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Citation	Luhar, Mitul, Jeffrey Rominger, and Heidi Nepf. "Interaction between flow, transport and vegetation spatial structure." Environmental Fluid Mechanics 8.5-6 (2008): 423-439. Web. 2 Feb. 2012. © 2008 Springer Science+Business Media B.V.
As Published	http://dx.doi.org/10.1007/s10652-008-9080-9
Publisher	Springer-Verlag
Version	Author's final manuscript
Citable link	http://hdl.handle.net/1721.1/69014
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# Interaction Between Flow, Transport and Vegetation Spatial Structure

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## Abstract:

This paper summarizes recent advances in vegetation hydrodynamics and uses the new concepts to explore not only how vegetation impacts flow and transport, but also how flow feedbacks can influence vegetation spatial structure. Sparse and dense submerged canopies are defined based on the relative contribution of turbulent stress and canopy drag to the momentum balance. In sparse canopies turbulent stress remains elevated within the canopy and suspended sediment concentrations are comparable to that in unvegetated regions. In dense canopies turbulent stress is reduced by canopy drag and suspended sediment concentration is also reduced. Further, for dense canopies, the length-scale of turbulence penetration into the canopy,  $\delta_e$ , is shown to predict both the roughness height and the displacement height of the overflow profile. In a second case study, the relation between flow speed and spatial structure of a seagrass meadow gives insight into the stability of different spatial structures, defined by the area fraction covered by vegetation. In the last case study, a momentum balance suggests that in natural channels the total resistance is set predominantly by the area fraction occupied by vegetation, called the blockage factor, with little direct dependence on the specific canopy morphology.

# Introduction

Aquatic vegetation improves water quality via nutrient uptake and oxygen production (*e.g.* Chambers and Prepas 1994, Kadlec and Knight 1996, Wilcock et al. 1999). The potential removal of nitrogen and phosphorous is so high that some researchers advocate widespread planting in waterways (Mars et al. 1999). In addition, aquatic vegetation can sequester heavy metals including arsenic, mercury and lead (Windham et al. 2003). Vegetation promotes biodiversity, by creating different habitats and spatial heterogeneity in the stream velocity (Kemp et al. 2000). Finally, coastal marshes and mangroves provide coastal protection by damping waves and storm surge (*e.g.* Turker et al. 2006, Massel et al. 1999, Othman 1994). Through the processes described above, aquatic vegetation provides ecosystem services with an estimated annual economic impact of over ten trillion dollars (Costanza et al. 1997).

In rivers, aquatic vegetation was historically considered only as a source of flow resistance, and vegetation was frequently removed to reduce flooding during extreme flow conditions (*e.g.*, Kouwen and Unny 1973, Kouwen 1990, Wu et al. 1999). However, as noted above, vegetation also provides ecological services that make it an integral part of river ecosystems. The trade-off between flood and ecological management underlines the need for a reliable method to predict channel resistance in the presence of vegetation. The problem is particularly pressing given that over half of the world's major river networks are regulated to manage water resources and reduce flooding (Nilsson et al. 2005), and that the frequency and magnitude of storms is projected to increase due to climate change (Oki and Kanae 2006, Sellin et al. 2003). However, translating vegetation characteristics into simple resistance parameters, such as Manning's friction factors, remains an open challenge. Recent field (*e.g.* Green 2005, Champion and Tanner 2000) and laboratory studies (e.g. Meijer and van Velzen 1998, Järvelä

2002) have had some success, but more work is still needed to develop predictive, rather than fitted, drag models.

Finally, by reducing local bed-stress, vegetation creates regions of sediment retention (Leonard and Luther 1995, Lopez and Garcia 1998, Palmer et al. 2004), which can impact local bathymetry. Fonseca et al. (1983) observed that finite patches of seagrass were associated with local bed maxima and attributed this to enhanced particle retention within the meadow. They suggest that the bedforms grow until the enhancement in bed stress associated with the bedform is balanced by the reduction in bed stress associated with the vegetation. Similarly, Tal and Paola (2007) experimentally show how single-thread channels are primarily formed and stabilized by vegetation. The tendency for vegetation to inhibit resuspension is also a key factor in stabilizing clear water conditions in shallow lakes (Jeppsen et al. 1999, Barko and James 1998)

The above examples point to important ways that vegetation shapes the form and function of an aquatic ecosystem. Recognition of this control has focused significant new research on flow through and around vegetation. This paper summarizes the recent advances physical understanding of vegetation hydrodynamics, and then uses it to explore three case studies. The first study examines the link between suspended sediment concentration and shoot density within a seagrass meadow. The second study uses the connection between flow and meadow structure to explain why seagrass meadows favor specific values of area coverage. Finally, the last study uses a momentum balance to improve our understanding and prediction of channel resistance.

## **Aquatic Vegetation Canopies and Momentum Balance**

Aquatic vegetation most often exists in canopies or meadows, *i.e.* close groupings of individual plants. Aquatic canopies are highly heterogeneous, varying from a height, *h*, that occupies only a small fraction of the water depth, *H*, to being fully emergent, as well as varying in stem density and geometry in both the horizontal and vertical direction. For stem-scale processes, *e.g.* flux across the boundary layer of an individual leaf, one must parameterize the morphology of each stem and leaf. In this paper, however, we limit our attention to processes occurring at scales greater than individual stems, *i.e.* the canopy scale. At the canopy scale vegetation can be described by an average, distributed morphology using the parameter *a*, frontal area per volume. If individual stems have a characteristic frontal area,  $A_{f}$ , and the canopy contains *m* stems per bed area, the canopy has a *frontal area index ah* = mA<sub>f</sub>. The same parameter is used to describe the solidity,  $\lambda = ah$ , of urban and terrestrial canopies (*e.g.* Grimmond and Oke 1999, Jimenez 2004).

Many species of vegetation have simple stem morphology that can be characterized by the stem or blade width, *d*, for which a = md. The porosity of the canopy is  $n \approx (1-ad)$ . Aquatic vegetation spans a wide range of porosity. Marsh grasses are relatively sparse, with porosity n >0.99, stem diameters d = 0.1 cm to 1 cm, and a = 0.01 to 0.10 cm<sup>-1</sup> (*e.g.* Valiela et al. 1978, Leonard and Luther 1995, Lightbody and Nepf 2006, Hena et al. 2007). Submerged vegetation spans a = 0.01 to 1 cm<sup>-1</sup>, with the lower limit associated with marine grasses, and the higher limit associated with channel vegetation (*e.g.* Kouwen and Unny 1973, Chandler et al. 1996, Ciraolo et al. 2006). With blade widths of d = 0.3 to 1 cm, the porosity is generally high, n > 0.90. Mangrove forests, or mangals, are the densest canopies, with porosity as low as n = 0.55, root diameters d = 4 cm to 9 cm, and a = 0.2 cm<sup>-1</sup> (Mazda et al. 1997, Furukawa et al. 1997). Within each canopy, flow is forced to move around individual stems and branches, such that the velocity field is spatially heterogeneous at the stem scale. A double-averaging method, *e.g.* as described in Raupach and Shaw (1982), reduces this heterogeneity to a tractable form. We define the coordinates *x* and *z* as parallel and normal to the local mean bed-slope, with z = 0 at the bed and positive away from the bed. The velocity vector  $\vec{u} = (u, v, w)$  corresponds to the coordinates (x, y, z). First, the instantaneous velocity and pressure (p) fields are decomposed into a time average (overbar) and deviations from the time-average (single prime). The time-averaged quantities are further decomposed into the spatial mean in a plane parallel to the bed (angle bracket) and deviations from that spatial mean (double prime). In this paper we restrict our attention to canopies of high porosity, so we may assume  $n \approx 1$ . For a homogeneous canopy, the resulting momentum balance is then (e.g. Nikora et al 2007)

$$\frac{D\langle \overline{u} \rangle}{Dt} = g_{x} - \frac{1}{\rho} \frac{\partial \langle \overline{p} \rangle}{\partial x} - \frac{\partial}{\partial z} \langle \overline{u'w'} \rangle - \frac{\partial}{\partial z} \langle \overline{u''w''} \rangle + \nu \frac{\partial^{2} \langle \overline{u} \rangle}{\partial z^{2}} + \frac{1}{2} C_{D} a \langle \overline{u} \rangle |\langle \overline{u} \rangle| \quad . \tag{1}$$
(i) (ii) (iii) (iv)

Here,  $g_x$  is the component of gravity parallel to the bed,  $\rho$  is the density of the fluid and v is the kinematic viscosity. Term (i) is the spatially-averaged turbulent stress. Term (ii) is an additional stress, called the dispersive stress, associated with spatial correlations in velocity. The dispersive stress is negligible compared to (less than 10% of) the turbulent stress for ah >=0.1; and increases only to 30% at ah = 0.03 (Poggi et al. 2004b). Although the dispersive stress makes some contribution in sparse canopies, the Reynolds' stress is dominant the stress for nearly all aquatic canopies. Within the canopy the viscous stress (term iii) is negligible compared to the

canopy drag (term iv), and above the canopy it is negligible compared to the turbulent stress. Finally, the spatial perturbation in velocity and pressure occurring at the surface of each plant element gives rise to viscous and form drag, which is typically modeled with a quadratic drag law (term iv). The drag coefficient,  $C_D$ , can vary with canopy density, a, and stem Reynolds' number,  $Re_d = \langle \overline{u} \rangle d/v$ , as well as the morphology and flexibility of individual plants (*e.g.* Raupach 1992, Tanino and Nepf 2008a, Wilson et al. 2003). Using the assumptions described above and denoting  $S = (\partial H/\partial x + \partial z_{bed}/\partial x)$ , with  $z_{bed}$  the position of the bed above a constant datum, we arrive at a simplified momentum balance that is applicable in most aquatic canopies

$$\frac{D\langle \overline{u} \rangle}{Dt} = gS - \frac{\partial}{\partial z} \langle \overline{u'w'} \rangle + \frac{1}{2} C_D a \langle \overline{u} \rangle |\langle \overline{u} \rangle|$$
<sup>(2)</sup>

From this momentum balance we will now define two regimes, sparse and dense canopies. For steady, uniform flow ( $D < \overline{u} > /Dt = 0$ ), the potential forcing (gS) is balanced by the sum of turbulent stress and canopy drag. When the turbulent stress dominates, the velocity profile approaches that of a turbulent boundary layer. This will be called sparse canopy behavior. As first demonstrated by Raupach et al. (1996), when canopy drag is sufficient, the drag discontinuity at the top of the canopy creates an inflection point in the velocity profile, and the profile resembles a free-shear-layer (FSL). This will be called dense canopy behavior.

To predict the transition from sparse to dense canopy behavior we compare the scales of the turbulent stress and canopy drag in (2). Because u' and  $w' \sim 0.1 < \overline{u} >$ , we expect the drag term in (2) to exceed the turbulent stress when  $C_{D}ah > 0.02$ . Empirical evidence, however, places the transition at a slightly higher value. That is, a clear inflection point is observed when

 $C_Dah > 0.1$ , and clearly absent when  $C_Dah < 0.04$  (as discussed in Nepf et al. 2007). Based on this, we define dense canopies as those for which  $C_Dah > 0.1$ .

For dense canopies, the inflection point occurring near the top of the canopy leads to the generation of large coherent vortices via the Kelvin-Helmholtz instability, as also seen in free shear layers (Brown and Roshko 1974). These energetic, coherent vortices dominate mass and momentum exchange between the canopy and the overlying water (*e.g.* Finnigan 2000, Ghisalberti and Nepf 2005, 2006). In a free-shear-layer, the KH vortices grow continually downstream, predominantly through vortex pairing (e.g. Winant and Browand, 1974). In a canopy shear layer, however, the KH vortices reach a fixed scale and a fixed penetration into the canopy ( $\delta_e$  in Figure 1b) at a short distance from the canopy's leading edge (Ghisalberti and Nepf 2004). Scaling analyses supported by observations show that the penetration scale,  $\delta_e$ , is inversely proportional to the canopy drag, as parameterized by  $C_{Da}$  (Nepf et al. 2007).

$$\frac{\delta_e}{h} = \frac{0.23 \pm 0.06}{C_D a h}.$$
(3)

The penetration scale segregates the canopy into two layers (Figure 1b). Within the upper canopy turbulent transport and water renewal are enhanced by the energetic KH vortices. In contrast, within the lower canopy ( $z < h-\delta_e$ ) turbulence is generated only within the wakes of individual canopy elements, and thus has significantly smaller scale, set by the stem diameters and spacing (Nepf and Vivoni 2000, Poggi et al 2004a, Tanino and Nepf 2008b). As a result, the mass transport in the lower canopy is 10 to 100 times slower than in the upper canopy (Ghisalberti and Nepf 2005).

The length-scale  $(C_D a)^{-1}$  may be interpreted as the length over which any momentum

transferred into the canopy is dissipated by canopy drag. One then anticipates that  $(C_Da)^{-1}$  sets the flow-transition length-scale at all canopy boundaries. Indeed, for canopies of finite width,  $L_y \sim (C_Da)^{-1}$  determines the lateral penetration of shear at the edge of the canopy (White and Nepf 2007). Similarly, for canopies of finite length,  $L_x \sim (C_Da)^{-1}$  is the length-scale for flow adjustment at the leading edge of the canopy (Jackson and Winant, 1983). These transition scales are depicted in Figure 2.

In the sections that follow we apply the physical concepts developed above to provide new insight into previous observations made in vegetated systems. In the first case the transition between sparse and dense submerged canopies is shown to impact both mass, specifically sediment, and momentum transport. In the second case, the relation between currents and the spatial structure of seagrass meadows gives insight into the stability of different meadow structures, described by the area fraction covered by vegetation. In the last case, the momentum balance suggests that in natural channels the total resistance is set predominantly by the area fraction occupied by vegetation, or blockage factor, with little direct dependence on the specific canopy morphology, as reflected in  $C_Dah$ . This supports the recommendation by Green (2005) to use blockage factor alone as a simple, robust predictor of channel resistance.

## **Case 1: Sparse versus dense canopies**

Although the drag coefficient  $C_D$  varies with flow and morphology, it may often be assumed to be close to one, so that the transition between sparse and dense canopies can be taken at  $ah \approx 0.1$ . In sparse canopies we expect turbulence and turbulent stress to remain elevated close to the bed, whereas in dense canopies turbulence and turbulent stress near the bed are reduced by the canopy drag (Figure 1). Because turbulent stress near the bed plays a role in resuspension, we anticipate reduced resupension and reduced suspended sediment concentration within dense canopies. Observations from Moore (2004) support this conjecture and demonstrate that this transition from sparse to dense canopy behavior can occur within a growing season. Moore (2004) investigated the influence of the seagrass *Zostera Marina* on water quality by contrasting vegetated and unvegetated sites within the Lower Chesapeake Bay. Moore compared the total suspended solids (*TSS*, mg/l) at vegetated and unvegetated sites. He concluded that the difference in suspended solids inside and outside the grass beds,  $\Delta TSS$  [mg/l], was dependent on seagrass biomass, and that the difference was negligible when the average above-ground biomass per unit area was less than 100 g/m<sup>2</sup> (dry mass). The dry mass measure can be converted to frontal area index using the following formula,

$$Biomass/m^2 = \rho_{zm}aht. \tag{4}$$

For *Zostera Marina* the characteristic blade thickness is  $t \approx 0.3$  mm (Enriquez et al. 1992), and the material density is  $\rho_{zm} \approx 760$  kg/m<sup>3</sup> (Fonseca, 1998). The difference in TSS between vegetated and unvegetated sites can now be considered in the context of the transition in flow structure described by *ah* (Figure 3). The threshold noted by Moore (1984), 100 g/m<sup>2</sup>, corresponds to *ah* = 0.4. A significant drop in *TSS* is observed for canopies with *ah* greater than this value (Figure 3). Thus, the observed transition in *TSS* is consistent with the transition threshold predicted from the momentum balance. Specifically, when *ah*  $\geq 0.1$ , turbulent stress cannot penetrate close enough to the bed to generate sediment resuspension. Above this density a meadow will promote sediment retention, stabilizing the bed and improving light conditions, two feedbacks that may promote meadow survival. Conversely, a reduction in canopy density below this threshold sets off a negative feedback, with increased sediment resuspension leading to both a loss of bed stability and a reduction in light climate, both of which can lead to further canopy deterioration.

The canopy density also impacts the structure of flow above the canopy. Sufficiently far above a canopy the velocity profile is logarithmic (c.f. Thom 1971, Raupach 1994):

$$\left\langle \overline{u} \right\rangle(z) = \frac{u^*}{\kappa} \ln((z - z_m) / z_o) \tag{5}$$

The friction velocity  $u_* = (gS (H - z_m))^{0.5}$  (*e.g.* Nepf and Vivoni 2000);  $\kappa$  is the von Karman constant ( $\approx 0.41$ ); and  $z_m$  and  $z_o$  are the displacement and roughness heights, respectively. As discussed below, both of these heights depend on the canopy density.

For dense canopies, the penetration length-scale,  $\delta_e$ , describes the distance over which turbulent stress penetrates the canopy from above. Similarly, the displacement height,  $z_m$  is the vertical centroid of momentum penetration into the canopy (Thom 1971). This similarity leads to the following physically-intuitive scaling,

$$\frac{z_m}{h} \approx 1 - \frac{1}{2} \frac{\delta_e}{h} = 1 - \frac{0.12 \pm 0.03}{C_D a h},\tag{6}$$

which was confirmed for canopy density up to  $ah \approx 1$  (Nepf and Ghisalberti 2008). Here, the comparison is extended to ah up to 3 (Figure 4a). In each case the value for  $z_m$  was obtained by fitting logarithmic velocity profiles to the flow over the canopy. Note that, as ah increases, the displacement thickness tends towards the value  $z_m = h$ , indicating that the canopy is essentially

cut-off from the overflow. Further,  $z_m$  approaches zero at  $ah \approx 0.1$ , which is consistent with the proposed transition to sparse canopy behavior, for which  $z_m = 0$ .

As noted by previous researchers (*e.g.* Jimenez 2004, Raupach et al. 1980) the dependency of the roughness height,  $z_{o}$ , on frontal area index, *ah*, differs significantly above and below the threshold of  $\lambda = ah \approx 0.1$  (Figure 4b). In the sparse canopy range (ah < 0.1), the roughness height increases with increasing *ah*. In sparse canopies the flow penetrates the entire canopy height, such that we expect  $z_o \sim h$ . Further,  $z_o$  should be proportional to the drag provided by the canopy,  $C_Dah$ , so that  $z_o/h \sim C_Dah$ . This dependency was confirmed in Jimenez (2004). In contrast, in dense canopies (ah > 0.1), the roughness height decreases with increasing *ah*. This decrease has been attributed to the mutual sheltering of individual canopy elements, which increases with *ah*, but no theories exist to explain the observed power law dependence (Jimenez 2004). We suggest that the penetration scale defined in (3) can provide an explanation. The effective height of the canopy, as seen by the overflow, is the penetration scale,  $\delta_e$ . It is likely, then that the roughness height depends on this effective height, rather than the full canopy height, *i.e.*  $z_o \sim \delta_e \sim a^{-1}$ . This power dependency is supported by observations in dense canopies (ah > 0.1), specifically  $z_o/h \sim (ah)^{-1}$ , as shown by the dashed line in Figure 4b.

In this case study we provided two examples of how flow and transport behavior shifted between sparse and dense canopies, with the main point being that flow and vertical transport are vigorous throughout a sparse canopy, but in a dense canopy are limited to the upper region, defined by  $\delta_e$ . In some cases, this disconnection of the lower canopy from the overflow may be beneficial. By reducing the momentum penetration, a dense canopy shelters itself from high flow, which is critical during extreme events such as floods. In addition, as shown in the first example, the reduction in bed stress associated with dense canopies can stabilize the bed and improve water clarity. Understanding this stability threshold is important to rehabilitation efforts (Moore 2004). However, dense canopy structure also diminishes the mass exchange into the canopy, potentially limiting the availability of nutrients for the macrophytes.

## **Case 2: Structure-Flow Feedbacks in a Seagrass Meadow**

Under natural conditions, seagrass is organized in different geometries, from lush meadows, to distributed patches. The different geometries are the result of many factors, including access to sunlight, nutrient availability, and the physical stresses associated with waves and currents (Fonseca et al. 1983, Zimmerman et al. 1997, Koch 2001). Fonseca and Bell (1998) examined the relationship between flow and meadow structure for two species: *Zostera marina* (eelgrass) and *Halodule wrightii* (shoalgrass). They used aerial photographs to map grass cover, and then correlated the fractional coverage to three environmental factors: current speed, wave exposure, and water depth. The seagrass cover ranged from isolated patches of 1 m<sup>2</sup> (the resolution of the surveys) to lush, continuous canopies. A negative correlation was found between fractional coverage and all three environmental factors, but the strongest correlation was with the maximum tidal current. Similarly, Fonseca et al. (1983) found a strong negative correlation between maximum tidal current and the height/length ratio for seagrass patches.

In tidal regions, the balance between the tidal forcing and the drag exerted by the bed and/or vegetation determines the magnitude of the local current. Higher drag within the vegetation can divert flow to open areas, resulting in reduced flow within the canopy and accelerated flow in the open areas (Gambi et al., 1990). This diversion of flow to open areas tends to be self-reinforcing, as the reduced flow within the canopy creates favorable conditions for continued growth, while the accelerated flow in the open areas creates a stressful environment that damages plants and prohibits growth (Scoffin 1970, Fonseca and Fisher 1986, Duan et al. 2006). However, in order for this feedback to operate, the open areas must have sufficient continuity to form channels. We appeal to percolation theory to understand the fractional coverage at which this occurs. The fractional area occupied by vegetation will be described by  $A_{\nu}/A$ , where  $A_{\nu}$  is the bed area covered by vegetation within a total area A. Starting with full coverage,  $A_{\nu}/A = 1$ , imagine removing randomly placed pockets of vegetation. When only a few unvegetated regions exist (large  $A_{\nu}/A$ ), those regions are unlikely to be connected. According to percolation theory, randomly placed landscape elements become connected when they represent 60% of the area (Stauffer 1985). That is, the open regions must reach 60% of the area before significant connection and channeling will occur. This corresponds to a vegetative cover of 40%. It is important to note, that this limit was derived for randomly placed landscape elements. The propagation of vegetation is not a purely random process. Whether propagation occurs via sexual or vegetative reproduction, there is an inherent bias to grow adjacent to existing plants (Sintes, et al. 2005, Marba and Duarte, 1998). The loss of vegetation may have a similar bias, *i.e.* vegetation near open areas may be more likely to be degraded. The later tendency may shift the area fraction at which channelization occurs to a higher value.

The limits prescribed by percolation theory are used to define two flow regimes within a seagrass landscape, *i.e.* landscapes with  $(A_v/A < 0.4)$  and without  $(A_v/A > 0.4)$  connected channels. As in Fonseca and Bell (1998), the flow is assumed to be driven by tidal variation in water surface elevation,  $S = \partial H/\partial x$ , which is assumed to be uniform over the entire region of interest. This driving force is balanced by the drag associated with the vegetation and the bed. When  $A_v/A < 0.4$  connected channels are present, and a separate momentum balance is possible

within the channels and within the vegetation. Assuming steady uniform conditions, the depthaveraged momentum balance reduces to,

$$\rho gS = \frac{1}{2} \rho C_D a \frac{h}{H} U_v^2 \qquad \text{for } A_v / A < 0.4, \text{ in vegetation} \qquad (7a)$$

$$\rho gS = \frac{1}{2} \rho \frac{C_f}{H} U_o^2 \qquad \text{for } A_v A < 0.4, \text{ in channels}$$
(7b)

The depth-averaged velocity within the vegetation and channels is denoted  $U_v$  and  $U_o$ , respectively. The bed-drag coefficient,  $C_f$ , represents the turbulent stress at the bed, which we assume is negligible compared to  $C_Dah$  within the vegetation.

The maximum tidal forcing,  $\rho gS$ , was estimated from data provided in Fonseca and Bell (1998). Let  $U_o^*$  equal the maximum current observed in the absence of vegetation  $(A_v/A = 0)$ , and let  $U_v^*$  equal the maximum current observed in regions will full coverage  $(A_v/A = 1)$ . Using these values (7a) and (7b) can be solved simultaneously for  $\rho gS$  and the drag ratio  $C_Dah/C_f$ . The resulting drag ratio,  $C_Dah/C_f = 25$ , is comparable to what one would estimate from observed values of *a* and *h* and independently estimated values of  $C_D$  and  $C_f$  (Werner at al. 2003, Ghisalberti and Nepf 2006, Tanino and Nepf 2008a). The maximal tidal forcing,  $\rho gS$ , can now be used in (7a) and (7b) to evaluate  $U_c$  and  $U_v$  for  $A_v/A = 0$  to 0.4. Note that (7a) assumes uniform conditions, and it is therefore not suitable for very short patches of vegetation. As shown in Fig. 2, upon entering a vegetation patch, flow requires a distance  $L_x = (C_Da)^{-1}$  to adjust to the vegetation drag and attain the momentum balance implied by (7a). For patches shorter than this adjustment length, the flow within the vegetation will remain elevated, *i.e.*  $U_v \approx U_c$ .

According to the percolation threshold, when  $A_{\nu}/A > 0.4$  continuous channels are

unlikely. Because the open regions are unconnected, they do not provide a flow-path along which 7b applies. Instead, the essentially contiguous, but spotty, coverage of vegetation dictates a uniform mean velocity, *U*, across all regions, both open and vegetated. The depth- and area-averaged momentum balance then becomes,

$$\rho gS = \frac{1}{2}\rho C_D a \frac{h}{H} \frac{A_v}{A} U^2 \qquad \text{for } A_v A > 0.4. \tag{8}$$

Using (7) and (8), the velocities  $U_o$ ,  $U_v$ , and U are estimated for the full range of area coverage (Figure 5). For  $A_v/A < 0.4$ , the area-average velocity is  $U = (A_v/A)U_v + (1-A_v/A))U_c$ . Although the model is discontinuous at  $A_v/A = 0.4$ , we expect a smooth transition in natural systems. Remember that the tidal forcing is calibrated to the conditions observed in Fonseca and Bell (1998), and consistent with this the modeled, average velocity, U, agrees in magnitude with the velocities measured in that paper. In their field system, Fonseca and Bell (1998) observed that sediment motion was initiated at  $U \ge 25$  cm/s. This threshold is also shown in the Figure 5. The model suggests that when channels are present ( $A_v/A < 0.4$ ) sediment motion will occur within the channels but not within the vegetation (Figure 5). However, when channels are absent ( $A_v/A > 0.4$ ), sediment motion does not occur either in the vegetated or open regions. As discussed in the next paragraph, this transition in behavior explains the higher probability of occurrence for meadows with area fraction close to the channelization limit (40%).

Using data provided in Fonseca and Bell (1998), a probability density function of the observed fractional coverages,  $A_{\nu}/A$ , was constructed (Figure 6). The pdf has two peaks, near 100% and near the channelization limit of 40%. These peaks suggest that 100% and 40% represent stable conditions. The model described above explains this stability. Above an area

faction of 40%, the velocity in all regions remains below the limit for sediment motion. If a disturbance generates regions of open area, but  $A_v/A$  remains above 0.4, the open areas will probably be able to refill, because the local velocity remains depressed and conducive for growth. Therefore, area cover percentages between 40 and 100% are unstable, with re-growth pushing conditions back to 100%. However, if a disturbance drives the area fraction below 40%, channels can form, and the velocity in the channels increases above the threshold for sediment motion (Figure 5). This inhibits re-growth in the channels, stabilizing the channels as well as the area coverage  $A_v/A$  near or just below 40%. Finally, as area coverage approaches zero, individual patches become too short to decelerate the oncoming flow, so that the in-canopy velocity remains above the threshold for sediment motion, and these patches will likely be eroded. Specifically, isolated patches of grass of length less than  $L_x = (C_D a)^{-1}$  are unstable. In this system of seagrass,  $Lx \approx 1$  m. This implies another threshold in area coverage is present, below which the vegetation coverage is unstable and tending to 0%.

## **Case 3: Predicting Resistance Coefficients in Vegetated Channels**

The flow resistance generated by macrophytes limits discharge in channels (*e.g.* Kouwen 1990, Wu et al. 1999). This has led to the frequent removal of vegetation to increase discharge capacity and reduce the risk of flooding. Vegetation resistance is influenced by a number of factors including plant morphology, stiffness, and the distribution of vegetation within the channel. Converting these highly heterogeneous characteristics into a simple predictot of Manning roughness coefficient,  $n_M$ , remains a challenge. Recently, Green (2005, 2006) provided experimental support for the concept that resistance is predominantly determined by the spatial distribution of vegetation within the channel, which he describes through three blockage factors.

The cross-sectional blockage factor,  $B^X$ , is the fraction of the cross-section blocked by macrophytes. The surface area blockage factor,  $B^{SA}$ , is the proportion of horizontal area containing vegetation. Finally, the volumetric blockage factor,  $B^V$ , is the fraction of reach volume containing vegetation. These factors were compared using field measurements made by Green at thirty-five river sites containing the macrophyte *Ranunculus Batrachium* (watercrowfoot). As intuitively expected, a positive, linear relationship was found between each blockage factor and the Manning resistance coefficient.

Here, we will advance Green's result by using a momentum balance to reveal more detail in the dependence between blockage factor and channel resistance, which leads to an improved prediction of  $n_M$ . Consider a representative cross-section with some distribution of vegetation (top panel Figure 6). In different cross-sections of the same channel, the distribution of vegetation will likely differ, however, we can imagine that the average over many such crosssections can be represented by a reach-averaged blockage factor, as described by Green (2005), and that this can be simplified to an equivalent geometry shown in the bottom panel of Figure 6. On the vegetated side of the channel, y = 0 to b, the depth-averaged velocity,  $U_v$ , is given by equation (7a). On the open side of the channel, y = b to B, the depth-averaged,  $U_o$ , is given by equation (7b). The cross-sectional-average velocity, U, is then the area-weighted average of  $U_v$ and  $U_o$ . Normalizing by the potential velocity, (gSH)<sup>-1/2</sup>,

$$\frac{U}{\sqrt{gSH}} = \frac{b}{B} \left[ \frac{2}{C_D ah} \right]^{1/2} + \left( 1 - \frac{b}{B} \left[ \frac{2}{C_f} \right]^{1/2} \right].$$
(9)

The conceptualized cross-section shown in Figure 6b represents an average along the reach, such

that b/B can be interpreted as the surface area blockage factor,  $B^{SA}$ . The data provided in Green (2005) verifies this substitution and the momentum balance given in (9). That study provides measurements of  $B^{SA}$ , U, S, and hydraulic radius, R. We will assume that  $R \approx H$ , which is reasonable for shallow channels. An average bed friction coefficient,  $C_f = 0.06 \pm 0.01$  (S.E.), is estimated from the bare-channel Mannings' coefficient,  $n_b$ , provided by Green (2005). As described above, channel vegetation typically has  $a = 1 \text{ cm}^{-1}$ , and h = 10 to 50 cm. Again, we make the reasonable assumption that  $C_D \approx 1$ , such that  $C_D ah = 10$  to 50. The normalized velocity predicted by (9) is highly correlated with the measured velocity ( $R^2 = 0.8$ , N = 34), with a slope of one (Fig. 8), demonstrating that the model captures the essential physics. A physically-based estimator for  $n_M$  can now be extracted from (9). Letting  $b/B = B^{SA}$ ,

$$n_{M} = \frac{KH^{1/6}}{B^{SA} \left[ 2g/C_{D}ah \right]^{1/2} + (1 - B^{SA}) \left[ 2g/C_{f} \right]^{1/2}}.$$
(10)

 $K = 1 \text{ m}^{1/3} \text{s}^{-1}$ , is a coefficient necessary to make the equation dimensionally correct. It is generally true that the vegetative drag parameter,  $C_Dah$ , is much larger than the bed drag parameter,  $C_f$ , so that right-hand term in the denominator of (10) is dominant. Specifically for the parameter values given above, the vegetation drag (left-hand term of the denominator) can be neglected when  $B^{SA}$  is less than 0.6 or 0.8, for  $C_Dah = 10$  or 50, respectively. Applying this simplification, (10) becomes,

$$n_{M} = \frac{KH^{1/6}}{(1 - B^{SA}) [2g/C_{f}]^{1/2}} = \frac{n_{b}}{1 - B^{SA}}.$$
(11)

Equation 11 tells us that for a large range of blockage factor ( $B^{SA} < 0.6 - 0.8$ ), the detail morphology of the vegetation is not important, and the channel resistance is set by the blockage factor alone. This is the physical explanation for the qualitative arguments presented in Green (2005). However, in contrast to the linear relation,  $n_M \sim B^{SA}$ , explored by Green, (11) implies a non-linear relation, namely  $n_M \sim (1-B^{sa})^{-1}$ . Indeed, this non-linear relation provides a higher correlation ( $R^2 = 0.77$ , Figure 9), than the linear relation  $n_M \sim B^{sa}$  ( $R^2 = 0.64$ ), or  $n_M \sim B^x$  ( $R^2 = 0.64$ ) 0.66) (data not shown). As a consistency check, note that the slope of the regression (Figure 9) implies a bare channel coefficient  $n_b = 0.05$ , which falls within the range of values reported in Green ( $n_b = 0.04 \pm 0.01$ , S.D.). Please note that in all of the above analyses we have excluded the outlier Site 10, as justified by Green. The observed and predicted Mannings' coefficients are plotted against blockage factor to examine limitations of (11) at high  $B^{SA}$  (Figure 10). Even at the highest observed blockage factors,  $B^{SA} \approx 0.8$ , the Mannings' coefficient is reasonably predicted from the bare-bed coefficient and blockage factor alone. This suggests that, except for conditions of sparse vegetation (ah < 10), channel resistance can be predicted without detailed information on vegetation morphology. As suggested by Green (2005), we should put more attention into methods for quickly and robustly estimating the blockage factor, as this appears to be a robust predictor of resistance. Recent advances in remote sensing technology can accelerate this work (e.g. Alberotanza et al 1999, Sabol et al 2002, Bostater and Bassetti 2004) by enabling rapid, extensive, and high resolution mapping of vegetation distribution.

# **Conclusion:**

With increased physical understanding we have been able to better explore the interaction between flow and vegetation in aquatic systems. For submerged vegetation, the penetration of turbulence and momentum from the overflow has a significant influence on canopy function. Specifically, when  $ah >\approx 0.1$ , turbulent stress cannot penetrate to the bed. Above this density a meadow can promote sediment retention, stabilizing the bed and improving light conditions, two positive feedbacks that promote meadow persistence. Conversely, a reduction in canopy density below this threshold will lead to increased flow and stress near the bed, increased sediment resuspension, a loss of bed stability, and a reduction in light climate, all of which can lead to further canopy deterioration. The horizontal structure of a seagrass meadow is controlled by similar feedbacks. When area coverage drops below the channelization threshold ( $A_{\nu}/A \approx 40\%$ ), differences in flow between the vegetated and open regions reinforce the existing distribution of vegetation, *i.e.* high flows within channels maintain the channels, and diminished flow in the vegetation maintains the vegetation. Finally, when the flow domain is confined by river banks, the momentum balance suggests that total resistance is set predominantly by the area fraction occupied by vegetation, or blockage factor, with little direct dependence on the specific canopy morphology, as reflected in  $C_{Dah}$ . As a result, for most stream conditions the Manning's coefficient can be predicted from only the blockage factor and the bare-bed friction factor.

#### ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant No. EAR\*\*\*\*\*. Any opinions, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation

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**Figure 1.** Flow within and above a submerged canopy of height *h* in water depth *H*. Profiles of mean velocity and turbulent stress are shown. (a) For a sparse canopy the profile resembles a turbulent boundary layer and turbulent stress remains elevated at the bed. (b) For a dense canopy, the canopy-induced shear layer (CSL) generates shear-scale vortices via Kelvin-Helmholtz (KH) instability. These energetic KH vortices penetrate a distance  $\delta_e$  into the canopy, and turbulent stress near the bed is reduced, relative to canopy-free flow. Profiles based on Ghisalberti and Nepf (2002) and Dunn et al. (1996).



**Figure 2.** Plan view of a finite patch of aquatic vegetation showing the transition length scale,  $L_x$ , and lateral penetration scale,  $L_y$ , of the upstream velocity. Both scales are set by the momentum absorption length  $(C_D a)^{-1}$ . Over these lengths, momentum from the surrounding flow is dissipated by canopy drag.



Figure 3. Difference in total suspended solids (TSS) between inshore and channelward locations. The data is from Moore (2004); equation (4) is used to convert the reported dry mass values to frontal area. Note that ah = 0 corresponds to a inshore site with no vegetation.



**Figure 4.** Measured (a) displacement height,  $z_m/h$ , and (b) roughness height,  $z_0/h$ , as a function of the frontal area index, *ah*. The dashed line in (a) corresponds to equation (6) with  $C_D = 1$ . The line in (b) is a reference slope,  $(ah)^{-1}$ .



**Figure 5**. Velocity in open regions,  $U_o$ , in the vegetation,  $U_v$ , and cross-sectionally averaged, U, modeled by (7) and (8).



**Figure 6**. The probability density function of fraction area coverage,  $A_v/A$ , based on observations in seagrass meadows. Peaks near 40%, and near 100% suggest that these represent stable landscapes.



**Figure 7.** Schematic showing (a) a representative channel cross-section with distributed vegetation and (b) the simplified, equivalent geometry. The shaded regions represent the area occupied by vegetation.



**Figure 8.** Velocity predicted by (9) with  $C_Dah = 10$  and  $C_f = 0.06$  compared to velocity measured by Green (2005). Outlier Site 10 is excluded for reasons explained in Green (2005).



**Figure 9**. Mannings' coefficient measured by Green (2005) versus a blockage factor function based on the momentum equation (9). The outlier Site 10 is excluded, for the reasons explained in Green (2005).



**Figure 10.** Measured Mannings' coefficient (x) from Green (2005). Predicted values from (11), using  $n_b = 0.05$ . The thinner lines reflect the 95% confidence limits on  $n_b$ .