Open Channel Flow through Different Forms of Submerged Flexible Vegetation

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Abstract: Laboratory experiments are used to explore the effect of two forms of flexible vegetation on the turbulence structure within a submerged canopy and in the surface flow region above. The two simulated plant forms involve flexible rods (stipes) of constant height, and the same rods with a frond foliage attached. These plant forms were arranged in a regular staggered configuration, set at the same stipe density. The plant geometry and its mechanical properties have been scaled from a real aquatic plant using Froudian similarity, and the methods used for quantifying the bending stiffness, flexural rigidity, and drag force−velocity relationship of the vegetation are outlined. Experimental results reveal that within the plant layer, the velocity profile no longer follows the logarithmic law profile, and the mean velocity for the rod/frond canopy is less than half of that observed for the simple rod array. In addition to the mean flow field, the turbulence intensities indicate that the additional superficial area of the fronds alters the momentum transfer between the within-canopy and surface flow regions. While the frond foliage induces larger drag forces, shear-generated turbulence is reduced due to the inhibition of momentum exchange by the frond surface area. It is known that the additional drag exerted by plants reduces the mean flow velocity within vegetated regions relative to unvegetated ones, but this research indicates that plant form can have a significant effect on the mean flow field and, therefore, potentially influence riverine and wetland system management strategies.

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Introduction

The status of vegetation within river systems has changed in recent years. Both aquatic and riparian vegetation have become central to river restoration schemes and the importance of their preservation to river ecology has now been recognized. The reduction in mean flow and production of turbulence induced by a vegetated region relative to a nonvegetated region means that this is of fundamental significance to flood conveyance estimation, as well as to contaminant and sediment transport.

In recent years, considerable advances in our understanding of air flow in deeply submerged plant canopies have come from meteorologists working on terrestrial systems (Plate and Quraishi 1964; Raupach 1981; Brunet et al. 1994). Similarly, work from the coastal engineering community, who have been interested in such topics as the damping of waves by submerged vegetation and the impact of the kelp harvesting on beach erosion (Dubi 1995; Lovas 2000) has also made a significant contribution. However, in the river or wetland environment, there have been few detailed studies reported on the effect of submerged flexible plants on the turbulence structure within the canopy or in the surface flow region.

Much of the earlier work on the hydraulic properties of riverine vegetation was conducted by agricultural engineers who concentrated on determining roughness coefficients or developing design methods, rather than on obtaining a better understanding of the physical processes (Ree 1958; Thompson and Robertson 1976, etc.). More recent work has picked up this latter theme and has looked at the hydraulics of rigid emergent vegetation, where the vegetation has been simulated by a group of cylinders of the same height and diameter at regular spacing (Pasche 1984; Tsujimoto et al. 1992; Tsujimoto and Shimizu 1993; Fairbanks and Diplas 1998; Meijer and Van Velzen 1999; Nepf 1999). Fairbanks and Diplas (1998) have examined turbulence statistics for a rigid canopy for a submerged and emergent state and found that both the longitudinal and vertical turbulence intensity profiles are variable and dependent on the spatial sampling location. Nepf (1999) has conducted detailed laboratory experiments on rigid nonsubmerged cylindrical rods, where the researcher tested a physically based model which links vegetation form drag, turbulence intensity, and turbulent diffusion.

There have been fewer laboratory studies on flexible vegetation (Dunn et al. 1996; Tsujimoto and Kitamura 1998; Nepf and Vivoni 1999; Stephan and Wibmer 2001). Kouwen (1988) and Kouwen and Li (1980) used a roughness height approach for determining the hydraulic resistance of a grass-lined channel. They were the first to define a biomechanical parameter, MEI (the product of stem density M, stem modulus of elasticity E, inertia of the second moment of the stem area I) which could then be related to hydraulic resistance. Temple (1987) undertook laboratory experiments on grasses correlating MEI to undeflected veg-

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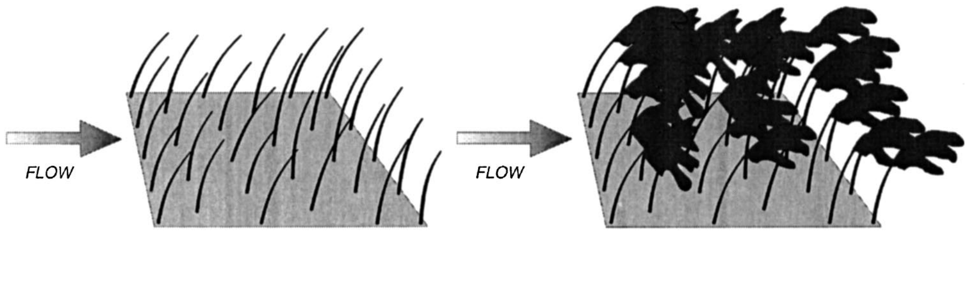

Fig. 1. Plant forms investigated (a) rod array (b) rod/frond canopy

etation height and found a large disparity between growing and dormant grass. More recently, Fathi-Maghadam and Kouwen (1997) have conducted flume experiments on pine and cedar tree saplings and branches for emergent conditions. They found that in flexible vegetation, a considerable area of foliage is hidden behind the frontal areas that also absorbs momentum in addition to the projected plant area. Thus, for a continuous plant canopy, the momentum absorbing area should be based on a total foliage area (in the flow direction) per unit volume. Stephan and Wibmer (2001) have examined the vertical velocity profiles for three species of flexible macrophyte in attempting to quantify flow resistance. Nepf and Vivoni (1999) have conducted high spatial resolution experiments on a simulated flexible plant canopy. They examined the transition from emergent to submerged flow conditions and, for the latter condition, investigated the turbulence structure both within the vegetation canopy and in the surface flow region above.

For both rigid and flexible vegetation types in emergent conditions, the Reynolds stresses within the flow are relatively small and the streamwise turbulence fluctuations are found to be small. However, when the vegetation becomes submerged, a horizontal shear layer forms which is active over some depth of the canopy and in the surface flow region above. The Reynold's stress profile reaches a peak at the interface and decays within and above the canopy. It seems that this characterizes the flow irrespective of the vegetation being rigid or flexible (Tsujimoto et al. 1992; Nepf and Vivoni 1999).

However, the research on both rigid and flexible vegetation has focused on only one type of plant form per study. Also, the few experimental studies that have been conducted on flexible vegetation have generally not documented the bending stiffness or flexural rigidity of the simulated plants and how this can be scaled from real vegetation. This paper addresses the issue of scaling biomechanical properties from real vegetation and outlines the methods used in quantifying these parameters. It also explores, for the first time, the effect of two forms of flexible vegetation on the turbulence structure within the submerged canopy and in the surface flow region.

Table 1. Scalar Relationships for Froudian Law of Scaling

Type	Quantity	Dimensions	Froude law model scale 1:x
Geometric	Length	L	x
	Area	L^2	x^2
Kinematic	Velocity	L/T	$x^{1/2}$
Dynamic	Force	ML/T^2	x^3
	Bending stiffness (K)	M/T^2	x^2
	Flexural rigidity (EI)	ML^3/T^2	x^5

Geometry and Biomechanical Plant Properties

The turbulence characteristics of uniform flow through flexible vegetation were investigated under two simulated plant forms: Flexible rods (stipes) of constant height, and density, and the same rods with a frond foliage attached (see Fig. 1). These simulated plants were 1/10 scale replicas of a species of kelp (*Laminaria hyperborea*) and all parameters, both geometric and kinematic, were scaled using the Froude law (see Table 1 for scalar relationships, and Figs. 2 and 3 for notation and cross-sectional properties, respectively). They were manufactured from a liquid plastic of the necessary density to cast the 1/10 scale plants with the appropriate stiffness. This work and the quantification of the biomechanical properties of the plant were carried out at the University of Trondheim (by A. Torum and his team, see Dubi 1995; Lovas 2000). While here we use a marine species as a model plant, the simulated vegetation does bear a morphologic and biomechanical resemblance to commonly encountered riverine plants (Larsen et al. 1990). Without foliage, the rodlike vegetation could

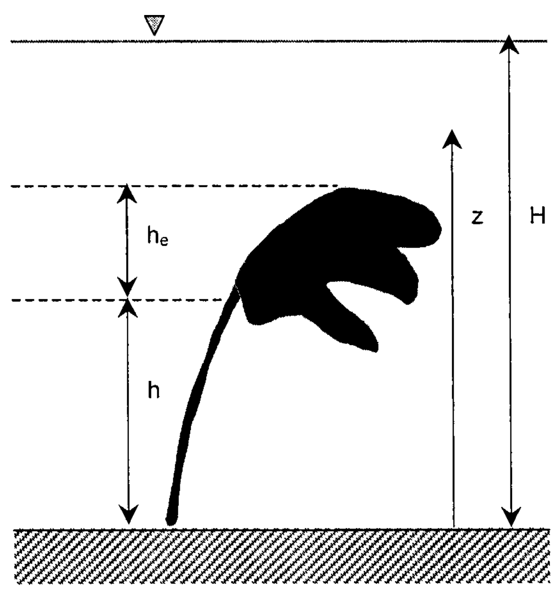

Fig. 2. Notation used in study (see also Table 2)

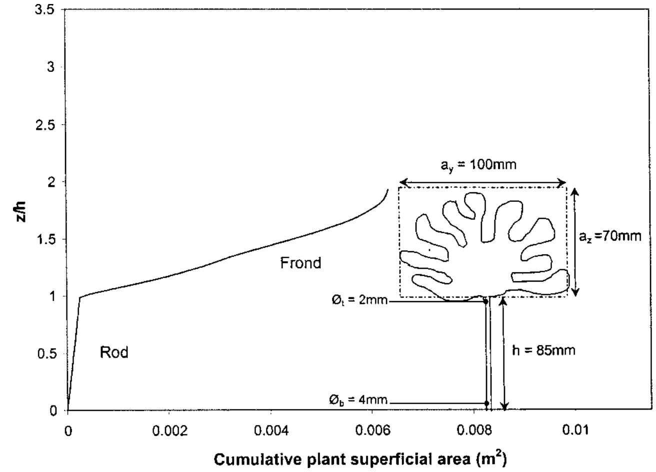

Fig. 3. Variation in plant area with depth ratio and approximate frond dimensions

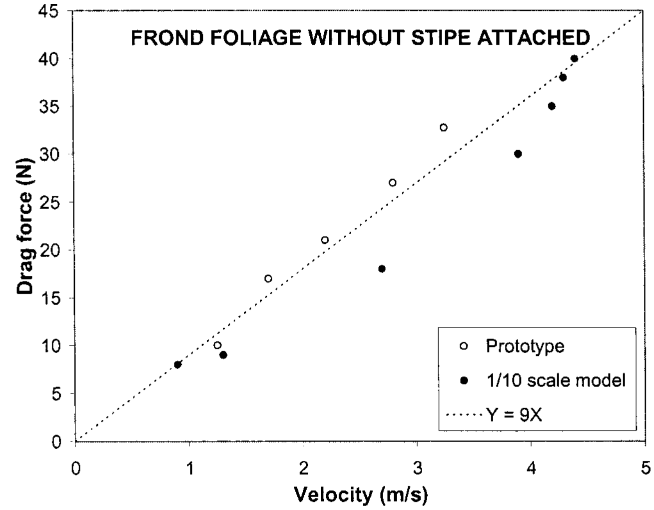

Fig. 4. Drag force–velocity relationship for the 1/10 scale model frond and one prototype frond, shown at prototype scale according to the Froudian law of scaling

be considered equivalent to long grasses or reeds, while the plants with foliage bear a resemblance to a number of species of aquatic macrophyte. It is, hence, an appropriate analogue for use in these exploratory simulations. This is a similar approach to that adopted by other authors (e.g., Nepf and Vivoni 1999) who have studied scale models of flexible vegetation and who have found it necessary to use simplified and generalized plant forms compared to the complexity of real vegetation assemblages.

The bending stiffness of the prototype stipes was measured both in the field and the laboratory. After removal from the sea bed, the kelp stipes were immediately tested on a deck of the boat. For the laboratory testing, the kelp stipes were transported in plastic wrapping and then subsequently kept in saltwater until tests were conducted in the laboratory the day after their removal from the field. In both cases, the stipes were tested in cantilever bending and the natural kelps of the same stipe length were chosen. The larger diameter end was fixed horizontally and weights were attached to the smaller diameter end.

Seven kelp samples were tested in the field and a total of 58 force-deflection measurements were taken. Of these, 84% fell within the linear range giving a mean bending stiffness of 16.7 N/m with a standard deviation of 9.2 N/m.

Three manufactured stipes were tested in the laboratory and a total of 22 measurements was conducted. The manufactured stipes exhibited a relatively nonlinear relationship compared to the natural kelps, with 27% of the measurements being within the linear range. Within this range, the mean bending stiffness was 11.0 N/m with a standard deviation of 3.6 N/m. Based on all of the measurements (both in the nonlinear and linear ranges), this compares with a mean bending stiffness of 45.1 N/m with a relatively larger spread of values (standard deviation was 30.3 N/m).

This would suggest that when relatively smaller loads are applied and while both materials (natural and manufactured stipes) exhibit linear force-deflection behavior, the natural stipes have greater bending stiffness. However, at relatively larger loads, there is a larger variability in the bending properties of the manufactured stipes compared to the natural stipes and, overall, the manufactured ones have a greater bending stiffness. This highlights the difficulties involved in comparing material properties of different materials types.

For the flow conditions examined in the experimental investigation, the flexural rigidity (J) of the model stipes, which is defined as the product of the modulus of elasticity (E) and the second moment of area (I), was evaluated as approximately in the range of 6.8 to 11.3×10^{-5} Nm^2, which corresponds to a full scale flexural rigidity in the range of 6.8 to 11.3 Nm^2. For the natural stipes, the flexural rigidity was evaluated as being in the range of 1.0 to 6.1 Nm^2. This was computed using the relationship between the force (F), deflection (w), beam length (L), modulus of elasticity (E), and the second moment of area (also referred to as the moment of inertia) (I):

$$EI=\frac{F}{w}\frac{L^3}{3} \tag{1}$$

where the bending stiffness (F/w) or gradient of the force–deflection curves is defined from the linear range of the curves.

The drag force–velocity relationship of the model frond (without the stipe attached) was measured in the laboratory in a flume 500 mm wide and 10 m long. This involved connecting the frond by a thread to a force transducer, and then passing the thread over a pulley before being fixed. The velocity was then measured by a minipropeller meter located at the same depth within the flow as the frond. A representative sample of the prototype fronds were tested in a similar manner in the field (see Fig. 4, all results are scaled up to full scale). The fronds and force transducer were attached to a pole and suspended into the water at a depth of 5 m below the water surface. A propeller current meter was also positioned at the same depth.

The drag forces on the artificial and prototype fronds are linearly proportional to the velocities in the practical range of 0.75–3 ms^{-1}, and can both be represented by a linear function $Y=CX$ where $C=9$ N/(ms^{-1}) (where $Y=$drag force and X $=$velocity). There is a fair agreement between the scaled frond and the kelp (prototype) frond (see Fig. 4). See Dubi (1995) for further details. A summary of the physical and biomechanical properties is given in Table 2.

Experiments of Flow through Flexible Aquatic Vegetation

The experiments were conducted in a flume 0.5 m in width and 10 m in length, with longitudinal bed slope set at 1/1,000. These

Table 2. Summary of Physical and Biomechanical Parameters

Parameter	Variable	Value
Stipe/rod		
Stipe length	h_{stipe} or h	85 mm
Stipe base diameter	Φ_b	4 mm
Stipe top diameter	Φ_t	2 mm
Mean bending stiffness	K	11.0 Nm^{-1} (in linear range) 45.1 Nm^{-1} (based on all measurements in both linear and nonlinear ranges)
Flexural rigidity	J	$1-2\times10^{-5}$ Nm^2
Frond		
Frond surface area	A_{frond}	0.006 m^2
Approximate height of frond when stretched (see Fig. 3)	a_z	70 mm
Approximate width of frond when stretched (see Fig. 3)	a_y	100 mm
Rod array		
Stipe projected area	A_{stipe}	
Array height	h_{stipe} or h	85 mm
Stipe/rod density	λ_s	1.67 m^{-1}
Rod/frond canopy		
Thickness of pronated fronds	h_e	20 mm
Canopy height in pronation	$h_{stipe}+h_e$	105 mm
Plant density	λ_p	22.4 m^{-1}
Hydraulic		
Flow depth	H	0.128–0.290
Depth ratio	H/h	1.5–3.4
Area mean Reynolds number	$R_a=((Q/A)H)/v$	6,000–20,000

experiments were conducted at the Norwegian Hydrotechnical Laboratory (Trondheim, Norway). The length of vegetation canopy (7 m) was sufficient for the establishment of uniform flow. A V-notch sharp crested weir was used to measure discharges calibrated in the range of 0.5–25 l/s, this was constructed and operated under BS3680 (1965). BS3680 recommends a constant value for the coefficient of discharge of 0.585, for all heads in excess of 0.16 m. The water surface profile was controlled by the

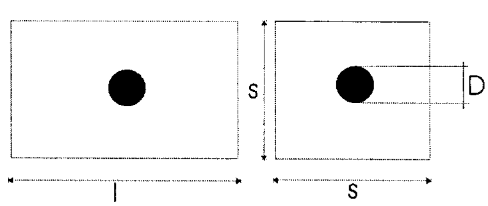

Fig. 5. Notation used in definition of stipe/rod density λ_s

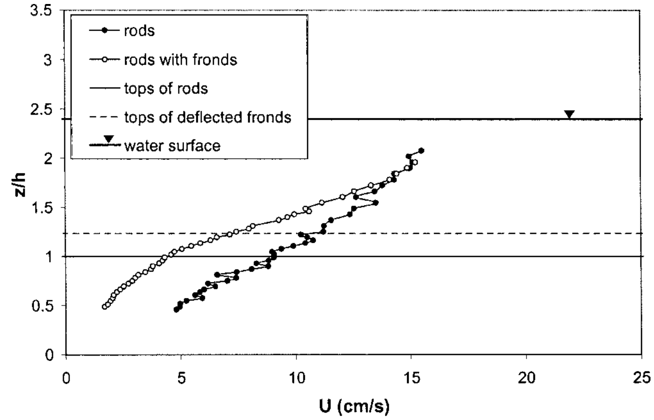

Fig. 6. Mean velocity profile for depth ratio (H/h) 2.4

downstream tailgate weir which can be raised and lowered by a gear system allowing its height to be set with a high degree of accuracy. To establish uniform conditions, flow depths were measured along the flume and the tailgate weir was adjusted accordingly. The flow depth was varied to produce depth ratios (H/h) where h = plant stem height, H = water depth, from 1.5 to 3.4. A three-dimensional sideways looking Acoustic Doppler Velocimeter, measuring at a frequency of 25 Hz, was used to measure the velocity and turbulence statistics. A 240 s sampling period was used.

Previously, most experiments have been conducted with arrays of rigid emergent cylindrical elements of constant diameter (Tsujimoto et al. 1992; Tsujimoto and Shimizu 1993; Nepf 1999) where the momentum absorbing area of the plant is constant with plant height and so the plant density or stipe density has been defined as

$$\lambda_s=\frac{\text{Projected area of stipe}}{\text{Total volume}}=\frac{D}{s^2}\ \text{or}\ \lambda_s=\frac{D}{s\ell} \tag{2}$$

where D = stipe/rod diameter; and s and ℓ = lengths of the control volume which is dependent on the plant spacing (see Fig. 5). Extending this definition for use with submerged plant forms of a stipe/frond structure where the cross-sectional area varies as a function of the plant height gives

$$\lambda_p=\frac{\text{Total momentum absorbing area}}{\text{Total volume}}=\frac{A_{frond}+A_{stipe}}{s^2(a_z+h_{stipe})} \tag{3}$$

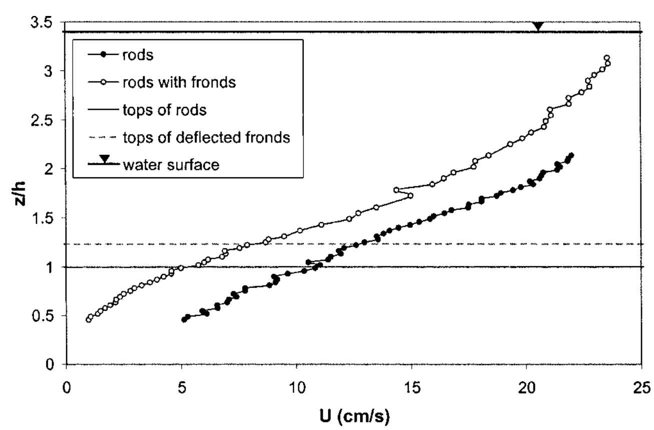

Fig. 7. Mean velocity profile for depth ratio (H/h) 3.4

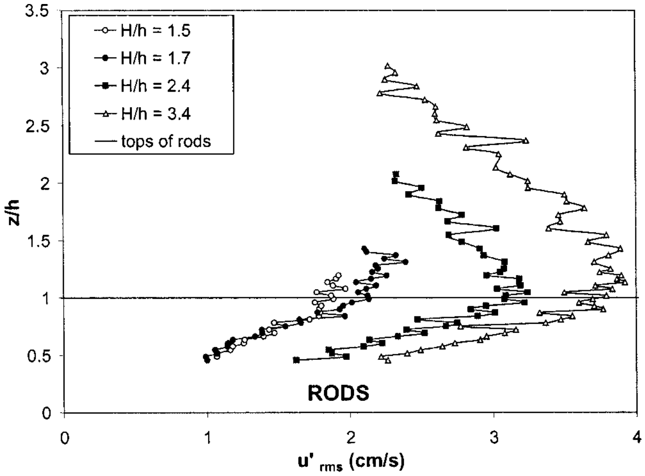

Fig. 8. Representative profiles of streamwise turbulence for simple rod array

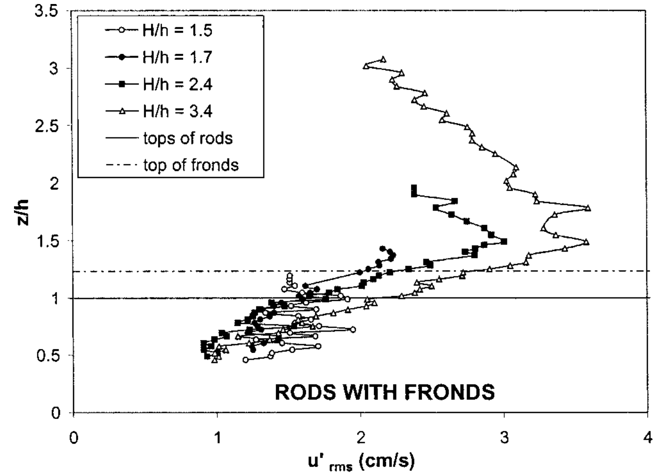

Fig. 9. Representative profiles of streamwise turbulence for rod/frond canopy

(see Table 2 for notation). The total surface area of the frond A_{frond} is used in this expression rather than the projected frontal area since a considerable area of foliage or frond is hidden behind the frontal area, and this absorbs momentum in addition to the projected area (Fathi-Maghadam and Kouwen 1997). Whether the hidden foliage absorbs as much momentum as when it is fully spread remains unknown and untested. However, the use of total surface area in this definition helps us to quantify and standardize the vegetation density of a natural and complex plant form.

The stipe plants were placed and glued into prepared holes into boards which were fitted into the length of the flume. The stipe plants were set at a staggered configuration at a stipe density (λ_s) of $1.67\ \text{m}^{-1}$ [given by Eq. (2)]. The plant density, λ_p, $22.4\ \text{m}^{-1}$ [given by Eq. (3)] was for the rod/frond canopy.

Experimental Results and Discussion

A representative selection of velocities, u (time-averaged velocity measured at the center of four plants), turbulence, u'_{rms} (root-mean square of the time series of streamwise velocity fluctuations) and Reynold's stress, $\overline{u'w'}$ (instantaneous streamwise velocity fluctuation multiplied by the instantaneous vertical velocity fluctuation, then time averaged) are shown in Figs. 4–9, where z is the vertical distance from the channel bed. The dotted line in Figs. 4–9 denotes the approximate top of the deflected frond canopy for all flow conditions and the solid line represents the stipe tops. It was found that the height of the stipe and frond top were not sensitive to the flow depths examined.

The velocity profiles (Figs. 6 and 7) show that the mean flow in the plant layer is greatly retarded and no longer follows the logarithmic law profile. This is in agreement with findings for both rigid and flexible vegetation (Tsujimoto et al. 1992; Nepf and Vivoni 1999, respectively). Profiles for both the rod and the frond canopy show significant variation in mean velocity and characterize the generation of a horizontal shear layer. Within the plant layer, the magnitude of the mean velocity for the frond canopy is less than half of that observed for the simple rod canopy. The streamwise turbulence peaks at the level of the rod tops for the rods alone, while it peaks above the frond tops for the frond canopy situtation (see Figs. 8 and 9). A relatively higher magnitude of turbulence occurs within the simple rod canopy than within the frond canopy, although at a higher level of relative flow depth ($z/h>1.9$), the distribution of turbulence in the upper surface flow region is unaffected by the plant form.

The additional surface area of the fronds alters the momentum transfer between the canopy and the surface flow region. The fronds shift the peak Reynold's stress to a higher level in the flow, above the canopy (Figs. 10 and 11). The turbulent shear layer penetrates a relatively larger proportion of the rod canopy than the frond canopy. This suggests that the fronds at the top of the canopy inhibit the momentum exchange between the interior of the canopy and the overlying surface flow by confining the lower layer. The drag of the frond surfaces induces additional turbulence which shifts the maximum turbulent stresses to a level above the top of the canopy. For flow conditions where the depth ratio (H/h) is greater than or equal to 2.4, the turbulent stress profiles converge at a similar depth in the flow, at 60–70% of the total flow depth, and the turbulence structure is unaffected by the additional drag imposed by the frond foliage. Higher levels of turbulence stress generated by the rod array over its submerged depth imply that the shear interaction and turbulent mixing between the plant canopy and surface flow region are greater for the rods alone than the rod/foliage combination. So, although the fronds induce larger drag forces, shear generated turbulence is

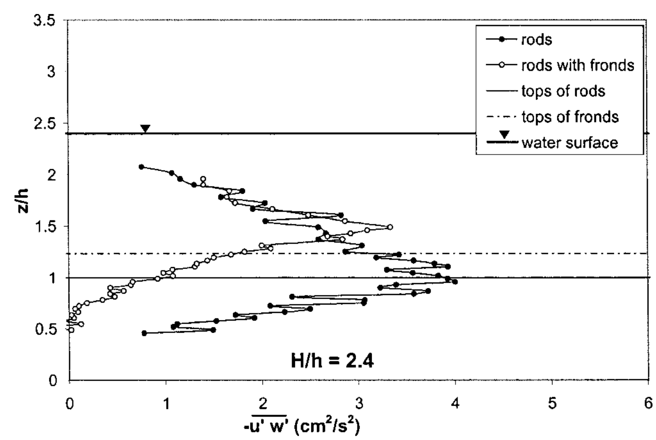

Fig. 10. Representative profiles of Reynolds stress for simple rod array and rod/frond canopy at depth ratio (H/h) of 2.4

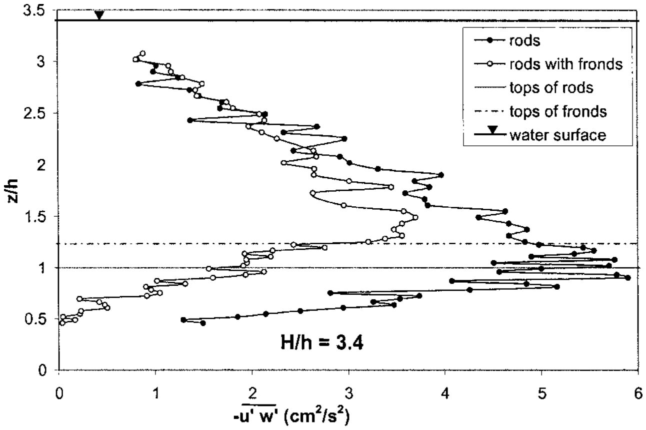

Fig. 11. Representative profiles of Reynolds stress for simple rod array and rod/frond canopy at depth ratio (H/h) of 3.4

reduced possibly due to the inhibition of the vertical momentum exchange by the greater surface area of the fronds.

The thickness of the active momentum exchange layer h_p, can be defined as the distance from the top of the canopy to the level within the plant canopy or array by which the turbulent stress has decayed to 10% of its maximum value (Nepf and Vivoni 1999). The relationship between h_p and the relative flow depth (H/h_c) is shown in Fig. 12 along with data reported by others. Although plants used by Nepf and Vivoni (1999) were of a different form (six blades attached to a short basal stem), the flexural rigidity of the blades ($J=1.0\times10^{-5}$ Nm^2) was lower than the model stipes used in these experiments but was similar to the prototype kelp stipes. Dunn et al. (1996) used commercial drinking straws of constant diameter to simulate a flexible stipe array.

Curves in Fig. 12 are drawn so that $h_p/h_c=0$ for $H/h_c=1.0$ based on the assumption that negligible turbulent stresses are produced in the emergent condition. For the same stipe density but differing magnitudes of momentum absorbing area due to plant form, the penetration ratio (h_p normalized by h_c) decreases with the addition of foliage and the increase in the momentum absorbing area (see Fig. 12). This has a similar effect to increasing stipe density and hence increasing the momentum absorbing area over the full height of the plants per unit volume.

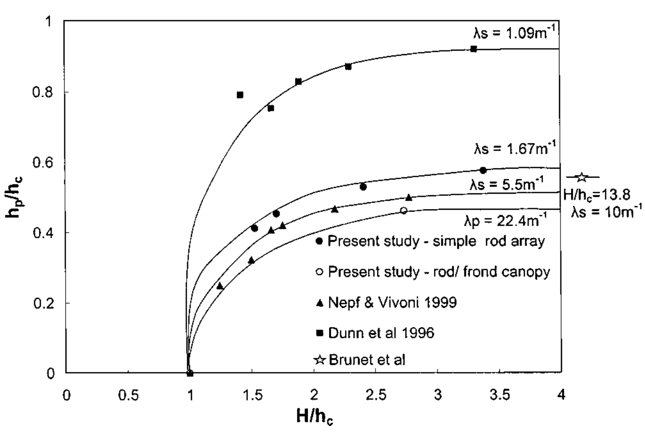

Fig. 12. Transition from emergent (H/h_c) to deeply submerged conditions. Penetration thickness, h_p, was based on the Reynolds stress profiles. h_c is plant canopy thickness.

Conclusions

An experimental study has been conducted to explore the effect of two forms of flexible vegetation on the turbulence structure within the submerged canopy and in the surface flow region. The plant geometry and its biomechanical properties have been scaled from a real plant and the methods for quantifying the latter properties have been outlined. The paper provides a new data set in this relatively unstudied area and complements the limited number of existing studies [Dunn et al. (1996), Fairbank and Diplas (1998), and Nepf (1999) are the only examples we have found] in the goal of building up a general picture of the interaction of flow with vegetation. The paper also provides insight into the effect of different forms of submerged plant canopy on momentum transfer and addresses the issue of scaling biomechanical properties from real vegetation.

The additional surface area of the fronds significantly increases the momentum absorbing area of the plants. This results in a decrease in the mean primary velocities within the canopy layer and for a proportion of the surface region flow above. When the level of submergence is increased, the magnitude of streamwise turbulence within the canopy layer for the "with-foliage" plants is undisturbed relative to the nonfoliage plants. So while the foliage induces larger drag forces, the shear-generated turbulence is reduced due to the inhibition of momentum exchange by the frond surface area. The addition of the plant foliage at the top of the stems inhibits the turbulent mixing between the two flow regions, the canopy layer, and the surface flow layer, and shifts the turbulent stress peak to a level above the canopy top surface.

While it is known that the additional drag exerted by plants reduces the mean flow velocity within the vegetated regions relative to unvegetated ones, this research indicates that the greater momentum absorbing area provided by some plant forms, can have significant effect on the mean flow field of the entire channel. For the stipe density considered, with-foliage plants significantly reduce the mean velocities relative to plants without foliage. This suggests that in regions prone to scour and erosion with-foliage macrophytes may give better protection relative to their nonfoliage equivalents. Riparian buffer zones are often used to address nonpoint-source pollution; the additional momentum absorbing area of a foliage plant canopy relative to a nonfoliage one may lead to more effective retention and processing.

These findings have further implications in the restoration and enhancement of riverine and wetland systems. The presence of with-foliage plant canopies will offer a different habitat in terms of velocity and bed shear stress relative to their nonfoliage counterparts. Undoubtedly, the establishment of macrophyte species plays a crucial role in physically shaping boundaries and providing food, fish habitat, and substrate for aquatic invertebrates.

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