Vegetated Canopies in Aquatic Systems

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The drag-discontinuity at the top of a submerged canopy creates a region of strong shear that resembles a free-shear-layer (Raupach et al. 1996). A shear-layer is characterized by large coherent vortices that form via Kelvin-Helmholtz (K-H) instability and which dominate the transport across the layer. A unique aspect of aquatic canopies is the possible condition that the canopy-shear-layer occupies a large fraction of the flow domain, which is then called a shallow shear-layer (Figure 1b). This is in contrast to terrestrial canopies (deep shear layers), for which the K-H vortices exist within a field of larger boundary-layer vortices (Figure 1a). As a result, K-H structures are more intermittent within the deep-shear-layer.

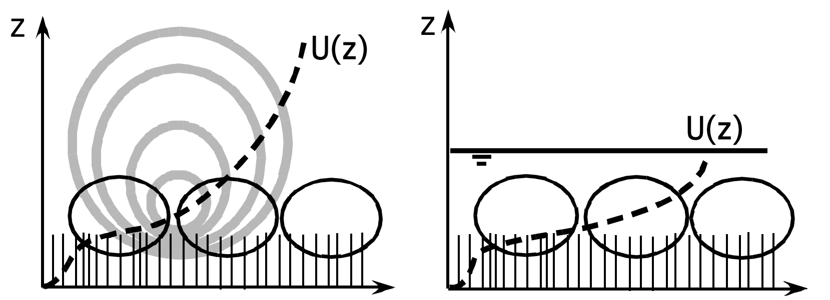

Figure 1. a) In deep canopy-shear-layers K-H vortices (black) interact with larger-scale boundary-layer turbulence (grey). B) In shallow canopy-shear-layers K-H vortices may dominate through the flow domain.

The persistence of K-H vortices in shallow canopy-shear-layers allows detailed study of their growth and structure, and more detailed comparison to unobstructed shear-layers. In an unobstructed shear-layer, the vortices, as well as the shear-layer width, grow continually downstream, predominantly through vortex pairing (Winant and Browand, 1974). In contrast, in canopy-shear-layers the vortices initially grow, but eventually reach a fixed scale. The constraint on vortex scale is reflected in the arrested growth of the shear-layer. This is consistent with observations of the roughness sub-layer, the top of which corresponds to the top of the shear-layer. After a short development region the width of the roughness sub-layer is independent of distance along the canopy, remaining constant even as the overlying boundary layer continues to develop (*e.g*. Cheng and Castro 2002).

The arrested growth of the canopy shear-layer appears to occur when the dissipation of the K-H structures by canopy drag balances their production from shear. This balance is possible because the presence of the canopy continually reinforces the shear, even as it draws energy from the resulting coherent structures. In contrast, in a free-shear-layer the shear gradually decays as the layer grows. The turbulent kinetic energy budget yields the following equilibrium parameter that is remarkably constant over a wide range of canopy Reynolds' number, $Re_h = U_h h/\nu$, where h is the canopy height, U_h is the velocity at the top of the canopy, and ν is viscosity.

$$CSL = \frac{\langle \overline{u} \rangle C_D a}{\partial \langle \overline{u} \rangle / \partial z} \qquad (1)$$

Here, a is the canopy frontal array per volume and C_D is the canopy drag coefficient. The stream-wise velocity, u, is temporally (overbar) and spatially (bracket) averaged, and z is the vertical coordinate. From the parameter CSL one can derive a length-scale δ_e that describes the penetration of the K-H vortices into the canopy.

$$\delta_e \sim \left(C_D a\right)^{-1} \qquad (2)$$

If the penetration scale is less than the canopy height, $\delta_e < h$, the canopy is segregated into two regions. The upper canopy has more rapid water renewal through the action of K-H vortices. The lower canopy has slower water renewal, limited by the smaller-scale turbulence generated by individual canopy elements.

Most submerged, aquatic plants are flexible, and the passage of the K-H vortex street drives a coherent, progressive waving, known as *monami*. The *monami* is triggered when the velocity at the top of the canopy increases above a threshold value, which increases with plant rigidity. The *monami* allows the vortices to penetrate closer to the boundary, which may facilitate the overall flushing of the canopy. However, the presence of *monami* decreases the turbulent transport of momentum across the shear-layer and across the canopy interface, relative to flows over rigid vegetation and over flexible vegetation without *monami*. The reduction in momentum transport is associated with a decrease in mixing-length and vortex-velocity-scale above the waving canopy. That is, rigid (and non-waving flexible canopies) generate comparatively larger and more rapidly rotating vortices than their waving counterparts.

Figure 2. A flexible canopy model dynamically similar to eelgrass. Model design and photo by M. Ghisalberti.

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