shear stress induced by the floods in the storage locations. By contrast, a SSC signal directly produced by run-off erosion on watersheds ("direct phase") should be more closely correlated to the discharge signal.

It is difficult to derive continuously the mean bottom shear stress τ from water level time series only. Ultrasonic devices such as H-aDcp systems offer the opportunity to do so as they provide both the bulk velocity $V=Q/S$ and the hydraulic radius $R_h=S/P$. The wetted area $S(h)$

and the wetted perimeter *P(h)* were derived from the cross-section bathymetry and the water level *h*. Stream gauging campaigns show that the bathymetry can be considered constant during all the period.

At Saint-Georges gauging station, the mean bottom shear stress was estimated following the classical formula:

$$\tau = \rho g R_h J_e \qquad (1)$$

with J_e the energy slope, ρ the water density (1000 kg.m^{-3}) and g the gravity (9.81 m.s^{-2}).

From the Manning-Strickler formula:

$$V = K\, R_h^{2/3} J_e^{1/2} \qquad (2)$$

with K (=*1/n*) the Strickler coefficient (set to 30 here),
the mean bottom shear stress can be expressed from V and R_h as time-varying parameters:

$$\tau = \frac{\rho g}{K^2} V^2 R_h^{-1/3} \qquad (3)$$

This last equation was used to compute τ during the whole period of interest. The 6-hour averaged results are plotted in Fig. 5 (thin line). The general shape of the shear stress time series is quite similar to the discharge time series. So at the event-scale the SSC is not directly correlated to τ as well.

An interesting difference between Q and τ signals occurs just before the last flood peak. This is linked to a quick change in the hydraulic conditions, likely due to operations at the first dam just downstream Lyon: Q goes on increasing while V and so τ drop dramatically, giving birth to this small shear stress peak. This might explain why the last SSC peak does not seem to follow the regular decrease exhibited by the first four SSC peaks.

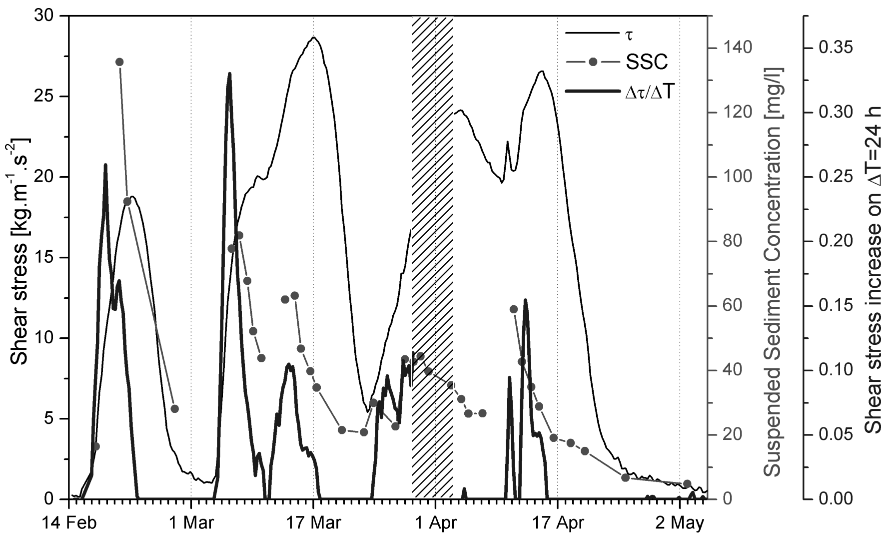


Figure 5. SSC and mean bottom shear stress evolution (computed from H-aDcp data).

By contrast, a clearer correlation between SSC peaks and shear increase periods appears in Fig. 5 (thick line). This shear stress increase was computed from the 6h-averaged τ as $\Delta\tau/\Delta T$, with ΔT=24h. Positive variations only are plotted, leading to 5 peaks roughly matching in time with SSC peaks. This is coherent with the assumption of sediment stocks that would need an increase of shear stress to be resuspended. Periods with no increase in shear stress values, even with high shear stress values, correspond to fast decrease in SSC.

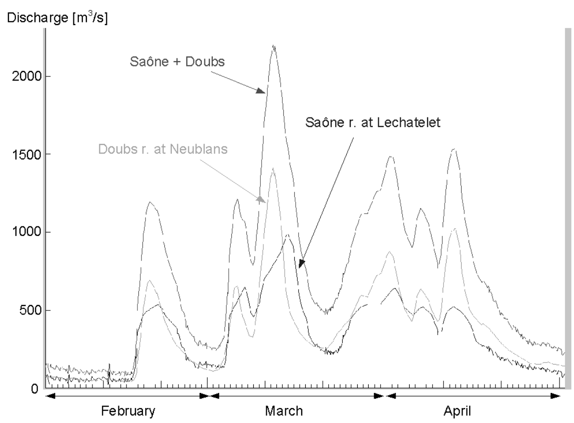
In the 4 first events, the $\Delta\tau/\Delta T$ peak seems to occur a few days before the corresponding SSC peak. This could stem from the slower propagation of suspended-load resuspended upstream: the water velocity is usually lower than the flood propagation rate in rivers with low gradient slope (Lewis, 1921; Marcus, 1989). It is difficult to test this assumption in the absence of detailed SSC and water velocity monitoring at upstream gauging stations.

SOURCES AND PROPAGATION

Since the suspended-load observed at Lyon St-Georges seems to mainly come from upstream resuspension, a rough analysis of flood formation and propagation during spring 2006 was carried out, thanks to Diren Rhône-Alpes hydrometric data.

Fig. 6 shows that most of the Saône discharge observed in Lyon can be explained by six successive flood peaks occurring simultaneously in the upper (or “Petite”) Saône river and in the Doubs river. All main patterns of the flood signal in Lyon are already in preparation in the expected discharge at the confluence, i. e. the sum of both flows.

Then each flood wave propagates and flattens out throughout the lower (or “Grande”) Saône channel, via Chalon, Tournus, Mâcon, Trévoux gauging stations (Fig. 7). In the process, the 5th peak disappears before Mâcon. Water supply from tributaries does not seem to alter significantly the flood shape, except for the sudden rise just before the last flood peak.



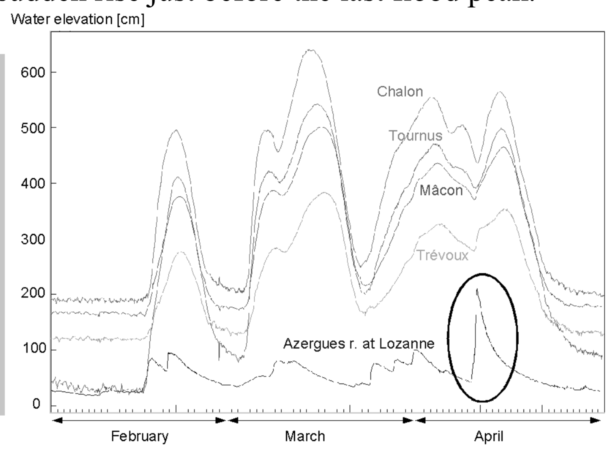


Fig. 6. Flood formation upstream the junction between Petite Saône and Doubs rivers
Fig. 7. Flood propagation in the Grande Saône and behaviour of lowest tributary Azergues

This anomaly must be due to the activation of lower tributaries by local storms: the lowest major tributary, the Azergues river, rises dramatically as can be seen in Fig. 7. As expected from Lyon SSC data analysis, the 5th and last SSC peak is generated by a different mechanism. Indeed, it is possible that a significant suspended-load amount was supplied by run-off erosion on the watershed of the Azergues river and of other neighbouring ungauged tributaries. Those watersheds are made of hills partly covered with vineyards and can produce high SSC during storms.

CONCLUSION AND PERSPECTIVE

In the absence of continuous SSC monitoring in Lyon and in upstream gauging stations, this study is a first step towards the understanding of suspended-load dynamics in the Saône river during floods. The analysis of the 2006 spring events shows that:

- the SSC is homogeneous enough in the St-Georges section to be accurately monitored by point sampling. However concentrations and fluxes close to the river bed remain unknown;
- the link between flood and SSC peaks is not straightforward in terms of intensity and lag times. The decrease in successive peak SSC and the correlation with phases of bed shear stress increase suggest that the resuspension of upstream sediment stocks occurs. Further investigation is needed to reveal the location, nature and availability of those sediment stocks;
- a rough analysis of the 2006 spring flood formation and propagation indicates that storm floods in lower tributaries may also supply significant suspended sediment amounts; another explanation for odd SSC peaks may lie in fast changes in the hydraulic regime of dam-influenced reaches.

This short study shows that an at-a-station SSC continuous monitoring can provide a very interesting insight of the upstream catchment behaviour. Hydrometric and sediment monitoring remains difficult and expensive to extend to a dense gauging network. Our next project will be to try to convert the H-aDcp backscatter into SSC estimates. First comparisons (not presented here) indicate that this is not a straightforward operation.

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REFERENCES

Astrade, L., 1998, La Saône en crue : dynamique d'un hydrosystème anthropisé, *La Houille Blanche*, No. 1, pp. 13 – 17.

Balland, P. and Cottereau, C., 1991, Une méthodologie d'approche des critères multiples d'un cours d'eau, Elaboration d'un schéma d'aménagement hydraulique de la Saône destiné à limiter l'impact des crues juste débordantes, *La Houille Blanche*, No. 7/8, pp. 603 – 608.

ISO 11923, 1997, Water quality – Determination of suspended solids by filtration through glass-fibre filters. Published standard, 6 p.

Lewis, A.D., 1921. Silt observations of the river Tigris. Minutes of Proceedings of the Institution of Civil Engineers, No. 212, pp. 393 – 399.

Marcus, W.A., 1989. Lag-time routing of suspended sediment concentrations during unsteady flow. Geological Society of America Bulletin, Vol. 101, pp. 644 – 651.

NF EN 872, 2005, Qualité de l'eau - Dosage des matières en suspension - Méthode par filtration sur filtre en fibres de verre. Norme homologuée, 14 p.

Pierrefeu, G., 2006, Monitoring the Saône river discharge in Lyon by H-ADCP, In: *TRDI "ADCPs in Action"*, Cannes, France.