Density-driven exchange flow between open water and an aquatic canopy

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Received 16 November 2007; revised 23 April 2008; accepted 28 May 2008; published 9 August 2008.

[1] Differences in water density can drive an exchange flow between the vegetated and open regions of surface water systems. A laboratory experiment has been conducted to investigate this exchange flow, using a random array of rigid, emergent cylinders to represent the canopy region. The flow pattern was captured using a CCD camera. The velocity of the current entering the canopy and the volume discharge both decrease with increasing vegetative drag and also decrease gradually over time. Theoretical predictions for velocity and discharge rate are developed and verified with experimental observations. Extensions to field conditions are also discussed.

Citation: Zhang, X., and H. M. Nepf (2008), Density-driven exchange flow between open water and an aquatic canopy, Water Resour. Res., 44, W08417, doi:10.1029/2007WR006676.

1. Introduction

[2] Convective water exchange produced by spatial heterogeneity in water temperature plays an important role in the transport of nutrients and other substances, in particular, between the littoral and pelagic regions of surface water bodies [Adams and Wells, 1984; James and Barko, 1991; James et al., 1994; James and Barko, 1999; Machnlyre et al., 2002; Horsch and Stefan, 1988]. Most commonly, temperature differences develop between shallow and deep regions when the same incoming solar radiation is distributed over different depths. This process has been studied in a triangular cavity both numerically [Farro and Patterson, 1993] and experimentally [Lei and Patterson, 2002]. Farro [2004] extended this work to arbitrary bathymetry and described the transient and steady components of the flow, as well as the pattern of reversing flow that is generated by the diurnal cycle of heating and cooling. Under weak wind conditions, these flows control the flushing of littoral regions, reducing the flushing time by several orders of magnitude from turbulent diffusion alone. Similarly, the presence of phytoplankton can affect the penetration of irradiance into the water column so that spatial heterogeneity in phytoplankton, or other sources of turbidity, can also produce density gradients [Edwards et al., 2004]. Coates and Patterson [1993] used scale analysis supported by experiment to describe the flow generated when an opaque layer, representing a region of high turbidity, shelters the water column.

[3] Shading associated with aquatic macrophytes can also influence local water temperature [e.g., Chimney et al., 2006; Ultsch, 1973]. Lightbody et al. [2007] observed that daytime temperatures within the marsh region of a constructed wetland remained, on average, 2.0°C cooler than the open areas of the same wetland. Similarly, water temperature within a stand of the emergent Schoenoplectus acutus and S. californicus was as much as 2.5°C lower than within the nearby open water [Sartoris et al., 2000]. Shading by floating vegetation and the resulting convection have been studied by Coates and Ferris [1994]. They observed exchange flows of O(1) mm s⁻¹ beneath mats of water fern (Azolla) and duckweed (Lemna perpusilla). A thin root layer beneath the floating macrophytes displaced the flow downward, indicating a modifying influence of vegetative drag. But, this effect was not quantified in the study. In this paper, we consider rooted vegetation which, in addition to generating temperature difference, provides drag over the entire flow domain, which should significantly alter the flow response.

[4] A lake is generally divided into the pelagic zone, the region of open water, and the littoral zone, where rooted vegetation exists. The littoral zone is further divided into several regions based on the distribution of aquatic vegetation. The upper infralittoral zone is occupied mainly by emergent vegetation. The middle infralittoral zone is occupied by floating-leaved rooted vegetation. The lower infralittoral zone contains submersed rooted vegetation. The results of this paper apply mostly to the middle and upper infralittoral zone, where vegetation exists throughout the water depth. The impact of the submersed vegetation is discussed briefly in section 5.

[5] To model the impact of littoral zone vegetation on density-driven exchange flow, we must characterize the vegetative drag. Several models for vegetative drag have been considered in the literature. In a numerical study, Horsch and Stefan [1988] modeled vegetative drag as an enhanced viscosity. Drag characterizations based on porous media flow have also been used [Oldham and Sturman, 2001]. However, vegetative drag is most commonly modeled using a quadratic law, e.g., by Burke and Stolzenbach [1983], Mazda et al. [1997], and Nepf [1999]. The canopy drag coefficient, CD, must be determined empirically. For solid volume fraction, φ, up to 9%, the drag coefficient, CD, may be

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0043-1397/08/2007WR006676
estimated by the empirical expression for isolated cylinders [White, 1991]

\[ C_D \approx 1 + 10.0Re^{-2/3}, \]  

(1)

where \( Re \) is the cylinder Reynolds number and is given by

\[ Re = \frac{u_d \rho}{\nu}, \]  

(2)

in which \( \nu \) is the kinematic viscosity. For higher solid volume fraction, Tanino and Nepf [2008] measured \( C_D \) for random arrays up to \( \phi = 35\% \) and \( Re = 25 \) to 685.

[5] In this work, we conduct a lock exchange experiment in which the density difference between open and vegetated regions is constant. This is a simplification of the field situation in which the density difference varies over the course of the diurnal heating. However, we will show that the setup, or transient, time scale for the exchange flow is short compared to the time scale of diurnal temperature variation, so that this simplification is justified in evaluating velocity scales. In section 2, we present a theory that predicts the velocity in both the open and vegetated regions, as well as the total exchange rate between these regions. Section 3 introduces the experimental methods, including setup, image acquisition, and data analysis. In section 4, experimental results are presented and discussed. Section 5 connects the new model and lab observations to field conditions, exploring the range of exchange flow magnitude expected for different canopy density and solar forcing.

2. Theory

[7] The lock exchange experiment has been widely used to study exchange flows in a laboratory setting. The exchange flow is produced by initially filling two reservoirs with fluids of different densities. The reservoirs are separated by a gate. When the gate is removed, the denser fluid propagates along the bottom while the lighter fluid propagates in the opposite direction along the top boundary. The flow evolves under a constant density difference.

[8] The classic exchange current is depicted in Figure 1a. Benjamin [1968] found that, under the condition of negligible momentum dissipation, the interface is essentially horizontal; that is, each layer occupies half of the total depth, and each front travels at speed \( u_i \), where the subscript “i” indicates inertial conditions:

\[ u_i = \frac{1}{2} \sqrt{g' \Delta H}. \]  

(3)

\( \Delta H \) is the total depth of water, and \( g' \) is the reduced gravity which is expressed as

\[ g' = \frac{\rho_2 - \rho_1}{\rho_2} g. \]  

(4)

where \( \rho_2 \) and \( \rho_1 \) are the densities of the heavier and lighter fluid, respectively, and \( g \) is gravity. Later, our observations show that the velocity in the open region is controlled by the inertial velocity scale given in equation (3).

[9] Shin et al. [2004] extended Benjamin [1968]’s theory to cover different initial fluid depths. By considering the currents propagating in both directions in the energy balance, they derived a more general theory in which the depth of the propagating current, \( h \), need not be \( H/2 \). Specifically, the speed of the front is given by

\[ u_i = \sqrt{\frac{h}{H} \left( 1 - \frac{h}{H} \right) \sqrt{g' \Delta H}}. \]  

(5)

For the case \( h = H/2 \), equation (5) correctly reduces to equation (3).

[10] Tanino et al. [2005] studied a lock exchange entirely contained within an array of circular cylinders of diameter, \( d \). The arrays consisted of \( N \) cylinders per bed area, \( A \). The array density was characterized by the frontal area of the cylinders per unit volume, \( a \), and the porosity, \( n \), which are expressed as

\[ a = N d / A, \]  

(6)

\[ n = 1 - (\pi/4) a d = 1 - \phi, \]  

(7)

respectively. For convenience, we also define the solid volume fraction, \( \phi \), which is the ratio of total cylinder volume to the total volume. When the array is sufficiently dense, the exchange flow is controlled by the canopy drag and exhibits an interface that is inclined to the horizontal plane rotating about its midpoint (Figure 1b). The drag-dominated frontal velocity is [Tanino et al., 2005]

\[ u_v = \sqrt{-\frac{2n}{C_D a} g' S H}{L}, \]  

(8)

where the subscript \( v \) indicates parameters within the vegetation, \( C_D \) is the canopy drag coefficient discussed earlier, and \( S \) is a scale constant that describes the interfacial slope in proportion to the geometric ratio \( H/L \), where \( L \) is the frontal length, as shown in Figure 1b. Equation (8) was confirmed by experiment by Tanino et al. [2005], and the scale factor, \( S \), was found to be 0.6.

[11] Equation (8) is valid only when inertia is negligible compared with the canopy drag, which was shown by scaling and experiment to occur when \( C_D a L > 10 \). Note that \( L \) is equal to zero at the start of the exchange \((t = 0)\) and increases as the two fronts propagate away from the center, such that at early time \( C_D a L \to 0 \) and the exchange flow is controlled by inertia and evolves according to inertial theory. As \( L \) increases, more fluid is brought into motion and the contribution of canopy drag increases \((C_D a L \) increases) and \( u_v \) declines (equation (8)). In addition, \( C_D \) may be slowly varying as \( u_v \) varies (equations (1) and (2)). But, \( C_D \) varies much more slowly than \( L \) and within the time scale of the experiments, \( C_D \) does not vary significantly.

[12] In this work, we consider a new configuration in which only half of the tank, i.e., only one side of the lock, is occupied by a model canopy (Figure 1c). Compared with the work by Tanino et al. [2005], the new configuration is a better simulation of the field, where exchange flows are more likely to occur between a vegetated area and the open water, because of differential shading, than to be contained wholly within the vegetation. When the gate is removed, we
expect the exchange flow to be initially controlled by inertia. However, as the current goes deeper into the canopy, the total canopy drag grows and eventually dominates inertia. Once this occurs, the boundary conditions within the canopy match those considered by Tanino et al. [2005] and thus we expect that equation (8) will still be valid within the canopy, with the following modification. We define $L_v$ as the length of front contained within the vegetation. From geometric considerations, we replace $L$ by $2L_v$ so that the interface slope within the canopy is given by $SH/2L_v$ (Figure 1c). Then, from equation (8), we predict that for the case of exchange flow between an open region and an canopy, the velocity within the canopy will be

$$u_v = \frac{dL_v}{dt} = \sqrt{\frac{ngHS}{C_D a \alpha}}.$$  \hspace{1cm} (9)

It is not known a priori whether the interface geometry and thus the scale constant will be the same as that found previously for exchange flow contained within a canopy, and so it will be determined by experiment.

[13] On the basis of the visual observations reported in section 4, once the flow has reached the drag-dominated regime, the interface between the inflow and outflow is linear within the canopy (Figure 1c). Then, at any time, the total volume per unit width that has entered the vegetation, $V_v$, can be estimated from geometry (see shaded region in Figure 1c) as

$$V_v = \frac{1}{2} L_v h_v.$$  \hspace{1cm} (10)

where $h_v$ is the thickness of the current entering the vegetation measured at $x = 0$ (Figure 1c).

[14] The length of the front in the array can be obtained by integrating equation (9),

$$\frac{2}{3} L_v^{3/2} = \sqrt{\frac{ngHS}{C_D a \alpha}}(t - t_0),$$  \hspace{1cm} (11)

in which $t_0$ is a reference time that corrects for the initial transient; that is, $t_0$ is the time scale of the transition from inertia to drag-dominated flow. It is defined shortly.

[15] Using equations (10) and (11), we can write $V_v$ as

$$V_v = \frac{1}{2} L_v h_v = \frac{1}{2} \alpha L_v H = \frac{1}{2} \alpha \left[ \frac{3}{2} \sqrt{\frac{ngHS}{C_D a}}(t - t_0) \right]^{2/3} H,$$  \hspace{1cm} (12)
and α is given by

$$\alpha = \frac{h_v}{H}. \quad (13)$$

The value of α as well as the assumption that α is constant will be evaluated by experiment.

[16] The volume discharge rate per unit width $q_v$ is obtained by taking the time derivative of equation (12):

$$q_v = \frac{\alpha}{3} \left[ \frac{3}{2} \left( \frac{ngHS}{C_{D\alpha}} \right)^{1/2} \right]^{2/3} (t - t_0)^{-1/3} H. \quad (14)$$

From equation (14), we can see that the total exchange rate $q_v$ is a function of $C_{D\alpha}$ and is thus controlled by drag provided by the vegetation. From conservation of mass, the total volume of water going into the canopy must be equal to the total volume intruding into the open region.

[17] The transition time scale $t_0$ can be estimated from the momentum

$$n \frac{Du}{Dt} = -n \frac{1}{\rho} \frac{\partial P}{\partial x} - \frac{C_{D\alpha}|u|}{2}, \quad (15)$$

in which $P$ is the hydrostatic pressure, $\rho$ is the mean fluid density, and $C_{D\alpha}|u|/2$ is the canopy drag. When the flow is just initiated, little fluid volume is in motion, making the total drag small. During this period, the flow is controlled by inertia and $\partial u/\partial t = 0$. As the exchange evolves, more fluid is brought into motion and the effect of the drag increases. At some point the vegetative drag equals inertia:

$$n \frac{\partial u}{\partial x} \sim \frac{C_{D\alpha}|u|}{2}. \quad (16)$$

Scaling $x \sim L_v$, the above equation gives the frontal length at which drag equals and then surpasses inertia:

$$L_v \sim \frac{2n}{C_{D\alpha}}. \quad (17)$$

Because, up to this length, $u = u_t$, the time scale $t_0$ to reach $L_v$ is $t_0 \sim L_v / u_t$, and using equations (3) and (17), the initial period of inertia flow is limited to the time:

$$t_0 \sim \frac{2n}{u_t} \sim \frac{4n}{C_{D\alpha} \sqrt{g'H}} = \frac{4n}{C_{D\alpha} \sqrt{g'H}} \frac{H}{\sqrt{g'}}. \quad (18)$$

3. Experimental Methods

[18] To explore the impacts of vegetative drag on the velocity scale in the open and vegetated regions, a series of lock exchange experiments were conducted in a 200.0 cm x 12.0 cm x 20.0 cm Plexiglas tank with a horizontal bottom. The tank was separated into two regions of equal length by a removable gate which was 5 mm thick. A thin layer of felt was attached to the edge of the gate to form a seal, and two Plexiglas blocks were attached on the top of the tank to guide the gate as it is pulled out vertically. A perforated PVC board was placed atop half of the tank. Dowels with diameter $d = 6$ mm and length $l = 36.4$ cm were pushed through the holes in the board and extended down to the bed. The holes in the board were randomly distributed, and when completely filled with dowels, the board produced a maximum stem density, $a = 0.75$ cm$^{-1}$, corresponding to $\phi = \pi a d/4 = 0.35$. Each of the holes was assigned a number, and a numerical program was used to randomly choose a subset of holes to create arrays of different densities. Here, we will consider cases when $\phi = 0$ to 0.35, which corresponds to the full range observed in field canopies [Kadlec, 1990]. For example, the water lily (Nymphaea odorata) has a typical diameter $d = 1$ cm and $\phi$ is 0.10 to 0.04. The most dense canopies are mangroves, which have $d = 4$ to 9 cm and $\phi$ as high as 0.45 [Mazzu et al., 1997].

[19] For most experiments, the canopy was filled with saltwater of density $\rho_2$ and the saltwater was dyed black or blue with food dye. The open region was filled with fresh tap water with a density $\rho_1$ smaller than $\rho_2$. In seven runs, the density difference was reversed; that is, the lower-density water was placed in the model array. The reversed cases were included for two reasons. First, the effects of bottom drag can be examined by comparing the normal and reversed cases with identical experimental parameters, e.g., same $\phi$, $\rho_1$, and $\rho_2$. Second, the reversed condition occurs during nighttime when the heat in the open water radiates faster than that in the vegetated region, where emergent vegetation tends to diminish radiation losses [Pokorny and Kvet, 2004]. The reversed cases are marked in Table 1. The density of water in each region was measured with a hydrometer with a precision of ±0.0005 g cm$^{-3}$.

[20] From equation 9, the nondimensional velocity is

$$\frac{u}{\sqrt{g'H}} = \sqrt{\frac{n}{C_{D\alpha} \sqrt{H}}} \frac{S}{T_r}. \quad (19)$$

The experimental conditions were scaled to field conditions based on the velocity scale, $\sqrt{g'H}$, as well as the dimensionless drag, $C_{D\alpha}H/n$. In the field, a typical water depth for vegetated zones is in the range of $H = 10$ to 100 cm and a typical $g' = 1.0 \text{ cm s}^{-2}$ (based on temperature differences observed by Dale and Gillespie [1976], James and Barko [1991], Nepf and Oldham [1997], and Lightboby et al. [2007]). Thus, in the field, $\sqrt{g'H}$ is in the range of $O(1)$ to $O(10)$ cm s$^{-1}$. In our experiments, the depth of water, $H$, and the density of the salt water, $\rho_2$, were chosen so that the velocity scale, $\sqrt{g'H}$, in the laboratory fell within these field conditions. The dimensionless parameter that describes the canopy drag, $C_{D\alpha}H/n$, was also matched to field conditions. With a reasonable simplification that $C_D = 1$ for sparse canopies ($\phi < 0.09$) but increases to $C_D = 3$ for very dense canopies ($\phi > 0.3$) [Tanino and Nepf, submitted manuscript, 2007], we estimated that $C_{D\alpha}H/n$ ranges from $O(1)$ (e.g., water lily) to $O(100)$ (e.g., mangrove). In our experiments, the dimensionless drag covered a similar range from 0.6 to 76 (Table 1).

[21] When imaging the exchange flow, the back of the tank was illuminated with four 40 W fluorescent lights to enhance contrast. Tracing paper was used to diffuse the light. When the gate was removed, the salt water flowed along the bottom because of its larger density, while the fresh water flowed along the free surface. The whole experiment was captured by a Pulnix TM-6702 CCD.
camera with a resolution of $640 \times 480$ at a rate of 1 fps. The CCD camera was mounted on a tripod in front of the tank, and the distance between the camera and tank was set as long as possible (5.4 m) to minimize the parallax error (less than 1%).

[22] The images were analyzed using the Matlab image processing toolbox. First, the images were converted from grayscale to binary pictures. The threshold was manually chosen such that the binary images gave the best agreement with the original images. At each longitudinal position, the height of the interface was identified at the transition from white to black pixels. For the cases with solid volume fraction, $f$, up to 9%, the toe velocity in each region was calculated from the displacement of the toe at both the bed and the free surface between two consecutive images divided by the time interval between these two images.

For the cases with high solid volume fraction, i.e., $f > 0.09$, the flow in the canopy could not be imaged clearly with the camera because too much of the domain was blocked by cylinders. The velocity of the toe for these cases was estimated by visual tracking and manually timing the movement of the toe between fixed points with a stopwatch. The velocity in the vegetation, $u_v$, was then used to calculate the drag coefficient from equation (1) and the empirical relations given by Tanino and Nepf [2008].

At each time point, the total volume intruding into the open region per unit width, $V_o$, was estimated by integrating the interface over $x < 0$. A similar estimate was made for $V_v$, the volume intruding into the vegetation, with corrections made for $f$. The discharge rate, $q_o$ (or $q_v$), was calculated as the difference of $V_o$ (or $V_v$) between two consecutive images divided by the time interval. The discharge rate, $q_o$, was measured in every case ($f = 0$ to 0.35), but $q_v$ could only be measured up to $f = 0.09$. At higher solid volume fraction, the visual obstruction from the array introduced too much error to provide a reliable estimate of $V_v$.

### 4. Results

[24] After the removal of the gate, the gravity currents start to propagate. Figure 2 shows the temporal evolution of the interface in both the open region and the canopy for case 26. The time interval between each curve is 4 s. At the first
time step (bold line in Figure 2a), the interface resembles that of a classic inertial exchange, with the two currents having nearly equal depth ($h/H \approx h_s/H \approx 0.5$). A pronounced head is also present at the toe of each current. Shortly after, however, the exchange flow deviates from the classic inertial evolution. The toe of the current in the open region continues to propagate at a constant speed, but the toe in the canopy decelerates. In the open region the top of the outflowing gravity current is horizontal, as in a classic inertial exchange, but the thickness of the current is less than that observed in a classic lock exchange; that is, $h/H < 0.5$. In the vegetative region, as the current intrudes farther into the canopy, the height of the current at the toe decreases and the interface gradually becomes linear. At the fifth profile ($t = 20$ s), the interface is clearly linear within the vegetation (Figure 2b). From equation (18), the transition to drag-dominated flow occurs at $t_0 = 6$ s for this case. However, linear profile is expected to be developed after $t_0$, i.e., after the transition to the drag-dominated regime, because the interface has some memory of its initial shape.

Note that undulations are observed along the interface in the open region. These reflect mixing and overturning that result from the strong shear along the interface between the inflow and outflow. Similar mixing and undulation have been observed in free gravity currents (e.g., Figure 9 from Shin et al. [2004]). Within the canopy, however, the presence of the vegetative drag suppresses the instability leading to overturning, as discussed by White and Nepf [2007] (e.g., see their Figure 21) and no mixing is observed along the interface within the canopy. Finally, at the transition to drag-dominated flow, the depth of the current intruding into the vegetation, $h_s$, has increased to 0.62 $H$, where it remains for the duration of the experiment. The same progression was seen for each value of $C_D a H/n$, with the final $\alpha = h_s/H = 0.70 \pm 0.05$ (data not shown, standard deviation across the observed cases). There was no correlation between $\alpha$ and $\phi$.

The length of the gravity current in the open region increases linearly with time, indicating that the toe velocity in the open region, i.e., the slope of $x_o(t)$, is constant (Figure 3). The velocity of the toe in the canopy, however, decreases over time, due to increasing drag ($C_D a L$); that is, the slope of $x_v(t)$ is decreasing. The same development is observed in all cases. As an example, the positions of the toe in the open region and in the vegetation, $x_o$ and $x_v$, respectively, normalized by the water depth, $H$, are shown for case 26 (Figure 3). The time, $t$, is normalized by $\sqrt{g H}$.

The toe velocity in the open region, $u_{to}$, is not a strong function of canopy drag parameterized by $C_D a H/n$. 

Figure 2. (a) Evolution of the entire interfacial profile and (b) a close up of the region within the vegetative model for case 26. The time interval between each curve is 4 s. Cylinder array occupies $x > 0$.

Figure 3. Temporal evolution of the toe position in the open region, $x_o$ (dots) and the vegetated region, $x_v$ (open circles) for case 26.
For the standard cases, i.e., open region gravity current at the bed (solid circles), $u_o/\sqrt{g H} = 0.40 \pm 0.04$ (standard deviation). For the reversed cases, i.e., open region gravity current at the surface (open circles), $u_o/\sqrt{g H} = 0.47 \pm 0.05$ (standard deviation). For gravity currents propagating along the bed (Figure 4, solid circles), the observed Froude number, $F_H = u_o/\sqrt{g H}$, is smaller than the theoretical prediction for inertial gravity currents, $F_H = 0.5$ [Benjamin, 1968]. However, a diminished Froude number has been observed in other studies as well, e.g., $F_H = 0.42$ [Shin et al., 2004] and is attributed to the viscous drag associated with the bed. For the reversed cases, in which the gravity current propagates along the free surface (shown as open circles in Figure 4), the Froude number is actually greater than 0.5 for some cases. Simpson [1997] found similar results in an open rectangular tank, observing a Froude number of 0.59 for the surface current.

The fact that the velocity of the open current does not change with canopy drag is somewhat surprising because the depth of the current in the open region, $h$, decreases with increasing canopy drag, $C_D a H/\nu$ (Figure 4b). One might expect $u_o$ to adjust following equation (5), but a shift in velocity scale is not observed until $h$ grows quite small, $h/H < 0.2$, which corresponds to $h \leq 2$ cm in these experiments (Figure 4c). The constant value suggests that the current propagating into the open region has its speed set by the initial inertial conditions, $u_i$ (i.e., equation (3)). The data

Figure 4. (a) Normalized toe velocity in the open region, $u_o/\sqrt{g H}$, versus canopy drag, $C_D a H/\nu$. The mean of the standard cases (solid circles) is shown by the horizontal line. (b) The variation of the normalized thickness of the current in the open region, $h/H$, with $C_D a H/\nu$. The dashed horizontal line is the thickness of the current along the bottom for the cases when $\phi = 0$. (c) The variation of the normalized toe velocity in the open region, $u_o/\sqrt{g H}$, with $h/H$. In each subplot, the open circles represent the reversed cases, i.e., current propagating into the open region at the surface, which are denoted by an asterisk in Table 1. The upward- and downward-facing triangles represent currents along the bottom and surface, respectively, for the classic cases ($\phi = 0$).
suggest that $u_e$ may become sensitive to array drag for $C_D a H/n > 10$, declining as drag increases. For these cases, the initial inertial transient may be too short to imprint upon the frontal velocity. Indeed, for these cases, $t_0 < 0.5$ s. In addition, the shallowness of the layer for $C_D a H/n > 10$, as can be seen in Figure 4b, enhances the bed drag; that is, as $h$ decreases, the bottom shear stress $\tau_w \sim \rho u_e h$ increases. For $h < 2$ cm, the bed stress may become sufficiently significant to slow the current.

Next, we consider the current propagating into the model canopy. When the flow has reached the drag-dominated state, the front velocity, $u_e$, decelerates slowly because of the drag exerted by the cylinders. The toe velocity in the canopy is then given by equation (9). The scale constant, $S$, in equation (9) can be determined by fitting the observed frontal length, $L_o$, to equation (11). The following normalization collapses all the cases, indicating that this scaling is universal:

$$L_o = \left( \frac{3}{2} \right)^{2/3} L_v \left( \frac{nH^2}{C_D a} \right)^{-1/3},$$

$$\hat{t} = t \sqrt{\frac{g}{H}}$$

Using equations (20) and (21), equation (11) can be written as

$$\hat{L}_o^{3/2} = \sqrt{S}(\hat{t} - \hat{t}_0).$$

Equation (22) implies that $\hat{L}_o^{3/2}$ is proportional to $(\hat{t} - \hat{t}_0)$, and the constant of proportionality is $\sqrt{S}$. Here, we remark that $t_0$, as predicted by equation (18), is in the range of 0.06 to 6 s in our experiments; that is, the transition from inertia to the drag-dominated regime is short compared to the duration of the experiment, $\alpha(50)$, even for the very sparse cases.

Figure 5 shows the evolution of $L_v$ with $\hat{t}$ for $\phi$ ranging from 0.03 to 0.09. Although experiments with $\phi$ as high as 0.35 have been conducted, the temporal evolution of $L_v$ cannot be detected with sufficient resolution for $\phi$ higher than 0.09. The scale constant, $S$, can be obtained by evaluating the slope of the curves (which is essentially $\sqrt{S}$) in Figure 5. The value of $S$ falls between 0.5 and 0.7, with no correlation with $\phi$ over this range. Tanino et al. [2005] obtained a similar value, $S = 0.6$, in their study of exchange flow contained within a uniform canopy (see Figure 1b). Given that no correlation with $\phi$ is detected, we anticipated that $S = 0.6$ will apply at higher $\phi$ as well.

In the drag-dominated regime, the total volume of water entering the canopy array is given by equation (14), which can be written in the following dimensionless form,

$$\hat{V}_o = \alpha(\hat{t} - \hat{t}_0)^{2/3},$$

in which $\hat{V}_o$ is given by

$$\hat{V}_o = \frac{V_o}{\left( \frac{3}{2} \frac{nH^2}{C_D a} \right)^{1/2}}.$$

Since the volume discharge into the open region, $V_o$, equals the volume discharge into the array, $V_v$ and $V_o$ can be measured more reliably, the discharge into the open region has been used to evaluate the relationship shown in equation (23). $\hat{V}_o$ versus $\hat{t}$ is shown in Figure 6 for the cases where $\phi$ ranges from 0.03 to 0.14. For the cases where $\phi = 0.20$ or 0.35, the difficulty in visualizing the flow within the canopy makes it difficult to estimate $C_D$ with less than a factor of 2 uncertainty. Since the normalization is sensitive to $C_D$, these cases are excluded. Although the data do not collapse perfectly, $V_o$ in all cases follows the same trend, specifically nonlinear in time. The best fit for the experimental data is

$$\hat{V}_o = (0.63 \pm 0.18)[\hat{t} - (0.1 \pm 1.1)]^{0.74 \pm 0.08}.$$
different cases, \( \dot{q}_o \) was estimated at the dimensionless time, \((t - t_0) = 10\), for each case. The solid line represents the theoretical prediction (equation (26)) evaluated at \((t - t_0) = 10\) with \(S = 0.6\) and \(\alpha = 0.7\), which were found experimentally, as shown in Figures 5 and 6, respectively. The dashed lines are the upper and lower bounds of the theoretical prediction. The open circles represent the reversed cases. The parameters \(S\) and \(\alpha\) used to calculate \(q_o\) were obtained by fitting the data for \(\phi < 0.14\).

5. Field Applications and Limitations

[35] Using the theoretical and empirical relations developed in section 4, we now consider the evolution of the exchange flow in real field systems. During the daytime, because of shading by emergent vegetation, water within a canopy absorbs less solar energy than the adjacent open water. The density difference associated with this differential absorption of energy will drive an exchange flow. This situation is sketched in Figure 9a. The differential heating associated with vegetative shading was recently observed in a wetland [Lightbody et al., 2007]. The water depth, \(H\), was 0.5 m. The marsh grass, Zizaniopsis miliacea, had a solid volume fraction \(\phi = 0.1\), and the diameter of the stem was 3 cm. The average diurnal variation in water temperature in the canopy and in the adjacent open water is shown in Figure 9b. The temperature difference was nearly zero from midnight to early morning, then increased gradually to reach the peak value of \(\Delta T = 2^\circ\)C around 4:00 P.M. EST, and finally decreased to zero again at midnight. This temperature record will be used to estimate the density-driven exchange flow as it varies over the course of the day. The drag coefficient, \(C_D\), is assumed to be equal to one, which is reasonable for this solid volume fraction. The transient time scale, \(t_0\), is estimated from equation (18) to be less than 50 s, which is short compared to the time scale of the thermal variation in the daily cycle. Consequently, the inertial transient can be neglected and a quasi-steady estimate of flow should be reasonable. We divide the period (from 10:00 A.M. to midnight) into 1 h subdivisions and apply equation (11) to estimate the intrusion length, \(L_t\), at the end of each hour. The volume discharge, \(V_t\), occurring in each hour in response to the temperature variation in Figure 9b is shown in Figure 9c. In a single day the exchange flow can theoretical value does not go back to 0.5 as \((t - t_0)\) goes to zero.
penetrate \( \sim 100 \) m into the vegetation. This suggests that if the band of vegetation is less than 100 m in width, it can be fully flushed each diurnal cycle. The average discharge rate per unit width during the 12-h cycle is \( 1.7 \text{ m}^3 \text{ m}^{-1} \text{ h}^{-1} \), which is the same of order of magnitude as the mean flow through the vegetative band of this wetland, \( 1.8 \text{ m}^3 \text{ m}^{-1} \text{ h}^{-1} \), as measured by Lightbody et al. [2007]. Therefore, the thermally driven exchange flow adds significantly to the total flushing in this wetland.

When applying our model to field conditions, we assume that the flow structure is two layer, even though the stratification is likely to have a more continuous vertical structure. Many studies in the field, lab, and numerical domain have considered exchange flows driven by differential heating. In each case, the temperature profiles are forced by the absorption of solar radiation, which results in continuous stratification. However, in each case the resulting flow is a two-layer exchange [Andradottir and Nepf, 2001; Oldham and Sturman, 2001; Coates and Ferris, 1994; Coates and Patterson, 1993; Farrow and Patterson, 1993]. Multiple intrusions have not been observed. Therefore, the two-layer exchange observed in our study appears to be consistent with what would be observed in the field. [37] To evaluate the potential impact to a broader range of systems, we have repeated the above scenario for 1 m deep water and for a range of canopy densities, representing the most sparse to most dense canopies observed in the field. The intensity of radiation is assumed to vary over the day, with peak radiation intensity \( I_0 = 400,600 \) and 800 Wm\(^{-2}\) s\(^{-1}\). This produces variation in \( \Delta T \) of the same form as shown in Figure 9, with peak value \( \Delta T_0 \). Figure 10 shows the predicted average discharge rate over a daily cycle as a function of \( C_{\gamma d}aH/n \) and \( I_0(\Delta T_0) \). Figure 10 can be used to compare to other flushing mechanisms, and thus it provides an easy way to evaluate the significance of the density-driven exchange flow in different systems.

The spatial extent of flushing from within a canopy is given by the maximum penetration of the front, \( L_v \). For the cases shown in Figure 10, the maximum \( L_v \) ranges from \( O(400) \) m for low-density canopies \( (C_{\gamma d}aH/n = 1) \) to \( O(100) \) m for high-density canopies \( (C_{\gamma d}aH/n = 100) \). It is useful to compare this length scale with the spatial footprint of
exchange associated with wind-driven currents. First, consider wind-driven currents running parallel to a canopy edge (Figure 11a). As described by White and Nepf [2007], these currents penetrate a distance into the canopy of scale \((C_{DA}/C0)^{1}\) and, therefore, contribute to canopy flushing only over this length scale. For typical field values, \((C_{DA}/C0)^{1}\) is on the order of 1 m or less. Second, consider wind-driven currents approaching perpendicularly to the canopy edge (Figure 11b). Assuming the canopy blocks all wind stress at the water surface, the flow into the canopy is quickly decelerated by the canopy drag over the length scale \((C_{DA}/C0)^{1}\), e.g., by Jackson and Winant [1983]. The associated surface setup can drive an exchange flow near the edge of the canopy. In both scenarios, wind-driven currents can promote flushing only over scales of the order of 1 m. Whereas density-driven currents can promote flushing over tens to hundreds of meters. Thus, thermally driven exchange is likely to be the dominant vehicle for flushing of littoral regions with dense vegetation.

A limitation of the model discussed here is that it does not explicitly account for bed drag in the open region. In the field, flow exiting a region of sheltering, emergent vegetation may encounter submerged vegetation, which would enhance the bed drag. On the basis of our experimental observations, the velocity in the open region may be diminished because of this bed drag. However, the total discharge rate would still be controlled by the emergent canopy drag and, therefore, unchanged. A slower velocity in the open region due to bottom drag would simply cause the thickness of this current to increase. In addition, because of the diminished velocity, material flushed from the canopy will not be distributed as far from the vegetation edge. Although unlikely, if the bed drag in the open region becomes comparable to that in the emergent canopy, the conditions will revert to those described by Tanino et al. [2005], with total exchange dependent upon the drag throughout the entire flow domain.

Finally, the present work is limited to the condition of uniform temperature over depth. Under field conditions, the absorption of solar radiation in water decreases exponentially away from the surface according to Beer’s law and heating may not occur over the full depth. If solar radiation penetrates less than the water depth, we expect, on the basis of the work by Coates and Patterson [1993] and Coates and Ferris [1994], that the vertical extent of the resulting exchange current will scale on the extinction depth. However, the velocity scales should follow a dependence on canopy drag similar to that described here. In addition, the present work assumes that the solid volume fraction, \(\phi_s\), of aquatic vegetation is constant over water depth. Vertical structure in \(\phi_s\) would impact the vertical structure of the velocity, but to first order, the total exchange should still scale on the depth-averaged solid volume fraction, \(\phi_s\), as reflected in the depth-averaged \(C_{DA}H/n\).

6. Conclusion

The density-driven exchange flow between open water and adjacent vegetation has been studied using a lock exchange experiment. Unlike a classic lock exchange or the

Figure 10. The variation of the mean discharge rate, \(q_v\), over a daily cycle with \(C_{DA}H/n\) for different radiation intensity \(I_0\) assuming that \(H = 1\) m. \(I_0 = 400\) Wm\(^{-2}\) s\(^{-1}\) (\(\Delta T_0 = 2^\circ\)C) (asterisks); \(I_0 = 600\) Wm\(^{-2}\) s\(^{-1}\) (\(\Delta T_0 = 3^\circ\)C) (crosses); \(I_0 = 800\) Wm\(^{-2}\) s\(^{-1}\) (\(\Delta T_0 = 4^\circ\)C) (pluses).

Figure 11. (a) Top view of canopy with wind-driven currents running parallel to a canopy edge [after White and Nepf, 2007]. (b) Cross-sectional view of wind-driven currents perpendicular to a canopy and exchange flow and resulting flushing currents. Density-driven flushing shown with dashed line, and wind-driven flushing shown with solid line.
exchange flow subject to uniform drag, the exchange flow occurring between two regions of dissimilar drag, i.e., canopy and open water, is asymmetric. The gravity current in the open region moves at a constant speed set by the initial inertial condition, while the speed of the current in the vegetative region is controlled by the canopy drag and decreases with time. The total discharge rate is also controlled by the vegetative drag, decreasing with increasing canopy drag and also decreasing slowly with time. Application of the theoretical model to typical field conditions suggests that thermally driven exchange is likely to be the dominant process in flushing littoral bands of vegetation.

Notation

- \( u_i \): inertia-dominated velocity.
- \( g' \): reduced gravity.
- \( d \): diameter of cylinder.
- \( N \): number of cylinders in a bed area \( A \).
- \( A \): bed area.
- \( a \): frontal area of cylinders per unit volume.
- \( n \): porosity.
- \( \phi \): solid volume fraction.
- \( u_v \): drag-dominated velocity.
- \( S \): scaling constant.
- \( C_D \): drag coefficient.
- \( Re \): cylinder Reynolds number.
- \( \nu \): kinematic viscosity of water.
- \( H \): total water depth.
- \( L \): total frontal length.
- \( L_v \): total frontal length in the vegetated region.
- \( h_v \): thickness of the current entering the vegetation at the edge of the vegetation.
- \( V_v \): total volume per unit width entering the vegetation.
- \( \alpha \): ratio of \( h_v \) to \( H \).
- \( q_v \): volume discharge rate per unit width in the vegetation.
- \( q_o \): volume discharge rate per unit width in the open water.
- \( t_0 \): time scale for the transition from inertia- to drag-dominated regime.

\[ [42] \] The variables with carets are normalized terms.

\[ [43] \] Acknowledgments. This material is based on work supported by the National Science Foundation under grant EAR0509658. Any opinions, findings, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of the National Science Foundation. The authors thank Mirmosadegh Jamali for his insightful comments and suggestions.

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