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Experimental investigation of sediment deposition on floodplains

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ABSTRACT: This paper presents results of a new experimental campaign that investigates sediment exchanges between main-channel and floodplain during overbank flows. More precisely, the lateral sediment transfer and the subsequent deposition patterns are studied. Two kinds of experiments were led. The first series were performed in a compound channel flume with mobile main channel bed and recirculating sediment-laden water from this subsection. The second series featured compound channel flow over a rigid bed initially sediment-free and sediment injection upstream of the main channel. Weighting of deposited sediment and digital imaging were used to evaluate the deposition formation. Results in terms of sediment mass flow rate towards the floodplains are presented. Lateral and longitudinal distribution are also analysed for different water depth and floodplain roughness. Strong dependence upon those two parameters is observed. Results are also analysed according to the floodplain's stream power. The suspension efficiency, as well as the velocity gradient in the interaction zone seem to provide interpretation bindings between the different experiments.

Keywords: Compound channels, Fine sediment transport, Floodplain deposits, Bagnold's stream power

1 INTRODUCTION

Our present media recurrently reminds us of the threat imposed by rivers on the neighbourhood, the houses and infrastructures when, following a major flood, those rivers overflow their main channel and invade the floodplains. The flood discharge is submitted to a compound cross section and the consequent damages are often aggravated by muddy deposits, especially in urban areas. In this context of growing risk due to more and more frequent floods and need of floodplain restoration and management, studies centred on compound channel flows and sedimentation processes have undergone increasing interest. Understanding river morphological processes and assessing the impact of the long-term of human interference with river systems definitely requires improved knowledge over transport and deposition of fine sediments in river systems including their floodplains.

Overbank flows are inherently complex: a region of high shear is formed at the interface between the fast main channel flow and the slower floodplain flow over usually rougher surface, producing large lateral eddies which transfer longitudinal momentum (Sellin, 1964; Shiono & Knight, 1991). Secondary currents arising from non-isotropic turbulence (e.g. Naot et al., 1993) in the shear layer are other three-dimensional features, which are usually recognised as significant in the influence of solute transport processes because they not only transport solute but also affect the momentum and solute exchange coefficients (Shiono et al., 1997).

Due to this interaction, exchanges of suspended sediments and solute will be associated to water and momentum exchanges, leading to floodplain sedimentation. The larger sediment transport capacity in the main channel implies sediment concentration gradients between the two subsections resulting in a net transfer from the main channel to the floodplain. Once transferred to the plain region, sediment tends to settle out because of the reduced transport capacity of the flow in this region. As mentioned above, large floodplain sedimentation can become more problematic than flooding itself. For example, Woo & Kim (1997) report sediment deposits up to 1.5 m on floodplains used as recreational areas after a 3-day flood of river Han in Korea in 1990. Sediment deposition on floodplains also determines the long term morphological evolution of the river basin. As reported by Narinesingh et al. (1999) for a project in The Netherlands, this can significantly affect the long term results of re-naturalisation and flood control works.

This paper presents the results from an experimental study of fine sediment transport and deposition in a prismatic symmetrical compound channel flume (Université catholique de Louvain, Belgium). Following Garcia (2008) sediments were expected to be mainly transported by suspension, given its median diameter (d_{50} = 91 μm). Lateral sediment transfer and deposition was measured in a re-circulating flume with mobile main channel bed (showing bed forms) featuring various floodplain roughness and configurations. Other tests were performed with upstream sediment feed in the main channel over an initially rigid bed. The percentage of mass transferred and deposited towards the floodplain was related to the floodplain's stream power (Bagnold, 1966). Results are also confronted to previous works on the subject, presented in the following section.

2 PREVIOUS WORKS

Increasing economic impact of floods, together with the behaviour of floodplain acting as pollutants sink (Walling, 1999) justifies the interest for sediment transport and deposition during overbank flows. Different approaches are adopted in literature: field observations, laboratory experiments and numerical simulations.

Marriott (1996) performed field observations and examined sediment samples collected after a significant flood on River Severn, UK. He appreciated the quantities deposed, sediment composition, textural patterns, and variations of grain size with distance from the main channel bank. Deposits appeared near the banks of the main channel with a reduction in grain size with increasing distance from this bank. Walling (1999) also observed a decreasing sedimentation rate with the water depth and increasing distance from the main channel.

Field observations are typically site-specific. Laboratory flume experiments enable methodical study of deposition patterns as function of the flood intensity, channel planform, channel sediment load and sediment characteristics. Some exploratory studies were performed in the Flood Channel Facility (FCF) at HR Wallingford, UK (Benson et al., 1997; Knight et al., 1999; Bathurst et al., 2002). Highest floodplain deposits were observed near the main channel banks, with little sediment transferred further onto the floodplain.

Very few authors managed to construct sediment transport and deposit simulation models. James (1985) and Pizzuto (1987) both developed a numerical transport model to predict the transverse distribution of deposits over the floodplain and the grain-size distribution, assuming steady uniform flow. Accordingly, they deal with floodplain deposition due to lateral diffusion only. Convection due to secondary currents is not expressed explicitly, but is encompassed in the transverse diffusion coefficient given by Rajaratnam and Ahmadi (1979) and Lau and Krishnappan (1977). These models are therefore essentially applicable to simplified conditions such as straight channels with continuous prismatic floodplains on both sides. However, these models, validated by experiments, provide results that concurs previous laboratory and field observations: (1) an exponential decrease in the deposition rate with distance to the main channel; (2) a decrease in the sediment particle size deposited with the distance from the main channel; and (3) a depositional trend, which depends on the micro-topography of the floodplain.

Since sediment transport and deposition rely on mixing processes in compound channels, predicting the way sediments will settle on the floodplains requires analysis of the diffusion/dispersion and convection phenomena occurring during overbank flow. Fraselle et al. (2008) investigated diffusion processes in the UCL compound channel flume involving solute concentration measurements instead of sediments. The presence of strong turbulent features at the interface between the subsections enhanced mixing in this region and lateral transfer towards the floodplains by the same occasion, as explained by Guymer et al. (1998). Respective role of turbulence and secondary currents on transport rate is rather complex. Shiono and Feng (2003) showed how the transport rate varies with the different mechanisms along the channel.

If the action of turbulence on fine sediments may be assumed to be analogous to a diffusion-dispersion process (Graf, 1971), it does not account for all influences and specific empirical theories will often be used to describe sediment transport (see e.g. Garcia, 2008, for a literature review), especially when bed load transport gains increasing importance. Among those functions capable of predicting the (total) sediment transport rate in river reaches, we find the Engelund-Hansen sediment transport equation (Engelund, 1966, Engelund and Hansen, 1967) and the Ackers-White formula (Ackers and White, 1973) which will both be used in this study, considering that their underlying hypothesis fit the present experimental conditions. Besides those transport laws extracted from experimental data, authors such as Bagnold (1966) adopted a more theoretical approach. Based on Bagnold's stream-power concepts, Verbanck (1995) suggested the following power balance equation (W/m^2 of riverbed area):

$$(\rho_s - \rho_l) g\, w_s\, C_{SL}\, R = \rho_l\, \eta_{SL}\, C_* u_* (u_*^2 - u_{*c}^2) \qquad (1)$$

where ρ_s is the sediment density, ρ_l the fluid density, g the gravity acceleration, w_s the effective settling velocity, C_{SL} the suspended particle matter concentration, R is the hydraulic radius, C_* the non-dimensional Chezy coefficient ($C/g^{1/2}$), η_{SL} the suspension efficiency, u_* the shear velocity, and u_{*c} the shear velocity at the onset of motion for sediments forming the channel bed. Without η_{SL}, the right part of Eq. (1) is the stream power, calculated as the product of one-dimensional velocity and shear stress in excess of that required to put the deposited particles into motion. The power balance simply expresses that the gravitational power of the transported material uses a certain fraction (η_{SL}) of the available stream power to remain suspended in the water column. Eq. (1) clearly identifies the main parameters at stake when studying sediment transfer and deposition on the floodplains. Higher transfer of sediments from the main channel towards the floodplain is characterized by an increased floodplain C_{SL} and ease of deposition is conditioned by η_{SL}, C_* and u_*.

3 EXPERIMENTAL APPROACH

3.1 *Physical model*

Experiments were performed in a 10 m long compound channel flume with a bed slope S_0 = 1.9/1000 (Figure 1). The flume is equipped with upstream subsection discharge differentiation in order to obtain equilibrated flow distribution from the inlet section (Bousmar et al., 2005) and with an automatic positioning device, which allows systematic measurements all over each cross section.

This flume was used under 2 configurations, with respective cross-sections pictured on Figure 2. Either the experiments were performed over a mobile main channel bed (h_s = 25 mm), with no additional sediment feeding and recirculation of the main channel sediment-laden water (named "mobile bed" experiments). Or sediment was injected at the upstream end of the main channel section and transport was observed in fresh water over a rigid bed (named "rigid bed" experiments). For all experiments, the sediment median diameter was d_{50} = 91 µm.

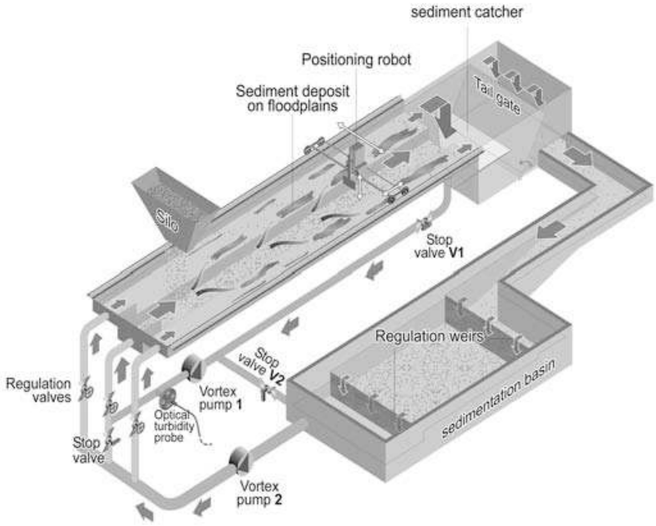

Figure 1. Experimental setup for (a) mobile bed with recirculation experiments: sediment feeding is not active and sediment bed is installed in the main channel. The pump 1 discharges the sediment-laden main channel flow and the pump 2 injects fresh water on the floodplains; (b) upstream sediment feed over rigid bed experiments: the valve 1 is closed and pump 1 also injects fresh water in the main channel (V2 opened).

3.2 *Experimental conditions*

Different water discharges were used for both configurations, in order to modify the subsections transport capacity and water depth. The floodplain's roughness was also varied throughout the tests. Sediment deposits were observed over "smooth" floodplains, were the same material as the rest of the section was used, namely coated plywood. Further, the influence of "rough" floodplains with "trapping" abilities was tested by overlaying the floodplains with steel sheeting (0.7 mm thickness) with squared 8 mm side holes. Finally, in order to reduce drastically the floodplain water velocity through increased drag, "vegetated" floodplains were tested by placing steel nets every 50 cm in the longitudinal direction (Figure 3).

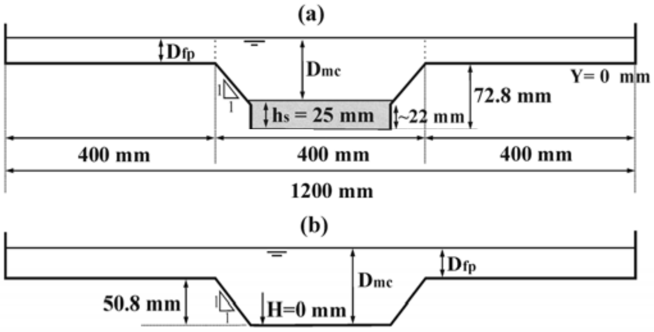

Figure 2. Flume cross sections for (a) mobile bed with recirculation experiments and (b) upstream sediment feed over rigid bed experiments.

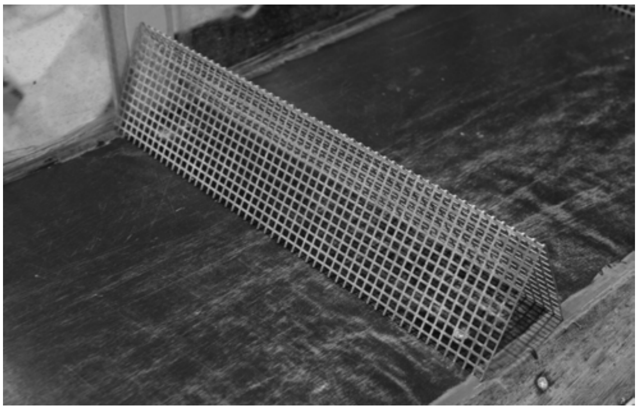

Figure 3. Steel nets on the floodplains (1/50 cm) for “vegetated” configuration.

Table 1 gives a summary of the experimental conditions for all different tests, with the whole section discharge Q (l/s), the main channel water depth D_{mc} (mm), the main channel discharge Q_{mc} (l/s), the main channel measured sediment concentration C (g/l) or for rigid bed experiments, the injected sediment load Q_s (g/s).

Table 1. Experimental conditions

		Q (l/s)	D_{mc} (mm)	Q_{mc} (l/s)	C (g/l)
Mobile Bed	Smooth FP * MBS	6.6	56.22	5.33	0.24
		7.6	61	5.73	-
		9.1	62	6.07	0.4
		10	64.6	5.82	0.46
		15	70.5	7.665	0.75
		20	77.2	10.06	1
	Rough FP MBR	7.4	62.5	5.62	0.37
		9.09	65.3	6.43	0.44
		11	70.4	6.82	0.45
		14	74.6	8.54	0.38
		20	82.2	10.6	0.95
	Vegetated FP MBV	7.07	63.5	6.15	0.43
		9	69.7	7.35	0.5
		11	77.3	8.81	0.8
		14	93.2	10.7	0.68
		Q (l/s)	D_{mc} (mm)	Q_{mc} (l/s)	Q_s (g/s)
Rigid Bed	Smooth FP RBS	15	62	12.6	*10.02*
		20	69	14.98	*13.78*
	Rough FP RBR	15	66	12.8	*10.02*
		20	72.7	15.5	*13.78*

* FP stands for floodplains

3.3 *Measuring techniques*

For every flow regime, a detailed set of velocity measurements (Pitot tube) was recorded in order to check uniform flow conditions. For mobile bed experiments, the morphological equilibrium was verified using ultrasonic probes for free surface detection and bed profiler PV07 (Delft Hydraulics) for sediment bed tracking.

Dynamic evolution of sediment deposition was monitored by two different means. Sediment traps (Figure 4) were installed on the floodplains every 2.5 meters (x = 2.5 m, 5 m and 7.5 m) to capture mobile sediment deposits (slowly drifting downstream) and to give thus a measure of the sediment transferred to the floodplains, deposited and not resuspended. During and after every experiment, the global sedimentation pattern was pictured using digital imaging techniques. An example of such instantaneous global view is depicted in Figure 6 (a).

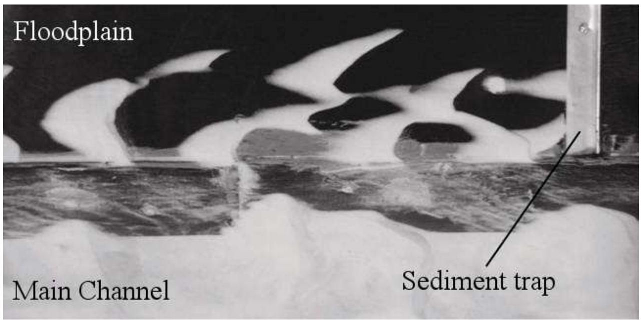

Figure 4. Sediment captured in traps displayed every 2.5 m on the floodplains.

The main channel sediment transport capacity was deduced from numerous samplings made all along the flume. The measured concentrations were confronted to sediment transport prediction laws and we see in Figure 5. that the Engelund-Hansen and Ackers-White calculated sediment load give a relatively correct approximation. When reaching higher flow regimes, concentration data become more scattered, somehow due to bed form instability observed when reaching morphological transition regime.

Post-experimental manipulations included weighting of sediments in sand traps but also sediment mass deposited over the floodplains, with distinction of various longitudinal and lateral zones. Moreover, very precise topography measurements were realized all over the flume by using a laser distance sensor (Keyence LK-G).

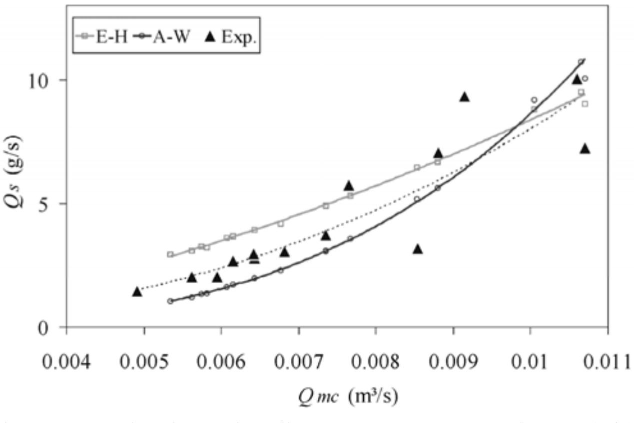

Figure 5. Main channel sediment transport capacity Q_s (g/s) function of the main channel flow regime Q_{mc} (m³/s) through (a) Engelund-Hansen (b) and Ackers-White relationships using experimental hydraulic parameters and (c) experimental concentration measurements.

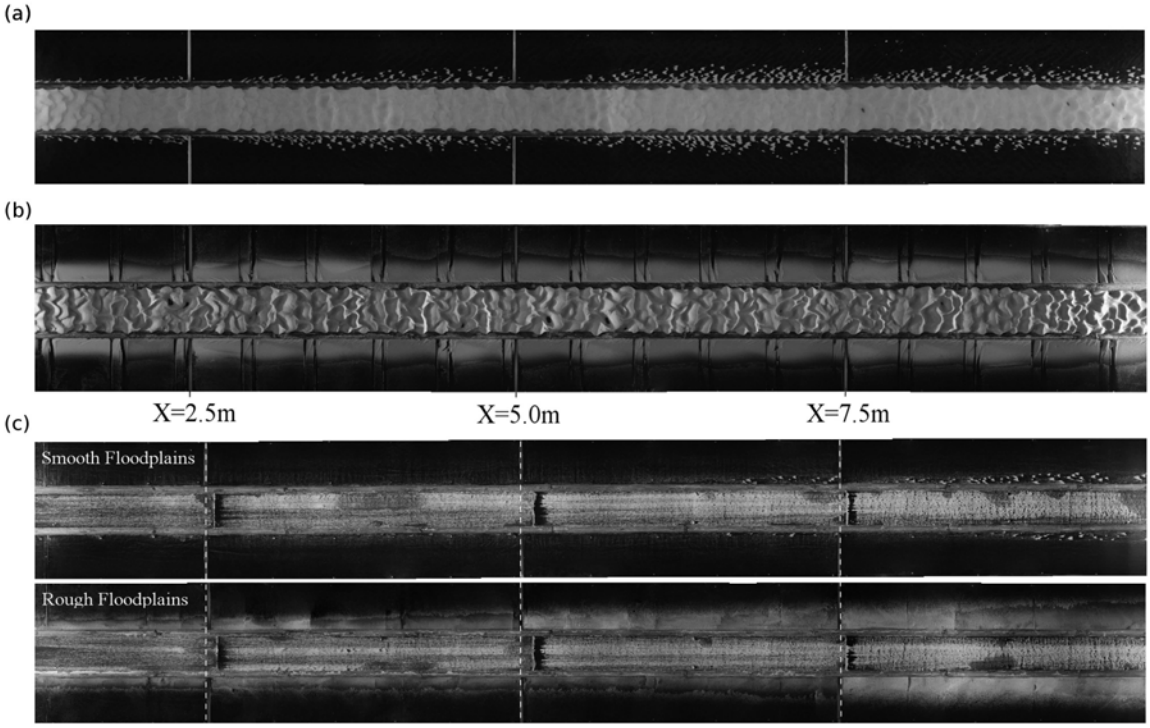

Figure 6. (a) Instantaneous deposition patterns for MBS 15 l/s experiment. (b) Final deposition patterns for MBV 11 l/s experiment. (c) Final deposition patterns for smooth and rough floodplains at 20 l/s (with rigid bed)

4 RESULTS AND DISCUSSION

Careful attention towards the influence of the hydraulic parameters on the sediment deposition rate over the floodplain is requested. The floodplain stream power, the right hand side of Eq. (1) without η_{SL}, seems to characterize correctly the available driving force available for suspended transport (Verbanck et al., 2007). The floodplain stream power was calculated for every experiment using the measured water depth and velocities (Figure 7). Those curves already show the effect of the floodplain configuration, with for a given water depth more stream power available for smooth than for roughened or vegetated floodplains.

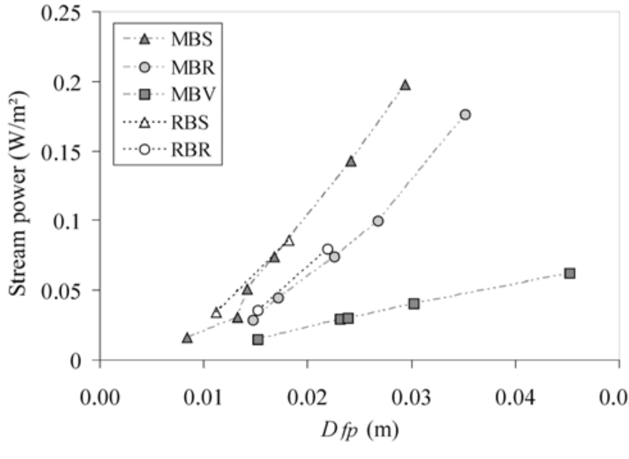

Figure 7. Floodplain stream power (W/m²) function of subsection depth D_{fp} (m) for mobile and rigid bed experiments

4.1 *Mobile bed with smooth floodplains*

Lateral transfer and deposition of sediments from the mobile main channel towards the smooth floodplains (*MBS* experiments) was analyzed under regime conditions. Once the regime (mobile) deposits were formed over the floodplains with the associated main channel bed forms, the sediment traps were wiped out and the collected sediments from this time gives by mass conservation the lateral transfer rate of sediments towards the floodplains and per unit length ($q_{s,l}$) for the 2.5 m long zone preceding the sediment trap:

$$q_{s,l} = \frac{Q_{s,trap}}{L} \quad [g/h \cdot m] \tag{2}$$

with $Q_{s,trap}$ the collected sediment per unit time and L the length of the zone preceding the trap. This equation comes with the hypothesis that no sediment jumps towards the next 2.5 m longitudinal zone, which is justified by the triangular-shaped deposition pattern in each zone (Figure 6 (a)). $q_{s,l}$ increases with the flume discharge and with the longitudinal position of the zone, which seems to indicate an enhanced transfer downstream of the flume along with convection/diffusion of sediments on the floodplains.

An interesting trend of the regime deposition is shown in Figure 8, as if higher transport capacity of the main channel first favours the formation of deposit (more sediment transferred and C_{SL} from Eq. (1) increases) but is confronted then to a sudden decrease of those deposits when a certain threshold of floodplain stream power is reached. This means that from this point, increase in resuspension of deposited sediments on the floodplain is more efficient than increase in lateral sediment transfer towards the floodplain.

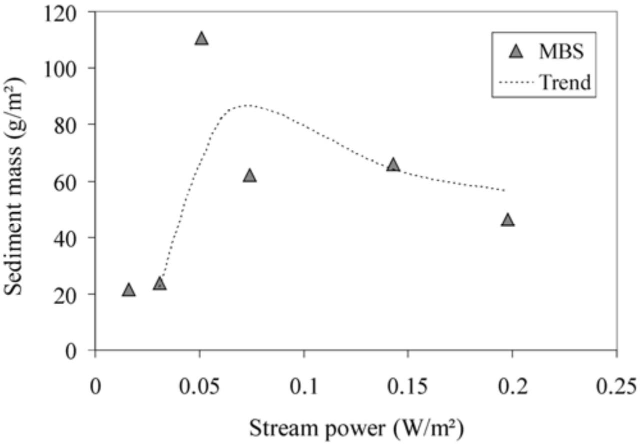

Figure 8. Equilibrium sediment deposits on floodplains (total mass (g/m²)) as a function of the floodplain stream power (W/m²) for mobile bed with smooth floodplains experiments.

4.2 *Effect of floodplain roughness*

We already observed in Figure 7 and Table 1 the effect on hydraulic parameters of changes in floodplain configuration. Floodplain roughening increases local water depth and decreases velocity but also changes sediment deposition patterns. Steel sheeting on the floodplains (MBR and RBR) enhances sediment fixation/absorption capacity of the floodplain and limits sediment resuspension. Convection/diffusion processes on the floodplain and local velocities condition the longitudinal distribution of sediment deposits (Figure 9). Meanwhile, vegetated floodplains create great additional drag in the flow and very low velocities force the transferred sediments to almost immediate deposition, as suggested by Figure 9, where relative deposition shows more uniform trend. This tendency is also illustrated on Figure 6 (b), where the final deposition pattern for MBV 11 l/s is presented.

Lateral deposition rate profiles suggest this ability of rough/absorbing floodplains to limit resuspension in interaction zone near the interface where higher velocities and bed shear take place (Figure 10). This phenomenon was also underlined by James (1985), where he used “smooth” surface defined numerically by a zero deposition probability $p = 0$ and absorbing surface showing $p = 1$.

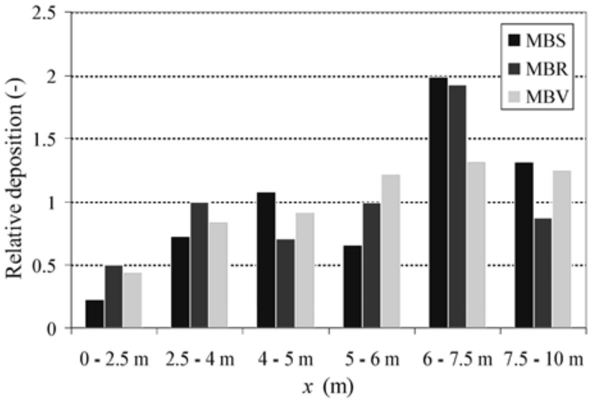

Figure 9. Floodplain relative deposition (-) (both sectional floodplain’s deposits per longitudinal unit length/mean deposits per unit length) along the flume for MBS 15 l/s, MBR 14 l/s and MBV 14 l/s.

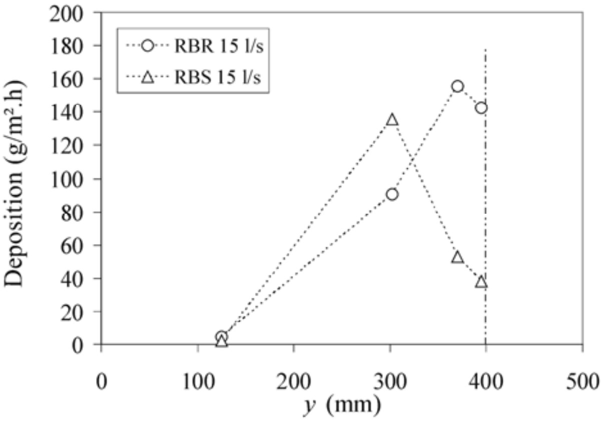

Figure 10. A comparison of deposition rate (g/m² h) over the left floodplain near the interface for experiments over rigid bed with smooth or rough floodplains (RBR 15 l/s and RBS 15 l/s)

4.3 *Lateral sediment transfer over rigid bed*

Injection conditions for rigid bed experiments are well-controlled, and a precise percentage of mass deposited against injected mass is presented in Table 2. By nature, RBR experiments compared to RBS experiments measure different deposition rates. Due to its absorbing characteristics, rough floodplain experiments will provide a percentage of sediments transferred towards the floodplains and deposited while smooth floodplains indicate a transfer/deposition rate of non-resuspended sediments.

Table 2. Percentage of sediment mass collected on the floodplains towards mass injected in the main channel (-)

	Q = 15 l/s	Q = 20 l/s
RBS	1.80 %	0.82 %
RBR	6.02 %	8.48 %

Figure 6 (c) shows the impact of resuspension on sediment deposits and triangular-shaped deposition show the intensity of convection/diffusion processes on the floodplains, which could be used for numerical models validation.

4.4 *Floodplain deposition function of stream power*

As for MBS experiments, sediments collected on the floodplains (per unit time) are plotted against the floodplain stream power in Figure 11 for MBR, MBV, RBS and RBR experiments. Obviously, vegetated floodplains offer perfect conditions for lateral sediment transfer and deposition. Small velocities favour sediment deposition and high velocity gradient at interface enhances lateral sediment mixing and transfer (Prinos, 1992). This phenomenon is even more evident while focusing on MBR and RBR where for the same hydraulic conditions and trapping capacity of the floodplain, more sediment is collected for the latter. Figure 12 presents the depth averaged velocity profiles in both cases and the high velocity gradient for the rigid bed case favours momentum transfer in the shear zone, together with sediment transfer, along with vertical axis eddies development which positively influences the interface sediment mass flux (Guymer et al., 1998).

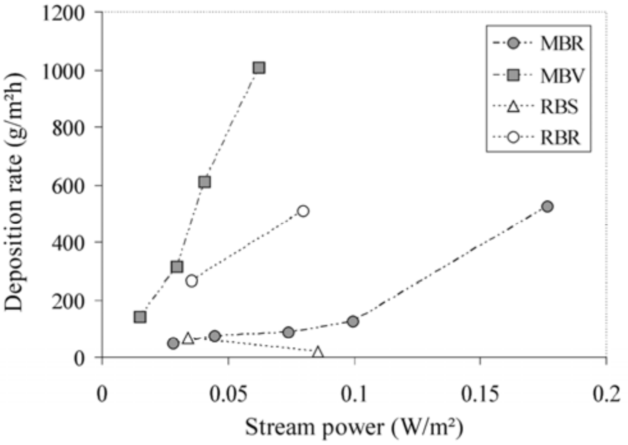

Figure 11. Sediment deposition rate on floodplains (total mass (g)/experiment time(h)/m²) as a function of the floodplain stream power (W/m²) for MBR, MBV, RBS and RBR experiments

Parallel to MBS experiment, RBS show a decreasing sedimentation rate with floodplain stream power, as if the present evolving hydraulic conditions were more likely to increase re-suspension than lateral sediment transfer, in the absence of trapping capacity of the floodplain.

Analysis of Figure 11 shows in a certain way the parameters that should complete this work in a near future: (a) the lateral velocity gradient in the shear zone at the interface between main channel and floodplain which acts on the transferred sediment and influences C_{SL} and the available sediment for deposition; and (b) the floodplain suspension efficiency η_{SL} which is presumed to show a link with the hydraulic conditions over the floodplain and characterizes the conditions for deposition.

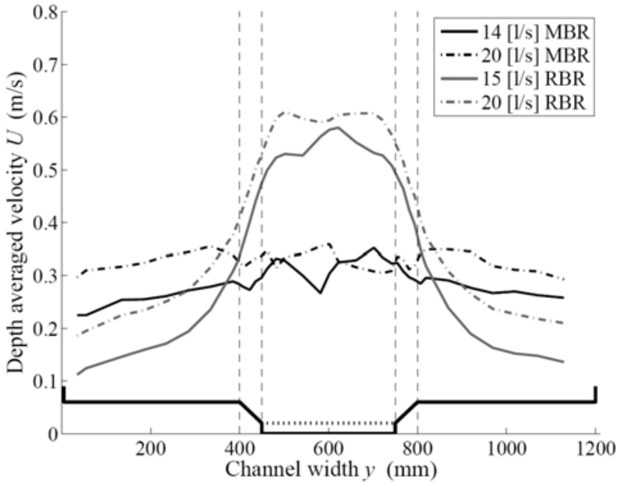

Figure 12. Cross section (x= 8 m) depth average velocities U (m/s) for mobile bed and rigid bed experiments with rough floodplains

5 CONCLUSION AND PERSPECTIVES

Sediment transport and deposition during flood is a challenging problem for the engineer. The present laboratory campaign was initiated to improve our understanding of these phenomena. The study focuses on sediment exchanges between main-channel and floodplains. More precisely, the lateral sediment transfer and the subsequent deposition patterns are studied. Two different experimental configurations were considered, with experiments either performed over a mobile main channel bed with recirculation of the main channel sediment-laden water, or with sediment feeding at the upstream end of the main channel section and transport observed in fresh water over a rigid bed. In both cases, the collected sediment on the floodplains gave a measure of the transfer rate of sediments towards the floodplains from the main channel, deposited and not re-suspended.

The paper presents the influence of hydraulic parameters on sediment deposition rate, taken into account through the calculated stream power over the floodplains. A quantitative and qualitative study of sediment deposition is also performed in correlation with various floodplain roughness or configurations.

Smooth floodplains basically showed a certain threshold in stream power where increase in re-suspension of deposited sediments is more efficient than increase in lateral sediment transfer, due to higher main channel transport capacity. A thorough study on this re-suspension phenomenon could link those experiments to the roughened floodplain cases.

Steel sheeting playing the role of absorbing surface with higher roughness presented a constant evolution of the deposition with the stream power over the floodplains, which comes along with an increased sediment concentration over the floodplains due to an enhanced lateral sediment transfer, especially when high velocity gradient is present in the interaction zone.

Vegetated floodplains reduce drastically the velocities over the floodplains and optimize the sediment transfer towards the floodplains, but also the conditions for deposition. This indicates that when rivers invade their floodplains, enormous quantities of sediments could be collected especially in these vegetated zones.

This study reports comprehensive experimental data which could be used to validate different numerical/theoretical models. Ultimately, the determination of the influence of the transfer of longitudinal momentum on suspended particles should lead to the ability to model the sediment deposits laid on the river banks. This would request a thorough investigation of all turbulent features present in such geometry which condition the mixing mechanisms, but also sediment transport.

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