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Observations on flow hydraulics in a gauging station of a small stream with high suspended sediment load (Vallcebre, eastern Pyrenees)

GUILLAUME NORD, MONTSERRAT SOLER, JÉRÔME LATRON & FRANCESC GALLART

Institute of Environmental Assessment and Water Research (IDÆA), CSIC, Sole i Sabaris s/n, 08028 Barcelona, Spain
guillaume.nord@idaea.csic.es

Abstract Water depth and sediment concentration have been measured with a good time resolution (every 2 min during flood events and every 20 min for the rest of the time) since 1994 at the gauging station of the Cal Rodó catchment (4.17 km^2). Since October 2008, mean water velocity has been measured at the same resolution using an incoherent (or continuous) Doppler instrument mounted on the bottom of the gauging station. This study focuses on the impact of suspended sediment transport on water depth measurement and the effect of high loads of suspended sediment on flow hydraulics. We take into account the effect of suspended sediment concentration on the measurement of water depth by the hydrostatic pressure probe. We also examine the relationship between water depth and flow velocity and the effect of suspended sediment concentration on this relationship.

Key words suspended sediment; stream; flow velocity; water depth

INTRODUCTION

Investigations started 20 years ago in the Vallcebre research basins with the objective of a better understanding of the hydrological functioning and the suspended sediment dynamics of Mediterranean mountains basins (Gallart *et al*., 2002). This region is characterized by alternating periods of dry and humid conditions. Flash floods are relatively frequent, especially in summer and autumn, and are associated with high suspended sediment transport coming from badlands (Gallart *et al*., 2005). Water depth and sediment concentration have been measured with a good time resolution (every 2 min during flood events and every 20 min for the rest of the time) since 1994 at the gauging station of the Cal Rodó catchment (4.17 km^2).

In October 2008 an incoherent (or continuous) ultra-sonic Doppler instrument was mounted on the bottom of the gauging station to measure flow velocity in a vertical of the river section. The initial objective was to provide an alternative to the traditional measurement of flow discharge using the stage–discharge relationship. However, it proved difficult to relate the velocity measured by the Doppler sensor to the average channel velocity due to the complex geometry of the section. This analysis therefore focused on studying the hydraulic properties of flow including the effect of the presence of sediment on the measurement of water depth and velocity. Concentrations of suspended sediment are eventually very large in this mountain stream (up to 100 g/L). Very few studies in the literature deal with water runoff laden with suspended sediment. The experimental data are very rare and little is known about the effect of suspended sediment on measurement by this new generation of ultrasonic flow measurement systems.

MATERIALS AND METHODS

Study area

The Cal Rodó catchment has an area of 4.17 km^2 (Fig. 1) and is located within the Vallcebre research basin, in the headwaters of the Llobregat River, in the southeastern Pre-Pyrenees (1°49′E and 42°12′N). Elevation ranges between 1100 m and 1650 m. The climate is Mediterranean sub-humid, average annual precipitation is about 900 mm with heterogeneous distribution through the year. Autumn and spring are the seasons with more precipitation. Land cover is dominated by

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pastures and forest. Badlands represent 2.8% of the surface of the catchment. More details on the study area may be found in Gallart *et al*. (2002).

Gauging station and equipment

The gauging station (Fig. 2) is controlled by a two-level rectangular notch weir with two different widths and contraction conditions designed for ensuring a unique relationship between stage and

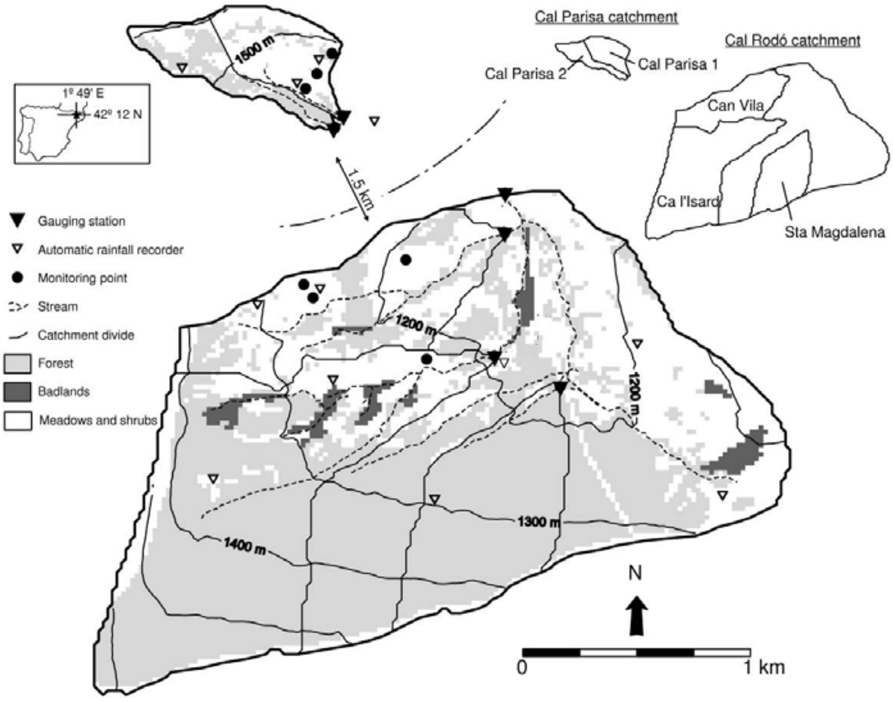

Fig. 1 Map of the Cal Rodó catchment.

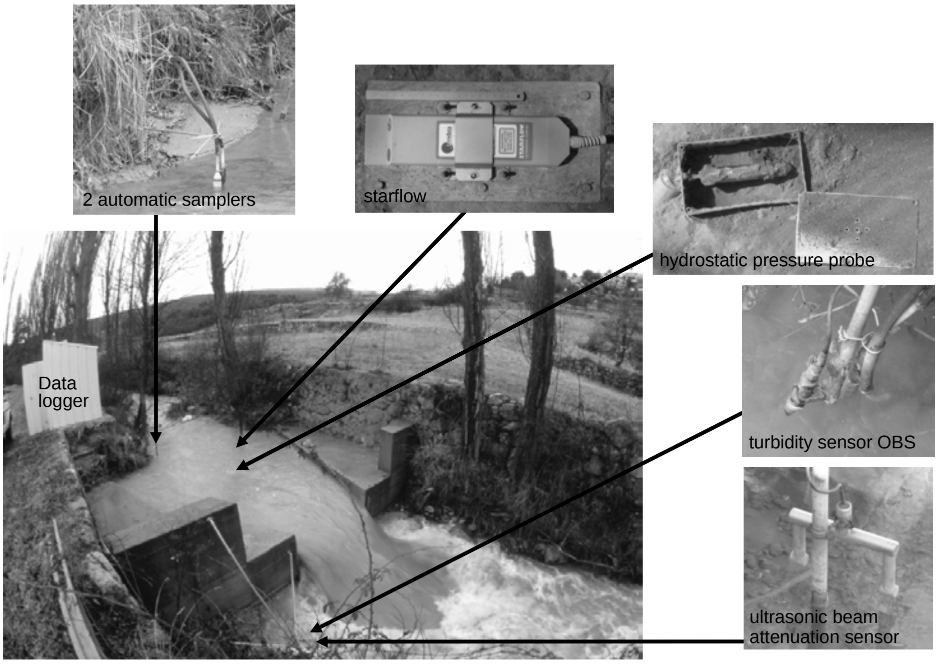

Fig. 2 Instruments installed at the Cal Rodó gauging station.

discharge. The first weir is 0.8 m high and 1.8 m wide and the second weir is 0.9 m higher and 1.8 m wider than the first one. The structure, designed to flush sediment, enables the capture of a wide range of discharges (Balasch *et al.*, 1992). Water level is measured continuously using a hydrostatic pressure probe (UNIDATA Model 6542B) fixed on the ground, in the middle of the gauging station, 3.4 m upstream the control reach. Sediment concentration is sampled sporadically using two automatic ISCO 2700 water samplers. Turbidity is measured continuously using two types of sensors: an OBS-3 D&A infra-red backscattering turbidity sensor for sediment concentrations up to approximately 7 g/L and a Mobrey MSM 40 ultrasonic beam attenuation suspended sediment sensor for sediment concentrations up to 70 g/L (Soler *et al.*, 2010).

Water Velocity of the profile is measured by STARFLOW Doppler flowmeter (UNIDATA model 6526B) mounted on the bottom of the gauging station of the Cal Rodó catchment, 3.75 m upstream the control structure. STARFLOW is an incoherent (or continuous) Doppler instrument that, during measurement cycles (in general 2 seconds), transmits continuously ultrasonic sound at a fixed frequency (1.563 MHz), called a carrier. A receiver listens for reflected signals from any targets (particles and microscopic air bubbles carried in the water) and detects any frequency changes. A processing system accumulates and analyses these frequency changes, calculates a representative Doppler shift from the range received, and outputs an averaged water velocity component along the beam.

All these instruments are connected to a data logger (dataTaker DT50) that reads every 20 s and records the average value every 2 min during floods and every 20 min for the rest of time. The period selected for this study is from October 2008 to October 2009. During this period two instruments were installed. The first one was installed in October 2008 but was broken during a significant flood (h_{max}= 1.2 m, Q_{max}= 4 m^3/s, V_{max}= 1.5 m/s) at the beginning of November 2008 due to the unusual bed load transport of coarse material. In April 2009 a second instrument was installed with a protection located directly upstream of the sensor in order to prevent it from shocks caused by particles rolling along the stream bed. This protection does not affect the performance of the instrument. It has been working correctly so far although a huge flood occurred in July 2009.

Measurement of water depth and correction for the effect of suspended sediment

The hydrostatic pressure probe (UNIDATA Model 6542B) is fitted with a piezo-resistive electric pressure sensor. The data logger records the output voltage delivered by the probe, so it is then necessary to convert the output voltage into water depth. A scale is set on the wall of the gauging station and readings of the water depth are done regularly. The zero of the scale corresponds to the ground of the gauging station. A linear regression is obtained between the values of water depth read on the scale and the values of voltage recorded by the data logger at the time of the reading. Estimation of water depth (*h*) at any time is made using this regression. Note that this regression is valid for clear water only.

In this study, we took into account the effect of suspended sediment on the measurement of the water depth by the hydrostatic pressure probe. The specific weight of a submerged mixture is the total weight of solid and water in the voids per unit total volume (Julien, 1998):

$$\gamma_m = \rho_s g(1-p) + \rho g p \tag{1}$$

where γ_m is the specific weight of a mixture (kg/m^2/s^2), ρ_s the mass density of solid particles (kg/m^3), ρ the mass density of water (kg/m^3), g the gravitational acceleration (m/s^2), and p the porosity (–) defined as a measure of the volume of void per total volume:

$$p = \frac{V_w}{V_w + V_s} = 1 - C_V = 1 - \frac{C_{g/L}}{\rho_s} \tag{2}$$

where V_w is the volume of water (m^3), V_s the volume of solid particles (m^3), C_V the volumetric sediment concentration (–), and $C_{g/L}$ the sediment concentration measured as the ratio of the dry mass of sediment in grams to the volume of the water-sediment mixture in litre. In this study, the mass density of solid particles is 2650 kg/m^3.

The depth of the water–sediment mixture h_m (in m) is calculated as:

$$h_m = h\frac{\gamma}{\gamma_m} = h\frac{\rho}{C_{g/L} + \rho\left(1 - \dfrac{C_{g/L}}{\rho_s}\right)} \tag{3}$$

where γ is the specific weight of water (kg/m^2/s^2) and h the water depth of clear water (m).

We assumed that there is a homogeneous sediment concentration within the flow depth. Mean particle diameter of suspended sediment is approx. 10 μm and D_{90} is approx. 40 μm. In such conditions, the concentration gradient in the stream is not significant (Steegen & Govers, 2001). Calibration of turbidity sensors and errors in sediment concentration measurement due to variable grain size of suspended sediment are discussed in another paper (Soler *et al.*, 2010). In this study, the concentration of suspended sediment is calculated using the results derived from the OBS turbidity sensor, the ultra sonic beam attenuation sensor and the automatic water samples.

RESULTS AND DISCUSSION

Examples of results for two events

Figures 3 and 4 show the results of water depth, velocity and concentration of sediment in suspension for two events: one occurring in autumn (the 1 November 2008 event) and another in summer (the 30 June 2009 event). Water level was corrected to account for the effect of the concentration of suspended sediment. The 1 November 2008 flood event was rather long and characteristic of the autumn period. The highest concentrations (up to 14 g/L) were observed before the flood peak and then became relatively low during the flood peak and the entire decline. The highest velocities were observed during the flood peak and lasted for several hours after the flood peak.

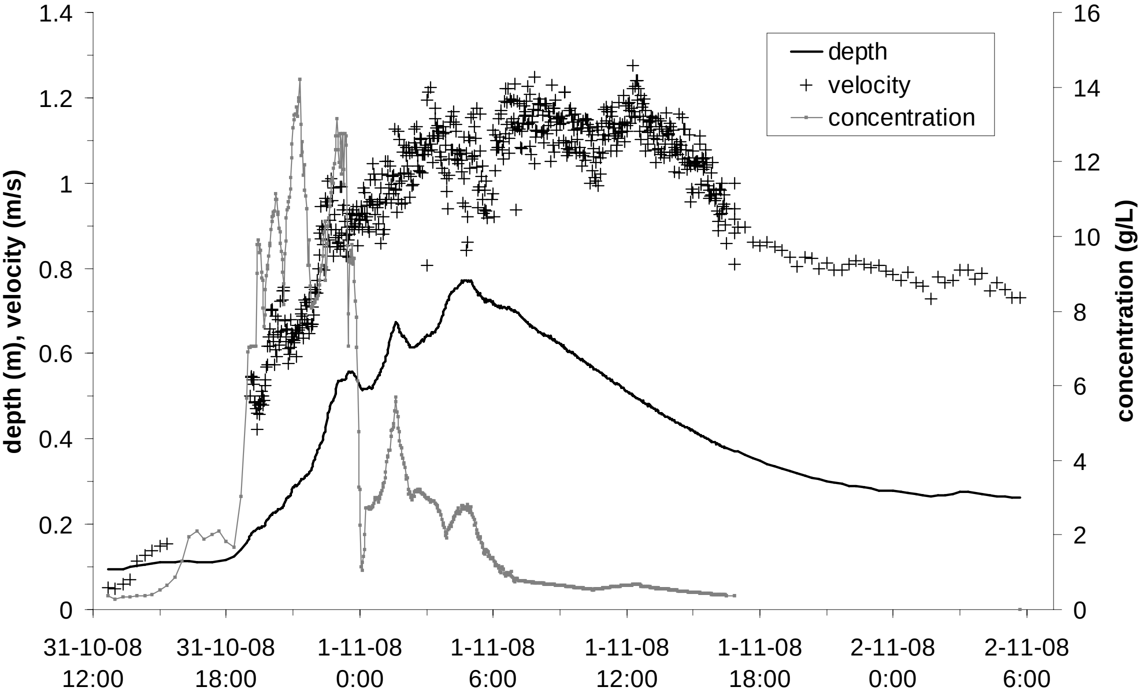

Fig. 3 Flow depth, flow velocity and suspended sediment concentration for the 1 November 2008 event.

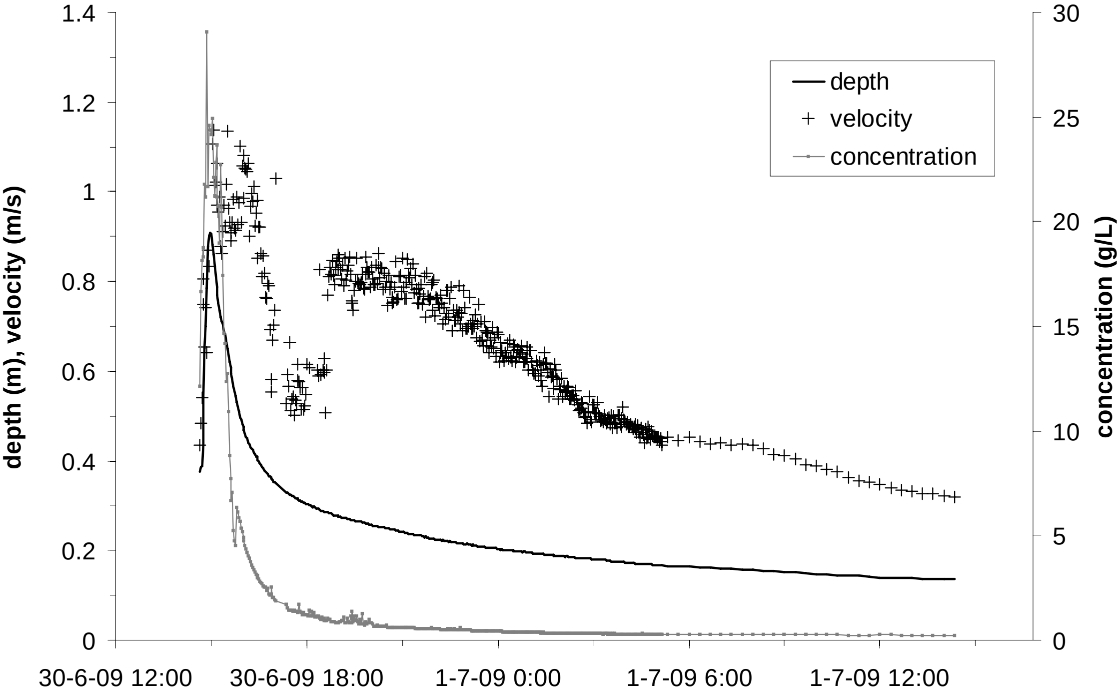

Fig. 4 Flow depth, flow velocity and suspended sediment concentration for the 30 June 2009 event.

The 30 June 2009 flood event was brief, relatively intense and characteristic of the summer period. The highest concentrations (approx. 30 g/L) coincided with the flood peak and then became very low during the recession. The highest velocities were observed during and after the flood peak. About two hours after the flood peak, a sudden increase of flow velocity of about 0.25 m/s occurred while the water level continued to decline. In Figs 3 and 4 we note the great variability of flow velocity measurements and the complex relationship between water depth and velocity. This relationship was not always linear and not continuously increasing. Vermeyen (2004) indicated that variable water quality, sediment transport and hydraulic conditions are factors that affect the performance of incoherent ultrasonic Doppler instruments like STARFLOW. Less noisy measurements of velocity were obtained during the last part of the flood recession since the data logger recorded the average value every 20 min instead of every 2 min during the rest of the flood.

Relationships between water depth and velocity

Figure 5 shows flow velocity *vs* water depth for all the floods that were recorded between October 2008 and October 2009. Two groups of points were distinguished: those for which the suspended sediment concentration is between 0 and 1 g/L and those for which sediment concentration exceeds 1 g/L. The velocity values were systematically larger when the concentration was between 0 and 1 g/L, which demonstrates that the STARFLOW measurements were affected by the concentration of suspended sediment. The envelope formed by all the black dots would represent the hydraulic behaviour of the system in clear water conditions. For this latter group of points, the relationship depth *vs* velocity had a good correlation and variability was relatively low. The relationship depth *vs* velocity was linear for increasing water depths below 0.35 m. However, velocity was almost constant for water depths ranging between 0.35 and 0.7 m. The hydraulic behaviour in this range of water depths is still not well understood. It is possible that hydraulic effects (hysteresis or the downstream influence) lead to differences between events or between ascending and descending stages. We intend to install a hydrostatic pressure probe upstream of the gauging station to study more carefully what happens with the slope of the water surface during events. Activation of the second threshold (second weir of the gauging station, see Fig. 2) for a water depth of about 0.8 m is clearly visible in Fig. 5. For values of water depth larger than 0.8 m, the correlation between water depth and velocity was relatively good, even though the variability of velocity measurements was still important. Note that the concentration is always greater than 1 g/L when water depth exceeds 0.7 m. Indeed, in times of high water, flow always carries sediment.

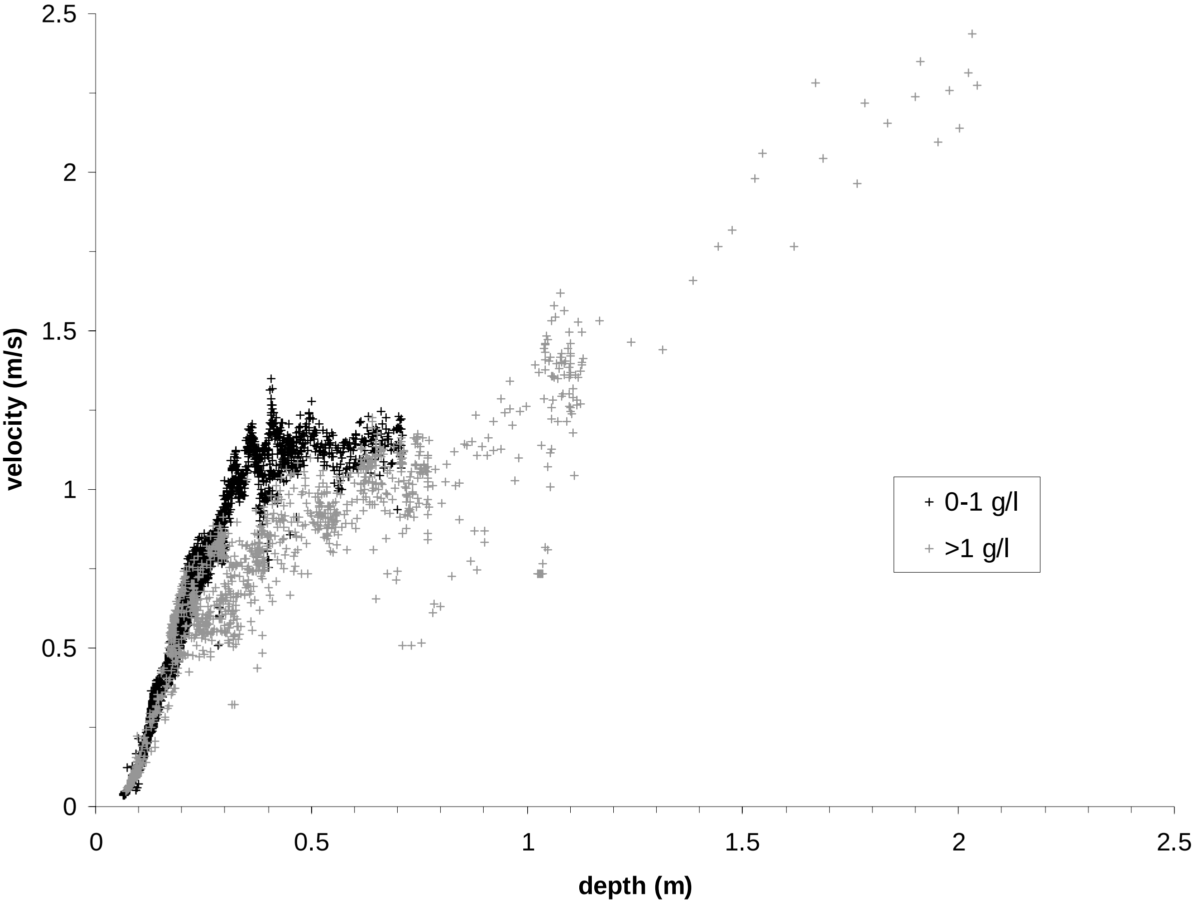

Fig. 5 Flow velocity *vs* flow depth for all the flood events measured during the period October 2008–October 2009. Two groups are represented in function of the value of the suspended sediment concentration.

Two hypotheses are considered to explain the effect of sediment on the STARFLOW measurements. The first hypothesis concerns the acoustics: for high concentrations of suspended sediment, the attenuation of the ultrasonic beam would decrease or prevent the sampling of the higher velocities in the upper part of the profile, resulting in an underestimation of the averaged profile velocity. The second hypothesis concerns the hydraulics; the presence of sediment would alter the distribution of flow velocity due to the attenuation of turbulence caused by the suspended load (Merten *et al.*, 2001). To test these two hypotheses, we plan to carry out experiments in a laboratory flume where conditions of velocity, concentration and size distribution of particles may be controlled.

CONCLUSION

The STARFLOW is an interesting instrument but difficult to exploit in the operational field under conditions such as that encountered at Vallcebre. If the objective is to estimate discharge from the flow velocity and water depth measurements, the operation becomes difficult especially when working on a section of river with a complex geometry. Vermeyen (2004) showed that it is necessary to calibrate the STARFLOW to be able to relate the measured velocity to the average channel velocity.

Nevertheless, the complex information provided by this instrument evidenced some gaps in the knowledge of the hydraulics of the gauging station and encouraged us to a deeper study. An additional hydrostatic pressure sensor installed upstream of our gauging station would help us to study the slope of the water line and interpret changes in the hydraulic behaviour, and experiments in a laboratory flume should allow us to assess the effect of the concentration of suspended sediment on the signal attenuation of the STARFLOW sensor. Finally, it is worth noting that the instrument must be protected upstream to avoid the impact of particles rolling along the bottom. It is also preferable to connect it to a data logger even though the instrument has its own data logger.

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REFERENCES

Balasch, J. C., Castelltort, X., Llorens, P. & Gallart, F. (1992) Hydrological and sediment dynamics network design in a Mediterranean mountainous area subject to gully erosion. In: *International Symposium on Erosion and Sediment Transport Monitoring Programmes in River Basins* (ed. by J. Bogen, D. E. Walling & T .J. Day), 433–442. IAHS Publ. 210, IAHS Press, Wallingford, UK.

Gallart, F., Llorens, P., Latron, J., Regüés, D. (2002) Hydrological processes and their seasonal controls in a small Mediterranean mountain catchment in the Pyrenees. *Hydrol. Earth. System Sci.* **6**(3), 527–537.

Gallart, F., Balasch, J. C., Regües, D., Soler, M. & Castelltort, X. (2005) Catchment dynamics in a Mediterranean mountain environment: the Vallcebre research basins (south eastern Pyrenees) II: temporal and spatial dynamics of erosion and stream sediment transport. In: *Catchment Dynamics and River Processes: Mediterranean and other Climate Regions* (ed. by C. Garcia & R. Batalla), 17–28. Elsevier Amsterdam, The Netherlands.

Julien, P.-Y. (1998) *Erosion and Sedimentation.* Cambridge University Press, Cambridge, UK.

Merten, G. H., Nearing, M. A. & Borges, A. L. O. (2001) Effect of sediment load on soil detachment and deposition in rills. *Soil Sci. Soc. Am. J.* **65**, 861–868.

Soler, M., Nord, G., Catari, G. & Gallart, F. (2010) Assessing suspended sediment concentration measurement error in relation to particle size using continuous sensors in a small mountain stream (Vallcebre catchments, Eastern Pyrenees). *Z. Geomorphol*. (accepted)

Steegen, A. & Govers, G. (2001) Correction factors for estimating suspended sediment export from loess catchments. *Earth Surf. Processes Landf.* **26**(4), 441–449.

Vermeyen, T. B. (2004) A Laboratory Evaluation of Unidata's Starflow Doppler Flowmeter and MGD Technologies Acoustic Doppler FlowMeter (ADFM). Water Resources Research Laboratory, Bureau of Reclamation, Denver, Colorado (available at http://www.usbr.gov/pmts/hydraulics_lab/tvermeyen/starflow/index.html).