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A flume experiment on sediment transport with flexible, submerged vegetation

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ABSTRACT

Vegetation affects sediment transport by obstructing the flow and changing the turbulence characteristics. Common sediment transport equations are not applicable to situations with submerged vegetation. A laboratory experiment was carried out in which flow, turbulence characteristics and sediment transport were measured in a 80 cm wide flume with a 15.85 m long section of 18 cm high, artificial, flexible, submerged vegetation in a sand bed. Measured profiles of velocity and turbulence were analysed and simulated with a 1DV numerical model to obtain estimates of the bed shear stress. Results show a reduction of the bed shear stress with about 80%, and an increase in sediment transport rate compared to a case without vegetation.

INTRODUCTION

To reduce flood risks in the Netherlands, measures to increase the flood conveyance capacity of the Rhine River will be implemented. These measures provide more space for the river and include lowering of the floodplains and excavation of secondary channels. Moreover, these measures provide opportunities for ecological rehabilitation of the floodplains. However, it is expected that floodplain vegetation slows down flow velocities and enhances sedimentation. To date, the interaction between sediment transport and vegetation in river floodplains is to a large extent unknown. A lot of research efforts have been put into the effects of vegetation on hydraulic roughness, but the effects of vegetation on suspended sediment transport are less known and even less is known about the effects of vegetation on bedload transport. Many references can be found on research into the hydraulic roughness of vegetation. Research has been conducted on experiments with artificial and natural vegetation in flumes (Meijer & Van Velzen 1999, Stephan & Gutknecht 2002, Järvelä 2002; Righetti & Armanini 2002), on analytical approaches for the vertical velocity profile (Klopstra *et al*. 1997), on biomechanics and streamlining of vegetation (Kouwen & Li 1980, Fahti-Maghadam & Kouwen 1997) and on turbulence characterisation for submerged rods and vegetation (Nepf & Vivoni 1999, Nepf & Vivoni 2000, Fisher-Antze *et al*. 2001, López & Garcia 2001). Several studies have been carried out on the interaction of vegetation and suspended sediment. These include field and laboratory measurements as well as numerical modelling (Nakagawa *et al*. 1992, Watanabe & Hoshi 1996, Houwing *et al*., 2000, Teeter *et al*. 2001, Madsen *et al*. 2001). The interaction of vegetation and bedload transport however, is hardly being studied. Common sediment transport predictors have been derived from experiments in laboratory flumes without vegetation. Studies for the effect of vegetation were usually based on modelling of the drag force of vegetation and its effect on the bed shear stress (Li & Shen 1973, Tsujimoto 1999, Bing *et al*. 2001). Experiments on sediment transport in vegetated regions were conducted

(Abt *et al*. 1994, Prosser *et al*. 1995; James *et al*., 2001) and field studies were conducted as well (Okabe *et al*. 2001). However, no reliable bedload and suspended load sediment transport equation in submerged floodplain vegetation of lowland rivers is found. It can be concluded that to this moment, a gap in the knowledge on the interaction between vegetation and geomorphology exists with respect to the magnitude of sediment transport in vegetated regions of floodplains.

MATERIAL AND METHODS

Experiments were conducted in a 35-m long by 80-cm wide, straight, horizontal open channel with concrete bottom and glass walls. The flume set-up is presented in Figure 1. A longitudinal section of artificial, flexible vegetation with a density of 400 m^{-2} was installed over a length of 15.85 m. Plastic aquarium plants, AQUASCAPERS®, from Metaframe Corporation, USA, type Anacharis (*Egeria densa*) X-large were used. In total 4755 plants of 27 cm length were mounted onto 18mm wood-cement boards in a rectangular pattern of 5 by 5 cm by sticking the upper end of the plant into 2.0 mm diameter drilled holes. A 9-cm thick layer of sand was distributed evenly between the submerged plants using a carrier with a perforated metal box that drives on top of the flume. The upright plant height protruding from the bed is therefore 18 cm. The quartz sand has a D_{50} of 321 μm with a uniformity of 1.19, defined as the square root of D_{84} over D_{16}. Downstream of the plant section a fixed heightened floor continued at the elevation level of the sand bed. This structure sloped down near the end of the flume. Upstream of the vegetated section a heightened, fixed floor with a length of 1.25 m was installed. Stainless steel mesh screens that damped turbulence achieved smooth inlet conditions.

All instruments used were fabricated by WL | Delft Hydraulics. Vertical profiles of the longitudinal (*u*), lateral (*v*) and vertical (*w*) velocities were measured with two two-dimensional Electromagnetic Velocity Sensors (EMSs), E30type, mounted in two different directions. An immersible Laser Doppler Anemometer (LDA) was applied as well to measure velocity in *u* and *w* directions. Mean and turbulent velocity statistics were obtained from 300s records sampled at 5Hz for the EMSs and 100Hz for the LDA at fixed positions along the flume. These instruments were mounted at location M5, which is at 10 m distance from the beginning of the vegetated section. The longitudinal profile of the water level was measured with a Dynamic Liquid-level Meter. The longitudinal bed profile was measured with two electric conductivity Bed Profilers. These instruments were mounted on a carrier with adjustable speed.

Table 1. Hydraulic conditions for the test runs.

	Flume discharge (m^3/s)	Depth-averaged velocity (m/s)	Depth at location M5 (m)
Test 1	0.081	0.38	0.265
Test 2	0.129 - 0.137	0.53 - 0.56	0.305 - 0.307
Test 3	0.101	0.44	0.287
Test 4	0.085	0.41	0.26
Test 5	0.113	0.45	0.315
Test 6	0.155	0.60	0.323

Mean velocities of 0.3 to 0.6 m/s at flow depths of about 30 cm were considered to represent floodplain conditions at flood situations and to have high enough flow for initiation of movement of sand particles. Two series of experiments were conducted. In the first series three experiments were carried out with artificial plants mounted to the flume floor. In the second series three similar flume discharges were applied without plants attached to the flume floor. Hydraulic conditions for these experiments are presented in Table 1. The data for the first test proved to be useless, so the emphasis in the analysis is put on test 2 and 3 and their reference tests number 6 and 5 respectively. The depth-averaged velocities for the reference tests were slightly higher than for the tests with vegetation.

The flow duration in the series with plants was about 30 hours, for series without plants about 3 hours. No sediment feed was applied and flow was stopped as soon as a significant amount of sand eroded out of the moveable bed section and deposited in the downstream section of the flume. The amount of sediment that was transported out of the section with the moveable bed was determined in two ways. The first approach is a direct way of collecting and weighing the sand that has deposited in the downstream section of the flume. The second approach is an estimate obtained by determination of the volumetric change of the moveable bed using the average of two bed profiler measurements and convert this to mass weight.

The horizontally averaged momentum balance of flow with vegetation has an additional drag force *F(z)* from the plants:

$$\int_d^{\zeta} \frac{\delta \tau_{xz}}{\delta z} dz + \int_d^{h_p} F(z) dz + \int_d^{\zeta} \frac{\delta p}{\delta x} dz = 0 \qquad (1.1)$$

where ζ, d and h_p are water level, bed level and plant level respectively, τ_{xz} is the shear stress in xz-direction and $\delta p/\delta x$ is the pressure gradient. Integration of formula (1.1) yields:

$$-\tau_{xz}(z) + \int_d^{h_p} F(z) dz + (\zeta + d - z) \frac{\delta p}{\delta x} = 0 \qquad (1.2)$$

The unknown drag force from the vegetation *F(z)* is assumed to depend on the mean horizontal velocity U^2 as in Nepf (1999):

$$-\tau_{xz}(z) - \frac{1}{2} C_d a \int_d^{h_p} U^2(z) dz + (\zeta + d - z) \frac{\delta p}{\delta x} = 0 \qquad (1.3)$$

where C_d is drag coefficient and *a* is canopy density. Shear stress is characterised by the Reynolds stress, omitting the viscous term:

$$\tau_{xz} = -\overline{u'w'} \qquad (1.4)$$

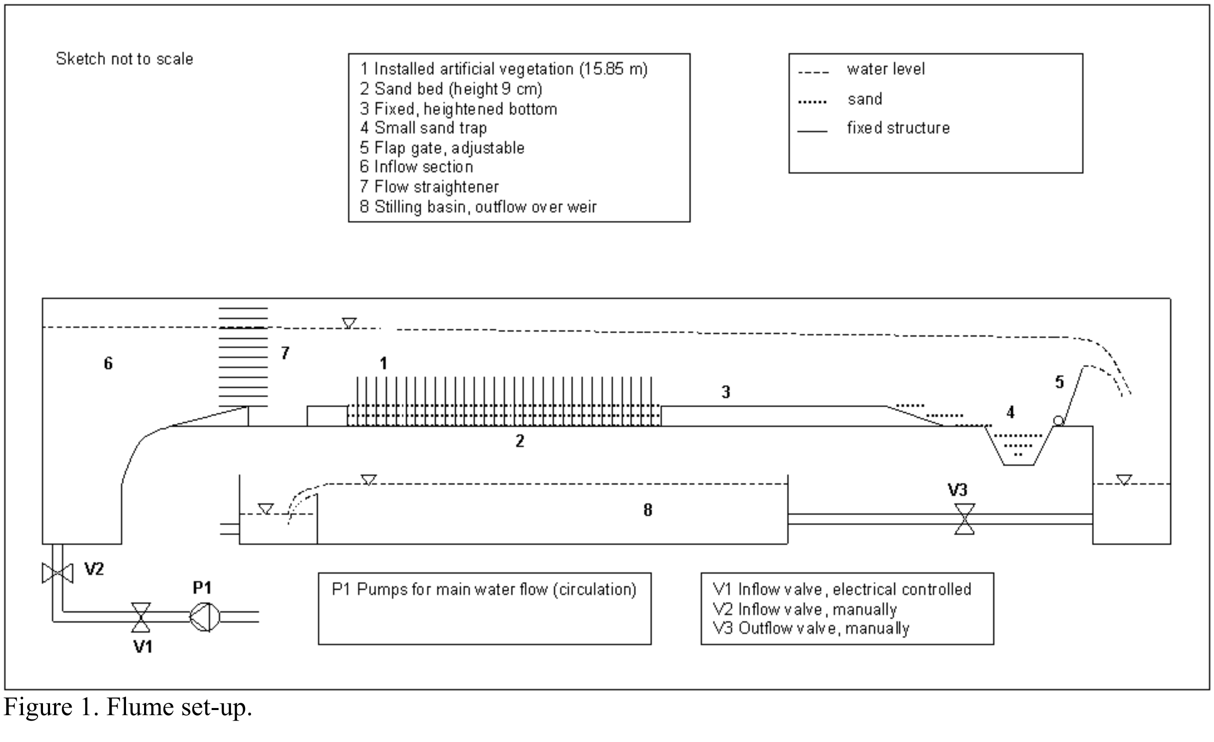


Figure 1. Flume set-up.

RESULTS

Flow and Reynolds stress measurements

For all experiments Reynolds ($>8 \cdot 10^5$) and Froude ($<<1$) numbers indicate turbulent, subcritical flow. The observed vertical profiles for velocity and Reynolds stress show deceleration of flow within the vegetation layer and a maximum Reynolds stress at the tops of the plants. Figure 2 shows vertical profiles for horizontal velocity along the flume length. Note that the flow has a non-uniform character.

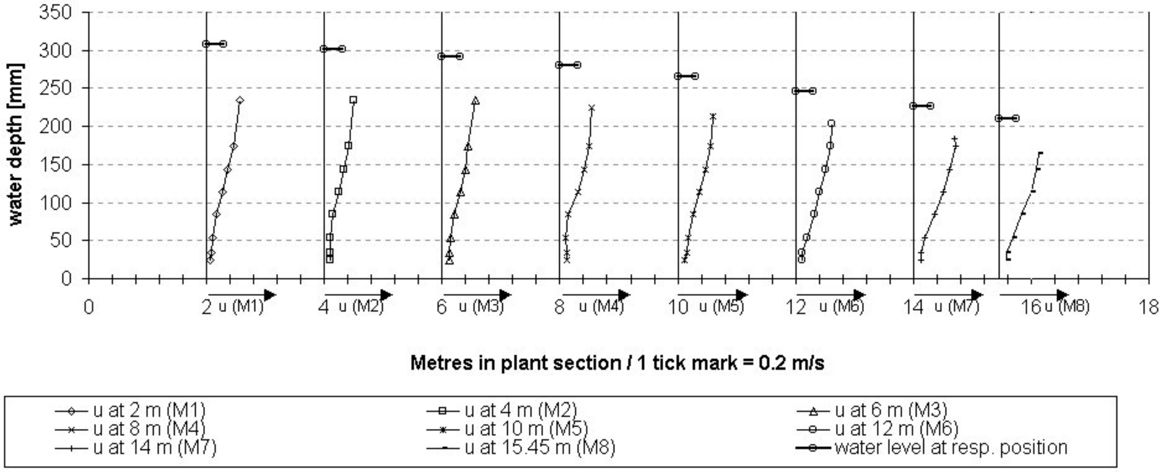


Figure 2. Vertical profiles of velocity along the flume length for test 1.

Figures 3 to 5 show profiles for velocity and Reynolds stress measured at position M5, at 10 m distance from the beginning of the vegetated section. Since the bed of the flume is a moveable bed, the heights of the measurements were corrected for the actual bed height. In Test2 an EMS as well as a LDA was applied, results are shown for both instruments.

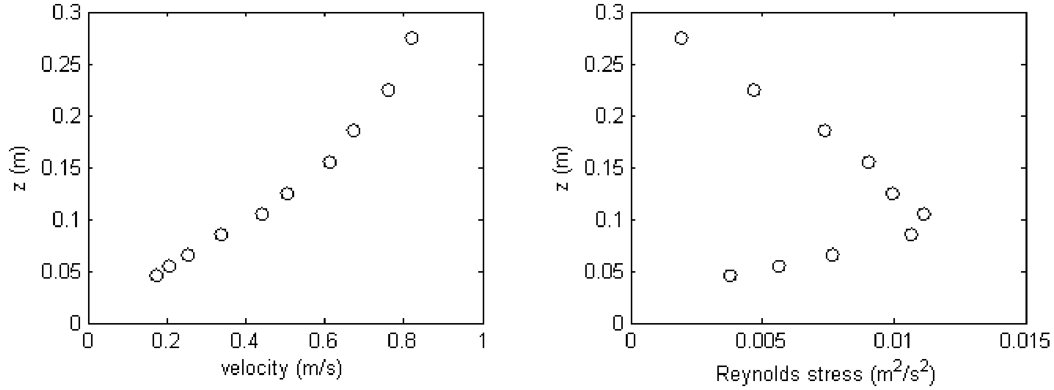


Figure 3. Vertical profile of velocity (left) and Reynolds stress (right) for test 2, EMS measurements.

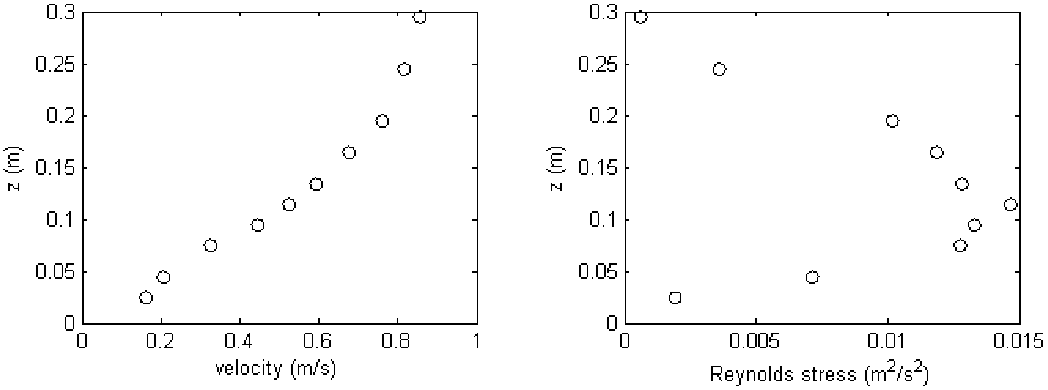


Figure 4. Vertical profile of velocity (left) and Reynolds stress (right) for test 2, LDA measurements.

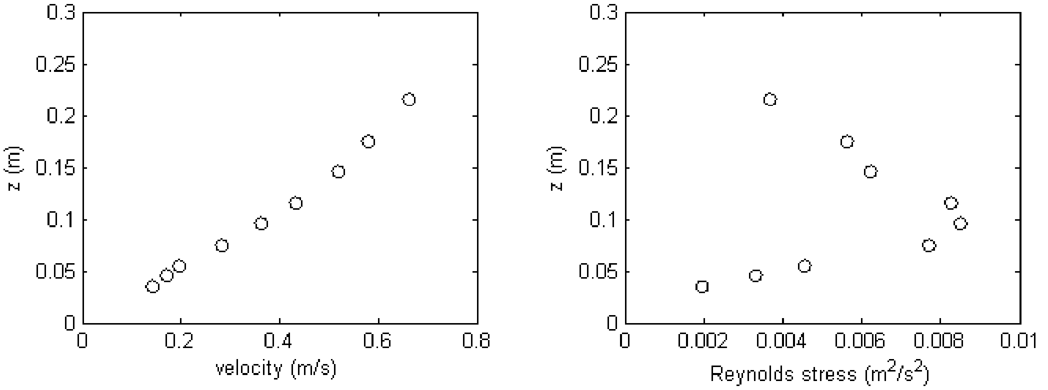


Figure 5. Vertical profile of velocity (left) and Reynolds stress (right) for test 3, EMS measurements.

The Reynolds stress profiles for Test2 differ between the EMS and LDA measurements. The LDA is capable of measuring smaller scale (both spatial as temporal) turbulence. Linear extrapolation of the measurements above the vegetated layer to z=0 gives an estimate of the total shear stress that can be compared against the total shear stress *g·h·i*. This comparison indicates that the LDA measurements give better estimates of the Reynolds stress than the EMS measurements.

Drag force from vegetation

The unknown drag force from the vegetation follows from the momentum balance, formula (1.3):

$$\frac{1}{2}C_d a\int_{d}^{h_p} U^2(z)dz = (\zeta + d - z)\frac{\delta p}{\delta x} + \overline{u'w'}(z) \qquad (1.5)$$

In Figures 6 to 8 (left) the measured Reynolds stress is subtracted from the pressure gradient, resulting in the plant force over *z*, presented relative to the plant height h_p. The bent plant height h_p was chosen at the level of the lowest Reynolds stress measurement that fits to the linear pressure gradient. Values for $½C_d(z)a(z)$ can now be derived from the vertical profile of the plant force and the integration of U^2 over z. The canopy density $a(z) = m(z)\cdot d(z)$ is the stem density per m^2 multiplied with the stem diameter. The canopy density is assumed uniform over depth and equal to 400 m^{-2} · 0.005 m = 2.0 m^{-1}. Figures 6 to 8 (right) present the vertical profiles of $C_d(z)$, applying this geometric schematisation of the vegetation.

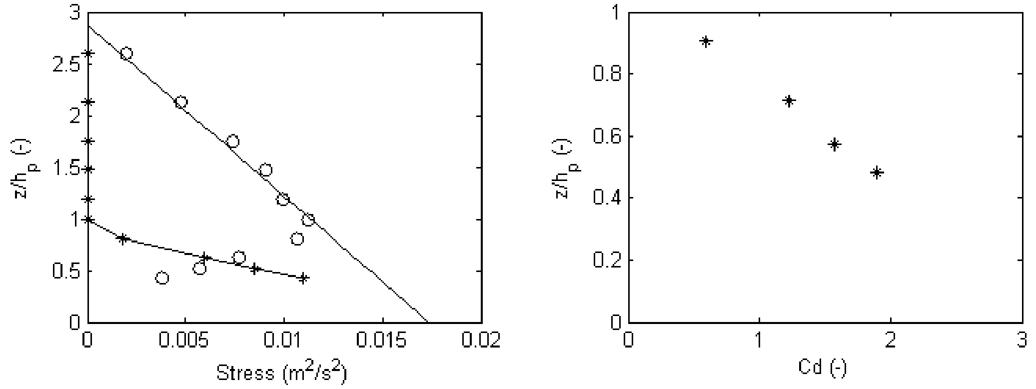


Figure 6. Left: Reynolds stress (circles), pressure gradient (line) and resulting plant force (stars). Right: Drag coefficient. Test 2 EMS measurements.

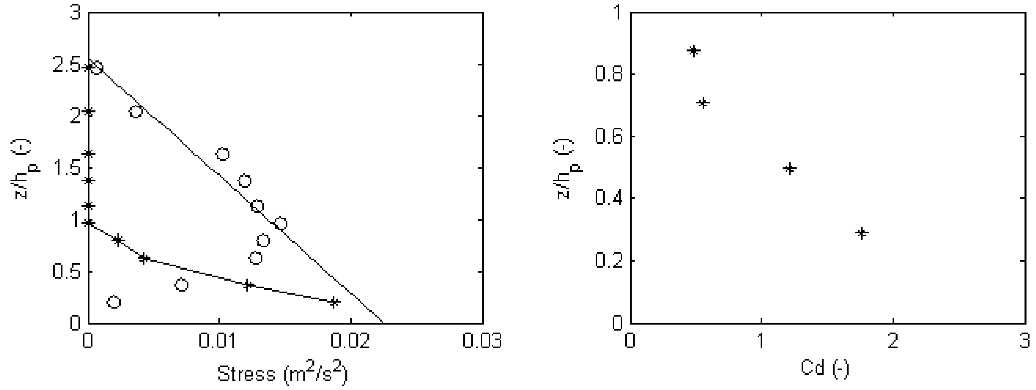


Figure 7. Left: Reynolds stress (circles), pressure gradient (line) and resulting plant force (stars). Right: Drag coefficient. Test 2 LDA measurements.

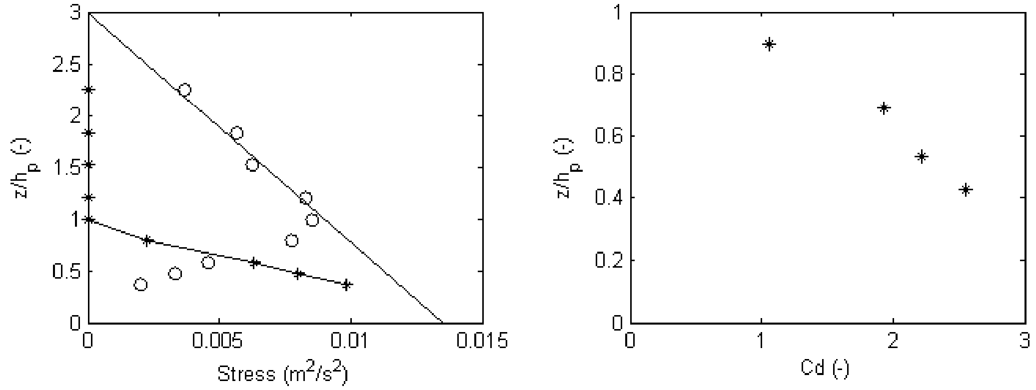


Figure 8. Left: Reynolds stress (circles), pressure gradient (line) and resulting plant force (stars). Right: Drag coefficient. Test 3 EMS measurements.

The resulting vertical profiles for the drag coefficient show rather strange characteristics. Preliminary assessments have shown that it is very important to apply a correct geometric schematisation of the vegetation. When the geometry is schematised right, uniform profiles of C_d over z may be achieved. However, because the vegetation is flexible and moving in the flow, this is not straightforward. Moreover, these profiles prove to be very sensitive to the plant height h_p used in the equation for the plant force, which is also not a constant height. Further work remains to be done here.

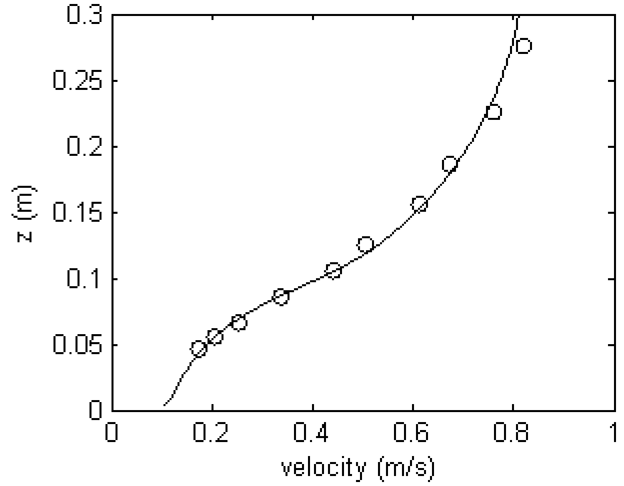
The bed shear stress follows from the momentum balance at the bed, z=0. However, it is not exactly known how the profiles of Reynolds stress and plant force extent to the bed. The extrapolation of the Reynolds stress profile to the bed depends on the penetration depth of the vertical turbulence and thus the uniformity of the vertical velocity profile near the bed. Furthermore, the resulting bed shear stress is very sensitive to the estimates of Reynolds stress and plant force near the bed, because the bed shear stress is the result of the subtraction of two large figures to obtain a small figure. To estimate the bed shear stress, a 1DV numerical model was applied.

1DV numerical model

A numerical 1DV model for flow in and above vegetation was developed by Uittenbogaard, Stelling & Van Kester of WL | Delft Hydraulics. The model is based on the Delft3D shallow water equations. Additional formulations for flow through plants were added, based on the drag force of cylinders in flow. Additional parameters for plants are a drag coefficient, $C_D(z)$, a typical diameter of branches or stems, $d(z)$ and the number of cross sections of stems or branches per m^2, $m(z)$. These parameters can be defined for each vertical layer of the model. This allows for multiple bifurcation of vegetation, by adjusting the number of cross sections, the diameter of the stems and the drag coefficient per depth-layer. The model is described in Uittenbogaard (2003).

1DV model application

The 1DV model was applied to simulate the measured profiles for horizontal flow velocity for each experimental test. One hundred vertical layers were defined, exponentially distributed over the vertical in order to have enough detail for the near bed conditions. Plant density $m(z)$ was defined at 400 m^{-2} uniform over depth, stem diameter $d(z)$ at 0.005 m uniform over depth. The drag coefficient $C_D(z)$ was implemented according to the measurement results depicted in Figures 6 - 8. An estimate of the drag coefficient at z = 0 was made at a value of 2.5. Figure 9 presents the simulated and measured horizontal velocity profiles. The depth-averaged velocities were 0.53 m/s for Test2EMS, 0.56 m/s for Test2LDA and 0.44 m/s for Test3EMS.



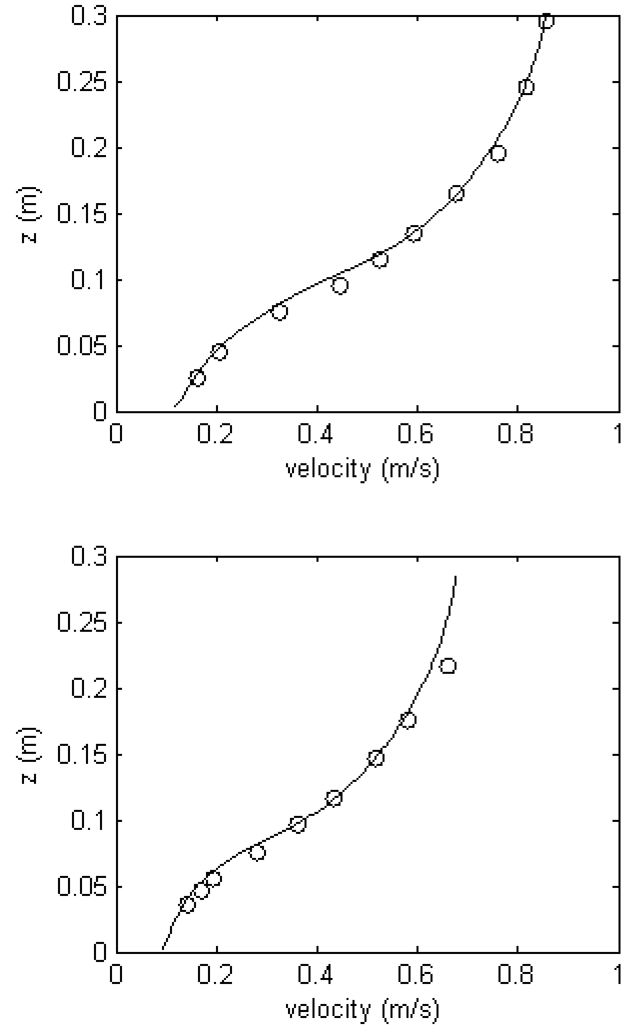


Figure 9. Measured (circles) and simulated horizontal flow velocity profiles for Test2EMS (top), Test2LDA (middle) and Test3EMS (low).

From the 1DV model simulations an estimate of the shear velocity at the bed can be obtained resulting into a bed shear stress. Table 2 presents the results. The total shear stress τ of the experiments with vegetation is obtained by extrapolating the measured Reynolds stress profile above the vegetation to the bed. The bed shear stress τ_b is derived from the combination of the measurements and model simulations. These values are compared to the bed shear stress that results of flow simulations for similar depth-averaged velocities and flow depths as used in the experiments with vegetation. The latter are not the results of the reference tests, because their conditions deviate too much. The results show that the reduction in bed shear stress as a result of the presence of the vegetation is about 80% compared to a situation without plants.

Table 2. Values for total shear stress and bed shear stress with and without vegetation.

	Total shear stress with vegetation (N/m^2)	Bed shear stress with vegetation (N/m^2)	Bed shear stress without vegetation (N/m^2)	Reduction in bed shear stress due to vegetation (%)
Test 2EMS	17.6	0.30	1.42	-78.9
Test 2LDA	22.6	0.33	1.53	-78.4
Test 3	13.5	0.22	1.07	-79.4

Bed level changes and sediment transport

It proved difficult to apply a flat bed in between the plants. Therefore, the initial bed profile shows bed level changes up to several centimetres. During the runs, the bed level showed net erosion. It was observed that the erosion started at the most downstream end of the plant section, where the flow velocities were highest, due to the non-uniform flow conditions. The erosion gradually progressed in backward direction. An analysis of the bed level profiles shows these trends, see Figure 10.

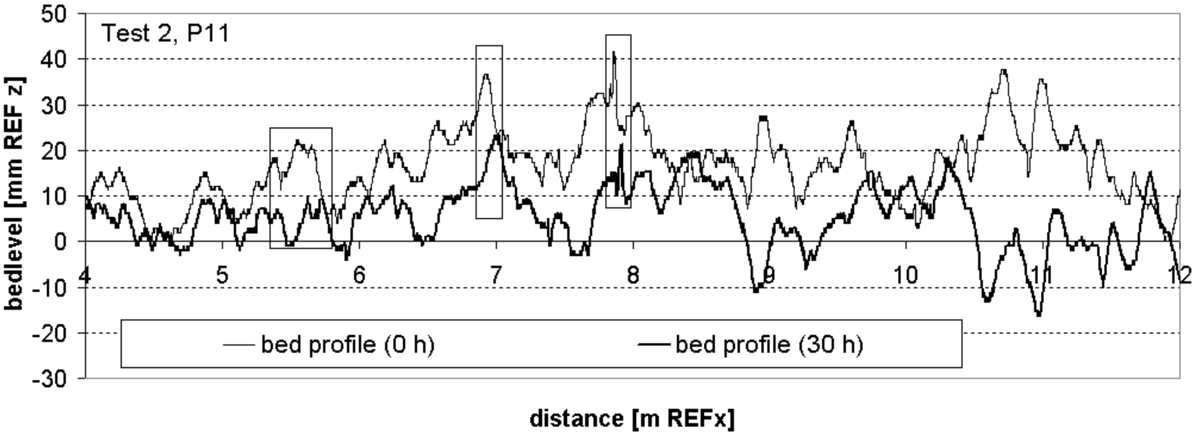


Figure 10. Bed levels for Test2, at t=0 (thin line) and t=30 hours (thick line).

There are several other interesting observations. First, there is an absence of bed forms, such as ripples, although these were clearly observed in the reference runs. Second, typical bed level peaks or troughs that were already present in the initial profile were still found after prolonged run-times, see boxes in Figure 10. It seems that the bed shows a general vertical movement due to erosion, rather than a horizontal movement of bed transport.

Finally, the sediment transport rate of the eroding bed was obtained using two different methods (see material and methods section) and plotted against the bed shear stress in Figure 11. Figure 11 shows that a similar transport rate for a case with vegetation can be realised at a lower bed shear stress compared to a case without vegetation.

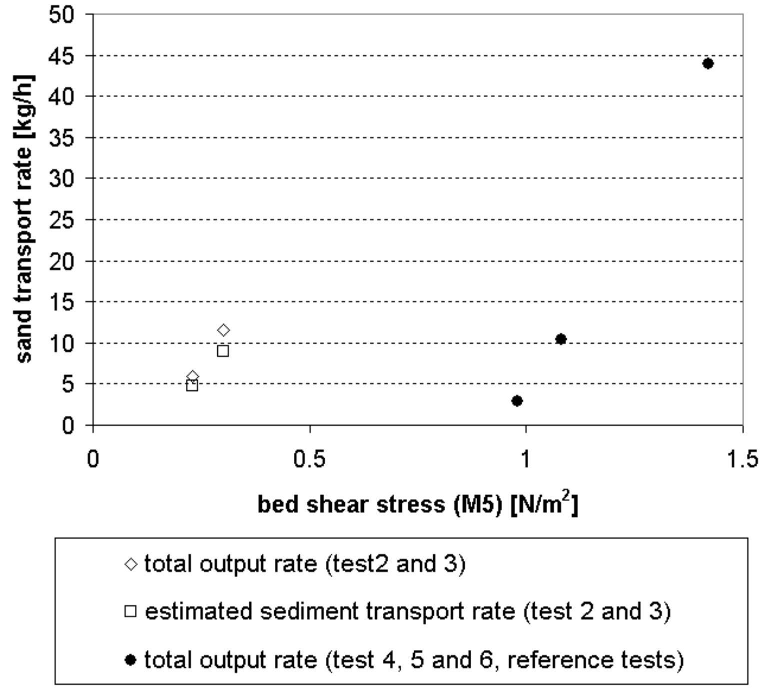


Figure 12. Sediment transport rates.

It is hypothesised that the relative increase in sediment transport at comparable bed shear stress levels is due to the increased turbulence levels within the vegetation. The increased turbulence is capable of picking up the sediment more effectively and thus bringing the sediment in suspension. Figure 13 compares the turbulence intensity for tests with and without vegetation. Figure 13 shows that the turbulence levels within the vegetation are increased by a factor 4 compared to the cases without vegetation.

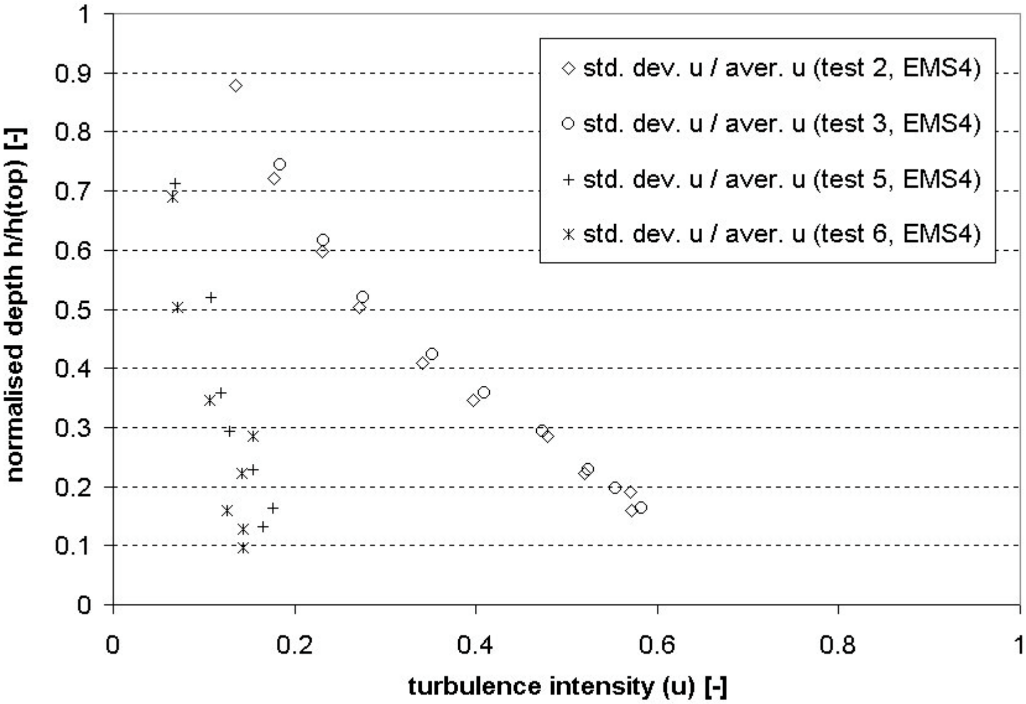


Figure 13. Turbulence intensity for tests with (2 and 3) and without (5 and 6) vegetation.

DISCUSSION AND CONCLUSIONS

These flume experiments have shown that vegetation reduces the bed shear stress by 80%. This reduction percentage cannot be applied to other cases directly, because the reduction is very much dependent on the submersed depth and other vegetation properties. Furthermore, the bed shear stress in between the submersed vegetation was not measured directly, but stems from model simulations with a numerical 1DV-model. These values could therefore be dependent on model assumptions, boundary conditions and model schematisation.

The sediment transport measured in these experiments is a measurement of erosion under non-uniform flow conditions. This is the case for the vegetated tests as well as for the reference tests. The results are therefore not comparable to formulations for equilibrium, uniform flow conditions. It was found that at seemingly lower bed shear stresses for the vegetated case a same amount of sediment could be transported compared to the reference case. The analysis of the bed level profiles gives rise to the hypothesis that the sediment transport is mainly in the form of suspended transport. The increased turbulence levels in between the vegetation are capable of picking up the sediment more effectively and thus bringing the sediment in suspension.

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