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FIELD EXPERIMENT ON THE DYNAMICS OF FINE AND COARSE SEDIMENTS OVER A GRAVEL BAR IN AN ALPINE RIVER

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ABSTRACT

Alpine gravel-bed rivers are characterized by very poorly sorted sediments and significant grain sorting is generally observed on gravel bars. The grain size variability may significantly influence the inception of movement for each of the classes represented over a gravel bar. The purpose of this paper is to present some field measurements achieved on the Arc en Maurienne River, France. The main objective is to characterize the dynamics of fine and coarse sediments for conditions close to the incipient motion of gravels and for different degrees of clogging of the river bed. The field campaign was carried out on a gravel bar located 10 km downstream of St Jean de Maurienne during the dam flushing event on June 17th, 2014. Six patches including tagged pebbles (using PIT-tag) were built up with three different characteristics: clean patches formed with gravels and pebbles only, patches with a natural mixture where tagged pebbles were substituted to naturally arranged ones, and patches artificially clogged with fine sediments. These patches were located on the side of a secondary channel on the gravel bar. Surface grain size analyses of the gravel (using the Woolman method and photo analyses using BaseGrain) as well as topographic measurements were achieved the day before the event. During the flushing event, surface velocities over the gravel bar were measured thanks to video analysis (LSPIV). Water levels and mean slope in the secondary channel were measured thanks to pressure gauges positioned on the side of the secondary channel. An estimation of the bed shear stresses over the patches was thus possible all along the event. Intense water sampling was also carried out both upstream and downstream the secondary channel. During the post-event survey the day after, the PIT-tag search showed that the coarse particles did not move. On the other hand, a significant amount of fine sediments were deposited on the patches and infiltrated on the clean patches. Grain size analysis showed that deposited sediments were much coarser than sediments in suspension. An estimation of the fine sediment deposition rate and a discussion on the sediment dynamics is proposed from these measurements.

Keywords: *sediment mixture, gravel bar, infiltration, incipient motion*

1. INTRODUCTION

Alpine gravel-bed rivers are often characterized by very poorly sorted sediments and significant grain sorting is observed on gravel bars with relatively coarse sediments on the bar head and transverse channel and fine sediments on the bar tail (Lisle et a., 1991, 1993, Diplas, 1994, Lanzoni, 2000, Eekhout et al., 2013). The grain size variability significantly influences the inception of movement for each of the classes represented over a gravel bar (Konrad, 2002). In particular, fine sediment infiltration in the bed and fine sediment deposits are often observed over gravel bars in alpine rivers (Diplas 1994, Lisle & Hilton, 1999). Depending on the fine sediment content, fine sediments may limit or enhance gravel mobility (Diplas & Parker, 1992). The purpose of this paper is to present some field measurements performed on the Arc en Maurienne River, France. Main objectives are to characterize the dynamics of fine and coarse sediments for conditions close to the incipient motion of gravels and for different degrees of clogging of the river bed. The field campaign was carried out on a gravel bar located 10 km downstream of St Jean de Maurienne during the dam flushing event on June 17th, 2014. Patches with different degrees of clogging were built with tag gravels. Main hydraulic parameters measured during the event were water surface levels and surface velocities. Sediment characteristics of the patches were estimated before and after the event. A discussion of the impact of this event on the bed evolution, more especially on the infiltration dynamics is provided.

2. EXPERIMENTAL SITES AND DATA

2.1 Description of the experimental site

The fieldwork took place in the Arc River, located in the French Alps (Figure 1). The catchment area is 1957 km^2 (grey area in Fig. 1) with a nival hydrologic regime and a mean water discharge from 6-8 m^3/s in winter to 15-20 m^3/s in summer (Jodeau, 2007, Jaballah, 2013). The river bed has been largely modified and artificially straightened in many places in order to allow the 1 km wide valley to contain a road, a highway and a railway. Consequently, only 5% of the river reaches remain with their natural flow patterns and morphology. In addition the flow is regulated by many hydraulic constructions (several dams and pipes) for hydroelectricity production. The present regulated flow regime has significantly altered the natural river discharges and sediment transport. Although its bed is made of gravel, the Arc en Maurienne River has unusually high fine sediment transport, supplied by tributaries. The main ones are the Arvan and Glandon streams, which supply large amounts of predominantly black Lias schist.

The area of interest is a system of alternate bars located 18 km from the downstream reservoir at Sainte-Marie-de-Cuines (see Figure 1). This system is apparently forced due to the presence of a bend and a bridge pier at the downstream boundary (Jaballah et al., 2015). Lateral limits are set by 5 m high embankments made of boulders and scattered young trees leading to a river width of 50m in average. The mean slope of this reach is approximately 0.6 %. The fieldwork was more precisely carried out on a gravel bar located on the left side of the river 2.5 km upstream the confluence with the Glandon tributary (2 km upstream the bridge).

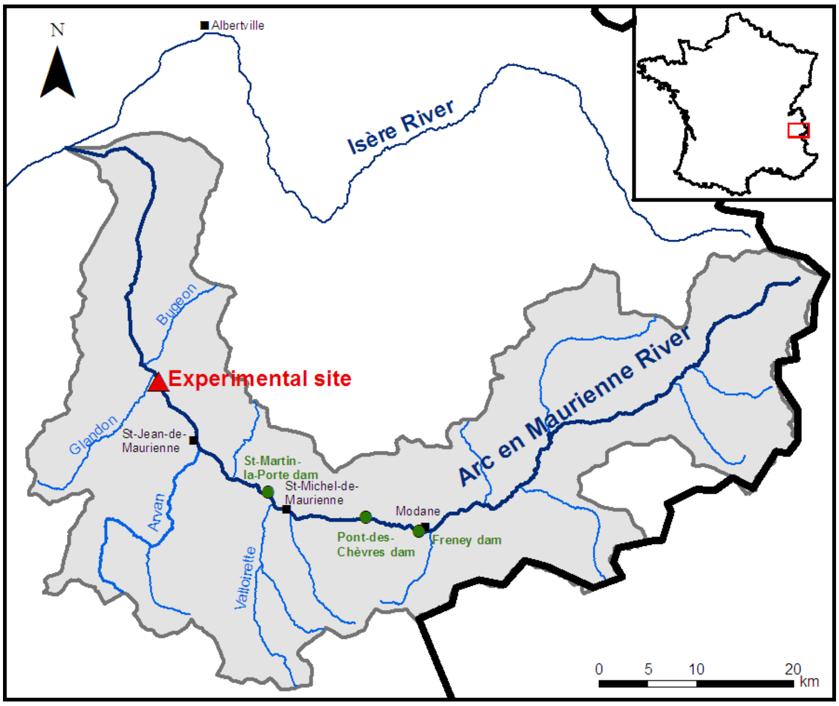

Figure 1. Map of the study site (green circles correspond to the three river dams).

2.2 Experimental set-up

A procedure is proposed here to study incipient motion of gravel particles for different conditions of clogging. Six patches were built on a gravel bar, which separates a secondary channel from the main channel (see Fig. 3). This secondary channel diverts a low percentage of the main channel flow discharge (about 10%). The gravel bar is totally covered for high flow conditions (over 110 m^3/s approximately). The six patches included 20 tracers (natural particle with a Pit-tag inserted) laid following a regular grid (Fig. 3, Camenen et al., 2010). Their size was one square meter approximately. The six patches were prepared in two rows parallel to the flow on the side of the secondary channel (cf. Fig; 3d). They were built in order to obtain three different characteristics:

- two clean patches made of cobbles of 4 to 10 cm in diameter (approx.), see Fig. 2a.
- two unmodified patches where natural cobbles are substituted by tagged cobbles, see Fig. 2b.
- two clogged patches for which a large amount of very fine sediments surrounds the tagged cobbles, see Fig. 2c.

Preparation of the different patches is detailed as follows. For unmodified patches, the bed structure was not modified and twenty cobbles initially present in the bed were manually substituted by tagged cobbles. The tagged cobbles were distributed in four rows of five cobbles each, with a distance of more than 20-25 cm between them. For the other type of patches, a surface of approximately one square meter was first excavated to a depth of approximately 10 cm. In case of clean patches, the resulting hole was then filled with cobbles and pebbles between 5 and 10cm in diameter including twenty tagged cobbles distributed similarly as for the unmodified patches. In case of clogged patches, it was filled with silt and clay sized material found in nearby (fine deposits on the gravel bar); and eventually, twenty tagged cobbles were introduced within this layer forming four rows of five cobbles each. The position and code of each tagged particles was identified within each patch. Coordinates (in the Lambert 93 system) of the four corners of each patch were measured using DGPS tool. A topographic survey of the gravel and secondary channel was also achieved before the flushing event.

An estimation of the grain size distribution for each of these patches was made using photo analysis thanks to the software Basegrain (Detert & Weitbrecht, 2012) to be compared with the Wolman (1954) pebble count procedure achieved on several places of the gravel bars. The median grain size varies from 1 to 3 cm around the patches with a standard deviation of approximately 3.5; detailed results are not presented in this paper.

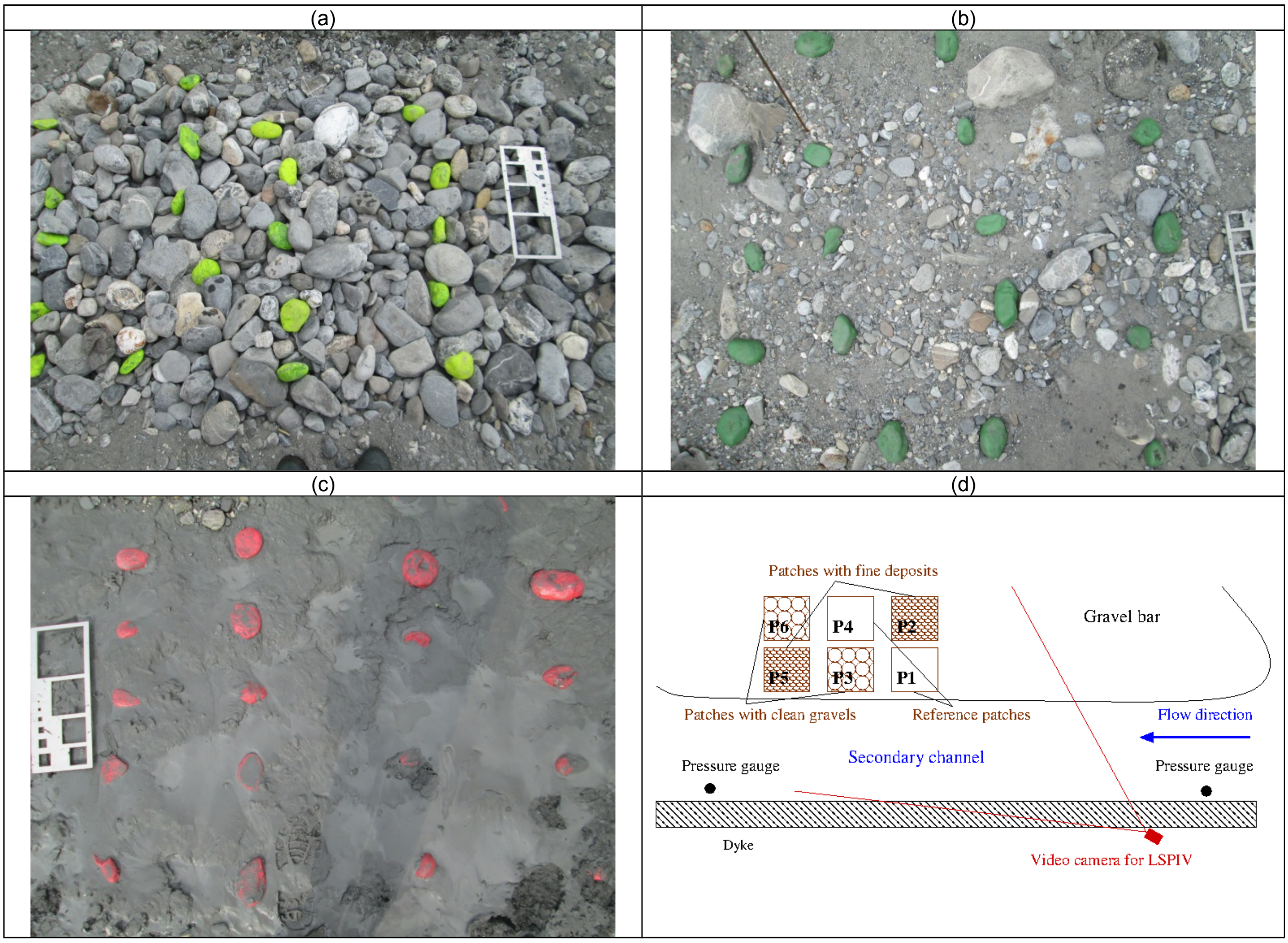

Figure 2. Photos of the different patches built: (a) cleaned patch P6 (b) natural patch P1 (c) clogged patch P5, and (d) schematic view of the experimental set-up.

During the flushing event, several measurements were achieved to obtain a better idea of the hydro-sedimentary conditions over the patches. A system for video analysis was implemented using a camera fixed at the top of a telescopic mast on the side embankment (Fig. 3). The Large Scale Particle Image Velocimetry (LSPIV) method was used to measure the surface flow velocities during the event. Ground Reference Points (GRPs) were positioned in the view field using square targets (red and white) on the gravel bar and on the bank. They allow a geometrical correction of the pictures (Jodeau et al., 2008). The software Fudda-LSPIV (Le Coz et al., 2014) was eventually used to process the movies in order to get the velocity field and estimate the discharge within the secondary channel. 10 movies of 30 s were eventually taken during the event, which corresponds to a movie every 40 minutes in average.

Two pressure gauges were installed upstream and downstream the secondary channel in order to obtain an estimation of the water level and slope within the secondary channel. Atmospheric pressure effects were taken into account using a third pressure gauge outside water.

Since fine sediment concentrations may be very high during these events (up to 30 g/l, Antoine et al., 2011), a possible deposition of fine particles was expected along the secondary channel during the event. Intense water sampling (every half an hour) was performed at both upstream and downstream ends of the secondary channel. Sediment concentration was measured for each sample using the filtration method and grain size analysis was made by laser diffractometry.

After the event, we intended to make a search of the tagged particles using a specific antenna to detect each particle with their own code together with a DGPS to note the location of each particle detected (Camenen et al, 2010). However, as discussed later, the flushing event was interrupted unexpectedly and the discharge did not reach 130 m^3/s as planned. As a consequence, three of the patches remained outside water during the event and velocities were too low over the three other patches to transport coarse particles. None of the tagged particles moved but a significant infiltration / deposition of fine particles was eventually observed.

Figure 3. Photo of the set-up for video analysis showing GRPs (photo inserted: mast on which the camera is fixed).

3. EXPERIMENTAL RESULTS

3.1 Discharge and sediment concentrations

The discharge was measured at the hydrometric station of Pontamafrey located 9 km upstream. It was estimated that the time for the wave to travel from Pontamafrey to Sainte-Marie-de-Cuine is Δt = 45mn. Flushing operations are conducted yearly in June with the exception of years for which a large flood occurred previously. Since the same procedure is followed, similar discharge time series are generally observed with a first plateau at 80-100 m^3/s lasting approximately 4 hours and a second plateau at 120-130 m^3/s lasting approximately 4 hours (see red line in Fig. 4a corresponding to the 2011 flushing event). It appears clearly that the 2014 flushing event was shorten with nearly no existence of the second plateau, which obviously affected our experiment. This was explained later due to an incident in one of the dam reservoirs.

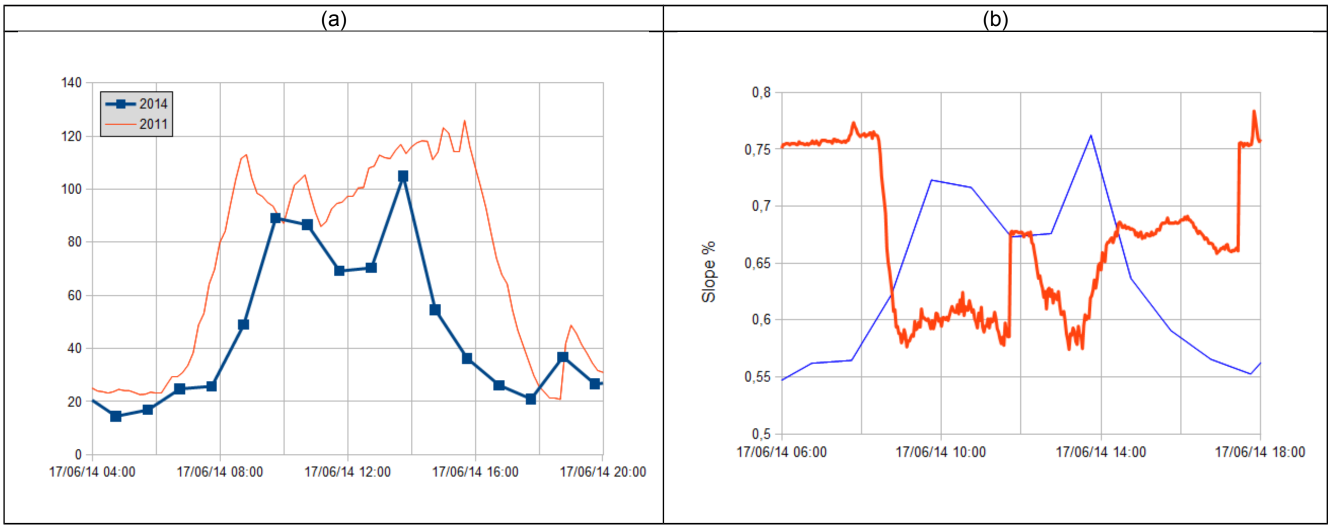

Figure 4. Discharge time series (TU+2) measured at the hydrometric station of Pontamafrey with Δt = 45mn (a) and water slope on the secondary channel (red line, the blue line corresponds to the discharge) (b).

In Fig. 4b, the slope in the secondary channel during the event is presented, as estimated from the two pressure gauges installed. Interestingly, it appeared that the slope first decreased with the increase of discharge, maybe due to the downstream boundary influenced by the main channel level. It varied between 0.6 and 0.7% during the event. From the water level and LSPIV measurements, we also estimated the duration for which patches P1, P3 and P5 were under water: $T = 60$ mn.

Results for concentration measurements are presented in Fig. 5. Concentration levels clearly follow the discharge time-series. A plateau at 4 g/l is observed during the first plateau for Q followed by a pick at 12 g/l at the pick of discharge for which supercritical flow occurs in dam reservoirs. This may explain the much larger concentrations observed. However, these concentrations remain relatively low compared to previous flushing events (Antoine et al., 2011). Grain size analyses (Fig. 5b) show that the composition of the suspension did not evolve significantly during the event (d_{50} = 17 µm). One can observe a small pick at the pick discharge with (d_{50} = 20 µm).

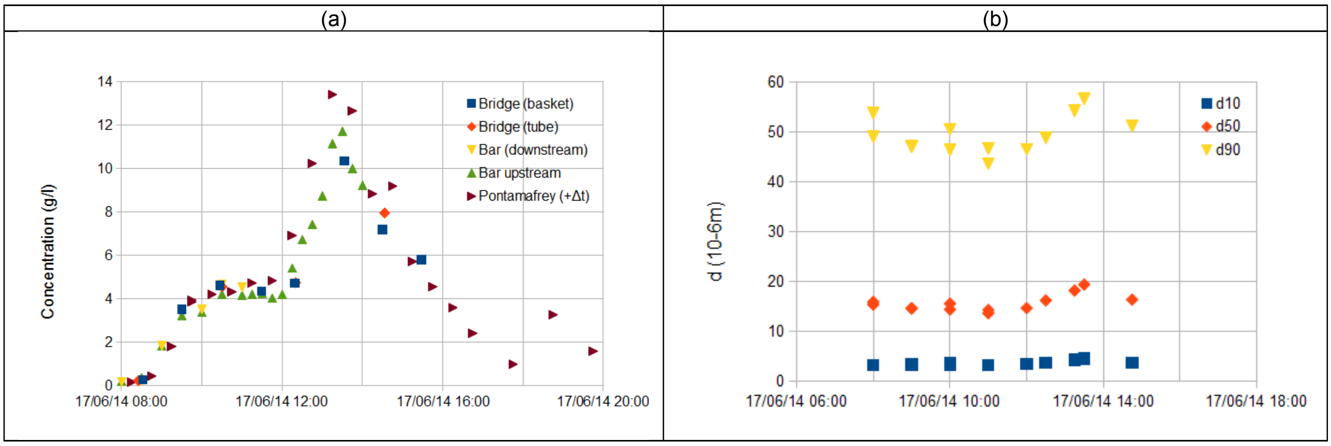

Figure 5. Concentration time series measured upstream and downstream the gravel bar, 1km downstream from a bridge and 10 km upstream at the hydrometric station of Pontamafrey with Δt = 45mn (a) and grain size analysis of samples next to the gravel bar (b).

3.2 Surface velocity and bed shear stresses

LS-PIV is an image-based method, which consists in calculating the most likely displacements of patterns between two successive images using statistical identification (Fujita et al., 1998, Jodeau et al., 2008). Fig. 6 presents some typical results from the LSPIV post-processing using Fudaa-LSPIV (Le Coz et al., 2014). If a cross-section of the river bed is available (see yellow line in Fig. 6a), it is also possible to estimate the discharge assuming a ratio between the depth averaged velocity and the surface velocity of 0.85 (rough bed). Similarly, assuming a roughness length $k_s = 2d_{90} \approx 8$ cm, it is also possible to estimate the local bed shear stress. Focusing on the side of the secondary channel next to the patches (Fig. 6b), it is interesting to see the deflection of the surface velocities toward to side of the channel. It actually corresponds to small waves propagating toward the gravel bar with a celerity of 10 cm/s approximately. Because of mass conservation, a small undertow current should be present with a main direction toward the center of the channel.

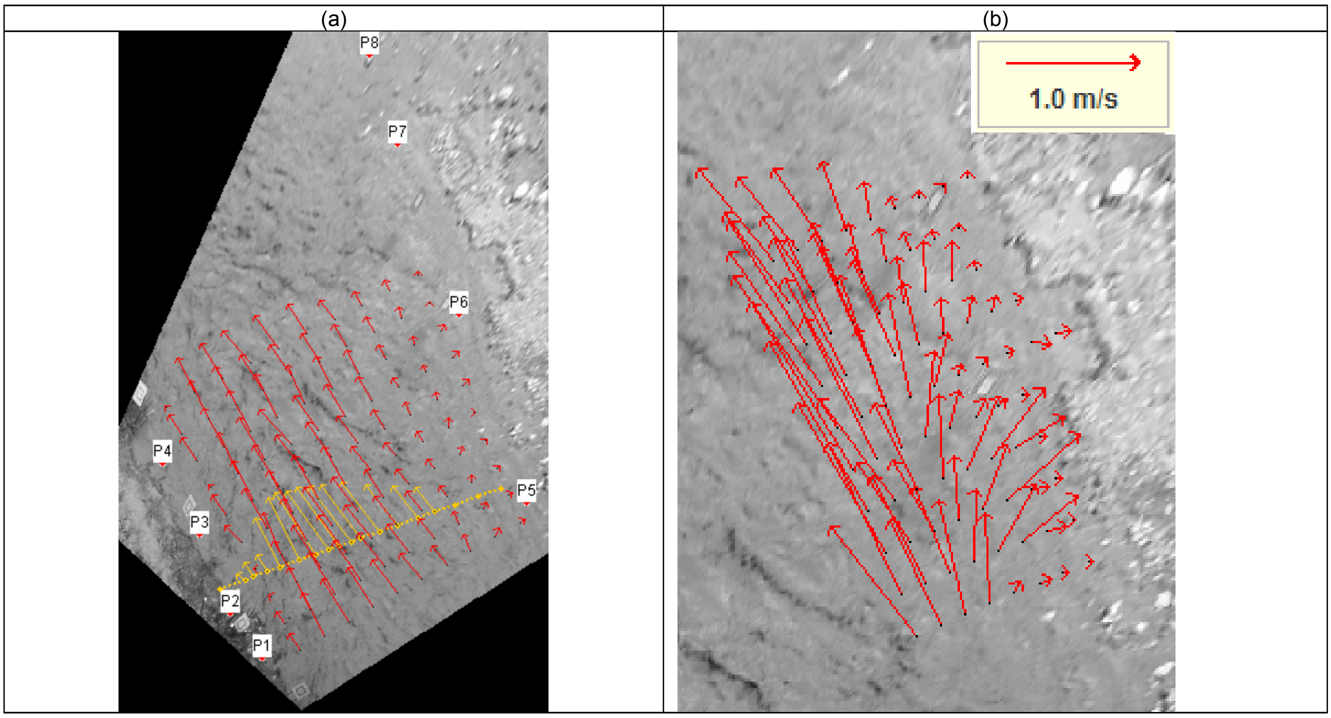

Figure 6. Estimation of the surface velocity using LSPIV in the secondary channel at 13:30 over the whole section (a) and making a zoom close to the patches (b).

Best shear stress estimates using both LSPIV and water level measurements are presented in Fig. 7. As discussed before, LSPIV allows an estimation of local bed shear stress as soon as bed topography measurements are available. Fig. 7a presents the bed shear stress distribution throughout a secondary channel section. Values over 100 Pa were observed in the middle of the secondary channel that is sufficient to mobilize the coarsest particles forming the bed. Section-averaged bed shear stress are presented in Fig. 7b, either using the "law of the wall" method with data from Fig. 7a or using the reach averaged method:

$$\tau = \rho C_f V^2 = \rho g R_h I \qquad [1]$$

with ρ the water density, $C_f = f(R_h, k_s)$ the friction coefficient, V the section-averaged velocity, g the acceleration of gravity, R_h the hydraulic radius, and I the water slope. The "law of the wall" method was applied locally using the local depth-averaged velocity and assuming $R_h = h$ with h the local water depth. Good agreement is observed between the two methods used to estimate the section averaged bed shear stress in the secondary channel. Results from the LSPIV measurements are however very sensitive to the water level estimation, especially when water depths are shallow. This explains the very low value obtained at t = 07:23. In the zone over the patches, it was difficult to estimate the local bed shear stress. By extrapolation to what we could measure, we estimate it close to zero. However, some possible erosion of fine sediments could have been possible because of the propagation of the small waves described above.

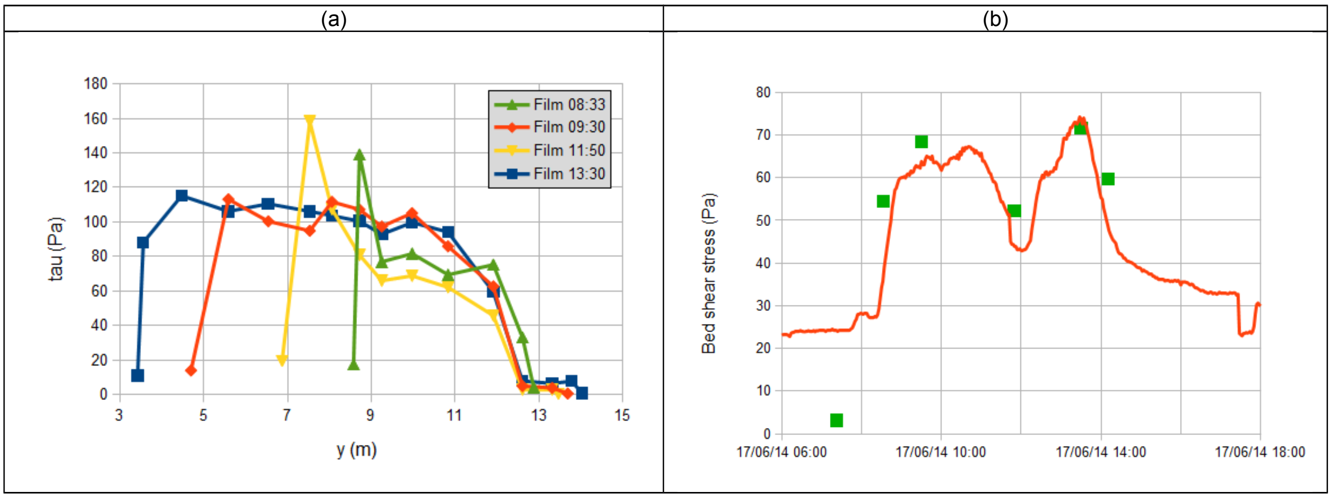

Figure 7. Local bed shear stress distribution throughout the secondary channel next to the patches from LSPIV measurements (a) and mean bed shear stress in the secondary channel from slope measurement and LSPIV measurement (green square) (a).

3.3 Fine sediment infiltrated

Although no movement of the tagged particle could be observed, a significant amount of fine sediments infiltrated the clean patch P3. An estimation of the amount of fine sediments infiltrated was made using the following method (Fig. 8): a surface of approximately 0.2 m² (0.45 × 0.45 m) was selected within patch P3. All fine sediments infiltrated in cobble layer (approximately 10 cm thick, see Fig. 8c) were collected in a basket. Coarse particles were taken out and cleaned in the same basket. Eventually, a sample of 5.23 kg was collected. Since some sandy particles may have been collected at the bottom of the layer, this sample was sieved at 0.5 mm. It remained 4.56 kg.

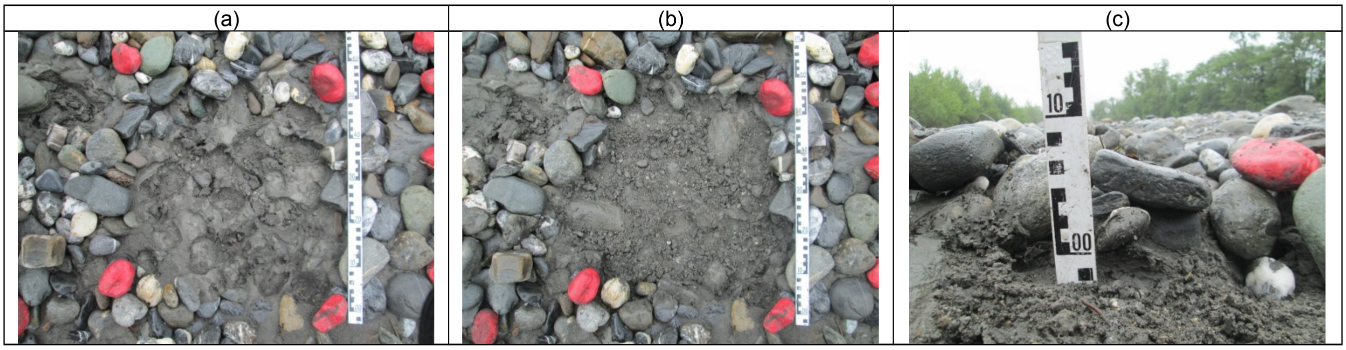

Figure 8. Estimation of the fine sediment infiltration in patch P3; photos of the sampling surface after taking off pebbles (a) and cleaning all deposits (b), side picture of the sampling surface (c).

When fine sediments are much smaller than coarse sediments, fines can percolate without getting trapped as they pass through the pore throats, therefore being deposited only on the top of coarse grains or on an eventual impermeable layer located under the gravel bed. In this situation, the bed is filled from the bottom upwards and tends to a relatively uniform distribution of fines over the bed depth. This infiltration mechanism that corresponds typically to our case is commonly known as unimpeded static percolation (Gibson et al., 2009, Evans & Wilcox 2013). Assuming an initial porosity of 0.4 for the patch P3, and a porosity of 0.4 for the fine sediments infiltrated, the maximum amount of fine sediments that could infiltrate the 0.2 m² is $M = 2650 \times 0.4^2 \times 0.1 \times 0.2 = 8.5$ kg. This means that approximately 50% of the pores were clogged with fine sediments in 60 minutes.

In Fig. 9, the grain size distributions of the suspended sediments and of the sediments infiltrated in the patch 3 are plotted. For the sediment in suspension, 6 classes predominate:

- one class of clay with *d* ≈ 5 µm,
- one class of fine silts with *d* ≈ 12 µm,
- four classes of coarse silts with *d* ≈ 25, 35, 47, and 68 µm, respectively

The very same classes are observed for the sediments infiltrated in patch 3 but with different proportions. A class of poorly sorted fine sands with d ≈ 120 µm is also present in the deposits. It clearly shows the grain sorting occurring over the bed for the infiltration process. Coarser particles with larger settling velocity do settle and infiltrate easier even when bed shear stresses are very low. The presence of the fine sand class indicates that this sediment fraction travels in a graded suspension with concentration much larger close to the bottom. Surface water sampling on the side of the river do not allow to detect this class of sediments.

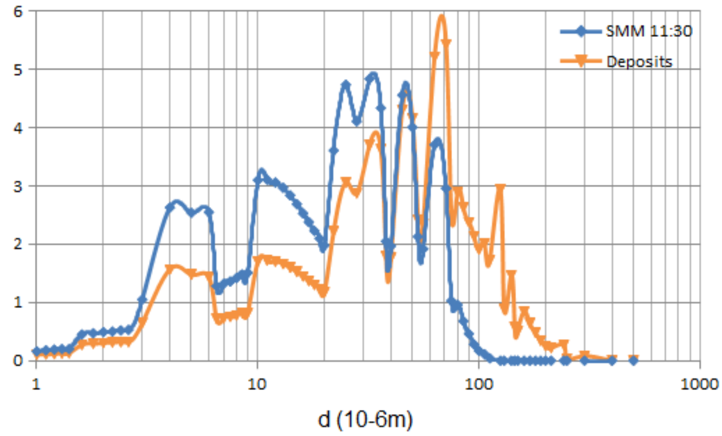

Figure 9. Grain size distribution comparison between the sediments in suspension and the sediments infiltrated in the patch 3.

4. CONCLUSIONS

A field survey to study the dynamics of fine and coarse sediments in an alpine river during a flushing event is presented. It included flow velocity measurements and surface water sampling during the event and characteristics of the bed and reference patches before and after the event.

The proposed methodology appeared successful to better understand the local dynamics of a mixture of sediment. Estimation of bed shear stress in the secondary channel using both pressure gauges and LSPIV measurements were in good agreement. An intense sampling frequency for the fine sediment in suspension is necessary for such event since the concentration values can change rapidly.

However, the flushing event was interrupted unexpectedly and bed shear stress remained too low to transport coarse particles. None of the tagged particles moved but a significant infiltration / deposition of fine particles was eventually observed. The infiltration rate was estimated at 50% in the clean patch after a period under water of 60 minutes only. Grain size analyses of both fine sediment in suspension and infiltrated sediment gave an interesting view of the fine sediment dynamics over the gravel bar.

A similar experiment is planned for the 2015 flushing event with the objective of better estimating the inception of motion of coarse particles for different fine sediment contents.

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