9th ISE 2012, Vienna

FLOW MEASUREMENTS AROUND A SUBMERGED MACROPHYTE PATCH IN AN IN-SITU FLUME SETUP

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In most aquatic ecosystems, hydrodynamic conditions are a key abiotic factor determining species distribution and aquatic plant abundance. Recently, local differences in hydrodynamic conditions have been shown to be an explanatory mechanism for the patchy pattern of *Callitriche platycarpa* Kütz. vegetation in lowland rivers. Those patches are often subject to strong hydrodynamic forces as they act as a resistance against the current. A plant's ability to tolerate water movement without suffering mechanical damage often relies on minimizing the hydrodynamic forces by avoiding stress. In this paper, we have quantified the behaviour and influence of a *C. platycarpa* patch in an in situ flume, manipulating the incoming discharge on a single patch. The knowledge obtained helps to understand the plant-flow-sediment interactions that form the basis of the explanatory mechanism for the patchy vegetation pattern.

1 INTRODUCTION

The interaction between macrophytes and the hydrologic regime of streams has been a subject of research for over decades now. Hydraulic engineers want to know how plants can steer flow velocity patterns and water heights. Others are interested how this diversity in flow patterns can benefit the streams' ecology (Schoelynck et al. [16]), influence geomorphology (Gurnell *et al*. [10]) or even management (Bal et al. [3]). Many studies focused on a single-plant scale (e.g.: Bal et al., [2]) or on a uniformly distributed vegetation (Champion and Tanner [7]). However, one of the difficulties in studying flow-plant interactions under natural conditions is compounded by the fact that plants often form patches which together with non-colonised spaces, or spaces colonised by different types of vegetation, form irregular mosaics (Sukhodolov & Sukhodolova [18]). This is probably why only a few studied in situ patch behaviour with changing discharges and stream velocities from an ecological point of view or from a hydraulic point of view (e.g. Sukhodolov & Sukhodolova [18]). Conventions for the characterisation of flow-plant interactions relevant for natural conditions, based on physical principles, are strictly necessary, but detailed data sets that allow rigorous examination of flow-plant interactions are still unavailable (Sukhodolov & Sukhodolova [18]).

Spatial self-organisation, which is demonstrated for many ecosystems, is the phenomenon where large-scale ordered spatial patterns emerge from disordered initial conditions through local interactions between organisms and their environment, the so-called scale-dependent feedback interactions (Rietkerk and Van de Koppel [13]). This principle of scale-dependent feedback implies that the presence of an organism has a positive feedback effect that is short-ranged (i.e. local facilitation through resource concentration or stress reduction) and a negative feedback effect that is long-ranged (i.e. inhibition in its surroundings by resource depletion or stress concentration). Recently, scale-dependent feedbacks have been shown to be an explanatory mechanism for the patchy pattern of *Callitriche platycarpa* Kütz. vegetation in lowland rivers too (Schoelynck et al. [16]); analogue to *Spartina anglica* C.E.Hubb patches on flood plains (Temmerman et al. [19]). Biomass slows down the current inside and in the immediate vicinity of vegetation patches, promoting the deposition of sediment and organic matter. This generally results in greater and deeper light penetration (Horppila and Nurminen [11]) and a higher nutrient availability (Brock et al. [6]). Alongside the patch, enhanced stream velocity can lead to erosion. This can lead to a depletion of nutrient availability and an increase of physical disturbance (Sand-Jensen and Madsen [15]); hence a long-range negative feedback on plant productivity. Despite the clear presence of a negative feedback, proven with transplantation experiments (Schoelynck et al. [16]), erosion could (till now) not be withheld as an explanatory factor of negative feedback. It was therefore suggested that for aquatic river vegetation at base flow regimes, the proposed dynamics are most likely to be important but erosion is not the main negative feedback acting upon patch growth, but rather enhanced flow velocity and reduced sedimentation (Schoelynck et al. [16]).

In this current study, the interaction between a flexible submerged macrophyte patch of *C. platycarpa* and the hydrodynamic regime in a stream has been studied in situ. *In situ* flume experiments are often used to study reach scale phenomenons (Gibbins et al. [9]) and provide an excellent tool to work under the natural environmental conditions that are present in the studied ecosystem. It was preferred in the present study to measure the effect of plant-velocity interaction on turbulence, bed shear stress and hence possible erosion. By manipulating the incoming discharge, the existing equilibrium between velocity, bathymetry and vegetation becomes unbalanced, increasing the possibility to measure adequately critical stress zones. With this information, following research questions are addressed in this paper:

1) How are the velocities (re)distributed around the patch ?
2) Are specific critical zones nearby patch edges recognized, which can cause risk on erosion, patch uprooting or stem breakage?
3) How do velocity distributions correspond to zones of erosion or sedimentation?

In the fully integrated study, laboratory experiments were performed to understand the patch behavior and its dimension with changing stream velocities. This variation of patch dimensions, according to incoming velocity (which is a measure of environmental stress), is of major importance as it will greatly influence the magnitude and pattern of the critical stress zones. However, this lab results are not presented here and the reader is refered to the paper of Schoelynck et al. [17].

2 MATERIAL AND METHODS

2.1 Study site and vegetation description

The *in situ* flume measurements were performed in September 2009 in the Zwarte Nete, a typical lowland river of the Scheldt catchment in the NE of Belgium, with good water quality. The river has an average width of 4.5 m and an average slope of 0.0012 m m^{-1}. Water runs through a sandy river bed (D_{50} = 167 µm) with an average stream velocity around 0.1 m s^{-1} and an average discharge of 0.2 m^3 s^{-1} in September. Water depth rarely exceeds 1 m. The aquatic vegetation comprises seven common true aquatic species, partly dominated by C*allitriche platycarpa* Kütz, covering 20% of the river (Schoelynck, personal communication). It has a dense submerged biomass of flexible stems with small leaves. Stems can end in rosette shaped floating leaves surrounding flowers in spring. The species grows in distinct, rather small and confined patches.

2.2 In situ flume setup

Two flumes were constructed around two resembling, existing *C. platycarpa* patches which had an average size (1.2 m long, 0.8 m wide, 110 g DM) at the beginning of the experiment (Fig 1a-b). The flumes were 1.2 m wide and 10 m long and built up out of PVC coated sails attached to two rows of wooden poles. The first two meters at the upstream part of the flume were adjustable to be able to narrow or to widen the inlet, reducing or enhancing incoming discharge on day 2 of the experiment. By manipulating the incoming discharge, the existing equilibrium between velocity, bathymetry and vegetation becomes unbalanced, increasing the possibility to measure adequately critical stress zones. The test section was 4.8 m long and situated at the downstream end of the flume. A free flowing section of 5 m between the inlet and the beginning of the test section was created to avoid upper boundary effects. To minimise possible side effects, measurements were never carried out in the 0.1 m vicinity of the flume borders leaving a test section of 1 m wide and 4.8 m long.

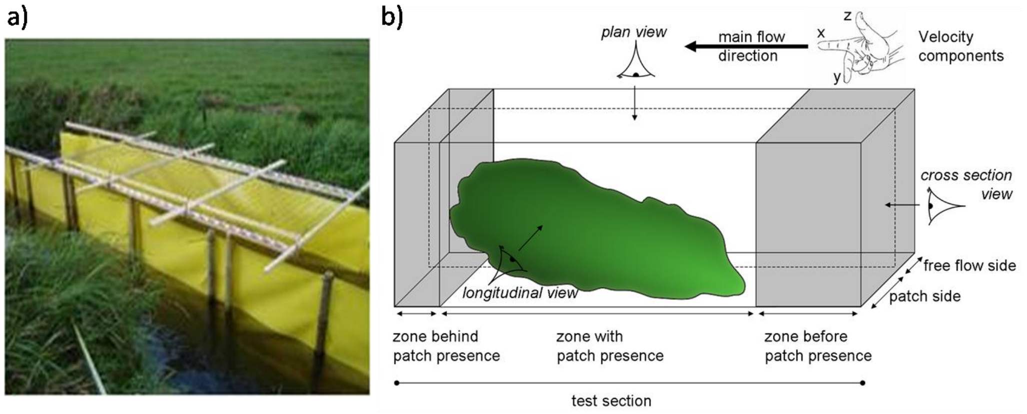

Figure 1: (a) Picture of in situ flume with maze covering. Results from the test section are 3-dimensional and an explanatory key is presented in (b). There are three viewpoints: plan view, cross section view and longitudinal view. The test section is longitudinally divided into three zones: before patch presence, with patch presence and behind patch presence and divided into two cross sections: a free flow side without patch presence and a side with patch presence. In the scheme, the main stream flows from right to left. Positive velocities are orientated corresponding to the right-hand, as shown.

The *C. platycarpa* patch under consideration, is situated at the left bank side of the flume and fills about 75% of the flumes' width. A free flowing zone of minimum 0.10 m was present above each patch, which had an average inclination between 20° and 30° with the horizontal. This results in a cross-sectional blockage area of about 60%. Apart from the investigated patch, all vegetation and other obstacles were removed to ensure a uniform incoming stream velocity.

2.3 Bathymetry, velocity and discharge measurements

Measurements were done on day 1 of the experiment, to measure the initial conditions, on day 2 before and after changing the inlet position and on days 3 and 4.

On top of the flume, a permanent grid was attached with a maze size of 8 by 8 cm. Bathymetry was measured in each maze with a regular measuring stick (error = 0.5 cm) yielding a measurement density of 156 measurements per m². To verify the sediment quantity that settled during the experiment, six plate sediment traps were placed after construction of the flume. Three traps were located before the test section in the middle of the flume, serving as references, one trap is placed just in front of the patch, the two others respectively adjacent to and just behind the patch. Sediment was collected on day 5, dried for 48 h at 70 °C and weighted. Grain size distribution was determined using a laser diffraction unit (Mastersizer S, Malvern Instruments, Worcestershire, UK).

Detailed, 3-dimensional stream velocity measurements in the flumes' test sections were performed using an Acoustic Doppler Velocitymeter (ADV Vectrino, Nortek AS). ADV measurements were collected over a sampling period of 90 seconds at a sampling rate of 25 Hz. As post-processing, data with a poor quality (SNR < 15 dB and correlation < 0.70) were removed and replaced by an interpolation of neighbouring samples, as was done with spikes too. Measurements were performed in four longitudinal sections: (i) at the entrance of the test section, (ii) before the patch, (iii) through the patch and (iv) closely behind the patch. In every cross-section, at least three profiles were measured (maximally 0.30 m separated from each other) and 5 to 9 depth measurements per profile were performed.

Discharge, and additional 1D-velocity measurements, in the river and in both flumes were obtained using an ElectroMagnetic Flow meter (EMF; Valeport model 801, Totnes, UK). EMF measurements were collected over a sampling period of 30 seconds at a sampling rate of 2 Hz. River discharge, calculated with the velocity-area method, was measured on a daily basis.

Water levels were continuously monitored using CTD-divers (Eijkelkamp, NL).

3 RESULTS

During the whole measuring period, only minor fluctuations of the water level (about 5%) were observed and river discharge remained stable around 0.20±0.02 m^3s^{-1}. Discharges in the flumes were different from each other before changing the inlet position (0.11±0.01 m^3s^{-1} and 0.07±0.06 m^3s^{-1} for the flume that was about to be narrowed, respectively widened). The discharge through the flumes with a narrow inlet and a wide inlet respectively dropped 32% to 0.07±0.01 m^3s^{-1} and increased 24% to 0.09±0.06 m^3s^{-1}, after changing the inlet position. As such, the difference in discharge between both flumes was little and because the effect of the vegetation patches on the bulk flow structure in both flumes was in great extent the same, no distinction between both cases is made in the analyses of the results.

3.1 Velocity (re)distributions around a patch

Results of the 3D, depth-averaged velocities are presented in Figure 2, shown in plan view, as relative values compared to the incoming stream velocity. It can be clearly seen that the uniform flow conditions, which are quite well achieved at the entrance, evolve to highly inhomogeneous flow conditions in the vicinity of the vegetation patch. The maximum (depth-averaged) stream wise velocities, V_x were consistently found in the zone behind the patch on the free flowing side and are typically 10 % to 30 % higher than the incoming (depth-averaged) velocities. The minimum stream wise velocities are found behind the patch itself where the incoming velocity is reduced by 50 % to 80 %. The relative difference between the stream wise velocity behind and next to the patch ranges as such between 2.5 and 4. Also in the transverse velocities, V_y, a quite clear pattern can be recognised. In the zone behind patch presence, a clear flow from the free flowing side towards the zone behind the patch is observed. At the edge of the patch, the depth-averaged velocity is nearly zero, as the negative values above the patch seem to compensate the positive values under the patch (plot with longitdunal profiles are not shown). In the vertical direction, V_z shows a clear upward trend parallel to the plant obstruction and a downwards trend behind the patch, which can be clearly seen at the free flowing side.

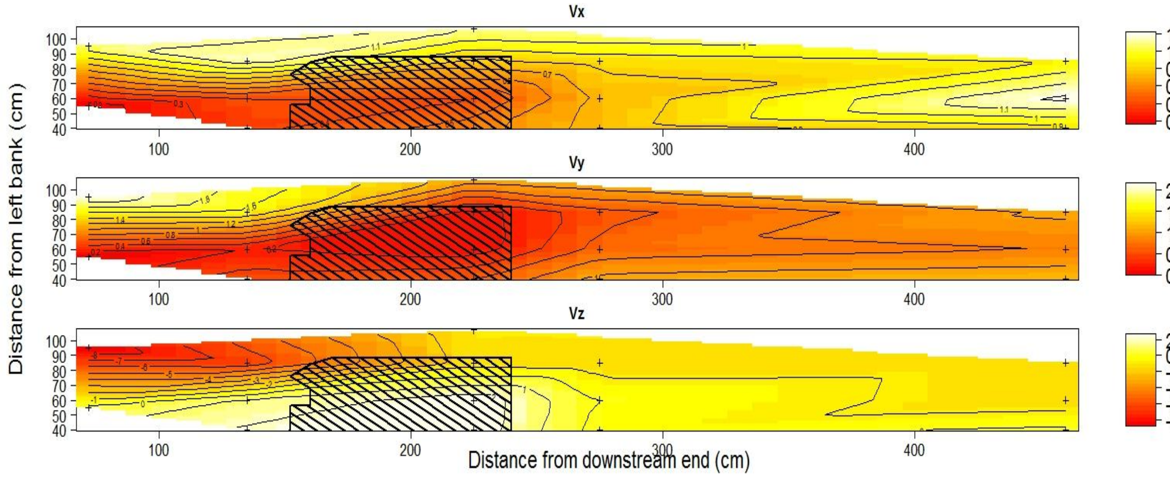

Figure 2: Plan view of the stream wise (a), transversal (b) and vertical (c) depth-averaged velocities, expressed relatively compared to the incoming velocities (V_x = 12.03 cm s^{-1}, V_y = 1.65 cm s^{-1}, V_z = 0.18 cm s^{-1}). Positive velocities are oriented corresponding to the right-hand law (see Fig. 1b). The patch is represented by a hatched polygon. Measurements are obtained on day 4 of the experiment in the field flume with small inlet.

Also if one focuses on the flow velocity profiles, clear distinctions between the different regions can be observed, as is depicted in Figure 3. In the cross-sections measured (far) before the vegetation, the normal logarithmic boundary profile is observed (Figure 3a). This profile is also seen in the profile of the free flowing side of the cross-sections through the vegetation (Figure 3b). However, the profiles in the (dense) vegetation show very low and constant in the vegetation and a steep increase above the vegetation. The profile at the edge of the vegetation shows a double-maximum. It should be noted that maximum velocities at the free-surface in Figure 3, is equal in any case. After the vegetation (Figure 3c), more or less the same profiles are observed, but the values close to the free surface are not equal anymore. The streamwise velocities show small negative values, probably because of the presence of eddies.

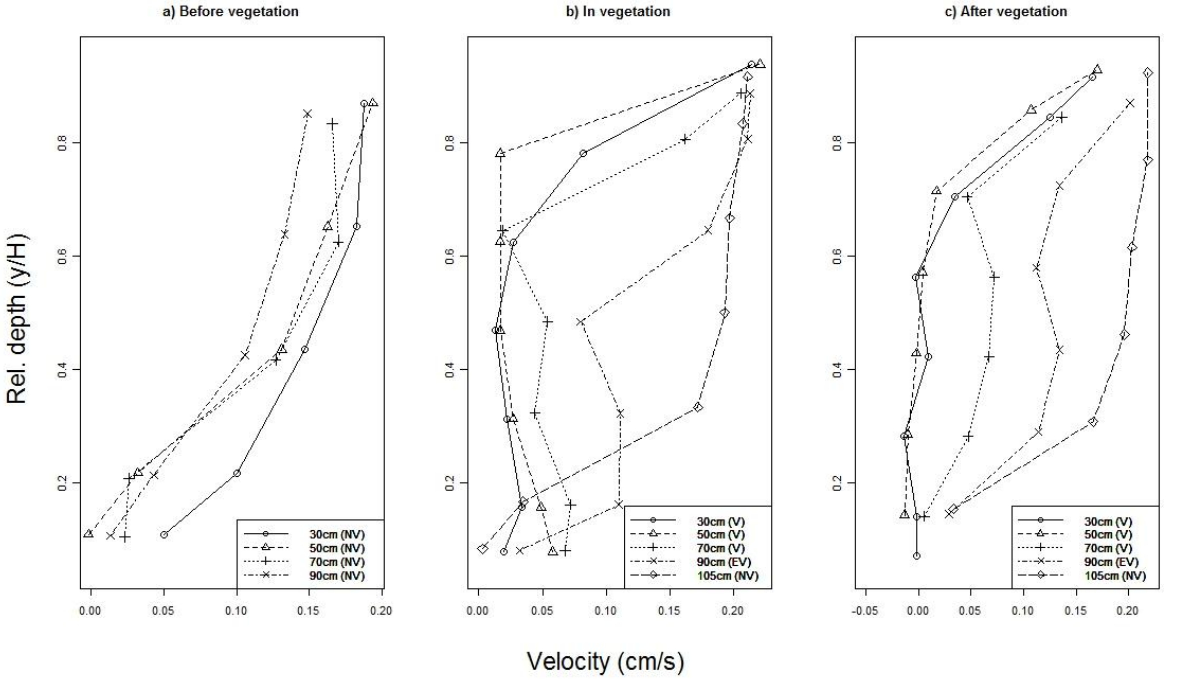

Figure 3: Vertical profiles of the mean stream wise velocity in a cross-section before the vegetation (a), through the vegetation (b) and behind the vegetation (c). “°, Δ, +, x, ◊“ are streamwise velocity measurements respectively located at 30 cm, 50 cm, 70 cm, 90 cm and 105 cm from the left edge of the in situ flume. In the legend: (NV), (V) and (EV) respectively stands for ‘No Vegetation’, ‘Vegetation’ and ‘Edge of Vegetation’.

3.2 Recognition of specific critical zones nearby the patch edges

More insight in the flow structure can be obtained by analysing the components of the Reynolds stresses, which represent the momentum transport due to turbulent motions. The spatial distribution of components - <u’w’>, -<u’v’> and - <v’w’> (u’, v’ and w’ represent the stream wise, lateral and vertical velocity fluctuations respectively and the < > symbol denotes a time average) are shown in two different views: a longitudinal view on the edge between patch side and free flowing side (Fig. 4a) and a longitudinal view along the patch (Fig. 4b).

Critical zones with increased values of the first component - <u’w’>, can be noted near the downstream end of the vegetation on the border between the patch and the free flowing side (Fig. 4a). This upward “stress” transport could probably be responsible for an increased risk on erosion in these specific zones (Knight et al. [12]). Maximal values are consistently found in the top layer of the vegetation and just behind it (Fig. 4b).

The second, transversal, component - <u’v’> shows a heterogeneous spatial pattern which is more or less equal to the first component and values are in the same order of magnitude. The most pronounced values are found on the border between the vegetation and the free flow zone and at the top of the canopy (Fig. 4a,b).

The values of the third component - <v’w’> are consistently smaller than these of the other shear stress components. Nevertheless, these momentum fluxes are still important for transport processes because of their contribution to mechanical dispersion of substances, as they are indicative for rotational motions (Sukhodolov and Sukhodolova [18]). Adjacent to the patch, values are highest near the bottom towards the patch (figure not shown). In the longitudinal section on the edge of the vegetation and through the vegetation maximum values are found on the height of the canopy itself (Fig. 4 a&b).

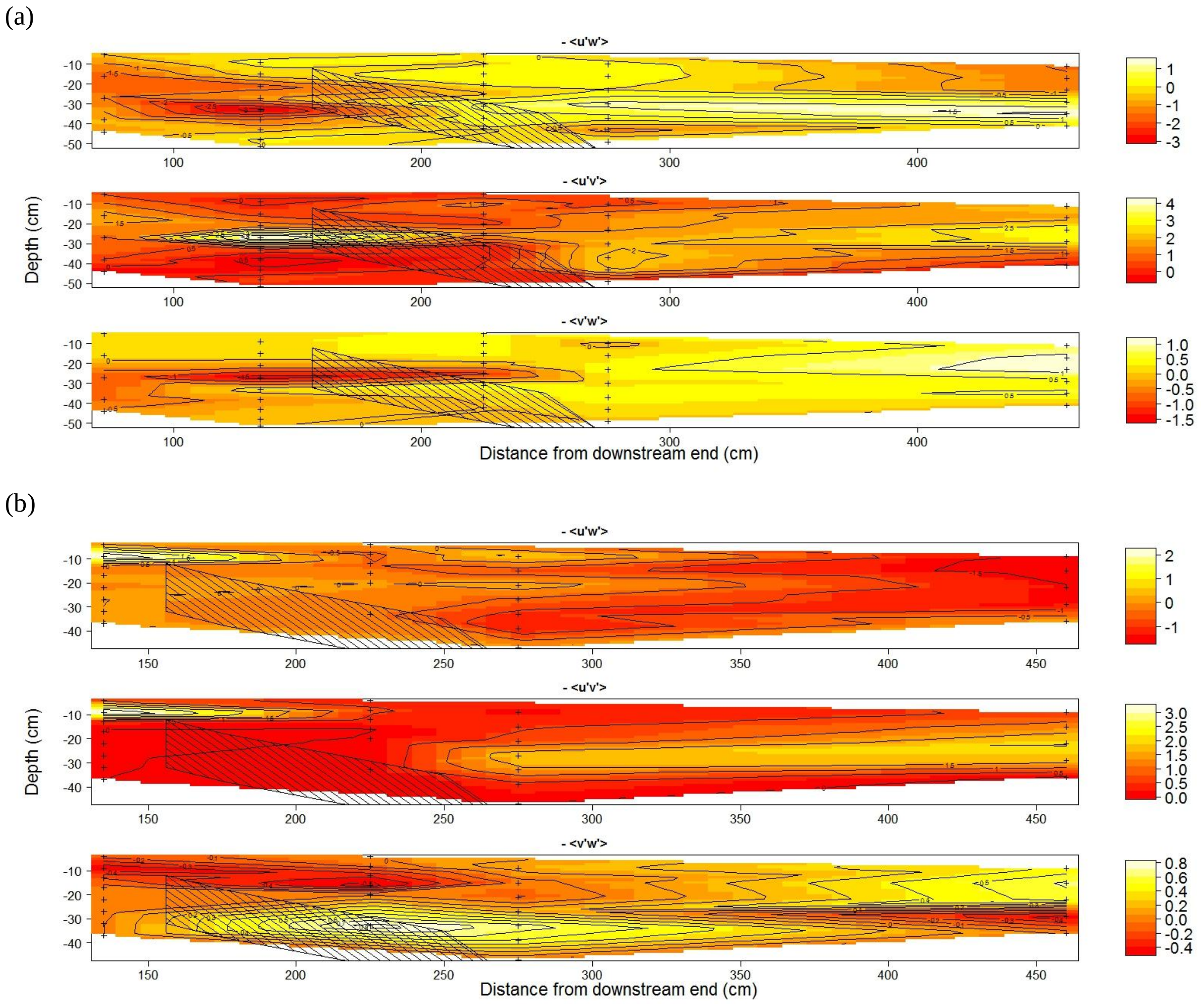

Figure 4: Distribution of the turbulent stresses - <u'w'> (vertical), - <u'v'> (stream wise) and - <v'w'> (transversal) in a longitudinal view adjacent to the patch, on the edge between patch side and free flowing side (a) and in a longitudinal view through the vegetation (b). Absolute values are expressed in cm^2 s^{-2}. The patch is represented by a hatched polygon. Measurements are obtained on day 4 of the experiment in the field flume with wide inlet.

3.3 Comparison between velocity distributions and zones of erosion and sedimentation

The change in bathymetry between day 1 and day 4 in both field flumes is depicted in Figure 5. It can be noted that mainly sedimentation is observed. The zones of highest sedimentation are observed behind the patch. The zone of marginal change (or slight erosion) is observed in the free flowing side, and most intense in the zone shortly behind the patch presence. These patterns are further confirmed by the results from sediment traps (results are not shown) from the test section. Differences are observed around the patch with highest sedimentation is observed before and behind the patch, compared to very low sedimentation adjacent to the patch. Almost all grain sizes (except for 2) are all considered to be 'fine sand', classified along the Udden (1914) and Wentworth (1922) scale. Highest values (coarser) are found in the inlet of the narrowed field flume and before the patch in both field flumes. Lowest values are found in the inlet of the widened field flume (considered 'very find sand'). However, overall d_{50} of the sediment are in the same order of magnitude and no clear trends are observed.

A fundamental variable in river studies to link flow conditions to sediment transport is the bed shear stress τ_0. A good qualitative agreement between the average velocities, which can be related with the square root of bed shear stress (Biron et al., [5]) (indicated as vectors) and the bathymetry is shown in Fig. 5. As the scale of both measurements (616 times 0.08 m x 0.08 m measurements for topography compared to 15 point measurements for velocity) in the flumes are quite different, no quantitative analysis is performed.

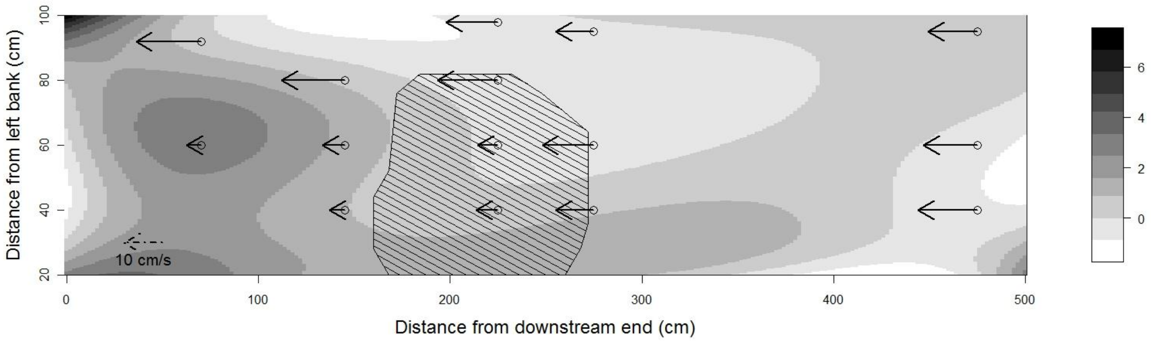

Figure 5: Plot indicating the relative zones of erosion and sedimentation (in cm) between the measurements of day 1 and day 4 within the test section of the field flume with narrowed inlet. Arrows show the depth averaged velocities (cm/s). The start point of the arrow (indicated with o) denotes the location of the measuring point.

4 DISCUSSION

Scale-dependent feedbacks between organism and environment are generally considered as a necessary condition for self-organised patchiness to form (Rietkerk and Van de Koppel [13]). The current alteration in and around a *C. platycarpa* patch, which was clearly demonstrated in the field flumes, is proposed to induce such scale dependent feedbacks. Stream velocities are altered as a result of the, partially, blocking effect of the patch itself. A stream-wise current acceleration up to 30 % of the incoming velocity was recorded next to the patch as well as a current deceleration up to 70 % behind the patch. Both values correspond to values previously published by Schoelynck et al. [16] for patch mimics.

The flow structure around vegetation is of interest because it determines sediment and solute budgets (Folkard [8]). Insight in this flow structure can be given by analyzing velocity profiles and by Reynolds stress values and can help to recognise critical zones of potential positive (i.e. increased sedimentation) or potential negative feedbacks (risk on erosion, uprooting or stem/leaf breakage). On the one hand, inside the patches and especially in the wake behind, sedimentation did occur to a significant extend. The bathymetric map shows sedimentation zones that correspond to the places of low depth-averaged velocities (which can be related to bed shear stress too (Biron et al., [5])). On the other hand, the bathymetric map shows zones with small erosion or marginal change that correspond to the zones of high near bed shear stress, calculated from the turbulent kinetic energy (results not shown). However, erosion was not very deep and mostly just nothing has happened (status quo). The stress was probably not large enough to evoke erosion. To get a mean grain size of 167 µm into motion, a minimal bed shear stress of 0.15 to 0.16 N m^{-2} is needed according to the Shields diagram. The bed shear stresses, calculated based on the kinetic turbulent energy (see Biron et al. [5] for further information), in the field flumes rarely exceed this threshold, and as such no real erosion places have been observed.

Despite the fact that flow acceleration can be an important stressor for *C. platycarpa* to grow (Riis and Biggs [14]), the patch apparently seems capable of benefitting from a positive feedback (sedimentation) while not suffering a lot from a negative feedback. This negative feedback is supposed to manifest on two fronts. First, there is an increase of the drag, not only on individual shoots or leaves, but also on the entire patch. To avoid stem- or leaf breakage, strength tissue is produced involving expensive costs (Schoelynck et al. [16]). Secondly, the total aboveground drag force must be balanced with belowground root anchorage strength. Anchorage increases with root size and substrate type, but also with increasing sediment stability (Angers and Caron [1]). Slow velocities near the river bed have less eroding capacity, hence stabilising the plant roots. Plants or patches thus benefit twice from less acceleration and a tempered negative feedback effect. This tempering effect on flow acceleration at different levels of incoming velocity, is tried to be maintained by the (flexibility of the) plant, by adjusting its position in the water column (reconfiguration). Laboratory flume results clearly demonstrate this proposed stress avoiding strategy and for a further in depth discussion on this topic, one refers to the paper of Schoelynck et al. [17].

5 CONCLUSIONS

In this paper it is clearly shown that the presence of vegetation alters the normal open-channel flow into a complex, three-dimensional flow field. This flow pattern alteration in and around a *C. platycarpa* patch, which was clearly demonstrated in the field flumes, is proposed to induce the necessary scale dependent feedbacks, leading to self-organised patchiness. This results in a local differentiation of sedimentation and the river system adapts to this situation. Local sedimentation provides the patch with a positive feedback; the potential harmful effects of a negative feedback are partly avoided by the patches.

ACKNOWLEDGEMENTS

D.M. would like to thank the BOF (Bijzonder Onderzoeksfonds, B/10677/02 – BOF09/DOC/353) for personal research funding. J.S. would like to thank IWT (Agency for Innovation by Science and Technology) for personal research funding. We would also like to acknowledge Dimitri Van Pelt, Davy Haerens, Stefan Bliki and Salam Ziadat for outstanding technical assistance.

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