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# INFLUENCE OF VEGETATION ON FLOW STRUCTURE IN FLOODPLAINS AND WETLANDS

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**ABSTRACT:** Flume studies have been carried out to investigate flow structure for relatively low velocities and inundation for vegetation typical to floodplains and wetlands, such as grasses and bushes. Mean velocity profiles and turbulence characteristics from flume experiments on three different natural vegetal roughness types are reported. Two relatively new approaches for describing vertical velocity profiles are evaluated with new data.

## 1 INTRODUCTION

Natural river floodplains and adjacent wetlands have vital ecological functions in riverine landscapes (Newson 1992, Ward et al. 2001). They grow typically a diverse and heterogeneous combination of herbs, shrubs and trees, which play an essential role in determining water, sediment, nutrient, and pollutant transport (Nepf and Vivoni 2000). Thus vegetation is a key factor in the interrelated system of flow, sediment transport, and geomorphology in rivers (Tsujimoto 1999). Effects of vegetation on flow are significant and cause difficulties in hydraulic design.

Generally non-submerged and submerged conditions are distinguished, since flow phenomena become more complicated when flow depth exceeds the height of plants (Stone and Shen 2002). In addition, two types of vegetation are usually defined: stiff (typically woody or arborescent plants) and flexible (herbaceous plants). Significant advances have been made to gain a better understanding of flow phenomena in floodplain and wetland flows. However, an abundance of studies are based on laboratory experiments with simple artificial roughness (in uniform flow), whereas in reality natural vegetation exhibits a wide variety of forms and flexibility.

The present study was carried out with the intention to reduce uncertainty in determining resistance coefficients for natural floodplain and wetland flows. The purpose of this paper is to 1) report mean velocity profiles and turbulence characteristics from flume experiments on different natural vegetative roughness types and discuss the natural variability; and 2) evaluate with new data two relatively new approaches for determining velocity profile in vegetated flow. To support these objectives, flow structure is investigated in the case of relatively low velocities and inundation when grassy and bushy type of vegetation are present. These conditions are often found in low-gradient stream valleys and wetlands.

## 2 PREVIOUS RESEARCH

Considerable amount of research has been carried out in developing resistance laws for channels with stiff vegetation (e.g. Petryk and Bosmajian 1975, Pasche and Rouvé 1985), flexible vegetation (e.g. Kouwen and Unny 1973, Kouwen and Fathi-Moghadam 2000), and various combinations (e.g. Freeman et al. 2000, Järvelä 2002). Recently, several studies have focused on velocity profiles and turbulent characteristics of vegetated channels (e.g. Shimizu and Tsujimoto 1994, Naot et al. 1996, Nepf 1999, López and García 2001).

A common approach to determine flow resistance is by using mean cross-sectional velocity *U* and shear velocity $u_*$ to determine friction factor *f*

$$\frac{U}{u_*} = \sqrt{\frac{8}{f}} \tag{1}$$

The velocity profile is given by Prandtl's log law modified by Nikuradse

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln \frac{z}{k_s} + C \tag{2}$$

where $\kappa$ = von Karman constant, $k_s$ = equivalent sand roughness, and *C* = integration constant. Integration of Eq. 2 yields the mean velocity *U*.

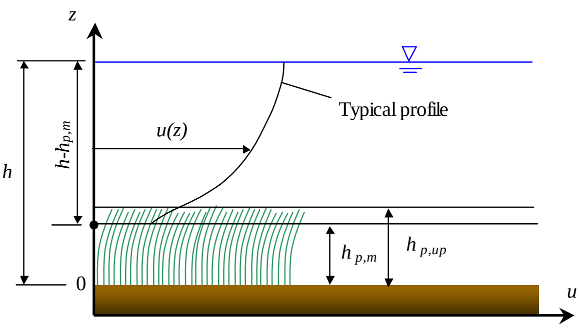


*Figure 1. Definition sketch for the used parameters.*

Among the latest approaches to describe velocity profile in vegetated flow are works by Stephan (2001) and Carollo et al. (2002). Stephan (2001) modified the log law and derived an equation for velocity profile above vegetation

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln \frac{z - h_{p,m}}{h_{p,m}} + 8.5 \tag{3}$$

where $\kappa$ = 0.4 and $h_{p,m}$ = mean deflected height of vegetation (definitions in Figure 1). Based on flume experiments with three species of highly flexible aquatic vegetation it was concluded that the log profile well described the velocity profile above the plants. The mean deflected height described the hydraulic roughness of the plants by summarising the plant and flow characteristics (Stephan 2001, Stephan and Gutknecht 2002). Relative submergence $h/h_{p,m}$ was 1.8–5.5 in the investigations.

Carollo et al. (2002) presented a single equation to compute velocity inside and above vegetation

$$\frac{u}{u_*} = b_0 + \arctan\frac{h_p / h - a_1}{a_2} \tag{4}$$

where four semi-empirical parameters can be defined as

$$b_0 = \frac{u_{\max}}{u_*} - b_1 \arctan\frac{1 - a_1}{a_2},\ a_1 = \frac{h_p}{h},\ a_2 = \frac{6\,e^{-0.36 h_p}}{h},\ b_1 = \frac{25.5(h_p / h)^{-0.44}}{u_*} \qquad \text{(5a,b,c,d)}$$

Their flume experiments were conducted with a mixture of three grass species. Four stem densities were examined (28,000; 31,000; 33,700 and 44,000 stems/m$^2$). Relative submergence $h/h_p$ was 1.6–8.8. The data presented in this paper will be used to test the approaches of Stephan (2001) and Carollo et al. (2002).

## 3 FLUME EXPERIMENTS WITH LIVING VEGETATION

Experiments were conducted in a 50-m long by 1.1-m wide re-circulating glass-walled flume. The studied plants covered a 6-m long section in the midway of the 36-m long section designed for these experiments (Figure 2). Wheat, sedges, grasses and willows were used in the experiments as vegetation cover. 15-m long sections before and after the test area were covered with 10-cm thick layer of crushed rock (diameter 16–32 mm), except the last 2.5 m before the test area. This section was covered with smoother crushed rock (diameter 3–5 mm). Vegetation was installed in the flume in metal boxes with thin walls. The properties of the three studied set-ups of vegetation are as follows, additional information is given in Table 1:

i) **Series R4**: Seeds of **wheat** were planted in a 10-cm thick layer of topsoil and covered with a jute cloth. The flume was first used as a greenhouse with a plastic cover. At the time of the experiments the wheat showed a flexibility comparable to grass. The average length and width of the stems were approximately 28 cm and 2.8 mm, respectively. The wheat covered the test area with an average of 12,000 stems/m$^2$, though the cover was sparser close to the seams of the boxes.

ii) **Series S3**: Slender tufted-**sedges** (*Carex acuta*) were planted in natural floodplain topsoil by boring holes for planting pots (diameter 4 cm) in an approximately 10-cm by 10-cm staggered pattern. The pots contained several individual stems of 3 mm in average diameter giving an average of 512 stems/m$^2$. In the pots the stems were randomly distributed in clusters or apart; typically the diameter of the stems as a group was ~20 mm. Average stem length was kept at 30 cm by cutting.

iii) **Series RP1**: Natural mixed **grasses with leafy willows** (*Salix sp.*) formed a combination of flexible and stiff vegetation. The grasses were a natural mixture of relatively flexible herbs averaging 30 cm in length. The grasses were collected with a 10-cm layer of topsoil. Four willows were installed without roots in each row at a longitudinal and lateral spacing of $a_x$ = 66.7 cm and $a_y$ = 27.5 cm, respectively. The stems averaged 70 cm in length and had no major branches.

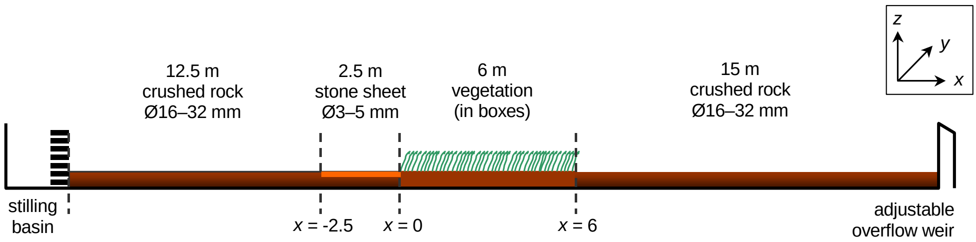


*Figure 2. Experimental set-up and definition for the coordinate axes (not to scale).*

*Table 1. Experimental conditions.*

| Test run[#] | $Q$ (l/s) | $h$ (cm) | $U$ (cm/s) | $Re$ | $Fr$ | $S_e$ | $u_{*1}$ (cm/s)[a] | $u_{*2}$ (cm/s)[a] | $u_{*3}$ (cm/s)[a] | $u_{*4}$ (cm/s)[a] | $h_{p,m}$ (cm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| R4-1 | 40 | 30.60 | 11.88 | 24242 | 0.069 | 0.0015 | 6.75 | 3.88 | 2.89 | 0.82 | 20.5 |
| R4-2 | 100 | 30.84 | 29.48 | 60606 | 0.169 | 0.0036 | 10.43 | 7.35 | 5.58 | 4.66 | 15.5 |
| R4-3 | 40 | 40.65 | 8.95 | 24242 | 0.045 | 0.0005 | 4.35 | 2.87 | 2.43 | 2.05 | 23.0 |
| R4-4 | 100 | 40.41 | 22.50 | 60606 | 0.113 | 0.0013 | 7.16 | 5.21 | 3.97 | 3.91 | 19.0 |
| R4-5 | 143 | 40.70 | 31.94 | 86667 | 0.160 | 0.0020 | 8.94 | 6.96 | 6.06 | 5.00 | 16.0 |
| R4-6 | 40 | 50.44 | 7.21 | 24242 | 0.032 | 0.0002 | 2.94 | 2.11 | 1.68 | 1.50 | 24.5 |
| R4-7 | 100 | 49.50 | 18.36 | 60606 | 0.083 | 0.0006 | 5.58 | 4.16 | 3.68 | 3.09 | 22.0 |
| R4-8 | 100 | 70.65 | 12.87 | 60606 | 0.049 | 0.0002 | 3.40 | 2.70 | 2.61 | 1.93 | 26.0 |
| R4-9 | 143 | 70.37 | 18.47 | 86667 | 0.070 | 0.0003 | 4.61 | 3.84 | 3.58 | 2.72 | 21.5 |
| S3-1 | 40 | 40.03 | 9.08 | 24242 | 0.046 | 0.0004 | 4.13 | - | - | - | 29.5 |
| S3-2 | 100 | 39.61 | 22.95 | 60606 | 0.116 | 0.0010 | 6.23 | - | - | - | 20.0 |
| S3-3 | 143 | 39.42 | 32.98 | 86667 | 0.168 | 0.0018 | 8.34 | - | - | - | 17.0 |
| RP1-1 | 40 | 29.82 | 12.19 | 24242 | 0.071 | 0.0006 | 4.03 | - | - | - | - |
| RP1-2 | 100 | 29.45 | 30.90 | 60667 | 0.182 | 0.0017 | 6.96 | - | - | - | - |

[#] R4 = wheat; S3 = sedges; RP1 = leafy willows with grasses
[a]See Eq. 6 for definitions

Flow was released from a head tank to the flume through a stilling basin and a flow straightener. Desired flow depth was gained by adjusting an overflow weir at the downstream end of the flume. A set of seven flow depths at the beginning of the test area, called the entrance flow depth $h_0$ (25, 30, 40, 50, 60, 70, 80 cm) and six discharges $Q$ (40, 70, 100, 143, 201, 292 l/s) was adopted for the study. Flow was non-uniform in all test runs. Water surface slope along the test section was measured by a differential pressure transducer in 3–7 longitudinal locations averaging over a period of 30–60 seconds. The entrance flow depth was recorded with a pressure transducer. Deflected plant height was determined visually by a ruler or a measuring tape fixed to the flume wall and verified with digital images or video clips. Three levels of deflection were determined: lower $h_{p,low}$, mean $h_{p,m}$ and upper $h_{p,up}$. Detailed information about the experimental set-up can be found in Järvelä (2002).

Flow velocities were measured using a 3-D acoustic Doppler velocimeter (ADV) manufactured by Nortek. Mean velocity components ($u$, $v$, $w$) correspond to the stream-wise ($x$), lateral ($y$), and vertical ($z$) directions, respectively. Velocities were recorded for 1–2 minutes for each point with a sampling frequency of 25 Hz. The sampling volume of the downward-looking ADV is cylindrical in shape (height = 9.0 mm and diameter = 6.0 mm) and is located approximately 55 mm below the tip of the instrument. Disturbance due to canopy elements entering the sampling volume limited measurements close to canopy in some test runs. For the test runs with sedges, it was possible to measure profiles beginning from the bottom soil. Filtering of the raw data was performed with WinADV (Wahl 2000). Special care is essential when interpreting ADV measurements. The Doppler noise can change the true turbulence characteristics significantly, even for high-level turbulence flows (Nikora and Goring 1998). Other sources of error include low signal-to-noise ratio, probe orientation and measuring time (e.g. Babaeyean-Koopaei et al. 2002).

## 4 EXPERIMENTAL RESULTS AND ANALYSIS

### 4.1 Wheat: flow structure above flexible vegetation

For wheat, velocity profiles were measured at three longitudinal locations ($x$ = 3.5, 3.65 and 3.8 m) to investigate possible effects of non-uniformity on the longitudinal development of the velocity profile. Relative submergence $h/h_{p,m}$ ranged from 1.5 to 3.3 for this set of measurements. It was found that for each test run the three vertical velocity profiles were almost identical, though scatter was evident because of natural variability in the roughness cover. Here, a simple spatial averaging procedure was introduced because of the insufficient number of profiles for the double averaging technique described by e.g. Nikora et al. (2001). For the streamwise velocity $u$, the point measurements of the three measured profiles were averaged for a given distance from the bed $z$ (Figure 3). Averages for the turbulence intensity $u_{rms}$ (Figure 4, left) and the Reynolds stress $-\overline{u'w'}$ (Figure 4, right) were calculated with the same averaging procedure.

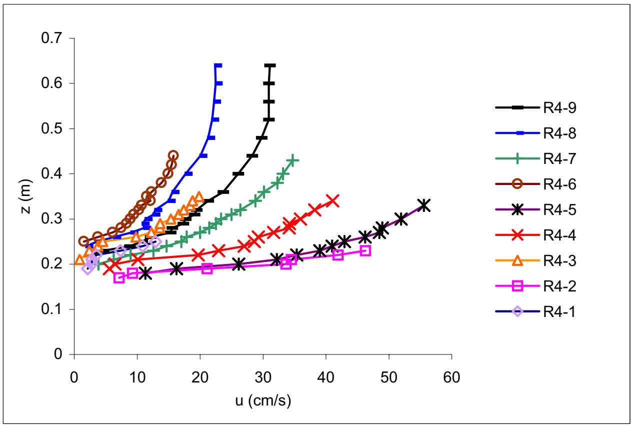


*Figure 3. Average velocity profiles for wheat. See Table 1 for series description and deflected plant heights.*

The observed velocity profiles are comparable to typical profiles above flexible plants. Flow velocity rapidly increased in the region between $h_{p,low}$ and $h_{p,up}$, which denote the minimum and maximum observed deflected plant height, respectively. The amplitude of the waving plant tips was approximately 3–6 cm. The velocity profile in this region appeared to be almost linear for most test runs. Flow characteristics in this region were further investigated by plotting the vertical ordinate $z$ against the corresponding ratio of standard deviation of velocity fluctuations $u_{rms}$ to average velocity $u$. The value of this ratio was small and almost constant in the non-vegetated cross-section, but increased significantly at the level of the plant tips. Several studies report that the maximum turbulence intensity is found at the top level of vegetation (e.g. Tsujimoto et al. 1992, Ikeda and Kanazawa 1996). In the present study, the maximum values for $u_{rms}$ and $-\overline{u'w'}$ were recorded at approximately $h_{p,up}$, i.e. slightly above the mean deflected height (Figure 4). No relation between the maximums of $u_{rms}$ and the corresponding $h/h_{p,m}$ could be found.

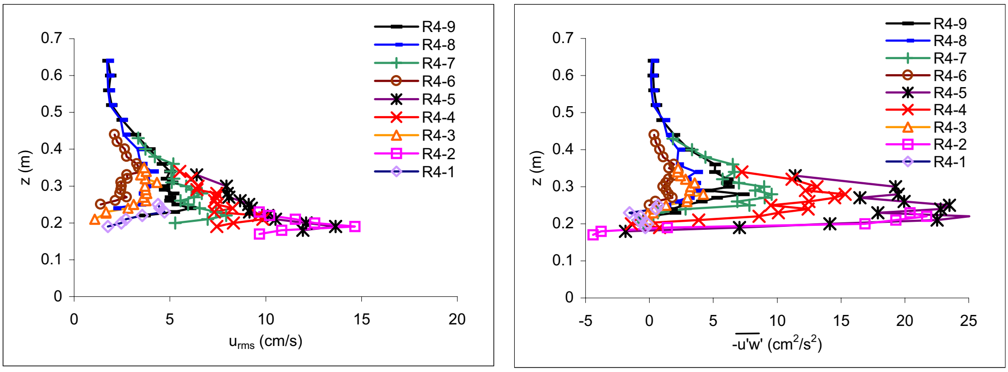


*Figure 4. Averaged profiles for turbulence intensity (left) and Reynolds stress (right) for experiments with wheat.*

Additionally, friction factors were determined for 23 *Q–h* combinations based on head loss measurements. The range of *f* was 0.23–3.21 with an average value of 0.87. From the measurements the average flexural rigidity per unit area (*MEI*) (Kouwen and Unny 1973) was calculated to 1.2 N $m^2$ (assuming the shear velocity equal to $u_{*1}$, see Eq. 6). Further discussion on the velocity data is presented in Section 4.4.

## 4.2 Sedges: flow structure inside vegetation

Velocity profiles were measured at three longitudinal locations ($x$ = 0.9, 1.5 and 5.5 m) to examine the longitudinal development of the velocity profiles. Several measurements were taken close to the bottom to examine the possible effects of uneven natural floodplain soil. In addition, four lateral locations were recorded for $x$ = 5.5 m to examine the influence of the staggered plant pattern. Relative submergence $h/h_{p,m}$ was 1.4–2.3. Figure 5 shows velocity profiles and Figure 6 the corresponding profiles of $u_{rms}$ and $-\overline{u'w'}$ for the position $x$ = 5.5 m and $y$ = 0.55 m.

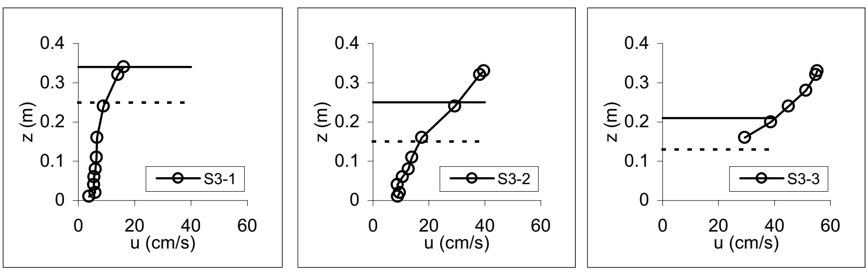


*Figure 5. Velocity profiles for the sedges (test runs described in Table 1). Horizontal lines depict the upper and lower limits of the deflected plant height.*

The determination of $h_p$ was particularly difficult for the sedges. Thus Figure 5 shows a wide range of the measured deflected height for each test run (see horizontal lines). The flexural rigidity of the sedges was not constant over the height, and there was a considerable difference in the flexibility of the individual stems. Furthermore, an abrupt change in roughness could be observed at the transition between test section and gravel bed. The flow gradually decelerated inside the vegetation and accelerated above it. As expected, the longitudinal and lateral differences in the profiles were far more significant than in case of denser vegetation due to the staggered plant pattern. For example, the shape of the velocity profile inside the vegetation changes notably at the downstream location $x$ = 5.5 m as $U$ and $h/h_p$ increase (Figure 5). In S3-1 the flow appears to be dominated by vegetal drag, but in S3-2 a stronger shear layer is apparent and turbulent stress from the non-vegetated part of the cross-section contribute momentum to the flow inside the vegetation (Figure 6). For S3-3, the lowest points could not measured because of the waving vegetation.

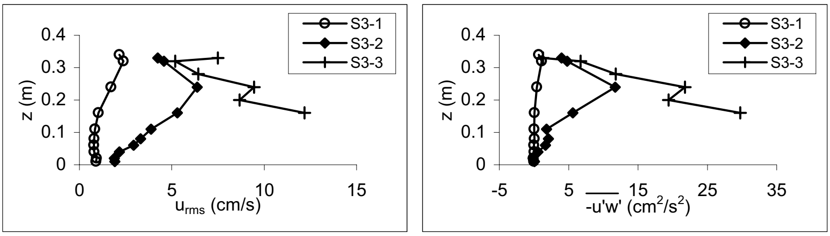


*Figure 6. Plots of turbulence intensity (left) and Reynolds stress (right) for the sedges.*

## 4.3 Leafy willows and grasses: flow structure inside a combination of flexible and stiff vegetation

Considerable amount of data is available for the combination of grasses and leafy willows. Velocity profiles were measured at several longitudinal ($x$ = 1.27, 2.33, 2.463, 2.596, 2.729, 2.862, 3.95, 5.27 m) and lateral ($y$ = 0.55, 0.685, 0.775, 0.865, 0.995, 1.02 m) locations, but typically with only 4–5 vertical points. The primary purpose of this arrangement was to examine flow structure inside the willow canopy. Therefore, measurements were carried at a high spatial density at $x$ = 2.33–2.862 m. Further data was recorded at several longitudinal locations for a reference basis and were additionally supplemented by measurements over the gravel bed before and after the vegetated area. The data provide insight into the 3-D structure of the flow within the complex vegetation pattern. Due to space limitations, detailed analysis cannot be included in this presentation and will be a topic for a subsequent paper.

## 4.4 Evaluation of approaches by Stephan (2001) and Carollo et al. (2002)

In the following, the approaches of Stephan (2001) and Carollo et al. (2002) reviewed in Section 2 will be tested. Both approaches were used to reproduce the velocity profiles for the experiments carried out with wheat. The properties of the young wheat used in the study should at least partly resemble the grasses of Carollo et al. (2002). Differences are more significant, when the wheat is compared with the aquatic plants of Stephan (2001). Furthermore, to be able to calculate the velocity profile according to both approaches, the shear velocity $u_*$ must be estimated. Here, the sensitivity of the approaches on the definition of $u_*$ is tested by introducing four different definitions:

$$u_{*1} = \sqrt{ghS_e}\ ,\ u_{*2} = \sqrt{g(h-h_{p,m})S_e}\ ,\ u_{*3} = \sqrt{g(h-h^*)S_e}\ ,\ u_{*4} = \sqrt{-\left(\overline{u'w'}\right)_{\max}} \qquad \text{(6a, b, c, d)}$$

where $g$ = gravitational acceleration; $S_e$ = energy slope; and $h^*$ = flow depth corresponding to the maximum measured value of $-\overline{u'w'}$. The definition of $u_{*1}$ does not include any plant parameters, whereas the reduced flow cross section due to the vegetation is included into the definition of $u_{*2}$ by means of $h – h_{p,m}$. From a practical point of view $u_{*2}$ is a convenient definition as $h_p$ can be easily measured. The definitions of $u_{*3}$ and $u_{*4}$ are based on both turbulence characteristics and influences of vegetation.

Applying the approach of Stephan (2001) was straightforward and produced in overall good results. Largest discrepancies between the measured and predicted profiles were related to the higher discharges with larger relative submergence $h/h_{p,m}$. Measured and predicted velocities are compared in Figure 7 for $u_{*2}$ (left) and $u_{*3}$ (right), which gave the best results. Similar analysis of the data with $u_{*1}$ and $u_{*4}$ showed major discrepancies. The corresponding plots are not shown here.

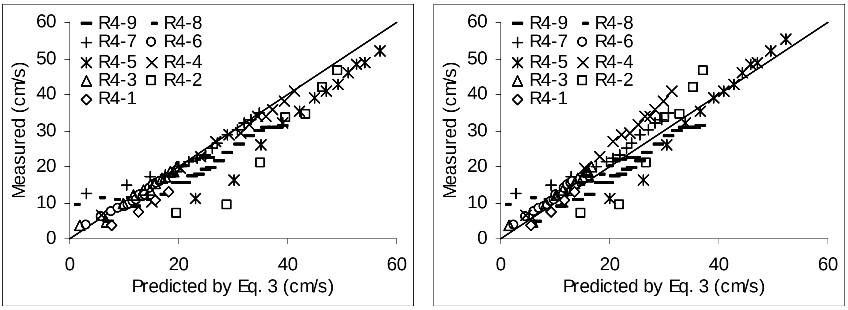


*Figure 7. Velocity measured and predicted by Eq. 3 with $u_{*2}$ (left) and $u_{*3}$ (right).*

Applying the approach of Carollo et al. (2002) revealed major problems. With the present data, Eq. 5 returned unrealistic values. It can only be concluded that the semi-empirical parameters in the equations depend on the boundary conditions of the experiments of Carollo et al. It appears that the approach is strongly scale dependent and that differences in the experimental set up are responsible for its inapplicability in this study.

## 5 SUMMARY AND CONCLUSIONS

Mean velocity profiles and turbulence characteristics were reported from flume experiments on three different natural vegetal roughness types. The flow above the wheat reasonably followed the log law. In the region $h_{p,low}$–$h_{p,up}$ the flow velocity increased rapidly and almost linearly. For the cases of small relative submergence with low velocity, unambiguous determination of the deflected plant height was difficult. Maximum values of $u_{rms}$ and $-\overline{u'w'}$ were found at approximately $h_{p,up}$. Inside the sedges, the velocity profile was almost constant up to $h_{p,low}$ in the case of low discharge. With increasing discharge the velocity profile started to incline as turbulence-driven vertical momentum transfer contributed to the flow within the plants.

Measured velocity profiles for the experiments carried out with wheat were described well by the approach of Stephan (2001). Introducing the simple definition of shear velocity $u_{*2} = \sqrt{g(h - h_{p,m})S_e}$ yielded good results for the comparison of measured and calculated velocity profiles. Similar results were obtained with the definition of $u_{*3} = \sqrt{g(h - h^*)S_e}$ , which includes data from turbulence measurements. However, from a practical point of view, $u_{*2}$ is a convenient definition for shear velocity as the mean deflected plant height $h_{p,m}$ can be easily measured. The approach of Carollo et al. (2002) appeared to offer only limited applicability in its present form. In overall, the experimental results revealed a great diversity of flow structures in the case of natural plants which will be analysed in more detail in a subsequent paper.

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## APPENDIX A: NOTATION

The following symbols are used in this paper:

| | |
|---|---|
| $a_1$, $a_2$, $b_0$, $b_1$ | parameters in Carollo et al. (2002) |
| $a_x$, $a_y$ | longitudinal, lateral distance between the plants |
| $C$ | integration constant |
| $f$ | friction factor |
| $g$ | gravitational acceleration |
| $Fr$ | Froude number |
| $h$ | flow depth (bottom to free surface) |
| $h_0$ | flow depth at the beginning of the test area |
| $h_{p,m}$ | mean deflected plant height |
| $h_{p,low}$, $h_{p,up}$ | minimum and maximum deflected plant height |
| $h*$ | flow depth corresponding to the maximum measured Reynolds stress |
| $k_s$ | equivalent sand roughness |
| $MEI$ | flexural rigidity per unit area |
| $Q$ | discharge |
| $Re$ | Reynolds number (=$Uh/\nu$) |
| $S_e$ | energy slope |
| $U$ | mean cross-sectional velocity |
| $u$, $v$, $w$ | mean velocity component (longitudinal, lateral, vertical direction) |
| $u_*$ | shear velocity (see Eq. 6) |
| $u_{rms}$ | RMS turbulence intensity |
| $-\overline{u'w'}$ | Reynolds stress |
| $x$, $y$, $z$ | longitudinal, lateral, vertical coordinate |
| $\kappa$ | von Karman constant |