Velocity and suspended sediment concentration profiles in rivers: in situ measurements and flux modelling

P. Laguionie[1], A. Crave[2] & A. Jigorel[1]
[1]*Laboratoire de Génie Civil et de Génie Mécanique, INSA de Rennes, France*
[2]*Géosciences Rennes, CNRS, France*

Abstract

River basin sediment management is increasingly needed to address both sediment quantity and quality studies. In this context, the sampling of suspended sediment through a river cross-section is unavoidable. Rivers have the interesting property of concentrate sediment and processes through a river cross-section are representative of the whole upstream hydro-sedimentary processes.

Evaluating sediment budget at the outlet of a river basin is closely related to the experimental method used, as suspended sediment concentration and velocity are non-constant over the water height. This paper presents results obtained from an in situ experimental program, which aims to measure the velocity and suspended sediment concentration profiles in rivers during different hydrological conditions. In particular, the study focuses on the region located near the interface between water and settled sediment. This region is usually neglected as it corresponds to the dead zone of non-intrusive instruments such as Acoustic Doppler Current Profilers. This is achieved by the use of specific instruments. A velocity profiler was used to measure the velocity profile within the few percents of the water height located near the interface between water and settled sediment. In addition, sediment concentration profiles were measured either by a turbidity sensor moved over the water height or by 144 turbidity sensors mounted on a vertical stick, which allows one to record instantaneously the turbidity profile close to the interface between water and settled sediment.

In situ measurements are compared to theoretical models commonly used: the Rouse profile for suspended sediment concentrations, and the logarithmic law for velocities. Results notably show that during low water flows, 35% of the total sediment flux may be located within the first 15% of the water height. Then, following the sampling strategy adopted, the error on the mean suspended sediment flux may be up to 50%.
Keywords: in situ measurement, river, suspended sediment profile, velocity profile, sediment flux.

WIT Transactions on Ecology and the Environment, Vol 104, © 2007 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/RM070321

1 Introduction

Non-linear correlation between suspended sediment and water flux through a river cross-section asks the questions: what processes to control sediment transfer in rivers, and how to measure in situ suspended sediment flux?

There are many models to predict, in rivers, suspended load, bedload, or both of them, generally based on both sediment physical properties and hydraulic constraints (obtained from the classical hydrodynamic theory) [1–3]. These models are validated from laboratory experiments, and consequently, their transposition to natural environment is not immediate. In this way, there is clearly a lack of in situ data, partly due to the difficulty, in rivers, to carry on the measurement of velocity and suspended sediment concentration profiles and to study their spatiotemporal variability [4, 5].

In this paper, in situ velocity data are confronted to the logarithmic law, eqn. (1). The logarithmic law, initially defined in the laminar and transitional sub-layers, is commonly extended to the whole water height when a great accuracy on results is not required [6]. In eqn. (1), $\overline{u(z)}$ is the mean velocity at the height z, u^* the shear velocity, κ the Von Karman's constant (equal to 0.41), k_s the bed rugosity, and B_s an empirical coefficient. The introduced variables a and b play the role of fitting parameters.

$$\frac{\overline{u(z)}}{u^*} = \frac{1}{\kappa}\ln\left(\frac{z}{k_s}\right) + B_s \text{, with } a = \frac{u^*}{\kappa} \text{ and } b = u^*\left(B_s - \frac{1}{\kappa}\ln\left(k_s\right)\right) \tag{1}$$

In situ suspended sediment concentration data are confronted to the Rouse profile, eqn. (2). Rouse profile is a classical model, often used in sediment transport studies. Other models are compiled in [7]. In eqn. (2), $C_s(z)$ is the sediment concentration at the height z, $C_{s,0}$ the reference sediment concentration at the height z_0, h the water depth, w_s the sediment settling velocity, and β a constant. The introduced variable A plays the role of the fitting parameter.

$$C_s(z) = C_{s,0}\left(\frac{z_0}{z}\frac{h-z}{h-z_0}\right)^{\frac{w_s}{\beta\kappa u^*}} \text{, with } A = \frac{w_s}{\beta\kappa u^*} \tag{2}$$

From eqn. (1) and eqn. (2), a unitary suspended sediment flux (flux per river cross-section squared meter) is introduced: $\varphi(z)$ at the height z, eqn. (3).

$$\varphi(z) = \left(a\ln(z) + b\right)\left(\frac{z_0}{z}\frac{h-z}{h-z_0}\right)^{A} \tag{3}$$

Then, for a velocity profile completely defined, the error on the mean suspended sediment flux arising from a ponctual sediment sample may be estimated.

2 Study area

In situ measurements were carried on the river Vilaine catchment between longitudes 1.0560°W and 2.1270°W, and latitudes 47.5770°N and 48.1870°N, fig. 1. River Vilaine catchment is located in the region of Brittany in the northwest of France, and characterized by low gradients and predominantly agricultural land use. The drained 10 400 km² elevate from 0 to 300 m above the sea level and receive an average annual rainfall around 800 mm. The river Vilaine is schist-, sandstone- and mud-bed river.

The main river section under interest is located between Rennes which is an urban area of around 200 000 inhabitants, and Redon, a village located 80 km downstream from Rennes. At Rennes and upstream Redon, the daily mean water flows are respectively 11 and 27 $m^3.s^{-1}$ in average and up to 183 and 491 $m^3.s^{-1}$ during flood events. The five main tributaries along this river section are rivers Meu, Seiche, Semnon, Chere and Don.

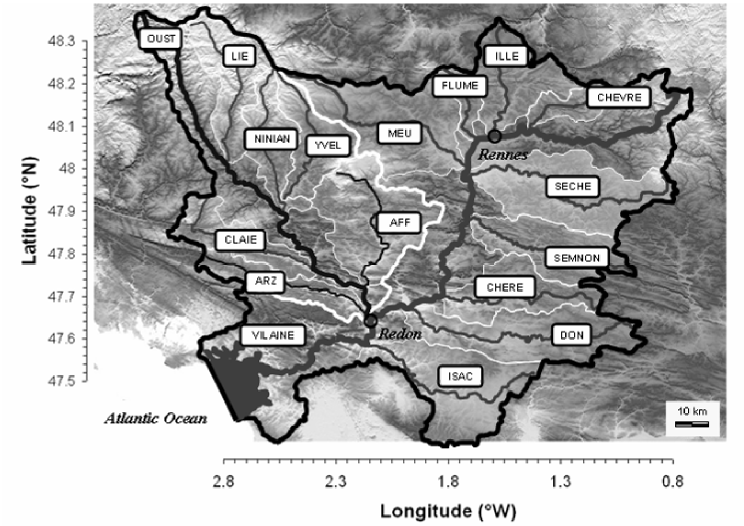

Figure 1: River Vilaine catchment and localisation of the main sub-catchments, Rennes city and Redon village.

3 Means and methods

3.1 Velocity profile

Velocity profiles were measured by a Nivus PCM Pro velocity profiler. The sensor was fixed on a ballasted base, directed toward the flow, and possibly overturned through 180 degrees around a horizontal axis, fig. 2. Then, each velocity profile is composed of two acquirings: one toward the river surface and one toward the river bottom. The sampling frequency is 0.2 Hz. Mean velocities corresponds to data averaged over 10 minutes.

The main interest of the specific acquiring toward the river bottom is to well-define the velocity profile within the few water height percents located near the river bottom. Velocity measurement within these few percents is of primary importance when determining the bending of a modelled velocity profile. Note that this area corresponds to the dead zone of non-intrusive instruments such as ADCP (Acoustic Doppler Current Profiler).

In the studied river sections, the interface between water and sediment is defined with no ambiguity: the interface is made of millimetre- to centimetre-sized mineral particles.

3.2 Suspended sediment concentration profile

Suspended sediment concentration profiles were measured either in a non-instantaneously way, moving a turbidity sensor from the top of water to the river bottom, or in an instantaneously way by 144-turbidity sensors mounted on a vertical stick, fig. 3. The turbidity sensor is fixed on a Troll 9000 XP/e probe and was calibrated with in situ sampled material. Mean concentration at the height z corresponds to data averaged over 1 minutes. About 15 minutes are required to record a suspended sediment concentration profile.

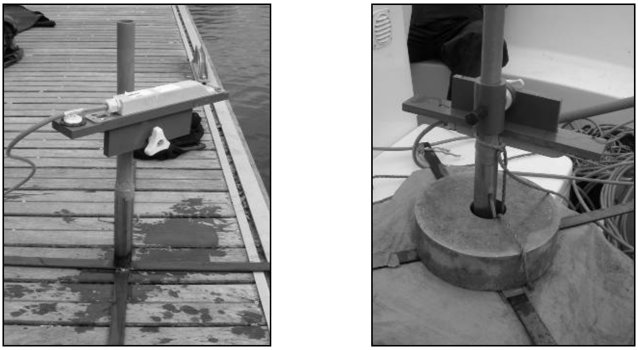

Figure 2: Nivus PCM Pro velocity profiler (left and right) fixed on a ballasted base (right). Measurement layout with acquiring toward the river surface (left) and toward the river bottom (right).

The stick used is the ASM-IV Argus, fig. 3. At each of the 144 sensors corresponds a specific calibration curve, plotting in laboratory from in situ sampled material. The sampling frequency is 0.5 Hz. Mean concentrations correspond to data averaged over 1 minute.

4 Results and discussion

In total, 79 velocity profiles were recorded in situ by the velocity profiler, 123 suspended sediment concentration profiles by the turbidity sensor fixed on a probe and 12 suspended sediment concentration profiles by the 144-turbidity sensor stick.

Acquirings were carried out between March 2005 and April 2006. At Rennes, and due to the rainfall deficiency between 2001 and 2006, the maximum water flow over this period of time was below 20 $m^3.s^{-1}$ (around twice the daily mean water flow rate). And, water flows were most often comprised between 1 and 5 $m^3.s^{-1}$. The water depth was between 0.3 m and 4.4 m, with a mean at 1.8 m, and the river width between 20 m and 60 m, with a mean at 34 m. At the low water stage, suspended sediments are made of organic material and, for water flows until 20 $m^3.s^{-1}$, of an organic material and silt particle mixture. A particularity of the river Vilaine drainage basin is that the apparent mean particle diameter remains constant at 10 μm within the occurred water flow range.

4.1 Velocity and suspended sediment concentration profiles

Results show that the in situ velocity distribution over the water height may be modelled by the logarithmic law, fig. 4. Mean values of fitting parameters *a* and *b* are respectively 0.030 and 0.036, table 1. In addition, no correlation was found between *a* and *b*, the water depth, the mean velocity or the river local slope. This may be explained by the presence of locks in the river Vilaine.

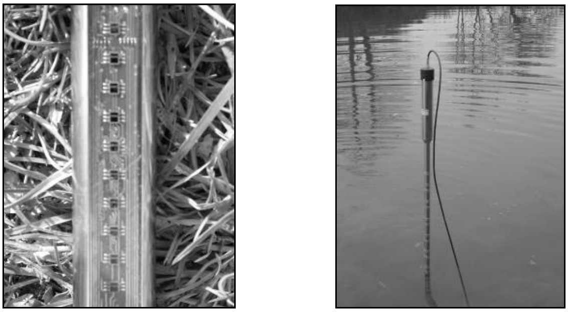

Figure 3: ASM-IV Argus stick (left and right). Zoom on 10 of the 144-turbidity sensors (left), spaced with 1 cm. Instrument in working configuration (right), with its data retrieval top.

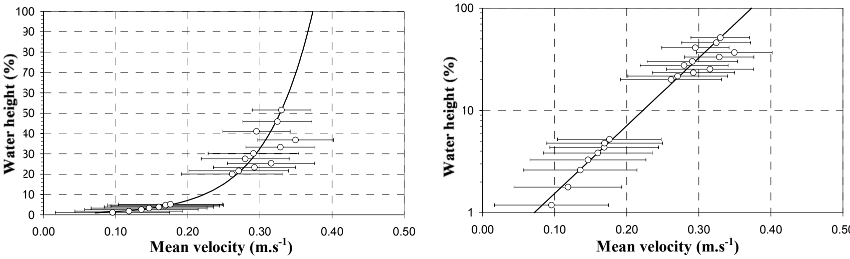

Figure 4: Example of in situ measured velocities plotted on a graph with linear axis (left) and logarithmic axis (right). The smooth curve is the least-squares fitted according to the logarithmic law. Error on the mean velocity is defined as plus or minus 2 standard deviations.

Concerning the suspended sediment concentration profiles, the reference concentration $C_{s,0}$ is taken at $z_0 \approx 0.65h$ when profile is recorded with the turbidity sensor fixed on a probe, and at $z_0 \approx 0.20h$ when profile is recorded with the 144-turbidity sensor stick, fig 5.

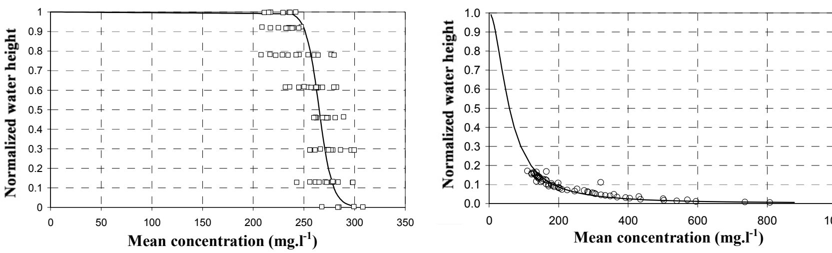

Figure 5: Examples of in situ suspended sediment concentration profiles measured with the turbidity sensor moved over the water height (left), and the 144-turbidity sensor stick (right). The smooth curve is the least-squares fitted according to the Rouse model.

Table 1: Fitting parameter mean values of velocity and suspended sediment concentration profile models, and standard deviations.

Velocity profile				Suspended sediment concentration profile			
Nivus PCM Pro velocity profiler				Sensor fixed on a probe		144-sensor stick	
a		b		A		A	
$\bar{a}$	$\pm\sigma$	$\bar{b}$	$\pm\sigma$	$\bar{A}$	$\pm\sigma$	$\bar{A}$	$\pm\sigma$
0.030	0.034	0.036	0.135	0.050	0.108	0.547	0.171

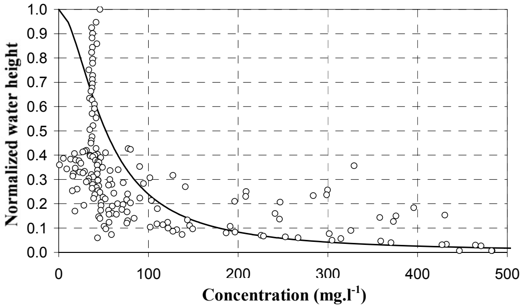

Figure 6: Example of an in situ suspended sediment concentration profile measured by the combination of both the turbidity sensor moved over the water height and the 144-turbidity sensor stick. The smooth curve is the best least-squares fitted according to the Rouse model.

In all cases, an A value allows to fit the Rouse model with empirical data. From this observation, Rouse model calibration seems possible in rivers. However, A is found to be equal to 0.050 from the first measurement method (probe) and to 0.547 from the second one (stick), which is ten times higher, table 1.

When superposing data recorded by both methods on the same water height, from the river bottom (where sediment concentrations are measured with a 1 cm resolution) to the surface, fig. 6, the Rouse model is weak to explain the in situ suspended sediment concentration distribution. Two zones may be distinguished: a first one, corresponding to the first 30% of the water height above the river bottom, where the concentration gradient is high, and a second one, corresponding to the complementary 70%, where the concentration gradient is nearly null.

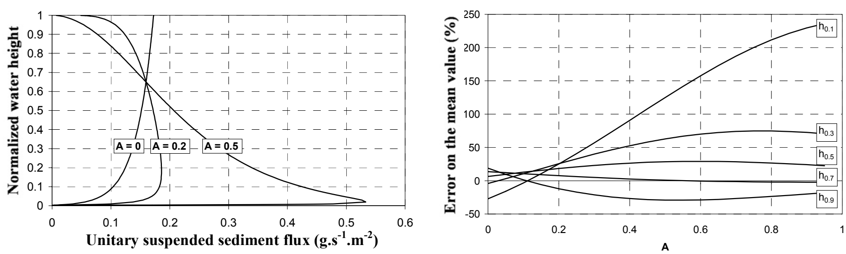

Figure 7: Unitary suspended sediment flux profiles (left) calculated for different A values and from $\bar{a}$ and $\bar{b}$, table 1. Error on the estimation of the mean suspended sediment flux (right) when the suspended sediment concentration is estimated from a punctual sampling at the normalized water height h_i (right), with i varying from 0.1 to 0.9.

4.2 Sediment flux profile

As shown in paragraph 4.1, the suspended sediment concentration profile shape depends on the experimental method used. High-resolution measurement near the river bottom, without disturbing local hydrosedimentary processes by moving a probe, allows one to define a pseudo-Rouse profile (high A values) within the first 30% of the water height. Unitary suspended sediment flux profiles, calculated from a well-defined velocity profile, are drastically different when $A = 0.05$ or $A = 0.5$, fig. 7 (left).

Error on the mean suspended sediment flux value is calculated when the suspended sediment concentration is estimated from a punctual sampling, fig. 7 (right). This corresponds to the experimental method commonly used when suspended sediments are sampled by automatic samplers. Error may be higher than 50% when $A > 0.3$, and is the most important in the particular case of a surface sampling.

Figure 8: Experimental device used to estimate the in situ unitary suspended sediment flux (Nivus PCM Pro and 144-sensor stick coupling).

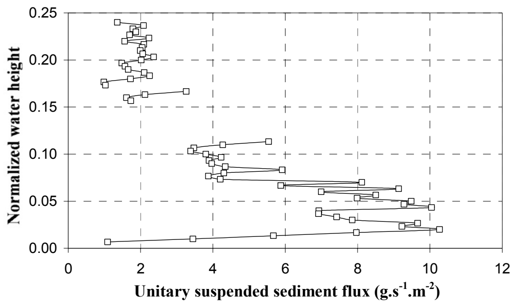

Figure 9: Example of a unitary suspended sediment flux profile in the first 25% of the water height, obtained by the in situ simultaneous measurement of velocities and suspended sediment concentrations.

An additional test was carried out, putting together the 144-turbidity sensor stick and the velocity profiler, fig. 8. Result of the unitary sediment flux over the first 25% of the water height above the river bottom, fig. 9, shows that 35% of the total sediment flux is located within the first 15% of the water height. And, the sediment flux located at 5% of the water height is five times more important than the one after 15%. There is a great sediment flux gradient within 10% of the water height, located in the inferior sixth of the water height.

5 Conclusions

Results presented in this paper are part of an in situ experimental program, which aims to measure the velocity and suspended sediment concentration profiles in rivers during different hydrological conditions. A particular emphasis is put on the region located near the interface between water and settled sediment.

Results show that, in the river Vilaine (France), the in situ velocity distribution over the whole water height may be modelled by the logarithmic law for water flow rates, at Rennes city, until 20 $m^3.s^{-1}$. The suspended sediment concentration profile shape depends on the experimental method used: a turbidity sensor moved over the water height (non-instantaneous suspended sediment profile measurement) or 144-turbidity sensors mounted on a vertical stick (instantaneous suspended sediment profile measurement). A Rouse profile always seems to be fitted to in situ data. However, the fitting parameter may vary by one order of magnitude.

Results also show that during low water flows, 35% of the total sediment flux may be located within the first 15% of the water height. Then, following the sampling strategy adopted, the error on the mean suspended sediment flux may be up to 50%, and more in the particular case of a surface sampling.

The main perspective of this experimental work is to estimate in situ unitary suspended sediment flux profiles during larger water flow events, say during the flood events.

Acknowledgements

The authors gratefully acknowledge the CNRS-INSU department for their support, and the IAV Institute.

References

[1] Engelund, F. & Hansen, E., A Monograph on Sediment Transport in Alluvial Streams. Ed. T. Vorlag, 1967.

[2] Meyer-Peter, E. & Müller, R., Formula for bed load transport. *Proceedings of the 2nd IAHR Congress, Stockholm*, 1948.

[3] Van Rijn, L.C., Sediment transport, Part II: Suspended load transport. *Journal of Hydraulic Engineering, ASCE*, **110(11)**, pp. 1613-1639, 1984.

[4] Guo, J. & Julien, P.Y., Shear Stress in Smooth Rectangular Open-Channel Flows. *Journal of Hydraulic Engineering, ASCE*, **131(1)**, pp. 30-36, 2005.

[5] Sanchez, M., Grimigni, P. & Delanoë, Y., Steady-state vertical distribution of cohesive sediments in a flow. *C. R. Geoscience*, **337**, pp. 357-365, 2005.

[6] Graf, W.H. & Altinakar, M.S., Hydraulique fluviale - Tome 2 - Ecoulement non permanent et phénomènes de transport. *Presses Polytechniques et Universitaires Romandes*, in French, 1996.

[7] Yang, G.L., Modèle de transport complet en rivière avec granulométrie étendue. *Institut National Polytechnique de Grenoble*, PhD, in French, 1989.