# FInal Report



**Final Project Report**
**CALFED Science Program Project Number: 1053**
**Original Project Term: July 1, 2007 – June 30, 2010**
**Revised Project Term: July 1, 2007 – June 30, 2011**
**Project Title: The Transport and Dispersion of Rafting Vegetation in the Sacramento-San Joaquin Delta**
**Amount Funded:**

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***Project Summary:***

Our project focused on the dynamics that govern the movement of rafting vegetation in the Sacramento-San Joaquin Delta. Our original approach relied on a combination of field and numerical analysis to develop a mechanistic understanding of how rafts of vegetation respond to both wind and tidal forcing in the Delta. In our initial testing, however, we found that field-based measurements of forces, stresses and accelerations were not sufficiently accurate to develop a mechanistic understanding of raft movement. In view of this, we shifted to a laboratory-based analysis of the interaction of vegetation rafts and the movement of water or air. This approach still led us to a mechanistic understanding of the dynamics of raft movement, and we were also able to examine the detailed structure of the interaction of flows with root canopies, which shapes the local ecosystem for the floating vegetation.


**Budget Summary: Submitted Separately from Extramural Funds Accounting**

**List of Tasks and Activities Performed**

By way of summary, our activity has included field observation, laboratory-based model development, and reporting of our results at conferences and in the peer-reviewed literature. The work funded under this grant also led to a Ph.D. degree for the primary graduate student on the project (Maureen Downing-Kunz, degree to be conferred December 2011). In the next sections, we summarize the scientific findings in each of the first two tasks; the section on Task 3 will describe the publication of results.

Task 1: Field Observations

Lagrangian drifters that log GPS location continuously, which have been developed in another lab here at Berkeley, were used to provide raft trajectories. In order to measure the shear force exerted on the raft, an acoustic Doppler velocimeter (ADV) was used to measure the detailed velocity variability in the boundary layer on the underside of the raft.

In the spring of 2008, a floating frame was constructed of PVC pipe on which we mounted both the GPS drifter and the ADV. The frame was approximately 2 meters on each side, and had sufficient buoyancy to support both the GPS drifter and the ADV. Our first test deployment of the frame was on Lake Merritt in March, 2008, and consisted of about a 30 minute drift for the frame, during which position and water velocities were logged continuously. In Figure 1, this experiment is summarized. The GPS trajectory shows a primarily eastward drift (Figure 1a), as was expected under the forcing from the westerly wind. More importantly, the velocity measurements from the ADV and from the GPS were entirely consistent with one another (Figure 1b, 1c). The raft velocities as determined by the GPS are shown on each figure, as is the ADV velocity after subtracting the raft velocity. The result is a measure of the water velocity, which is seen to be much less than the raft velocity (and, in fact, near zero), as would be expected when the raft is strongly wind-influenced.

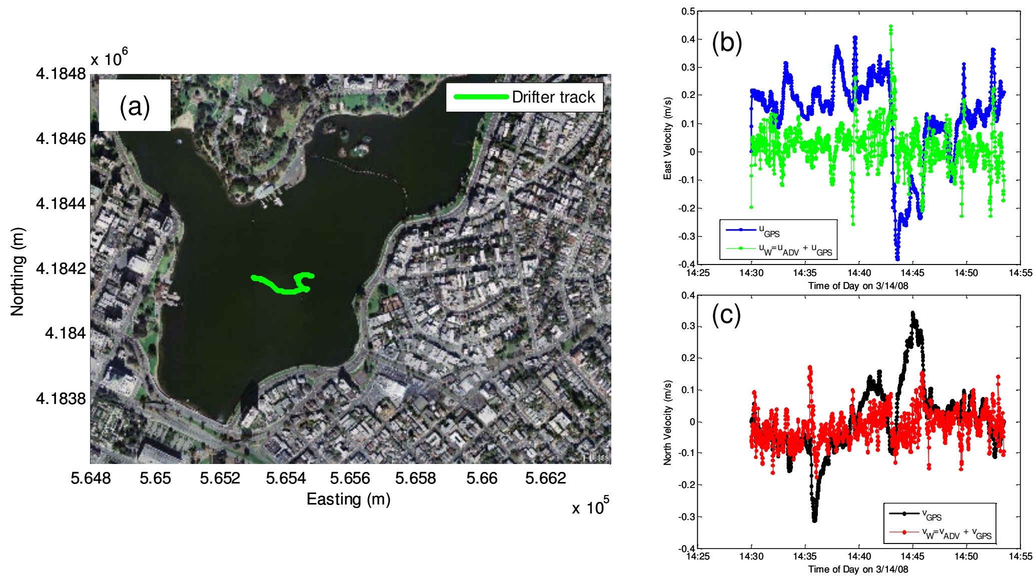


*Figure 1: Overview of Lake Merritt experiment, March 2008. (a) GPS track of raft (green) overlaid on satellite photograph. Eastward drift due to wind forcing, abrupt shift mid-track was due to manual repositioning of the raft; (b) eastward component of raft velocity (blue) and water velocity (green); (c) northward component of raft velocity (black) and water velocity (red).*

A second set of experiments was performed in May, 2008 in the Sacramento-San Joaquin Delta. Here, the frame with GPS and ADV was released at a variety of locations in the Delta to span a wide range of flow and wind conditions. From both of these experiments, we evaluated raft and instrument performance, but were not focused on the effects of vegetation.

Finally, in Summer 2008, we performed a suite of Delta deployments with the Lagrangian drifters incorporated into a raft of vegetation. Additionally, we measured currents and winds using an acoustic Doppler current profiler and an anemometer. It was clear in these measurements (Figure 2) that the rafts responded to both tidal currents and winds, and the dominant forcing changed through the deployment. Unfortunately, the ADV measurements were not sufficiently accurate to resolve the stresses acting on the raft and we found it difficult to constrain the mechanistic transport model based on these field measurements. This is discussed further in the next section.

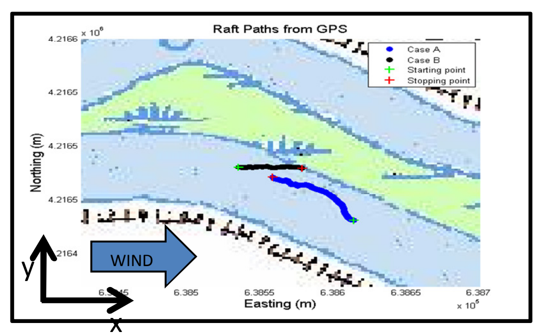


*Figure 2: Raft trajectories during summer 2008 experiment. First release (blue) shows influence of ebbing tide (drift is to the west). Second release (black) demonstrates wind dominance (drift is directly east).*

<u>Task 2: Model Development</u>

Our approach to analyzing raft trajectories focuses on a mechanistic force balance to describe the acceleration of the rafts. This will require an evaluation of the shear stresses that the raft experiences from above and below due to the interaction of the raft with both the air and the water. The basic force balance is described as:

$$M_{raft}\frac{\partial V_{raft}}{\partial t} = A_{raft}\left(\tau_{air} + \tau_{water}\right).$$

where $M_{raft}$, $A_{raft}$ and $V_{raft}$ are the mass, surface area and velocity of the raft, respectively; $\tau_{air}$ and $\tau_{water}$ are the shear stresses the raft experiences on the air and water sides of the raft. For an individual raft, the solution to this equation numerically is straight-forward, and has been developed in matlab.

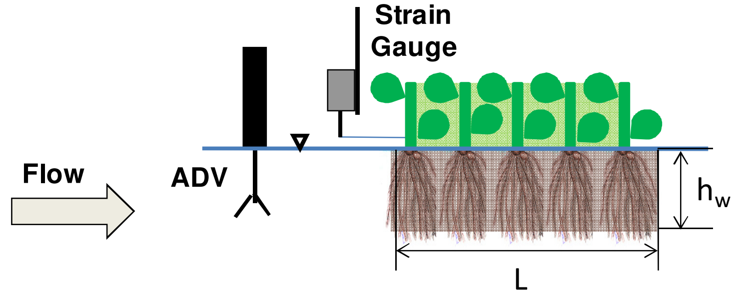


*Figure 3: Schematic of laboratory set-up with acoustic Doppler velocimeter (ADV) to measure mean and turbulent velocities and strain-gauge to measure the total flow-induced force on the raft of hyacinths. Note that we are using actual hyacinths in these experiments, not model replicates.*

Our initial intent was to use field-based measurements of the shear stresses and the accelerations to develop and calibrate this model. Unfortunately, the ADV measurements were not able to accurately resolve the stresses near the raft. Further, form drag appeared to be an important contributor to the water drag force, which was impossible to quantify in the field. Finally, we could not independently measure the drag on the air side of the raft and were relying on the force balance to inform that wind-induced drag.

*Laboratory Measurements: Water-Induced Drag*

In view of all of these limitations, we have now turned to laboratory-based measurements of the forces to establish the underlying dynamics of raft movement. The laboratory set-up is shown in Figure 3 and includes rafts of live water hyacinths placed in a recirculating flume in the hydraulics laboratory at UC-Berkeley. Instrumentation included an acoustic Doppler velocimeter (the lab version is more accurate and smaller in scale, allowing measurements closer to the base of the raft) and a strain-gauge calibrated to measure the bulk force imposed on the raft. The flow facility was restored from other funds and has been made available to this project, as has the necessary instrumentation.

By varying the flow rate in the flume, we have been able to measure the flow-induced force on the raft across a range of Reynolds numbers (Figure 4). The total drag force, as measured with the strain-gauge, increases approximately linearly with Reynolds number (Figure 4a). As a result, the drag coefficient, which relates the drag force to the velocity squared must decrease with Reynolds number, as shown in Figure 4b. The decrease in drag coefficient with Reynolds number implies a shift in the flow structure around the root structure. Separate measurements of the biomechanics of the plants, as well as qualitative observations, suggest that this

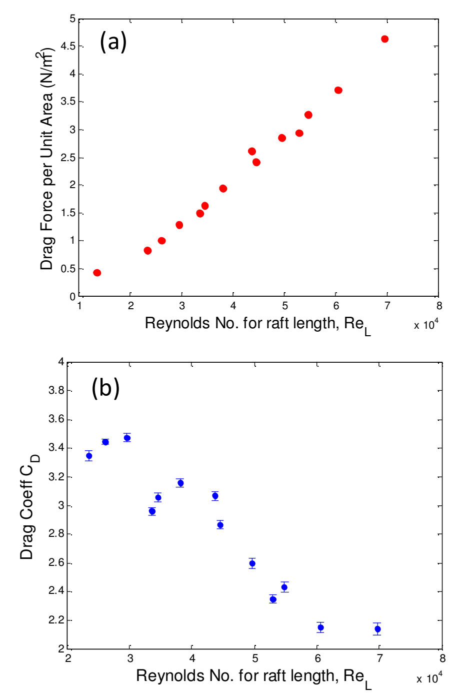


*Figure 4: Variability with Reynolds number (based on raft length) of (a) Total Force exerted; and (b) dimensionless drag coefficient.*

shift is due to a streamlining of the root structure, which reduces the effective drag coefficient.

To examine the flow structure in more detail, we used the ADV to measure both the mean flow (Figure 5a) and the turbulent stresses (Figure 5b) in the volume surrounding the root structure. The increase in mean flow at the base of the roots is due to the constrained nature of the laboratory flow, where the raft blocks a portion of the cross-section and the remaining area must have a higher velocity to conserve mass. The development of a boundary or mixing layer at the base of the raft is clear, however, as is a low-velocity wake behind the raft (flow is from left to right). Each of these features (the mixing layer and the wake) is even more pronounced in the turbulent stresses, with turbulent momentum transfer (as represented by <u'w'>) having maxima both in the mixing layer and at the base of the wake. Understanding this flow structure will inform our modeling of the forces experienced by the raft, and will also allow us to consider mixing and mass transport into the roots.

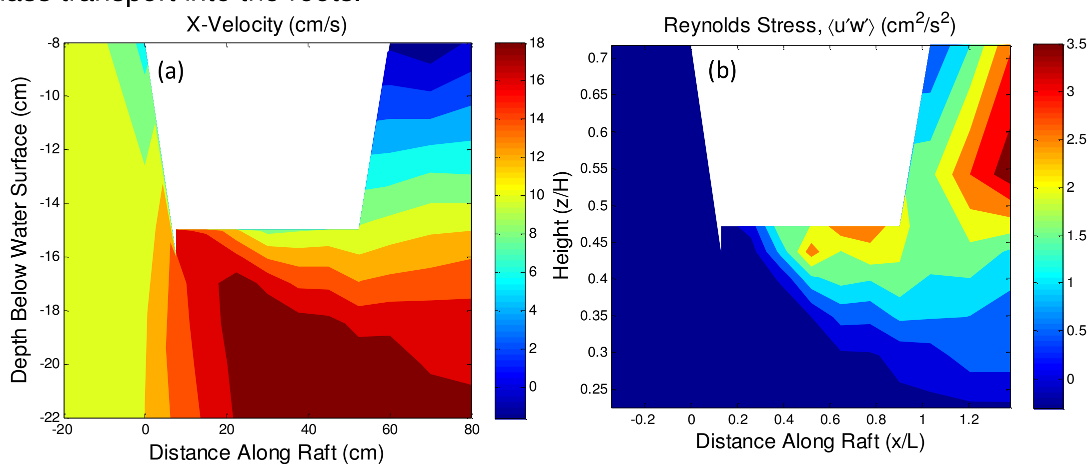


*Figure 5: ADV measurements of (a) mean flow; and (b) turbulent stresses on the underside of raft. White region represents root structure (note vertical axis is at different scale from horizontal for clarity).*

An example of the analysis of the processes responsible for mixing at the base of the root structure is shown in Figure 6. Here, the skewness of the velocity distribution as a function of distance below the raft is shown. The skewness is the third moment of the velocity distribution and is essentially a quantification of asymmetries in the distribution; a Gaussian distribution has no skew. In Figure 6, the upstream skewness for *u* and *w* (horizontal and vertical velocities) is compared to that under the rear part of the raft where the mixing layer appears to be reasonably well-developed (upstream values are the vertical green and blue lines with square symbols overlaid). The skewness is seen to be negative throughout much of the region below the raft, which is indicative of ejections of low-momentum fluid from the roots into the open part of the flow. The dominance of ejections (as opposed to sweeps, which would be the movement of high-momentum fluid into the roots) is consistent with that documented by Raupach et al. (1996) for flow adjacent to a terrestrial vegetation canopy.

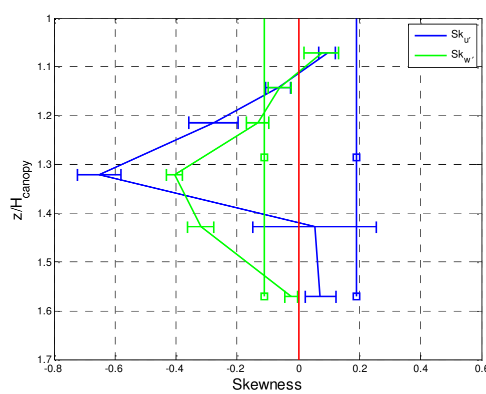


*Figure 6: Profiles of skewness upstream of raft (vertical profiles with square symbols) and beneath downstream one-third of raft (profiles with error bars). Blue is horizontal skewness and green is vertical.*

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Additional analysis of the vertical structure of flow adjacent to the root structure has focused on the use of a mixing layer model to describe our data. In the mixing of two fluid layers with no external drag elements, a hyperbolic tangent velocity profile is expected (e.g. Ho and Heurre, 1984). Comparison of that vertical structure with our observations is made in Figure 7, where the comparison is seen to be remarkably good. At the same time, a persistent error is made near the edge of the roots (i.e. "canopy"), where the observed velocities are lower than the theory both just within and just outside the root zone. We hypothesize that this difference is due to the drag effects of the roots, which extracts momentum from the flow. In a pure mixing layer, this momentum would remain in the flow and the velocity around the mixing layer would be increased. Note that this analysis imposes the two limiting velocities (at top and bottom of Figure 7), so the effects of drag deep within the root zone would not be visible here. We believe our results demonstrate the effects of both the root canopy and the constrained nature of the flow beneath the canopy, which reinforces the shear layer created at the base of the canopy.

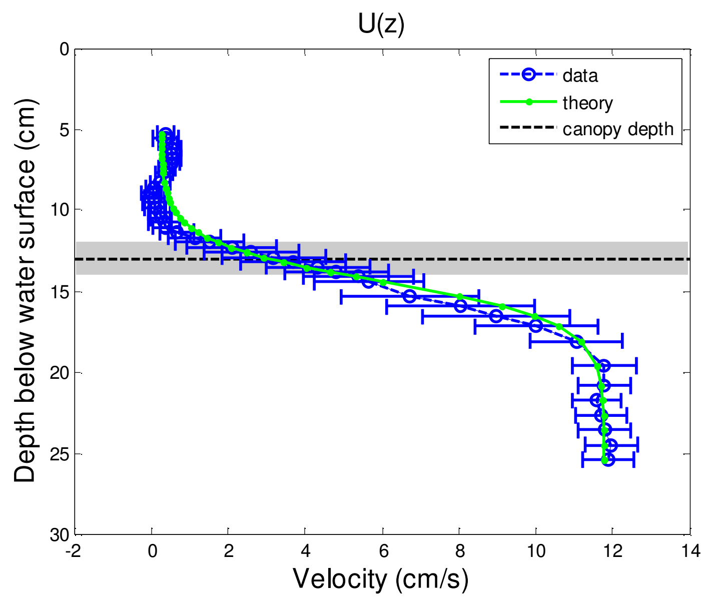


*Figure 7: Comparison of observed velocity profile to mixing layer theory of Ho and Heurre (1984). Observed profile has lower velocity just above and below the canopy limit (i.e., roots).*

*Laboratory Measurements: Wind-Induced Drag*

We have now completed a second set of measurements in another laboratory facility, which consists of a wind tunnel blowing air over a water tank. In this facility (which is also provided from other funds), the same strain-gage measurements of the total force exerted on the raft were made, but in this case the water was motionless and wind was blowing across the upper surface of the plants. Putting these measurements together will all of the water drag measurements (Figure 8), it is evident that the drag coefficient for the air side of the rafts is much smaller than that on the water side. This was a different result than we anticipated, and it suggests that for similar wind and current forcing, the rafts will respond much more strongly to water drag than to air drag. Interestingly, we have found that the drag coefficient on the air side of the raft is *not* a function of the wind velocity in contrast to the water side, which suggests that the streamlining observed in the roots does not occur in the stems.

In addition, a sonic anemometer (acquired with other funds) was used to measure the detailed air velocity distribution above the raft in the same way an ADV was used to quantify the dynamics on the water side of the raft. Preliminary results from this analysis indicates that both the mean flows and the turbulent stresses in the air are similar in structure to those on the water side of the raft. The anemometer data was considerably noisier than the ADV data, however, and our analysis of this data is still underway.

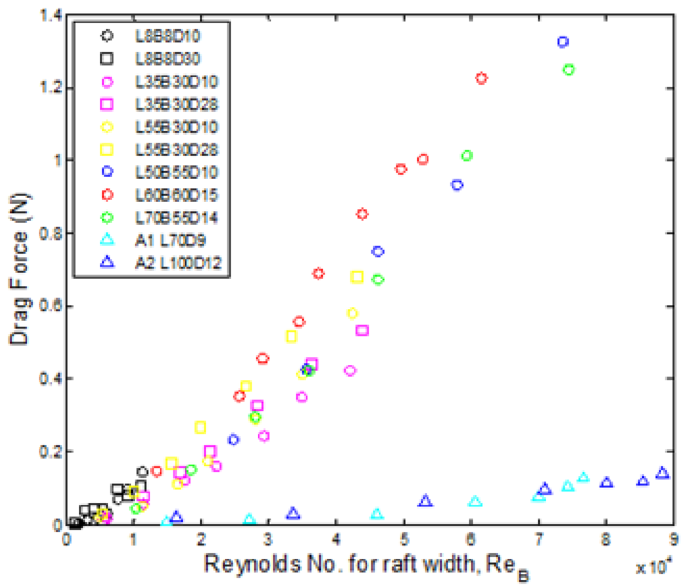


*Figure 8: Compilation of drag force measurements versus Reynolds number based on raft width. Blue triangles are from wind tunnel (i.e., air drag); all other measurements are from flume (i.e., water drag).*

Task 3: Evaluation

A detailed evaluation of the drag forces and their variability with water and wind velocities is the focus of a publication that recently appeared in *Hydrobiologia*. We include a copy of this publication with this report.

The graduate student on this project has now completed a second manuscript that describes the detailed structure of flow around the root structure, which we are submitting to *Limnology and Oceanography: Fluids and Environment*. We have included a copy of this manuscript with this report, but please not that it is still under review and revision and is not yet ready for distribution.

In addition, Maureen is in the process of completing her Ph.D. thesis, which will be conferred in December, 2011. As part of her Ph.D. training, and to further extend the communication of her results, Maureen has made a number of presentations of this work at scientific conferences, including the Bay-Delta Science Conference (fall 2010), a student workshop on Physical Oceanography at the University of Washington (fall 2010) and at the Physical Processes of Natural Waters conference in Guelph, Canada (summer 2011).

Achieved Objectives, Findings and Major Contributions:

Previous analyses of the movement of rafting vegetation have focused on the effects of wind forcing. This is largely due to an emphasis on freshwater environments in which water movement was quite limited. In contrast, the Sacramento-San Joaquin Delta is an energetic *tidal* freshwater environment in which forcing by water movement may dominate the transport of vegetation rafts. In fact, our laboratory measurements, which were reinforced by field observations, demonstrated that water-induced drag forces are likely to dominate the movement of rafts except in the case of very strong wing events (or for limited periods around slack water). This finding justifies a transport modeling approach that incorporates both water and wind forcing into predictions of raft movement. The details of these analyses and results were reported in our *Hydrobiologia* publication (2011).

At a more detailed level, there has been a reasonable amount of research activity looking at how submerged vegetation interacts with the flow moving across the top of the canopy. In the studies performed on this grant, we have (somewhat literally) turned this flow structure on its head by considering flow beneath the root canopy of floating vegetation. There is an important distinction between these two flow environments which is the effect of the bottom boundary that constrains the flow beneath the root canopy. We found that in the case of flow beneath a root canopy, many flow structures were similar to those previously seen in conjunction with submerged vegetation, particularly the development of a mixing layer at the canopy edge. In our measurements, however, a second shear layer, which also produces turbulent stresses, is found to be maintained just outside the mixing layer; we attribute this shear layer to the reinforcement of shear by the constrained flow moving beneath the canopy. This finding is important in that it means that constrained flows, or shallow water flows, interact with canopies in a fundamentally differently way from semi-infinite flows (such as the atmospheric boundary layer, which has received extensive research attention). The details of these results and analyses have been written up in a manuscript that we are submitting to *Limnology and Oceanography: Fluids and Environment*.

Finally, we note that an important educational outcome is the training and development of a Ph.D. student, Maureen Downing-Kunz, who has built her entire Ph.D. thesis around the work funded under this grant. Maureen will have her degree conferred in December 2011, and has begun a position with the U.S. Geological Survey working with David Schoellhamer on Delta transport.

<u>Management Implications of Project Findings:</u>

Our findings now make it possible to pursue mechanistic modeling of rafting vegetation in the Sacramento-San Joaquin Delta. The strong drag force induced by water movement suggests that in the Delta, tidal and river forcing are likely to dominate large-scale dispersion of floating vegetation, but will be perturbed by wind forcing locally. From a management perspective, this implies that only local distributions would be expected to be set by wind and that strategies informed by tidal transport and dispersion will be more effective at the scale of the Delta.

<u>Project Deliverables:</u>
We have been strongly focused on communicating the results of our research activity to both managers and the scientific community. As such, Maureen Downing-Kunz has made several presentations of our work, each with a slightly different emphasis. These presentations have included:

- Brown Bag Seminar, Sacramento, CA, November 2010
- Bay-Delta Science Conference, Fall 2010
- Student Workshop on Physical Oceanography at the University of Washington, Fall 2010
- Physical Processes of Natural Waters conference in Guelph, Canada, Summer 2011

Based on the work presented at these conferences, we have also produced a Ph.D. thesis and two manuscripts for the peer-reviewed literature. The first of these has already appeared in *Hydrobiologia*:

Downing-Kunz, M. and Stacey, M.T. "Flow-induced forces on free-floating macrophytes," *Hydrobiologia*. DOI 10.1007s/10750-011-0709-1. 2011.

The second manuscript is complete and ready for submission to *Limnology and Oceanography: Fluids and Environment*:

Downing-Kunz, M. and Stacey, M.T. "Observations of mean and turbulent flow structure in a free-floating macrophyte root canopy," to be submitted to *Limnology and Oceanography: Fluids and Environment*, August 2011.